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Holocene environmental change resets lichen surface dates on Recess Peak glacial deposits in the Sierra Nevada, California

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ABSTRACT

Development of an accurate chronology for glacial deposits in the Sierra Nevada has long been problematic given the lack of suitable organic material for radiocarbon dating. Lichenometry initially appeared promising as ages showed an increase from cirque headwalls to down-canyon moraines. However, while Recess Peak lichen age estimates range from 2 to 3 ka, recent work shows these deposits to be at least 10 ka older. Here, we present evidence for a late Holocene reset of Recess Peak lichen ages by significant post-depositional climate change. Following late-Pleistocene deposition of Recess Peak moraines, warming through the mid-Holocene allowed forests to advance into shallow basins eliminating local inverted tree lines. This produced a partial canopy where shading killed the original post-Pleistocene crustose lichen colonies. Late-Holocene cooling resulted in forest retreat from these basins as alpine tree line fell. Lichens then recolonized the re-exposed Recess Peak deposits. We conclude that while Recess Peak lichen ages are accurate to within the dating uncertainty of the technique, existing lichen ages actually date the timing of post-mid-Holocene cooling and recolonization, and not the original emplacement of these deposits. Thus, applications of Lichenometry should consider post-depositional environmental change when interpreting the meaning of these dates.

Introduction

Reconstructions of middle-to-late Holocene glacial/environmental change in the Sierra Nevada, until recently, were limited by a pronounced lack of radiocarbon datable macrofossils (Pohl et al., 1996; Clark and Gillespie, 1997). In the absence of direct radiocarbon dating, the relatively unweathered Recess Peak advance found between 3000 and 3400 m from Yosemite National Park on the north to Cottonwood Basin on the south (Burbank, 1991; Clark and Gillespie, 1997), was first interpreted as post-mid-Holocene climatic optimum using boulder weathering relative dating approaches (Birman, 1964; Burke and Birkeland, 1983; Scuderi, 1984). However, recent dating of organic debris from lakes (Clark and Gillespie, 1997; Bowerman and Clark, 2004), moraines and pro-glacial lake deposits (Konrad and Clark, 1998), chironomids (Potito et al., 2006) and macroscopic charcoal (Hallett and Anderson, 2010) allowed the development of a more comprehensive chronology of environmental variation where the Recess Peak advance is now recognized as being late Pleistocene (~13,500–12,500 cal yr BP) in age. Subsequent work (Clark and Gillespie, 1997) suggested that there was a single post 700 cal yr BP late-neoglacial Matthes advance, an interpretation that implies a relatively ice-free Holocene Sierra Nevada, with possibly only minor advances, between 11,000 and 700 yr ago.

This Sierran Holocene chronology was refined in recent years (Konrad and Clark, 1998; Bowerman and Clark, 2004, 2011) to include multiple neoglacial advances with the earliest occurring at ~3200 ^{14}C yr BP (3400 cal yr BP) and the latest and most extensive equivalent to the Matthes Little Ice Age advance at ~250 to 170 cal yr BP. This latest advance overrode earlier neoglacial advances, eliminating most evidence of these earlier cold intervals. This newest revision places Sierran neoglacial history in line with chronologies worldwide with multiple and distinct glacial maxima that show glacial advance and significant climate change following early to mid-Holocene climatic warmth (Gillespie and Clark, 2010).

Lichenometry was initially used in the Sierra Nevada by Curry (1969) and Scuderi (1984, 1987a) as a means to establish the age of moraine stabilization on Recess Peak and Matthes age moraines but has since proved to be problematic. Used successfully in similar environments worldwide (Denton and Karlen, 1973; Benedict, 1993; Beget, 1994; Benedict, 2009), its application in the Sierra Nevada provides ages that are far too young for Recess Peak deposits in light of the most recent dating. While possible circular reasoning in Curry's (1968, 1969) dating control points (discussed in Clark and Gillespie, 1997) may explain a portion of the discrepancy, we note that the environmental setting in which the Sierran Recess Peak moraines were emplaced may complicate the interpretation of lichen ages.

In Cottonwood Basin (Fig. 1) cirque glaciers heading along the main crest of the Sierra Nevada 2.5 km west of our study site produced a complex of blocky moraines covering a low-lying depression ~1 km^2. Similar to Recess Peak deposits found throughout the Sierra

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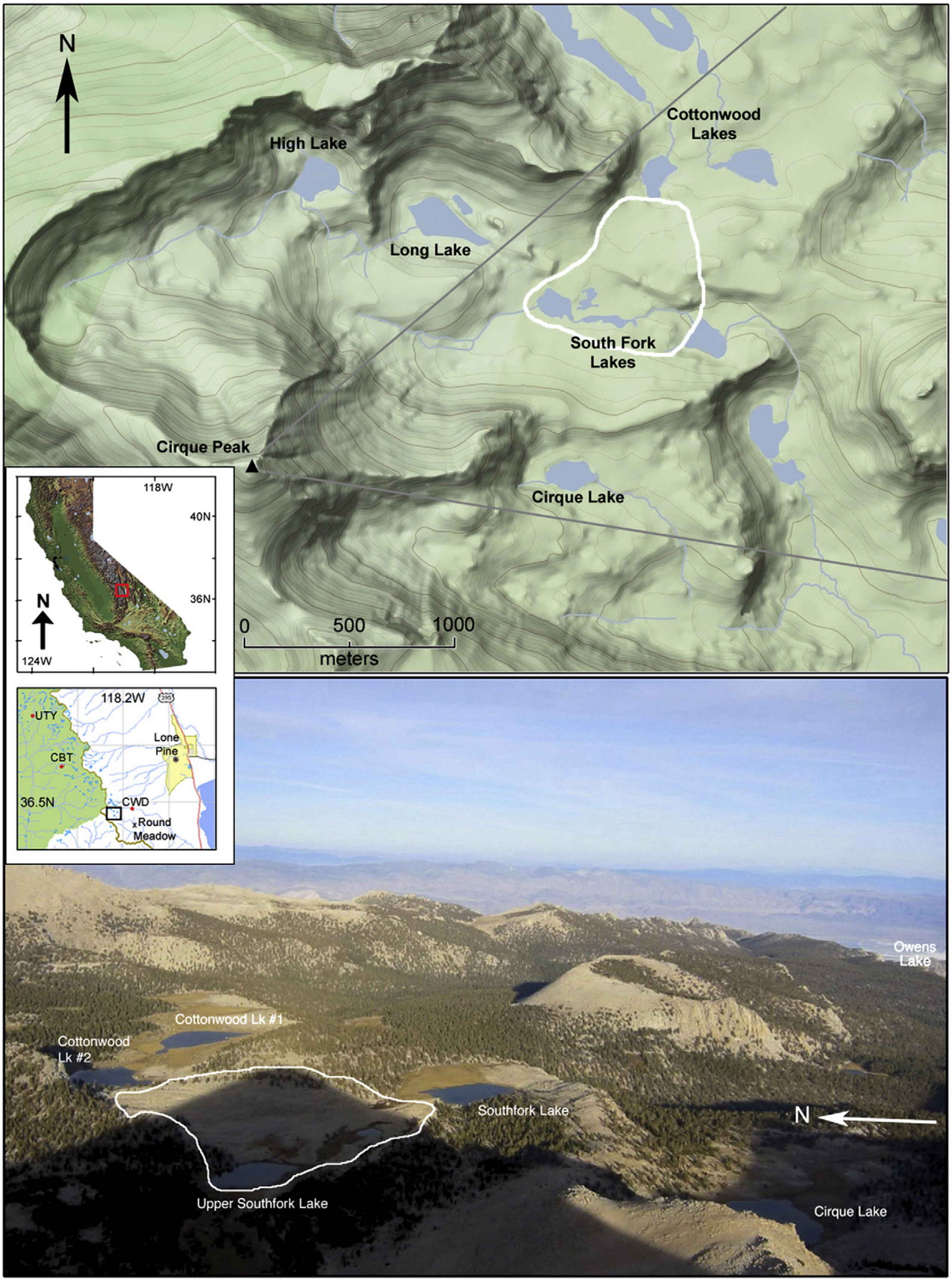

Figure 1. Top: Southern portion of Cottonwood Basin with area of Recess Peak glacial deposits indicated with white border. Gray lines indicate sight lines of lower image. Bottom: Cottonwood Basin looking northeast from the summit of Cirque Peak. The study area inverted treeline is outlined in white and contains Recess Peak moraines. The tree line examined in this study is at the apex of the shadow of Cirque Peak. Other areas of cold-air collection and inverted treelines can be seen around Cottonwood Lakes 1 and 2 and at Southfork Lake. Scale varies across image. Boxes on inset maps show location of study site. Red dots indicate weather station locations (UTY — Upper Tyndall Creek, CBT — Crabtree, CWD — Cottonwood). Black X indicates location of the Round Meadows/Horseshoe Meadow inverted tree line sensors.

Nevada (Birman, 1964; Scuderi, 1987a; Clark and Gillespie, 1997) these deposits look fresh, are stabilized, and are primarily treeless with a substantial lichen cover.

In this paper we discuss the implications of environmental setting on lichen growth and survival, and specifically focus on the possible role of cold air pockets that produce inverted tree lines that may have influenced lichen colonization and survival. We provide evidence that suggests that the largest lichen thalli on Recess Peak deposits may represent recolonization that began ca. 4200 yr ago following an interval of warmer climate and forest expansion.

Methods

To better understand why lichen ages appear to underestimate the true ages of Recess Peak deposits, we examined the geomorphology and ecology as well as the modern climatic and paleoclimatic setting of Recess Peak deposits in the Cottonwood Basin of the southern Sierra Nevada (Fig. 1). We radiocarbon-dated pieces of remnant wood from foxtail pines in several basins that contain both alpine and inverted tree lines, characterized the degree of weathering of individual samples and associated standing snag cohorts, quantified the modern climatic setting of the basins, and mapped the distribution of lichen ages with respect to modern inverted tree lines and relict wood locations.

Remnant wood

The study was conducted within a large portion of the Recess Peak moraine complex surrounding South Fork Lakes within Cottonwood Basin that were originally mapped and lichen-dated by Scuderi (1984). Three separate *in-situ* tree stumps (samples SFLP01, SFLP02, SFLP03) discovered during transects across the middle of the now treeless moraine complex were documented (Fig. 2) and sampled for radiocarbon dating. The area adjacent to the Recess Peak moraines was mapped and sawn samples were collected from nine samples from standing dead snags (SFL2002-01 to SFL08) (Fig. 3, Table 1). Samples used for AMS radiocarbon dating represent the outermost 30 to 50 rings of trees that averaged 1000 and 1500 yr old for standing snags and stumps found in growth positions within the Recess Peak moraines and 700 to 800 yr in age for trees at the edge of the morainal area.

To test our hypothesis that similarly weathered and colored/stained remnant snags from different elevations are representative of growth within the same timeframes, we radiocarbon and dendrochonologically dated additional samples of each of three cohorts. Two samples of heavily weathered and deeply stained wood from the upper limits of tree line on Cirque Peak (Scuderi, 1987b) (Cohort 1) with similar surface weathering characteristics (color, degree of weathering) to those found in the center of the Recess Peak moraine area were used for comparison of older wood specimens. Additional representative samples from standing snags 30 m above the Cirque Peak tree line (Cohort 2) (Scuderi, 1987b, 1993) as well as samples at the current tree line (Cohort 3) with known dendrochonologic ages were used for these comparisons.

Lichenometry

Recess Peak deposits were mapped and dated using the lichen growth curve for the highly abundant brown to blackish *Lecidea atrobrunnea* (Ram.) Schaer. (Curry, 1968, 1969; Scuderi, 1984, 1987a). Maximum diameter, mean maximum diameter for the five largest lichens, and percent lichen cover, were recorded for each of 100 boulders on each moraine within the Recess Peak complex. In addition, weathering characteristics including erosion-pit depth and a measure of boulder roundness were recorded at each sampling location.

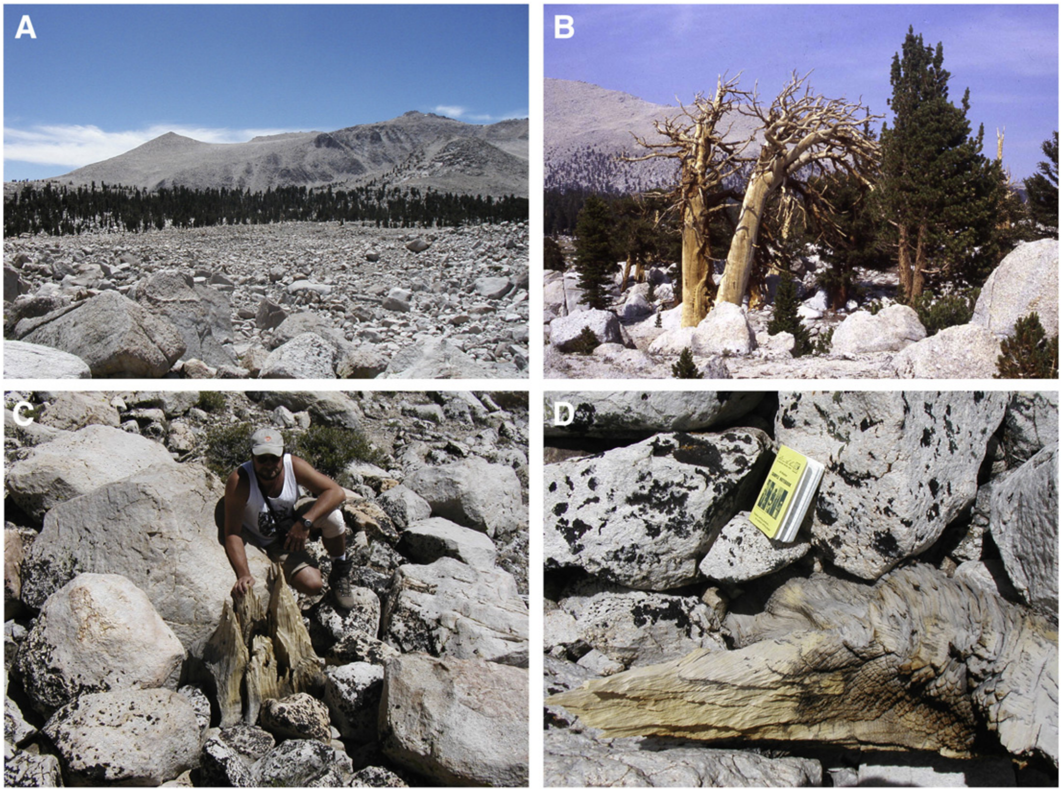

Figure 2. Details of the modern inverted treeline basin containing Recess Peak deposits. (A) Recess Peak deposits with the edge of the inverted treeline basin, (B) living and late Holocene standing snags with krummholz of cohort 2 of foxtail Pine (*Pinus balifouriana*) at the margin of the modern inverted tree line, (C) a mid-Holocene relict stump of foxtail pine in growth position in the center of the inverted treeline basin (SFLP02), (D) second example of a mid-Holocene relict stump in growth position (SFLP03). Notebook for scale.

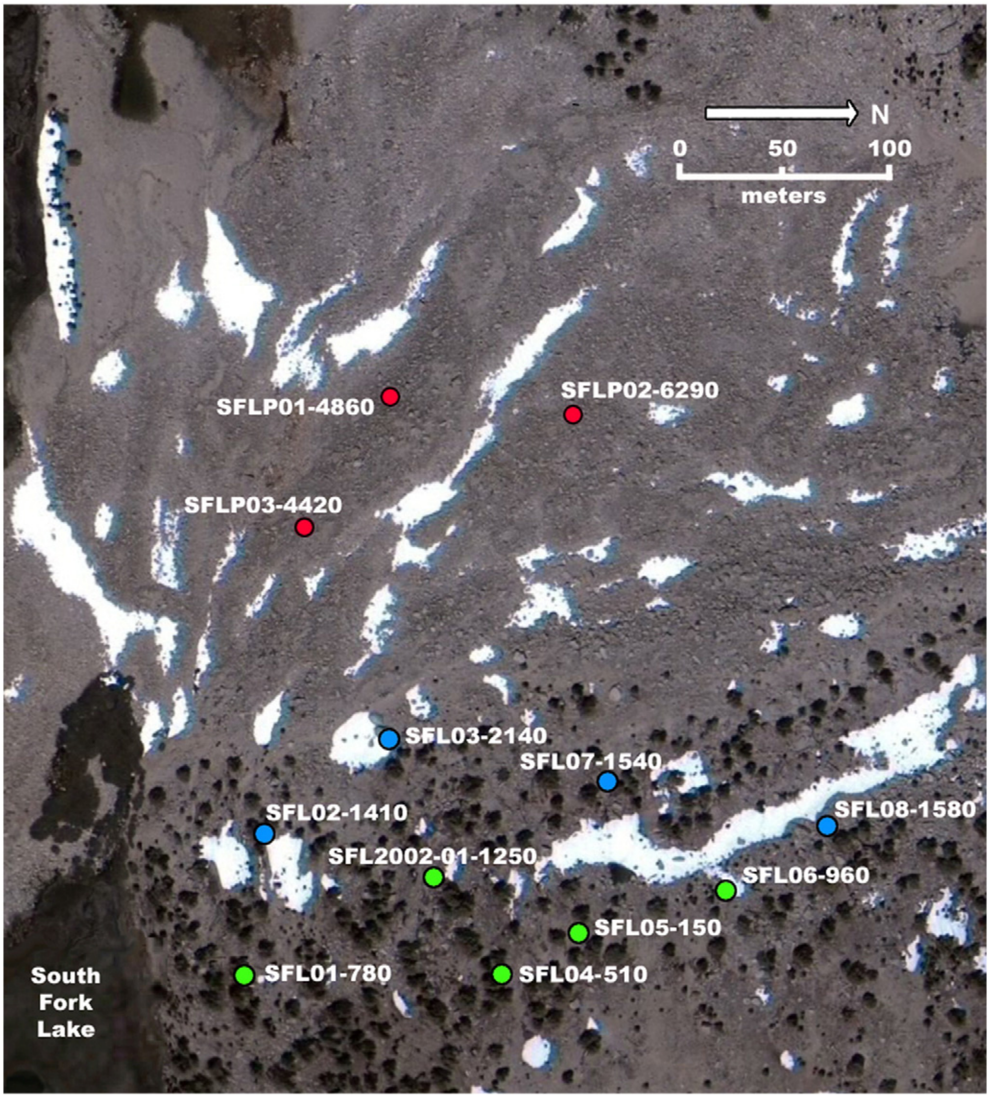

Figure 3. Location of radiocarbon-dated samples from standing snags near South Fork Lake (SFL) and from *in situ* dead stumps on unvegetated surfaces within the moraine complex (SFLP). Cirque headwall ~2 km to top (west) of image. Cohort 1 (highly weathered, dark-colored resinous wood) indicated in red. Cohort 2 (moderately weathered, light-colored wood) indicated in blue. Cohort 3 (lightly weathered, light-colored wood) indicated in green. Sample number followed by median age, cal yr BP.

Ground-based sensors

To provide a framework for understanding temperature variability at alpine tree line and within the lower elevation inverted treeline basins, we monitored temperatures at multiple locations for 3 to 7 yr. Temperature variability at tree line was evaluated with ground-based temperature sensors (HOBO Pendant Temperature Data Logger—UA-001-64, Onset Corporation). Three sensors emplaced along a transect on Cirque

Table 1
Radiocarbon dating of wood samples sorted by age (Calibration after Reimer et al., 2004).

Cohort[a]	Sample	Measured ^{14}C age, ^{14}C yr BP (1 σ)	^{13}C-corrected age, ^{14}C yr BP (1 σ)	Median age, cal yr BP	Calendar date	2-sigma calendar date
1	SFLP02	5440 ± 80	5490 ± 80	6290	4340 BC	4500–4070 BC
1	SFLP01	4260 ± 70	4330 ± 70	4860	2910 BC	3330–2700 BC
1	SFLP03	3910 ± 60	3970 ± 60	4420	2470 BC	2830–2290 BC
2	SFL03	2100 ± 50	2160 ± 50	2140	190 BC	360–50 BC
2	CP048	1830 ± 60	1900 ± 60	1860	AD 100	40 BC- AD 240
2	SFL08	1610 ± 60	1700 ± 60	1580	AD 370	AD 170–530
2	SFL07	1560 ± 50	1650 ± 60	1540	AD 410	AD 250–540
2	SFL02	1480 ± 50	1540 ± 60	1410	AD 540	AD 410–640
3	SFL2002-01	1230 ± 60	1290 ± 60	1250	AD 700	AD 650–880
3	SFL06	970 ± 50	1060 ± 50	960	AD 990	AD 870–1150
3	SFL01	820 ± 60	890 ± 60	780	AD 1170	AD 1030–1250
3	SFL04	380 ± 50	460 ± 50	510	AD 1440	AD 1330–1620
3	SFL05	80 ± 50	160 ± 50	150	AD 1800	AD 1660–1950

[a] Cohort 1: dark-colored, highly weathered, resinous wood. Cohort 2: light-colored, highly weathered wood. Cohort 3: lightly weathered, light-colored wood.

Peak beginning ~80 m below tree line (3520 m, CP1) and extending to near the current limit of growth (3566 m, CP3) cover the period from July 1998 to July 2001. Estimation of the magnitude of temperature inversions in low-lying areas was evaluated using an array of 18 temperature sensors emplaced along a transect extending from Round Meadow to Horseshoe Meadow (centered on 36.441°N, 118.176°W, 3020 m) with data collection between September 2006 and August 2012.

Additional temperature data from similar environmental settings was compiled using hourly data from existing weather stations at Upper Tyndall Creek (UTY: 36.650°N, 118.397°W, 3474 m, 8/03/1988–present), Crabtree Meadow (CBT: 36.563°N, 118.345°W, 3261 m, 10/01/1985–present), Chagoopa Plateau (CHP: 36.497°N, 118.442°W, 3139 m, 10/14/1986–present) and Cottonwood (CWD: 36.483 N, 118.177 W, 3094 m, 1/28/1986–present) (CDEC, 2011). All measurements were assessed for data inconsistencies and recording errors and corrected for systematic data offsets.

Results

Timing of Holocene forest-cover changes from remnant wood

Due to the similarities in weathering characteristics, wood color, resin content and overall density to samples from the adjacent Cirque Peak tree line (Scuderi, 1984, 1987b, 1993) we postulated that weathering characteristics could be used to approximate the age of other remnant wood samples in the southern Sierra Nevada. In order to examine this possibility we split the samples into three cohorts (Table 1) corresponding in appearance to similar material from tree line on Cirque Peak and generally similar to that found across alpine and inverted tree line transitions throughout the southern Sierra Nevada.

Cohort 1 (7500–4500 yr ago)

The similarity of wood characteristics from rooted stumps within the lower elevation Recess Peak moraine complex (SFLP01, 02 and 03) to ~30 highly weathered remnants from near the mid Holocene alpine growth limit (~60 to 75 m above the current alpine tree line) suggests that both populations have a similar weathering history and length of exposure. Two existing radiocarbon-dated samples from highly resinous and dark-colored wood previously obtained from the highest level of alpine tree line in the region (Scuderi, 1987b) with calibrated dates of 6300 cal yr BP (UCLA 2418-A) and 3530 cal yr BP (UCLA 2463-C) are comparable to those dated from within the moraine complex (6290 to 4420 cal yr BP, Fig. 3, Table 1) and support our assumption of similar exposure time and weathering histories for these samples.

Cohort 2 (4500–1500 yr ago)

A second cohort of heavily weathered/light colored standing snags at the edge of the moraine complex (Fig. 1, white bounded area, Fig. 2A,B) was compared to dendrochronologically dated snags of known age from a similar appearing weathered cohort approximately 25 to 35 m above tree line on Cirque Peak (Scuderi, 1984: Samples CP046 to CP065, unpublished field data). The time of death of a single representative sample from tree line (CP048), radiocarbon-dated to 1900 ± 60 ^{14}C yr BP, compares well with the range of dates of cohort 2 snags at the edge of the moraine complex between ~2160 ± 50 and 1540 ± 60 ^{14}C yr BP. These standing snags are likely part of a cohort that germinated in the region between 3300 and 2600 yr ago and died during a 700-yr interval between 2100 and 1400 yr ago. Large populations of remnant snags with similar weathering characteristics (currently undated) are found throughout Cottonwood Basin and in surrounding canyons suggesting that they are coeval with snags with similar appearance at alpine tree line.

Cohort 3 (1250–150 yr ago)

Outer rings from a zone of dead but lightly weathered and light colored snags interfingering with living trees at the edge of the inverted tree line produced radiocarbon dates that indicate that these snags died between 1250 and 150 cal yr BP. Age/size relationships suggest that these trees germinated between ~1800 and 900 yr ago. These snags are similar in appearance to those found at the transition between living and dead trees at modern alpine tree line at 3560–3600 m in the southern Sierra Nevada. Past work (Scuderi, 1984, 1987a, 1987b) indicates that the time of death of the alpine tree line portion of this cohort dates between 1200 and 300 yr ago.

Lichenometry

Lichen dating of morainal crests using Curry's (1968, 1969) lichen curve (Fig. 4, Table 2) reveals a pattern of lichen ages that range from a minimum of 2700 yr old near the outer edges of the Recess Peak deposits to a maximum of 3700 yr near the center of the complex. These dates are comparable to those derived from interpolation of lichen curves from western North America (Fig. 5 lines B, C and D).

While the majority of dates are in excess of 3000 yr old there is a spatial pattern of larger thalli that suggests that the central area saw earlier lichen colonization with progressively later lichen colonization towards the outer edges of the area. New surface colonization appears to have terminated ca. 2700 yr ago. This relationship is especially clear in the age progression of moraines from younger at the outer edge of the area (moraines 12, 14 and 17: 2700, 2850 and 2900 yr old, respectively) to older in the center on moraines 20 and 21 (3700 and 3600 yr old respectively) (Fig. 4, Table 2). This diffusion pattern is counter to what would be expected if moraine ages were dependent on position down canyon with younger moraines closer to the cirque headwalls and strongly suggests that the lichen dating pattern that we observe is influenced by factors other than age alone.

Temperature measurements

The Recess Peak deposits in the study occur within shallow basins that are currently treeless due to cold air pockets forming at locally inverted tree lines. Here cold-air collection coupled with down slope drainage can produce air pockets at night resulting in minimum temperatures well below those in the surrounding forests (Paton, 1988; Coop and Givnish, 2008; Shi et al., 2008). Within forested areas these depressions produce inverted tree lines where tree establishment, growth, and survival may be limited by cold temperatures. Like their counterparts at upper tree line, inverted tree lines are impacted by temperature variability. However, unlike an upper tree line that moves upward during prolonged warming and downward during prolonged cooling, inverted tree lines move in the opposite direction with respect to temperature change.

Conceptual models of inverted tree line dynamics suggest that low overnight temperatures are produced by thermal inversions, and are often coupled with cold air drainage from higher elevation slopes. Even during the warmest months of the summer, cold-air drainage causes freeze damage and photo-inhibition that regularly eliminates new seedlings (Coop and Givnish, 2008; Shi et al., 2008). Hence, trees at inverted treeline boundaries are likely to be very sensitive to temperature variability, with this variability possibly altering their ability to survive extreme temperature minimums and affecting their migration in and out of these cold pockets.

Comparison of mean daily temperature at Upper Tyndall Creek (UTY) and the slightly higher elevation Cirque Peak (CP) site shows a high degree of correlation between the two ($R^2 > 0.90$, prob. < 0.0001) with mean annual temperature at CP between 0.25°C and 0.84°C colder depending on the elevation of the CP sensor. This corresponds to an average annual lapse rate of ~9.0°C/1000 m. Both the Cottonwood (CWD) station data and Round Meadow (RM) sensors on the drier eastern slope are significantly colder (2.0 to 3.0°C) than predicted using this lapse rate.

Comparison of the Round Meadow (RM) and Cottonwood (CWD) monthly mean temperature records between 2006 and 2012 (Fig. 6)

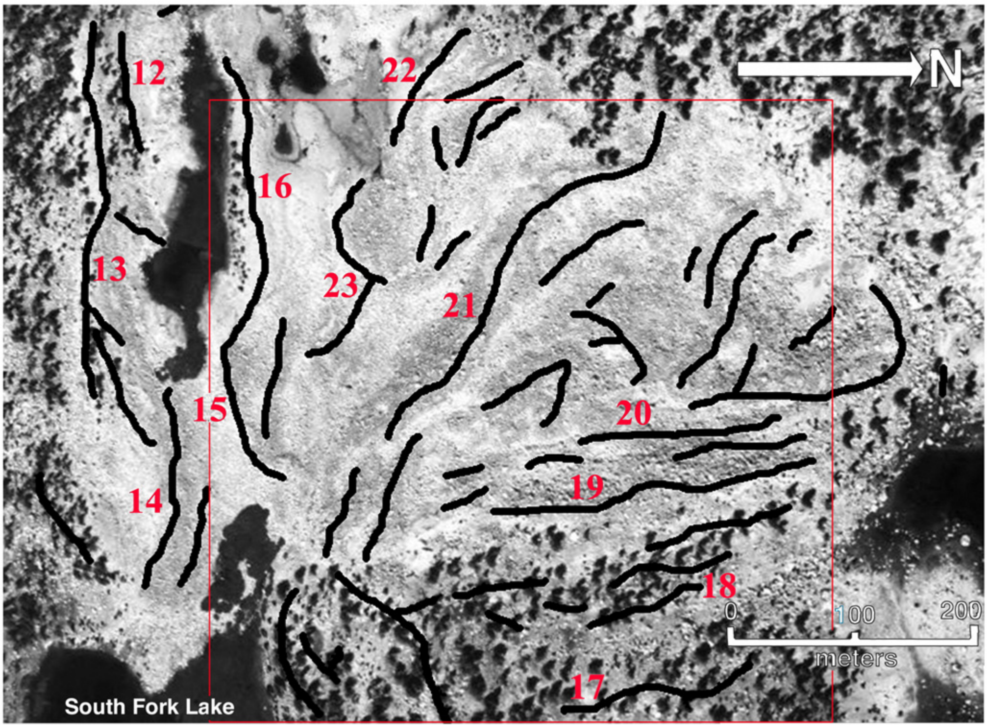

Figure 4. Recess Peak moraines near South Fork Lake. Numbers correspond to surfaces dated by lichenometry listed in Table 2. North is to the right. The cirque headwall is ~2 km from the top of image. Red box is area mapped in Fig. 3.

shows a lower level of correlation (R^2 ranging from 0.63 to 0.74, Prob. values < 0.0001) with the RM inverted tree line site experiencing significantly colder temperatures at night and higher temperatures during the day. This relationship is especially strong at the meadow/forest inverted tree line boundary where nighttime temperatures are on average approximately 3.6°C lower than those in more protected full-forest environments at the Cottonwood station. Random nighttime temperature sampling during the summer season, as well as satellite derived temperature estimates suggest that minimum temperatures in the lower portions of the meadows may be several degrees colder, and especially on calm nights with little turbulent mixing.

Absolute minimum temperatures at the inverted tree line sites are 2 to 3°C colder than those recorded both at higher-elevation meteorological stations and at the Cirque Peak tree line, and more than 3°C colder than those recorded at the nearby CWD station with daytime temperatures up to 2°C warmer in open areas exposed to full sunlight. Based on these observations it appears that these open sites create both extreme temperature variation and, due to their exposed nature, extreme radiation stress that severely impacts the ability of trees to survive (Ball et al., 2006; Coop and Givnish, 2007, 2008).

Table 2
Lichen thalli size measures, percent cover and lichen dating within the Recess Peak moraines. Maximum values for each parameter in bold italic. Minimum values underlined. Moraines 1–11 are found closer to the cirque headwall at higher elevations, exhibit smaller lichen thalli (Scuderi, 1984, 1987a) and were not covered by forests at any time during the Holocene. Max (mm) is the size of the largest thalli measured, MeanMax5 (mm) is the average of the five largest thalli, and Percent Cover is the portion of the total boulder surface covered by lichen thalli. Age (yr) after Curry (1969) shown as SierraA lichen curve in Fig. 5.

Moraine #	Max (mm)	MeanMax5 (mm)	Percent cover	Age (yr)
12	145.79	126.89	20.08	2700
13	151.38	142.54	20.48	3100
14	146.30	129.03	26.59	2850
15	148.34	145.89	20.44	3200
16	158.50	153.52	26.36	3500
17	147.32	130.56	20.60	2900
18	155.96	150.47	29.33	3400
19	159.51	152.91	23.70	3500
20	**175.26**	**165.30**	20.88	**3700**
21	171.70	157.99	**31.00**	3600
22	163.07	147.12	23.04	3250
23	151.38	140.61	16.00	3100

Discussion

Alpine and inverted tree lines

Our results suggest that the forest and meadow inverted tree line boundaries of Cottonwood Basin are analogous to that of local alpine tree line and that the causal mechanisms that produce them are probably similar. The high diurnal temperature range and low nighttime temperatures coupled with radiation extremes at both tree lines likely inhibit growth and seedling survival through photo-inhibition and freeze damage (Blennow et al., 1998; Germino et al., 2002; Ball et al., 2006; Coop and Givnish, 2007; Coop and Givnish, 2008). This produces a forest edge response over time that may also be highly sensitive to climate variability. As such these inverted tree lines and the locations of relict populations of the cohorts may contain a paleoenvironmental record as comprehensive as that found at upper tree line.

Using our knowledge of Sierran Holocene tree line dynamics and climatic variation Scuderi, 1987b; Clark and Gillespie, 1997; Konrad and Clark, 1998; Bowerman and Clark, 2011), we can construct a model of how alpine and inverted tree lines may have responded to climate change during the Holocene (Fig. 7) and use this to infer how this change might have impacted lichen colonization and survival. We note that at some locations in the southern Sierra Nevada the movement of alpine tree line upwards allowed trees to directly invade cold air pockets and as such the two tree lines are the same. However, in Cottonwood Basin area during the Holocene these two tree lines were, and still are, at distinctly different elevations forming separate alpine and inverted tree lines.

Following the late-Pleistocene Recess Peak advance of ~12,000–13,000 yr ago (Fig. 7a) (Clark and Gillespie, 1997), glacial retreat and warming temperatures allowed trees to advance into cold air pockets at lower elevations within Cottonwood Basin at the same time that alpine tree lines were being established at higher elevations on the surrounding peaks (Fig. 7b). In western North America alpine tree lines reached maximum elevations between 8000 and 5000 yr ago (LaMarche, 1973; Scuderi, 1987b) likely coincident with the timing of forest expansion into lower-elevation inverted tree line sites. In the Cottonwood Basin study area it appears that the Recess Peak moraines may have had a partial forest canopy cover during this interval. Large stumps in the center of the cold-air pocket suggest that these trees may have been in excess of 1000 yr old at the time of their deaths.

In response to cooling climate from ~5000 to 3000 yr ago trees retreated down-slope at alpine tree line (LaMarche, 1973; Scuderi, 1987b) and conditions that initially produced cold-air pockets and inverted tree lines at the end of the Pleistocene once again began to dominate low-lying areas. Following this initial neoglacial cooling, living trees survived on Recess Peak moraines for ca. 500 to 700 yr due to growth-persistence (Scuderi, 1994; Lloyd and Graumlich, 1997) and microclimatic effects that reduced temperature extremes and radiation loading. Trees first disappeared from the coldest portions of the cold-air depressions ~3500 to 3000 yr ago (Fig. 7c) and eventually stabilized near the current inverted treeline boundary within the last 1000 yr (Fig. 7d) producing the pattern of apparent lichen ages within the moraine complex. During this interval modern alpine tree lines were being established at ~3600 m on the surrounding mountainsides.

The remaining wood from this early-to-mid Holocene forest cover decayed as climate transitioned to the colder and wetter conditions of the late-Holocene leaving a small amount of resinous, heavily weathered and dark-colored wood above the modern tree line at Cirque Peak as well as similar *in situ* rooted stumps near the center of the lower elevation Recess Peak moraine area in Cottonwood Basin. Because of this weathering loss that appears to be ubiquitous across the southern Sierra Nevada, it is unlikely that significant quantities of wood older than ~6500 yr remain. Due to this preservation limitation, tree-ring reconstructions from high-elevation sites in the Sierra Nevada may be limited to the last 7000 yr.

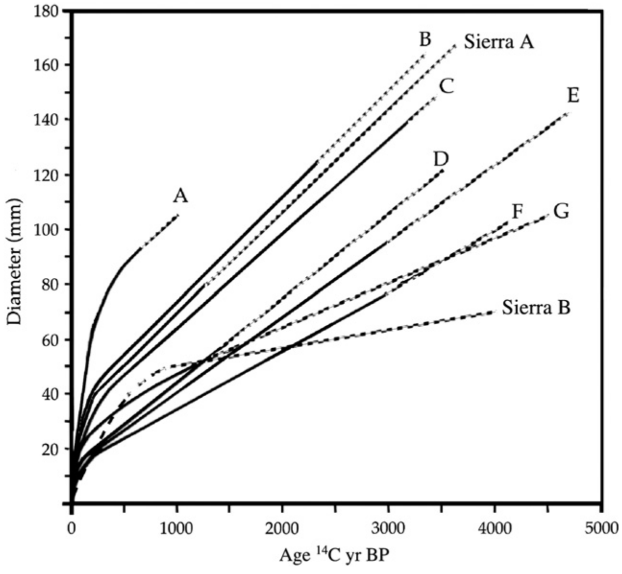

Figure 5. Published lichen growth curves for *Rhizocarpon*. Solid portions of curves indicate calibrated lichen dating while dashed portions are extrapolations that should be used with caution. (A) Tasman Glacier, New Zealand, (Gellally, 1982), (B) Central Alaska Range, United States (Beget, 1994; Wiles et al., 2010), (C) Wrangell-St Elias Mountains, United States (Denton and Karlen, 1973), (D) Colorado Front Range, United States (Benedict, 1993, 2009), (E) East Baffin Island, Canada (Miller and Andrews, 1972), (F) Kamchatka, Russia (Savoskul and Zech, 1997). (G) Cordillera Blanca, Peru (Rodbell, 1992), (SierraA) lichen growth curve for *L. atrobrunnea*, Cottonwood Basin, California, United States (Scuderi, 1984, 1987a) cross-referenced from Curry's (1968, 1969) Sierra Nevada *Rhizocarpon* curve. (SierraB) Lichen growth curve for *Acarospora* and *Rhizocarpon*, Muir Pass, California, United States (Konrad and Clark, 1998). The divergence of the SierraB curve from other lichen curves illustrates the problems introduced by using only younger lichens to extrapolate lichen ages. Figure modified from Benedict (2009).

The distribution of radiocarbon dates (Fig. 3, Table 1) reveals that the oldest trees were located near the center of the moraine complex, while the youngest are found at the edge of the area where living trees and standing snags interfinger. The three samples (SFLP01-03) from cohort 1 located in growth positions within the moraines have outer rings that date to between 6300 and 4400 cal yr BP suggesting germination between 7300 and 5100 yr ago assuming an average age of 700 to 1000 yr at the time of death.

Crustose lichens

Lichen growth reflects a complex interplay between climate and local site exposure (Bradwell, 2009; Armstrong and Bradwell, 2010) with crustose lichens responding to a range of environmental factors including temperature, moisture availability, and light availability (aspect, shading, light intensity). Reduced growth rates have been associated with surfaces experiencing low light intensity (Armstrong, 2005) possibly related to a shorter thermal operating period (Bradwell, 2001). However, studies of lichen growth under varying light-exposure conditions remain inconclusive (Orwin, 1972; Innes, 1985; Mahaney, 1987; Spence and Mahaney, 1988).

Comparisons of crustose lichen growth on boulder faces with a range of insolation regimes show that while an aspect preference exists for some crustose species (Birkeland, 1973; Bradwell, 2001) moderate-to high-insolation sites show no differences in growth. However, growth rates at low-insolation sites are significantly lower and half as fast as those from at medium insolation levels (Haworth et al., 1986). This suggests that low light levels can significantly inhibit lichen growth in alpine environments. At the forest–open area interface different lichen species have been shown to respond differently to different light intensities (Pardow et al., 2010) and the effects of shading may significantly reduce crustose lichen growth rates. It is possible that a partial forest, with perhaps as little as 30 to 40 percent cover, and much like that we believe may have existed in the Cottonwood Basin Recess Peak moraine area during the mid Holocene, may totally eliminate most crustose lichens.

Taking into account the effects of light shading on lichen growth, the pattern of Holocene climate change and forest cover can help guide the interpretation of lichen surface ages. In the absence of late Pleistocene

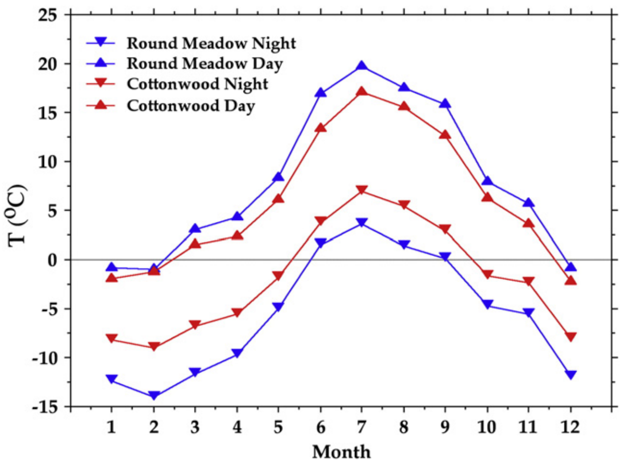

Figure 6. Monthly mean maximum and mean minimum temperatures from sensor and station data (2006 to 2012) for two sites at similar elevations (~3000 m). Higher maximum and lower minimum temperatures at the inverted forest edge Round Meadow site relative to the forested Cottonwood site indicate that climatic conditions at the forest edge and within inverted tree line areas may preclude tree establishment and survival. Inverted tree line environmental conditions are as extreme as those found above local alpine tree line (3400 m).

to early Holocene wood remnants, we assume that lichens established themselves during the late-Pleistocene and early-Holocene on newly exposed Recess Peak moraines. For the first few thousand years they grew unimpeded and their size distribution in the early Holocene might have looked much like what we see today. By ~8000 yr ago continued warming allowed trees to encroach on these moraine deposits. The reduction in light intensity at first reduced lichen growth and then, with a denser partial forest cover in place, eliminated most crustose lichens on the shaded moraine surfaces. Based on our observations of lichen free surfaces at tree line and in open-forest areas surrounding our study site this lichen removal may take place with percent cover as low as 30 to 40%.

Conditions remained unchanged with little to no lichen growth until a decrease in temperature ~4200 to 3500 yr ago (Scuderi, 1984, 1987a). The subsequent death of trees in the reformed cold-air pockets (3700 to 2800 yr ago) again exposed Recess Peak surfaces with lichen colonization resetting the lichen clock. Most of the study area Recess Peak deposits were devoid of tree cover by ~3000 yr ago thus explaining the range of lichen ages between 3700 and 2850 yr ago reported by Scuderi (1984, 1987a).

We note that a few small areas with excessively large lichens and a lichen cover approaching 100% are found in the study area (Scuderi, 1984 and unpublished field notes). Extrapolation of the lichen curves of either Curry (1969, Fig. 3, Curve Sierra A) or Konrad and Clark (1998, Fig. 3, Curve Sierra B) suggests an age in excess of 8000 yr. However, we note, as do Konrad and Clark (1998), that such extrapolations must be used with caution and that the operational limit of lichenometry in the Sierra Nevada may be ~3000 yr. These isolated areas probably represent what Recess Peak moraines might have looked like today without forest encroachment during the early Holocene. We also note that alternative explanations, such as snow kill (Koerner, 1980; Porter, 1981; Benedict, 2009) or the effects of chemicals associated with needle fall may eliminate lichen cover and explain some of the patterns that we observe. However, we also note that if snow kill produced the lichen colonization patterns that we document, we would expect that such events would have occurred later in the Holocene rather than during early-to-mid Holocene warm conditions.

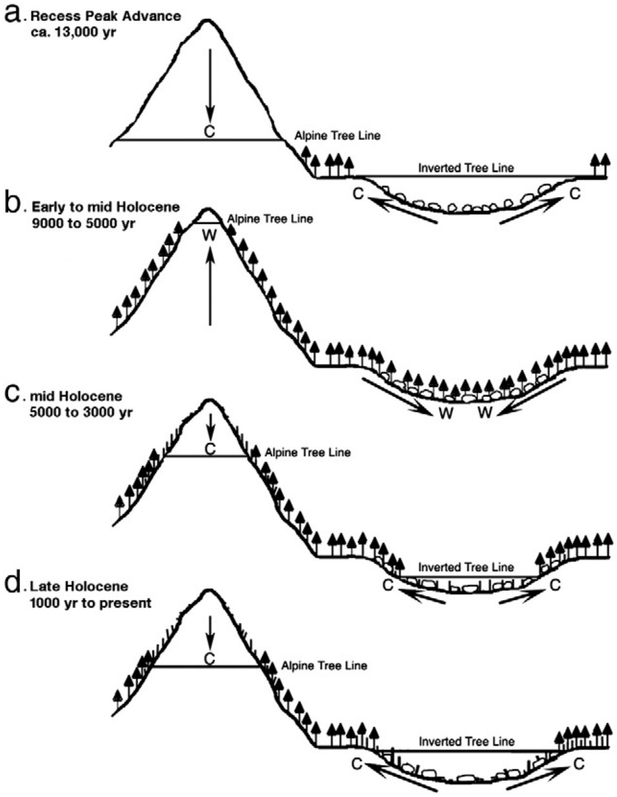

Figure 7. Hypothesized alpine and inverted tree line boundary change from the late Pleistocene to present. a. Alpine tree line was lower during the late Pleistocene while inverted tree line cold air pockets were larger in size. Lichens colonized these open areas post-Pleistocene glacial retreat. b. During the warming early-to-mid Holocene, alpine tree line moved higher while within the basins cold-air pockets diminished in size and became tree-covered. Shading from this tree invasion killed off the lichen cover that had been established after the Recess Peak advances. c. At the end of the mid Holocene, and in response to cooling conditions, alpine tree line moved lower with cold air pockets increasing in size. This reestablished an inverted tree line, exposed the Recess Peak deposits to recolonization by lichens and reset the lichen clock. d. Continued late-Holocene cooling produced continued downward movement of alpine tree line and further expansion of cold-air pockets. In all panels C refers to cooling climate and W refers to warming climate.

The timing of Holocene environmental change in the Sierra Nevada documented by our lichen ages and radiocarbon dating of relict forest wood is well corroborated by other paleoclimatic records in the western U.S. Early- to mid-Holocene maximum warming is shown by treeline expansion in the Sangre de Cristo range in northern New Mexico (Jiménez-Moreno et al., 2008), and by buried soil carbon isotopic compositions in the central great plains (Nordt et al., 2007). A chironomid temperature record from the northern Sierra Nevada also shows peak Holocene temperatures by 6500 yr ago (Potito et al., 2006) and cooler temperatures by ~3500 yr ago. The neoglacial advance in the Big Pine Creek area of the Sierra Nevada (approximately 80 km to the north of our study site), shows the first glacial advance at ~3200 yr ago (Bowerman and Clark, 2011), which is very close in time to the first lichen colonization dates from our study area.

Our results suggest that the significant underestimation of the timing of moraine exposure by lichen ages is best interpreted as the result of changing environmental conditions that reset the lichen clock. In the case of Recess Peak deposits in the Sierra Nevada, initial post-glacial surface lichen growth was killed off by early to mid-Holocene warming and forest expansion that shaded the lichen colonies. Neoglacial cooling starting ca. 4000 yrs ago caused an expansion of the inverted tree lines in shallow basins and exposure of the Recess Peak deposits. Subsequent recolonization of the now forest-free moraine surfaces effectively reset the lichen clock. This is similar to the issue of cosmogenic surface dates being reset by forest fires, snow cover, and even vegetation changes (Bierman and Gillespie, 1991; Cerling and Craig, 1994). Rather than recording glacial advance as assumed by earlier workers, these lichen dates compliment the alpine tree line record of Holocene climate change and record a highly significant period of Sierran climate history.

The use of lichenometry as a dating technique for geomorphic surfaces such as moraines has a long, yet controversial history. In the case of the mid to upper elevation Recess Peak moraines on the western slopes of the Sierra Nevada, several studies have demonstrated that reported lichen surface ages are significantly younger than the true age of the moraines. This suggests that lichen dates cannot be used to date geomorphic surfaces accurately. However, modern calibration studies show that the relationship between lichen diameter and time is robust and repeatable (Armstrong, 2005; Benedict, 2009; Armstrong and Bradwell, 2010). This poses a paradox that we argue is resolved by careful interpretation of what lichen dates actually represent: in many cases, climatic and environmental changes may reset the lichen clock such that it no longer dates the original emplacement of the surface.

Conclusions

Curry's (1968, 1969) original lichen-based interpretation of Recess Peak depositional ages significantly underestimated their true age (Clark and Gillespie, 1997). However, in light of new dendrochronologic and radiocarbon dating of rooted remnant wood found in growth positions within and beside the Recess Peak moraines, we argue that these lichen ages are in fact valid, dating significant Holocene environmental change in the Sierra Nevada rather than the initial emplacement of the deposits. We conclude that lichen ages may be used to date deposits in the Sierra Nevada for up to several thousand years but care must be taken in their interpretation, just as it should be in other surface-dating techniques. When coupled with recent evidence of small glacial advances in the Palisades Glacier Basin (Bowerman and Clark, 2011), our record provides a comprehensive and complimentary record of past environmental change in the Sierra Nevada that also reconciles the lichen record with other climatic indicators. We conclude that correct use of the lichen dating technique first requires careful interpretation of the environmental context before dating geomorphic surfaces, a step that with few exceptions (e.g., Konrad and Clark, 1998 who noted possible local snow kill) has not been appreciated in most prior applications of this technique.

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