

Variations in fire frequency and climate over the past 17 000 yr in central Yellowstone National Park

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ABSTRACT

A 17 000 yr fire history from Yellowstone National Park demonstrates a strong link between changes in climate and variations in fire frequency on millennial time scales. The fire history reconstruction is based on a detailed charcoal stratigraphy from Cygnet Lake in the rhyolite plateau region. Macroscopic charcoal particles were tallied from contiguous 1 cm samples of a 6.69-m-long core, and the data were converted to charcoal-accumulation rates at evenly spaced time intervals. Intervals of high charcoal-accumulation rates were interpreted as local fire events on the basis of information obtained from modern charcoal-calibration studies in the Yellowstone region. The record indicates that fire frequency was moderate (4 fires/1000 yr) during the late glacial period, reached highest values in the early Holocene (>10 fires/1000 yr), and decreased after 7000 calendar yr B.P. The present fire regime (2–3 fires/1000 yr) was established in the past 2000 yr. The charcoal stratigraphy correlates well with variations in July insolation through time, which suggests that regional climate changes are responsible for the long-term variations in fire frequency. In the early Holocene, summer insolation was near its maximum, which resulted in warmer, effectively drier conditions throughout the northwestern United States. At this time, the fire frequency near Cygnet Lake was at its highest. After 7000 calendar yr B.P., summer insolation decreased to present values, the regional climate became cooler and wetter, and fires were less frequent. The Cygnet Lake record suggests that long-term fire frequencies have varied continuously with climate change, even when the vegetation has remained constant.

Keywords: fire history, charcoal analysis, Yellowstone, Holocene.

INTRODUCTION

The recent occurrence of large fires in the western United States raises questions about the effect of climate change on fire regimes at present, as well as in the past and future. One source of fire history information is the records of fire-scarred tree rings and forest-stand age classes that span the past 300–500 yr. Because such dendrochronologic records sample only a small interval of environmental history, they provide little information on the relationships between fire and climate on centennial to millennial time scales. Longer fire histories are obtained from charcoal and other fire-proxy data preserved in radiocarbon-dated lake-sediment cores. Stratigraphic changes in particulate charcoal show variations in fire frequency that can be compared with pollen-based reconstructions of vegetation and climate. Although lake-sediment records lack the spatial specificity of dendrochronologic fire reconstructions, they disclose information on the temporal variability of fire occurrence and the role of fire during periods of major climate and vegetation change.

There are few high-resolution charcoal records available from the western United States (Long et al., 1998; Mohr et al., 2000; Cwynar, 1987; Smith and Anderson, 1992), and none from the northern Rocky Mountains. Most of these records come from sites where past variations in fire occurrence coincided with periods of climate and

vegetation change. As a result, it has not been possible to assess whether changes in the fire regime are driven primarily by changes in climate or in plant communities and fuel conditions. In order to examine the links between fire and climate directly, we present a high-resolution fire history from Cygnet Lake (lat 44°39'N, long 110°36'W, elevation 2530 m) in the Central Plateau region of Yellowstone National Park (Fig. 1). The site was chosen because pollen studies reveal that the composition of Central Plateau forests did not change during the Holocene, despite regional changes in climate (Whitlock, 1993). Thus, the site offers a natural “experiment” that allows us to consider the sensitivity of fire regimes to climate change alone. The complacency of the vegetation is attributed to the influence of infertile rhyolite soils, which limit the establishment and growth of most conifer species on the Central Plateau (Despain, 1990; Whitlock, 1993). At present, the plateau region supports uniform forests of lodgepole pine (*Pinus contorta*) despite climate and fire regimes that are suitable for Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and whitebark pine (*Pinus albicaulis*). In the past few centuries, large (>2500 ha), infrequent (200–400 yr mean fire interval), stand-replacing fires have resulted in a forest mosaic composed of different stand ages of lodgepole pine and little species diversity (Romme and Despain, 1989). The Cygnet Lake record provides the first char-

coal-based fire history from the Yellowstone region, and its unique geologic setting offers an opportunity to examine long-term variations in fire frequency that are primarily the result of climate.

METHODS

A 6.69-m-long core was collected from Cygnet Lake by use of a 5-cm-diameter square-rod piston corer. An age model was developed from nine radiocarbon (including six mass accelerator) dates and the ages of tephra from known volcanic eruptions (Table 1). Radiocarbon years were converted to calendar ages based on CALIB 3.0 (Stuiver and Reimer, 1993). A weighted third-order polynomial regression (constrained to pass through 0 calendar [cal] yr B.P.) was used to interpolate between calibrated radiocarbon ages. Calibrated dates were assigned a weighting of 0.1, 0.5, or 1.0 depending on our confidence in their accuracy (Table 1). A weight of 1.0 was given to both age 0 and 7630 cal yr B.P. (the accepted age of Mount Mazama ash). Because at least one late Holocene age determination was out of sequence, the five youngest calibrated ages were given weights of 0.1. The basal age of the core (17 360 cal yr B.P.) was also weighted at 0.1, because the sample was obtained from sediment of low organic content. Calibrated ages for the early Holocene were given a higher weighting of 0.5 on the grounds that they were in chronologic order. The age assignments derived from the weighted polynomial regression model compared well with a simpler model based on linear interpolation between 0 and 7630 cal yr B.P. (Mount Mazama ash), and between 7630 and 13 760 cal yr B.P. (Glacier Peak tephra). The

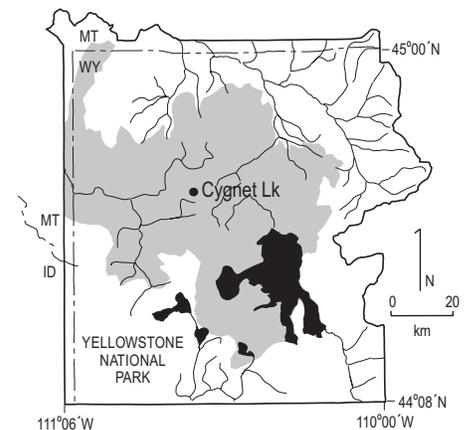


Figure 1. Location of Cygnet Lake within Central Plateau region (shaded) of Yellowstone National Park (bold outline). Black areas are large lakes.

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TABLE 1 UNCALIBRATED AND CALIBRATED AGE DETERMINATIONS FOR CYGNET LAKE

Depth in core (CL#91B) (m)	Material	Lab no.	Age $\pm 1 \sigma$ (^{14}C yr BP)	Calibrated calendar age & 1σ range* (cal yr BP)	Weighting†
0					1.00
0.75-0.79	Charcoal	Beta-80620	3480 \pm 100	3627 (3707) 3863	0.10
0.88-0.90	Charcoal	Beta-77421	3800 \pm 60	4087 (4149) 4267	0.10
1.05-1.08	Charcoal	Beta-80621	4720 \pm 100	5313 (5349) 5587	0.10
1.67-1.70	Charcoal	Beta-74921	4010 \pm 60	4411 (4502) 4532	0.10
2.16-2.18	Charcoal	Beta-77422	6390 \pm 60	7212 (7262) 7376	0.10
2.80-2.81	Mazama			7630§	1.00
3.78-3.80	Charcoal	Beta-77423	8030 \pm 80	8675 (8960) 8991	0.50
4.38-4.40	Charcoal	Beta-74922	9100 \pm 60	9988 (10033) 10073	0.50
5.13-5.17	Charcoal	Beta-77424	10190 \pm 110	11344 (11939) 12180	0.50
6.24-6.25	Glacier Peak	Pitt-0554	11800 \pm 190#	13522 (13755) 14008	0.50
6.86-6.96	Sediment	Pitt-0459	14490 \pm 700#	16532 (17358) 18117	0.10

* Minimum of 1σ calibrated age range, (calibrated calendar age), maximum of 1σ calibrated age range. (1σ = square root of sample SD2 + curve SD2; Stuiver and Reimer, 1993).

† See text for explanation.

§ From Zdanowicz et al. 1999

Ages for Glacier Peak B (Pitt-0554) determined in core CL#88A (Whitlock, 1993), but used to establish chronology for CL#91B.

smooth regression curve, however, eliminated the effects of abrupt changes in sedimentation rate that often occur with linear interpolation methods.

Variations in the abundance of charcoal particles provided the primary record of past fires. Samples of sediment, 5 cm³ each, were taken from contiguous 1 cm intervals of the core. A sampling interval of 1 cm represents, on average, ~20 yr of sediment accumulation (based on age vs. depth relationships), which is sufficiently short to resolve fire events in the charcoal record, considering that the mean fire interval at present is ~200–400 yr (Romme and Despain, 1989). Samples were gently washed with water through sieves of 125 and 250 mm mesh size. The choice of mesh size was based on modern charcoal studies following the 1988 fires in Yellowstone (Whitlock and Millspaugh, 1996) and theoretical models of charcoal transport (Clark, 1988; Clark and Patterson, 1997). These studies indicate that particles >125 mm in size (i.e., macroscopic charcoal) are generally not transported far from their source and thus provide a reliable record of local fires. The total number of charcoal particles >125 mm in each sample was counted under a stereomicroscope, and counts were converted to concentration values (particles/cm³) (Fig. 2A). Charcoal-concentration data and sedimentation rates were interpolated to pseudo-annual values. The averages of these concentration values were integrated over 10 yr intervals and multiplied by the average sedimentation rate for that decade to produce charcoal-accumulation rates (CHAR in particles/[cm² · yr]; Fig. 2, B and C).

The charcoal record was decomposed into two components that provided complementary information about fire history. The slowly varying trend in the charcoal data, or background CHAR, was determined by use of a locally weighted (moving) average function (see Cleveland, 1979,

and Millspaugh, 1996), (2) varies in abundance depending on standing biomass and fuel load (i.e., charcoal production), and (3) comes from regional fires outside the watershed (Long et al., 1998; Clark and Royall, 1996). The peaks component of the charcoal record refers to CHAR higher than the background. It was determined by identifying values above a CHAR “threshold ratio” (individual CHAR divided by background CHAR at the same point in time) (Fig. 2D). Peaks are assumed to represent local fire events that occurred within or near the watershed. This assumption is based on the observed increase in charcoal abundance that occurred in lakes in burned watersheds following the 1988 Yellowstone fires (Whitlock and Millspaugh, 1996). It is also supported by the close correlation between the year of historic fires and the age of charcoal peaks in ²¹⁰Pb-dated short cores from the region (Millspaugh and Whitlock, 1995). The peak frequency was averaged by using a 1000 yr window (Fig. 2E).

A window width of 750 yr was used to define the background levels of CHAR at Cygnet Lake, and values above background were considered fire peaks (i.e., a threshold ratio of 1.00 was used). These parameters were chosen because they generated results that suggested a mean fire interval for the past millennium that was similar to that obtained from dendrochronologic studies. Differ-

ences between the charcoal record and dendrochronologic studies are likely due to differences in the definition of fire events and the time scale used for averaging.

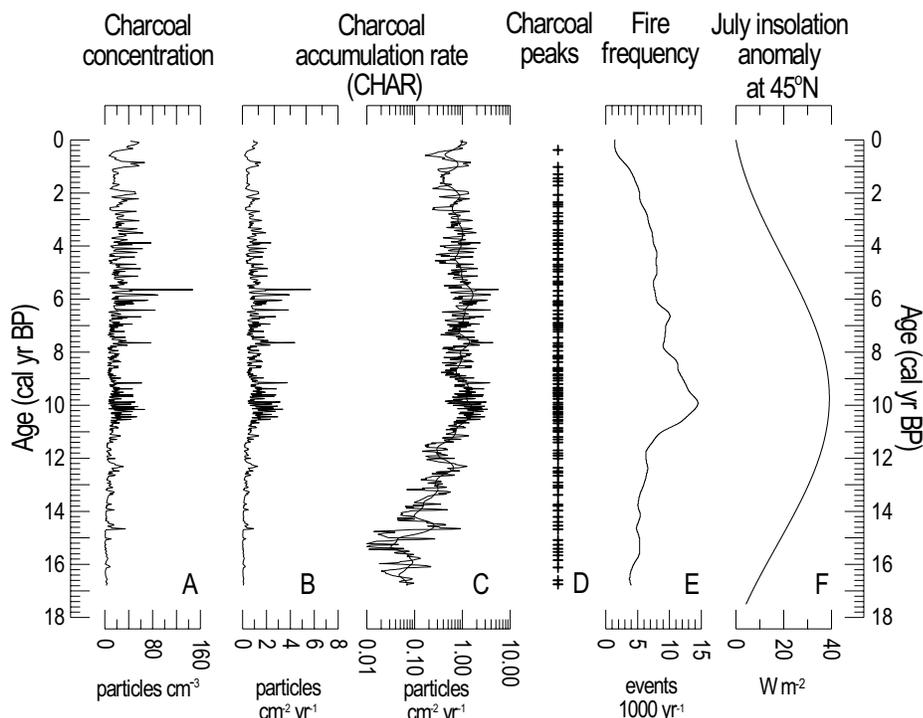


Figure 2. Charcoal results from Cygnet Lake based on an examination of macroscopic particles in contiguous 1 cm samples (total number of samples = 696). Results are presented as charcoal concentration (A) and charcoal accumulation rates (CHAR) plotted on normal scale (B) and logarithmic scale (C). Line through CHAR values in C represents CHAR background values. Charcoal peaks (+) above background levels define fire events (D), which are summarized as number of fires/1000 yr (E). Long-term trend in fire frequency compares well with July insolation anomaly (F) (Berger, 1978).

ent combinations of parameters for window width (200–1000 yr) and threshold ratio (1.00–1.20), however, were performed on both untransformed and transformed (logarithmic) CHAR, and the results showed the same trends in fire frequency described in the following (Millsbaugh, 1997).

Magnetic susceptibility was measured to identify the presence of allogenic minerals in the sediment (Thompson and Oldfield, 1986). Readings were taken at contiguous 1 cm intervals (the same intervals as the charcoal analysis) from the long core by use of a coil-cup sampling device attached to a Sapphire SI-2 magnetic susceptibility meter. Measurements were presented in electromagnetic units (emu). Emu concentration data were transformed to electromagnetic accumulation rates (EMAR; $\text{emu}/[\text{cm}^2 \cdot \text{yr}]$) by the same method that was applied to charcoal-concentration data. Records of organic content (Dean, 1974), charcoal, and magnetic susceptibility were correlated with a pollen stratigraphy developed from a previously analyzed core (Whitlock, 1993).

CLIMATIC AND VEGETATIONAL HISTORY OF THE CENTRAL PLATEAU

Paleoecologic data and paleoclimate model simulations jointly indicate that Holocene climate variations in Yellowstone National Park were a manifestation of changes in the climate system that affected western North America. Foremost among the large-scale controls were changes in the seasonal cycle of insolation caused by variations in the tilt of the Earth's axis and the timing of perihelion (Berger, 1978). The climate in the late glacial period was initially colder and wetter than at present, on the basis of the establishment of tundra communities throughout the northern Rocky Mountains. Warming, brought about by increasing summer insolation, allowed the establishment of subalpine forests of *Picea*, *Abies*, and *Pinus* between 14 000 and 11 000 cal yr B.P. in adjacent non-rhyolite regions (but not the Central Plateau) (Whitlock, 1993). The amplification of the seasonal cycle was greatest at about 10 000 cal yr B.P., when insolation was 8.5% greater in summer (and 10% less in winter) than at present at the latitude of Yellowstone National Park (Fig. 2F). High summer insolation apparently led directly to high temperatures and low effective moisture, and indirectly to changes in atmospheric circulation (Barnosky et al., 1987). Paleoclimate model simulations of the early Holocene (Thompson et al., 1993) show that greater than at present summer insolation strengthens the eastern Pacific subtropical high-pressure system, which, in turn, intensifies summer drought in the northwestern United States. The summer insolation maximum also increases the onshore flow of moisture from the Gulf of California, which enhances summer monsoons in the American Southwest. The eastern Pacific subtropical high and the southwestern monsoon both influence the

climate of Yellowstone National Park at present and account for the juxtaposition of summer-wet and summer-dry regimes in a limited region (Whitlock and Bartlein, 1993). Pollen records from Yellowstone suggest that the intensification of these regimes in the early Holocene created a sharply delimited spatial response in which some areas became drier and others became wetter compared to the present. These contrasts weakened after 7500 cal yr B.P. with the attenuation of the seasonal cycle of insolation (Whitlock and Bartlein, 1993; Whitlock et al., 1995). Southern and central Yellowstone, including the Central Plateau, are within the region that had warmer drier summers in the early Holocene and cooler moister conditions in the late Holocene.

A pollen study from Cygnet Lake in the Central Plateau indicates that high percentages of sagebrush (*Artemisia*) and grass (Poaceae) were present between ca. 17 000 and 12 800 cal yr B.P., when the region was colonized by tundra or grassland (Whitlock, 1993; Fig. 3). An increase in *Pinus* (diploxylon-type) pollen between ca. 12 800 and 11 300 cal yr B.P. marks the establishment of lodgepole pine forest at the site. Unlike sites in nonrhyolitic regions (Whitlock, 1993), the *Pinus* assemblage at Cygnet Lake has persisted with little modification for the past 11 300 cal yr, despite changes in temperature and effective moisture.

Lake productivity was low in Cygnet Lake during the late glacial period, as evidenced by the low organic content of the sediments, but increased after 11 200 cal yr B.P. (Fig. 3). High magnetic susceptibility values during the late glacial period are probably the result of the continuous influx of

allochthonous mineral material from a sparsely vegetated landscape. Development of closed *Pinus* forest ca. 11 300 cal yr B.P. and stabilization of soils in the early Holocene are probably responsible for the sharp decline in erosion rates.

FIRE AND CLIMATIC CHANGE FOR THE PAST 17 000 YR

Fire frequency variations are well correlated with the July insolation anomaly over the past 17 000 yr ($r = 0.799$; $p < 0.001$). This correlation suggests that changes in fire frequency were a response to the changes in regional climate that resulted from variations in the seasonal cycle of insolation. The frequency was 4 fires/1000 yr ca. 17 000 cal yr B.P. in the cool humid late glacial period. A gradual rise in fire frequency from 4 to 6 fires/1000 yr occurred between 17 000 and 11 700 cal yr B.P., when the climate became warmer and drier with increasing summer insolation. Increasing background CHAR during this period was probably caused by changes in biomass as tundra was replaced by park land and then forest. Fires were more frequent after ca. 11 700 cal yr B.P. as a result of greater summer warmth and aridity brought about by the direct and indirect effects of increasing July insolation. A fire frequency of 15 fires/1000 yr was attained ca. 9900 cal yr B.P., near the time of the early Holocene insolation maximum ($>39 \text{ W/m}^2$; Berger, 1978). The short interval between fires suggests that most events were small and likely limited by the availability of fuels. The pollen data did not detect changes in understory vegetation associated with changes in stand-age distribution, but the dominance of *P. contorta*-type

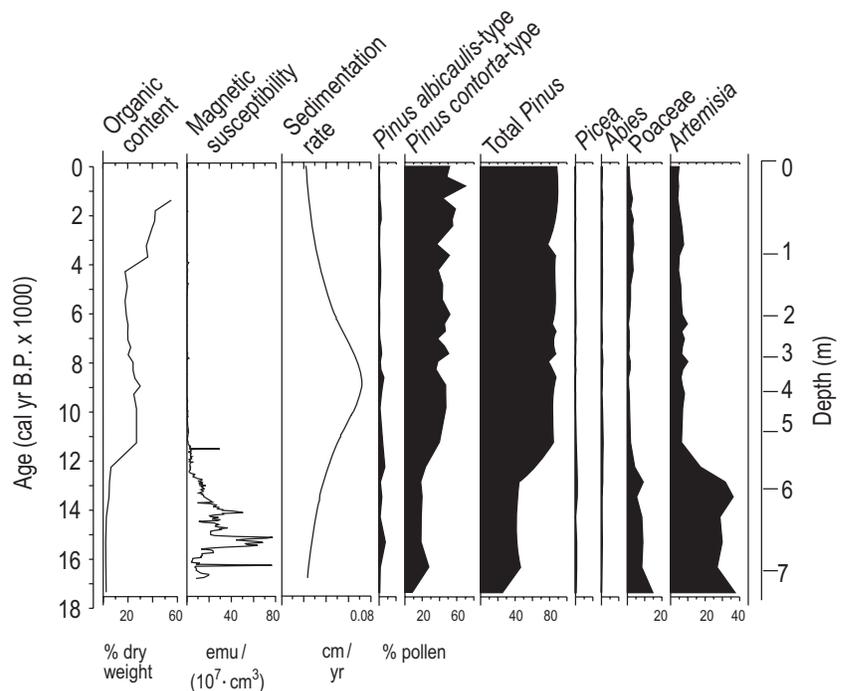


Figure 3. Profiles of organic-matter content, magnetic susceptibility, sedimentation rate, and percentages of selected pollen types.

pollen in this region and the low amounts of *Artemisia* and herbaceous pollen suggest few forest openings. After 9900 cal yr B.P., the number of fires gradually decreased to present-day frequencies (<2–3 fires/1000 yr), coinciding with decreased summer insolation and cooler and effectively wetter conditions than before. In the past two millennia, fire frequency has been lower (2–5 fires/1000 yr) than at any time in the Holocene. Protracted periods without fire have allowed forest stands to mature and the mosaic of *P. contorta* to become more connected in the late Holocene. This type of landscape pattern promotes fire spread and contributes to the current fire regime of large, stand-replacing fires in drought years, including 1988 (Balling et al., 1992). Contrary to assumptions implicit in dendrochronologic fire reconstructions, the charcoal record shows no recurrent fire return interval or obvious fire cycle. Instead, fire occurrence at Cygnet Lake is a nonstationary process that varies over time with climate.

The variations in the charcoal record at Cygnet Lake cannot be attributed to changes in sedimentation rate (cm/yr; Fig. 3), because charcoal concentration (Fig. 2A) is not significantly correlated with sedimentation rate ($r = -0.019$, $p = 0.63$). On the basis of our age model, sedimentation rates were initially low in the late glacial period, increased to their highest value ca. 8900–9000 cal yr B.P., and then decreased in the late Holocene. Charcoal concentration and total CHAR (Fig. 2, B and C) were low in the late glacial period, increased between ca. 17 000 and 11 000 cal yr B.P., and remained high thereafter. CHAR peak frequency (Fig. 2, D and E) reached its highest level at 9900 cal yr B.P., before the period of maximum sedimentation rates. Beyond the lack of correlation, no obvious mechanism links high charcoal abundance or peak frequency with high sedimentation rates. Instead, one would expect that high sedimentation rates would decrease charcoal concentration and increase the spacing between charcoal peaks.

Cygnet Lake has relevance to discussions of how fire regimes may vary with future climate changes. Climate model simulations that incorporate higher levels of CO₂ than at present project increased evapotranspiration and enhanced summer drought in the interior western United States (Bartlein et al., 1997). The models further predict that higher temperatures and greater convective activity will result in more frequent thunderstorms and increased lightning fires (Price and Rind, 1994). Although the controls of early Holocene climate are not an exact analogue for those implicated in future climate change, our results show that variations in fire frequency have closely paralleled long-term variations in summer drought. The historic trend toward infrequent severe fires, such as those in 1988, will be short-lived and in all likelihood replaced by a regime of many small fires in the future as a result of dry

fuel conditions and more frequent ignitions. With fire frequencies like those of the early Holocene, the forests of central Yellowstone will change, not so much in composition as in stand-age distribution. Thus, the disturbance regime will serve to perpetuate lodgepole pine where it now grows and also allow its expansion to higher elevations.

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