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Watershed and Aquatic Ecosystem Evolution During the Late-Glacial and Early-Holocene Inferred From High-Resolution Diatom and Geochemical Records in the Yellowstone Region

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WATERSHED AND AQUATIC ECOSYSTEM EVOLUTION DURING THE LATE-GLACIAL
AND EARLY-HOLOCENE INFERRED FROM HIGH-RESOLUTION DIATOM AND
GEOCHEMICAL RECORDS IN THE YELLOWSTONE REGION

by

Yanbin Lu

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WATERSHED AND AQUATIC ECOSYSTEM EVOLUTION DURING THE LATE-GLACIAL
AND EARLY-HOLOCENE INFERRED FROM HIGH-RESOLUTION DIATOM AND
GEOCHEMICAL RECORDS IN THE YELLOWSTONE REGION

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University of Nebraska, 2014

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High-resolution diatom records spanning the late-glacial and early-Holocene were developed from three lakes in the Yellowstone region to infer the lake history and to evaluate the relative importance of climatic versus non-climatic factors on the aquatic ecosystem evolution. Synchronous shifts in diatom community structure occurred in all lakes, which are located in regions of varied surficial geology and precipitation seasonality, in the intervals of 13.9-13.8, 13.2-13.1, 11.3-11.0 and 8.8-8.7 cal ka. The synchronous diatom community structure shifts suggest that large-scale climatic change is the primary driver of the aquatic ecosystem evolution in this region, whereas the influence of non-climatic factors is secondary.

Four lake sediment cores collected from the Yellowstone region were examined with high-resolution geochemical analysis to investigate trends in watershed and lake evolution during the late-glacial and early-Holocene. During the

early stage of lake development, clastic input was high, and lake productivity was low, and they decreased and increased, respectively, as vegetation gradually developed in the catchment. The decrease of clastic input was asynchronous among regional lakes, and occurred time transgressively from south to north. The long-term pattern of change in calcite precipitation was controlled primarily by lake-level change in small and shallow lakes and by lake productivity in large and deep lakes.

The late-glacial and early-Holocene history of terrestrial and limnological development also was reconstructed from a high-resolution record of pollen, charcoal, diatom, geochemical, and lithologic data from Dailey Lake in southwestern Montana. Following deglaciation, the surrounding landscape was unstable and sparsely vegetated. As summer insolation increased, open parkland developed, and diatoms established in the lake at ~13.4 cal ka. Closed subalpine forest developed at ~12.2 cal ka and then was replaced by open forest at ~10.2 cal ka. Warm dry summers prevailed after ~11.0 cal ka, as indicated by increasingly open forest and increased benthic diatoms, which differs from some nearby records that are located at higher elevation.

Acknowledgments and dedication

I dedicate this work to my family, especially my dear wife, Cuicui Song, for her unlimited support and encouragement and to my parents, who have always been supportive, even if having to face up the fact that their son is a Pacific Ocean away from them.

Foremost, I would like to thank my advisor Dr. Sherilyn Fritz for providing me an opportunity to study in the United States and for her valuable guidance and kind support on both my academic and daily life over the past four years. I want to acknowledge the financial support of the Department of Earth & Atmospheric Sciences (summer research fellowships, teaching assistantships, and student travel grant). I am grateful to my committee members, Drs. David Watkins, John Gates, and Steve Thomas, for their feedback and advice on my research. I would also like to thank Trisha Spanbauer, Jeffery Stone, Karlyn Westover, Vicky Chraibi, and Marie Weide for their help on my study; James Benes for his friendship and lab assistance; Dr. Cathy Whitlock for designing the Yellowstone research project together with Dr. Sherilyn Fritz; Dr. Kenneth Pierce, Teresa Krause, and Virginia Iglesias for sharing their data; Stacey Gunther and Christie Hendrix of Yellowstone National Park, and Linda Franklin and staff of Grand Teton National Park for their logistical support in the field.

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CHAPTER 1
INTRODUCTION

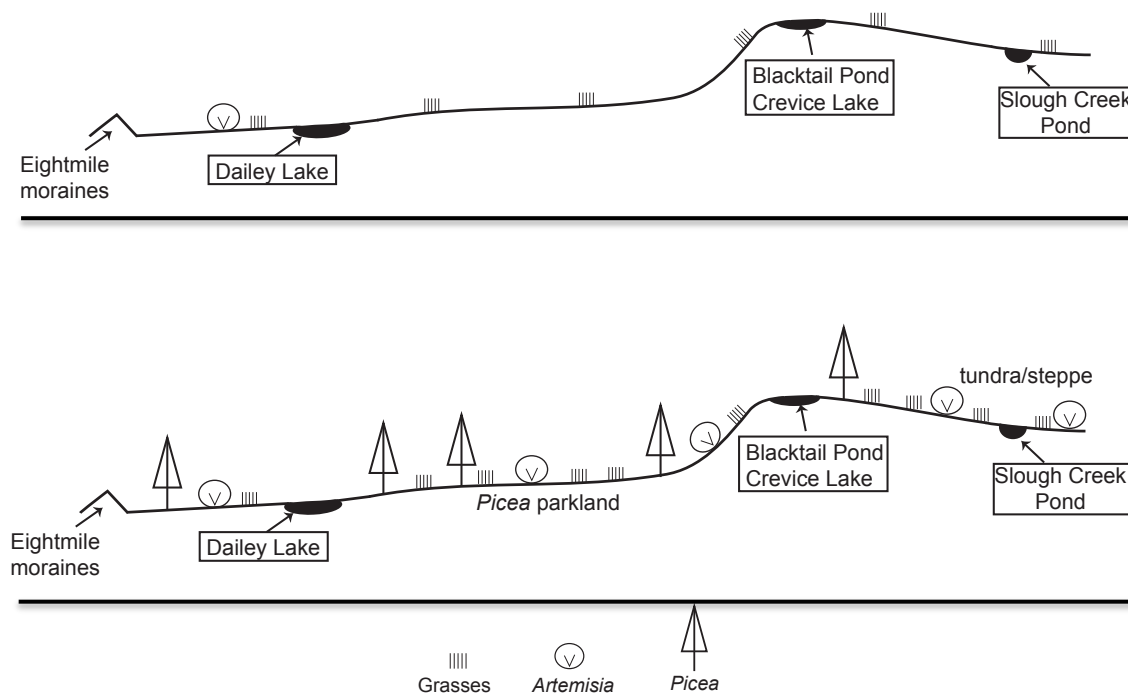
1.1 Background

During the late-glacial and early-Holocene period, large and rapid climate fluctuations occurred in many regions, including western U.S. (Alley and Clark, 1999; Shakun and Carlson, 2010). The greater Yellowstone region underwent widespread ice recession beginning ~17 ka BP, when ice extent had reached its local maximum, and the ice sheet was largely gone by ~14 ka BP (Licciardi et al., 2004; Pierce, 2004; Licciardi and Pierce, 2008; Thackray, 2008). Glacial retreat during the late-glacial period was associated with increasing summer insolation (Berger, 1978). As the ice retreated, it created hundreds of lakes in the Yellowstone region. Following lake formation, the evolution of lacustrine systems was affected by many environmental controls, including both climatic change and catchment process. Climatic change influences a lake's thermal and hydrological budgets (precipitation-evaporation) (Fritz and Anderson, 2013; Battarbee, 2000), whereas catchment processes affect lake development as the newly exposed landscape stabilizes and soils and vegetation develop (Fritz and Anderson, 2013).

In the modern Yellowstone region, surficial geology and the resulting chemistry of soils vary (Whitlock, 1993). Central Yellowstone is underlain by nutrient-poor rhyolitic rocks. Other areas have nutrient-rich calcareous glacial sediments or nutrient-intermediate andesitic bedrocks. In addition, two precipitation regimes have been identified (Whitlock and Bartlein, 1993). Northern Yellowstone receives considerable rainfall in summer (summer-wet) due to summer monsoonal circulation from the Gulf of Mexico. In central and southern Yellowstone, most of the precipitation falls in winter as a result of the strong influence of westerly

storms, whereas an expanded Pacific subtropical high-pressure system suppresses rainfall in summer (summer-dry). Thus, the varied soils and local climate regimes provide a useful setting for evaluating ecological responses to past environmental change and investigating the role of climatic change versus catchment processes on ecosystem evolution following deglaciation.

Most paleoenvironmental reconstructions in the Greater Yellowstone region are based on pollen and charcoal records, providing insights on the evolution of terrestrial vegetation and fire activity (Whitlock, 1993; Millspaugh et al., 2000, 2004; Huerta et al., 2009; Whitlock et al., 2012; Krause et al., 2013). Following deglaciation, the landscape was not vegetated or only had sparse vegetation, soils were not developed, and the catchment was very unstable. Over time the landscape was gradually vegetated and organic-rich, soils were developed, with different patterns in high versus low-elevation regions (Fig. 1.1). Only a few studies focus on or involve the limnological history of the region, but the late-glacial period has not been covered in any detail in prior studies (Bracht et al., 2008, 2012; Whitlock et al., 2012; Theriot et al., 2006; Engstrom et al., 1991). The research reported in this dissertation is part of a large collaborative project to investigate watershed and limnological history and the controls on aquatic ecosystem evolution during the late-glacial and early-Holocene period in the Greater Yellowstone region. Here, high-resolution diatom data, elemental data, and sediment carbon and nitrogen data collected from different lakes are employed to answer the following questions, with the aid of additional data, such as pollen and charcoal:



Modified from Teresa et al., 2013

Figure 1.1 Illustration of vegetation on newly glaciated landscape and gradually vegetated landscape.

- 1) What is the watershed and lake history during the late-glacial and early Holocene in the studied lakes?
- 2) What are the general patterns of watershed and lake development?
- 3) Are there any synchronous events during the lake development? If so, what do they suggest about the primary controls on aquatic ecosystem evolution?
- 4) How do these records compare with other regional records of environmental change?
- 5) What are the links between catchment process, large-scale climatic change, and limnological development?

1.2 Thesis overview

The dissertation is composed of three papers, each of which will be submitted to a peer-reviewed journal or is currently in review. A brief review of each chapter of the thesis is discussed below:

Chapter 2 examines diatom records from three lakes in the greater Yellowstone region to infer the limnological history in each site during the late-glacial and early Holocene. These records were compared to reveal synchronous and asynchronous shifts in diatom community structure, whose nature is then discussed. The inferred limnological results also were compared to other paleoenvironmental records from the same sites or the region in order to evaluate the role of climatic versus non-climatic factors on aquatic ecosystem evolution in this region.

Chapter 2 of the dissertation is a collaborative effort. Dr. Sherilyn Fritz provided the research idea and funding and helped with valuable feedback on the manuscript. Dr. Jeffery Stone, Dr. Cathy Whitlock, Trisha Spanbauer, Teresa Krause, Diego Navarro, Jennifer Giskaas, and Stacey Gunther collected the sediment cores. Dr. Jeffery Stone counted diatom samples from Blacktail Pond and Hedrick Pond, and I counted the Cub Creek Pond samples. I analyzed and interpreted the data and took primary responsibility for writing the manuscript, which was prepared for submission to *Quaternary Research*.

Chapter 3 discusses the general pattern of watershed and limnological development during the late-glacial and early-Holocene in the greater Yellowstone region. High-resolution XRF data and sediment carbon and nitrogen data were collected from four lakes to infer the watershed and lake history. A synthesis of the results from these sites revealed the general patterns of change in clastic inputs and endogenic calcite production. The results were compared to other proxies, such as diatom, pollen, and charcoal, to investigate the relationship between watershed processes, terrestrial vegetation, lake development, and climatic changes.

This research project is a collaborative effort. Dr. Sherilyn Fritz designed the framework, provided funding, and gave valuable feedback on the manuscript. Dr. Jeffery Stone, Dr. Cathy Whitlock, Trisha Spanbauer, Teresa Krause, Diego Navarro, Jennifer Giskaas, and Stacey Gunther performed the fieldwork. Dr. Jeffery Stone and Teresa Krause ran the XRF analyses in the laboratory of Dr. Erik Brown. James Benes and I prepared samples for sediment carbon and nitrogen analysis, and James Benes ran the analyses. I analyzed and interpreted the data and took primary

responsibility for writing the manuscript. This manuscript is targeted for the *Journal of Paleolimnology*.

Chapter 4 presents a high-resolution record of pollen, charcoal, diatom, geochemical, and lithological data from Dailey Lake in Montana to investigate the terrestrial and limnological development during the late-glacial and early-Holocene period. The links between catchment process, climatic change, and limnological development were explored. The results from this site were compared with records from sites in the Yellowstone region to reveal the primary control on the evolution of terrestrial and aquatic ecosystems at this site.

Chapter 4 of my thesis is part of collaborative research, which was principally authored by Teresa Krause, who performed the pollen and charcoal analysis. I completed all the diatom analyses and made contributions to the text and to the figures that refer to the diatom record. Dr. Cathy Whitlock, Dr. Sherilyn Fritz, and Dr. Kenneth Pierce provided valuable feedback on the manuscript. Dr. Jeffery Stone, Dr. Cathy Whitlock, Trisha Spanbauer, Teresa Krause, Diego Navarro, Jennifer Giskaas, and Stacey Gunther collected the sediment core. The manuscript of this chapter is currently in review in *Palaeogeography, Palaeoclimatology, Palaeoecology*.

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CHAPTER 2

**CONTROLS ON AQUATIC ECOSYSTEM EVOLUTION DURING THE LATE-GLACIAL
AND EARLY-HOLOCENE INFERRED FROM DIATOM RECORDS IN THE
YELLOWSTONE REGION**

2.1 Abstract

Three lake sediment cores collected from the greater Yellowstone region and covering the late-Glacial and early-Holocene were examined with diatom analysis to evaluate the relative importance of large-scale climatic change and catchment process on aquatic ecosystem evolution. The lakes occur in regions of varied surficial geology and precipitation seasonality. All lakes underwent synchronous shifts in diatom community structure in the intervals of 13.9-13.8, 13.2-13.1, 11.3-11.0 and 8.8-8.7 cal ka. The 11.3-11.0 cal ka shift is evident in other proxy records, such as pollen and charcoal, in the Yellowstone region. The synchronous shifts in diatom community structure indicate that large-scale climatic changes drive the evolution of aquatic ecosystem in this region, whereas the influence of local factors, such as precipitation seasonality and surficial geology, is secondary.

2.2 Introduction

The period of 20-8 ka experienced dramatic environmental changes (Alley and Clark, 1999) as a result of the retreat of continental glaciers, general increases in sea-surface and air temperature, and associated shifts in atmospheric circulation patterns (Webb et al., 1993; Kutzbach et al., 1993). The gradual late-glacial warming was interrupted by abrupt changes and reversals in climate, including the Bolling/Allerod warm period (14.7-12.7 ka) and the Younger Dryas cold interval (12.7-11.5 ka; Alley et al., 2002). The Greater Yellowstone region underwent widespread glacial retreat beginning ~17 ka as a result of increasing summer insolation and greenhouse gases (Clark and Bartlein, 1995; Licciardi et al., 2004).

Following formation by a retreating ice sheet, aquatic ecosystems were affected by a variety of environmental controls, including direct climatic impacts on a lake's thermal and hydrological budgets, as well as catchment processes, such as weathering, soil development, fire, and vegetation change (Fritz and Anderson, 2013). Within the Yellowstone region, surficial geology, microclimate, and vegetation development vary spatially (Whitlock, 1993). Thus, this region offers an opportunity to understand ecological responses to past environmental changes and to investigate the role of large-scale versus local drivers of aquatic ecosystem evolution following deglaciation.

Here we present diatom records spanning the late-glacial and early-Holocene period retrieved from three lakes that lie along the path of ice recession in the Greater Yellowstone region: Blacktail Pond, Cub Creek Pond, and Hedrick Pond. These lakes (Fig. 2.1) are located in the northern, central, and southern part of this region, respectively, and vary in surficial geology, elevation, vegetation, and precipitation seasonality. Our objectives in this study are to: (1) infer the limnological history at these three lakes from the time of their formation until ~7000 yr BP; and (2) evaluate the relative roles of large-scale climatic change and catchment processes on the aquatic ecosystem evolution in this region. To do this, we compare high-resolution diatom records from these regional lakes. If shifts in diatom community structure are synchronous, large-scale climatic changes are the likely driver of aquatic ecosystem evolution. If diatom assemblages change

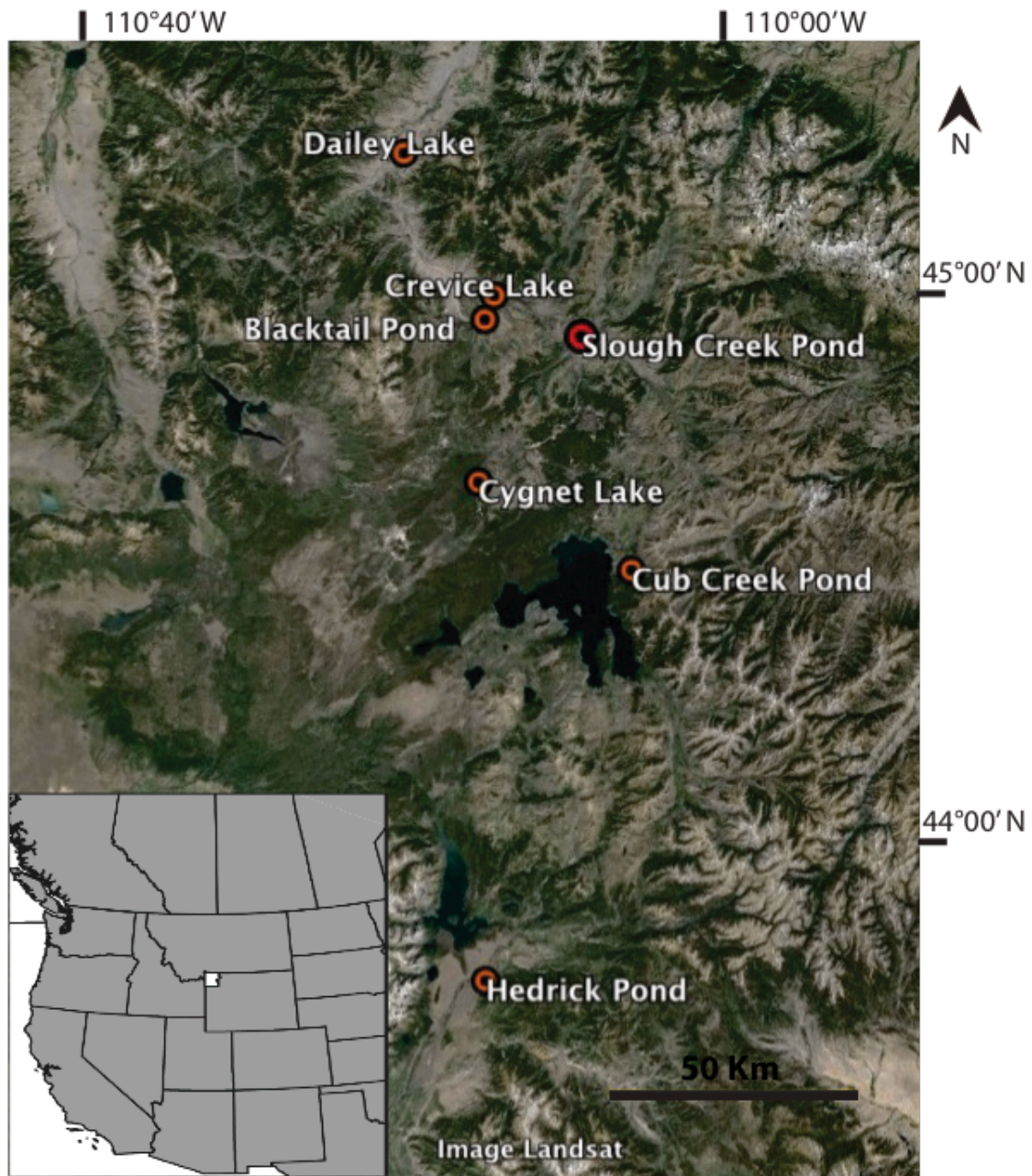


Figure 2.1 Locations of study sites and other Yellowstone region lakes mentioned in the text.

asynchronously, local factors, such as microclimate and surficial geology, are assumed to be the primary mediator of limnological change.

2.2.1 Environmental setting

The Yellowstone region was covered by the largest independent ice field in the western U.S. during the last glacial maximum, and outlet glaciers extended from the central ice field to the adjacent low elevation areas (Pierce 1979, 2004). In northern Yellowstone, one large complex of outlet glaciers flowed off the Beartooth Range (northeast of Yellowstone National Park) to the central Yellowstone Plateau, moved toward the north, and then terminated north of present-day Yellowstone National Park. In southern Yellowstone, outlet glaciers flowed down the central Yellowstone Plateau and the Absaroka Range (east of Yellowstone National Park) toward the south and southwest and terminated at the Burned Ridge moraine.

The modern vegetation patterns in the greater Yellowstone region are influenced by elevation and geology (Despain, 1990). Grassland and sagebrush (*Artemisia tridentata*) steppe communities are present below 1800 m elevation, whereas montane and subalpine conifer forests grow between 1800 and 2900 m elevation, and alpine tundra occurs at elevations above 2900 m. Within the forest zone, limber pine (*Pinus flexilis*) and Rocky Mountain juniper (*Juniperus scopulorum*) occur at lower elevations (1800 to 1900 m elevation), Douglas-fir (*Pseudotsuga menziesii*) (1900 to 2000 m elevation) and lodgepole pine (*Pinus contorta*) (2000 to 2400 m elevation) at middle to high elevations, and Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and whitebark pine (*Pinus albicaulis*)

dominate at the highest elevations (2400 to 2900 m elevation). Vegetation also varies with surficial geology: sagebrush steppe favors well-drained outwash deposits, lodgepole pine forests predominate on rhyolite soils, and forests of Engelmann spruce, subalpine fir, and whitebark pine grow best on Tertiary outcrops of andesite and basalt soils (Whitlock, 1993).

Two contemporary precipitation regimes have been identified in the Yellowstone region based on the relative amount of summer to winter precipitation. The so-called summer-wet regime in northern Yellowstone receives abundant precipitation in summer as a result of summer monsoonal circulation. In contrast, the summer-dry regime in southern and central Yellowstone region and at high elevations receives the majority of precipitation from westerly storms in winter, and precipitation is reduced in summer as a result of the expanded northeastern Pacific subtropical high-pressure system (Whitlock and Bartlein, 1993).

2.2.2 Lake sites

Blacktail Pond is a small closed-basin lake and lies in a remnant late-Pleistocene meltwater channel, which was formed when Blacktail Deer Creek abandoned its course during ice retreat and flowed north to the Yellowstone River (Pierce, 1979). Blacktail Pond occurs within calcareous glacial outwash and is surrounded by sagebrush steppe. Douglas-fir and lodgepole pine forest grow on adjacent rocky slopes of basalt/andesite and rhyolite, respectively. Stands of quaking aspen (*Populus tremuloides*) grow on the lower slopes, and small populations of fir (*Abies*) and pine (*Picea*) are found in nearby cold air drainages.

Around the lake margin, willow (*Salix* spp.), three-square bulrush (*Scirpus americanus*), sedge (*Carex* spp.), and broadleaf cattail (*Typha latifolia*) are common, with muskgrass (*Chara*), bladderwort (*Utricularia*), and water milfoil (*Myriophyllum*) growing underwater (Krause et al., 2013).

Cub Creek Pond lies on the central Yellowstone Plateau and is ~4 km east of Yellowstone Lake. It was on the east side of Yellowstone Plateau icecap-divide during the glacial period. During down wasting of the Yellowstone Plateau icecap, ice marginal streams deposited kame gravels adjacent to Cub Creek Pond. The Yellowstone Plateau is dominated by vast stands of lodgepole pine (Baker, 1976). Cub Creek Pond itself is bordered by ridges covered by lodgepole pine, spruce, fir, and whitebark pine (Waddington and Wright Jr., 1974).

Hedrick Pond is on a bench of Pinedale-2 glacial outwash that, in turn, is built on lake sediments deposited in a basin formed by a combination of Pinedale-1 glacial scour and outwash buildup (Pierce and Good, 1990). Surficial exposure ages of moraines buried by Pinedale-2 outwash indicate the Pinedale-2 phase is younger than ~14.6 ka. Therefore, the bottom of Hedrick Pond should also be younger than ~14.6 ka (Licciardi and Pierce, 2008). Hedrick Pond is surrounded by open forest of lodgepole pine, Douglas-fir, and sagebrush steppe. Common juniper (*Juniperus communis*), Canada buffaloberry (*Shepherdia canadensis*), common snowberry (*Symphoricarpos albus*), and Wood's rose (*Rosa woodsii*) grow in the openings. Quaking aspen, Engelmann spruce, Colorado spruce (*Picea pungens*), and subalpine fir are present on wetter slopes. Sagebrush steppe grows on the outwash gravels of southern Grand Teton National Park to the south of the site. Cattail (*Typha*) and

bulrush (*Scirpus*) are present at the lake margin, and Yellow pond lily (*Nuphar lutea*) grows in shallow water (Whitlock, 1993). Available liminological data are presented in Table 2.1.

2.3 Methods

2.3.1 Coring methods

A modified Livingstone square-rod piston corer (Wright et al., 1983) was used to collect sediment cores at Blacktail Pond and Hedrick Pond in 2008 and at Cub Creek Pond in 2009. Additional overlapping sediment cores with 50 cm offset were collected within a few meters of each other from each of the lakes. Blacktail Pond sediment cores were retrieved from the fen margin, and the core used for diatom analysis, BTP08B, was 2.85 meters long. Cub Creek Pond sediment cores, CUB09A and CUB09B, were collected at the fen margin and had length of 3.58 m and 3.18 m, respectively. Hedrick Pond cores were collected from a raft in open water (water depth=4m), and the core used for diatom analysis, HED08A, was 3.40 meters long. Core segments were extruded, measured, and described in the field, wrapped in plastic and aluminum foil, and transported back to laboratory and stored in a cold room until further analysis and sub-sampling. Cores were sampled at 0.5-cm intervals from the base to just above Mazama ash (Zdanowicz et al., 1999), where present, and individually packaged in Whirlpak bags. Subsamples for diatom analysis were then collected at 1-cm intervals.

Table 2.1 Limnological data for the study lakes.

	Lat.	Long.	Elev. (m)	Depth (m)	TP (mg/L)	TN (mg/L)	DOC (mg/L)
Blacktail Pond	44°57' N	110°36' W	2015	8	0.076	0.711	5.85
Cub Creek Pond	44°30' N	110°14' W	2573	n/a	0.366	6.688	25.3
Hedrick Pond	43°45' N	110°36' W	2051	4	0.126	1.553	14.5

Table 2.2 Uncalibrated and calibrated ^{14}C ages for Cub Creek Pond and Hedrick Pond.

Depth (cm)	Type	^{14}C Age (yr)	Age error (yr)	$\delta^{13}\text{C}$ (‰)	Median age (Cal yr BP)	
CUB09A-217.75	Pollen	8660	65	-19.60	9630	Rejected
CUB09A-231	Sediment Organic carbon	8620	40	-19.46	9576	Rejected
CUB09A-261	Sediment Organic carbon	9520	40	-19.49	10851	Rejected
CUB09A-292	Plant/Wood	8330	35	-27.50	9358	
CUB09A-330.5	Pollen	10900	60	-21.32	12771	Rejected
CUB09A-335	Sediment Organic carbon	11250	55	-20.86	13160	Rejected
CUB09B-378 (CUB09A-377)	Plant/Wood	9510	35	-24.95	10791	
CUB09A-394	Sediment Organic carbon	8840	35	-18.90	9926	Rejected
CUB09B-410 (CUB09A-416)	Plant/Wood	10150	55	-25.79	11819	
CUB09A-440.75	Pollen	12150	75	-18.17	13999	Rejected
CUB09A-468.5	Sediment Organic carbon	14600	75	-16.19	17766	Rejected
CUB09A-488	Glacier Peak ash	11600	50			
CUB09A-540	Sediment Organic carbon	18300	140	-16.88	21860	Rejected
HED05B-207	HED05B	2209	39	n/a	2232	
HED09A-375	pollen	5740	55	-28.53	6540	
HED09A-410	pollen	6860	45	-25.55	7692	
HED-09A442	wood	8020	55	-24.82	8880	
HED09A-454	wood	8490	40	-26.07	9503	
HED09A-475	pollen	9060	410	n/a	10225	
HED09A-505	pollen	11250	170	-25.81	13121	Rejected
HED09A-525	pollen	10850	55	-24.16	12722	
HED09A-570	pollen	14050	60	-25.59	17091	Rejected

2.3.2 Age models

AMS ^{14}C dates and tephrochronology were used to construct the age models. The Blacktail Pond chronology (Krause et al., 2013) is based on seven AMS ^{14}C dates and two volcanic ash layers: 1) Mazama ash was assigned an age of 6730 ± 40 ^{14}C yr BP (Zdanowicz et al., 1999); and 2) Glacier Peak ash was assigned an age of 11600 ± 50 ^{14}C yr BP (Kuehn et al., 2009). The Cub Creek Pond chronology is based on 3 AMS ^{14}C dates and Mazama ash. Twelve samples were dated for Cub Creek Pond, and the dates with $\delta^{13}\text{C}$ value greater than -24‰ were rejected, as these high values may result from old carbon contamination (Table 2.2). Hedrick Pond chronology is based on 6 AMS ^{14}C dates and 1 AMS ^{14}C date from a previously collected core from the same site. Among the 9 ^{14}C dates from Hedrick Pond, the sample HED09A-505 may have been reworked and thus was rejected (Table 2.2). The age of sample HED09A-570 near the base of the core exceeds estimates of the age of the lake basin based on cosmogenic dates (Licciardi and Pierce, 2008) and may have been reworked from the underlying sediments. It was also rejected.

All ^{14}C dates were converted to calendar ages using IntCal13 (Reimer et al., 2013) and Bayesian age models. Age models for Cub Creek Pond and Hedrick Pond were developed using Bacon 2.2 (Blaauw and Christen, 2011) (Fig. 2.2), while the Blacktail Pond age model is from an earlier publication (Krause et al., 2013) using MCAgeDepth (Higuera et al., 2008) and is used here for consistency. We have compared the Bacon model and MCAgeDepth model for Blacktail Pond, and they are in close alignment. All ages are reported in thousands of calendar years (ka) before radiocarbon present (1950 AD).

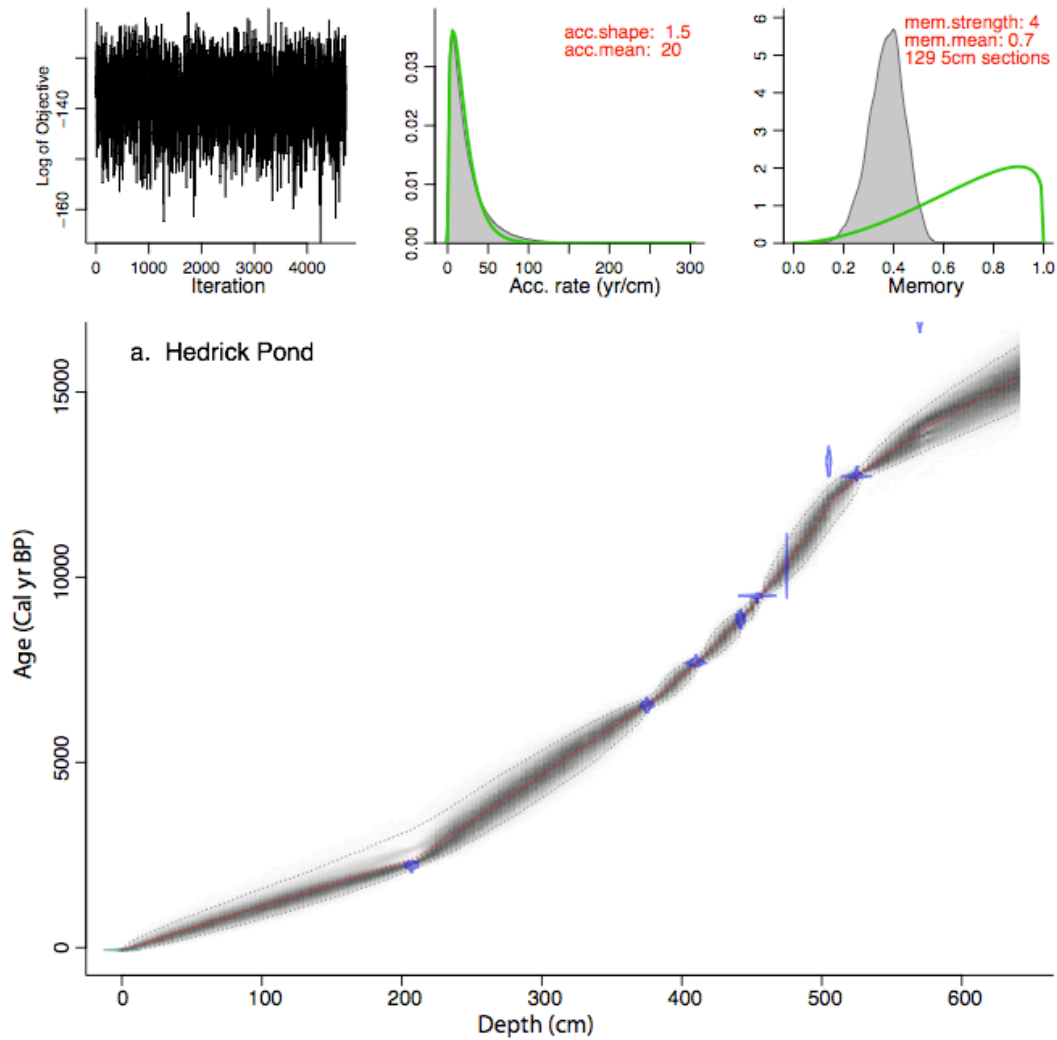


Figure 2.2a Age models for Hedrick Pond. Age model probability is represented by a grayscale cloud, which is bounded by dotted-line error ranges. Inset figures show the prior (lines) and posterior densities (area fills) for the mean accumulation rate (Acc. rate) and memory, the two prior estimates in the age model.

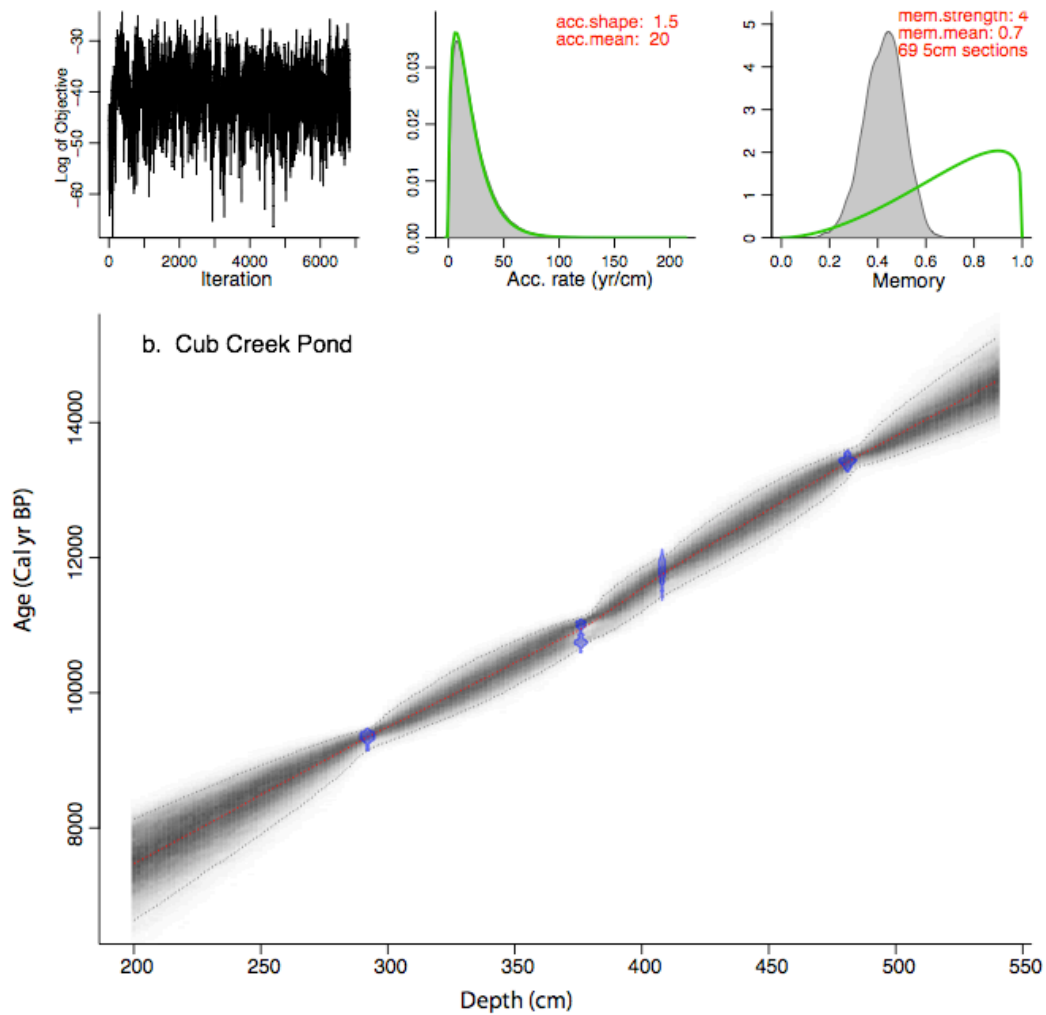


Figure 2.2b Age models for Cub Creek Pond. Age model probability is represented by a grayscale cloud, which is bounded by dotted-line error ranges. Inset figures show the prior (lines) and posterior densities (area fills) for the mean accumulation rate (Acc. rate) and memory, the two prior estimates in the age model.

2.3.3 *Diatoms*

Diatoms were analyzed at 1-cm intervals in each core. Diatom samples were first treated with 10% HCl (cold) to remove carbonate and then 30% H₂O₂ to digest organic material. In order to remove supernatant fluids after treatment, samples were then rinsed four times with reverse-osmosis purified water. Rinsed samples were dried onto coverslips and mounted onto slides with Zyrax, a high-refractive-index permanent mounting medium (Battarbee, 1986). At least 300 diatom valves were counted on each slide. Dissolution of diatoms prevented a count of 300 diatom valves for a few Hedrick Pond samples, and in these samples at least 200 diatom valves were counted. All diatom data are shown as abundance relative to the total number of valves counted. Blacktail Pond and Hedrick Pond diatom records were obtained from Cores BTP08B and HED08A, respectively, while Cub Creek diatom analysis was performed on Core CUB09A, except for the segment of 3.85 m-4.05 m, for which diatom data were obtained from Core CUB09B.

2.3.4 *Data analysis*

Diatom species percentages were plotted against our model age to show changes in diatom community structure for all diatom records. A zonation scheme was then developed for each lake with stratigraphically constrained cluster analysis on square-root transformed data, chord distance measure, using the CONISS (Constrained Incremental Sum of Squares cluster analysis) program in Tilia (Grimm, 1987). Zonation schemes were compared to detect synchronous diatom community shifts.

2.4 Results and Discussion

2.4.1 Limnological history

2.4.1.1 Blacktail Pond

The Blacktail Pond diatom record was divided into five zones (Fig. 2.3). From 14.6 to 14.3 ka BP, the lake was dominated by *Fragilaria* species (*F. pinnata* and *F. brevistriata*; 50%-90%), with low percentages of planktic *Cyclotella* species (*C. rossii*; <10%) and benthic *Nitzschia* (5-20%) and *Amphora* species (*A. pediculus* and *A. coppulata*; 5-20%). These *Fragilaria* species are tychoplankton that can live either in shallow benthic habitats or suspended in the water column as plankton. These species often occur in newly deglaciated terrain and in high-latitude lakes where the ice-free season is short (Smol, 1983). They also favor relatively high alkalinity (Battarbee, 1986), may tolerate relatively low-light conditions (Anderson 2000), and are characterized as adaptable and competitive (Lotter et al. 1999; Westover et al., 2006). In the early stage of Blacktail Pond formation, the catchment was sparsely vegetated (Krause et al., 2013), soils were not well developed, and erosion rates were likely high, and these conditions would favor the pioneering *Fragilaria* species.

The period from 14.3-12.6 ka BP was characterized by the co-dominance of tychoplanktic *Fragilaria* species, planktic *Cyclotella* species, and benthic species. Percentages of *Fragilaria* species (10-60%) decreased, and the abundance of *Cyclotella* species (*C. rossii*, *C. michiganiana*, and *C. radiosa*) was generally high, especially during the period of 13.8-13.2 ka (20-50%). Benthic species diversified and increased in abundance in this period (*Encyonopsis microcephala*, *Encyonema* sp. *minutum*, *Cymbella subleptoceros*, *Amphora pedicula*, *Achnantheidium saprophila*,

and *Gomphonema*; 30-80%). The development of a planktic diatom flora suggests that the lake was ice free during summer months and that the nutrient concentrations in the open water needed were sufficiently high for plankton, probably due to catchment stabilization and soil development. Euplanktic species, such as *Cyclotella*, commonly occur when lakes are thermally stratified during warm periods (Interlandi et al., 1999; Battarbee et al., 2002; Sorvari et al., 2002; Rühland et al., 2003, 2008; Smol et al., 2005; Saros et al., 2012). Studies of nutrient requirements and nutrient limitation of planktic diatoms show that small centric *Cyclotella* species are good competitors for nutrients when concentrations are relatively low. When lakes are thermally stratified, nutrients become depleted in the epilimnion (Petrova 1986), hence favoring *Cyclotella* species. In addition, *Cyclotella* species have light frustules and can remain buoyant when the lake is stratified (Winder et al., 2009). Thus, the abundant *Cyclotella* species during 13.8-13.2 ka BP suggest that Blacktail Pond had a relatively long ice-free period during summer and was thermally stratified as a result of warm summer conditions.

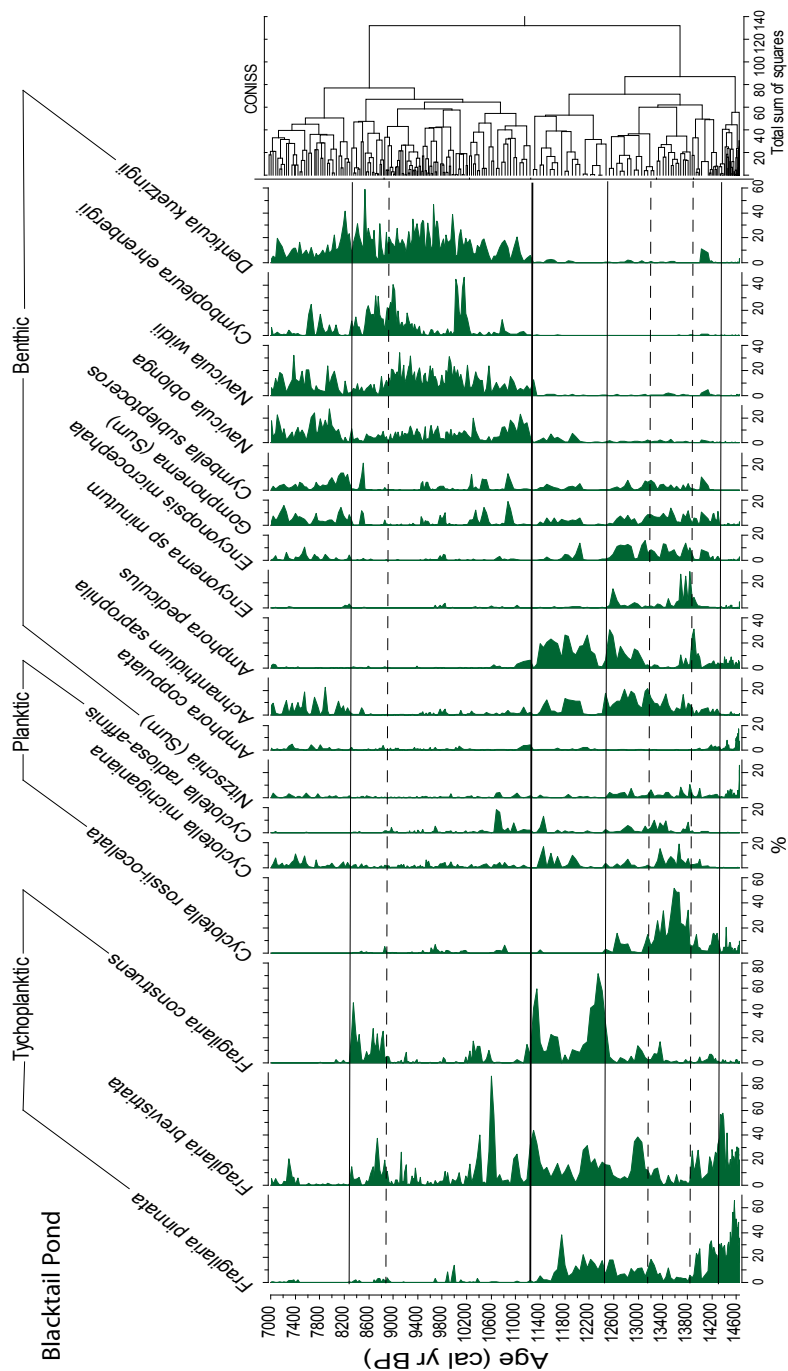


Figure 2.3 Blacktail Pond major diatom taxa. Solid lines denote zones as defined by cluster analysis, and dotted lines are sub-zones.

From 12.6-11.2 ka BP, the diatom stratigraphy was characterized by a decrease of *Cyclotella* species (<20%) and co-dominance by *Fragilaria* species (20-90%) and benthic species (10-60%). The decrease of *Cyclotella* species was mainly a function of declines in *Cyclotella rossii-ocellata*, which was gradually replaced by *Cyclotella michighiniana*. The *Fragilaria* assemblage was dominated by *F. pinnata*, *F. brevistriata*, and *F. construens*, while *Amphora pediculus* and *Achnanthisidium saprophila* were the major contributors to the benthic dominance. The lower overall abundance of *Cyclotella* species during this period indicates reduced nutrient availability and/or that springs and summers were cooler, which may have shortened the ice-free period and the duration of the open-water period and any associated stratification. The surrounding landscape was more densely vegetated, open parkland developed, and soils were better developed during this time (Krause et al., 2013). Therefore, nutrient loading to the lake was probably not reduced, suggesting that the assemblage changes were a product of cooling during summer months.

The period of 11.2-8.3 ka BP marks the most prominent community shift in this diatom record. It is characterized by the substantial increase or appearance of benthic species, such as *Navicula oblonga*, *N. wildii*, *N. radiosa*, *Denticula kuetzingii*, *Delicata delicatula*, *Sellaphora laevissima*, *Sellaphora pupula*, *Cymbella cistula*, and *Cymbopleura ehrenbergii*, indicating that the lake became shallower. In particular, the significant increase of *Denticula kuetzingii*, an indicator of alkaline water (Rioual et al., 2013), implies that the lake became alkaline. Thus, changes in diatom composition suggest a decrease in effective moisture, which, in turn, was probably

caused by warmer summer conditions. *Fragilaria* species decreased substantially in abundance compared to the previous period but still occasionally dominated the diatom community (such as 8.8-8.3 ka BP), implying variability of effective moisture. The shift at ~11.2 ka BP in diatom community structure matches broadly in timing with a change in terrestrial vegetation surrounding the lake, which shifted from tundra and open parkland to closed subalpine forest. It also is coincident with an increase in fire activity and inferred warmer summer conditions (Krause et al., 2013).

After 8.3 ka BP, most *Fragilaria* species disappeared, *Cyclotella* species maintained low percentages (~10-15%), and the lake remained dominated by benthic species (>85%), with contributions from *A. saprophila*, *Cymbella subleptoceros*, *Cymbella microcephala*, and *Gomphonema* species, which increased in percentages during this period. The substantial decrease of *Fragilaria* species and the dominance of benthic species implies that lake water levels remained low after 8.3 ka BP. Terrestrial vegetation also changed at ~8.3 ka BP. Forests surrounding Blacktail Pond became sparser, and open parkland developed (Krause et al., 2013). At Crevice Lake, 6 km east of Blacktail Pond, *Pinus* forests also were replaced by open parkland, and fire activity increased at ~8.3 ka BP (Whitlock et al., 2012).

2.4.1.2 Cub Creek Pond

The Cub Creek Pond diatom record was divided into three zones (Fig. 2.4). During the period of 14.5-13.9 ka BP, the lake was characterized by the dominance of *Fragilaria* species and benthic species. During the first few decades following the formation of the lake, benthic species, such as *Navicula* (10-25%), *Nitzschia* (10-25%), *Epithemia* (<10%), *Achnanthes* (<5%), and *Gomphonema* (<5%), had their highest abundance, but quickly decreased thereafter. At the same time, *Fragilaria* species increased substantially to more than 50% at ~14.4 ka BP and maintained dominance (~90%), except for a brief benthic species spike at ~14.0 ka BP. In addition to the pioneering *Fragilaria* species, benthic species are also common in other lakes on newly deglaciated terrain, because they are able to obtain nutrients from the substrates they inhabit. Local examples include Dailey Lake in northern Yellowstone, (Krause et al., in review) and Foy Lake in northwestern Montana (Stone and Fritz, 2006). Similarly in the Arctic, benthic species commonly dominated the diatom flora in the early stage of lake development, likely as a result of low nutrient concentrations associated with weakly developed catchment soils (Bigler et al., 2002, 2003; Birks et al., 2000; Bradshaw et al., 2000; Perren et al., 2012). The landscape surrounding Cub Creek Pond was covered by grassland and sparse trees at this time (Iglesias, unpublished data), and geochemical data indicate that minerogenic input was very high (Lu et al., in preparation).

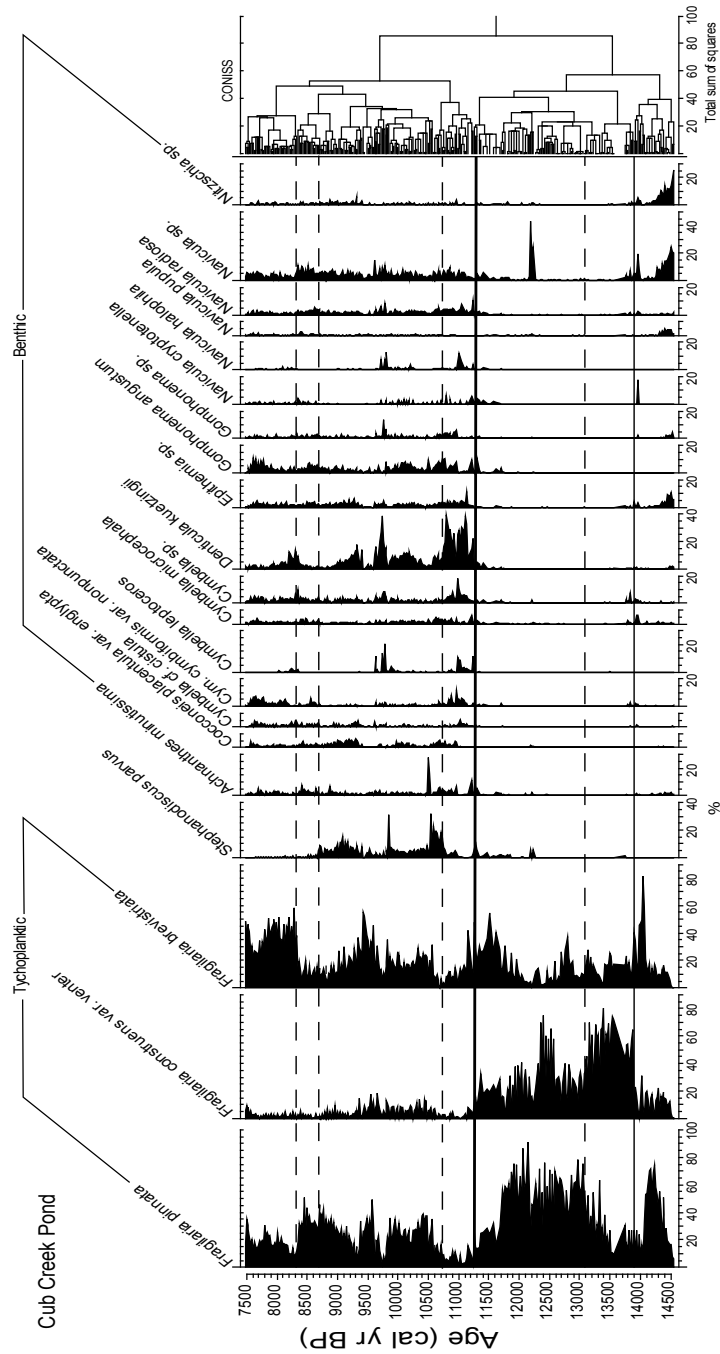


Figure 2.4 Cub Creek Pond major diatom taxa. Solid lines denote zones as defined by cluster analysis, and dotted lines are sub-zones.

From 13.9 to 11.3 ka BP, the lake was dominated by *Fragilaria* species (*F. pinnata*, *F. brevistriata*, and *F. construens* var. *venter*), with percentages greater than 80%. Benthic species maintained very low abundance (<10%), except for a spike at ~12.2 ka BP, which corresponds to an ash layer, followed by an increase of *Fragilaria* species at ~11.8 ka BP. Within this zone was a period from 13.9-13.1 ka BP marked by high percentages of *F. construens* var. *venter*, which, in timing, coincided with the period of *Cyclotella* dominance at Blacktail Pond. The local interpretation of this shift within *Fragilaria* is unclear, because the ecological differences within *Fragilaria* tycho planktic group are not well defined. The overall dominance of tycho planktic *Fragilaria* species and low abundance of benthic species suggest that the lake maintained an intermediate water depth during this period and was nutrient poor. Alpine tundra and sparse trees grew on the surrounding landscape (Iglesias, unpublished data), and terrestrial input to the lake was low and stable (Lu et al., in preparation).

A major shift in diatom community structure occurred at 11.3 ka BP, marked by a substantial decrease of *Fragilaria* species and the significant increase of benthic species. From 11.3 to 7.5 ka BP, Cub Creek Pond was co-dominated by benthic species and *Fragilaria* species (~50% on average). All benthic species increased in percentages during this period and, in total, maintained an average of around 40%. Within this period, benthic abundance was particularly high during 11.3-10.7 ka BP (>40%), mainly contributed by *Denticula kuetzingii*, which is indicative of alkaline water. The relative dominance of benthic species suggests that Cub Creek Pond was shallow and alkaline from 11.3 to 7.5 ka BP, probably as a result of warm summer

temperatures. *Stephanodiscus parvus/minutulus*, a planktic taxon, was also present at 5-20% during 11.3-8.7 ka BP. This taxon blooms during times of prolonged mixing, when P is mixed throughout the water column (Bradbury, 1988; Bracht et al., 2012). Thus, the presence of *S. parvus/minutulus* suggests extended isothermal mixing in spring to summer, perhaps as a consequence of early spring ice-off. A major shift also occurred on surrounding vegetation at ~11.3 ka BP. *Pinus* forest developed and replaced sagebrush and grassland (Iglesias, unpublished data).

2.4.1.3 Hedrick Pond

The Hedrick Pond diatom record was divided into three zones (Fig. 2.5). The period from 14.3-11.0 ka BP had high percentages (50-90%) of *Fragilaria* species (*F. pinnata* and *F. brevistriata*). Benthic species, such as *Encyonema minutum*, *Amphora pediculus*, *Navicula oblonga*, *Navicula lanceolata*, and *Denticula kuetzingii*, were also present in this period. *Encyonema minutum* and *Amphora pediculus* had relatively high percentages (10-50%, taken together) during the interval of 13.8-13.1 ka BP, while *N. oblonga*, *N. lanceolata*, and *Denticula kuetzingii* increased slightly from 13.1 ka BP and maintained low percentages until 11.0 ka BP. The dominance of *Fragilaria* species indicates that Hedrick Pond had an intermediate water depth during 14.3-11.0 ka BP. Within this period, the lake was slightly lowered from 13.8 to 13.1 ka BP, as indicated by the relatively high abundance of benthic species during that interval.

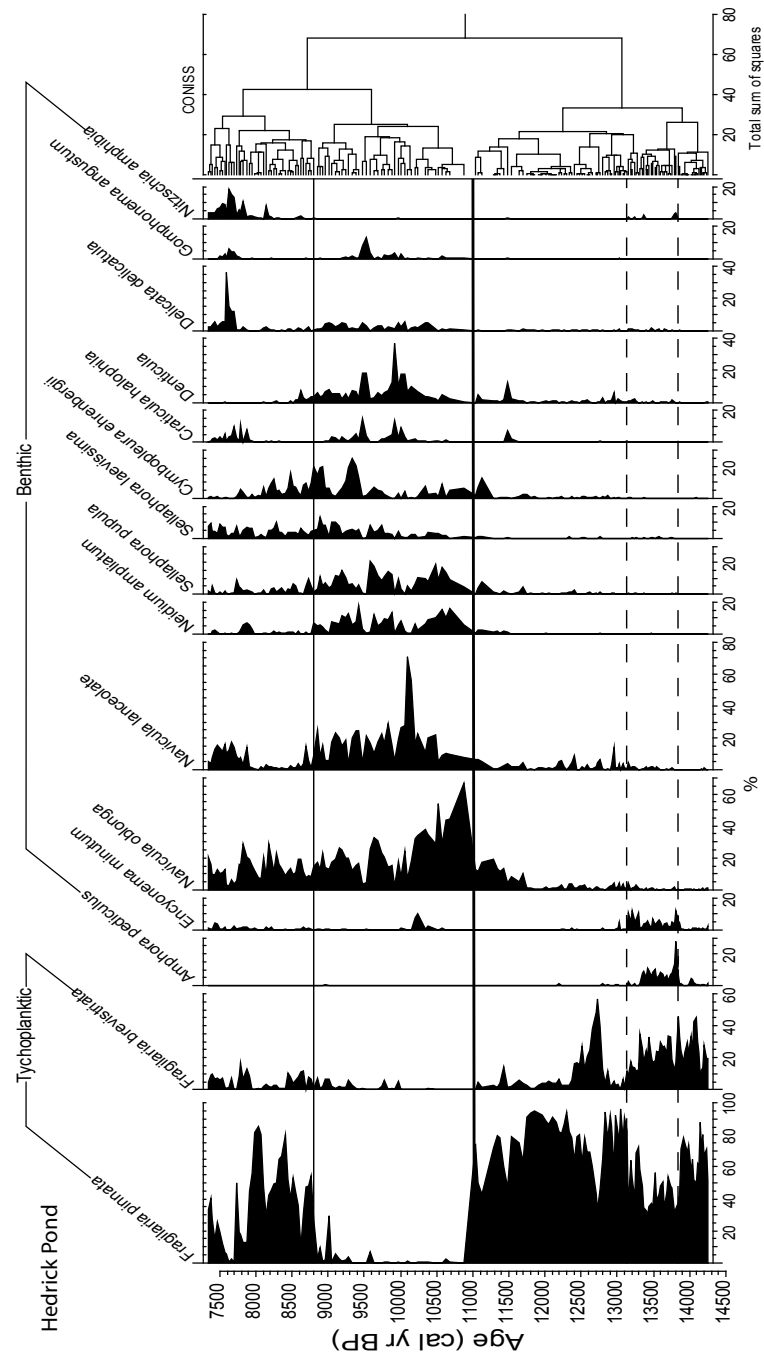


Figure 2.5 Hedrick Pond major diatom taxa. Solid lines denote zones as defined by cluster analysis, and dotted lines are sub-zones.

The transition from ~11.0-8.8 ka BP marks the most obvious shift in diatom community structure. The *Fragilaria* species that were dominant prior to ~11.0 ka BP were almost absent from the diatom record, and benthic species, such as *Craticula halophila*, *Neidium ampliatus*, *Navicula oblonga*, *N. lanceolata*, *Denticula kuetzingii*, *Cymboplectra ehrenbergii*, *Sellaphora laevissima*, *Sellaphora pupula*, *Gomphonema angustum*, and *Nitzschia amphibia* dominated the lake. The transition from *Fragilaria* dominance to benthic species dominance at ~11.0 ka BP indicates that the lake became shallower as a result of decreasing effective moisture.

From ~8.8 to 7.3 ka BP, the abundance of *Fragilaria* species (*F. pinnata* and *F. brevistriata*) increased (20-80%), and benthic species decreased (15-60%). The lake was not solely dominated by benthic species like the previous period, but instead was co-dominated by *Fragilaria* and benthic taxa, indicating the lake level was generally higher than the previous period. The relative abundance of *Fragilaria* species and benthic species varied within this period. Beginning at ~7.9 ka BP, the benthic species increased again and *Fragilaria* species decreased, suggesting that the lake became shallower in this interval.

2.4.2 Synchronous diatom community shifts

Major shift in diatom community structure occurred in all three lakes during the interval of 11.0-11.3 ka BP (Fig. 2.6). Prior to this interval, all three lakes were dominated or co-dominated by *Fragilaria* species, with percentages of 60-80% in Cub Creek Pond and Hedrick Pond, and 10-80% in Blacktail Pond. The general *Fragilaria* dominance in all three lakes reflects the common late glacial climatic conditions (low light, low nutrients, short ice-free period, as well as weakly developed soils due to sparsely vegetated landscape) prior to the onset of the Holocene. In fact, pollen records indicate that meadow, alpine tundra, and subalpine parkland characterizes the Yellowstone region after deglaciation (Whitlock, 1993).

After 11.0-11.3 ka BP benthic species dominated all three lakes. In Blacktail Pond, benthic species increased to 80-90%, with the appearance of substantial proportions of *Navicula* and *Denticula* species. Benthic species also increased from less than 10% to 30-70% in Cub Creek Pond, and from 10-34% to 30%-90% in Hedrick Pond. Benthic species live on bottom substrates in waters where they get sufficient light for photosynthesis. In these cases, the diatom community shift from *Fragilaria* dominance to benthic dominance in the interval of 11.0-13.0 ka BP suggests that all three lakes became shallower as a result of decreasing effective moisture (precipitation minus evaporation), reducing plankton and tychoplankton and favoring benthic taxa. A similar and synchronous shift also occurs in Dailey Lake, where planktic *Cyclotella* and *Aulacoseira* became less abundant, and benthic *Achnanthes*, *Amphora*, and *Cymbella* species increased, indicating a decrease in lake level (Krause et al., in review).

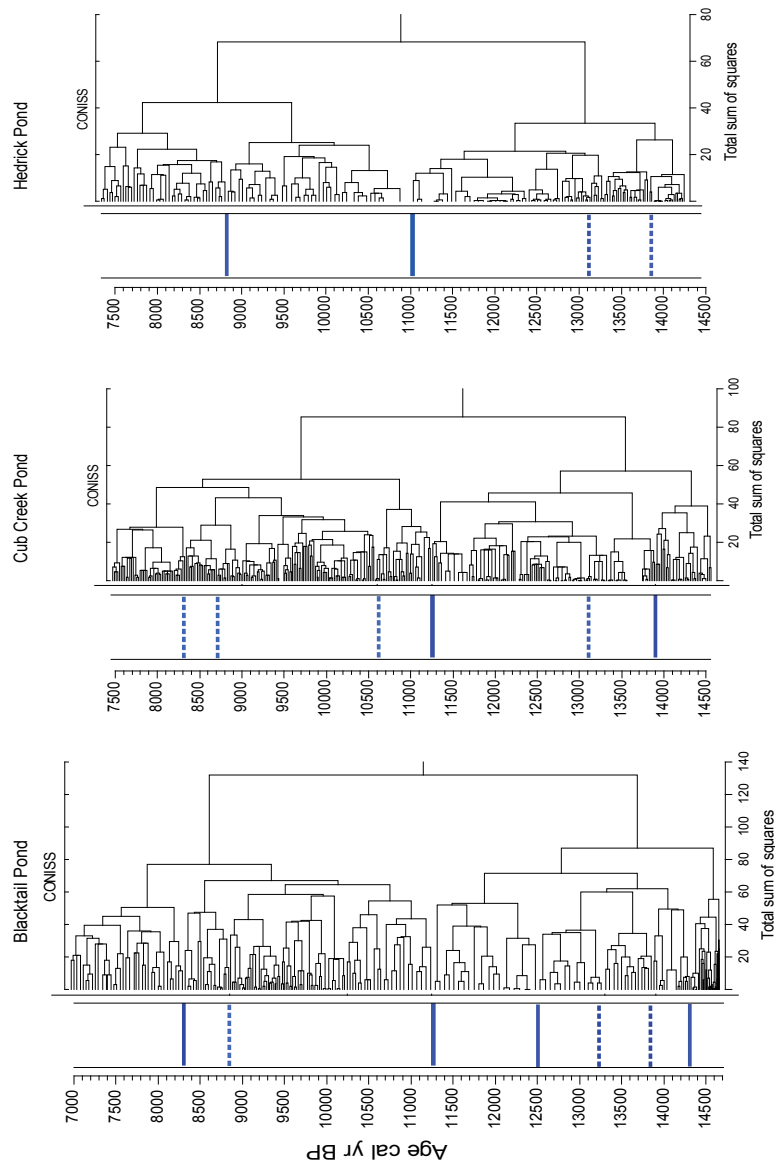


Figure 2.6 Comparison of the timing of shifts in diatom community structure. Solid lines indicate major zone boundaries defined by cluster analysis and dotted lines are sub-zones.

Other proxies at various sites in the Yellowstone region, including pollen and charcoal, also show a shift at approximately 11.0-11.3 ka BP. At Blacktail Pond, vegetation in the surrounding area changed from alpine tundra and *Picea* parkland to subalpine forest between ~11.5-11.3 ka BP, and fire activity also increased at the same time, indicating climate warming (Krause et al., 2013). At Slough Creek Pond, 20 km east of Blacktail Pond, closed forest developed at ~11ka BP (Millspaugh et al., 2004). At Dailey Lake, fire activity increased at ~11.0 ka BP (Krause et al., in review). In the Cub Creek Pond pollen record, *Poaceae* (grass) and *Cyperaceae* (sedge) dominated the landscape and were replaced by *Pinus* forest during the interval of 11.5-11.3 ka BP (Iglesias, unpublished data), suggesting warmer summers. At Cygnet Lake, around 30km to the northwest of Cub Creek Pond, closed *Pinus* forest was established at around 11.3-11.0 ka BP, replacing an open vegetation dominated by *Artemisia* and *Poaceae*, and fire activity increased at 11.0 ka BP (Whitlock, 1993, Millspaugh et al., 2000). Thus, regional vegetation data suggest widespread summer warming that shifted the composition of plant communities at these sites.

In addition to the synchronous shift in aquatic community structure during the interval of ~11.0-11.3 ka BP, other synchronous shifts in diatom community structure also are apparent in all three diatom records at ~ 13.8, ~13.2 and ~8.8 ka BP. At ~13.8 ka BP at Blacktail Pond, small planktic *Cyclotella* species, indicative of strong water column stratification in summer, increased in abundance (20-50%), and *Fragilaria* species decreased (10-20%). Then at ~13.2 ka BP, *Cyclotella* species decreased (5-20%) and *Fragilaria* species (20-60%) dominated the diatom

community, together with increased percentages (30-60%) of benthic species. The Cub Creek Pond diatom assemblages shifted at ~13.9 ka BP from the dominance of *F. pinnata* to *F. construens* var. *venter*, which remained at high percentages until 13.1 ka BP, when *F. pinnata* regained dominance. At Hedrick Pond, benthic species, such as *Encyonema minutum* and *Amphora pediculus*, increased from low percentages (<5%) to relatively high percentages (5-10%) at the expense of a slight decrease in *Fragilaria* species at ~13.8 ka BP, and then were replaced by other benthic species, such as *Navicula oblonga*, *N. lanceolata*, and *Denticula kuetzingii*, at ~13.1 ka BP, when *Fragilaria* species increased again. At Dailey Lake, *Cyclotella* species increased (20-40%) at ~13.1 ka BP, suggesting that the lake became thermally stratified during the summer months (Krause et al., in review). In the late-glacial period summer insolation continued increasing (Berger, 1978), the Laurentide ice sheet was rapidly wasting (Alley and Clark, 1999), and the associated increasing temperature likely lead to the shifts in diatom community structure at ~13.8 ka BP in Blacktail Pond and Hedrick Pond. At Cub Creek Pond, which is on the central Yellowstone plateau and higher than Blacktail Pond and Hedrick Pond, the gradual warming did not foster the development of a planktic flora, either because the lake was too shallow or instead was only ice-free for limited periods. Thus, the assemblage shift here was the trade-off within the *Fragilaria* species. A unified explanation of the trends at ~13.1 ka BP would suggest continued warming that made Blacktail Pond too shallow to support high abundances of planktic *Cyclotella* species and that also produced the succession of benthic species in Hedrick Pond,

the thermal stratification in Dailey Lake, and the composition change at ~13.9 and ~13.1 ka BP in Cub Creek Pond.

At ~8.8 ka BP, Blacktail Pond benthic diatom species decreased in abundance, and percentages of *Fragilaria* species increased, implying increased lake level. At Cub Creek Pond, *Stephanodiscus parvus/minutulus*, an indicator of high phosphorus generated during prolonged spring isothermal mixing, decreased at 8.7 ka BP, suggesting a shortened spring mixing period, possibly due to the fact that the lake ice melted later in the season than during the previous period. At Hedrick Pond, benthic diatom species decreased in abundance at ~8.8 ka BP, which suggests increased lake level and increased effective moisture. Thus, diatom assemblages from all three sites experienced composition change at ~8.8 ka BP, probably all driven by the same factors. After reaching a maximum in the early Holocene, summer insolation gradually decreased (Berger, 1978). The associated summer cooling may have produced a late melting of lake ice at Cub Creek Pond and a decrease of evaporation and thus an increase in lake level at Blacktail Pond and Hedrick Pond at ~8.8 ka BP. This explanation is consistent with the reduced calcite precipitation at Dailey Lake at about the same time (Chapter 3, Fig. 3.7).

2.4.3 Influence of precipitation seasonality on diatom assemblages

Blacktail Pond is in the summer-wet region, and Hedrick Pond is located in the summer-dry region, but they both are situated on calcareous glacial tills. Thus, a comparison of diatom records from these two lakes provides an opportunity to evaluate the impact of precipitation seasonality on aquatic ecosystem evolution.

Under the influence of large-scale climatic change, such as changes in summer insolation, both lakes showed synchronous shifts in diatom community structure during the interval of ~11.0-11.3 ka BP and also at ~8.8 ka BP, and the shifts suggest similar patterns of limnological change at these times. Both also showed evidence of warming between ~13.8-13.2 ka BP, which matches well in timing with the Bølling-Allerød warm period. In addition, during the early-Holocene, when summer insolation was at its maximum and precipitation seasonality was intensified, both Blacktail Pond (~11.2-8.8 ka BP) and Hedrick Pond (~11.0-8.8 ka BP) experienced low lake levels as a result of reduced effective moisture. Therefore, it seems the influence of differences in precipitation seasonality is not evident in the diatom floras and inferred limnological histories.

Nonetheless, differences do exist between the two records. After the synchronous shift at ~8.8 ka BP, relatively high percentages of *Fragilaria* species in Blacktail Pond were not persistent and decreased at ~8.3 ka BP and remained low in abundance thereafter. The substantial decrease of *Fragilaria* species at Blacktail Pond at ~8.3 ka BP, indicative of decreasing lake-level, was synchronous with changes in terrestrial vegetation that shifted from closed *Pinus* forest to open parkland (Krause et al., 2013), both suggesting a decrease of effective moisture. This transition to drier conditions also is evident in the nearby Crevice Lake sediment record, which showed a vegetation change from closed *Pinus* forest to open parkland and an increase in fire activity (Whitlock et al., 2012). However, at Hedrick Pond, *Fragilaria* species maintained relatively high percentages after ~8.8 ka BP and did not decrease until ~7.9 ka BP, indicating a later decrease in lake level. In

this case, the changes in the Hedrick Pond diatom community do not resemble shifts in vegetation composition (Whitlock, 1993).

2.4.4 Influence of surficial geology and basin morphology on diatom assemblages

Cub Creek Pond and Hedrick Pond are both located in the summer-dry region, but they differ in surficial geology, with Cub Creek Pond on nutrient-poor rhyolitic soils and Hedrick Pond on nutrient-rich calcareous glacial tills. Therefore, the impact of surficial geology on diatom assemblages can be evaluated by comparing diatom records from these two lakes. During the first few hundred years after the formation of Cub Creek Pond, the diatom community was dominated by benthic and tychoplanktic species, while at Hedrick Pond, it was solely dominated by tychoplankton. During ~13.8 to ~13.1 ka BP, Cub Creek Pond was characterized by high percentages of *F. construens* var. *venter*, whose environmental significance is not clear, while Hedrick Pond had an increased abundance of benthic species: both likely indicate a low lake-level phase probably as a result of warm summer conditions. Both lakes had an increase of benthic species during the interval ~11.0-11.3 ka BP, implying that lake-levels became even shallower, probably as a result of high summer insolation, but the amplitude of increase was different: at Cub Creek Pond benthic species were ~50% between ~11.3-8.7 ka BP, whereas at Hedrick Pond they were greater than 90% in this interval. The existence of moderate percentages (5-20%) of a planktic taxon, *S. parvus/minutulus*, suggests that Cub Creek Pond was probably deeper than Hedrick Pond during the period of ~11.0-8.7 ka BP. It is difficult to attribute the differences in the two diatom records to the

influence of surficial geology. Instead initial differences in lake depth likely affected the difference in the abundance of plankton, tychoplankton, and benthic species in the two basins.

2.5 Conclusion

During the late-glacial and early-Holocene period, the Yellowstone lakes studied here underwent shifts in diatom community structure. The lakes show synchronous changes in diatom stratigraphy during the period of ~ 13.8 - 13.2 ka BP, in the interval of ~ 11.3 - 11.0 , and at ~ 8.8 ka BP. The nature of these changes in diatom community structure varies, but the data suggest that they are all controlled by large-scale climatic change. The largest change in diatom assemblages occurred in the interval of ~ 11.3 - 11.0 ka BP, when all lakes changed from the dominance or co-dominance of tychoplanktic *Fragilaria* species into dominance by benthic species, indicating that the lakes became shallow as a result of decreasing effective moisture, driven by the early-Holocene summer insolation maximum. This shift at 11.3 - 11.0 ka BP coincided with terrestrial vegetation change, which shifted from alpine tundra and *Picea* parkland to closed *Pinus* forests, and also is correlative with intensified fire activity.

During the period of ~ 13.8 - 13.2 ka BP, Blacktail Pond had high percentages of *Cyclotella* species, indicative of strong water column stratification, probably as a result of warm summer conditions. Hedrick Pond was characterized by the relatively high abundance of benthic species, implying low water levels also probably caused by high summer temperatures. Cub Creek Pond also underwent

changes in diatom composition at the same time, although the climatic interpretation is less clear in this case. At ~8.8 ka BP, both Blacktail Pond and Hedrick Pond had an increase of tychoplanktic *Fragilaria* species at the expense of benthic species, suggesting an increase of lake level associated with increasing effective moisture, and in Cub Creek Pond planktic *S. parvus/minutulus* decreased at ~8.7 ka BP, indicative of a reduction in spring mixing. Reduced temperature during spring and early summer may have led to later ice-off and reduced evaporation, augmented by increased winter precipitation.

Given that the three lakes are located in different parts of the Yellowstone National Park and are different from each other in terms of precipitation seasonality and surficial geology, the synchronous shifts in diatom community structures in all these lakes suggest that large-scale climatic changes are the primary control on the evolution of diatom assemblages in this region, and that the impact of precipitation seasonality and surficial geology on diatom community development and limnological change is secondary.

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CHAPTER 3

TRENDS IN CATCHMENT PROCESSES AND LAKE EVOLUTION DURING THE LATE-GLACIAL AND EARLY-HOLOCENE INFERRED FROM HIGH-RESOLUTION XRF DATA IN THE YELLOWSTONE REGION

3.1 Abstract

High-resolution records of geochemical data from four lakes in the Greater Yellowstone region were used to investigate watershed and lake history during the late-glacial and early-Holocene in this region. Clastic input to lakes was high and variable during the early stage of lake development, when the surrounding landscape was unstable and sparsely vegetated, and it decreased as vegetation gradually developed in the catchment. In contrast, long-term organic matter concentration was inversely related to catchment erosion during the early stage of lake development. The decrease of clastic input was not synchronous among regional lakes but occurred time transgressively from south to north. Endogenic calcite production usually was low following lake formation and increased over time, and its long-term pattern of change was controlled primarily by lake-level change in small and shallow lakes and by lake productivity in large and deep lakes.

3.2 Introduction

Dramatic environmental change occurred in the late-glacial and early-Holocene period (Alley and Clark, 1999; Shakun and Carlson, 2010), as summer insolation gradually increased (Berger, 1978). In the Yellowstone region, glaciers started retreating after reaching a maximum at ~17 ka and largely disappeared by ~14 ka (Licciardi et al., 2004; Pierce, 2004; Licciardi and Pierce, 2008; Thackray, 2008).

Following deglaciation, the newly exposed landscape was unstable and sparsely vegetated, soils were not developed, and erosion was high. Newly formed

lakes were always colonized by benthic and tychoplanktic diatom species, likely as a result of low light and low nutrient conditions (Bigler et al., 2002, 2003; Birks et al., 2000; Bradshaw et al., 2000; Stone and Fritz, 2006; Westover et al., 2006).

Catchment processes are an important influence in the early stage of limnological development, as the landscape stabilizes and as weathering and soil development alter geochemical fluxes into lakes (Fritz and Anderson, 2013). Large-scale climatic changes also have an effect on lake development by influencing the lake's thermal and hydrological budgets (Fritz and Anderson, 2013; Battarbee, 2000). The greater Yellowstone region varies in elevation, surficial geology, and precipitation seasonality (Whitlock, 1993). Thus, this region offers a chance to investigate the general pattern of watershed and limnological development in response to catchment processes and large-scale climatic changes.

In this paper, we present high-resolution geochemical records covering the late-glacial and early-Holocene period from four lakes in different part of the greater Yellowstone region: Blacktail Pond (44°57' N, 110°36' W), Dailey Lake (45°16' N, 110°49' W), Hedrick Pond (43°45' N, 110°36' W), and Cub Creek Pond (44°30' N, 110°14' W) (Fig. 3.1). Our objectives in this study include: (1) to infer the watershed and lake history at these four sites from their formation until ~7.0 ka yr BP at Blacktail Pond, ~6.4 ka BP at Dailey Lake, ~4.8 ka BP at Hedrick Pond, and ~11.4 ka BP at Cub Creek Pond; and (2) to explore the links between limnological development, catchment processes, and large-scale climatic change in this region.

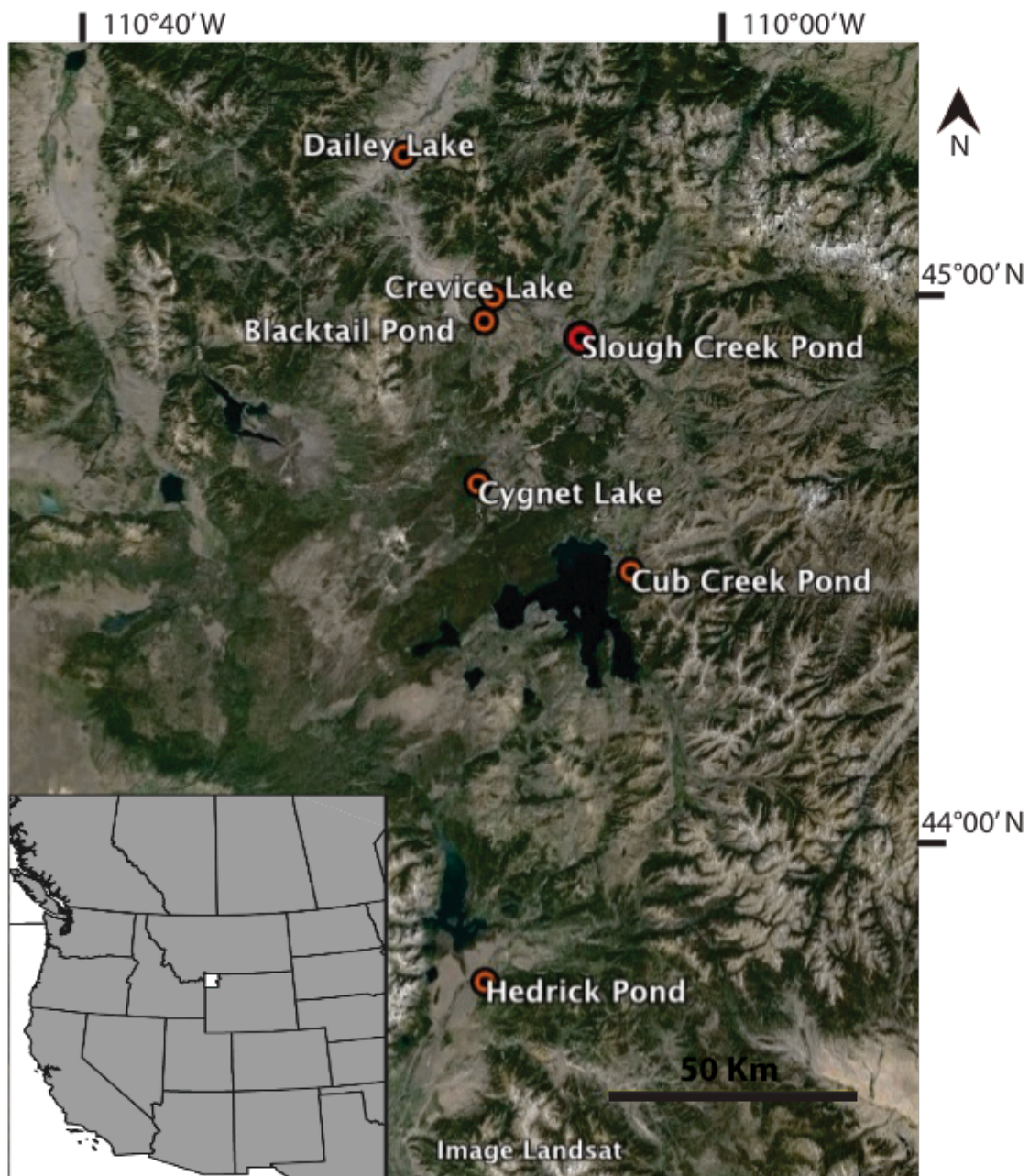


Figure 3.1 Locations of study sites and other Yellowstone region lakes mentioned in the text.

To answer these questions, we use high-resolution XRF data, magnetic susceptibility, and sediment carbon and nitrogen data to investigate watershed and lake history, including clastic inputs, endogenic calcite production, diatom productivity, organic matter concentration and source, and redox conditions. Other proxies, such as pollen, charcoal, and diatoms, are integrated with the geochemical data to explore the mechanisms underlying watershed and limnological development.

3.3 Site descriptions

Blacktail Pond is a small closed-basin lake. It is on a remnant late-Pleistocene meltwater channel formed as ice retreated during the late-glacial (Pierce, 1979). Situated on calcareous glacial outwash, Blacktail Pond is surrounded by sagebrush steppe. Trees are found on the surrounding landscape, with Douglas-fir (*Pseudotsuga menziesii*) and lodgepole pine (*Pinus contorta*) forest on adjacent rocky slopes, stands of quaking aspen (*Populus tremuloides*) on the lower slopes in areas of seepage, and small populations of fir (*Abies*) and pine (*Picea*) in nearby cold air drainages. The lake margin is occupied by willow (*Salix* spp), three-square bulrush (*Scirpus americanus*), sedge (*Carex* spp), and broadleaf cattail (*Typha latifolia*), whereas muskgrass (*Chara*), bladderwort (*Utricularia*), and water milfoil (*Myriophyllum*) grow underwater (Krause et al., 2013).

Dailey Lake is on a low bench 85 m above the Yellowstone River in the Paradise Valley of southwestern Montana. The semi-closed lake periodically discharges into a small wetland to the north through an outlet. The surrounding

landscape is primarily vegetated by grassland and steppe dominated by big sagebrush (*Artemisia tridentata*), rabbitbrush (*Ericameria nauseosa*), Idaho fescue (*Festuca idahoensis*), and Great Basin wild rye (*Leymus cinereus*). Along the lake margin and in the adjacent wetland grow isolated populations of Rocky Mountain juniper (*Juniperus scopulorum*). Willow, sedge, and cattail are present. Montane and subalpine forests grow on nearby mountain slopes, such as limber pine (*Pinus flexilis*), Douglas-fir, lodgepole pine, Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and whitebark pine (*Pinus albicaulis*). Alpine tundra occurs on high elevation above 2900 m.

Hedrick Pond is situated on a bench of Pinedale-2 glacial outwash that is further underlain with sediments from Pinedale-1 glacial outwash (Pierce and Good, 1990). Cosmogenic dating indicates that the Pinedale-2 phase is younger than ~14.6 ka. Therefore, the bottom of Hedrick Pond should also be younger than ~14.6 ka (Licciardi and Pierce, 2008). The surrounding vegetation includes open forest of lodgepole pine, Douglas-fir, and sagebrush steppe. In the open area, common juniper (*Juniperus communis*), Canada buffaloberry (*Shepherdia Canadensis*), common snowberry (*Symphoricarpos albus*), and Wood's rose (*Rosa woodsii*) are present. Quaking aspen, Engelmann spruce, Colorado spruce (*Picea pungens*), and subalpine fir grow on wetter slopes. Sagebrush steppe grows on the outwash gravels to the south of the site near the southern border of Grand Teton National Park. Around the lake margin, cattail and bulrush are present, and yellow pond lily (*Nuphar lutea*) grows in shallow water (Whitlock, 1993).

Cub Creek Pond is situated on the central Yellowstone Plateau and is ~4 km east of Yellowstone Lake. During the last glacial maximum, it was on the east side of Yellowstone Plateau icecap-divide. Kame gravels were deposited in ice marginal streams adjacent to Cub Creek Pond during down wasting of the Yellowstone Plateau icecap. The central Yellowstone Plateau is underlain by rhyolitic soils, and vast stands of lodgepole pine cover 81% of the park (Baker, 1976). On the ridges surrounding Cub Creek Pond, stands of lodgepole pine, spruce, fir, and whitebark pine are present (Waddington and Wright Jr., 1974). Available limnological data of the study lakes are given in Table 3.1.

3.4 Methods

A modified Livingstone square-rod piston corer (Wright Jr. et al., 1983) was used to collect sediment cores at Blacktail Pond and Hedrick Pond in 2008 and at Cub Creek Pond and Dailey Lake in 2009. A pair of overlapping sediment cores with 50 cm offset was collected within a few meters of each other from each of the lakes. Blacktail Pond sediment cores were retrieved from the fen margin, and the core used for analysis, BTP08B, was 2.85 meters long. Dailey Lake sediment cores were taken at the deepest part of the lake, where water depth is 7 m, and the core used for analysis, DLM09B, was 8 meters long. Cub Creek Pond sediment cores were collected at the fen margin, and the 3.58-m-long CUB09A core was analyzed for this study. Hedrick Pond sediment cores were collected in 4 m water depth, and the core used for analysis, HED08A, was 3.40 meters long.

Table 3.1 Limnological data for the study lakes.

	Lat.	Long.	Elev. (m)	Depth (m)	TP (mg/L)	TN (mg/L)	DOC (mg/L)
Dailey Lake	45°16' N	110°49' W	1700	7	0.054	1.403	18.6
Blacktail Pond	44°57' N	110°36' W	2015	8	0.076	0.711	5.85
Cub Creek Pond	44°30' N	110°14' W	2573	n/a	0.366	6.688	25.3
Hedrick Pond	43°45' N	110°36' W	2051	4	0.126	1.553	14.5

Cores were split at the Limnological Research Center (LRC), University of Minnesota and imaged with a DMT Core Scanner and analyzed for magnetic susceptibility every 0.5 cm with a point sensor. In addition to standard core logging methods, XRF data were produced by the ITRAX XRF core scanner at the Large Lakes Observatory (Duluth), University of Minnesota, using 30-s count times, 30 kV X-ray voltage, and an X-ray current of 20 mA to obtain data for the following elements: Si, K, Ca, Ti, V, Cr, Mn, Fe, Rb, Sr, Y, Zr, Ba, Pb. Statistical treatment of XRF data was carried out using PAST (Hammer et al., 2001).

Blacktail Pond, Dailey Lake, and Cub Creek Pond were analyzed for total carbon (TC), total inorganic carbon (TIC), and total nitrogen (TN) content from freeze-dried samples. Insufficient sediment was available for analysis of the Hedrick Pond core. TC and TN were measured by dry combustion analysis, using a Costech ECS 4010 CHNS-O Elemental Analyzer. TIC was measured on a UIC CM 5015 coulometer. Total organic carbon (TOC) was calculated as the difference between TC and TIC. Carbon and nitrogen fractions are expressed as a percentage of the sediment dry weight. C/N ratios are the ratio of TOC to TN, which were then multiplied by 1.167 to express the data as an atomic ratio (Meyers and Teranes, 2001).

Selected elemental intensities were graphed versus age: Ti, K, Rb, Si, Fe, Mn, Zr, Ca, and Sr. The values of some of these elements also were normalized to Ti to aid in environmental interpretation, because in lake sediments Ti is allogenic, not biologically active, and conservative during weathering and transport (Kylander et

al., 2011). In addition, correlation matrices were generated to show the strength of association between pairs of elements in the data sets.

AMS ^{14}C dates were used to develop age models, which follow previous work. Blacktail Pond chronology was after Krause et al. (2013), and Dailey Lake follows Krause et al. (in review, chapter 4 of this thesis), whereas Cub Creek Pond and Hedrick Pond are presented in Lu et al. (in prep., chapter 3 of this dissertation).

3.4.1 Interpretation of Selected Elemental Data

Scanning XRF is a non-invasive, whole-core analysis that measures elemental intensity as counts per second (cps) (Croudace et al., 2006). Element concentrations are not directly available from the XRF measurements and the processing software, but values can be used as estimates of relative concentrations. It is difficult to interpret long XRF elemental records, as there is no clear baseline from which to assess deviations (Kylander et al., 2011). However, in a paleoclimatic context the relative changes in the elemental profiles can provide information, especially when combined with other paleoecological and geochemical data, such as diatom, pollen, and sediment carbon content.

Titanium, Rb, K, Si, and Zr are indicative of clastic inputs, with Ti, Rb, and K associated with clay mineral assemblages, and Zr and Si generally linked to coarser silt and sand-size fractions (Kylander et al., 2011; Das and Haake, 2003; Koinig et al., 2003; Jin et al., 2006). Silicon has both mineral and biological sources. It is enriched in many aluminosilicate minerals, particularly alkali feldspars, but also is present in diatoms as a component of their frustules (Peinerud, 2000) and in other siliceous algae, such as chrysophytes (Zeeb and Smol, 2001). The Si/Ti ratio normalizes the

data to the mineral source of Si and thus represents Si production in the lake system. Chrysophyte scales and cysts are rare in the studied lakes. Therefore, the Si/Ti ratio can be interpreted as an indicator of diatom productivity.

Zirconium is abundant in medium to coarse silts and is associated with heavy minerals, such as zircon (Kylander et al., 2011), which may be elevated in volcanic sources (Moreno et al., 2007). Changes in Fe can indicate redox conditions in the lake or clastic inputs and/or changes in sediment source (Davison, 1993).

Calcium and Sr in lake sediments are associated with carbonate weathering in the catchment and endogenic calcite precipitation, with the incorporation of Sr into the calcite lattice during calcite formation. In addition to the endogenic incorporation of Sr in calcite, Sr also can be associated with silicates, particularly plagioclase feldspars, leading to the potential for positive correlations with Ti, K, Rb, Si (Kylander et al., 2011). Calcite precipitation occurs when lake waters are saturated with carbonate, as when lake waters are concentrated by increased evaporation and the potential resultant lowering of lake levels (Cohen, 2003). Calcite precipitation also occurs when algal photosynthesis during the summer months consumes CO₂ (Dean and Megard, 1993), and by increasing water temperature and pH (Wetzel, 2001). In addition, changes in groundwater flow can also lead to calcite deposition, especially in alkaline lakes where carbonate precipitation is Ca limited (Hobbs et al., 2011; Grimm et al., 2011). In the Yellowstone region lakes, the Ca/Ti ratio is interpreted as a measure of calcite production in the lake system, as a result of lowering lake level and/or increasing algal productivity.

The abundance of Mn in lake sediments is affected by changes in redox conditions at the sediment-water interface, because Mn forms a highly insoluble oxide in oxygen-rich environments (Moreno et al., 2007; Kylander et al., 2011). Thus, Mn in lake sediments is a result of Mn mobilization and subsequent precipitation in the form of Mn oxides in oxygen-rich waters (Aguilar and Nealson, 1998). Changes in oxygen levels at the sediment-water interface can be the result of lake level changes and water column ventilation, changes in biological activity (photosynthesis) (Davidson, 1993), and/or changes in the duration of seasonal stratification related to temperature and wind (Wetzel, 2001). Therefore, the Mn/Ti ratio can be interpreted as a proxy of oxygen levels at the sediment-water interface, which are affected by changes in lake level, photosynthesis, and/or the duration of stratification. In addition, Mn can precipitate out of the water column together with calcite, or complexed with carbonate, sulfate, and organic acids (Engstrom and Wright Jr., 1984).

3.5 Result and discussion

3.5.1 Blacktail Pond

3.5.1.1 Correlation matrix

A correlation matrix (Table 3.2) was generated to show the association between pairs of elements, and their changing patterns are shown in Fig. 3.2. This analysis indicates that there are three groups of elements in this dataset. Group 1 includes Ti, K, Rb, Fe, Si, and Zr. These elements have similar behaviors (Fig. 3.2) and are highly correlated with each other, with r values generally greater than 0.9.

Table 3.2 Correlation matrix (r values) for the Blacktail Pond sediment core.

	Si	K	Ca	Ti	Mn	Fe	Rb	Sr
K	0.96							
Ca	-0.76	-0.82						
Ti	0.92	0.97	-0.85					
Mn	0.18	0.25	-0.08	0.21				
Fe	0.86	0.95	-0.86	0.97	0.23			
Rb	0.95	0.99	-0.84	0.97	0.23	0.94		
Sr	-0.65	-0.77	0.80	-0.77	0.02	-0.83	-0.75	
Zr	0.81	0.91	-0.88	0.92	0.31	0.93	0.91	-0.79

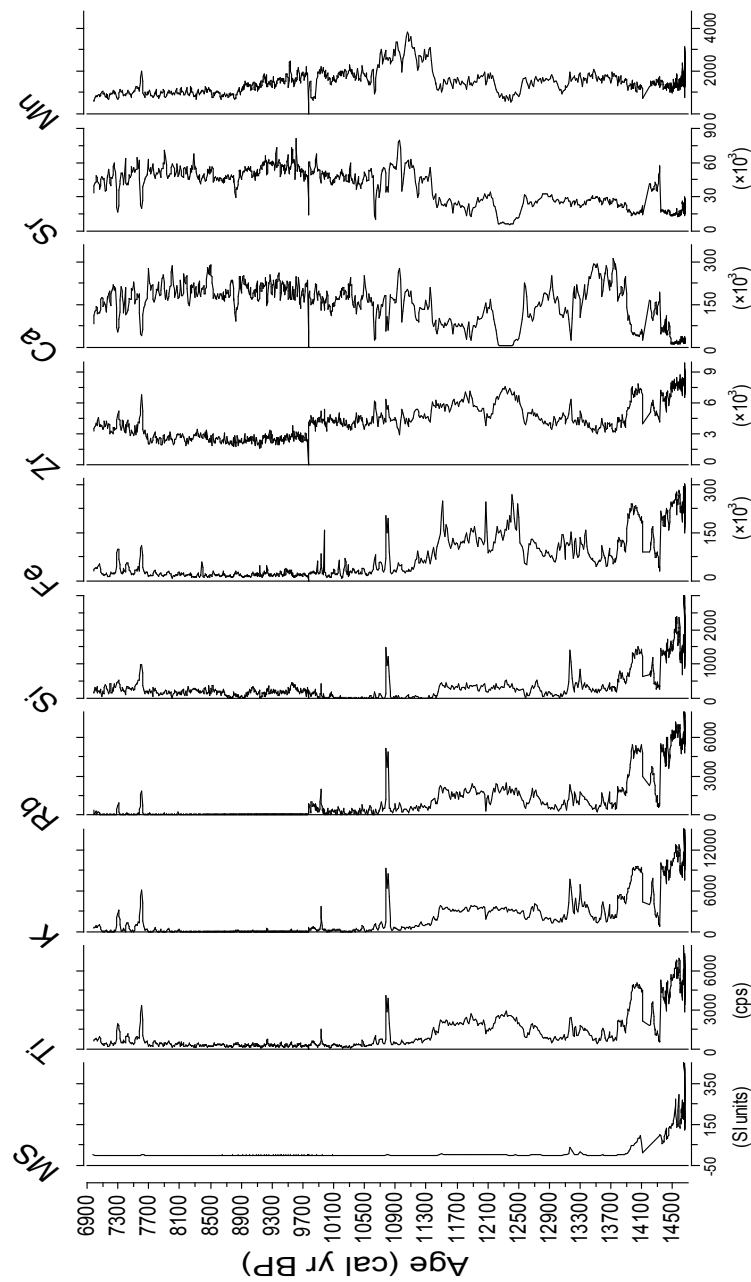


Figure 3.2 Magnetic susceptibility (MS) and selected elemental intensities (measured in “cps”) for Blacktail Pond.

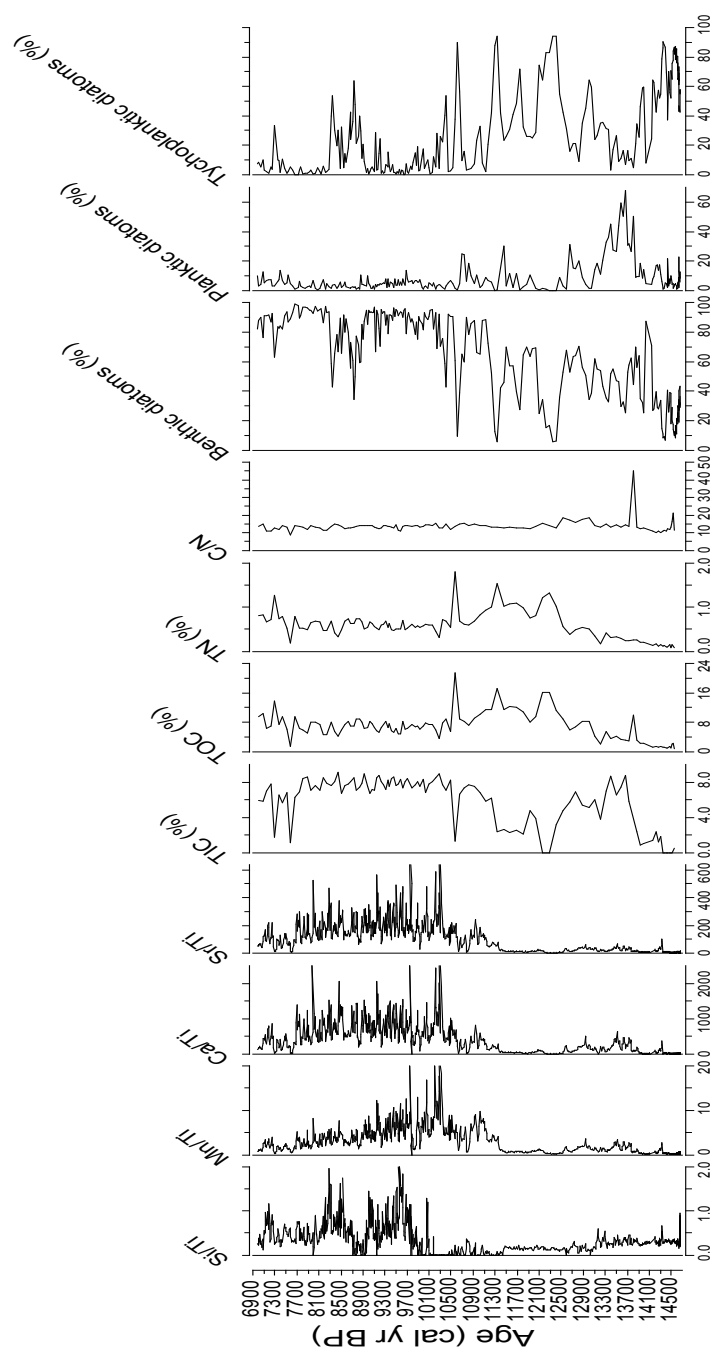


Figure 3.3 Selected elemental ratios, geochemical data, and diatom groups for Blacktail Pond.

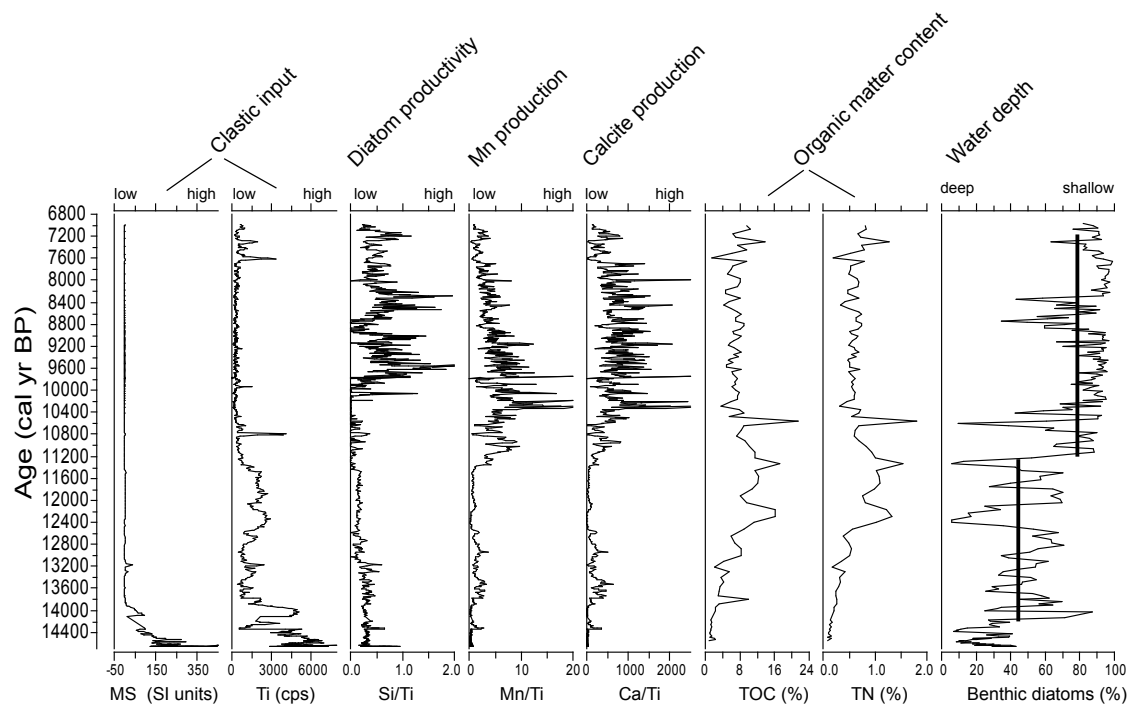


Figure 3.4 A summary diagram showing key environmental proxies for Blacktail Pond.

Strong correlations of Si with K, Ti, and Rb (with r values of 0.96, 0.92 and 0.95, respectively) suggest that Si behavior is mainly controlled by silicate sources in the Blacktail Pond sediment core. As is the case with Si, the strong correlation between Fe and Ti ($r=0.97$) suggests that Fe is controlled primarily by clastic input in the sediment core. Therefore, elements in this group are all associated with minerogenic input to the lake.

Group 2 contains Ca and Sr, which are strongly correlated, with an r value of 0.8. These two elements are negatively correlated with elements in group 1 (Ti, K, Rb, Fe, Si, and Zr), suggesting that Ca and Sr are not controlled by a clastic source. Instead, endogenic carbonate production strongly controls their behavior. Manganese behaves uniquely in the record and has low correlations with Ti, K, Rb, Fe, Si, and Zr (generally smaller than ~ 0.3), indicating that it is not influenced by clastic inputs to the lake.

3.5.1.2 Watershed and lake history

The changing patterns of selected elements and magnetic susceptibility from Blacktail Pond are shown in Figure 3.2, and Figure 3.3 shows the Ti normalized profiles of Si, Mn, Ca, and Sr, as well as carbon and nitrogen data together with diatom data. The Ti normalization of each element removes their allogenic sources and only indicates their in-lake production. Figure 3.4 shows the environmental proxies used for the interpretation of watershed and lake development for Blacktail Pond.

Figure 3.4 suggest that from 14.6 to 13.9 ka BP, clastic inputs to the lake were among the highest of the entire record, as indicated by the high intensities of Ti, K, Rb, Si, and Zr (Fig. 3.2). During this period, these elements also fluctuated in intensities and showed a generally decreasing trend, suggesting that clastic inputs to the lake were variable but decreased over time. There are multiple indicators in the core characteristic of a newly deglaciated landscape during this period. Magnetic susceptibility, another indicator of minerogenic input, also was high (Fig. 3.4), and the surrounding landscape was sparsely vegetated with the dominance of sagebrush (Krause et al., 2013). The lake diatom community was dominated by colonial tychoplanktic *Fragilaria* species (Fig. 3.3; Lu et al., in prep.), which are typical pioneering species in newly formed deglaciated terrains due to their ability to live in well-mixed water columns and in the low light conditions that result from high clastic inputs (Westover et al., 2006).

Titanium, K, Rb, Si, and Zr maintained relatively stable levels from 13.9 to 11.5 ka BP and were lower than the previous period, which implies that minerogenic inputs to the lake were generally stable and lower than before. Lower clastic inputs are also evident in the decreased magnetic susceptibility. Open parkland gradually developed in the surrounding region (Krause et al., 2013), and diatom community structure shifted at ~13.9 ka BP from the dominance of tychoplanktic *Fragilaria* species to planktic *Cyclotella* species, which are indicative of warmer summer water temperatures and the resultant well-stratified water column (Lu et al., in prep). Ca/Ti and Mn/Ti had relatively high values during the period of 13.9-12.7 ka BP, which was also characterized by high total inorganic

carbon (TIC), an indicator of carbonate content in lake sediments. Low lake level and high lake productivity could both lead to enhanced calcite production as indicated by high values of Ca/Ti. However, the dominance of the planktic diatom group, *Cyclotella*, suggests that the lake was well stratified during summer in this period. Thus, increased lake productivity likely caused the elevated calcite deposition and the co-precipitation of Mn during the period of 13.9-12.7 ka BP.

At ~11.5 ka BP, clastic inputs to the lake dropped to a new low level, evidenced by decreasing intensities of the clastic elements, and low values were maintained until ~7.7 ka BP, except for a peak in Ti, K, Rb, and Si intensities at ~10.8 ka BP. Landscape vegetation also changed around this time. Closed subalpine forest was developed at ~11.5 ka BP on terrains surrounding Blacktail Pond (Krause et al., 2013), consistent with the lowered clastic inputs to the lake. The most striking characteristic of the Ca/Ti and Mn/Ti records is that they gradually increased at ~11.3 ka BP and maintained higher values thereafter. This suggests either a decrease in lake level or an increase in lake productivity and photosynthesis, or a combination of both scenarios. However, total organic carbon (TOC) content, an indicator of carbon inputs from the watershed and/or within lake productivity, does not show an increase at ~11.3 ka BP, nor does the Si/Ti ratio, which only increases after ~10.0 ka BP. This suggests that the initial increase of Ca/Ti and Mn/Ti at ~11.3 ka BP was not caused by an increase in lake productivity and photosynthesis but instead was influenced by changes in lake level. A lake level decrease at ~11.3 ka BP is suggested by changes in diatom community structure, which shifted from the

dominance of *Fragilaria* species to the dominance of benthic species (Lu et al., in prep).

From 7.7 ka BP to the end of the analyzed record (6.9 ka BP), Ti, K, Rb, Si and Zr intensities were higher than in the previous period, although fluctuating, indicating that clastic inputs to the lake increased somewhat at ~7.7 ka BP and were maintained at moderate values until the end of this record. Ca/Ti and Mn/Ti values decreased at ~7.7 ka BP, which suggest a decrease in calcite precipitation and the co-deposition of Mn. The decrease of calcite production, which is also evident in the decrease of TIC values, could be a result of increased lake level and/or decreased lake productivity, but increased TOC and TN values suggest that organic matter inputs increased at ~7.7 ka BP. Thus, the decline of calcite production and associated Mn precipitation is likely a result of increased lake level, which is supported by the increase of planktic *Cyclotella* species and tychoplanktic *Fragilaria* species in the diatom flora at ~7.7 ka BP. On the surrounding landscape, forests became sparser, and lower parkland developed at ~8.2 ka BP and was maintained thereafter, likely facilitating catchment erosion, which became higher at ~7.7 ka BP as indicated by the increase in Ti, K, Rb, Si, and Zr.

3.5.2 Dailey Lake:

3.5.2.1 Correlation matrix

Figure 3.5 shows changes in intensities of Ti, K, Rb, Si, Fe, Ca, Sr, and Mn through time in Dailey Lake, as well as the magnetic susceptibility (MS) record. Table 3.3 shows the correlation table for these elements. Figure 3.6 illustrates the Ti

normalized profiles of Si, Mn, Ca, and Sr, as well as carbon and nitrogen data together with diatom data, whereas Figure 3.7 shows the environmental proxies used for the interpretation of watershed and lake development.

As shown in Figure 3.5, the patterns of Ti, Si, K, Rb and Fe are similar throughout the record, which also is evident in their high correlation values (greater than 0.80, Table 3.3). Silicon, K, Fe, and Rb are highly correlated with each other, with r values greater than 0.9, with a slightly lower correlation with Ti, with r values ranging from 0.83 to 0.89. Silicon has both a clastic input source and biogenic sources in lakes (as diatom frustules and chrysophyte scales and cysts), but its high correlation with Ti, K, and Rb (r values of 0.83, 0.94 and 0.90, respectively) suggests that Si behavior is mainly controlled by terrestrial silicate sources in the Dailey Lake sediment core. Similar to Si, high correlations between Fe and Ti, K, and Rb (r values of 0.89, 0.98, 0.97, respectively) indicate that Fe also is associated with clastic inputs in this record. Calcium and Sr show similar patterns in Figure 3.4, and they are positively correlated, with a r value of 0.85. Calcium and Sr, especially Ca, are negatively correlated with Si, K, Ti, Fe, and Rb, with r values ranging from -0.81 to -0.88 and -0.65 to -0.73, respectively. Manganese behaves uniquely in the elemental record, showing no correlation with other elements in the dataset, with r values ranging from -0.11 to 0.13. The changing pattern of magnetic susceptibility is similar to that of Ti, Si, K, Rb, and Fe, indicating that these measurements are controlled by the same factors.

Table 3.3 Correlation matrix (r values) for the Dailey Lake sediment core.

	Si	K	Ca	Ti	Mn	Fe	Rb
K	0.94						
Ca	-0.81	-0.86					
Ti	0.83	0.87	-0.83				
Mn	0.10	0.13	0.02	0.02			
Fe	0.93	0.98	-0.88	0.89	0.13		
Rb	0.90	0.98	-0.85	0.89	0.10	0.97	
Sr	-0.73	-0.68	0.85	-0.69	-0.11	-0.72	-0.65

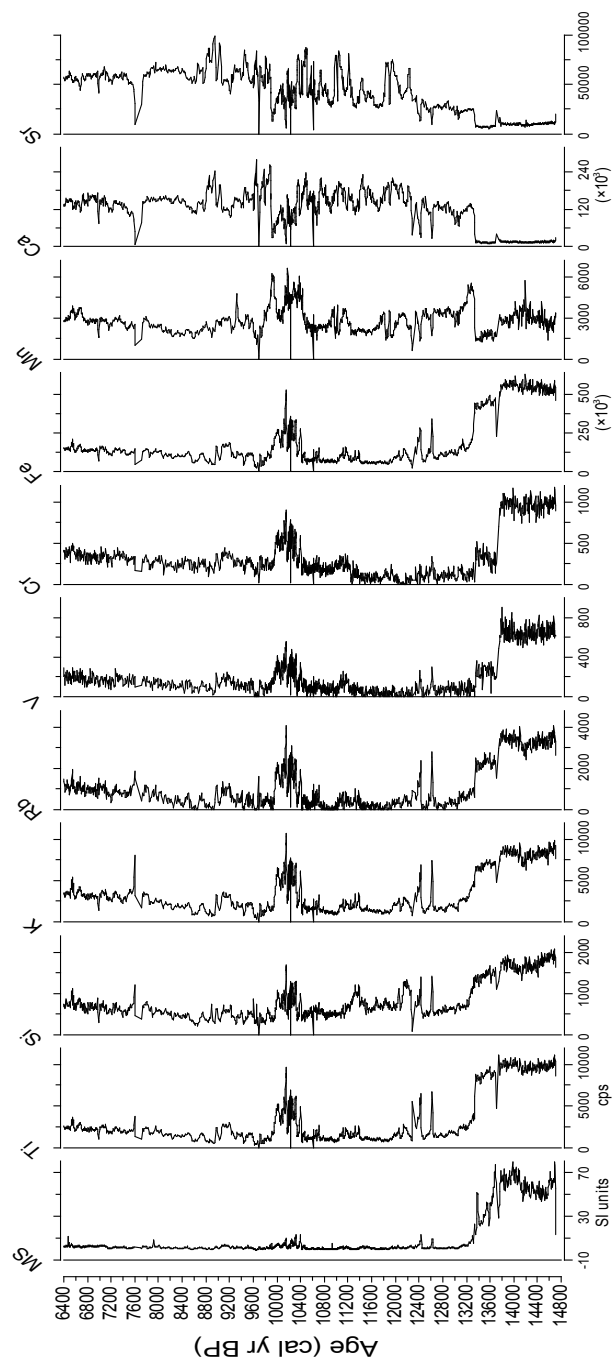


Figure 3.5 Magnetic susceptibility (MS) and selected elemental intensities (measured in "cps") for Dailey Lake.

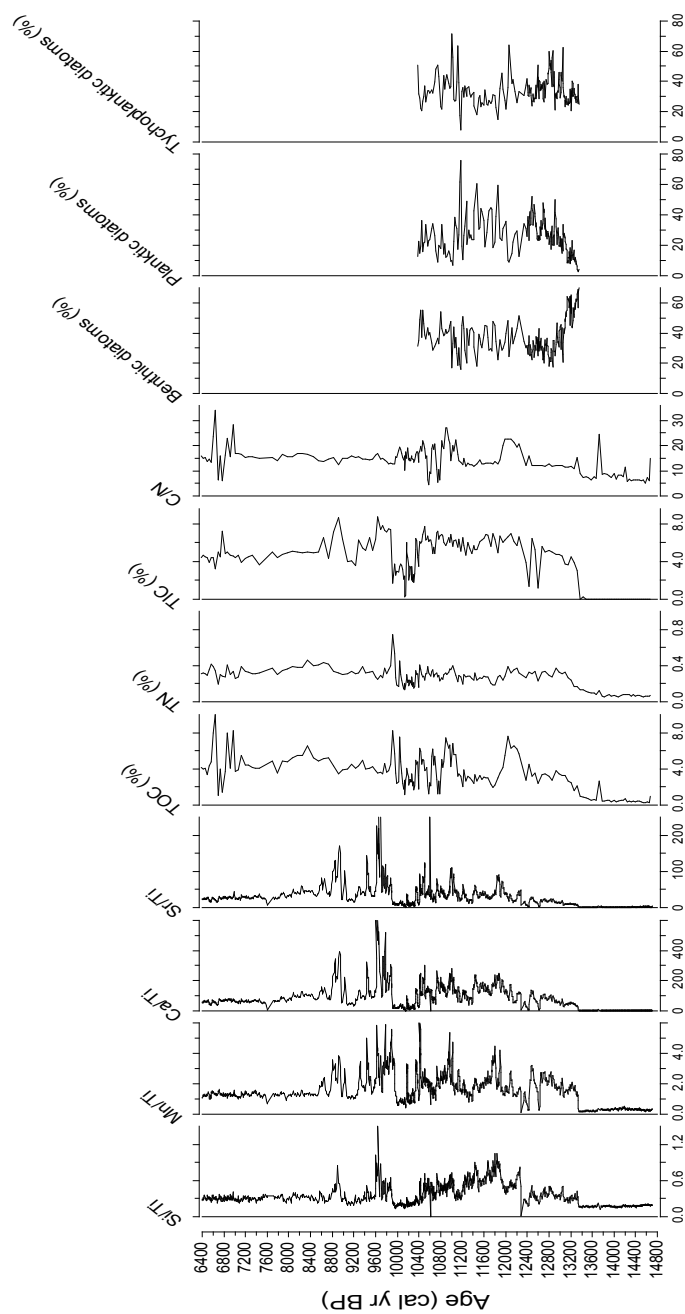


Figure 3.6 Selected elemental ratios, geochemical data, and diatom groups for Dailey Lake. Diatoms are not preserved in the sediments above 10,400 cal yr BP.

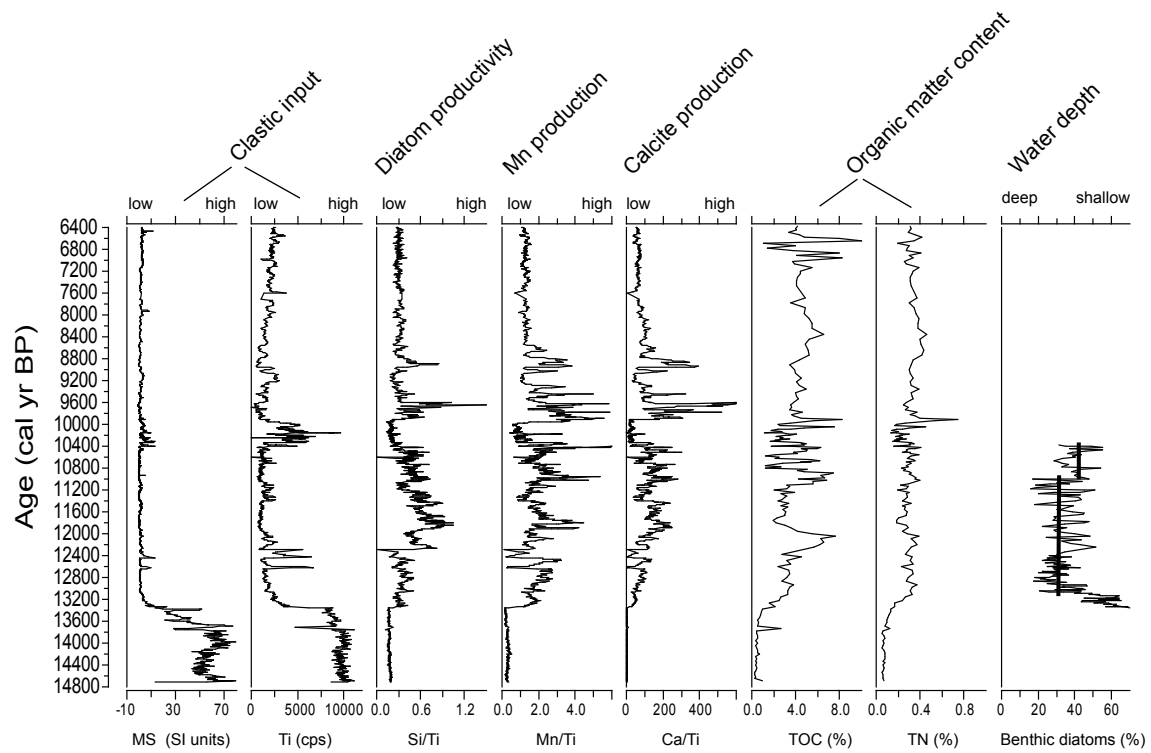


Figure 3.7 A summary diagram showing key environmental proxies for Dailey Lake.

Diatoms are not preserved in the sediments above 10,400 cal yr BP.

3.5.2.2 Watershed and lake history

From 14.7-13.4 ka BP, which is the base of the sediment core, Ti, Si, K, Rb, and Fe had extremely high intensities (Fig. 3.5), indicating high minerogenic inputs to the lake (Fig. 3.7). This also is evidenced in the highest values of magnetic susceptibility, which may be attributed to the influx of unsorted terrestrial sediments following the collapse of the ice block that formed the lake. Pollen records indicate that following deglaciation, the landscape surrounding Dailey Lake was sparsely vegetated and unstable, facilitating weathering activity and terrestrial erosion (Krause et al., in review). The absence of diatoms in the sediments during this period is likely the result of high clastic inputs to the lake, such that low light in the water column due to high clastic inputs made it impossible for diatoms to grow (Fig. 3.6; Lu et al., in prep.). Consistent with the absence of diatoms, the Si/Ti ratio was the lowest of the entire record. The Ca/Ti and Mn/Ti were also low, indicating that precipitation of calcite and co-precipitation of Mn were low in the lake, probably due to low lake productivity. The inference of low productivity is corroborated by TOC and TN values, which were also low (Fig. 3.6).

From 13.4-10.4 ka BP, clastic inputs to the lake were reduced, as indicated by low values of magnetic susceptibility and lowered intensities of Ti, K, Rb, Si, and Fe. Reduced terrestrial minerogenic input to the lake was probably a result of a stable and vegetated landscape. Pollen records showed that beginning at ~13.4 ka BP, open parkland developed around Dailey Lake, and closed subalpine forest became established at ~12.2 ka BP (Krause et al., in review). As the clastic inputs were reduced, diatoms developed at ~13.4 ka BP, and diatom productivity was high, as

indicated by high Si/Ti values. Ca/Ti and Mn/Ti were high during this period, suggesting increased calcite precipitation and associated Mn deposition, a pattern also evident in the high TIC values. TOC and TN values were also significantly elevated starting 13.4 ka BP, indicating that organic matter concentrations were high, possibly because of increased lake productivity, which could lead to enhanced calcite and Mn oxide production.

The period of 10.4-10.0 ka BP was characterized by high clastic inputs, as implied by elevated values of magnetic susceptibility and high values of Ti, Si, K, Rb, and Fe. Low Ca/Ti and low TIC values suggest that endogenic calcite production was low, as was Mn precipitation. Low Si/Ti values suggest diatom productivity was low, and diatom preservation decreased at ~10.4 ka BP, with only a few fragments preserved thereafter (Krause et al., in review). It is likely that Dailey Lake transitioned from an open/semi-closed system to a closed system at this time and became more alkaline so that diatoms were not preserved in sediments. TOC and TN also had lower values than the previous period, indicating decreased organic matter concentrations. The scenario of high clastic inputs during this period can be partly explained by fire-induced erosional events, because fire activity reached a maximum slightly before this interval (Krause et al., in review).

Clastic inputs decreased significantly at ~10.0 ka BP, as indicated by decreasing values of Ti, Si, K, Rb, Fe, and magnetic susceptibility, followed by a moderate trend of increasing values from ~9.7 to 6.4 ka BP. Si/Ti, Ca/Si, and Mn/Ti rapidly increased at 10.0 ka BP, maintained variable values until 8.8 ka BP, and then gradually decreased towards 6.4 ka BP. This suggests that diatom productivity,

precipitation of calcite, and co-precipitation of Mn substantially increased at ~10.0 ka BP, maintained high and variable values until ~9.7 ka BP, and then slowly decreased towards the end of this record. Organic matter concentrations, as indicated by TOC values, increased at ~10.0 ka BP and maintained relatively stable values until ~7.1 ka BP, when it became more variable. The large decrease of clastic inputs at ~10.0 ka BP is associated with a decrease in fire activity (Krause et al., in review).

3.5.3 Hedrick Pond

3.5.3.1 Correlation Matrix

Depth profiles of selected elemental intensities, namely Ti, K, Fe, Si, V, Cr, Mn, and Ca, are shown in Figure 3.8. Correlation tables are illustrated in Table 3.4 for the Hedrick Pond sediment core, which was separated into two sections. From 344-637cm (~15.3-5.8 ka BP), Ti and K, indicators of terrestrial clastic input, have almost identical patterns and are highly correlated ($r=0.96$, Table 3.4). Other elements, such as Ca, Mn, Fe, Ti, V, and Cr, are also highly correlated with Ti ($r>0.8$). To a lesser extent, Si is also correlated with Ti in this section ($r=0.68$). This somewhat weak correlation is a result of several sand layers at the base of the core (585-637cm, ~15.3-14.3 ka BP). The generally high correlation between Ti and Ca, Mn, Fe, Ti, V, Cr, and Si suggests that these elements are largely controlled by clastic inputs to the lake in this interval.

In the core section from 305-343 cm (~5.8-4.8 ka BP), the correlation patterns among elements change from the previous period. Titanium and K are still

correlated ($r=0.81$), and they are both correlated with Fe ($r=0.77$ and 0.75 , respectively). Yet other elements, such as Ca, Mn, V, Cr, and Si only show weak correlations with Ti, and with each other in this section. The decoupling suggests that these elements are not simply controlled by minerogenic inputs anymore.

3.5.3.2 Watershed and lake history

Figure 3.9 shows selected Ti normalized elemental ratios and diatom group data. Figure 3.10 illustrates the environmental proxies used for the interpretation of watershed and lake development. From ~ 15.3 - 14.2 ka BP, magnetic susceptibility had high and variable values and subsequently decreased (Fig. 3.8). Titanium and K intensities were also high and variable in this section, showing an overall decreasing pattern. This suggests that during this period, clastic input to the lake was high. Periods of high Si values within this core section correspond to sand layers. It is possible that these layers in the sediment core come from the underlying Pindale-2 outwash and Triangle-X-1 lake sediments, upon which Hedrick Pond is situated (Kenneth Pierce, personal communication). Therefore, the high ratios of Ca/Ti, Mn/Ti, and Si/Ti probably don't reflect the in-lake production of Ca, Mn, and Si, respectively but are likely to be a result of high clastic inputs. Probably as a result of the high clastic inputs, diatoms were rare in this section of the core.

Table 3.4 Correlation matrix (r values) for the Hedrick Pond sediment core.

	Si	K	Ca	Mn	Fe	Ti	V
305-343 cm							
K	0.50						
Ca	0.53	0.27					
Mn	0.16	0.17	0.53				
Fe	0.36	0.75	-0.09	-0.04			
Ti	0.37	0.81	0.05	0.04	0.77		
V	0.26	0.34	0.12	0.05	0.35	0.33	
Cr	0.04	0.06	-0.05	0.06	0.10	0.00	0.00
344-637 cm							
K	0.83						
Ca	0.77	0.88					
Mn	0.73	0.90	0.88				
Fe	0.43	0.78	0.62	0.71			
Ti	0.68	0.96	0.82	0.88	0.88		
V	0.59	0.85	0.71	0.75	0.83	0.90	
Cr	0.64	0.88	0.75	0.83	0.72	0.88	0.79

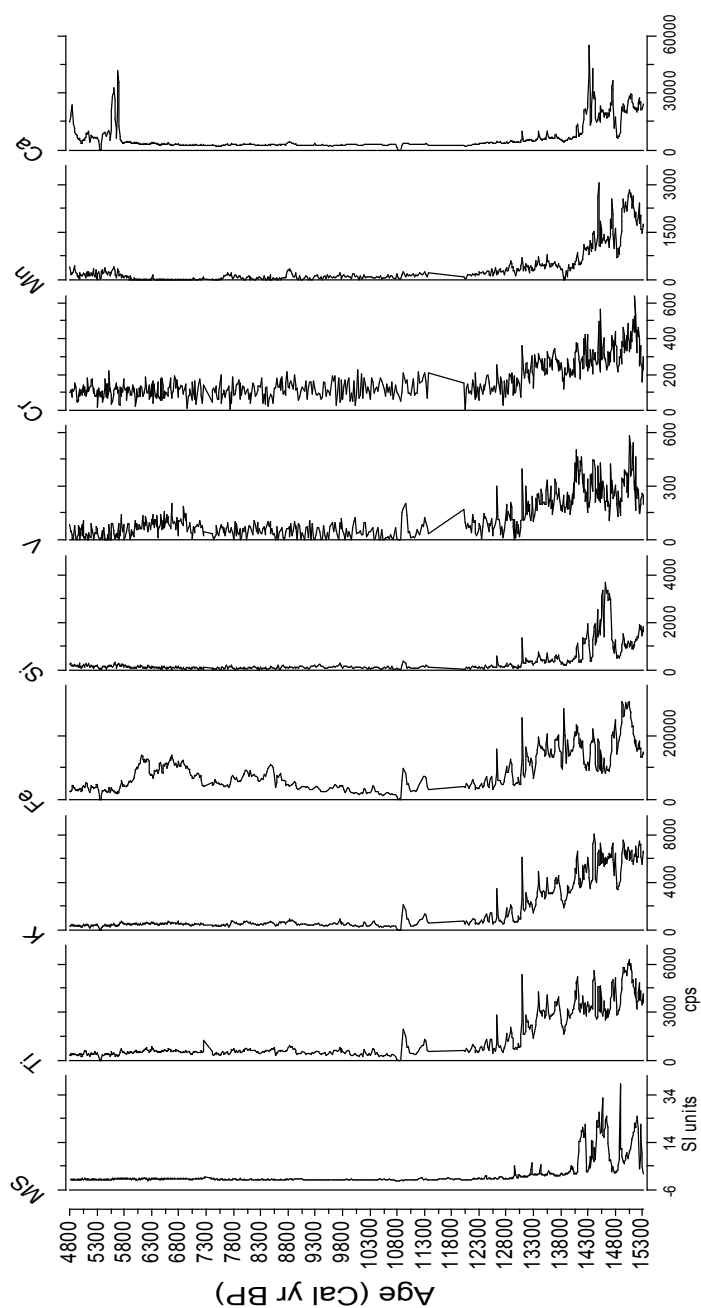


Figure 3.8 Magnetic susceptibility (MS) and selected elemental intensities (measured in “cps”) for Hedrick Pond.

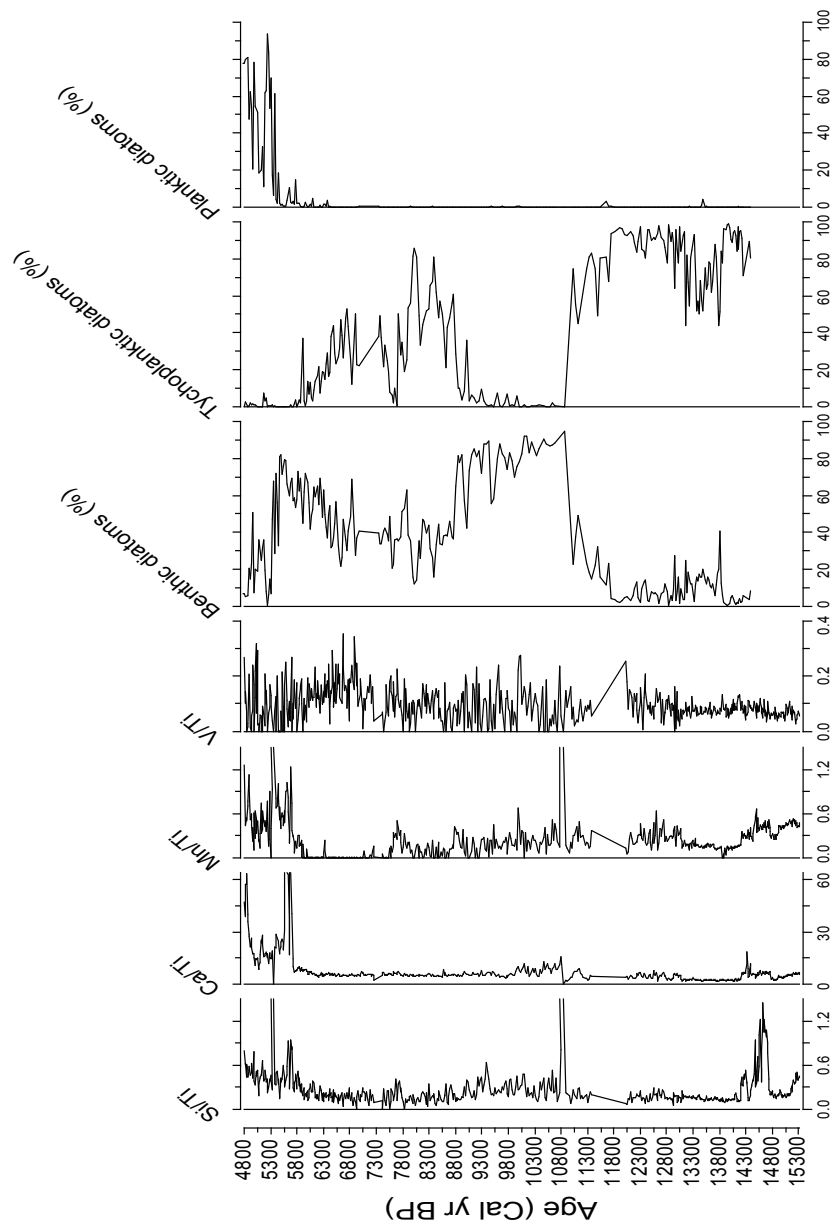


Figure 3.9 Selected elemental ratios and diatom groups for Hedrick Pond.

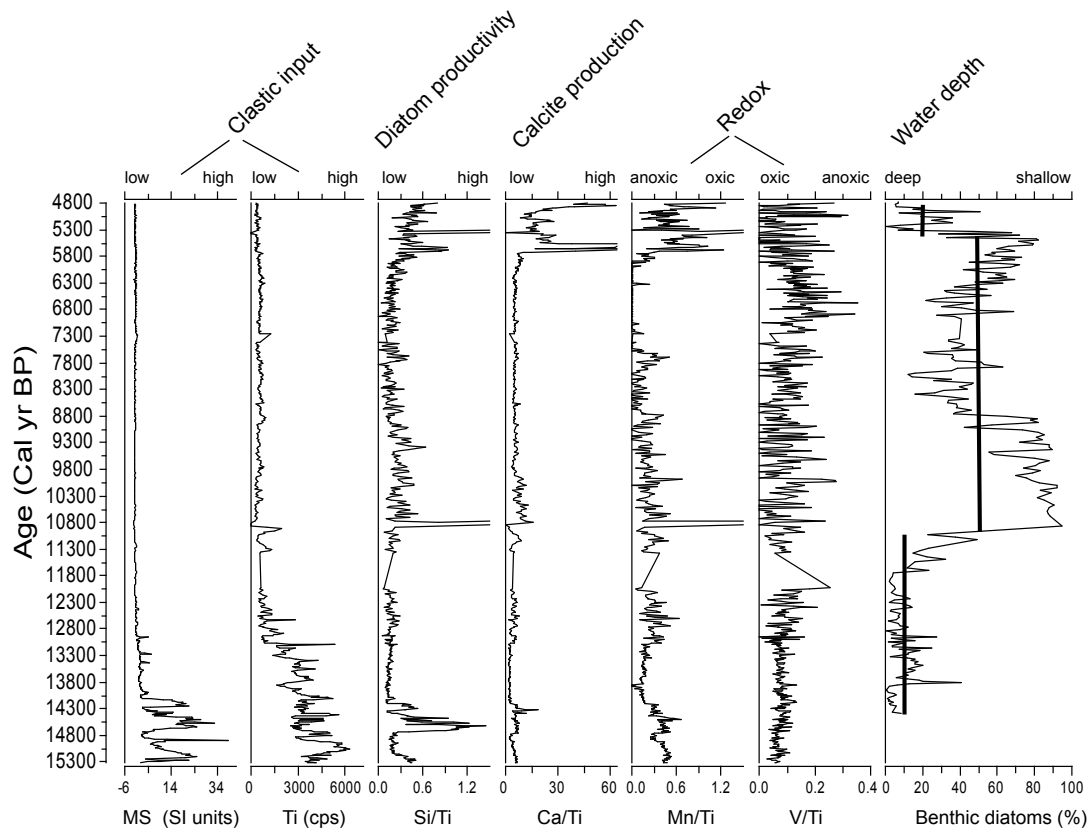


Figure 3.10 A summary diagram showing key environmental proxies for Hedrick Pond

From ~14.2-11.0 ka BP, magnetic susceptibility values decreased and were not as variable as in the previous period. Titanium and K, along with Si, Fe, V, Cr, Mn, and Ca, continued to decrease, suggesting that clastic input to the lake was decreasing during this period. The Ca/Ti values within this period were among the lowest of the entire record but showed a gradually increasing pattern, indicating that in-lake calcite production was low but slowly increased (Fig. 3.10). The diatom community was dominated by tychoplanktic *Fragilaria* species, which are indicative of intermediate water depth (Fig. 3.9; Lu et al., in prep.). Si/Ti values were low over this period, suggesting low diatom productivity. Low algal productivity is also suggested by the low Ca/Ti values.

The period of ~11.0-5.7 ka BP was characterized by low and stable values of magnetic susceptibility, Ti, K, and Si, indicating that minerogenic input to the lake was low. The Ca/Ti values increased significantly at ~11.0 ka BP and maintained stable values until ~5.7 ka BP, suggesting that calcite production was higher than the previous period. A shift in diatom community structure from the dominance of *Fragilaria* species to benthic species suggests low lake level (Fig. 3.10; Lu et al., in prep.). The Si/Ti values also were generally higher than the previous period, suggesting diatom productivity was enhanced. Thus, the enhanced calcite production over this period may be a result of lowered lake level as a result of increased evaporation and/or increased diatom productivity. Mn/Ti values, which were generally high and stable, decreased at ~7.3 ka BP, suggesting a decrease in oxygen levels. The increase of V/Ti, an indicator of anoxic conditions (Das et al., 2009), also supports this scenario of enhanced anoxia.

From ~5.7-4.8 ka BP, clastic input to the lake was further reduced, as indicated by the slightly decreased values of magnetic susceptibility, Ti, and K. The Si/Ti values increased at ~5.7 ka BP and continued to increase until the end of the analyzed sediments, indicating that diatom productivity was higher than the previous period. Ca/Ti increased at ~5.7 ka BP and maintained high but variable values thereafter. Therefore, high calcite production is indicated by high Ca/Ti values during the period of ~5.7-4.8 ka BP. Tychoplanktic *Fragilaria* species were entirely replaced by benthic species at ~5.7 ka BP, indicating a further lowering of lake level. Benthic species then decreased substantially in abundance at ~5.3 ka BP and were replaced by planktic species thereafter, which implies an increase in lake level. Mn/Ti dramatically increased, and V/Ti values decreased at ~5.7 ka BP, suggesting enhanced oxic water column, probably as a result of increased diatom productivity.

3.5.4 Cub Creek Pond

3.5.4.1 Correlation Matrix

Table 3.5 shows the correlation tables for Si, S, K, Ca, Ti, Mn, Fe, Rb, and Sr for the Cub Creek Pond sediment core, and the depth profiles of intensities for these elements are illustrated in Figure 3.11. Titanium and K, which are indicative of minerogenic input, have identical patterns and are highly correlated ($r=0.97$). Other elements, such as Si, Fe, and Rb, also have high correlations with Ti ($r=0.95$, 0.95 , and 0.94 , respectively), and they are highly correlated with each other with (r values ranging from 0.86 to 0.97), indicating that their behaviors are directly controlled by

clastic inputs. Manganese and Sr are related to Ti with slightly weaker correlations ($r=0.69$), suggesting that they are not solely influenced by terrestrial inputs. Calcium has weak correlations with Ti ($r=0.04$) and other erosion related elements, such as K, Si, Fe, and Rb ($r \leq 0.16$), but it is correlated with Mn and Sr ($r=0.62$ and 0.68 , respectively). This suggests that the Ca behavior is not influenced by clastic inputs, but rather by the factors that also influence Mn and Sr. The behavior of S is unique. It has weak negative correlations with Ti, K, Si, Fe, and Rb, with r values ranging from -0.56 to -0.36 .

3.5.4.2 Watershed and lake history

Figure 3.12 shows selected Ti normalized elemental ratios, sedimentary carbon and nitrogen contents, and diatom group data for Hedrick Pond, whereas Figure 3.13 illustrates the environmental proxies used for the interpretation of watershed and lake development. The Cub Creek sediment core reached to the basin bedrock. This section of the core is composed of coarse size sands and gravels and is characterized by high and unstable values of Ti, K, Si, Fe, Rb, and magnetic susceptibility (Fig. 3.11), suggesting that the landscape was unstable and erosion was high.

From ~ 14.6 - 14.0 ka BP was the early stage of lake formation. The core has high and steadily decreased values of Ti, K, Si, Fe, and Rb. Magnetic susceptibility values showed a similar decreasing trend. Therefore, terrestrial input to the lake was initially high and then steadily decreased during this period (Fig. 3.13). Ca/Ti and Mn/Ti values were low but showed a clear increasing trend. TOC and TN were

Table 3.5 Correlation matrix (r values) for the Cub Creek Pond sediment core.

	Si	S	K	Ca	Ti	Mn	Fe	Rb
S	-0.56							
K	0.96	-0.58						
Ca	0.13	0.16	0.16					
Ti	0.95	-0.56	0.97	0.04				
Mn	0.69	-0.15	0.71	0.62	0.69			
Fe	0.86	-0.36	0.91	0.05	0.95	0.72		
Rb	0.88	-0.55	0.93	0.03	0.94	0.66	0.90	
Sr	0.75	-0.36	0.79	0.68	0.69	0.81	0.62	0.68

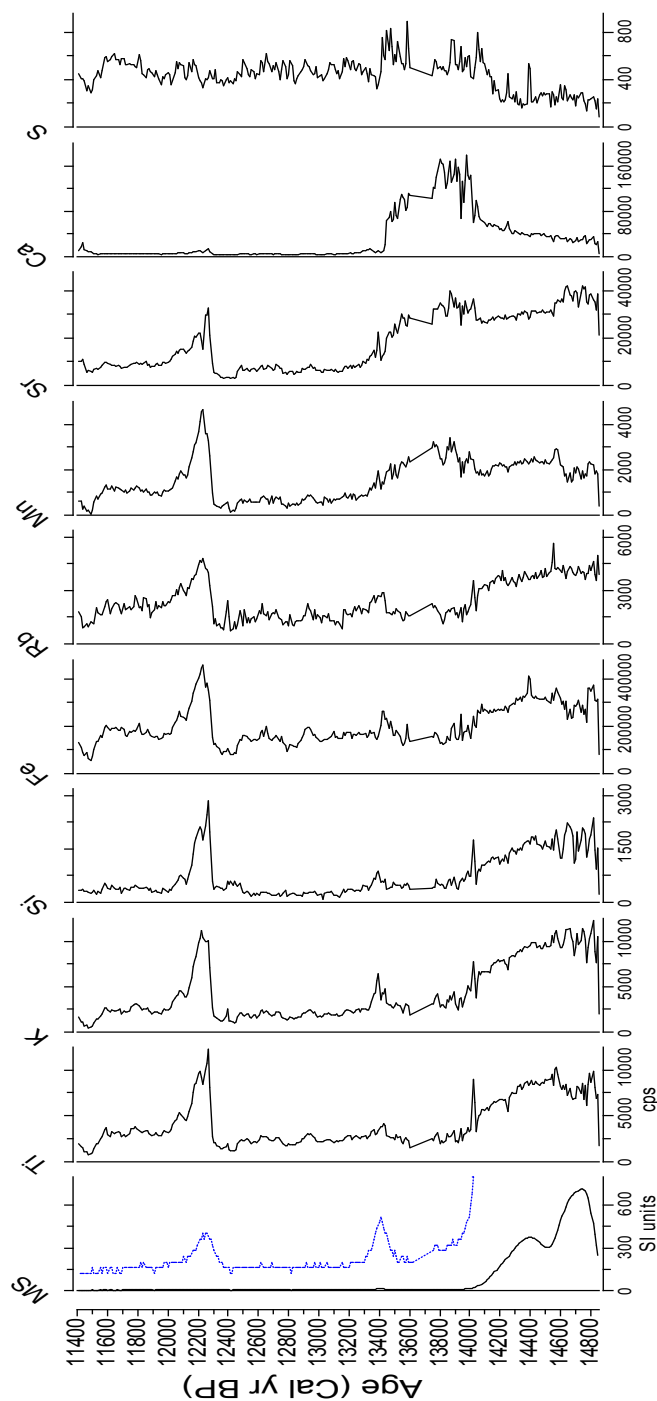


Figure 3.11 Magnetic susceptibility (MS) and selected elemental intensities (measured in “cps”) for Cub Creek Pond. Thin blue line denotes 40 times exaggeration for MS.

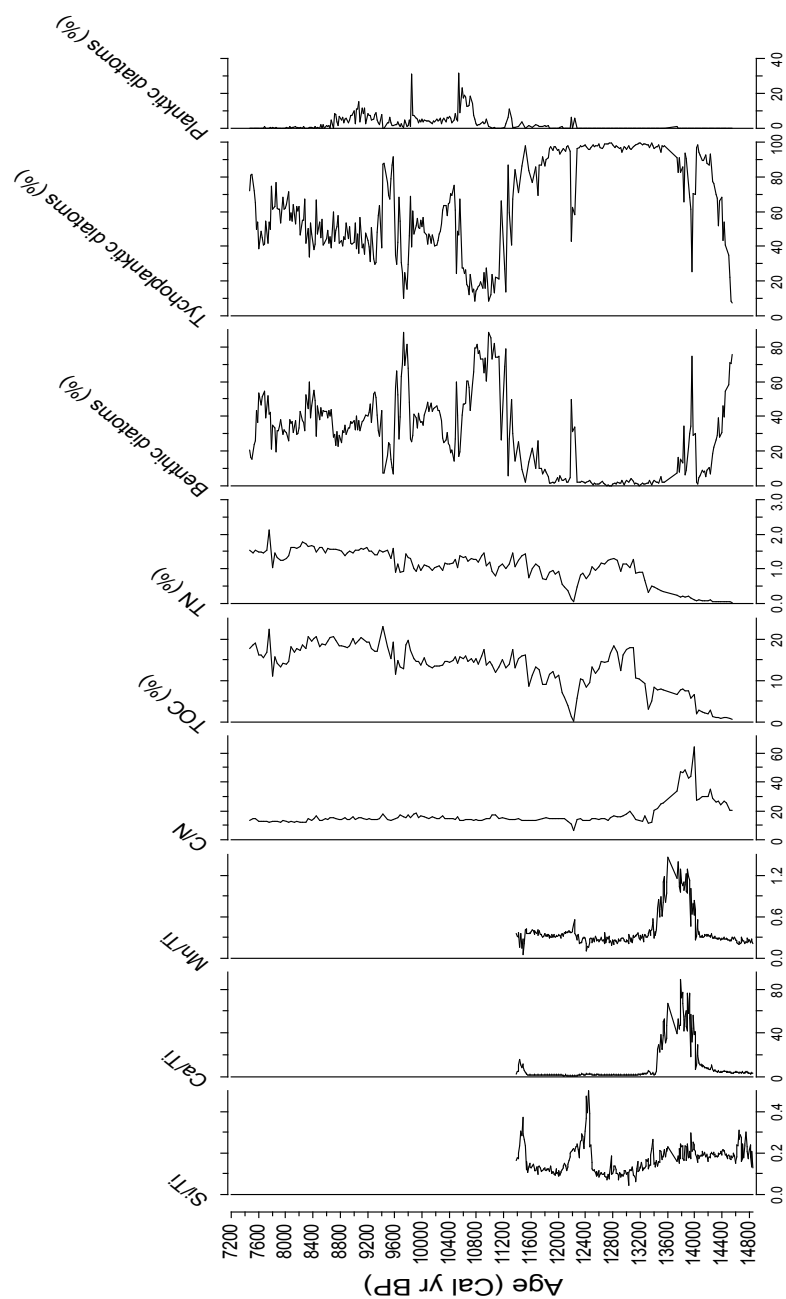


Figure 3.12 Selected elemental ratios, geochemical data, and diatom groups for Cub Creek Pond.

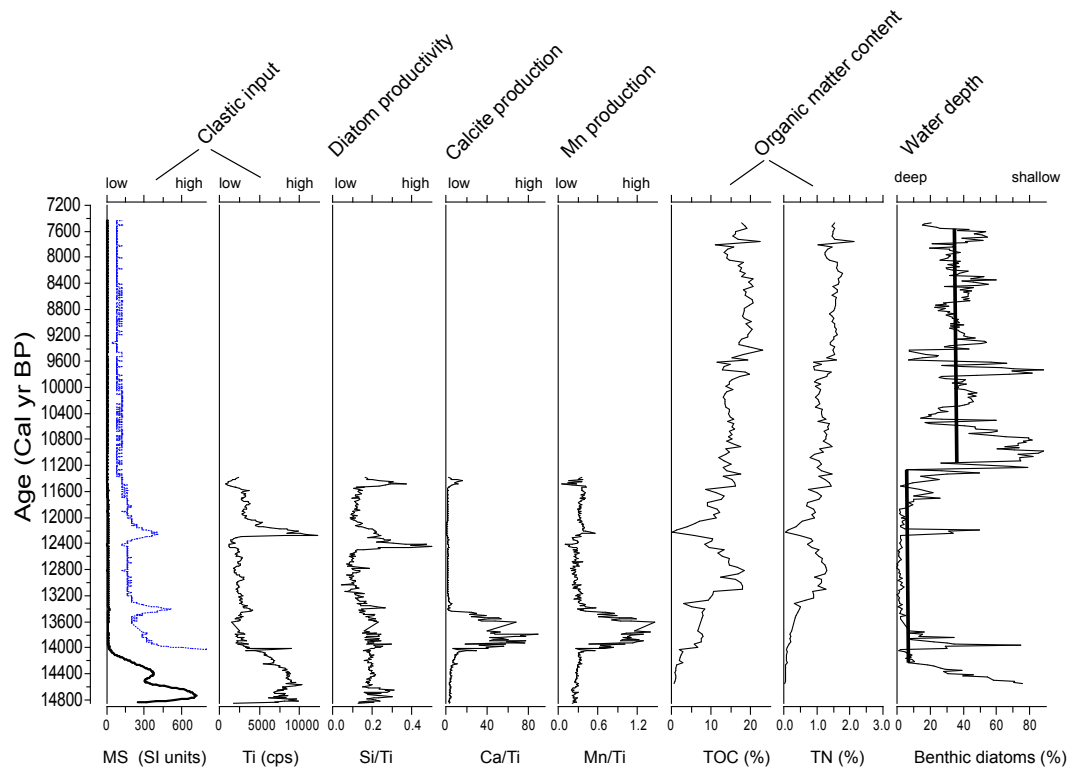


Figure 3.13 A summary diagram showing key environmental proxies for Cub Creek Pond.

among their lowest values but also gradually increased, but Si/Ti, which is indicative of diatom productivity, maintained low and stable values during this period. The values of C/N ranged from 17 to 30 (Fig. 3.12), suggesting that sediment organic matter had a mixed source of terrestrial plants and phytoplankton. The diatom flora developed during this period and was initially dominated by benthic species, which were subsequently replaced by tychoplanktic *Fragilaria* species (Fig. 3.12; Lu et al., in prep.), correlative with the decrease of clastic input to the lake.

The core section of ~14.0-13.5 ka BP was characterized by high values of Ca/Ti and Mn/Ti. Minerogenic inputs to the lake were stable but lower than the previous period, as indicated by low values of Ti, K, Si, Fe, Rb, and magnetic susceptibility. TOC and TN values were higher than the previous period and continued increasing. The C/N values were generally greater than 24, suggesting that sediment organic matter was contributed primarily by terrestrial plant input (Meyers et al., 2001). Diatom productivity, as indicated by Si/Ti, was stable. Diatom data show that benthic species increased substantially, corresponding to high Ca/Ti and Mn/Ti values, and then were replaced by tychoplanktic *Fragilaria* species, correlative with the decrease of Ca/Ti and Mn/Ti values. Therefore, lake level was generally lower than the previous period, leading to high precipitation of calcite and co-precipitation of Mn, as indicated by high values of Ca/Ti and Mn/Ti.

From ~13.5-11.4 ka BP, values of Ti, K, Si, Fe, Rb, and magnetic susceptibility were low and stable (except spikes in two ash layers centered at ~13.4 and ~12.2 ka BP), suggesting reduced clastic inputs probably as a result of stable landscape. The pollen record shows that the landscape surrounding Cub Creek Pond was vegetated

by trees, sagebrush, and grasses (Iglesias, unpublished data). Ca/Ti and Mn/Ti maintained stable and low values. Si/Ti also showed consistently low values. C/N values were generally stable around 15, except low values in the ash layers, suggesting that sediment organic matter came from both terrestrial plants and phytoplankton. TOC and TN values were among their highest in this core section, except in the ash layers, indicating enhanced organic matter concentrations. The diatom community was predominantly composed of tychoplanktic *Fragilaria* species, with short interval of benthic species dominance in ash layers. The *Fragilaria* dominance suggests an intermediate water depth, leading to low calcite production.

3.6 Synthesis of Regional Trends

High-resolution XRF analysis, along with carbon and nitrogen elemental data, in Yellowstone lake sediment cores provide insights into the watershed and lake history during the last deglaciation and early-Holocene in this region. Correlation tables illustrate common relationships among groups of elements that suggest common influences on elemental dynamics. In all cases, Ti, K, and Rb are closely correlated with each other, because they all have clastic sources from erosion of catchment minerals. Thus, the history of clastic input and catchment erosion were recorded in elemental intensity profiles of Ti, K, and Rb, together with magnetic susceptibility data. Calcium and Sr are always correlated in the data sets and are anti-correlated with the clastic elements, and are driven by in-lake carbonate production. Manganese behaves uniquely in Blacktail Pond and Dailey Lake, is

weakly correlated with clastic inputs in Cub Creek Pond, whereas in Hedrick Pond it is highly correlated with terrestrial inputs for most of the sediment core.

Overall, clastic inputs to these lakes were high and variable during the early stage of lake development, as ice retreated during the last deglaciation. At this time the surrounding landscape was still not vegetated or only had sparse vegetation, and therefore catchment erosion was high. This interval was associated with either a diatom flora characterized by pioneering species, or with very low diatom concentrations, likely due to low productivity associated with low light conditions and high minerogenic inputs. As the surrounding landscape was gradually vegetated and became stable, clastic inputs decreased. At Hedrick Pond in southern Yellowstone, high and variable minerogenic inputs decreased to relatively stable and low levels at ~14.2 ka BP. At Cub Creek Pond in central Yellowstone, clastic inputs reduced to low levels at ~14.0 ka BP. In northern Yellowstone at Blacktail Pond and further north at Dailey Lake, this occurred at ~13.9 and 13.4 ka BP, respectively. Thus, the timing of the reduced terrestrial input was not synchronous, but occurred later in northern Yellowstone than in central and southern part of the region.

In addition to catchment history, lake history also was investigated with the aid of diatom assemblage data, together with geochemical data that were interpreted in terms of sediment organic matter concentrations (TOC and TN) and source (C/N), calcite production (Ca/Ti), diatom productivity (Si/Ti), and redox conditions (Mn/Ti and V/Ti). On a large scale, organic matter concentration is negatively correlated with clastic inputs to lakes, probably because of dilution, with

low concentration during the early stage of lake development, when clastic inputs to lakes were high, and higher values as terrestrial inputs decreased. The source of sediment organic matter is always a mix of terrestrial plants and phytoplankton, except for the period of 14.0-13.7 ka BP at Cub Creek Pond.

Calcite production is triggered by different factors at the four sites, which vary in bedrock geology and basin morphology. At Blacktail Pond and Hedrick Pond, which are small and shallow lakes and are situated on calcareous glacial tills, calcite production is generally a result of lake-level change. Both sites had a substantial decrease in lake level at ~11.2-11.0 ka BP, triggering an increase of calcite production. At Dailey Lake, which also is situated on calcareous glacial tills but is large and deep, the change of calcite production was not evident at ~11.0 ka BP when lake level decreased. Instead the long-term calcite production is mainly a function of lake productivity. At Cub Creek Pond, which is small and shallow and is on rhyolitic soils, carbonates are almost absent in the sediment core, and calcite production, indicated by Ca/Ti, is mainly a result of lake-level change. The XRF record in Cub Creek Pond is not long enough to show the response of calcite production to the lake level decrease at ~11.3 ka BP in this lake, but the Ca/Ti values did show a trend of increase at the end of the record. In general, long-term calcite production seems to be a result of lake level change in small and shallow lakes and is more strongly influence by lake productivity in large and deep lakes. In addition, calcite production and Mn deposition are closely related in Blacktail Pond, Dailey Lake, and Cub Creek Pond, which have Ca intensities typically ranging from ~40,000-300,000 cps, but the correlation is weak in Hedrick Pond, whose Ca

normally changes from ~8,000-30,000 cps. Although the intensity of Ca measured by XRF is not a absolute measurement of sediment Ca content, it does allow a comparison between different sediment cores. Thus, it seems that in the greater Yellowstone region, Mn precipitation tends to be closely associated with calcite deposition at sites having relative high Ca intensities (carbonate content), as Mn is able to complex with carbonates, whereas at sites where Ca intensity is low, endogenic Mn deposition is influenced by changes in redox condition.

This study demonstrates that high-resolution elemental analysis is very useful in the exploration of watershed and lake history, particularly when other independent data are available to constrain the interpretation of elemental proxies.

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CHAPTER 4

PATTERNS OF TERRESTRIAL AND LIMNOLOGIC DEVELOPMENT DURING THE LATE-GLACIAL/EARLY-HOLOCENE TRANSITION INFERRED FROM MULTIPLE PROXY RECORDS FROM DAILEY LAKE, MONTANA, USA

4.1 Abstract

A high-resolution record of pollen, charcoal, diatom, geochemical, and lithologic data from Dailey Lake in southwestern Montana describes postglacial terrestrial and limnologic development from ice retreat ca. 16,000 cal yr BP through the early Holocene. Following deglaciation, the landscape surrounding Dailey Lake was sparsely vegetated, slopes were unstable, and loess deposition occurred. As summer insolation increased and ice recessional processes subsided, *Picea* parkland developed and diatoms established in the lake at 13,400 cal yr BP. Closed subalpine forests of *Picea*, *Abies*, and *Pinus* established at 12,200 cal yr BP followed by the development of open *Pinus* and *Pseudotsuga* forests at 10,200 cal yr BP. Increased planktic diatom abundance indicates a step-like warming at 13,100 cal yr BP, and alternations between planktic and tychoplanktic taxa suggest changes in lake thermal structure between 12,300 and 11,100 cal yr BP. An increasingly open forest, in combination with increased benthic diatoms, indicates warm dry summers during the early Holocene after 11,100 cal yr BP, in contrast to nearby records in northern Yellowstone that register prolonged summer-wet conditions until ca. 8000 cal yr BP. Because of its low elevation, Dailey Lake was apparently sensitive to the direct effects of increased summer insolation on temperature and effective moisture, registering dry summers. In contrast, higher elevations in northern Yellowstone responded to the indirect effects of an amplified seasonal insolation cycle on atmospheric circulation, including increased winter snowpack and/or enhanced monsoonal circulation.

Keywords: late-glacial, early Holocene, pollen, diatoms, inorganic geochemistry, Yellowstone

4.2 Introduction

The period from 20,000 to 8000 cal yr BP was a time of rapid environmental change in the western US as the region shifted from full-glacial conditions to the summer insolation maximum of the early Holocene. In the northern Rocky Mountains, glaciers receded from their maximum position by ca. 17,000 cal yr BP and were largely gone by 14,000 cal yr BP (Licciardi et al., 2004; Pierce, 2004; Licciardi and Pierce, 2008; Thackray, 2008). The freshly exposed landscapes created by ice recession afforded new habitats for plants and animals to colonize and set in motion a series of time-dependent changes in local-scale processes, including soil, vegetation, and limnological development.

Although the record of postglacial colonization is clear from paleoecological data throughout the northern Rocky Mountains (e.g., Whitlock, 1993; Brunelle et al., 2005; Power et al., 2011), the relative trade-off between climate and local-scale controls in shaping the sequence of biotic development during the late-glacial/early-Holocene transition is poorly understood. Large-scale climatic variability is clearly the primary driver of postglacial ecosystem change at broad temporal and spatial scales; however, substrate, local topography, and species life-history traits become increasingly important at finer scales (e.g., Brubaker, 1975; Millspaugh et al., 2000; Oswald et al., 2003; Briles et al., 2011). Furthermore, modern studies have highlighted strong linkages between limnologic development and trajectories of soil and vegetation development in newly deglaciated catchments (Engstrom et al.,

2000; Engstrom and Fritz, 2006), but few paleoecological sites compare terrestrial and aquatic responses in the past to understand how well these linkages were expressed in the early stages of postglacial landscape development (but see Birks et al., 2000).

This paper examines early postglacial ecosystem development in the Greater Yellowstone region during the period from ca. 16,000 to ca. 7000 cal yr BP based on pollen, charcoal, diatom, geochemical, and lithologic data from Dailey Lake, MT (45.262° N, 110.815° W; 1598 m elev, 82 ha). Dailey Lake is a low-elevation site located 23 km up-valley of the terminal moraine of the northern Yellowstone outlet glacier and thus provides one of the earliest records of postglacial environmental change in the region. Our objectives in this paper are to: (1) describe the sequence of terrestrial and limnologic changes that occurred between the time of ice retreat to the early Holocene insolation maximum; (2) identify linkages between vegetation and limnobiologic development to assess the dominant climatic and nonclimatic drivers of ecosystem development; and (3) compare the Dailey Lake reconstruction with other paleoecological records to better understand postglacial vegetation and climate dynamics in the northern Yellowstone region.

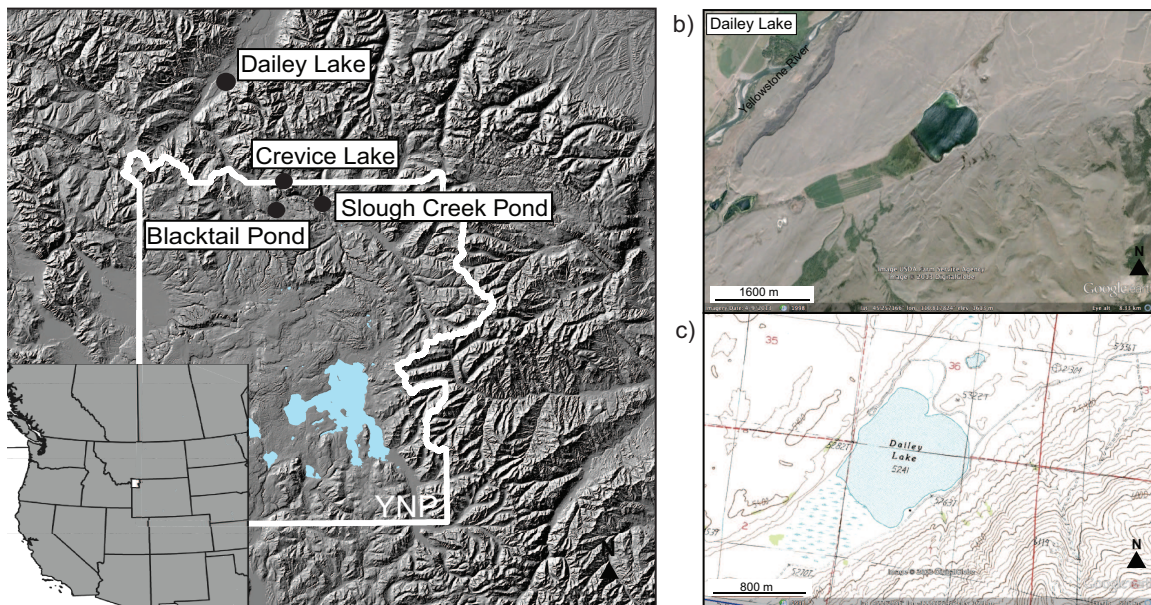


Figure 4.1 Location of Dailey Lake. a) Location of northern Yellowstone sites discussed in text. b) Aerial image of Dailey Lake. c) Topographic map of Dailey Lake. Contour interval 20 feet.

4.2.1 Modern Setting

Dailey Lake occupies a shallow trench on a low bench carved by the late-Pleistocene northern Yellowstone outlet glacier. The semi-closed basin lies on a bench 85 m above the Yellowstone River in the Paradise Valley of southwestern Montana, and the lake discharges periodically through a low-gradient outlet (0.3 m/500 m) into a 500 m² wetland to the north (Fig. 4.1). Present-day vegetation patterns in northern Yellowstone are strongly influenced by elevation (Despain, 1990). Dailey Lake is located 100 m below lower treeline (1700 m elevation), and the surrounding vegetation is primarily grassland and steppe dominated by *Artemisia tridentata* (big sagebrush), *Ericameria nauseosa* (rabbitbrush), *Festuca idahoensis* (Idaho fescue), and *Leymus cinereus* (Great Basin wild rye), with isolated populations of *Juniperus scopulorum* (Rocky Mountain juniper). *Salix* (willow spp.), *Carex* (sedge), and *Typha latifolia* (cattail) are present along the lake margin and in the adjacent wetland. Montane and subalpine forests grow on nearby mountain slopes: *Pinus flexilis* (limber pine) is most abundant between 1700 and 1900 m elevation; *Pseudotsuga menziesii* (Douglas-fir) and *Pinus contorta* (lodgepole pine) grow between 1900 to 2400 m elevation and are replaced by *Picea engelmannii* (Engelmann spruce), *Abies lasiocarpa* (subalpine fir), and *Pinus albicaulis* (whitebark pine) above 2400 m elevation. Alpine tundra occurs above 2900 m elevation.

At present, northern Yellowstone receives the majority of its precipitation during the summer months from convective storms and monsoonal circulation from the Gulf of Mexico and the subtropical Pacific Ocean (Mock, 1996). Winter

precipitation in the region is the result of westerly storm tracks from the Pacific Ocean. Available climate information for Dailey Lake comes from NOAA coop station Livingston 12S, located 31 km northeast of Dailey Lake in northern Paradise Valley. During the period from 1951 through 2012, January temperatures averaged -2.7°C , and July temperatures averaged 19.1°C . Mean annual precipitation was 41 cm, and May and June were the wettest months, 6.7 and 6.9 cm, respectively (<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mt5080>). The high summer/winter precipitation ratio (JJA/DJF=3.29) classifies the lake as a summer-wet site (*sensu* Whitlock and Bartlein, 1993), as a result of low winter precipitation (January average = 1.6 cm) and frequent summer convective storms (July average = 3.9 cm).

Dailey Lake is presently warmer and effectively drier than other parts of the northern Yellowstone region, because of its low elevation and location in precipitation shadows of the Gallatin Range and Yellowstone Plateau. This orographic effect particularly impacts westerly storm tracks during the winter months, and Dailey Lake receives approximately 165 cm of winter snowfall (<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mt5080>) compared with similar lower forest settings at higher elevations in northern Yellowstone that receive between 190-250 cm (<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wy9905>; <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wy9025>).

4.3 Methods

4.3.1 *Field*

A 14.40-m long sediment core was collected from the ice surface at Dailey Lake in February 2009 using a Livingstone square-rod piston sampler (Wright Jr. et al., 1983). Core segments were extruded in the field and wrapped in plastic and aluminum foil and transported back to the Montana State University Paleoecology Lab and refrigerated.

4.3.2 *Chronology*

Plant macrofossils, charcoal, and pollen concentrates were submitted for AMS radiocarbon dating. Pollen concentrates for dating were obtained from the pollen residue remaining after standard pollen preparation procedures (Bennett and Willis, 2001), except no alcohols were used in processing and a Schulze procedure was substituted for acetolysis to oxidize organics (Doher, 1980).

4.3.3 *Lithology and geochemical analysis*

Initial core descriptions were performed at the LacCore facility, University of Minnesota-Twin Cities. Cores were split, imaged, and magnetic susceptibility was measured at contiguous 0.5-cm intervals using a Geotek XYZ MSCL logger to record changes in mineral clastic sedimentation (Gedye et al., 2000). Measurements were reported in SI units. Geochemical elemental analysis of the cores was conducted at the Large Lakes Observatory, University of Minnesota-Duluth. Split cores were run through an ITRAX XRF scanner at contiguous 0.5-cm intervals. Here, we focus on

the calcium/titanium (Ca/Ti) and potassium/titanium (K/Ti) ratios derived from the XRF analysis.

The Ca/Ti record is interpreted as a measure of calcite production in the lake system through time. Calcite production is a proxy of lake productivity, in that calcite precipitation is triggered by algal photosynthesis during the summer months (Dean and Megard, 1993) and is thus related to high summer insolation and elevated air temperatures (Meyers and Ishiwatari, 1993). Ti is a clastic sediment indicator in our record, because it is only produced allogenically through the physical erosion of Ti-bearing rocks (Cohen, 2003), and minerals containing Ti are not sensitive to dissolution (Demory et al., 2005). The Ca/Ti ratio corrects the influence of clastic Ca on the Ca geochemical record, which varies with clastic Ti in the lake sediments.

The K/Ti record provides information on the delivery of freshly eroded clastic material to the lake (Muhs et al., 2001), where low K/Ti ratios indicate input of highly altered material, and high K/Ti ratios indicate the accumulation of freshly eroded sediments (Mischke et al., 2010). Loss of soluble elements, in this case K, relative to an insoluble element, Ti, is typical of highly weathered sediments (Muhs et al., 2001), and low K/Ti ratios could suggest loess deposition into the lake.

The magnetic susceptibility and K/Ti records serve as proxies of landscape stability. In this paper, landscape stability refers to the degree of erosion occurring in the Dailey Lake catchment as a result of ice-recessional processes, such as solifluction and surface run-off, poor soil development, and eolian activity. The combination of high magnetic susceptibility and low K/Ti ratios is hypothesized to

reflect sediment input into the lake system both from increased slopewash and from wind-derived sources. Landscape stabilization occurs when erosional and eolian activity subsides and soils develop, as indicated by decreased magnetic susceptibility and increased K/Ti ratios.

4.3.4 Pollen analysis

Samples of 1 cm³ were taken at 2 to 8 cm intervals and prepared using pollen methods described by Bennett and Willis (2001), except a brief Schulze treatment was substituted for acetolysis to oxidize organics (Doher, 1980). A *Lycopodium* tracer was added to the samples to calculate pollen concentration (grains cm⁻³) and pollen accumulation rates (PAR; grains cm⁻² yr⁻¹). Pollen grains were identified at magnifications of 400x and 1000x, and 200 to 400 terrestrial pollen grains were counted per sample. Identifications were made to the lowest taxonomic level possible using reference collections and atlases (e.g., Moore and Webb, 1978; Kapp et al., 2000). *Pinus* grains with intact distal membranes were distinguished between diploxylon-type and haploxylon-type. Based on phytogeography, diploxylon-type *Pinus* pollen is attributed to *P. contorta* and haploxylon-type *Pinus* pollen as either *P. albicaulis* or *P. flexilis*. *Pinus* grains missing a distal membrane were identified as “undifferentiated *Pinus*”. Pollen grains that could not be identified using available reference material were classified as “unknown”, while degraded or hidden pollen grains were classified as “indeterminate”.

Pollen percentages, ratios, and accumulation rates were used to reconstruct the vegetation history. Reconstructions were aided by comparisons to modern

pollen assemblages from surface samples in the Greater Yellowstone region (Baker, 1976; Whitlock, 1993; Fall, 1994) and from surface samples collected from Dailey Lake (Table 4.1). Percentages were calculated based on the total pollen sum of terrestrial taxa, including pteridophytes, unknown, and indeterminate grains. The pollen-percentage record was divided into zones based on constrained cluster analysis (CONISS; Grimm, 1988) and visual inspection.

Dailey Lake's position below present-day lower treeline enabled us to examine lower treeline dynamics relative to present-day. Comparison of the modern pollen rain at Dailey Lake, specifically the arboreal to nonarboreal pollen ratios (AP/NAP), to its fossil assemblages was used to infer the relative position of lower treeline and/or changes in forest density. At present, the AP/NAP ratio is 2.23, which lies within the range of modern surface samples from below treeline at other sites in the region (1.23-2.79; Whitlock, 1993; Millspaugh et al., 2000; Mumma et al., 2012). In general, the lower forest/steppe boundary in the Rocky Mountains is controlled by effective moisture (precipitation – evaporation) (Thompson et al., 1999). Higher AP/NAP values compared to modern values are evidence of a downward shift in lower treeline and/or of increased forest density in its existing position. In either case, the data imply an increase in effective moisture. Lower AP/NAP values than at present suggest an upward expansion of steppe and grassland and/or an opening of the forest and thus effectively drier conditions.

Table 4.1 Modern pollen rain from Dailey Lake.

Pollen Taxa	Relative Abundance
<u>Trees</u>	
Total <i>Pinus</i>	59%
<i>Pinus albicaulis/flexilis</i> -type	5%
<i>Pinus contorta</i> -type	7%
<i>Picea</i>	3%
<i>Abies</i>	2%
<i>Juniperus</i> -type	4%
<i>Pseudotsuga</i>	1%
<u>Shrubs and Herbs</u>	
<i>Alnus</i>	2%
<i>Salix</i>	2%
<i>Sarcobatus</i>	1%
<i>Betula</i>	1%
Rosaceae-type	1%
<i>Artemisia</i>	12%
Poaceae	7%
<i>Ambrosia</i> -type	1%

4.3.5 Charcoal analysis

Charcoal particles $>125\ \mu\text{m}$ were extracted at 2-cm intervals, 2 cm^3 volume samples at Dailey Lake using standard sieving methods (Whitlock and Larsen, 2001). Large charcoal particles $>125\ \mu\text{m}$ provide a record of high-severity fires within a few kilometers of the site (Higuera et al., 2010). Analysis focused on long-term trends in charcoal accumulation rates (CHAR; particles $\text{cm}^{-2}\ \text{yr}^{-1}$) rather than the frequency of fire episodes, inasmuch the charcoal sampling interval was not contiguous and individual fire events may not have been detected. CHAR was calculated using CharAnalysis software (Higuera et al., 2008). Charcoal concentrations and deposition times were interpolated into contiguous bins based on the median resolution of the record (19 years), and CHAR was calculated by dividing resampled concentrations (particles cm^{-3}) by resampled deposition times (yr cm^{-1}). The long-term trends (background CHAR=BCHAR) were calculated by smoothing the CHAR time series with a 500-year lowess smoother, robust to outliers. BCHAR reflects levels of arboreal fuel biomass, which is related to the amount of forest cover as well as the size and severity of fires that produce charcoal (Marlon et al., 2006).

4.3.6 Diatoms

Diatom samples were taken at 0.5 to 5 cm intervals and treated with cold hydrochloric acid and hydrogen peroxide to digest the carbonate and organic material, respectively. Samples were then rinsed four times and dried onto coverslips and mounted onto slides with a permanent mounting media (Battarbee,

1986). At least 300 diatom valves were counted on each slide, and diatom data are shown as relative abundance. Diatom zones were identified using constrained cluster analysis (CONISS; Grimm, 1988), using all species identified at any point in the record.

4.4 Results

4.4.1 Chronology

The Dailey Lake chronology is based on nine AMS ^{14}C dates and the accepted age of the Mazama Ash (Table 4.2; Fig. 4.2). Due to the lack of dateable material near the base of the sediment core, the age of the Chico recessional moraines (16.1 ± 1.7 ^{10}Be ka, assumed 16,100 cal yr BP; Licciardi and Pierce, 2008) located 10 km down-valley from Dailey Lake was used as the core's basal maximum age. No substantial moraines or outwash are noted between Dailey Lake and the Chico moraines, implying rapid ice recession. As a minimum age, the Deckard Flats moraines 20 km up-valley of Dailey Lake are dated as 14.2 ± 1.2 ^{10}Be ka (assumed 14,200 cal yr BP; Licciardi and Pierce, 2008). The use of the 16.1 ^{10}Be ka maximum age or the 14.2 ^{10}Be ka minimum age does not change the paleoecological interpretation. Two radiocarbon age determinations at 955.25 cm and 1020.0 cm depth in the Dailey Lake core were out of chronological order, and the error associated with an age determination at 1023.25 cm depth was considered anomalously high; these three dates were not included in the age model. Age determinations at 585.0, 604.5 and 663.0 cm depth were not significantly different from one another. The interval between 570.0 and 705.0 cm depth is associated

Table 4.2 Uncalibrated and calibrated ^{14}C ages for Dailey Lake.

Depth (cm) ^a	Uncalibrated ^{14}C age (^{14}C yr BP)	Calibrated age (cal yr BP) with 2 sigma range ^b	Material dated	Lab number/reference ^c
100.00	1740 \pm 25	1652 (1569-1710)	pollen	OS-98610
200.00	3550 \pm 25	3848 (3724-3910)	pollen	OS-98617
300.00	5080 \pm 35	5816 (5745-5910)	pollen	OS-98618
446.00	6730 \pm 40	7597 (7513-7667)	Mazama ash	Zdanowicz et al., 1999
509.25	8140 \pm 35	9074 (9004-9245)	pollen	OS-88594
585.00	9260 \pm 40	rejected	pollen	OS-95045
604.50	9120 \pm 50	rejected	pollen	Beta-330381
663.00	9130 \pm 35	10269 (10225-10399)	pollen	OS-88481
809.25	9630 \pm 40	10950 (10784-11178)	pollen	OS-88480
955.25	9660 \pm 45	rejected	<i>Carex</i> leaf	OS-76183
972.50	10750 \pm 50	12646 (12560-12765)	pollen	OS-95044
988.50	11100 \pm 45	12994 (12775-13127)	pollen	OS-95077
1005.00	11250 \pm 40	13161 (12979-13294)	pollen	OS-90974
1020.00	15550 \pm 75	rejected	pollen	OS-91010
1023.25	12000 \pm 510	rejected	charcoal	OS-87766
1441.0	na	16100	Chico Recessional Moraine	Licciardi and Pierce, 2008

^a Depth below mud surface^b Calibrated ages derived from CALIB 6.0. Two sigma range is given in parentheses.^c OS-National Ocean Sciences AMS Facility; Beta-Beta Analytic

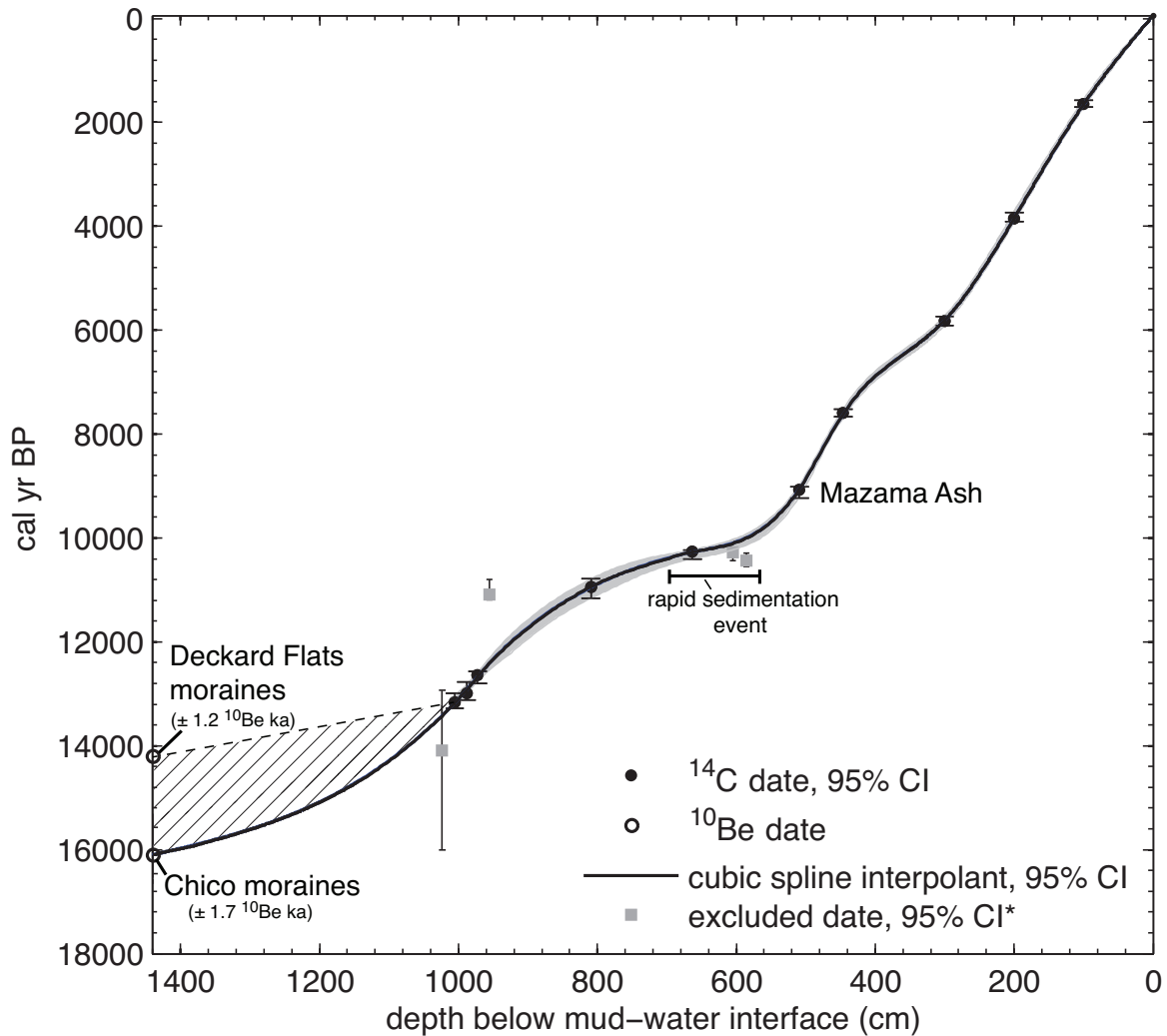


Figure 4.2 Age-depth model for Dailey Lake. Gray shading represents range of dates and black line indicates the 50th (i.e. median age) percentile of 1000 runs. The 50th (circle), 2.5th and 97.5th (bars) percentiles of the probability distribution function of calibrated dates are shown. Hatched shading represents ranges of ages constrained by minimum- (Deckard Flats) and maximum- (Chico) timing of glacial retreat at Dailey Lake based on ^{10}Be cosmogenic dating of recessional moraines (Licciardi and Pierce, 2008). See Table 2 for age determinations.

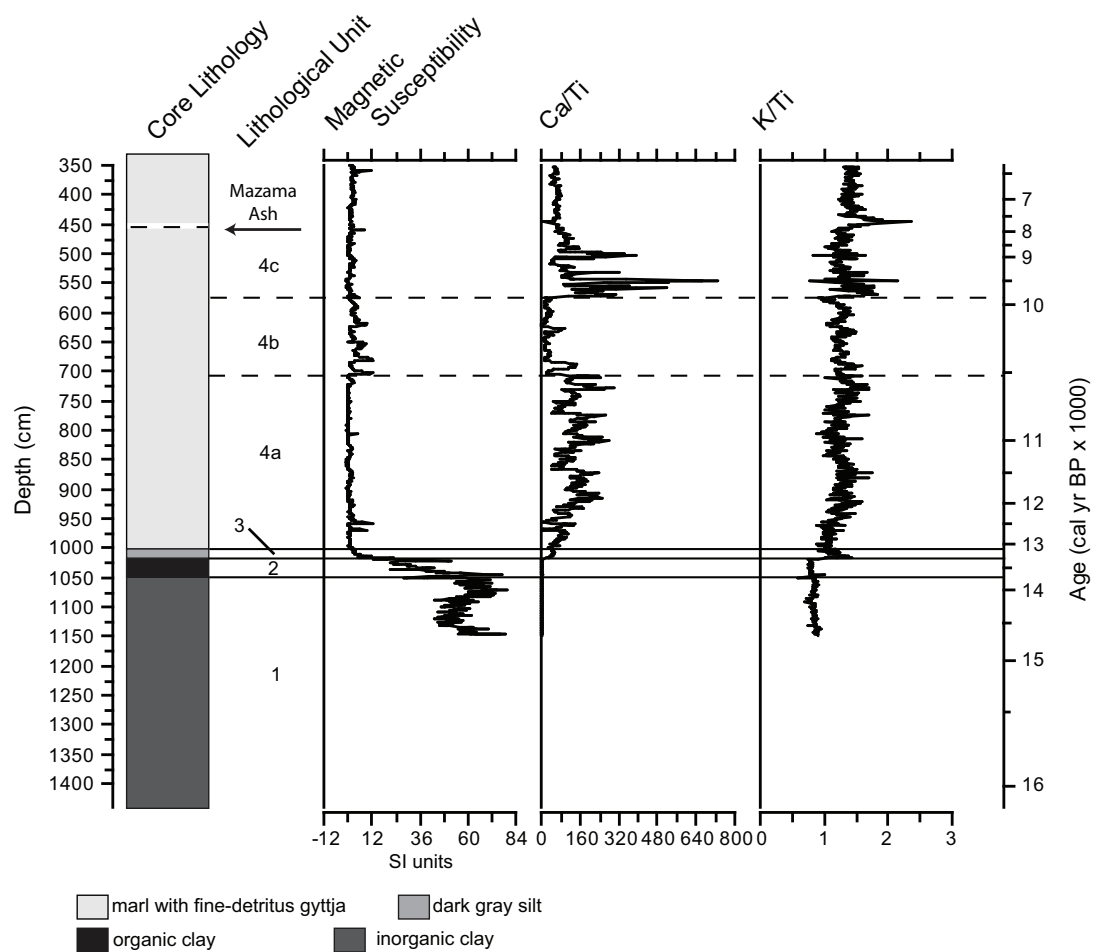


Figure 4.3 Lithologic and geochemical data from Dailey Lake.

with elevated magnetic susceptibility and decreased Ca/Ti, suggesting high sedimentation rates of allochthonous material. Given the likelihood that this is a very rapid sedimentation event, only the age determination at 663.0 cm depth was utilized in the chronology, and the age determinations at 604.5 and 585.0 cm depth were removed to eliminate error associated with any re-suspension of sediments.

The ^{14}C dates were converted to calendar ages using CALIB 6.0 (Reimer et al., 2009; Stuiver et al., 2010). The age-depth model was constructed with MCAgeDepth software (Higuera et al., 2008). This software applies a weighted cubic smoothing spline and calculates confidence intervals with a Monte Carlo approach that allows each date to influence the age model through the probability density function of the calibrated age (two sigma error; Higuera et al., 2008; Stuiver et al., 2010).

4.4.2 Lithology and geochemical analysis

The core lithology for the period of interest consisted of four units between 14.40 and 3.50 m depth (16,100-6370 cal yr BP; Fig. 4.3). Unit 1 (14.40-10.48 m depth; 16,100-13,720 cal yr BP) was glacial inorganic clay and featured the highest magnetic susceptibility (13.4-79.6 SI units; average = 57.0), indicating considerable mineral clastic input. Ca/Ti ratios (1.14-3.46; average = 1.40) and K/Ti (0.60-0.97; average = 0.84) were low in this unit, implying very little calcite production and deposition of highly altered sediments, most likely in the form of loess. Unit 2 (10.48-10.18 m depth; 13,720-13,350 cal yr BP) was composed of organic clay with decreasing magnetic susceptibility (12.9-76.8 SI units; average = 37.2) and somewhat elevated Ca/Ti (0.99-8.05; average = 1.46) and K/Ti ratios (0.74-1.00;

average = 0.79). Unit 3 (10.18-10.06 m depth; 13,350-13,180 cal yr BP) was a relatively thin layer of dark gray silt. Magnetic susceptibility decreased through this unit (2.5-23.0 SI units; average = 7.2), while Ca/Ti (6.60-56.59; average = 40.50) and K/Ti ratios (0.90-1.45; average=1.18) increased. Apparently, mineral clastic input was low at this time, and calcite production and accumulation of freshly eroded sediments in the lake basin increased. Unit 4 (10.06-3.50 m depth; 13,180-6370) was marly fine-detritus gyttja and was divided into three subunits based on changes in magnetic susceptibility and Ca/Ti ratios. K/Ti ratios were relatively stable over this period (0.82-2.15; average = 1.29). Unit 4a (10.06-7.00 m depth; 13,180-10,390 cal yr BP) had low magnetic susceptibility (-0.6-12.9 SI units; average = 0.8) and high Ca/Ti ratios (3.61-303.74; average = 121.90). Magnetic susceptibility increased (-0.1-12.7 SI units; average = 3.6) in Unit 4b (7.00-5.70 m depth; 10,390-9880 cal yr BP), while Ca/Ti ratios decreased (1.02-310.52; average = 39.0), which implies increased mineral clastic input and decreased calcite precipitation, respectively, coincident with a period of elevated sedimentation rates indicated by the age-depth model (Fig. 4.2). Unit 4c (5.70-3.50 m depth; 9880-6370 cal yr BP) features a return to low magnetic susceptibility (-1.1-11.4 SI units; average = 1.5) and high Ca/Ti ratios (12.33-732.22; average = 106.34).

4.4.3 Pollen and charcoal record

The pollen record at Dailey Lake was divided into four zones between 14,100 and 7500 cal yr BP (Fig. 4.4). Zone DLY-P1 (10.82-10.22 m depth; 14,100-13,400 cal yr BP) was characterized by very low pollen accumulation rates (100-1300 grains

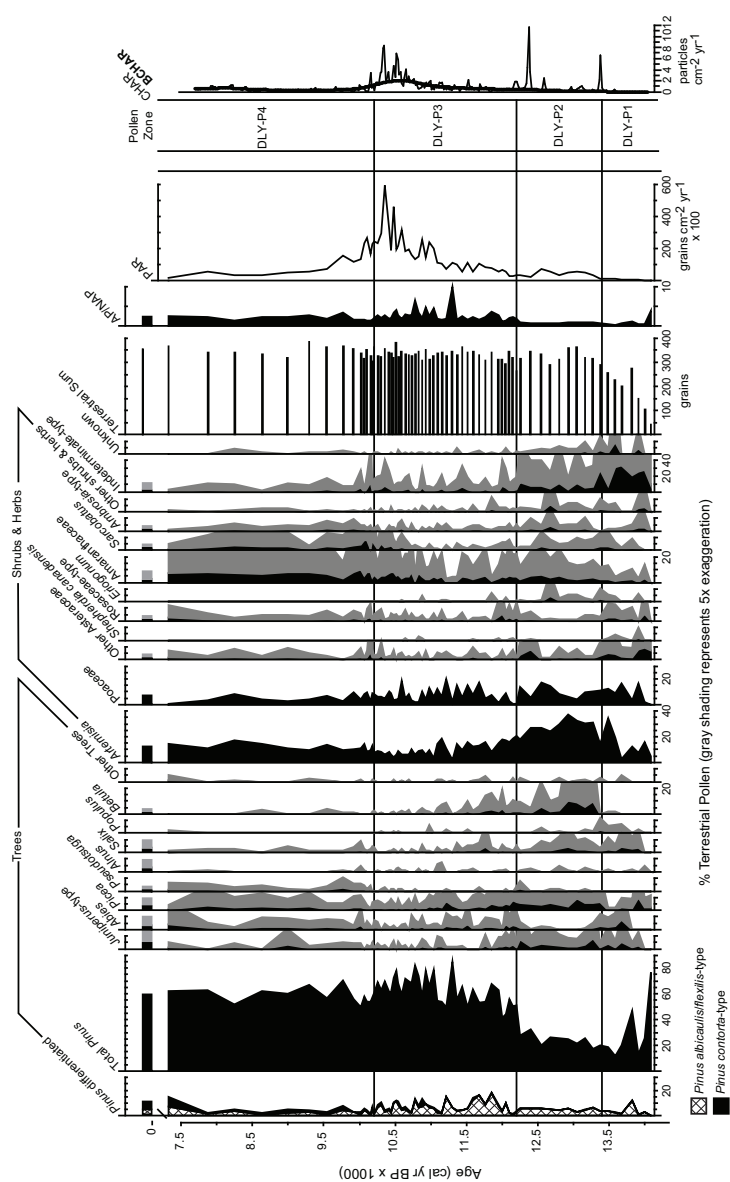


Figure 4.4 Charcoal and pollen data for selected taxa from Dailey Lake.

cm⁻² yr⁻¹), and high levels of indeterminate pollen grains (8-34%) suggest subaerial exposure prior to deposition. Taxa included early successional shrubs and forbs, including *Shepherdia canadensis* (<2%), *Juniperus*-type (<5%), Rosaceae-type (<6%), and Asteraceae (<10%). *Pinus* (12-77%) levels were high but likely originated from distant source populations and were artificially elevated due to low pollen counts early in the record. Significant levels of *Abies* (<7%) were present at 13,700 cal yr BP. BCHAR values were extremely low (average = 0.02 particles cm⁻² yr⁻¹).

Pollen zone DLY-P2 (10.22-9.40 m depth; 13,400-12,200 cal yr BP) featured high levels of *Artemisia* (14-37%) and *Picea* (3-9%). In addition, levels of *Betula* (<10%), *Juniperus*-type (1-8%), *Salix* (<4%), and Poaceae (1-17%) were high, while *Pinus* (17-51%), *Abies* (<3%), *Shepherdia canadensis* (<1%), and forbs such as Asteraceae (<8%) were moderate. Indeterminate-type grains (4-28%) decreased over DLY-P1, and average AP/NAP (0.81) was much lower than at present (2.23). PARs increased during this period (1300-7100 grains cm⁻² yr⁻¹), as did BCHAR (average = 0.31 particles cm⁻² yr⁻¹).

Pinus levels (41-85%) were at their highest of the record in pollen zone DLY-P3 (9.40-6.36 m depth; 12,200-10,200 cal yr BP). The majority of *Pinus* grains were attributed to *P. albicaulis*-type (1-18%) versus *P. contorta*-type (<6%). *Abies* (<4%) increased while *Picea* (<1-8%) and *Juniperus*-type (<3%) levels decreased. The majority of shrub and herb taxa decreased, including *Artemisia* (2-19%), *Betula* (<4%), Asteraceae (<3%), and *Ambrosia*-type (<3%). *Alnus* (<1%), *Salix* (<4%), and Poaceae (1-20%) remained relatively unchanged, while Rosaceae-type (<6%) was

elevated over the previous period, and *Sarcobatus* levels (<5%) increased towards the end of the zone. Average AP/NAP was slightly higher (2.74) than today (2.23). Indeterminate-type grains (1-8%) continued to decrease, and PARs were at their highest of the record (2800-59,100 grains cm⁻² yr⁻¹), as was BCHAR (average = 1.14 particles cm⁻² yr⁻¹). It is important to note that these values may be artificially elevated due high sedimentation rates near 10,400 cal yr BP.

Pinus pollen (49-70%) slightly decreased in pollen zone DLY-P4 (6.36-4.40 m depth; 10,200-7500 cal yr BP), while *Pseudotsuga* levels (<2%) increased. Other conifers such as *Picea* (<4%), *Abies* (<3%), *Juniperus*-type (<3%), and *P. contorta*-type (<4%) were unchanged in the record, while *P. albicaulis*-type decreased (1-5%). Riparian obligates like *Salix* (<2%), *Betula* (<1%), and *Alnus* (<1%) decreased, while levels of xerophytic shrub taxa, such as *Artemisia* (8-18%) and *Sarcobatus* (1-8%), were elevated. Average AP/NAP was lower (1.90) than at present (2.23). PARs decreased during this period (3500-26,600 grains cm⁻² yr⁻¹), as did BCHAR values (average = 0.52 particles cm⁻² yr⁻¹).

4.4.4 Diatoms

The diatom record at Dailey Lake was divided into four zones between 13,350 and 10,350 cal yr BP (Fig. 4.5). Diatoms were absent in older and younger sediments. Diatom zone DLY-D1 (10.18-10.03 m depth; 13,350-13,140 cal yr BP) was characterized by the dominance of pioneering benthic taxa, including *Achnanthes rosenstockii* (1-5%), *Achnanthes zieglerei* (<5%), *Amphora pediculus* (6-22%), *Amphora thumensis* (5-12%), and *Navicula diluviana* (17-29%), as well as by

relatively high percentages of the planktic species *Aulacoseira ambigua* (<1-16%). Colonial *Fragilaria* species (*F. brevistriata*, *F. pinnata*, *F. construens* var. *venter*, and *F. cf. tenera*) were also present in relatively high abundance (20-40%) within the zone.

An increase in the abundance of planktic taxa, such as *Cyclotella* *michiganiana*, *C. rossii*, *C. ocellata*, *C. radiosa*, (combined abundance of 5-46%) and *Stephanodiscus niagarae* (1-11%), marked the transition to diatom zone DLY-D2 (10.03 m-9.48 m depth; 13,140-12,300 cal yr BP). This increase coincided with a decline in the abundances of pioneering benthic species, including *Achnanthes* (1-13%), *Amphora* (2-23%) and *Navicula* (4-25%).

Diatom zone DLY-D3 was divided into two subzones. Zone DLY-D3a (9.48-9.08 m depth; 12,300-11,800 cal yr BP) was marked by lower abundances of the common *Cyclotella* species found in the previous zone (1-16%) and increased percentages of colonial *Fragilaria* species (15-64%) in the lower part of the subzone and *Cyclotella meneghiniana* (1-24%) and *Stephanodiscus parvus* (7-40%) in the upper part of the subzone. The transition to zone DLY-D3b (9.08-8.36 m depth; 11,800-11,140 cal yr BP) was characterized by the return of the *Cyclotella* species common in zone DLY-D2 (*C. michiganiana*, *C. rossii*, *C. ocellata*, *C. radiosa*—combined abundance of 1-38%) and an increase in *Aulacoseira ambigua* (1-30%).

Diatom zone DLY-D4 (8.36-6.89 m depth; 11,140-10,350 cal yr BP) included the youngest samples analyzed in the diatom record and was marked by decreasing percentages of *Cyclotella* (<19%) and *Aulacoseira* (<2%) species and increased abundance of all benthic species (17-55%) and *Stephanodiscus niagarae* (1-22%). Diatoms were not present above 6.89 m in the sediment core.

4.5 Discussion

4.5.1 Postglacial terrestrial and limnologic development at Dailey Lake

The Dailey Lake datasets document postglacial terrestrial and limnologic development in the Greater Yellowstone region. During the late-glacial/early-Holocene transition, the record features significant changes in catchment processes, vegetation, fire activity, hydrology, and limnobiota (Fig. 4.6).

4.5.1.1. Late-glacial period: >12,200 cal yr BP

Paleoclimate model simulations for western North America during the late-glacial period highlight the direct and indirect effects of increasing summer insolation on regional climate (Bartlein et al., 1998). Direct effects included rising summer temperatures and decreasing effective moisture relative to full-glacial conditions, whereas the indirect effects were a strengthening of the northeast Pacific subtropical high-pressure system in summer and a northward shift of the jet stream from its full-glacial position. As a result, summers were warmer and drier than before, and winter precipitation increased (Bartlein et al., 1998).

Driven by increasing summer insolation and temperatures, the northern Yellowstone outlet glacier retreated from its maximum extent at ca. 16,500 cal yr BP (16.5 ± 1.4 ^{10}Be ka, 16.6 ± 1.3 ^3He ka; Licciardi and Pierce, 2008) in Paradise Valley, and for the next 3000 years, ice recessional processes shaped the Dailey Lake area. Prior to 13,400 cal yr BP, lake sediments were characterized by high magnetic susceptibility and low pollen accumulation rates (PAR), indicating a sparsely vegetated unstable landscape with considerable clastic mineral input into the lake, either as eroded sediment from the freshly deglaciated landscape, meltwater, or

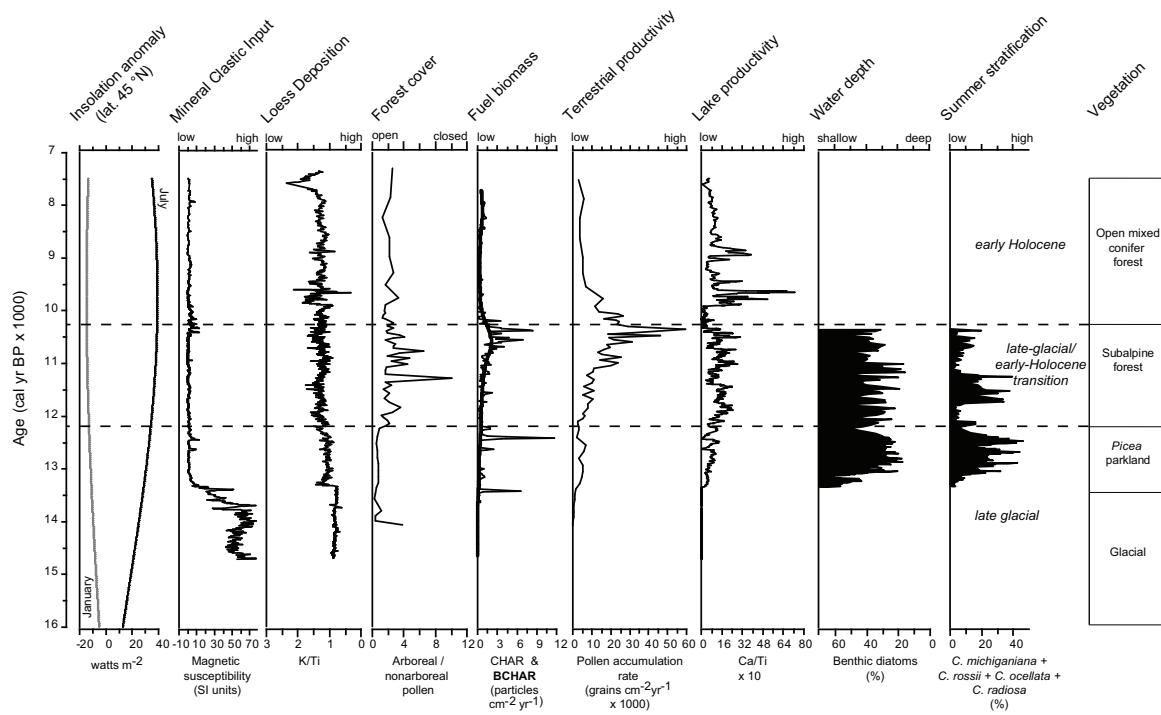


Figure 4.6 Summary of environmental proxy at Dailey Lake during the late-glacial/early Holocene transition plotted against January and July insolation anomalies.

wind-blown material (inferred from low K/Ti ratios). The pollen record implies discontinuous shrub-herb cover and early-successional species, such as *Shepherdia canadensis*, *Salix*, *Juniperus*, and Asteraceae species, likely established on stagnant outwash bars and rocky glacial till. Trees were rare; however, low persistent levels of *Abies* in the pollen record after 13,700 cal yr BP suggest local occurrence of *Abies lasiocarpa*. Low BCHAR values indicate limited fire activity, probably as a result of discontinuous fuels and cool conditions. Lake water temperatures and primary productivity were extremely low, as evidenced by low Ca/Ti ratios. Diatoms were absent from the lake during this time, likely as a result of high turbidity from the input of fine minerogenic sediment (Bradshaw et al., 2000).

Beginning at 13,400 cal yr BP, a number of environmental changes occurred in the vicinity of Dailey Lake. Magnetic susceptibility and K/Ti ratios reached their respective low and high values, indicating landscape stabilization as a result of decreased landscape erosion and the cessation of loess deposition. Overall PAR increased, and an abrupt rise in *Picea* pollen percentages marked the expansion of *P. engelmannii* populations. Increasing summer temperatures, in combination with more stable soils, likely favored its establishment. At present, *P. engelmannii* prefers moderately deep, well-drained soils compared to other subalpine tree species, such as *Abies lasiocarpa* which can establish on minerogenic substrates and rocky glacial till (Franklin and Mitchell, 1967; Alexander et al., 1984).

Within 100 years of landscape stabilization and *Picea* expansion, diatom populations developed in Dailey Lake, and lake productivity increased beginning at 13,350 cal yr BP. As slopes became increasingly stabilized, clastic mineral input into

the lake decreased and pioneering benthic diatoms, including *Navicula*, *Amphora*, and *Achnanthes* species, established in the lake. Shortly afterwards, populations of *Aulacoseira ambigua* expanded, reflecting increased nutrient availability for planktic diatom production and likely an unstratified water column because of the cool temperatures. Ca/Ti ratios also increased at this time, indicating increased calcite production as a result of warmer summers (Meyers and Ishiwatari, 1993). As summer temperatures continued to increase, euplanktic diatoms, particularly *Cyclotella* spp., colonized and expanded at 13,100 cal yr BP, and it is likely that the lake became thermally stratified during the summer months (Interlandi et al., 1999; Battarbee et al., 2002; Sorvari et al., 2002; Ruhland et al., 2003).

4.5.1.2 Late-glacial to early-Holocene transition (12,200-10,200 cal yr BP)

Summers became increasingly warmer and drier during the late-glacial/early-Holocene transition as summer insolation peaked in the region between 11,000 and 10,000 cal yr BP (Berger, 1978). Furthermore, increasing summer insolation indirectly strengthened the subtropical high-pressure system and summer monsoonal circulation, creating drier summers than at present in some areas of western North America and wetter conditions in others (Whitlock and Bartlein, 1993; Bartlein et al., 1998). Winter precipitation was also likely higher in the early Holocene as a result of diverted storm tracks by the lingering ice sheet (Williams et al., 2010) and lower-than-present winter insolation at that time (Bartlein et al., 1998).

Warmer drier summers than before facilitated the expansion of *Abies lasiocarpa* and *Pinus* (likely *P. albicaulis*) into *Picea* parkland beginning at 12,200 cal yr BP at Dailey Lake. The *Picea*, *Abies*, and *P. albicaulis*-type percentages during this period are consistent with those from modern *Picea-Abies-Pinus* forest in the Yellowstone region (Whitlock, 1993). Higher-than-present AP/NAP values suggest the upslope forest was either denser than it is presently, or forests grew at lower elevations where *Artemisia*-steppe and grassland grow today. Nonetheless, moderate levels of *Artemisia* and Poaceae pollen during this period indicate the presence of *Artemisia*-steppe/grassland but possibly only on the valley floor. Although conditions were likely warmer and drier than before, growing season moisture was apparently high enough to support a closed forest and/or forests at lower elevations than today.

At the end of the late-glacial period, the diatom record indicates a period of fluctuating conditions between 12,300 and 11,100 cal yr BP that is not evident in the pollen data. Starting approximately 12,300 cal yr BP, the dominant *Cyclotella* species decline in abundance and are replaced by a sequence of taxa, including tychoplanktic *Fragilaria* species, *Cyclotella meneghiniana*, and *Stephanodiscus parvus*. These taxa share a common life-history trait of blooming in unstratified waters, which suggests that lakewater temperatures cooled or the lake became shallower or both. At least for the period between 12,300 and 11,800 cal yr BP, the dominance of *C. meneghiniana* suggests a moderately shallow unstratified lake during summer months, consistent with the inference of summer warming evident in the vegetation data. At 11,800 cal yr BP, the resurgence of *Cyclotella* species

characteristic of stratified summer conditions (e.g., *C. rossii*, *C. ocellata*, *C. michiganiana*, *C. radiosa*) indicates that the lake became deeper and thermally stratified again, suggesting both warm summer conditions and increased water balance. A possible scenario for this interval is one of enhanced winter precipitation and snowpack coupled with early spring warming. The spring conditions, in particular, caused early ice off and longer periods of isothermal mixing. The moderate increase of *Aulacoseira ambigua*, a species characteristic of intervals of water-column mixing, is consistent with this hypothesis. Despite the high-frequency variation in the diatom assemblages, apparently the magnitude of the climate variability in this interval was not sufficient to alter the course of vegetation development.

Beginning 11,100 cal yr BP, lake level at Dailey Lake decreased, as indicated by increased percentages of benthic diatoms. Planktic taxa, such as *Cyclotella* and *Aulacoseira*, became less abundant, and percentages of benthic taxa, including *Achnanthes*, *Cymbella*, and *Navicula*, increased. In addition, colonial *Fragilaria* species (tychoplanktons) were also more abundant than in the previous period. Shallow lake conditions could explain the increased percentages of benthic and tychoplanktic species and the decrease in planktic taxa, and it is likely that Dailey Lake transitioned from an open/semi-closed lake system to a closed system at this time. Water levels continued to decrease after 10,400 cal yr BP, reducing recharge to the lake and increasing water alkalinity; these conditions caused diatom dissolution and the end of the diatom record.

Fire activity also increased between 11,000 and 10,000 cal yr BP, with rising summer temperatures, effectively drier summer conditions, and possibly more convective storms. High fuel availability is evidenced by high BCHAR, high terrestrial productivity (inferred from high PAR), and forest cover (based on the high AP/NAP ratios). Increased magnetic susceptibility, decreased Ca/Ti ratios, and increased sedimentation rates between 10,400 and 10,000 cal yr BP may be a result of fire-related erosional events at this time, as BCHAR peaked just prior to this sedimentation event.

4.5.1.3 Early Holocene (10,200-7500 cal yr BP)

At 10,200 cal yr BP, warm dry summer conditions produced a more open landscape at Dailey Lake than immediately before or at present. *Artemisia*-steppe was more extensive based on higher pollen percentages of *Artemisia*, *Sarcobatus*, and Poaceae. *Pseudotsuga* and *P. contorta* expanded into the lower forests above the site based on increases in their pollen abundances, and AP/NAP decreased from the previous period, indicating an upward displacement and/or opening of the lower forest. *Abies* and *Picea* were still present at moderate levels and likely moved to cooler higher elevations. The development of a lower forest composed of *Pseudotsuga* and *P. contorta* and the upslope expansion of *Artemisia*-steppe suggests that the period from 10,200 to 7500 cal yr BP was the warmest and effectively driest interval of the record. As the landscape became more open, fire activity decreased, indicated by low BCHAR after 10,000 cal yr BP, suggesting a shift to a fuel-limited system.

4.5.2 Linkages between vegetation and limnobiologic development

Because high-resolution terrestrial and limnologic data are available from the same cores at Dailey Lake, it is possible to compare the timing of biotic development in the watershed with that of the lake as well as the sensitivity of the two systems to climate change. Early in landscape development at Dailey Lake, large-scale changes in catchment processes elicited synchronous responses in the vegetation and limnobiota. In the initial period of deglaciation, the geomorphic instability created by stagnant ice, wind, and meltwater inhibited vegetation and limnobiologic development. After 13,400 cal yr BP, dramatic changes in lithology (decreased MS) and geochemistry (increased K/Ti ratios) indicate stabilization of the terrestrial environment. This shift was accompanied by an expansion of *Picea* populations in the upland vegetation and the colonization of pioneering benthic diatoms in the lake. Not only did warmer summers in combination with stabilizing substrates allow for the germination and establishment of *Picea*, but also increasing slope stability decreased minerogenic input into the lake, that until this time had limited the growth of diatoms. It appears that erosional processes associated with ice recession mediated the effects of climate change on early biotic development at Dailey Lake.

Other studies show similar linkages between catchment processes and limnobiologic development in glaciated regions (Fritz and Anderson, 2013). At Krakenes Lake in western Norway, postglacial limnobiologic colonization was initiated once deglacial silt settled, and during the Younger Dryas Cold Interval, there was very little aquatic life due to high silt inwash into the lake (Birks et al., 2000). In

northwestern Montana, Foy Lake shows a similar progression of postglacial vegetation and limnobiologic development as at Dailey Lake (Stone and Fritz, 2006; Power et al., 2011). At that site, *Picea* parkland establishment at 13,150 cal yr BP coincided with the colonization of *Navicula diluviana* within the lake system, and it is probable that landscape-scale processes of slope stabilization facilitated a synchronous shift in the terrestrial and aquatic system there as well. Like recently deglaciated lakes (Engstrom et al., 2000; Engstrom and Fritz, 2006), tight coupling between terrestrial succession and lake trophic change at Dailey Lake may have been facilitated by the establishment of nitrogen-fixing plants (e.g., *Shepherdia canadensis* and *Alnus*) that increased lake nitrogen loads and diatom productivity. However, synchrony between decreased minerogenic input and diatom establishment points to the importance of decreased landscape erosion in driving early limnobiologic development at Dailey Lake.

After 13,400 cal yr BP, vegetation and limnobiologic changes at Dailey Lake became asynchronous, reflecting different sensitivities to climate change. Vegetation development once initiated was unidirectional through time and tracked slowly increasing summer insolation and temperatures. The sparsely vegetated landscape became increasingly forested as *Picea* parkland developed, followed by the establishment of closed subalpine forest, and eventually open mixed conifer forest in the early Holocene. In contrast, the abrupt shifts in diatom assemblages between planktic and tychoplanktic taxa between 12,300 and 11,100 cal yr BP suggest a response to climate-driven changes in spring and summer lake thermal structure and lake depth.

In general, the limnobiota at Dailey Lake were sensitive to short-term variations in climate during the late-glacial/early-Holocene transition, whereas the vegetation was more strongly directed by orbital-scale changes in the seasonal cycle of insolation and its effect on temperature and effective moisture. This difference in sensitivity is also evident at Crevice Lake in northern Yellowstone, where the diatom assemblages show dramatic excursions attributed to summer water-column mixing and spring duration that are not matched in the pollen data. The charcoal record, on the other hand, shows fluctuations in the fire activity that match some of the diatom events and suggest shared responses to summer conditions (Whitlock et al., 2012). At Foy Lake, diatom data indicate low water levels between 12,500 and 11,000 cal yr BP (Stone and Fritz, 2006) as a result of cool dry conditions (Shuman et al., 2009) at a time when the pollen data indicate little change in the prevailing mesophytic vegetation (Power et al., 2011). Similarly, at Krakenes Lake in Norway, changes in terrestrial and aquatic assemblages occurred asynchronously during the Holocene, highlighting their independent responses and sensitivity to environmental drivers (Birks et al., 2000).

4.5.3 Comparison with other northern Yellowstone paleoecological records

To gain better insight on local vegetation and climate dynamics during the late-glacial/early Holocene transition, the Dailey Lake record was compared with other sites in the northern Yellowstone region (Fig. 4.7; see Fig. 4.1 for site locations). These include: Blacktail Pond (44.95° N, 110.60° W, elev. 2012 m; Huerta et al., 2009; Krause and Whitlock, 2013); Crevice Lake (45.00° N, 110.58° W, elev.

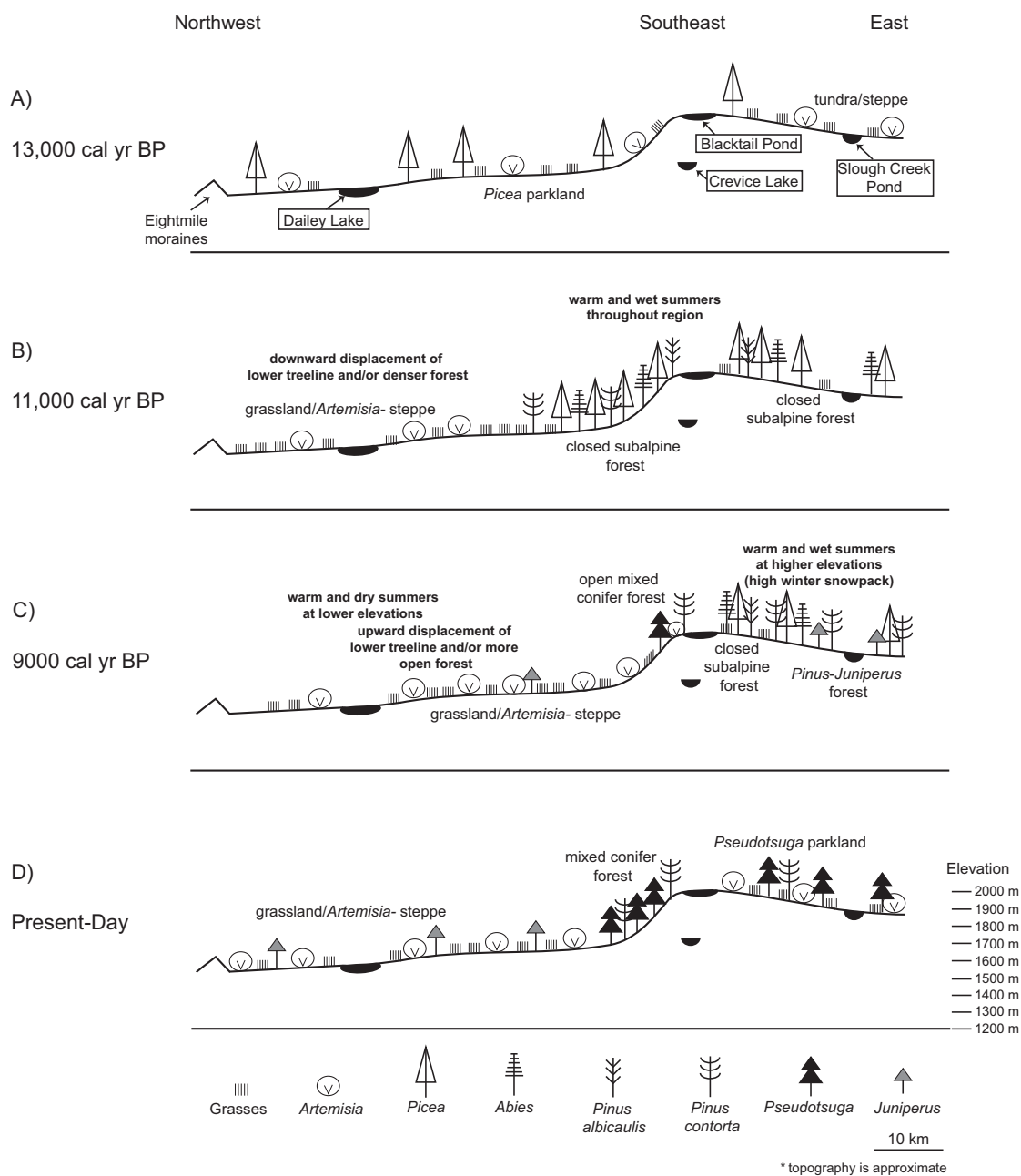


Figure 4.7 Schematic vegetation reconstruction of northern Yellowstone based on data presented in this paper and other published records.

1684 m; Whitlock et al., 2012); and Slough Creek Pond (44.92° N, 110.35° W, elev. 1884 m; Whitlock and Bartlein, 1993; Millspaugh et al., 2004; Krause, unpublished data). All sites are classified as summer-wet (*sensu* Whitlock and Bartlein, 1993), however, Blacktail Pond, Crevice Lake, and Slough Creek Pond are located 200 to 500 m in elevation above Dailey Lake and receive more winter snowfall. Blacktail and Slough Creek Ponds are situated on broad plateaus, and Crevice Lake lies in the Black Canyon of the Yellowstone River and has an analyzed record that begins 9800 cal yr BP. Dailey Lake's lower elevation in Paradise Valley and position in a precipitation shadow distinguish it from the other sites in northern Yellowstone; its climate is both warmer and drier.

Following deglaciation, sparsely vegetated landscapes transitioned to *Picea* parkland at 13,500 cal yr BP near Dailey Lake and Blacktail Pond (Krause and Whitlock, 2013), and later at Slough Creek Pond beginning 12,900 cal yr BP (Millspaugh et al., 2004). As growing season temperatures increased, closed subalpine forests developed on the upper slopes near Dailey Lake and Slough Creek Pond at 12,200 cal yr BP, and then later near Blacktail Pond at 11,350 cal yr BP. Although summers were gradually becoming warmer and drier than before, soil moisture was high enough to support closed forests at this time.

In the early Holocene, Crevice Lake, Blacktail Pond, and Slough Creek Pond, located above 1700 m in elevation, experienced relatively wet summer conditions. For example, mesophytic closed subalpine forests grew at Crevice Lake and Blacktail Pond until 8200 cal yr BP (Whitlock et al., 2012; Krause and Whitlock, 2013), and *Pinus-Juniperus* forest was present at Slough Creek Pond prior to 8000

cal yr BP (Millspaugh et al., 2004). In addition, charcoal data from the three sites indicate low fire-episode frequency during the early Holocene. Wet summers are attributed to a combination of high winter snowpack and/or summer precipitation from convectional storms. Low carbonate $\delta^{18}\text{O}$ values from Crevice Lake between 9800 and 8200 cal yr BP suggest that carryover of winter precipitation into the summer season was as important or more important than enhanced summer monsoonal circulation in producing wet summers in northern Yellowstone (Whitlock et al., 2012).

In contrast, Dailey Lake received less winter precipitation in the early Holocene than the other sites in northern Yellowstone due to its lower elevation and orographic setting. As a result, the site was more influenced by the direct effects of the summer insolation maximum, namely changes in summer temperature and effective moisture. As a result, alkaline lake conditions led to the dissolution of the diatoms after 10,400 cal yr BP, closed subalpine forests were replaced by open mixed conifer forest as early as 10,200 cal yr BP, and fire activity, as indicated by BCHAR, peaked between 11,000 and 10,000 cal yr BP.

4.6 Conclusions

Our multi-proxy paleoecological reconstruction from Dailey Lake contributes new information on early postglacial development of the Greater Yellowstone ecosystem. Following deglaciation, the Dailey Lake record describes an initial period of landscape instability driven by ice recessional processes from the northern Yellowstone outlet glacier. Once climate warmed and these processes

attenuated, *Picea* population expansion occurred and *Picea* parkland grew on the slopes above the lake. As slopes stabilized and minerogenic input into the lake decreased, limnobiotic communities within the lake established. The nearly synchronous terrestrial and aquatic responses to landscape stabilization suggest erosional processes in the catchment inhibited early vegetation and limnobiotic development.

Once established, the plant and limnobiotic assemblages at Dailey Lake responded independently to climate change. Vegetation development following deglaciation to the early Holocene was largely a response to increasing summer insolation and temperatures and their influence on effective moisture. Concurrently, the diatom assemblage registered short-duration variations in climate seasonality. The differing response to past climatic variations may be explained by the fast generation times of the limnobiota as compared with the slow rate of population change among the dominant tree species.

The sequence of vegetation changes at Dailey Lake following ice retreat is comparable to other sites in northern Yellowstone during the late-glacial period: sparsely vegetated landscapes to *Picea* parkland to closed subalpine forest. However, as the seasonal cycle of insolation amplified during the early Holocene, the high elevation sites were more strongly influenced by the indirect effects of insolation, namely changes in atmospheric circulation, whereas Dailey Lake at a low elevation was more strongly affected by the direct effects of greater-than-present summer insolation, higher summer temperature, and decreased effective moisture.

As a result, Dailey Lake shows drier-than-present summers when higher elevation sites in northern Yellowstone register prolonged summer-wet conditions.

Although climate was the primary driver of postglacial ecosystem development in the greater Yellowstone region, this study shows that non-climatic factors, such as catchment stabilization, species life-history traits, and local topography, mediated the impacts of climate change. Once established, the terrestrial and limnologic systems responded independently to climate change, reflecting their unique sensitivities and response times. In spatially complex mountainous regions like Yellowstone, the combination of climate and non-climatic factors produced heterogeneous environmental histories at different elevations and among different proxy. These historical legacies need to be considered in interpreting the modern landscape and in projecting future trajectories of change.

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