A high-resolution record of climate, vegetation, and fire in the mixed conifer forest of northern Colorado, USA

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ABSTRACT

High-resolution pollen, charcoal, $\delta^{13}C$, total organic carbon (TOC), and magnetic susceptibility data from sediment cores from a montane lake in northern Colorado record variations in vegetation, fire history, and sedimentation since 14.5 ka (1 ka = 1000 cal yr B.P.). This record shows warm conditions during the Bølling-Allerød and the coldest conditions in this area during the Younger Dryas event. Warming occurred throughout the early and middle Holocene, lasting until ca. 5 ka, when the warmest and wettest summer conditions were recorded. Progressive climate cooling and enhanced winter precipitation are then observed until present day. These long-term climatic trends correlate to changes in summer insolation. Charcoal accumulation rates (CHAR) increased along with the arboreal vegetation, from minima in the Late Glacial period to maxima during the early and middle Holocene, suggesting that charcoal influx was also controlled by climate and vegetation. TOC and $\delta^{13}C$ show a progressive increase and a decrease trend during the late Pleistocene and Holocene, respectively, related to changes in vegetation and productivity in the lake. Major peaks in the CHAR record correspond with peaks in magnetic susceptibility, indicating enhanced fire-induced erosion and sedimentation. Millennial- and centennial-scale changes are also observed throughout the different proxy records. They exhibit strong correlations with climate records from distant regions, including Greenland and the North Atlantic, providing evidence for global teleconnections among regional climates. A solar-climate connection is suggested by prominent ca. 225 and 390 yr cycles, which may correlate with the 208 yr (Suess) and 400 yr solar cycles.

INTRODUCTION

Montane and subalpine forests dominated by *Pinus contorta* var. *latifolia* (lodgepole pine), the most abundant of the four subspecies, are an important forest type in western North America, covering the majority of the species' ~26 million ha range (Lotan and Critchfield, 1990). Public attention has been increasingly focused on these high-elevation forests, particularly after severe fires, such as those that burned across the Yellowstone Plateau in 1988 (Romme and Despain, 1989). More recently, the threat of widespread fire after insect infestation has increased across northwestern Colorado and elsewhere (Romme et al., 2006), perhaps driven in part by anthropogenic climate change. If widespread changes are in store for high-elevation forests in the future, it is desirable to understand the role of climate and ecosystem processes in shaping the vegetation of the *Pinus contorta* forests of the Rocky Mountain corridor in the past, as a way of understanding the natural range of variability of forest composition in planning for the future.

Lake sediment proxies are sensitive recorders of climate and environmental change (e.g., Last and Smol, 2001a, 2001b; Smol et al., 2001a, 2001b), and they have been widely used in paleoecological studies, most directly through measurements of lake-level variations (i.e., Shuman et al., 2009), but also because they preserve pollen and charcoal particles that record changes on the vegetation and fire history around the lake area (Anderson et al., 2008a, 2008b; Whitlock et al., 2008; among others). A primary influence on long-term vegetation changes in Rocky Mountain forests is climate (Fall, 1997; Cairns and Malanson, 1998), but changes in fire regime are also important, and fire frequency is strongly linked to climate variability (Power et al., 2008). Thus, multiproxy studies are important in understanding the relationships among climate, vegetation, fire, and sedimentation (MacDonald et al., 1991; Anderson et al., 2008a; Jiménez-Moreno et al., 2008). In this paper, we use a high-resolution multiproxy approach, including pollen, charcoal, magnetic susceptibility (MS), organic carbon (TOC), and $\delta^{13}C$ data of a late Pleistocene and Holocene sediment core to determine these interactions. Our study site is a small lake in the montane zone of northwestern Colorado, southern Rocky Mountains (Fig. 1).

Study Site

Tiago Lake (40°34′49.21″N, 106°36′46″W; 2700 m above sea level) occurs in a moraine-dammed basin located ~20 km northeast of Steamboat Springs, Colorado, on the eastern flank of the Park Range in northwestern Colorado (Fig. 1). Though bedrock is not exposed directly in the small drainage basin, to the west of the lake, there are exposures of Precambrian granite, quartz monzonite, mica schist, and felsic gneiss, as well as Jurassic Morrison Formation and Cretaceous Dakota Sandstone; the lake itself occurs in hummocky dead ice terrain (Snyder, 1980). Atwood (1937) first mapped the glacial features of the range. Tiago Lake occurs in the drift of a lobe of the Newcomb Glacier complex—an outlet glacier of the Buffalo Pass ice cap—covering Mount Zirkel, ~25 km to the northwest. The age of glacier recession is unknown, but many glaciers in the southern Rockies began to recede after ca. 17 ka (Benson et al., 2005). When first visited in July of 1996, the maximum depth of the lake was ~15 m.

Northwestern Colorado is influenced both by winter storms originating from the Pacific, and summer convective storms influenced by

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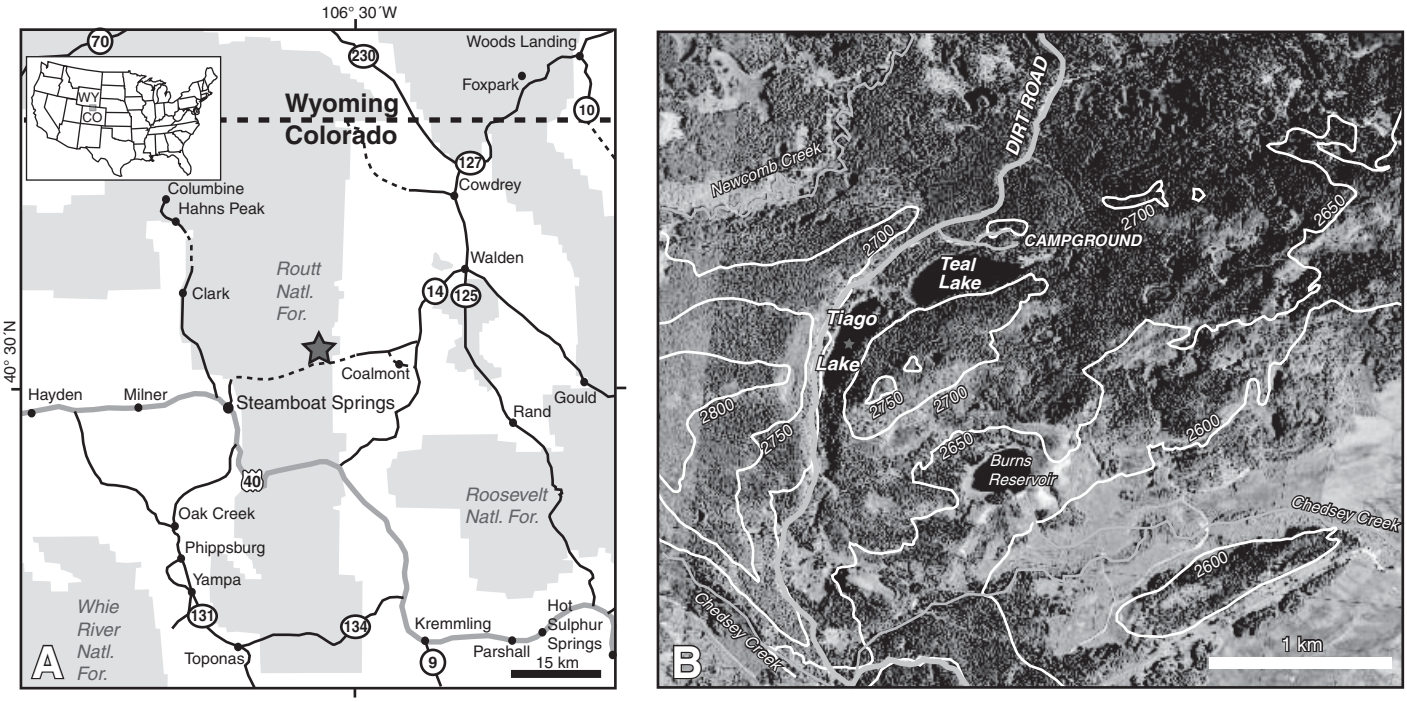

Figure 1. (A) The star marks the approximate location of Tiago Lake in the Routt National Forest. Shading shows National Forest areas. (B) Aerial photo of the Tiago lake area. The star indicates the location of the core. Note the contact between the *Artemisia* steppe (on the inferior right side) and the montane forest belt, characterized almost exclusively by *Pinus contorta* at ~2650 m.

subtropical air masses (Feiler et al., 1997). No climate data exist for Tiago Lake directly, but the Spicer, Colorado, station ~18.5 km SE is most similar in location (40°29′N, 106°26′W) and altitude (2540 m). December through February is the coldest interval (WRCC, 2009). Snow can fall in any month except July and August, but nearly all snow falls November through April. However, the wettest periods occur first in March, and then with monsoon rains in July through September.

Modern vegetation in this area follows elevation and precipitation gradients (Table 1; Feiler et al., 1997). Four vegetation belts occur near the study area: alpine tundra (above 3400 m), subalpine forest (3400–2900 m), montane forest (2900–2600 m), and *Artemisia* steppe (below 2600 m). The alpine tree line (between subalpine forest and tundra) is mostly conditioned by temperature (Fall, 1997). The lower-elevation tree line (between montane forest and *Artemisia* steppe) is usually determined by precipitation and is variable (Fall, 1997). Tiago Lake itself is located within the montane forest, presently surrounded by a *Pinus contorta* and *Populus tremuloides* forest.

MATERIALS AND METHODS

We collected both a 725-cm-long sediment core (Ti-6), using a Livingstone square-rod piston corer, and a frozen box core (Ti-3b), which included the unconsolidated upper 20 cm of sediments, within a meter of each other in the deepest part of Tiago Lake. Most sediment sections are laminated, indicating little if any bioturbation. Cores were sampled for pollen, charcoal, $\delta^{13}C$ isotopic composition, and radiometric dating at the Laboratory of Paleoecology (LOP), Northern Arizona University. In order to calibrate the sedimentary charcoal record, we collected several cores from trees in the drainage of the lake to date the most recent stand-replacing fire.

Lithology (Fig. 2) and wet Munsell color indexes were described from split core segments in the laboratory. Magnetic susceptibility, a measure of the tendency of sediment to carry a magnetic charge (Snowball and Sandgren, 2001), was measured with a Bartington MS2E meter in dimensionless cgs units (cgsu; Fig. 3). Measurements were taken directly from the core surface every 0.5 cm for the entire length of the Ti-6 core.

Samples for TOC and $\delta^{13}C$ isotopic composition were generally taken every 2 cm throughout the core at the same depths as the pollen samples (Fig. 3) and were measured on ~2–6 mg of dry and homogenized sediment. Carbon isotope ratios were measured on bulk sedimentary organic matter ($\delta^{13}C_{org}$) by elemental analyzer–continuous flow–isotope ratio–mass spectrometry at the Department of Earth and Planetary Sciences, University of New Mexico. Samples were ground to a fine powder and treated twice with 1 *M* hydrochloric acid overnight at 50 °C to remove

TABLE 1. MODERN VEGETATION AROUND THE TIAGO LAKE AREA

Vegetation belt	Elevation (m)	Most characteristic taxa
Alpine tundra	>3400	Dwarf *Salix* (willow), Poaceae (grasses), Cyperaceae (sedges), and other herbaceous taxa
Subalpine forest	3400–2900	*Picea engelmannii* (Engelmann spruce) and *Abies lasiocarpa* (subalpine fir)
Montane forest	2900–2600	Mostly *Pinus contorta* var. *latifolia* (lodgepole pine) but also *Picea pungens* (Colorado blue spruce), *Pseudotsuga menziesii* (Douglas fir), *Pinus ponderosa* (ponderosa pine), and *Populus tremuloides* (quaking aspen)
Artemisia - steppe	<2600	*Artemisia tridentata* (big sagebrush), *Chrysothamnus* spp, (rabbitbrush), *Purshia tridentata* (bitterbrush)
Wetland and aquatic plants	Within Tiago Lake (2700)	*Pedicularis groenlandica* (elephantella), *Maianthemum* sp. (false Solomon's seal), *Veratrum tenuipetalum* (false hellebore), *Heracleum sphondylium* (cow parsnip), Cyperaceae, *Equisetum* (horsetail), *Nuphar lutea* (yellow pondlily), and *Potamogeton* sp. (pondweed)

Note: Terminology follows Weber and Wittmann (2001).

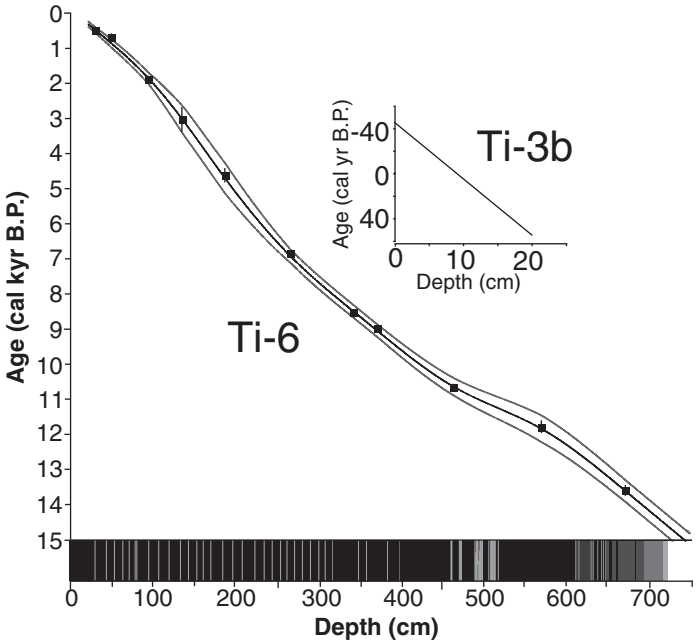

Figure 2. Lithology of the Tiago Lake record and age-depth diagram with 2σ ranges in error bars. A spline fit was constructed using formulations from Heegaard et al. (2005). The black line is the estimated age, and the gray lines are the 95% confidence interval. The black squares are the median probability with ½ 2σ ranges in error bars (see Table 2). We used a number of spline functions *K* = 8.

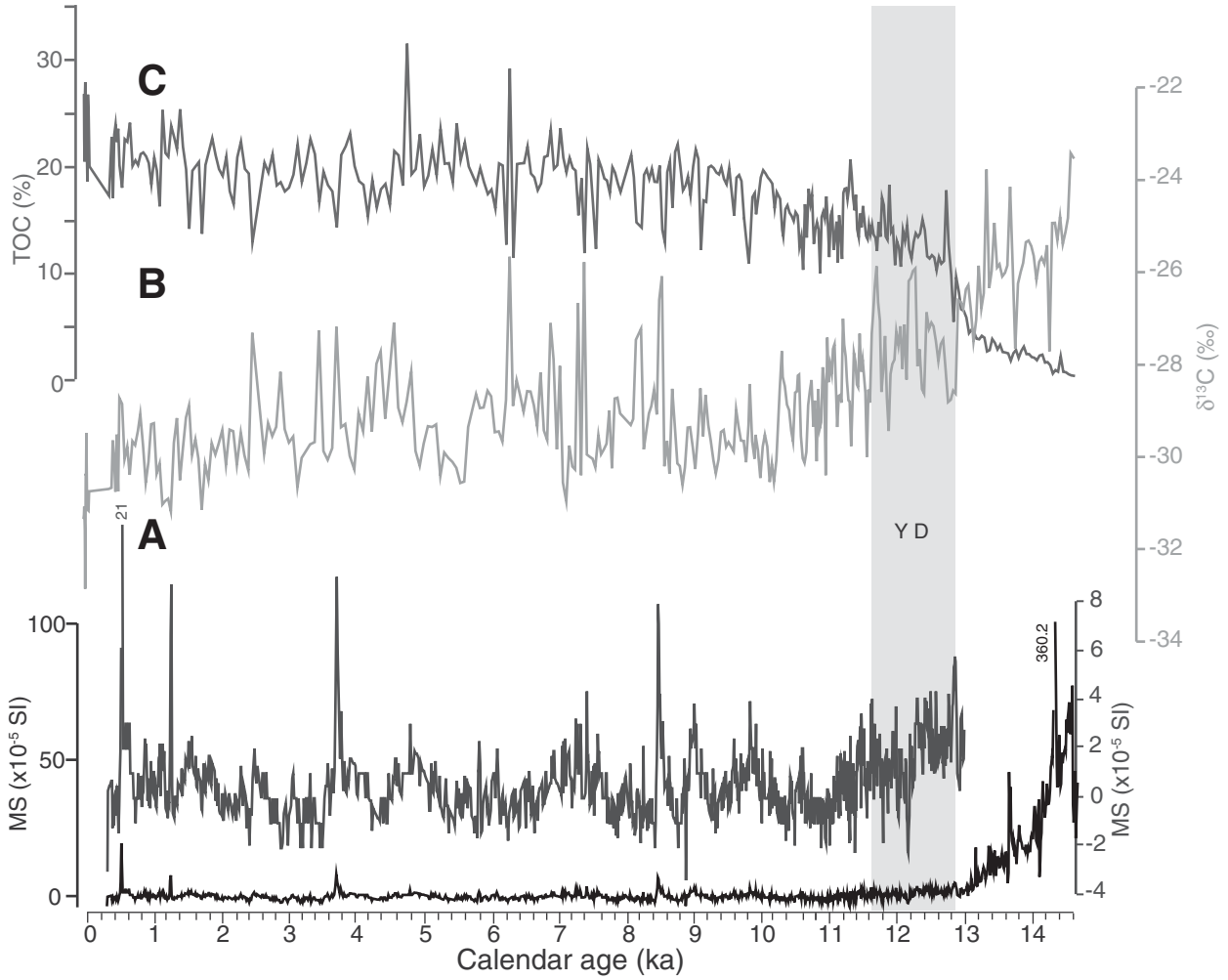

Figure 3. Comparison of (A) magnetic susceptibility (MS) profile of sediment core Ti-6 (with an exaggeration of magnetic susceptibility values for the last 13 k.y.); (B) $\delta^{13}C$ values of bulk sediment samples; and (C) total organic carbon (TOC) from bulk sediment samples for the Tiago Lake record. YD—Younger Dryas.

carbonates. Carbon concentrations and carbon isotope ratios were measured with a Costech ECS 4010 Elemental Analyzer coupled to a Thermo Finnigan Delta Plus mass spectrometer via a CONFLO II interface. Isotope ratios are reported in standard delta (δ) notation relative to Vienna Peedee belemnite (VPBD). Average analytical precision, based on routine analysis of a laboratory graphite standard, was better than 0.1‰ (1σ). The laboratory standard was calibrated against NBS 21, NBS 22, and USGS 24.

Samples for pollen analysis (1 cm^3) were taken every 2 cm throughout the cores (Fig. 4). Pollen extraction methods followed a modified Faegri and Iversen (1989) methodology. Counting was performed at 400× magnification to a minimum pollen sum of 300 terrestrial pollen grains. Fossil pollens were compared with their present-day relatives using published keys and the modern pollen reference collection at Northern Arizona University. The pollen results are plotted in a detailed diagram (Fig. 4).

Sediment samples (1 cm^3) were taken every 0.5 cm of the core length for high-resolution charcoal analysis. Samples were disaggregated in water and sieved with 125- and 250-mm-mesh soil sieves. Charcoal particles were counted using a dissecting microscope. Macroscopic charcoal particles (>100 μm) express occurrence of local fire, because particles of this size do not travel far from their source (Whitlock and Anderson, 2003). Charcoal counts for each sample were converted first to charcoal concentrations (CHAC; no. charcoal particles per cm^3), then to charcoal influx (CHAR; no. charcoal particles per cm^2 per yr), and finally decomposed into background and peaks components using CharAnalysis (Higuera et al., 2008; http://charanalysis.googlepages.com/). The analyses are based on the widely applied approaches that deconstruct a charcoal record into low- and high-frequency components (e.g., Clark et al., 1996; Long et al., 1998; Carcaillet et al., 2001; Gavin et al., 2006). We estimated the timing of fire events in our charcoal records by removing low-frequency trends. This approach accounts for changes in both the mean and variability of CHARs through time and the statistical nature of charcoal counts. We used dates of estimated fire events to calculate fire event frequency (FEF; per 500 and 1000 yr) and fire return intervals (yr between fire events; FRIs).

The Tiago Lake chronology was developed from a combination of ^{210}Pb dating of the upper sediments, and 11 calibrated Accelerator Mass Spectrometry (AMS) radiocarbon dates (Table 2; Fig. 2). Material for AMS dates consisted of terrestrial plant remains and bulk sediment samples (Table 2). Radiocarbon ages were calibrated to calendar ages using CALIB version 5.0.2 (Stuiver et al., 1998). An age-depth model was constructed using a spline fit and formulations from Heegaard et al. (2005). We used a number of spline functions, $K = 8$ (Fig. 2).

A cyclostratigraphic analysis was performed on the last 12 k.y. of the Ti-6 pollen, $\delta^{13}C$, and charcoal time series. We used the program REDFIT (Schulz and Mudelsee, 2002) with the objective of characterizing the different periodicities present in the unevenly spaced multiproxy time series and estimating their red-noise spectra. The spectral analysis assisted in identifying recurrent features or periodicities through spectral peaks registered at differing frequencies throughout the studied core.

RESULTS

Lithology, Chronology, and Magnetic Susceptibility

Sediments from Ti-6 are primarily inorganic in the lower portion of the core and progressively become more organic toward the top. The core bottom is at ~7.25 m, with 20 cm of yellowish, glacial clayey sand resting on bedrock. Greenish brown silty clays with sand layers occur up-core to ~5.66 m depth. Massive green-brown silty gyttja transitions to mostly laminated sediment by 5.22 m. Above this to the core top, there is laminated and indistinctly laminated gyttja (Fig. 2).

The chronology for the upper 20 cm of the record (core Ti-3b) is based on the ^{210}Pb stratigraphy, because there was insufficient sediment to determine ^{137}Cs content (M. Baskaran, 2008, personal commun.). A calculated sedimentary accumulation rate (SAR) of 2 mm/yr suggests that 20 cm in this core is ca. 1896 A.D. (54 cal yr B.P.) (Fig. 2; Table 2). We used this SAR to calibrate the sedimentary charcoal record of Ti-3b, additionally confirmed by tree-ring ages of trees apparently established subsequent to the most recent fire (see following).

The age-depth model for the 7.25 m of core Ti-6 covers the last ~14.65 k.y., with no reversals in any of the radiocarbon dates. The SAR ranges between 2 mm/yr (between 0 and 20 cm) and 0.32 mm/yr (between 187 and 135 cm). The average SAR is 0.49 mm/yr.

High magnetic susceptibility values characterize the bottom of the core, and three large peaks occur at ca. 14.3, 14.1, and 13.6 ka (Fig. 3). Magnetic susceptibility values gradually decrease until ca. 13 ka, when an average level of ~0.30 cgsu (×10,000) is reached. Magnetic susceptibility values between 13 ka to present generally oscillate between 4 and −3.3 cgsu, but several larger peaks are found at ca. 8.4, 3.6, 1.4, and 0.5 ka (Fig. 3).

Carbon Analyses

TOC values in the Tiago Lake core range from 0.3% to 31.4% (Fig. 3). TOC values are lowest at the bottom of the core until ca. 13 ka, when they increase considerably. Even though values vary significantly throughout the core, a slight increasing trend can be observed from 13 ka until present, with a shallow trough between 4.3 and 1.6 ka.

The $\delta^{13}C$ values are important in determining the relative inputs from different plant groupings (Osmond et al., 1981; Boon and Bunn, 1994; Meyers, 2003). The $\delta^{13}C$ values in the Tiago Lake core range from −23.5‰ in the Late Glacial period at ca. 14.4 ka to −32.8‰ at ca. 0.1 ka (Fig. 3). A trend toward more negative values is observed from the bottom to the top of the core. Individual major peaks in the $\delta^{13}C$ record correspond with troughs in TOC (such as at 11.7, 9.8, 8.5, 7.4, 6.2, 3.7, 2.4, and 1.5 ka; Fig. 3).

Pollen Analyses

Pollen concentrations were generally high (between 15.5×10^3 and 1160×10^3 grains cm^{-3}) throughout the core. Objective zonation by CONISS suggests five pollen zones with two subzones (Fig. 4). Because upper and lower elevation boundaries of forest species are primarily sensitive to temperature and precipitation, respectively (Fall, 1997; Cairns and Malanson, 1998), we interpret increases in subalpine species (mainly *Picea engelmannii* and *Abies lasiocarpa*) as a cooling-induced downslope elevational shift of the subalpine zone. On the other hand, declines in subalpine species and relative increases in lower elevation species (i.e., below lower tree line) such as *Artemisia* are interpreted as a warming- and drying-induced upslope elevational displacement of the steppe. We follow several studies from the southern Rocky Mountains (e.g., Markgraf and Scott, 1981; Carrara et al., 1984; Fall, 1997; Reasoner and Jodry, 2000; Toney and Anderson, 2006; Jiménez-Moreno et al., 2008) who have used this relationship to document tree-line fluctuations during the Holocene. We calculated the *Artemisia*/*Picea* ratio (A/P ratio) and the spruce (*Picea*)/total pine (*Pinus*) ratio (S/P ratio; Fig. 5) to track the elevation of tree line and the density of *Picea* forest (sensu Carrara et al., 1984; Toney and Anderson, 2006).

Zone Ti-6I (Ca. 14.5 ka to 12.7 ka; 720–620 cm depth)

Ti-6I is differentiated into subzones Ti-6Ia (ca. 14.5–13.5 ka) and Ib (ca. 13.5–12.7 ka). This zone is dominated by pollen of *Artemisia*, Poaceae, *Pinus haploxylon* (probably *Pinus*

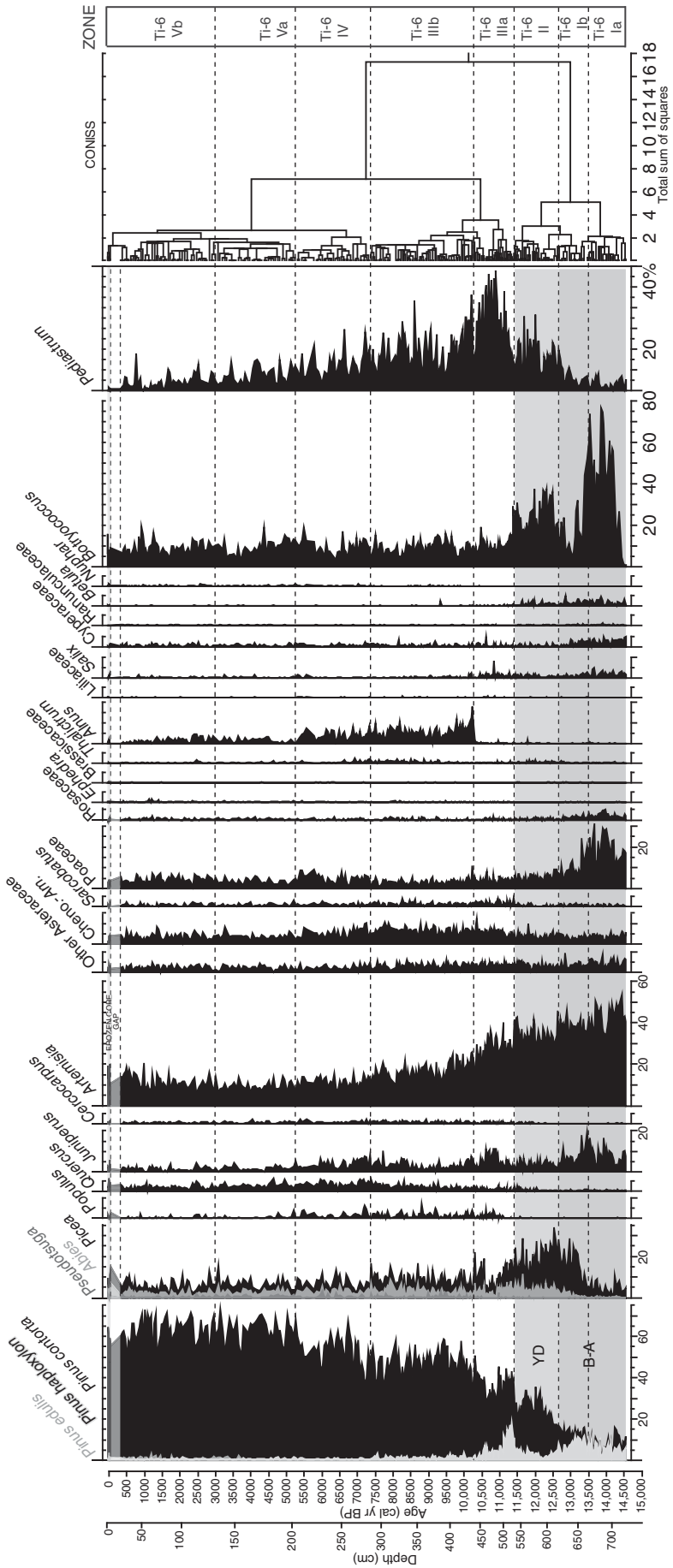

Figure 4. Pollen diagram of the Tiago Lake record showing percentages of selected taxa. The aquatics (including *Alnus*, *Betula*, *Salix*, *Typha*, Cyperaceae, Liliaceae, Ranunculaceae, *Thalictrum*, and *Nuphar*) were excluded from the total pollen sum. Percentages of algae (*Botryococcus* and *Pediastrum*) were calculated with respect to the terrestrial pollen sum. The zonation was made using cluster analysis provided by CONISS (Grimm, 1987). YD—Younger Dryas, B-A— Bølling-Allerød.

TABLE 2. AGE DATA FOR TIAGO LAKE, COLORADO

Lab number*	Core	Depth (cm)	Material dated	$\delta^{13}C$ (‰)†	Dating method	Age (^{14}C yr B.P., ±1σ, ^{210}Pb)	Calibrated age (cal. yr B.P., 2σ ranges)	Median
WSU Geology	Ti-3b	0	Bulk sediment	N/A	^{210}Pb	A.D. 1996	–46	–46
WSU Geology	Ti-3b	10	Bulk sediment	N/A	^{210}Pb	A.D. 1946	4	4
WSU Geology	Ti-3b	20	Bulk sediment	N/A	^{210}Pb	A.D. 1896	54	54
UCIAMS-37273	Ti-6	30	Bulk sediment	–27.9	^{14}C	480 ± 15	506–532	516
UCIAMS-58418	Ti-6	49.5	*Pinus contorta* needles	N/A	^{14}C	760 ± 70	628–799	703
UCIAMS-32508	Ti-6	93.5	Wood/needles	–32.6	^{14}C	1950 ± 25	1826–1968	1897
UCIAMS-58419	Ti-6	135	*P. contorta, Pseudotsuga* needles, wood	N/A	^{14}C	2890 ± 160	2738–3412	3053
UCIAMS-32509	Ti-6	187	Vegetal remains	–26.4	^{14}C	4110 ± 50	4448–4823	4642
UCIAMS-58420	Ti-6	266.5	Wood, bark	–28.4	^{14}C	6090 ± 25	6885–7013	6955
UCIAMS-31718	Ti-6	343	Wood	–25.9	^{14}C	7750 ± 15	8457–8588	8539
UCIAMS-58421	Ti-6	371.5	*P. contorta, Pseudotsuga* needles, twig, *Najas*	N/A	^{14}C	8080 ± 40	8969–9127	9012
UCIAMS-37274	Ti-6	464	Bulk sediment	–30.5	^{14}C	9435 ± 20	10,586–10,733	10,679
UCIAMS-31719	Ti-6	571	Wood/needles	–25.8	^{14}C	10,140 ± 20	11,651–11,975	11,811
Beta-183541	Ti-6	673	Wood	–27.0	^{14}C	11,760 ± 40	13,467–13,737	13,627

Note: All ages were calibrated using CALIB 5.0 (Stuiver and Reimer, 1993).

*Sample number assigned at radiocarbon laboratory; Beta—Beta Analytic, Inc.; UCIAMS—University of California at Irvine W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory; WSU Geology—Wayne State University Department of Geology.

†$\delta^{13}C$ values shown were measured to a precision of better than 0.1‰ on CO_2 aliquots, using a Finnigan Delta Plus IRMS with gas bench input. Some radiocarbon samples were too small to provide sufficient extra CO_2 for the $\delta^{13}C$ measurements.

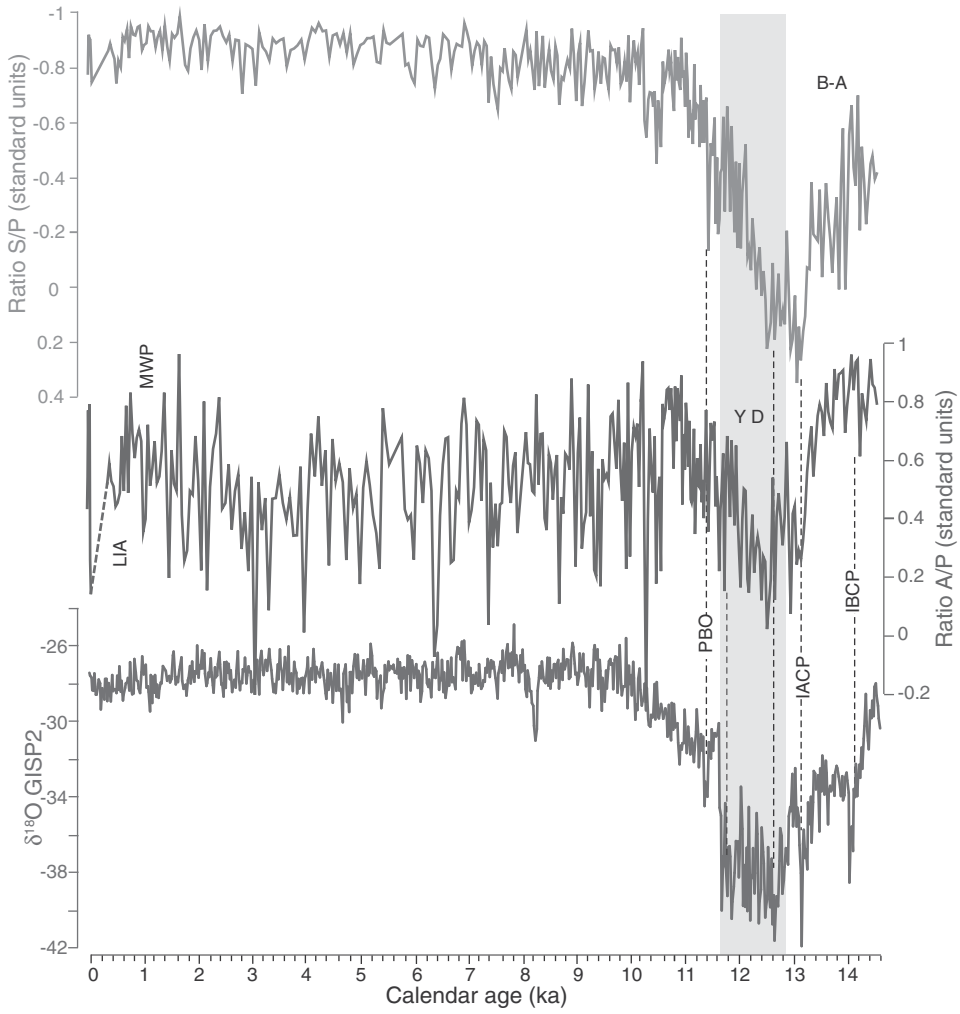

Figure 5. Comparison of raw *Artemisia/Picea* (A/P ratio) and spruce/pine (S/P ratio) ratios from Tiago Lake and the Greenland Ice Sheet Project 2 (GISP2) $\delta^{18}O$ record from Greenland. The A/P ratio is calculated as (A–P)/(A+P), where "A" represents percent *Artemisia*, and "P" represents percent *Picea*. The same method was using for calculating the S/P ratio. LIA, MWP, YD, B-A, PBO, IACP, and IBCP are Little Ice Age, Medieval Warm Period, Younger Dryas, Bølling-Allerød, Preboreal Oscillation, inter-Allerød cold period, and inter-Bølling cold period, respectively. Dashed lines represent tentative correlations between the two records.

flexilis, limber pine), and *Juniperus* (probably *Juniperus communis*), along with other nonarboreal pollen types—Cyperaceae (sedge), *Salix* (willow), *Betula* (perhaps dwarf birch), and members of the Rosaceae, Asteraceae, and *Chenodiaceae-Amaranthus* (Cheno.-Am) groups (Fig. 4). Boreal conifer pollen types—*Picea* and *Abies*—have low percentages, and consequently A/P ratios are relatively high (Fig. 5). Trees probably did not grow around the lake, based on these low percentages (pine is less than 20%); instead, the dominance by nonarboreal pollen suggests shrub tundra or steppe (sensu Fall, 1997). The highest percentage of *Botryococcus* suggests a well-developed lake ecosystem early in the sequence.

Subzone Ti-6Ia differs from subzone Ti-6Ib in that *Artemisia*, Poaceae, and *Juniperus*, and of course *Botryococcus*, are more abundant. In Ib, *Pinus* haploxylon, *Picea*, *Abies*, and most significantly *Pinus contorta*, begin to increase, suggesting that trees were becoming established on the landscape near the lake at the end of the Bølling-Allerød.

Zone Ti-6II (Ca. 12.7–11.5 ka; 620–540 cm depth)

In this zone, *Pinus* haploxylon pollen declines and is replaced by *Pinus contorta*. *Picea* and *Abies* pollen reach their maxima in the early and late part of the zone, respectively. *Artemisia* continues to decline, as does *Juniperus*. However, other pollen types characteristic of tundra or steppe maintain their presence, such as *Salix*, *Betula* (while disappearing completely at the end of the zone), Asteraceae, and even Cheno.-Am (the latter two may reflect vegetation changes at lower elevations). Toward the end of the zone, *Quercus* and *Cercocarpus* increase. *Botryococcus* increases again, but especially *Pediastrum*, suggesting increasing lake productivity. This zone is coeval with the Younger Dryas.

Zone Ti-6III (Ca. 11.5 ka to 7.5 ka; 540–290 cm depth)

Zone Ti-6III is differentiated into subzones Ti-6 IIIa (ca. 11.5–10.2 ka) and Ti-6IIIb (ca. 10.2–7.5 ka) based on changes in aquatic and wetland types (i.e., *Salix*, *Alnus*, and *Pediastrum*). The essential features of this zone are a continuing decline in *Artemisia* and *Picea* (although the A/P ratio is relatively high; Figs. 4 and 5) and a continuing increase in *Pinus contorta* (and thus a decrease in the S/P ratio). Increases occur in pollen of *Populus* and *Pseudotsuga*, as well as Cheno.-Am, *Sarcobatus*, and *Juniperus*.

The pollen record during Ti-6IIIa suggests continued warming, and perhaps wetter conditions (see following discussion) as *Pediastrum* reaches its highest Holocene percentages. After ca. 10.2 ka, during Ti-6IIIb, the dominant pollen types (*Pinus contorta, Artemisia*) stabilize, while *Pediastrum* declines and *Alnus* increases.

Zone Ti-6IV (Ca. 7.5 ka to 5.2 ka; 290–202 cm depth)

This middle Holocene zone shows continued importance of *Pinus contorta*, *Abies*, *Pseudotsuga*, and *Populus*, suggesting that the mixed conifer forest was well established. The A/P ratio averages somewhat lower values during this zone (Fig. 5). Higher percentages of species typical of lower elevations—*Quercus*, *Juniperus*, and even Poaceae—suggest that those communities expanded during this time.

Zone Ti-6V (Ca. 5.2 ka to the present; 202–0 cm depth)

The prominent feature of Ti-6V—subdivided into Ti-6Va (5.2 ka to ca. 3.0 ka) and Ti-6Vb (3.0 ka to present) —is the maximum occurrence in *Pinus contorta* (Fig. 4). Most other conifers—*Picea*, *Abies*, and *Pseudotsuga*—largely remain unchanged. A slight increase in Poaceae occurs over the previous zone, while there are slight declines in *Populus*, *Quercus*, *Juniperus*, Cheno.-Am, and *Alnus* percentages. Pollen spectra of Ti-6Vb, however, show gradual increases in *Pinus edulis*, and especially in *Artemisia*. This gradual increase in *Artemisia* contributes to the change in A/P ratios from being the lowest of the Holocene in Ti-6Va to some of the highest in Ti-6Vb (Fig. 5).

Calibration of Charcoal Deposition

The historical record of fire in NW Colorado is sparse, but at least one fire was documented in 1879 near Rabbit Ears Pass, 20 km due south of Tiago Lake (M. Cahur, 2009, personal commun.). We were unable to locate any historical records documenting fires around Tiago Lake. However, we used tree-ring cores from *Pinus contorta* to estimate the age of the last stand-replacing fire around the lake. Of the 15 trees, we hit the pith in four trees. To estimate the establishment age of the tree, we added 10 yr to the ring count to account for the time necessary to grow from germination to ~1.5 m (see Fulé et al., 1997). For the remainder of the trees, we missed the pith by an estimated 3–7 yr, and then added 10 yr to the ring count. Histograms for this small sample suggest most trees originated from a fire perhaps in 1888–1890 A.D. (Fig. 6).

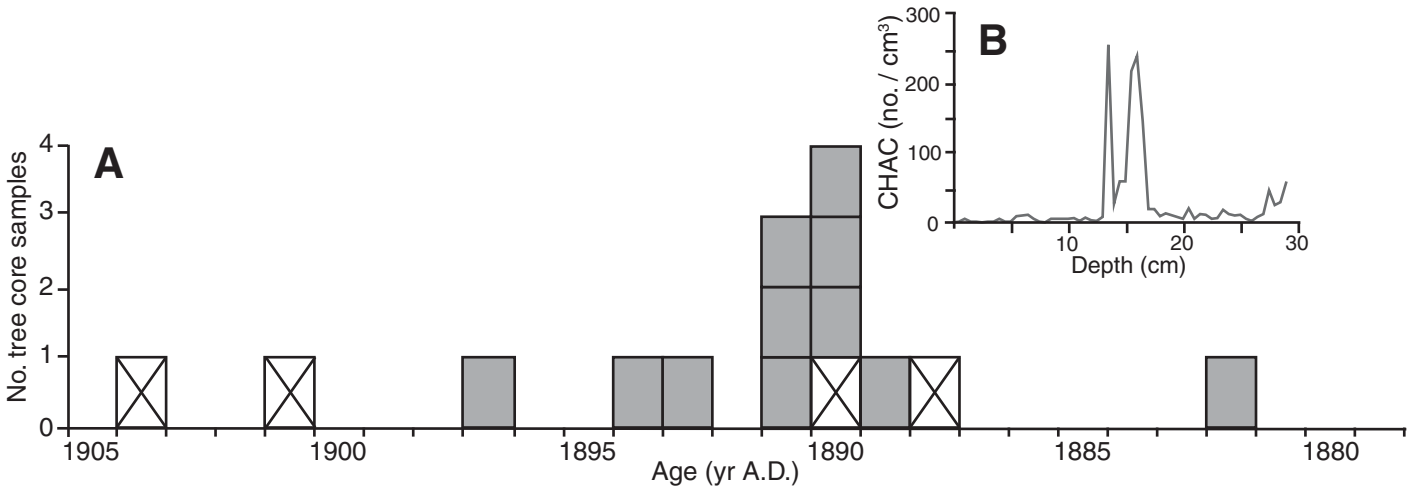

Figure 6. (A) Histogram showing reconstructed origination dates for living *Pinus contorta* trees growing near Tiago Lake. These trees presumably originated from the last major fire around the lake. Boxes with an X indicate trees where cores hit the pith. (B) Charcoal concentration (CHAC) of sediments from Ti-3b.

We used the tree-ring and ^{210}Pb data to calibrate the sedimentary charcoal record. The most recent major charcoal peak in Ti-3b begins at 16.5 cm depth (Fig. 6). The ^{210}Pb profile suggests a SAR of 0.2 cm/yr. This compares favorably to our tree-ring based SAR 0.16 cm/yr. This relationship provides confidence in the reconstruction of fire around the lake using the charcoal record.

Charcoal

Charcoal particle concentration (CHAC) and influx (CHAR) values oscillate considerably throughout the Tiago Lake record, varying from near 0 to over 1800 particles cm^{-3}, and over 60 particles cm^{-2} yr^{-1}, respectively (Fig. 7). CHAC and CHAR values are consistently lowest during the early part of the record, until ca. 13 ka, when charcoal influx increases. High fire event frequencies (FEF) above 6 fire events per 500 yr are recorded prior to, during, and immediately after the Younger Dryas. FEF began to decline by 10.5 ka, reaching minimum values of ~1 fire event per 500 yr at ca. 9.2–7.5 ka. FEFs then increased again for nearly 4000 yr, peaking at ~5.5 fire events per 500 yr between 4.6 and 4.2 ka. Subsequently, FEF declined to ~1 fire event per 500 yr from 3 to 2.5 ka, and rose to ~3.5 fire events per 500 yr by ca. 1.4 ka. Values decreased subsequently, reaching a minimum of ~1.5 fire events per 500 yr at ca. 0.6 ka. Fire return intervals (FRIs) vary similarly throughout the record, with an average value of 184 yr (Fig. 7).

DISCUSSION

Although many important investigations of millennial- and even centennial-scale variability in the fire history of western North American forests have been published (e.g., Anderson et al., 2008b; Power et al., 2008; Whitlock et al., 2008; Marlon et al., 2009; many others), a combination of fine-scale pollen and charcoal analyses is rarer (Jiménez-Moreno et al., 2007, 2008). These high-resolution analyses—along with other sedimentary proxies—allow us to compare the millennial- and centennial-scale environmental changes from the Tiago Lake record with other high-resolution records, for example the Greenland Ice Sheet Project (GISP2) ice core data, to examine interconnections between high and temperate latitudes. We note that the well-defined millennial- and centennial-scale variability is superimposed on the long-term late Pleistocene and Holocene trends.

Late Glacial Environments

Today, Tiago Lake occurs in the mixed conifer (*Pinus contorta*–dominated) montane forest, with subalpine coniferous forest at higher elevations, and *Artemisia* steppe at lower elevations. However, the pollen data clearly document that vegetation around Tiago Lake has been highly sensitive to changes in climate since the Late Glacial period. We deduce this not only from the changes in individual pollen species (Fig. 4) but also from the high similarity between our pollen record and the GISP2 ice-core record, particularly during the Late Glacial interval (14.5–11.7 ka; Stuiver et al., 1997; Fig. 5). The lake formed subsequent to deglaciation at ca. 14.5 ka, during the relatively warm Bølling-Allerød interstadial (14.5–12.7 ka; Stuiver et al., 1997). Pollen data, with high A/P ratios, show that the Bølling-Allerød Tiago Lake landscape supported steppe vegetation, with *Artemisia*, Poaceae, Asteraceae, and *Juniperus* (Figs. 4 and 5).

However, a progressive cooling—very similar to the GISP2 record—took place in the Tiago Lake area during the Bølling-Allerød (Fig. 5). The high-sampling resolution (~30 yr) of the pollen record during the Bølling-Allerød documents the presence of two abrupt climatic oscillations, at ca. 14.2 ka and 13.1 ka, which we correlate with GISP2 events (Fig. 5). Both events show steep declines in the A/P ratio, suggesting that *Picea* trees retreated downslope in response to colder conditions. We refer to these two events as the inter-Bølling cold period (IBCP) and inter-Allerød cold period (IACP), following the nomenclature of Hughen et al. (1996) from their study in the Cariaco Basin. Similar climate variability during the Bølling-Allerød has been observed in other North American sites. For example, in Owens Lake, California, the inter-Allerød cold period and inter-Bølling cold periods were observed through dry events in the δ^{18}O and pollen records (Benson et al., 1997). The inter-Allerød cold period (locally called Killarney oscillation) is also recorded in pollen records from the Ontario Lakes, Canada (Yu and Eicher, 1998), and Splan Pond, Canada (Levesque et al., 1997), which also reflect colder conditions at that time. Unfortunately, the Older Dryas event is not as evident in our record, perhaps due to our sampling resolution and the relatively shorter duration of the Older Dryas cold event (20–30 yr; Stuiver et al., 1997; Hughen et al., 1996).

Excluding a single peak at ca. 13.3 ka, little charcoal was deposited during the Bølling-Allerød interstadial (Figs. 7A and 7B), probably due to the minimal occurrence of forest vegetation and fuels at this time, but very high magnetic susceptibility characterized the Tiago Lake sedimentation during the Bølling-Allerød interstadial. This probably indicates high runoff from deglaciation in the basin, and low soil stability. Low TOC values also support this interpretation. Rapid accumulation of organic carbon–poor sediments appears to be a general feature of latest Pleistocene–age lake sediments in temperate climate zones (Meyers and Lallier-Vergès, 1999).

Relatively high δ^{13}C values (~–25 to –26‰) could be derived from a combination of sources, including the presence of C4 grasses on the landscape (note the abundance of Poaceae in Fig. 4) and the dominance of terrestrial plants with high water-use efficiency, and therefore heavy δ^{13}C values, such as *Artemisia* (many species of *Artemisia* have δ^{13}C values of ~–23‰; Anderson et al., 2008a). The highest abundance of *Botryococcus* was reached at this time (Fig. 4), probably indicating oligotrophic lake conditions (Smittenberg et al., 2005). *Botryococcus* is enriched in δ^{13}C under low atmospheric partial pressure of CO_2, i.e., conditions that occurred during the latest Pleistocene (Huang et al., 1999).

The progressive cooling during the Bølling-Allerød led to the coldest conditions in our record, which, at around 12.6 ka, coincides with the timing of the coldest conditions in Greenland during the Younger Dryas (Fig. 5). Vegetation around Tiago Lake during the Younger Dryas was clearly subalpine, with *Picea* as the main constituent. This suggests a downslope displacement of the subalpine vegetation of a minimum 200 m over today; this is in general agreement with other studies documenting that upper tree line was up to 600 m lower during this period (Markgraf and Scott, 1981; Fall, 1997; Reasoner and Jodry, 2000; Toney and Anderson, 2006; Jiménez-Moreno et al., 2008). Fire frequency increased during the Younger Dryas—to one event per 80–142 yr (Fig. 7)—most likely as a result of the establishment of the subalpine forest around Tiago Lake. The δ^{13}C values declined a small amount, from ~–26‰ during the Bølling-Allerød to around –27‰ and –28‰ during the Younger Dryas, probably indicating a different primary source in the input of ^{13}C. This minor change might reflect the change in vegetation at this time or an increasingly autochthonous organic component of the sediment due to increasing lake productivity, which is also shown by the high algae content and elevated TOC values (Fig. 5). A decreased water stress of C3 plants would also induce a decrease in δ^{13}C values (Farquhar et al., 1989).

Holocene Environments

The early Holocene was characterized in the study area by a continued warming of climate (Fig. 5), with perhaps wetter summer conditions. Pollen data during this time suggest a decrease in subalpine species (increase in A/P ratio; Fig. 5) and the regional development of

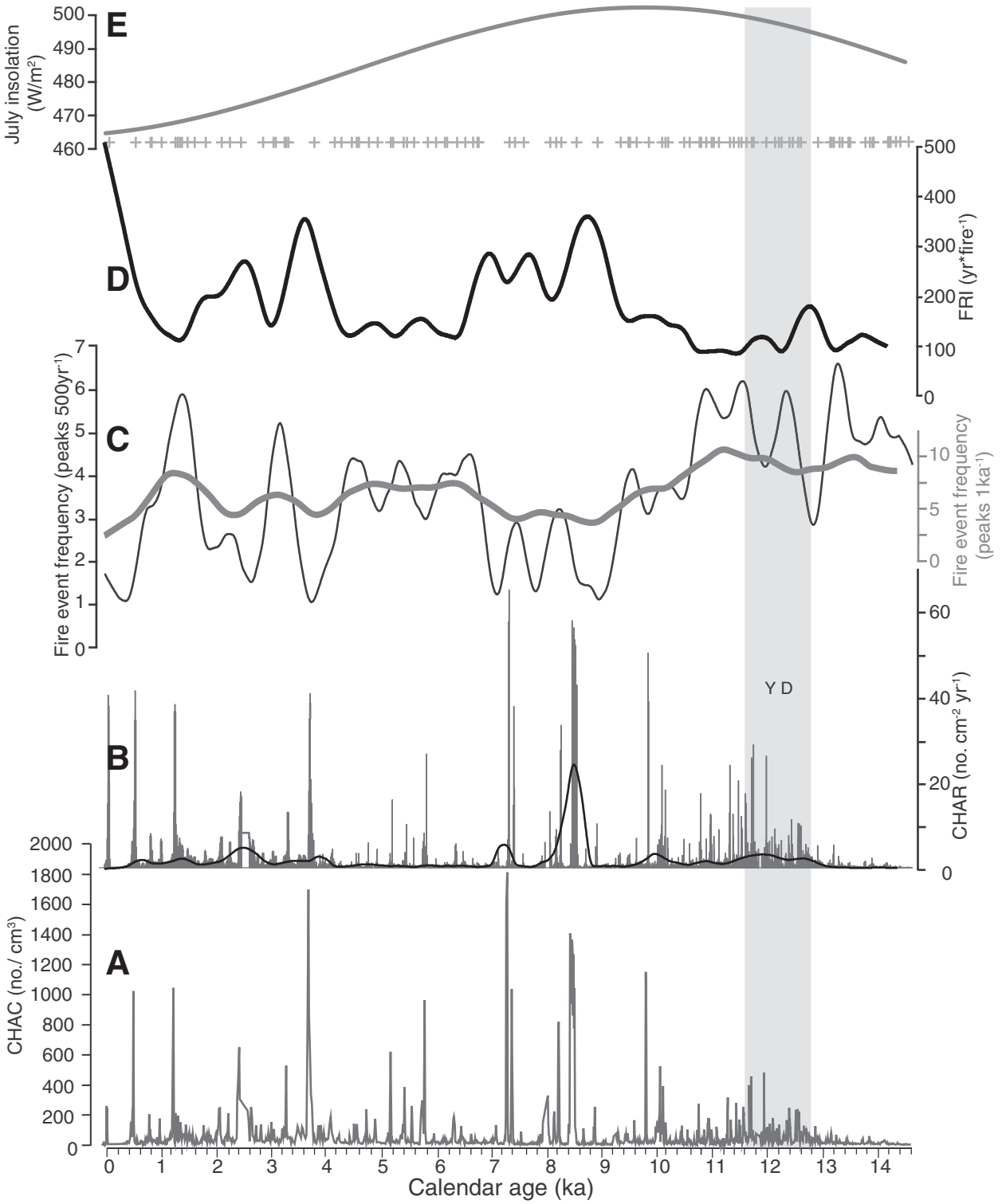

Figure 7. Charcoal record from Tiago Lake, Colorado. (A) Charcoal concentrations (CHAC; no. charcoal particles cm^{-3}). (B) Charcoal accumulation rates (CHAR; no. charcoal particles cm^{-2} yr^{-1} re-sampled at 10 yr constant time interval). Background is smoothed using a locally weighted regression with a time window of 500 yr. (C) Inferred fire event frequency (FEF) with a 500 (black line) and 1000 yr (gray line) smoothing window. (D) Fire return interval (yr between fire events; FRIs). The "+" symbols represent identified fire events using the software CharAnalysis (Higuera et al., 2008). (E) July insolation at 40°N (Laskar et al., 2004). YD—Younger Dryas.

montane forests with *Pinus contorta*, *Populus*, and *Pseudotsuga* (decrease in S/P ratio; Figs. 4 and 5). The increase in *Pinus contorta* and the decline in *Artemisia* probably represent expansion and contraction, respectively, downslope as summer precipitation increased. These changes undoubtedly occurred in response to an increase in summer insolation and its influence on summer temperatures (Kutzbach et al., 1998). With the development of the mixed conifer forest, the record shows the highest fire event frequencies in the Tiago Lake record (Fig. 7). Anderson et al. (2008b) advanced a combination of increasingly flammable coniferous biomass from establishment of conifers, as well as high summer insolation (Kutzbach et al., 1998) as the reason for high FEF values. Our reconstructions of FEF for Tiago Lake (Fig. 7C) are remarkably similar to reconstructions for several sites in the southern Rockies (e.g., Hunters Lake, Little Molas Lake, and DeHerrera Lake, Colorado, and Chihuahueños Bog, New Mexico; Anderson et al., 2008b). FEF at Tiago Lake was highest during the earliest part of the Holocene, with ~6 fire events per 500 yr at 11.6 ka. Although the species mix was different (*Picea engelmannii* and *Pinus contorta* at Tiago; primarily *Picea engelmannii* at the southern sites), we believe that mechanisms were the same at all locations.

At ca. 10.8 ka, *Pediastrum* reached its highest percentages, and may indicate the deepest water levels of the record. Elsewhere, this time witnessed the expansion of the summer monsoon (Fall, 1997). However, after ca. 10.2 ka, *Pediastrum* declined and *Alnus* increased, all suggesting a new equilibrium was reached around the lake. The rapid expansion of *Alnus* was probably a result of opening of a marginal fringe around the lake, perhaps resulting from dropping lake levels. These trends—lowered lake levels but expansion of lower-elevation species' limits—seem to counter each other. Yet, evidence for both trends is found in the region (Shuman et al., 2009). In central (Fall, 1997; Markgraf and Scott, 1981) and northwest (Mayer et al., 2005) Colorado, montane forest expanded downslope into *Artemisia* steppe, suggesting that summer monsoons continued to provide sufficient precipitation during the early and middle Holocene. Lake-level evidence from Hidden Lake (Shuman et al. 2009), just 8 km south, and at the same elevation, of Tiago Lake documents lowered lake levels throughout the same period. Further, Shuman et al. (2009) suggested that lowered lake levels were probably a result of minimal winter precipitation, while summer precipitation determined the precise location of the lower forest- steppe boundary.

Early-to-middle Holocene warming was ubiquitous in the southern Rockies (Carrara et al., 1984; Toney and Anderson, 2006; Anderson et al., 2008a, b; Jiménez-Moreno et al., 2008) as elsewhere, and the continuing thermal maximum from the early Holocene insolation maximum may be related to the lingering effects of the Laurentide Ice Sheet (Kaufman et al., 2004; Renssen et al., 2009), continued relatively high summer insolation (Berger, 1978; Kutzbach et al., 1998), and/or positive September and October insolation anomalies (Shuman et al., 2009), which lasted through the middle Holocene, perhaps essentially "lengthening" the summer and "shortening" the winter precipitation seasons.

These trends continued until ca. 5 ka, by which time maximum development of *Pinus contorta* forest had occurred (pollen percentage ~70%; Fig. 4). A *Pinus contorta*–mixed conifer forest has dominated around Tiago Lake since the mid-Holocene (Fig. 4). Concurrently, *Alnus* declined, suggesting probably loss of the marginal lake-fringe habitat, perhaps as a result of a long-term increase in regional lake levels (Shuman et al., 2009). Environmental responses around Tiago Lake continued to be complex, as increasing winter precipitation (Fall, 1997; Friedman et al., 1988; Rein et al., 2005) accompanied decreasing summer temperatures, resulting in the contraction of the lower tree line upslope, accompanied by an upslope movement of *Artemisia* (see also Markgraf and Scott, 1981; Allen et al., 2008; Anderson et al., 2008a, b; Jiménez-Moreno et al., 2008). This intensified by ca. 3 ka, as shown by the gradual increase in *Artemisia*.

By ca. 3.5 ka, however, the pollen record suggests a regional expansion of *P. edulis* (Colorado piñon) at ca. 3.5 ka, with a second increase at ca. 1.7 ka. Cooler summers and warmer winters from middle to late Holocene may have encouraged expansion of *P. edulis* (Holmgren et al., 2007; Anderson and Feiler, 2009), but other factors such as multidecadal climate variability and periodic drought (Gray et al., 2006; Jackson et al. 2005) or chance establishment by jays or Native Americans (Bentancourt et al., 1991) may have been important.

For Tiago Lake, FEF values decrease during the latest early Holocene and into the middle Holocene (~1–4 events per 500 yr), with minimum values of around 1 fire event per 500 yr at 8.6 and 7.6 ka (Fig. 7C). Even so, pronounced peaks in charcoal influx occurred at ca. 8.5 and 7.1 ka, which may have been a result of extended periods of fuels accumulation between fires, with a resulting less frequent, but more intense fire regime. Minimum FEF values were also found at Hunters Lake, DeHerrera Lake, and Chihuahueños Bog during the middle Holocene (Anderson et al., 2008a, 2008b).

Variable, but mostly higher FEF values (1–6 events per 500 yr) occurred after ca. 6 ka at Tiago Lake, with sustained values of ~3–4.5 fire events per 500 yr between ca. 6 and 4.4 ka (Fig. 7C). Fire frequency declined to ~1 fire event per 500 yr from 3 to 2.5 ka, and rose to below 3.5 events per 500 yr by ca. 1.4 ka, before declining to a minimum of ~1.5 fires per 500 yr at ca. 0.6 ka. Again, the general trends shown for Tiago Lake are those found in the southern Rockies sites, including the documentation of the highest FEF values at virtually all sites between 1 and 2 ka (Anderson et al., 2008a). The relatively high FEF values of the late Holocene generally correspond with the occurrence of a *Pinus contorta*–mixed conifer forest around Tiago Lake, and an increase in winter precipitation from a strengthened El Niño–Southern Oscillation (ENSO; Rodbell et al., 1999; Moy et al., 2002; Friddell et al., 2003; Rein et al., 2005), providing greater soil moisture. However, the late Holocene is also known to be a period of considerable variability in effective precipitation within the region, typified by periodic decadal-scale droughts alternating with extended wetter periods (Cook et al., 2004; MacDonald, 2007; Meko et al., 2007). Periodic droughts impacting high-elevation forests, stocked with considerable biomass, led to higher FEFs during this period of the latest Holocene (Anderson et al., 2008a, 2008b).

The similarities between the records from Tiago Lake and southern Rockies suggest that similar mechanisms have affected both locations since the Late Glacial period. This is not surprising, since even though Tiago Lake is at the northern extreme, both regions receive summer monsoonal and winter frontal precipitation (Anderson et al., 2008b; WRCC, 2009). The overall charcoal stratigraphy may be the best expression of the general trends, because they correlate with variations in July insolation through time, further suggesting that regional climate changes are responsible for the long-term variations in fire frequency (Fig. 7).

TOC exhibits a two-stage increase during the Holocene, with a break in the stages between ca. 5 and 4 ka (Fig. 3). The ^{13}C values are variable about a mean prior to ca. 5 ka, but they become increasingly more negative after ca. 5 ka. Both of these trends may be related to changing inputs of autochthonous and allochthonous organic matter. These values probably resulted from the combination of the progressive development of a montane conifer forest around the lake through the Holocene, with a switch from more positive $\delta^{13}C$ values prior to ca. 5 ka to more negative $\delta^{13}C$ values in the late Holocene. This is consistent with a shift from greater relative productivity and input from aquatic sources

(i.e., algae) or those with greater water-use efficiency (more positive values; Hodell and Schelske, 1998; Brenner et al., 1999; Meyers, 2003) to a more terrestrial source (i.e., conifer forest; Buchmann et al., 1997; Anderson et al., 2008a) after ca. 5 ka.

Holocene Millennial- and Centennial-Scale Variability

The long-term climatic trends during the Holocene in the Tiago Lake area do not obscure the occurrence of several prominent, shorter-term climatic oscillations (Figs. 8 and 9). The numerous and diverse proxies studied in this record show considerable covariation through time; for instance, the timing and duration of the peaks and troughs of the A/P ratio of pollen are markedly consistent with the ^{14}C production record (r = 0.22 [100 yr interpolation] for the past 10 k.y.; Reimer et al., 2004) and the hematite-stained grain abundance from the North Atlantic (% HSG; Bond et al., 2001), i.e., proxies for solar activity and climate variability in the North Atlantic, respectively (Fig. 9). In general, during warm periods, upper elevational limits of dominant species increased (higher A/P ratio; Fig. 8). On the other hand, during cooler periods, plant species moved toward lower elevations (lower A/P ratio; Fig. 8). Our data agree with previous studies that also show a rapid response of the vegetation to climate change at millennial scales during the late Pleistocene and Holocene (Reasoner and Jodry, 2000; Viau et al., 2002; Willard et al., 2005; Jiménez-Moreno et al., 2007, 2008).

Even though generally good correspondence appears to exist between the different proxy data from Tiago Lake and those from hemispheric and cosmic sources, some discrepancies are apparent when comparing those records in detail. For example, the pollen, the % HSG, and the ^{14}C records do not match between 6 and 4 ka, during which the pollen record leads the other two (Fig. 8). The apparent temporal offset between the Tiago Lake pollen record and the other two proxies might either reflect a real time lag between climatic changes in North America and the North Atlantic and/or differences in chronologies. Because there is no evidence for a significant lag in climate responses across the Atlantic, we ascribe these discrepancies to the uncertainty of the radiocarbon dating (Fig. 2; Table 2).

Considerable covariation exists for other proxies within the Tiago Lake record itself, including the TOC and $\delta^{13}C$ values (r = –0.34) and the fire record and magnetic susceptibility (r = 0.17) (Fig. 9). The correlation between the millennial-scale variability observed in the pollen ratio and the rest of the proxies is not straightforward; positive correlation occurs around 10, 7, 3.6, 2.5, and 0.4 ka, but more negative correlations occur at ca. 10.8, 8.8, 6.3, 5.4, and 4.4 ka (Fig. 9). This trend points to climate as a very important overall force controlling some of the millennial-scale variability, but not all. Other important processes in this regard include changes in lake internal processes (i.e., nutrient availability) for the TOC and $\delta^{13}C$ proxies, and the potential effect of Native American burning and slope instability for the fire history.

Even so, the Tiago Lake record shows well-defined centennial-scale cycles superimposed on the long-term late Pleistocene and Holocene trends. In order to test for the presence of cyclical variations in the pollen (A/P ratio), charcoal, and $\delta^{13}C$ record, we used a cyclostratigraphic analysis on the raw data for the last 12 k.y. (Fig. 10). Our analysis documents statistically significant (above the 80% confidence level [CL]) periodicities of ~225 and 390 yr that are common in three and two proxy records respectively (Fig. 10). These periodicities coincide with known solar cycles and are in agreement with previous studies that show centennial-scale variability in Holocene climatic records from widely dispersed geographic regions. For example, the 220 yr period is very similar to the 208 (Suess) and 232 yr solar cycles in ^{14}C production (Damon and Sonnett, 1991). This cycle has also been demonstrated from a pollen record from northern New Mexico (Jiménez-Moreno et al., 2008) and other records worldwide (e.g., Peterson et al., 1991; Bond et al., 2001; Hu et al., 2003; Poore et al., 2003). Periodicities of

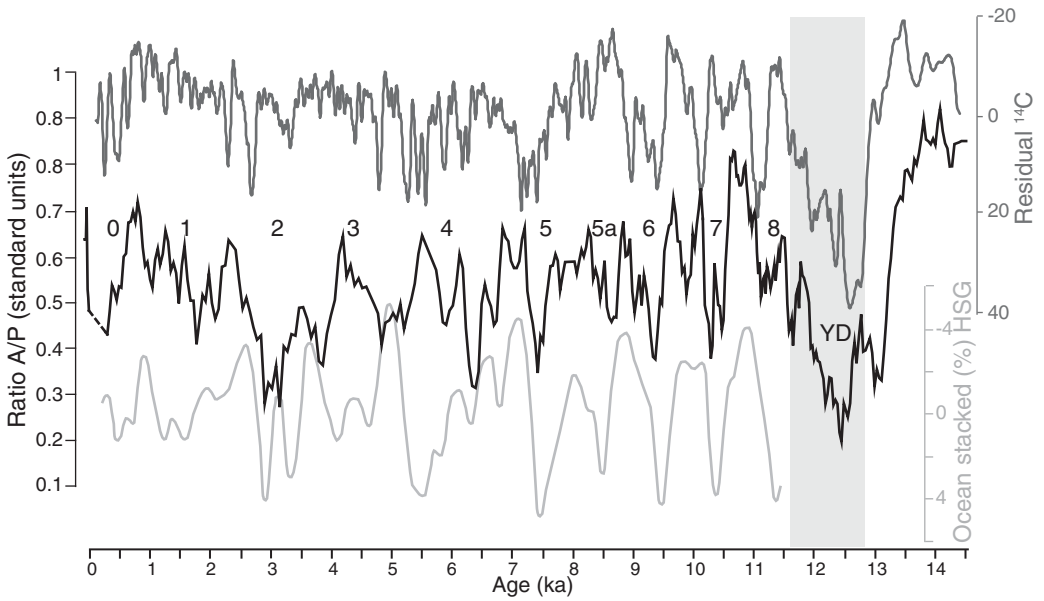

Figure 8. Covariation of 5 point averaged *Artemisia/Picea* ratios (A/P ratio) from Tiago Lake, 7 point averaged residual $\Delta^{14}C$ data calculated from IntCal04 $\Delta^{14}C$ (%) with a 2000 yr moving average subtracted (Reimer et al., 2004), and stacked marine hematite-stained grains (% HSG) records in percentage from the North Atlantic (Bond et al., 2001). Cold events are marked with numbers from 0 to 8 (Bond et al., 2001).

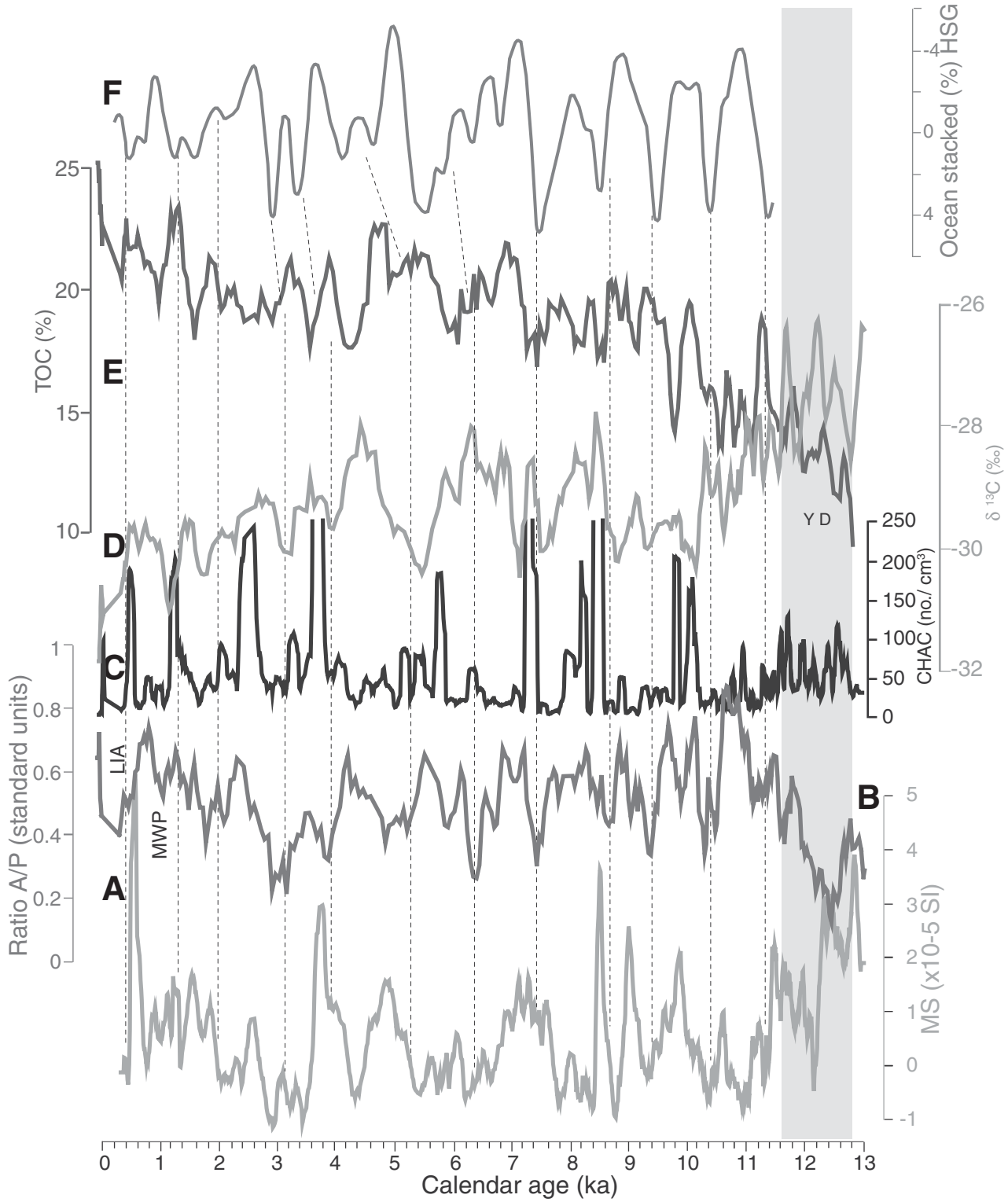

Figure 9. Comparison of different proxies studied from Tiago Lake for the last 13 k.y. (A–E) with the North Atlantic stacked hematite-stained grains (% HSG) record (F; Bond et al., 2001). (A) 11 point averaged magnetic susceptibility (MS). (B) 5 point averaged *Artemisia*/*Picea* ratios (A/P ratio). (C) 11 point averaged charcoal record (CHAC; no. charcoal particles cm^{-3}). (D) 5 point averaged δ^{13}C values from bulk sediment samples. (E) 5 point averaged total organic carbon (TOC) from bulk sediment samples. (F) Stacked marine hematite-stained grains (% HSG) record from the North Atlantic (Bond et al., 2001).

around 400 yr have also been documented in the ^{14}C production record (Damon and Sonnett, 1991), in the North Atlantic (Bond et al., 2001), and in the U.S. Great Plains (Dean, 1997).

The near-synchronous response of vegetation in the Tiago Lake area and other sites in Colorado (Reasoner and Jodry, 2000) with the onset and termination of the Younger Dryas event and other global cold events during the Holocene suggests a rapid coupled ocean-atmosphere hemispheric transmission of the climate oscillations. Variations in solar activity at millennial- and centennial-scales seem to have also played a great role in modulating climate (Stuiver et al., 1997; Bond et al., 2001; Hu et al., 2003; Asmerom et al., 2007; Jiménez-Moreno et al., 2008). A solar forcing of the climate could satisfactorily explain the hemispheric connection and the immediate response of the vegetation to climate change. However, the amplitude of temperature changes directly related to solar change is unknown (Rind, 2002) and may be smaller than that suggested by the vegetation changes. Recent work has also suggested a role for changes in North Atlantic thermohaline circulation and attendant changes in Atlantic basin sea-surface temperature gradients on Pacific ENSO variability (Dong and Sutton, 2007; Timmermann et al., 2007). It has also been suggested that the Atlantic Multidecadal Oscillation (AMO) can modulate large-scale patterns of precipitation variability in the western United States, including summer precipitation and winter precipitation variability associated with El Niño–Southern Oscillation (McCabe et al., 2004). These kinds of teleconnections between the Atlantic and Pacific might help to explain the correlation between northern Colorado and the North Atlantic for that part of the record due to changes in precipitation and basin hydrology.

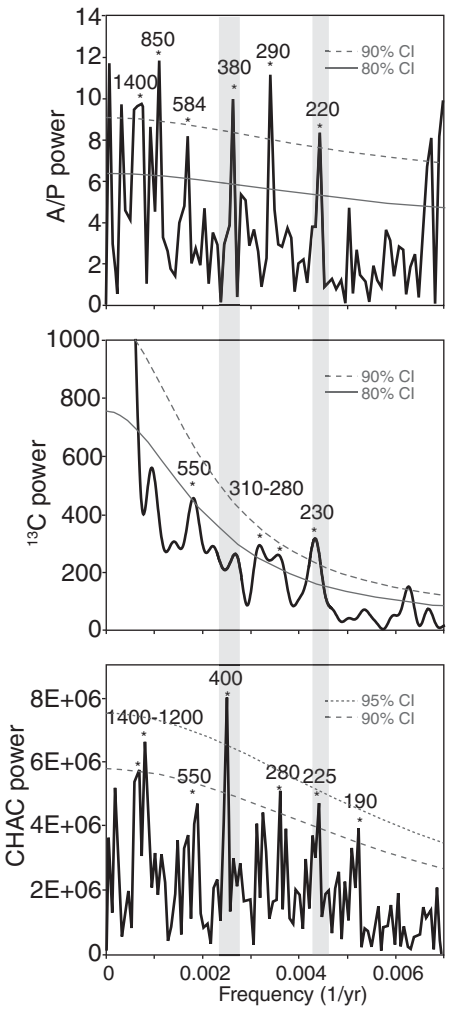

Figure 10. Spectral analysis of the Tiago Lake raw *Artemisia/Picea* (A/P) ratios, charcoal data (CHAC), and $\delta^{13}C$ values for the last 12 k.y. Confidence intervals (80%, 90%, and 95%) are shown. Significant periodicities (above the 80% confidence level) are marked. Shading highlights periodicities around 200 and 400 yr. The spectral analysis was done using REDFIT (Schulz and Mudelsee, 2002). Several overlapping (50%) segments (n_{seg}) of three- and Hanning-type spectral window were used.

SUMMARY AND CONCLUSIONS

A multiproxy approach in paleoecological research has become critical in providing a comprehensive understanding of paleoenvironmental change. Here, we used a combination of pollen, charcoal, magnetic susceptibility (MS), organic carbon (TOC), and $\delta^{13}C$ data from the mostly laminated Tiago Lake sediment core to determine these interactions during the postglacial for northwestern Colorado. The high-resolution record from Tiago Lake sediments allowed us to compare vegetation, and thus climate, changes there with the broader Northern Hemisphere record of climate change from Greenland (GISP2 record). Our ~30 yr sampling resolution demonstrates a strong climatic linkage across North America between the southern Rocky Mountains and the high Arctic. For instance, the near-synchronous response of vegetation in the Tiago Lake area and other sites in Colorado (Reasoner and Jodry, 2000) with the onset and termination of the Younger Dryas event and other global cold events during the Holocene suggests a rapid coupled ocean-atmosphere hemispheric transmission of the climate oscillations. This includes the recognition of two abrupt climatic oscillations around Tiago Lake at ca. 14.2 ka (inter-Bølling cold period [IBCP]) and 13.1 ka (inter-Allerød cold period [IACP]), which we correlate with GISP2 events.

The postglacial record of vegetation change at Tiago Lake is consistent with other studies from the southern Rockies. The Tiago Lake record also confirms and extends the assertion that lower montane tree line extended into *Artemisia* steppe during the early and middle Holocene as climate warmed but summer precipitation increased. Pollen ratios, such as the A/P (*Artemisia/Picea*) ratio, primarily used for upper tree-line fluctuations, can also be used to determine lower tree-line fluctuations in areas such as northern Colorado, where lower elevations in basins have nonarboreal vegetation. The late Holocene is characterized in our record by a cooling trend and an increase in winter precipitation. These climate changes are mainly associated with orbital-scale variations in Earth's insolation.

The fire history from Tiago Lake is very similar to those from other locations in the southern Rocky Mountains, probably reflecting a similar climate history during the postglacial. FEF values were highest during the earliest part of the Holocene, with ~6 fire events per 500 yr at 11.6 ka, probably due to a combination of increasingly flammable coniferous biomass from establishment of conifers and high summer insolation. The relatively high FEF values of the late Holocene correspond with the full development of the fire-dependent *Pinus contorta*–mixed conifer forest around Tiago Lake, probably related to an increase in winter precipitation (and increased fuel loads), coupled with periodic decadal-scale droughts.

Long-term climatic trends during the Holocene in the Tiago Lake area were punctuated by several prominent climatic oscillations. The numerous and diverse proxies studied in this record show considerable covariation through time, and the timing and duration of the peaks and troughs of the A/P ratio of pollen are markedly consistent with the ^{14}C production record and the hematite-stained grain abundance from the North Atlantic, which are proxies for solar activity and climate variability in the North Atlantic, respectively. The Holocene climatic fluctuations observed in our record may reflect a manifestation of climatic cycles related to variations in solar activity on millennial- and centennial-time scales as shown by prominent ~400 and 200 yr cycles in the different proxies studied throughout the Holocene.

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(U.S. Forest Service) helped with logistics; Mark Baskaran determined the ^{210}Pb ages of core Ti-3b; Caleb Schiff assisted with the age model; Erin Herring helped with the CharAnalysis program; and David Nelson helped with the interpretation of the ^{13}C data. We thank Achim Bechtel, an anonymous reviewer, and the associate editor, A. Hope Jahren, for helpful comments on this manuscript. Financial support was provided by the U.S. Geological Survey, Western Mountain Initiative (contract 04CRAG0033), and the U.S. Forest Service. This is Laboratory of Paleoecology Contribution 115.

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