HOLOCENE VEGETATION AND FIRE HISTORY OF THE FLORISTICALLY DIVERSE KLAMATH MOUNTAINS, NORTHERN CALIFORNIA, USA

by

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The Holocene vegetation and fire history of the Klamath Mountains (KM), northern California, was reconstructed at three sites based on an analysis of pollen and high-resolution macroscopic charcoal in lake-sediment cores. These data were compared with five existing records to examine regional patterns. The objective was to determine the relative importance of climate history, substrate, and disturbance regime on the development of the Klamath vegetation. In the first study, two middle-elevation sites were compared along a moisture gradient in the northern KM. The pollen data indicated a similar vegetation history, beginning with subalpine parkland in the late-glacial period, and changing to open forest in the early Holocene and closed forest in the late Holocene. However, the timing of these changes differed between sites and is attributed to the relative importance of coastal influences and topography. The second study examined the effect of substrate and nutrient limitations on the vegetation history. The pollen data suggest that ultramafic substrates (UMS), containing heavy metals and low nutrients that limit plant growth, supported xerophytic plant communities than those on non-ultramafic substrates (NUMS) for any given period. For example, between 14,000 and 11,000 cal yr BP, cooler and wetter conditions than present led to the establishment of a subalpine parkland of *Pinus monticola* and/or *Pinus lambertina*, *Tsuga, Picea* on non-ultramafic substrates (NUMS). On UMS, an open *Pinus jeffreyi* and/or *Pinus contorta* woodland developed. In the early Holocene, when conditions were warmer and drier than present, open forests of *Pinus monticola/lambertina*, Cupressaceae, *Quercus* and/or *Amelanchier* grew on NUMS, whereas open forest consisting of *Pinus jeffreyi/contorta*, Cupressaceae and *Quercus* developed on UMS. In the late Holocene, cool wet conditions favored closed forests of *Abies, Pseudotsuga,* and *Tsuga* on NUMS, whereas *Pinus jeffreyi/contorta,* Cupressaceae and *Quercus* forest persisted with little change on UMS. The charcoal data indicate that past fire activity was similar at all sites, implying a strong climatic control. The results of both studies suggest that the influence of Holocene climate variations, disturbance regime, and substrate type have helped create the current mosaic of vegetation in the KM.

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CHAPTER I

INTRODUCTION

The Klamath Mountains of northern California contain one of the most diverse temperate coniferous forests in the world (DellaSala et al., 1999). They are located east of Interstate 5 between Redding, California and Grants Pass, Oregon (Figure 1.1). Along the coast from Eureka, CA to the California/Oregon border, the Klamath forests are home to one of the tallest and largest trees in the world, *Sequoia sempervirens* (coast redwood), and they support a large number of other conifers (39 species and subspecies), including ten species of *Pinus*, nine species of Cupressaceae, four species of *Abies*, two species of *Picea,* two species of *Tsuga*, one species of *Pseudotsuga,* and one species of *Taxus* (not including subspecies) (Sawyer, 2004; Smith and Sawyer, 2006; Lanner, 1999; Barbour et al., 2007). The Klamath region today harbors over 3500 plant species, of which ~220 are endemic (found nowhere else in the world). The region is also host to a diversity of other organisms, including at least 115 species of butterflies, 235 species of mollusc (60% endemic), and 33 species of fish (42% endemic) (DellaSala et al., 1999).

The high biological diversity has brought both national and international recognition to the region. The World Wildlife Fund has described the Klamath Mountains as the "Galapagos of North America" (DellaSala, 2003). The World Conservation Union in 1992 proposed the Klamath region as an area of global botanical significance, and it has been given status as a "Global 200" ecoregion by the World Wildlife Fund (Ricketts et.

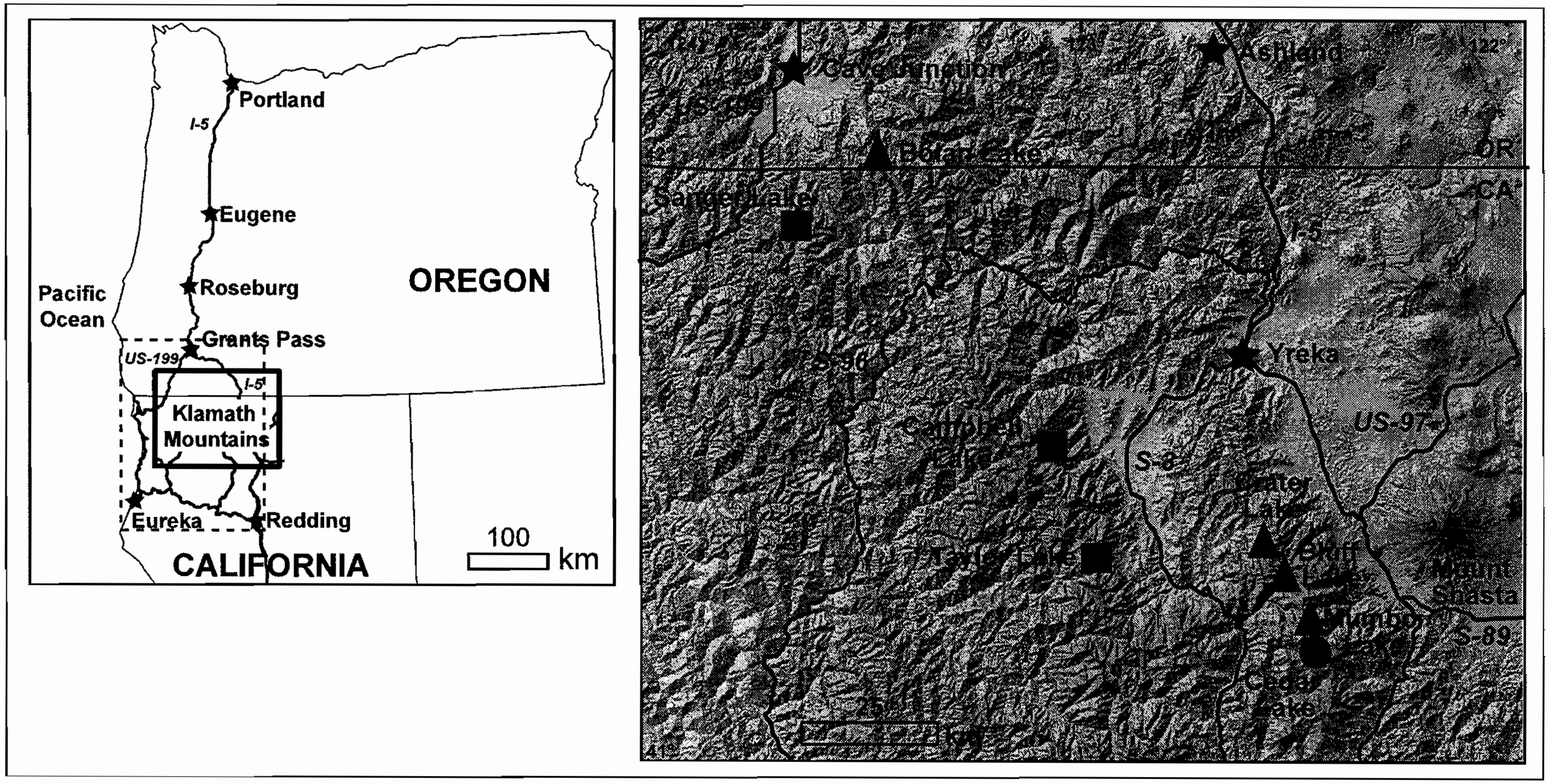


Figure 1.1. The Klamath Mountains (dashed line), study area (solid line), and lakes discussed in the dissertation (triangles= lakes with existing published records, circles=lakes with existing unpublished records, squares=new lakes presented in detail in the dissertation). Stars represent cities and towns. Solid lines are state highways (e.g., S-3), interstates (e.g., I-5), and US highways (e.g., US-199).

1999). Currently, it is being considered as a UNESCO World Heritage Site and Biosphere Reserve. Despite this attention, the region has limited protection from human-induced ecosystem degradation compared with other temperate coniferous forests (DellaSala et al., 1999). Most of the protected land occurs in large complexes designated as USDA Forest Service Wilderness Areas (e.g. Kalmiopsis, Siskiyou, Marble Mountain, Russian, Trinity Alps, Yolla Bolly; comprising ~12% of total land area in Klamath Mountains). President Bill Clinton established the Cascade-Siskiyou National Monument (22,000 hectares) in 2000, which connects the diverse Siskiyou Mountains in the northern Klamath Mountains with the southern Cascades in south central Oregon. Federal plans also help to protect the uniqueness of the Klamath Mountains. For example, under the Northwest Forest Plan (1994), late-successional forest reserves were established to protect old-growth habitat and endangered species. Most recently, the National Fire Plan and Healthy Forests Initiative (2004) were implemented to remove fuel buildup in forest understories to prevent catastrophic fires and protect human welfare and property. However, these federal plans are economically driven, target large regions (i.e., the Pacific Northwest to entire US), and ignore the Klamath Mountains ecological complexity (Franklin and Agee, 2003).

The explanation for the present richness of the flora and fauna of the Klamath Mountains has been long debated (Briles et al., 2005; Skinner and Taylor, 1998, 2003; Kruckeburg, 1992a,b; Keeler-Wolf, 1990; Sawyer and Thornburgh, 1988; Axelrod, 1988; Raven and Axelrod, 1978; Stebbins and Major, 1965). Several factors may contribute, including: a) the complex geology and unusual soil chemistry, b) a geological history that has promoted a diversity of environments through the Cenozoic, c) complex climate and climate gradients at present, and d) a spatially heterogeneous disturbance regime. These explanations will be addressed individually below.

The geology of the Klamath Mountains consists of Mesozoic sedimentary and volcanic rocks, which are significantly older than the Miocene volcanic rocks in the Cascade Range to the east (Harden 1997; Norris and Webb, 1990). Mountains formed in the region as the North American and Pacific continental plates collided (Harden, 1997; Norris and Webb, 1990), and welded ocean sediments onto the North American continent. The mountains are composed of mudstone, limestone, sandstone, chert, schist, serpentine, peridotite, several plutonic deposits (e.g., igneous intrusions of diorite and granodiorite rocks) and volcanic rocks (e.g., basalts). A complex of mountain ranges, including the Siskiyou Mountains to the north, the South Fork Mountains to the south, the Marble Mountains, Trinity Alps, and Salmon Mountain in the middle, and the North Coast Range along the coast, contribute to the topographic heterogeneity of the region, and give it the nickname the "Klamath Knot" (Wallace, 1983). Elevations range from sea level to 2800 m (on Mount Eddy) over short distances.

The soil composition reflects the complex geology. Several exposed sheets of ultramafic bedrock in the Klamath Mountains, including the Trinity Ultramafic Sheet and Josopine and Sexton ophiolites, are composed of serpentine and peridotite bedrock (Irwin, 1989). The soils derived from these rocks are deficient in critical minerals for plant growth, including calcium, nitrogen, phosphorus, and potassium, and they contain high concentrations of heavy metals that inhibit or restrict plant growth, including nickel, magnesium, chromium, and iron (Kruckeburg, 2002; Alexander, 2007). Thus, forests on ultramafic substrates are usually open, and due to high evapotranspiration rates, dry compared with those growing on other soil types (Kruckeburg, 1984, 2002; Alexander, 2007). Plants growing on ultramafic substrates have traits (e.g., hairy or waxy leaves, shallow roots) that allow them to tolerate drought conditions. They tolerate high concentrations of heavy metals by limiting their uptake and/or accumulating it in their roots, leaves and/or leaf hairs (Alexander, 2007). The harsh environmental conditions on ultramafic substrates have led to over 40 endemic "serpentine plant species" in the region that are adapted to the high concentrations of heavy metals and drought conditions.

The ancient, rugged landscape, geological diversity, and unique soil chemistry of the Klamath Mountains, along with their proximity to the coast, were critical for the survival of many plant species, such a *Picea*, *Taxus*, *Sequoia*, and *Chamaecyparis* as temperatures decreased during the late Cenozoic (Wolfe, 1994; Stebbins and Major, 1965). Megafossil data from the Klamath Mountains show a low-elevation swampy environment, dominated by hardwoods including *Ilex* (holly), *Juglans* (walnut), *Nyssa* (tupelo), *Tilia* (basswood), and *Umbellularia* (bay) and *Taxodium* (bald cypress) as the main conifers in the Klamath Mountains during the Miocene. As climate cooled and became drier in the Tertiary, temperate mixed-evergreen forests with conifers and evergreen hardwood developed. Once widespread *Sequoia sempervirens* (redwood) and *Metasequoia* (dawn redwood; absent from North America and only in China today) were restricted to coastal regions. By the late Pliocene, xerophytic species dominated in the Klamath Mountains, and more mesophytic species were restricted to riparian areas, north-facing slopes, or coastal locations. It is likely ocean circulation patterns and upwelling off the northern California coast kept the region wetter than others (Lyle et al., 2001), and the diversity of substrates provided many different environments for plant species to seek refuge.

Spatial variability of climate also provides a potential explanation for the present-day diversity. Today, the climate of the Klamath Mountains is stronger influenced by high- and low-pressure systems that develop in the northeast Pacific Ocean. During the winter, low solar radiation at high latitudes creates a steep latitudinal temperature gradient and more vigorous atmospheric circulation including faster westerlies that extend to lower latitudes than in summer. Land-ocean temperature contrasts (related to the thermal inertia of the ocean) superimposed on the steepened temperature gradient in winter, results in a stronger North Pacific low-pressure system (i.e., Aleutian Low). Winter storms that develop in the Aleutian Low entrain moisture from the subtropical and tropical Pacific, and bring considerable precipitation, delivered mostly as snow to higher elevations and as rain in the lower valleys. In summer, high solar radiation at high latitudes reduces the latitudinal temperature gradient, warms the continents in relation to the ocean, and creates a low-pressure system over the continents and a high-pressure system over the ocean (i.e., Eastern Pacific Subtropical High). The Klamath Mountains experience relatively dry summers due to subsidence associated with the high-pressure system, which suppresses precipitation. Surface heating during the summer causes steep environmental lapse rates, and consequently atmospheric instability and conventional storms, which are typically associated with lightning.

The topographic heterogeneity of the region produces a variety of different precipitation and temperature regimes, with higher elevation sites receiving significantly more precipitation and recording lower temperatures than the valleys (Taylor and Hannan, 1999). Steep climate gradients over short distances promote abrupt changes in species distributions. In addition, a sharply increasing moisture gradient from west to east is created as coastal mountains intercept precipitation on their windward side (Figure 1.2). The seasonal latitudinal temperature gradient and associated pressure systems result in a south-to-north gradient in moisture that influences many species ranges (Figure 1.3).

The fire regimes of the Klamath Mountain forests help maintain the diversity of plant species and communities. Recently, the region has received attention as large areas of forest and protected wilderness have experienced fires. Among the most famous and controversial (e.g., Donato et al, 2006) are the Biscuit Fire of 2002, the largest fire on record in Oregon (7th largest in the US; 202,000 ha burned), and the Silver Complex Fire of 1987 (74,000 ha burned), which affected the northern Klamath Mountains. Most of our understanding about fire in the Klamath Mountains comes from tree-ring studies extending back ~500 years. Fire regimes in the region have historically ranged from low to moderate severity in different forest types (Skinner et al., 2006; Taylor and Skinner, 2003, 1998). These studies suggest that fire activity is governed by the topographic and climatic heterogeneity of the region and also the spatial pattern of previous fires and their severity (Skinner et al, 2006; Taylor and Skinner, 2003, 1998). For example, fire severity tends to be highest on the upper third of dry south- and west-facing slopes, and lowest on the lower third of slopes on north- and east-facing slopes. The size of fire is influenced

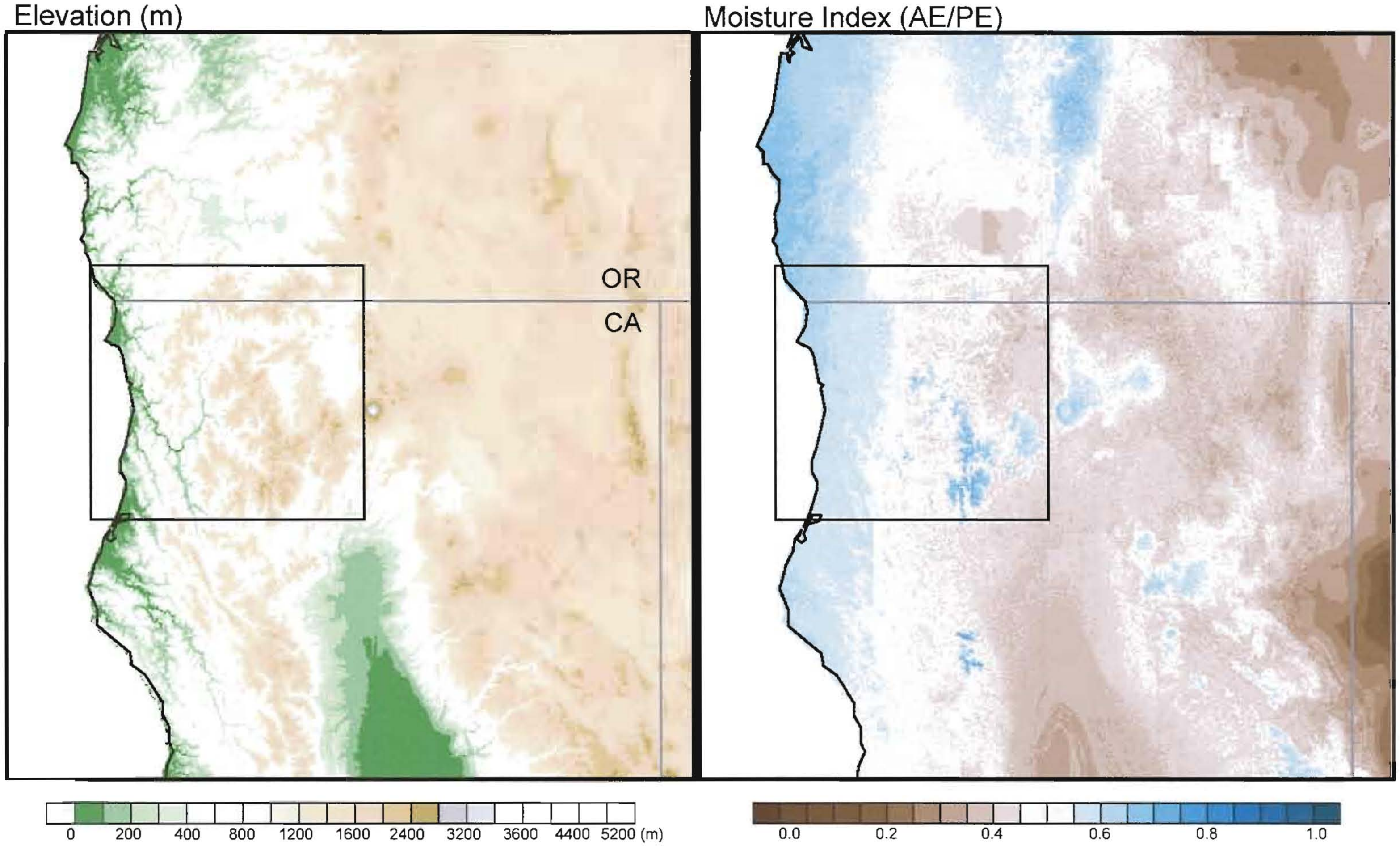
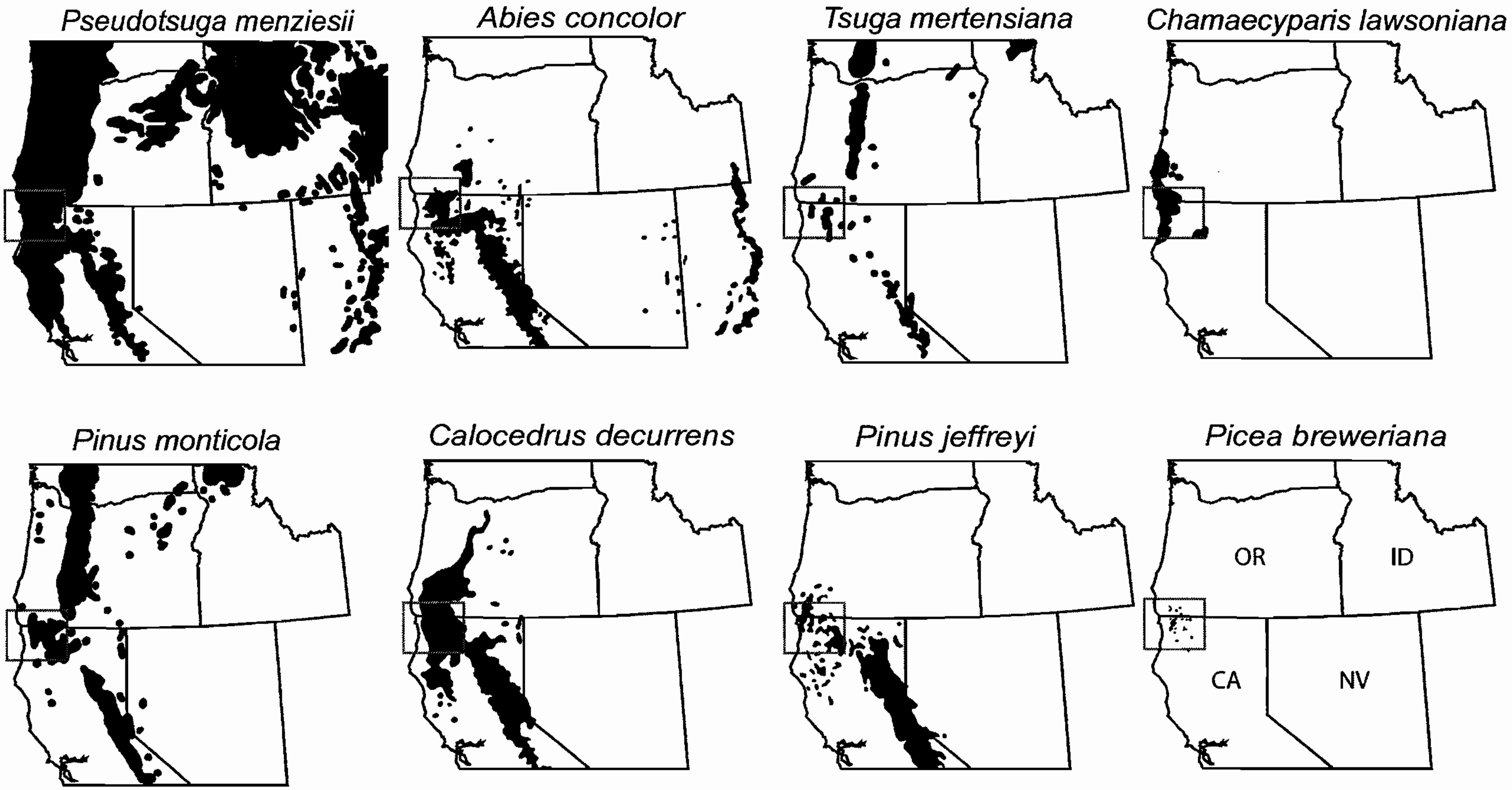


Figure 1.2. Topography in the Klamath Mountains and the amount of effective moisture represented by the ratio of actual to potential evapotranspiration. Notice the steep coastal-to-inland (west to east) moisture gradient (Bartlein and Shafer, unpub).



Pseudotsuga menziesii *Abies concolor* *Tsuga mertensiana* *Chamaecyparis lawsoniana*

Pinus monticola *Calocedrus decurrens* *Pinus jeffreyi* *Picea breweriana*

Figure 1.3. Conifer species discussed in the dissertation that either begin or end their ranges in or near the Klamath Mountains. *Chamaecyparis lawsoniana* (Port-Orford cedar) and *Picea breweriana* (Brewer spruce) are endemics to the region (Thompson et al., 1999).

by forest patch size and barriers to fire spreading (e.g., ridgetops, aspect changes, riparian zones, substrate differences). All of these factors combine to create a patchwork of different stands of different age and composition, and help maintain the biological diversity (Skinner et al., 2006).

Forest composition is often a good indicator of severity and frequency of fire (Skinner et al., 2006). For example, most locations discussed in the dissertation occur in mid-to-high elevation forests of *Abies concolor* (white fir) and *A. magnifica* (Shasta red fir). These species have thin bark when young and a low tolerance for fire, but as the trees mature, their bark thickens and they become more fire resistant. *Abies* needs long periods without fire to become established and the mean fire return interval (MFI) in *Abies* forests typically ranges between 25 and 64 years. Fires there tend to be low-to-moderate intensity surface fires, but crown fires may occur in densely forested areas where there are ample ladder fuels (Burns and Honkala, 1990; Skinner et al., 2006). In contrast, at lower-elevation, *Pseudotsuga menziesii* (Douglas-fir) and *Pinus ponderosa* (ponderosa pine) are the dominant conifers and develop thick bark early-on, root deeply, and have high, open crowns to restrict crown fires and survive frequent (6 to 22 MFI) surface fires (Burns and Honkala, 1990; Skinner et al., 2006).

The equation below describes schematically the conceptual model that underlies this research and includes four factors (modern climate, ancient landscape, geology, topography), which contribute to the modern plant diversity in the Klamath Mountains as discussed above, plus two additional factors (climate change since the last glaciation (which ended ca. 17,000 cal yr BP; Porter and Swanson, 1998; Clark and Gillespie, 1997) and fire activity) which help maintain the diversity. Even today, the varied climates, topography, soil types, and fire regimes make the Klamath Mountains a meeting ground for many plant species, such as *Pseudotsuga menziesii*, *Calocedrus decurrens*, and *Pinus jeffreyi* and also endemics such as *Picea breweriana* (Brewer's spruce), *Chamaecyparis lawsoniana* (Port-Orford cedar) (Figure 1.3).

Klamath Mountain Plant Diversity = Modern Climate + Ancient Landscape + Geology + Topography + Fire + ?Holocene Climate Variability?

It is well established that plant species have undergone major reorganizations in the Klamath Mountains as a result of Holocene climate variations. For example, Mohr et al. (2000) and Daniels et al., (2005) reconstructed the vegetation and fire history from the southeastern Klamath Mountains from Bluff, Crater, and Mumbo lakes on or surrounded by ultramafic substrates. These studies established the general sequence of vegetation changes including: subalpine parkland during the late-glacial period (>11,000 cal yr BP) when climate was cooler and wetter than today, a xerophytic mixed-conifer woodland in the early Holocene (11,000 to ~5000 cal yr BP) when climate was warmer and drier than today, and a *Abies* and diploxylon *Pinus* forest in the late Holocene (<5000 cal yr BP) as modern conditions became established. Fires occurred through the Holocene and were more frequent during drier periods, such as the early Holocene and Medieval Climate Anomaly. Briles et al. (2005) reconstructed the vegetation and fire history from Bolan

Lake on diorite soils in the northern Klamath Mountains and showed that plant communities were more strongly affected by variations in climate occurring on centennial and millennial time scales than the sites in the southeastern Klamath Mountains. Bolan Lake also supported more mesophytic species, such as, *Picea*, *Tsuga*, *Abies* and haploxylon *Pinus*, and less frequent fires during the late-glacial period and late Holocene, than the sites in the southeastern Klamath Mountains. However, the lack of paleoecologic records, in similar environmental settings, made it difficult to examine the interaction between Holocene climate and environmental gradients created by topography, soils, and natural disturbance in the Klamath Mountains.

This study extended the network of sites across the Klamath Mountains that allowed questions to be addressed that arose from modern observations and/or previous studies. In addition to the differences mentioned above, the modern forest at Sanger Lake on the California/Oregon border maintained a large population of *Picea breweriana* and *Chamaecyparis lawsoniana,* and these species did not occur 20 km to the northeast at Bolan Lake at a similar elevation. It was uncertain if the modern community differences were a result of the steep inland-to-coastal moisture gradient today and/or a difference in vegetation and fire histories. In addition, it was not clear if the differences in vegetation and fire histories at the northern and southern Klamath Mountain sites were related to differences in edaphic conditions or long-term climate variability. In order to test the influence of substrate, additional sites, Campbell and Taylor lakes, on non-ultramafic substrates (i.e., granodiorite and sedimentary rock) were selected in the southeastern Klamath Mountains to compare with the preexisting vegetation and fire histories on ultramafic substrates (i.e., Bluff, Crater and Cedar lakes). All sites had similar modern climates (determined using interpolated modern weather station data as in Figure 1.2) and were located at similar elevations.

The first objective of this study was to understand how the coast-to-inland moisture gradient has influenced the postglacial vegetation and fire regimes of mid-to-upper elevation mixed-conifer forests. To do this, vegetation and fire histories, reconstructed from pollen and charcoal preserved in the lake sediments, at Sanger (wetter site) and Bolan lakes (drier site) were compared (Figure 1.1). The records of vegetation and fire extended back 14,000 cal yr BP at both sites. Besides the modern vegetation differences between the two sites, the vegetation and fire history at Bolan Lake (Briles et al., 2005) showed trade-offs between *Pinus monticola* (western white pine) and Cupressaceae (likely incense cedar) in the early Holocene that were associated with changes in fire frequency, and it was of interest to determine if the relationships were more widespread at Sanger Lake. The results from the study are presented below in the second chapter. This chapter has been accepted for publication by *Palaeogeography, Palaeoclimatology, Palaeoecology*. The chapter was co-authored with Cathy Whitlock and Patrick J. Bartlein who assisted with the study design, ideas for data analysis, interpretation of the results, and editing of the manuscript and Philip Higuera who helped with data analysis and editing of the manuscript.

The second objective was to examine the spatial and temporal changes in vegetation and fire history on different substrates to determine how edaphic conditions influenced the response of vegetation and fire to past climate variations. Chapter 3 describes paleoecological records from the southeastern Klamath Mountains, including Taylor Lake (granodiorite substrates), Campbell Lake (various sedimentary substrates), Cedar Lake (peridotite substrates), and compares them with published records on peridotite substrates (ultramafic substrates), including Crater and Bluff lakes (Mohr et al., 2000), and Mumbo Lake (Daniels et al., 2005) on diorite soils but surrounded by ultramafic substrates (Figure 1.1). Bolan and Sanger lakes were also included in the comparison and both sites are located on diorite substrates in the northern Klamath Mountains. This study relies heavily on independent climate data from the region (i.e., climate model simulations, ocean records, and speleothem records) to establish Holocene climate variations, while the vegetation and fire records are used as indicators of ecosystem response to climate change. Another goal of the study was to determine how abrupt climate events such as the Younger Dryas cool event (12,900-11,600; Alley, 1993), the Little Ice Age (600-100 cal yr BP; Graham et al., 2007; Taylor, 1995), and the Medieval Climate Anomaly (1450-600 cal yr BP; Graham et al., 2007) influenced vegetation and fire across the region. The results of this study are presented below in the third chapter. The manuscript for this chapter is being prepared as a co-authored manuscript for *Ecological Monographs*. Cathy Whitlock and Patrick Bartlein assisted with the study design, data analysis ideas, interpretation of the results, and editing of the manuscript.

The paleoecological perspective offered by this research is important for understanding the resilience of the Klamath Mountains ecosystem to past and current environmental changes. There is growing concern that the biological diversity is threatened by a growing number of natural and human disturbances. As mentioned above, tree-ring records suggest that fires in the Klamath Mountains are consuming larger areas of land and at higher severities than they have in the past (Skinner et al., 2006). In addition, logging and mineral extraction were, and continue to be, significant industries in the Klamath Mountains and have resulted in disturbed and fragmented public lands. Over 30,000 miles of roads, used to extract these natural resources, add to the fragmentation (Strittholt and DellaSala, 2001).

With projected warmer and longer summers, comes the threat of more large intense fires in the future (Westerling et al., 2006). This research helps disclose the historical range of fire occurrence experienced by middle to upper elevation forests in the Klamath Mountains. It provides prehistoric fire reconstructions that can be used as a baseline for comparing with current fire events. The study also examines the importance of sub-millennial-to-millennial scale climate change, climate gradients and substrates in creating and maintaining the vegetation diversity of the Klamath Mountains. The information can be used to highlight plant communities that may be vulnerable to climate change and which, by nature of their history, may be more resilient.

CHAPTER II

REGIONAL AND LOCAL CONTROLS ON POSTGLACIAL VEGETATION AND FIRE IN THE SISKIYOU MOUNTAINS, NORTHERN CALIFORNIA, USA

Introduction

The environmental response to climate change in mountainous regions is complex and not well-understood (Shafer et al., 2005). Steep elevational gradients created by mountains transform large-regional scale climate patterns into site-specific microclimates in which different aspects and elevations strongly influence vegetation and fire across the landscape. The Siskiyou Mountains of northwestern California and southwestern Oregon, a sub-range of the Klamath Mountains, are known for their heterogeneous landscape and extraordinary gamma diversity (i.e., total number of species across the region). This diversity is attributed to spatial variability in soil, climate, disturbance regime (DellaSala et al., 1999); however, the role of long-term climate change or stability in shaping vegetation and fire across this complex landscape has only begun to be addressed (Briles et al., 2005; Daniels et al., 2005; Mohr et al., 2000; West, 1989).

The Siskiyou Mountains have traditionally been considered a region where the climate has remained stable during the Cenozoic Era, thereby providing a refuge for temperate forest taxa as conditions became cooler and drier elsewhere in the Pacific Northwest (Whittaker, 1960; Axelrod, 1988, Raven and Axelrod, 1978). This notion of stability is contradicted by evidence from the Quaternary which suggests that the region experienced significant climate fluctuations on millennial and shorter time scales (Vacco et al., 2005; Kaufman et al., 2004). Here we compare the postglacial vegetation and fire history in the northern Siskiyou Mountains from two sites located along a moisture gradient to further describe the nature of environmental change in the region following deglaciation 17,000 cal yr BP ago. The two sites are within 20 km of each other on similar substrates, but the site closest to the coast, Sanger Lake, is slightly wetter than the more inland site, Bolan Lake, and has a well-established population of endemic conifers, including *Picea breweriana* (Brewer's spruce) and *Chamaecyparis lawsoniana* (Port-Orford cedar), than the more inland site (see site descriptions below). One objective of this study was to determine whether the present vegetation differences arise from distinct vegetation, fire and climate histories or merely reflect local site differences. Another objective was to determine the geographic extent of early-Holocene trade-offs between haploxylon *Pinus* (likely *Pinus monticola*; western white pine) and Cupressaceae (likely *Calocedrus decurrens*; incense cedar), that were associated with changes in fire frequency recorded at Bolan Lake (Briles et al., 2005).

Site Descriptions

Sanger Lake (Lat. 41°54'06" N, Long. 123°38'49" W, 1550 m elevation, 4 ha) is located in a late-Pleistocene cirque (Figure 2.1). The bedrock around the lake is diorite, and upslope and downslope of Sanger Lake are serpentine deposits. The lake has no permanent inflowing streams and is mainly fed by groundwater. Sanger Lake lies in the

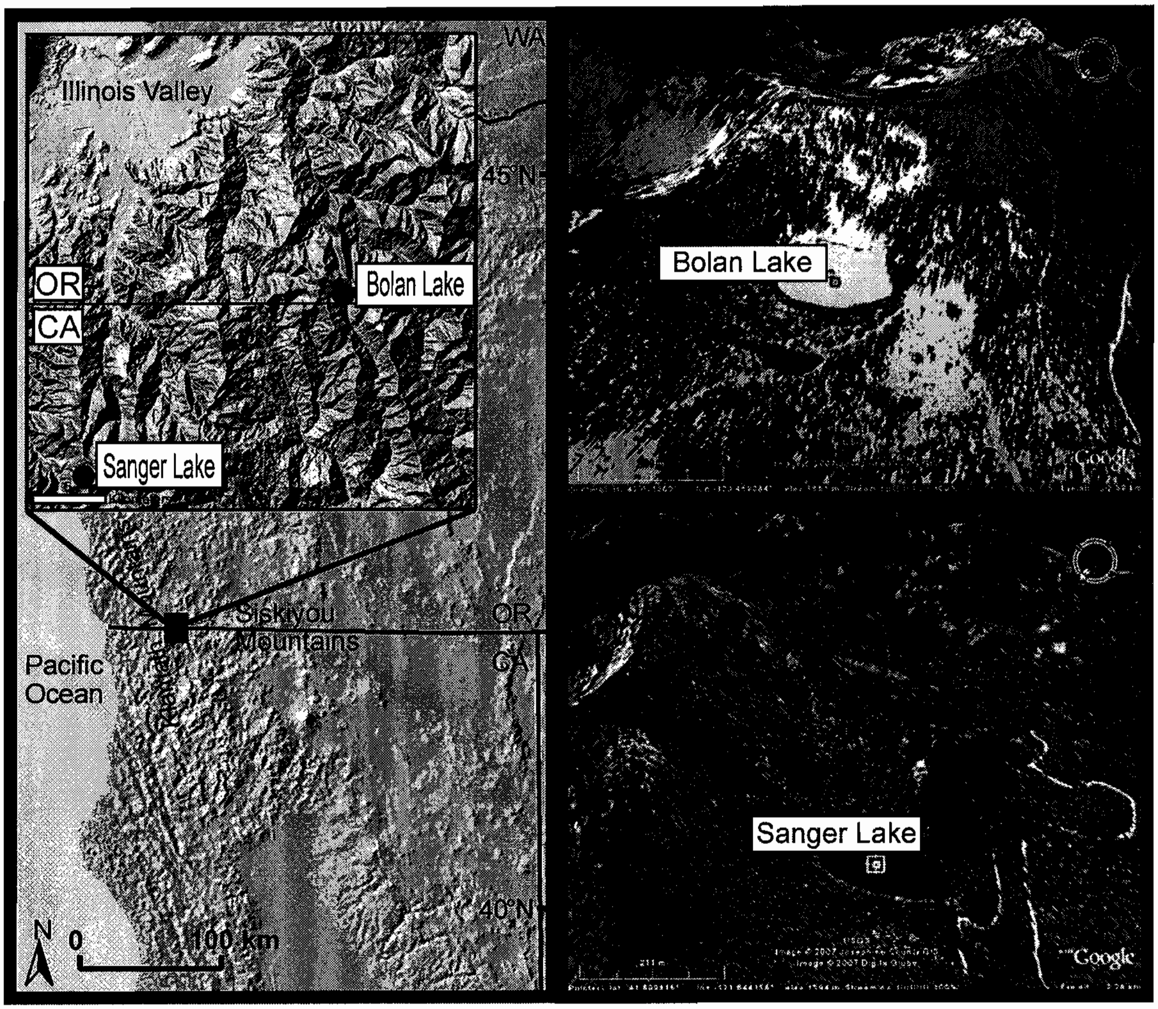


Figure 2.1. Map showing location of Sanger and Bolan lakes. Aerial perspective is from late winter for Bolan Lake and summer for Sanger Lake (from Google Earth).

Abies concolor (white fir) Vegetation Zone (1300-1900 m elevation) (Franklin and Dryness, 1988) (all botanical nomenclature is based on Hickman, 1993). The dominant conifers around the lake include *A. concolor, Picea breweriana, Chamaecyparis lawsoniana*, *Pinus monticola*, and *Pseudotsuga menziesii* (Douglas- fir). *C. lawsoniana* is restricted to, and dominates mesic serpentine slopes within the basin. The dominant shrubs around the lake include *Quercus vaccinifolia* (huckleberry oak)*, Chrysolepis chrysophylla* (golden chinquapin), *Lithocarpus densiflora* (tanoak), and *Ceanothus velutinus* (snowbrush).

The modern climate (based on elevation-adjusted interpolated station data; Bartlein and Shafer, unpublished data, 2007) at Sanger Lake is characterized by cool winters (1°C mean temperature) and mild summers (12.7°C mean temperature). The annual precipitation is about 1300 mm with 48% received in the winter and 15% in summer (Bartlein and Shafer, unpublished data). Sanger Lake is slightly more humid in the summer, with lower absolute maximum temperatures, and slightly warmer wetter winters than at Bolan Lake.

Young *Pseudotsuga* (<20 years old) on the south side of Sanger Lake have charred bark and *Chamaecyparis lawsoniana* on the southeast slope of the lake have fire scars, both attesting to recent fire in the watershed. The north slope of the lake supports a young cohort of trees <100 year old, whereas the east and south slopes have trees >300 years old. Fire return intervals (FRI) for *Abies concolor* forests in the region range between 25 and 64 years (Agee, 1993; Skinner et al., 2006), but the Sanger Lake forests likely have a longer FRI as a result of wetter cooler conditions.

Bolan Lake (Lat. 42.023, Long. 123.458, 1638 m elevation, 5 ha) is located in southwestern Oregon on the California/Oregon border about 20 km northeast of Sanger Lake (Figure 2.1). Like Bolan Lake, it also occupies a late-Pleistocene cirque basin underlain by diorite and serpentine and has no inflowing streams. The forest at Bolan Lake is more open than at Sanger Lake and is dominated by *Abies concolor, Pinus monticola* and *Pseudotsuga. Picea breweriana* and *Chamaecyparis lawsoniana* do not grow at the site today. Its warmer, drier setting, with 190 mm less annual precipitation (which occurs mostly in winter as snow), cooler winters (-0.5°C mean temperature), and warmer summers (13°C mean temperature) than at Sanger Lake (Bartlein and Shafer, unpublished data), is likely due to its more inland location..

Regional Vegetation and Fire Patterns

In addition to the *Abies concolor* Zone, five other vegetation zones occur in the Siskiyou region (Franklin and Dyrness, 1988). The Oak Woodland Zone (*Quercus garryana* (Oregon white oak) and *Quercus kelloggii* (California black oak)) occurs up to 800 m elevation and is warmer and drier than other zones. In the Mixed-Evergreen Zone from 800 to 1100 m elevation, *Pseudotsuga*, *Pinus ponderosa* (ponderosa pine), *P. jeffreyi* (Jeffrey pine), *Calocedrus decurrens* and *Lithocarpus densiflora* are common. As conditions become cooler and wetter, *A. concolor* and *Pseudotsuga* become dominant in the Mixed-Conifer Zone, from 1100 to 1300 m elevation. In both the Mixed-Evergreen and Mixed-Conifer zones, mixed-severity fires occur on average every 6-22 years (Taylor and Skinner, 1998). Above the *Abies concolor* Zone, *Abies magnifica* (red fir) and *Tsuga mertensiana* (mountain hemolock) grow from 1900 to 2300 m elevation as conditions become progressively cooler and wetter in the *Tsuga mertensiana* Zone. Fires are generally less frequent and of higher severity in progressively higher zones, with a FRI of >100 yr in the *T. mertensiana*-dominated forests (Skinner et al., 2006).

Fires in the Siskiyou Mountains usually occur with strong winds and low humidity in summer. Critical fire weather includes a persistent upper-level ridge, strong subsidence that suppresses precipitation, and low relative humidity that dries fuels, followed by a weak upper-level trough that causes atmospheric instability, strong winds, and dry thunderstorms with lightning (Agee, 1993). Topographic features determine areas of similar fire occurrence and size (Taylor and Skinner, 2003). Fires have consumed large areas of the Klamath Mountains in recent decades, including the Uncle, Orleans, and Bar fire complexes of 2006 (60,000 ha), the Biscuit Fire of 2002 (202,000 ha), and the Silver Creek Fire of 1987 (74,000 ha). The Biscuit Fire, currently Oregon's largest recorded fire on record and the 7th largest for the U.S, has spurred federal management decisions (e.g. Health Forest Initiative of 2003) and scientific debates (Donato et al., 2006).

Methods

Methods for the analysis of Sanger Lake record are described below. The two records were obtained with similar methods as described by Briles et al. (2005). However, to standardize the treatment of each record, the chronology and charcoal analytical methods used for Bolan Lake were modified from the original publication.

Field and Lithology

A 6.66-m-long sediment core and a 60-cm-short core were recovered from Sanger Lake with a floating platform and a 5-cm-diameter modified Livingstone square-rod piston sampler (Wright et al., 1983). Cores were extruded in the field, wrapped in cellophane and aluminum foil and transported to the laboratory where they were refrigerated. In addition, a 7.5-cm-diameter Klein piston corer was used to capture the mud-water interface and the upper sediments. This core was extruded at 1-cm intervals into plastic bags, and lithology was noted in the field. In the laboratory, long cores were split longitudinally and changes in lithology and color were noted.

Magnetic susceptibility was measured at 1-cm intervals to assess changes in inorganic allochthonous sediment (Gedye et al., 2000). Measurements were made on 10 cm^3 subsamples using a Bartington magnetic susceptibility meter unit and results were reported as cgs. Organic content of the lake sediments was measured as weight-loss after ignition at 550°C in $1cm^3$ samples taken at 2 to 5 cm intervals (Dean, 1974) to evaluate changes in lake productivity through time.

Chronology

Radiocarbon dates were obtained from plant macrofossils (seed, twigs, leaves, etc.) and gyttja at Sanger Lake. Dried sediment from the upper 10 cm of the core was ^{210}Pb dated at the USGS-Denver. Age-depth models were constructed based on radiocarbon and ^{210}Pb dating and tephrochronology from both long and short cores. Radiocarbon ages were calibrated using Calib 5.0.2 (Stuiver et al., 2005) for both Bolan and Sanger lakes and age-depth models were constructed using a cubic smoothing spline and a bootstrap approach that allowed each date to influence the age model through the probability density function of the calibrated age (Higuera et al., 2008). The smoothing parameter for each spline was selected based on the assumption that the predicted ages of each sample must fall within the confidence intervals of the calibrated ^{14}C dates. The overall uncertainty of each age estimate (i.e., two standard deviations) was used to weight the influence of each calibrated age in the age-depth model (e.g., Telford et al., 2004), and confidence intervals, reflecting the combined uncertainty of all age estimates in the model, were derived from 10,000 bootstrap-estimated chronologies. For each bootstrap chronology, the specific ages used to develop the chronology were selected randomly based on the probability distribution of the ^{210}Pb or calibrated ^{14}C date. The final chronology represents the median age of each depth from the 10,000 bootstrap-estimated chronologies.

Pollen

Pollen analyses provided information on the regional and local vegetation history. Pollen was sampled every 50-100 years for the last 2000 years and every 100-200 years for the remainder of the Sanger Lake record. A total of 89 pollen samples were processed using methods of Bennett and Willis (2002). A *Lycopodium* tracer was added to calculate pollen concentration (grains cm^{-3}). Pollen grains were identified at magnifications of 500 and 1250x, and counts ranged from 300 to 530 terrestrial grains per sample with at least 100 non-*Pinus* grains.

Pollen was identified to the lowest taxonomic level possible with reference collections, atlases (e.g., Kapp et al., 2000; Moore and Webb, 1978), and other publications (Jarvis et al., 1992; Hebda et al., 1988a, b). The assignment of pollen taxa was based on modern phytogeography. Haploxylon-type *Pinus* pollen was attributed to *Pinus monticola* but contributions from *P. lambertiana* (sugar pine) and/or minor amounts of *P. balfouriana* (fox tail pine) and *P. albicaulis* (whitebark pine) may also have been included. *Pinus* grains missing a distal membrane were identified as undifferentiated *Pinus*. *Abies* pollen grains were from *A. concolor* and *A. magnifica* and possibly *A. procera* (noble fir; although its range is limited in northern California and does not occur at either site today). *Picea* pollen was attributed to *P. breweriana* or *P. engelmannii* (Engelmann spruce). Cupressaceae grains probably come mostly from *Calocedrus* or *Chamaecyparis lawsoniana* but *Juniperus occidentalis* (western juniper) is also in the region but not near the sites today. *Chrysolepis*-type grains were either from *C. chrysophylla* or *Lithocarpus densiflora*. *Ceanothus* grains were from *C. cuneatus* (buckbrush), *C. integerrimus* (deerbrush), *C. prostratus* (squaw carpet), *C. pumilus* (dwarf ceanothus), *C. thyrsiflorus* (blue blossom ceanothus), or *C. velutinus* (snowbrush ceanothus). *Quercus vaccinifolia*-type pollen was distinguished from *Q. garryana*-type based on coarseness of the sculpturing elements and differences in the apertures (Jarvis et al., 1992). Pollen grains that were broken, corroded, hidden or otherwise damaged were counted as 'Indeterminate', and those that were unidentifiable were counted as 'Unknown.'

Pollen percentages and accumulation rates (PAR; grains cm^{-2} yr^{-1}) were used to reconstruct past vegetation. Percentages of terrestrial upland taxa were based on a sum of pollen from all trees, shrubs, herbs, and pteridophytes. The pollen-percentage record was divided into five zones by use of a constrained cluster analysis (CONISS; Grimm, 1988). PAR were determined by dividing pollen concentrations by deposition time (yr cm^{-1}).

Charcoal

Macroscopic charcoal samples were prepared following methods described by Whitlock and Larsen (2001) and the data was used to reconstruct past fire activity. Sediment samples of 2 cm^3 were taken at contiguous 1-cm intervals and soaked in 5% sodium hexametaphosphate and bleach for 24 hours. They were washed through 250- and 125-micron-mesh screens. Particles in each size class were counted in gridded petri dishes under a stereomicroscope at 50-100x magnification. Charcoal concentrations (number of particles cm^{-3}) from the two size fractions showed similar trends and were combined. Charcoal concentrations and deposition times were interpolated to the median sample resolution of each record (i.e., 20 yr cm^{-1}) to produce equally-spaced intervals within and between records. Charcoal accumulation rates (CHAR, particles cm^{-2} yr^{-1}) were determined by multiplying the interpolated charcoal concentrations (particles cm^{-3}) by the interpolated sedimentation rate (cm yr^{-1}) using CharAnalysis software (http://www.charanalsysis.googlepages.com; Higuera et al., 2008).

To identify peaks in CHAR likely related to local fire occurrence, the CHAR time series was decomposed into two components: 1) a *background component* and 2) a *peaks* *component*. The background component represents long-term variations in charcoal production, secondary transport, sediment mixing, and sediment sampling (Long et al. 1998, Higuera et al. 2007) and was defined by a locally-weighted regression using the tricube weight function with a 700-yr window, robust to outliers (Cleveland, 1979; 5 robustness steps). The peaks component represents high-frequency variability around background and was defined as the residuals after the background component was subtracted. The peaks component can be further separated into two sub-components: non-fire-related variability in CHAR (i.e. analytical and natural noise; assumed to follow a normal or Gaussian distribution) and fire-related CHAR peaks (i.e., signal). A Gaussian mixture model was used to identify the noise component (Gavin et al., 2006, Higuera et al., 2008), and the 95th percentile of this distribution was taken and the threshold value separating fire-related signal from noise in the peaks component (Higuera et al., 2008). The procedure was done on each 700-yr, overlapping portion of the CHAR record, producing a unique threshold for each sample. The individual threshold values were smoothed with a 700-yr tricubic locally-weighted regression to produce the final threshold values for the record. Finally, all peaks exceeding the locally-defined threshold were screened using the original charcoal counts contributing to each peak. If the maximum count in a CHAR peak had a > 5% chance of coming from the same Poisson-distributed population as the minimum charcoal count within the proceeding 75 years, then the "peak" was rejected (e.g. Charster user's guide, accessed March 2007, http://geography.uoregon.edu/gavin/charster/Analysis.html). Statistical treatment of the charcoal records was done using the program CharAnalysis (PEH, available online at http://charanalysis.googlepages.com).

Fire-episode frequency (number of fire episodes 1000 yr^{-1}) was determined by smoothing the binary peak series with a tricubic locally-weighted regression to summarize long-term (i.e., millennial scale) trends. Peak magnitude represents the total accumulation of charcoal for all samples of a peak exceeding the threshold value (particles cm^{-2} $peak^{-1}$). It is thought to be related to fire size, fire intensity, and/or charcoal delivery (Whitlock et al., 2006; Higuera et al., 2007).

Results

The chronology, lithology, charcoal and pollen results for Sanger Lake and chronology, charcoal peak magnitude, and fire-episode frequency results for Bolan Lake are presented below. Lithology, charcoal (background CHAR) and pollen results for Bolan Lake are described in Briles et al. (2005).

Chronology

The Sanger Lake chronology was based on 23 ^{14}C AMS dates on terrestrial plant macrofossils and gyttja found in the long core and seven ^{210}Pb age determinations on the upper sediments of the short core. Mazama Ash, at 3.96 m depth, was assigned an age of 6845 ± 50 ^{14}C BP (Bacon, 1983) and included in the chronology (Table 2.1; Figure 2.2a). A date just below the Mazama Ash layer (3.97 m depth) yielded a younger radiocarbon date than the accepted age of the ash layer; however, the range of calibrated dates

Table 2.1

Uncalibrated and calibrated ^{14}C and ^{210}Pb ages for Sanger Lake

Depth (m)[a]	Predicted age (cal yr BP; med. Prob.)[b,d]	Upper age range (cal yr BP)[c]	Lower age range (cal yr BP)[c]	^{14}C age BP	±	Material dated	Reference[e]
0.01	-48	-48.20	-47.80	-	-	gyttja ^{210}Pb	USGS-Denver
0.02	-40	-40.50	-39.50	-	-	gyttja ^{210}Pb	USGS-Denver
0.03	-31	-31.90	-30.10	-	-	gyttja ^{210}Pb	USGS-Denver
0.04	-22	-23.50	-20.50	-	-	gyttja ^{210}Pb	USGS-Denver
0.05	-13	-14.90	-11.10	-	-	gyttja ^{210}Pb	USGS-Denver
0.06	-4	-6.30	-1.70	-	-	gyttja ^{210}Pb	USGS-Denver
0.07	2	-0.30	4.30	-	-	gyttja ^{210}Pb	USGS-Denver
0.57	684	731	640	625	30	Twig	CAMS112965
0.79	699	747	655	1220	35	Needle	CAMS112995
1.415	714	763	670	1995	35	Needle	CAMS112966
1.64	2233	2293	2177	2215	35	Needles	CAMS119619
2.16	3001	3064	2947	2910	35	Wood	CAMS112967
2.42	3478	3533	3428	3205	35	Needle	CAMS112968
2.64	3979	4034	3921	3580	35	Wood	CAMS112969
3.25	5702	5757	5627	5035	35	Wood	CAMS118758
3.34	5955	6010	5881	5150	35	Leaf	CAMS112970
3.75	6992	7040	6940	6135	40	Wood	CAMS112971
3.96	7412	7452	7368	6845	50	Mazama Ash	Bacon, 1983
3.97	7430	7469	7386	6430	35	Needles	CAMS119619
4.26	7897	7942	7848	7005	35	Twig	CAMS118760
4.415	8144	8199	8085	7300	40	Wood	CAMS112972
4.775	8902	8983	8815	8060	45	Wood	CAMS112973
5.135	9901	10000	9815	8795	45	Wood	CAMS112974
5.395	10909	11002	10829	9455	35	cone scale	CAMS112996
5.4	10953	11046	10873	9625	45	Gyttja	CAMS118761
5.58	11810	11892	11734	10060	40	Gyttja	CAMS118762
5.68	12330	12406	12256	10435	50	Gyttja	CAMS118763
5.83	13143	13220	13071	11460	70	Gyttja	CAMS118764
5.95	13805	13892	13724	12025	40	Gyttja	CAMS112994
6.23	Too old	Too old	Too old	15720	510	Gyttja	CAMS112993

[a] Depth below mud surface.

[b] ^{14}C calibrated ages derived using a Monte Carlo approach based on the probability distribution function of all ^{14}C ages in the age-depth model (see Methods; Calib 5.0.2; Stuiver et al., 2005).

[c] 95% confidence interval based on 10,000 runs.

[d] ^{210}Pb dates were adjusted for the 53 years (the core was taken in 2003) since 1950 A.D. before being considered with the radiocarbon dates.

[e] ^{210}Pb ages and errors from USGS-Denver.

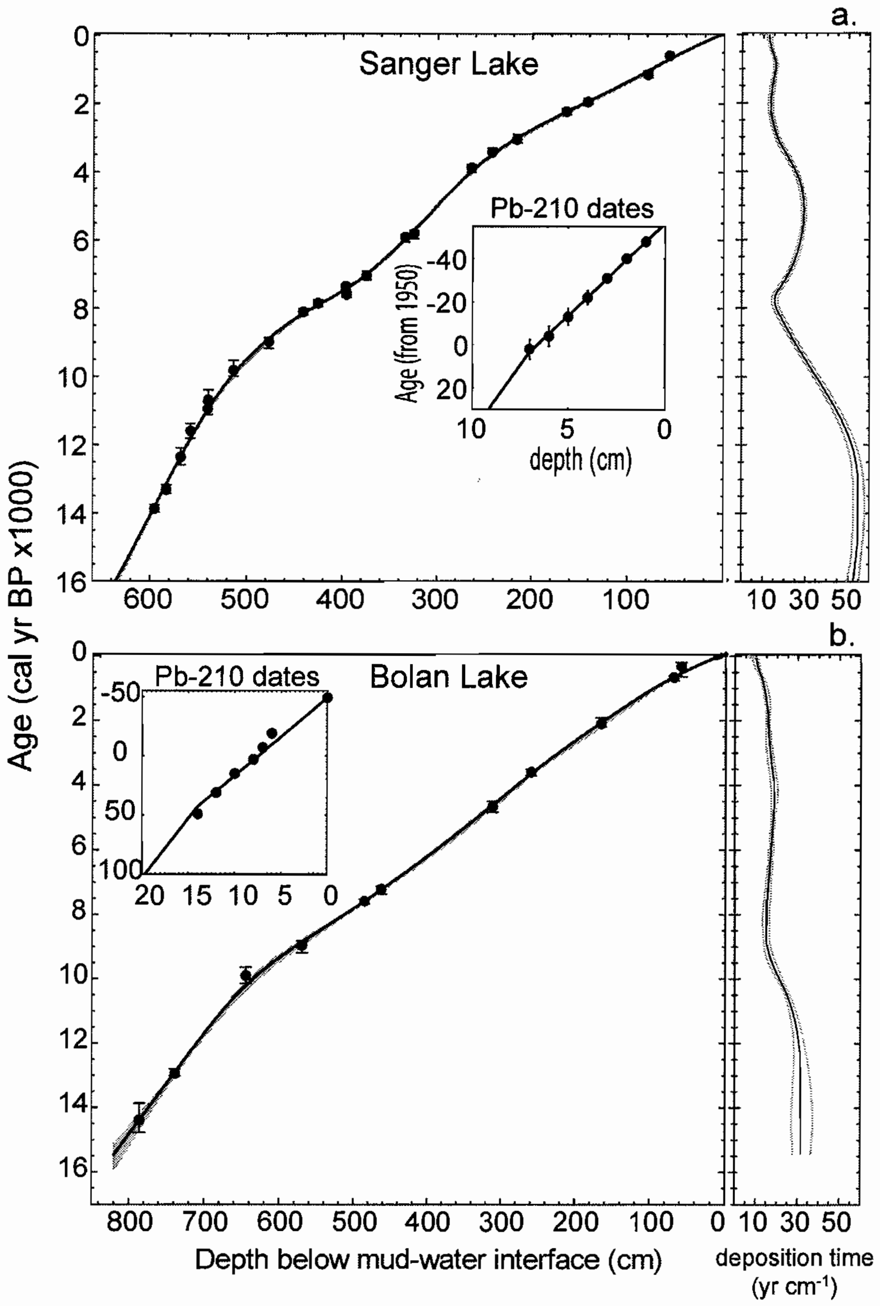


Figure 2.2. Age-versus-depth curves and deposition time for (a) Sanger Lake and (b) Bolan Lake based on ^{14}C and ^{210}Pb dates, and tephrochronology. The gray band reflects the modeled range of dates and deposition times and the black line the 50th (i.e., median age) percentile of all runs. Circles and bars reflect the 50th, 2.5th (i.e., lower age) and 97.5th (i.e., upper age) percentiles of the probability distribution function of calibrated dates. See Table 2.1 and Table 2.2 for age information.

overlap, which suggest the dates could be in stratigraphic order. A radiocarbon date on inorganic clay at the bottom of the long core (6.23 m depth) yielded an anomalously old calibrated age (~19,000 cal yr BP), earlier than the timing of deglaciation in the Pacific Northwest (after 17,000 cal yr BP) (Porter & Swanson 1998; Clark & Gillespie 1997) and large laboratory error. The date was left out of the chronology.

A new age model was constructed for Bolan Lake, following the same methods described for Sanger Lake, in order to utilize the new radiocarbon calibration curve (IntCal04; Reimer et al., 2004) and the bootstrapping approach for determining an age model (Table 2.2; Figure 2.2b). In most cases, the old chronology fell within the upper and lower confidence intervals; however, between -49 and 2150 cal yr BP, the ages exceeded the lower confidence interval up to 60 years, between 6800 and 8000 cal yr BP up to 37 years, and between 11,000 and 13,250 cal yr BP up to 125 years. The new Bolan Lake age-depth model is used in this paper; however, the new chronology did not substantially change the interpretations in Briles et al. (2005).

Lithology

The Sanger Lake long core contained two distinct lithological units (Figure 2.3). The first unit (6.00 to 6.66 m depth; >14,200 cal yr BP) was an inorganic clay with sand layers (<4% organic matter, >60x10^{-6} cgs magnetic susceptibility values) that preserved little to no pollen and charcoal. The second unit (6 to 0 m depth; <14,200 cal yr BP) consisted of mainly fine-detritus gyttja with abundant pollen and charcoal. Between 6.00 to 5.16 m depth (14,200 and 10,000 cal yr BP), magnetic susceptibility decreased from 60

Table 2.2

Uncalibrated and calibrated ^{14}C and ^{210}Pb ages for Bolan Lake.

Depth (m)[a]	**Predicted age (cal yr BP; med. Prob.)**[b,d]	**Upper age range (cal yr BP)**[c]	**Lower age range (cal yr BP)**[c]	**^{14}C age BP**	**±**	**Material dated**	**Reference**[e]
0.06	-19	-	-	-	-	gyttja ^{210}Pb	UWM
0.07	-7	-	-	-	-	gyttja ^{210}Pb	UWM
0.08	3	-	-	-	-	gyttja ^{210}Pb	UWM
0.1	15	-	-	-	-	gyttja ^{210}Pb	UWM
0.12	31	-	-	-	-	gyttja ^{210}Pb	UWM
0.14	49	-	-	-	-	gyttja ^{210}Pb	UWM
0.59	523	564	452	267	46	cone scale & needle	AA40215
0.71	670	719	589	708	41	Wood	AA40214
1.66	2057	2192	1982	2123	35	leaf & charcoal	AA44436
2.6	3637	3717	3549	3354	39	cone scale	AA44437
3.12	4603	4712	4496	4120	45	Wood	NSRL12159
4.63	7222	7280	7143	6290	45	Wood	NSRL12160
4.86	7583	7636	7517	6845	50	Mazama ash	Bacon, 1983
5.7	8854	8975	8717	8060	50	Wood	NSRL12161
6.45	10204	10369	10045	8827	62	Wood	AA40217
7.39	12895	13023	12796	11010	65	Wood	NSRL12162
7.86	14382	14697	14139	12360	120	Gyttja	WIS2085

[a] Depth below mud surface.

[b] ^{14}C calibrated ages derived using a Monte Carlo approach based on the probability distribution function of all ^{14}C ages in the age-depth model (see Methods; Calib 5.0.2; Stuiver et al., 2005).

[c] 95% confidence interval based on 10,000 runs. ^{210}Pb errors not specified by laboratory.

[d] ^{210}Pb dates were adjusted for the 53 years (the core was taken in 2003) since 1950 A.D. before being considered with the radiocarbon dates.

[e] ^{210}Pb ages based on concentration data provided by the center for Great Lake Studies, University of Wisconsin-Milwaukee (UWM; see Briles et al., 2005).

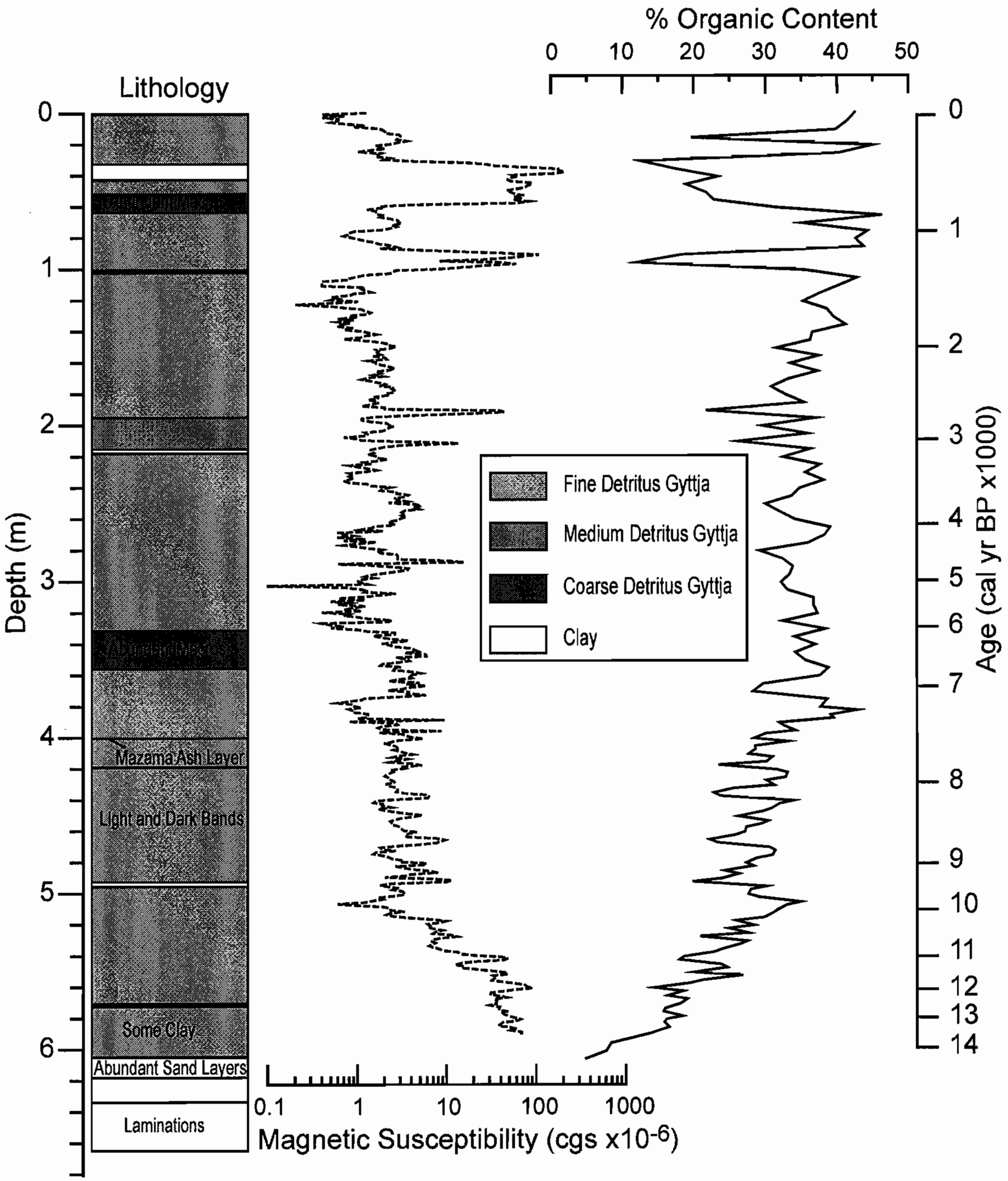


Figure 2.3. Lithology, magnetic susceptibility (dashed line) and percent organic content (solid line) from Sanger Lake.

to 8×10^{-6} cgs, and organic carbon content increased from 4 to 30%. Magnetic susceptibility between 5.16 and 1.06 m depth varied between 8 and 10 $\times 10^{-6}$ cgs. A 7 cm-thick clay layer was deposited from 0.42 to 0.36 m depth (380 and 470 cal yr BP), and occurred at approximately the same depth and thickness across the lake based on multiple gravity cores taken across the basin by Briles. Thin clay layers were also present at 1.01 m depth (1360 cal yr BP), 2.18 m depth (3030 cal yr BP), and 4.95 m depth (9340 cal yr BP). Organic carbon steadily increased between 6.00 and 3.76 m depth from 30 to 40% (10,000 to 7000 cal yr BP), dropped to 35% between 3.76 and 1.47 m depth (7000 to 2000 cal yr BP), and increased to 45% toward the top of the core.

Charcoal Record

Sanger Lake

Fire activity at Sanger Lake since14,500 cal yr BP fluctuated between 1.5 and 6.9 fire episodes 1000 yr^{-1} and background CHAR between 0.01 and 0.94 particles cm^{-2} yr^{-1} (Figure 2.4). The late-glacial period (>10,400 cal yr BP) recorded the lowest background CHAR (<0.2 particles cm^{-2} yr^{-1}) and low fire activity (1.5 to 3.7 fire episodes 1000 yr^{-1}). Peak magnitudes were small during this period (<9 particles cm^{-2} $peak^{-1}$).

Background CHAR increased from 0.2 to 0.84 particles cm^{-2} yr^{-1} between 10,400 and 6000 cal yr BP. Fire activity increased from 3.7 to 6.5 fire episodes 1000 yr^{-1} between 10,400 and 9200 cal yr BP and then decreased to 4.4 fire episodes 1000 yr^{-1} by 7200 cal yr BP. Peak magnitudes increased after 8450 cal yr BP to ~50 particles cm^{-2} $peak^{-1}$,

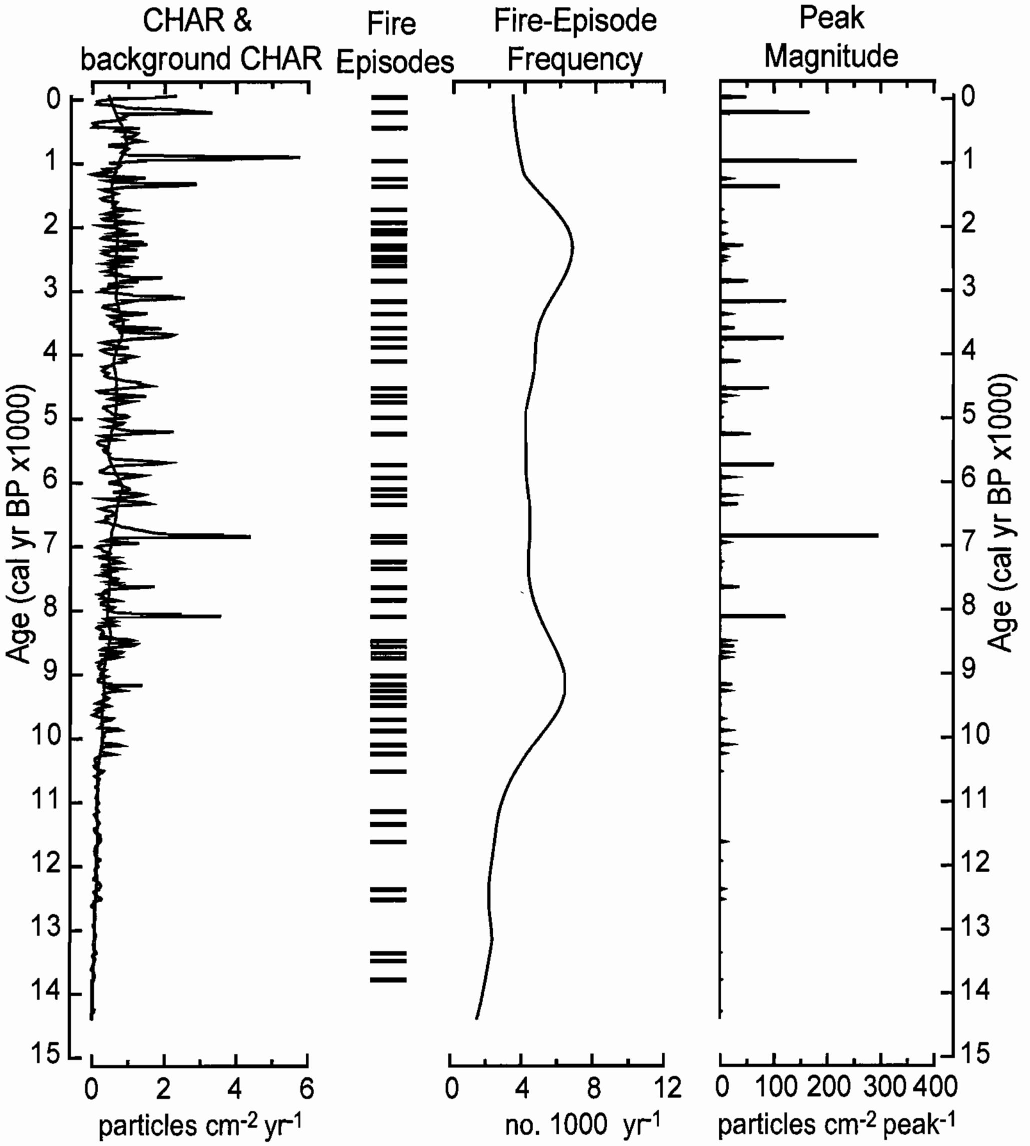


Figure 2.4. Charcoal accumulation rates (CHAR) for the last 14,500 cal yr at Sanger Lake. Accumulation rates were decomposed into background CHAR (the slowly varying curve overlying the accumulation rate curve; window-width = 700 yr) and peaks or fire episodes. The fire-episode frequency shows the number of peaks 1000 yr^{-1}, based on a 2500 year smoothing window. Peak magnitude (particles cm^{-2}) measures fire size, fire intensity, and/or charcoal delivery.

ending with a large peak (>300 particles cm^{-2} $peak^{-1}$) at 6900 cal yr BP (the largest peak of the record and spanning several samples).

Background CHAR declined after 6000 cal yr BP, fluctuating between 0.6 and 0.8 particles $cm^{-2}yr^{-1}$ until 1250 cal yr BP when it increased and reached the highest levels of the record at 660 cal yr BP (0.94 particles $cm^{-2}yr^{-1}$). Background CHAR then declined between 660 and the present to 0.45 particles cm^{-2} yr^{-1}. Fire activity continued to decline slightly between 7200 and 5300 cal yr BP to a 4.2 fire episodes 1000 yr^{-1} and then increased and reached the highest levels of the record by 2200 cal yr BP (6.9 fire episodes 1000 yr^{-1}). Fire-episode frequency declined after 2200 cal yr BP to 3.5 episodes 1000 yr^{-1} and was comparable to fire-episode frequencies of the late-glacial period. Peak magnitudes averaged ~100 particles cm^{-2} $peaks^{-1}$ between 6900 and 3000 cal yr BP, dropped to ~50 particles cm^{-2} $peaks^{-1}$ between 3000 and 1250 cal yr BP, and increased to ~200 particles cm^{-2} $peaks^{-1}$ between 1250 and the present.

Bolan Lake

Peak magnitudes were small (<35 particles cm^{-2} $peaks^{-1}$) between 14,000 and 11,800 cal yr BP, except for a large peak at 13,800 cal yr BP (380 particles cm^{-2} $peaks^{-1}$). A mix of large (300 to >400 particles cm^{-2} $peaks^{-1}$) and small (1 to <70 particles cm^{-2} $peaks^{-1}$) peak magnitudes occurred between 11,800 and 9500 cal yr BP. Small peaks (<100 particles cm^{-2} $peaks^{-1}$) occurred between 9500 and 6000 cal yr BP. Between 6000 cal yr BP and the present, the record was characterized by small-magnitude peaks (<50 particles

cm^{-2} $peaks^{-1}$) for 1000-year time spans and these were interrupted by a large-magnitude peak of >300 particles cm^{-2} $peaks^{-1}$.

Fire-episode frequency and background CHAR for Bolan Lake are described in full in Briles et al. (2005), however, fire-episode frequency is presented here again for purposes of comparing it with the Sanger Lake record in the Discussion section. Peak magnitudes were analyzed and presented below. Fire-episode frequency over the last 14,500 cal yr B.P. varied between 4 and 10 episodes 1000 yr^{-1}. Between 14,500 and 10,900 cal yr B.P., fire-episode frequency fluctuated between 3 and 7 episodes 1000 yr^{-1}, with the highest frequency at 13,000 cal yr B.P. and the lowest frequency at 14,000 and 11,500 cal yr B.P. (4 and 3 episodes 1000 yr^{-1}). Fire-episode frequency increased from 4 to 8 episodes 1000 yr^{-1} between 11,500 and 9200 cal yr B.P., declined to 7 episodes 1000 yr^{-1} between 9200 and 8500 cal yr B.P., and increased to 10 episodes 1000 yr^{-1}, the highest values of the record, by 7000 cal yr B.P. Fire-episode frequency steadily declined from 10 to 7 episodes 1000 yr^{-1} between 7000 and 3500 cal yr B.P., increased slightly from 7 to 8 episodes 1000 yr^{-1} between 3500 and 2500 cal yr B.P., decreased to 7 episodes 1000 yr^{-1} between 2500 and 1500 cal yr B.P. and then increased to 9 episodes 1000 yr^{-1} toward the present.

Sanger Lake Pollen Record

The Sanger Lake pollen record was divided into five zones (Figure 2.5):

Zone SA-1 (6.04-5.65 m depth; 14,200 to 12,000 cal yr BP) featured high percentages of haploxylon *Pinus*, *Tsuga*, *Picea* and increasing percentages of *Abies*

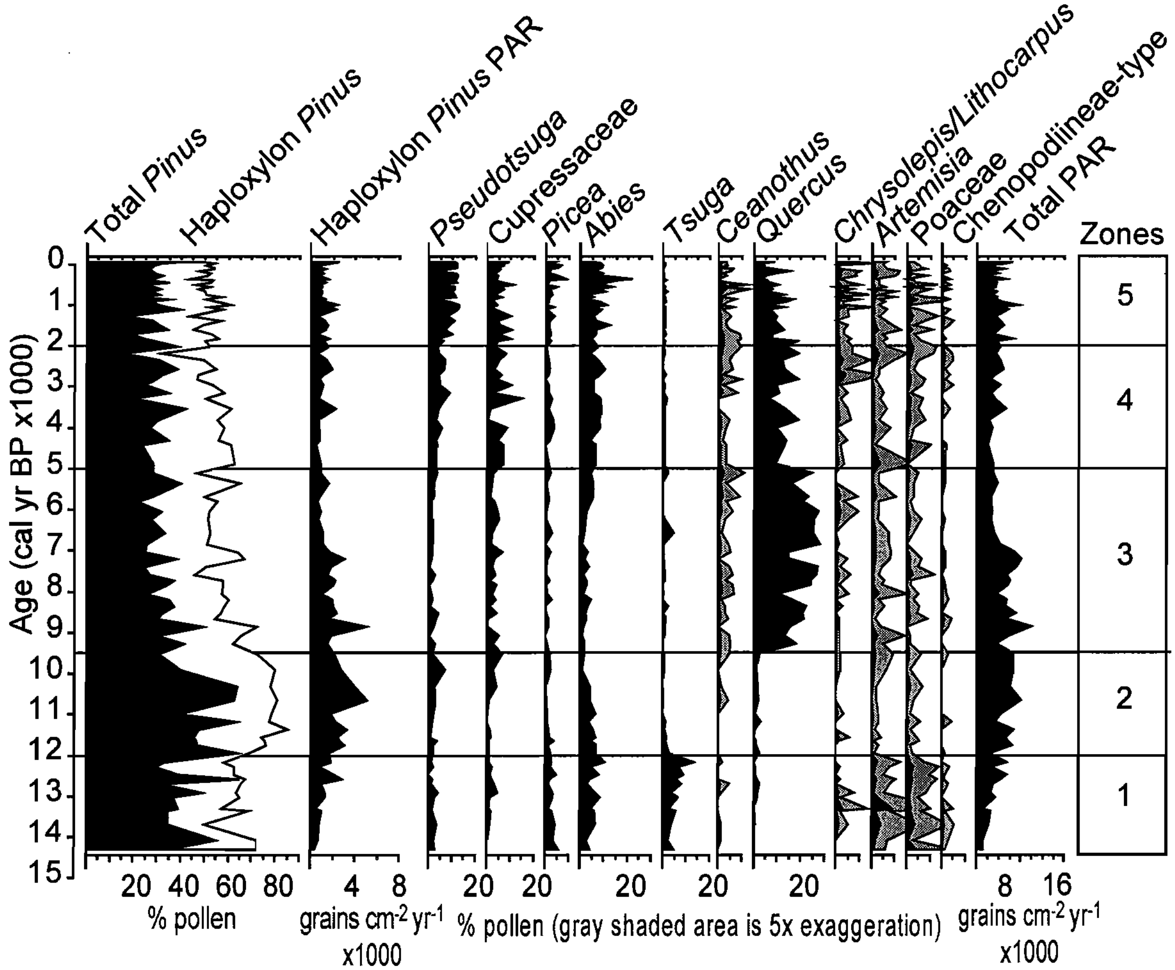


Figure 2.5. Pollen percentages of select taxa, total pollen accumulation rate (PAR) and haploxylon *Pinus* PAR from Sanger Lake.

concolor. Moderate percentages of *Artemisia*, Poaceae and Chenopodiineae and low but increasing pollen accumulation rates (PAR; 1000-3000 grains $cm^{-2}yr^{-1}$) suggest that the forest was initially open and became more closed (Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967). The forest composition was probably most similar to open forests of the *Tsuga mertensiana* Zone.

Zone SA-2 (5.65-5.01 m depth; 12,000 to 9600 cal yr BP) contained the highest percentages of haploxylon *Pinus* and high percentages of *Abies*. *Tsuga* dropped to low percentages and remained low for the rest of the record. *Pseudotsuga* and Cupressaceae percentages increased, especially between 9500 and 10,500 cal yr BP. *Artemisia*, Poaceae and Chenopodiineae percentages declined and PAR increased to the highest levels of the record (6000-8000 grains $cm^{-2}yr^{-1}$) suggesting that the forest became more closed than before (Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967). The pollen types represented in this zone come from taxa growing in the *Abies concolor* Zone today.

Zone SA-3 (5.65-3.05 m depth; 9600 to 5000 cal yr BP;) had high percentages of *Quercus* and low-to-moderate percentages of *Ceanothus*. Haploxylon *Pinus* percentages dropped to comparable amounts in Zone 1; however, PAR for the taxon dropped but remained higher than in Zone 1. The significantly increased percentages of *Quercus* likely resulted in an under representation of the haploxylon *Pinus* percentages in this zone as suggested by PAR. Cupressaceae percentages were the highest of the record. *Pseudotsuga* and *Abies* percentages were low. The forest composition was similar to present-day Mixed-Evergreen forests ~500 m below the watershed today (Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967).

Zone SA-4 (3.05-1.49 m depth; 5000 to 2000 cal yr BP) was characterized by increasing percentages of *Abies* and *Pseudotsuga. Ceanothus* and *Chrysolepis* percentages peaked between 2000 and 3000 cal yr BP. Cupressaceae percentages remained comparable to those in Zone 3. Haploxylon *Pinus* PAR continued to decrease to 1000 grains $cm^{-2}yr^{-1}$, while percentages remained similar to Zone 3. *Quercus* percentages decreased through the zone. The forest during this time was similar to the Mixed-Conifer Zone located ~200 to 300 m downslope today (Solomon and Silkworth, 1986).

Zone SA-5 (1.49-0 m depth; 2000 cal yr BP to present) featured the highest percentages of *Pseudotsuga* and *Picea* of the record. *Pseudotsuga*, *Quercus*, *Ceanothus*, *Artemisia*, and Poaceae were high between 2000 and 1200 cal yr BP and then decreased thereafter. *Picea* and *Abies* had increased percentages between 1200 cal yr BP and present. The modern forest became established at Sanger Lake within the last 2000 cal yr.

Discussion

The vegetation and fire records of Sanger Lake and Bolan Lake are compared in the following section (Figure 2.6). In addition, a brief overview is presented on what is currently known about the regional climate history of the last 14,000 cal yr BP inferred

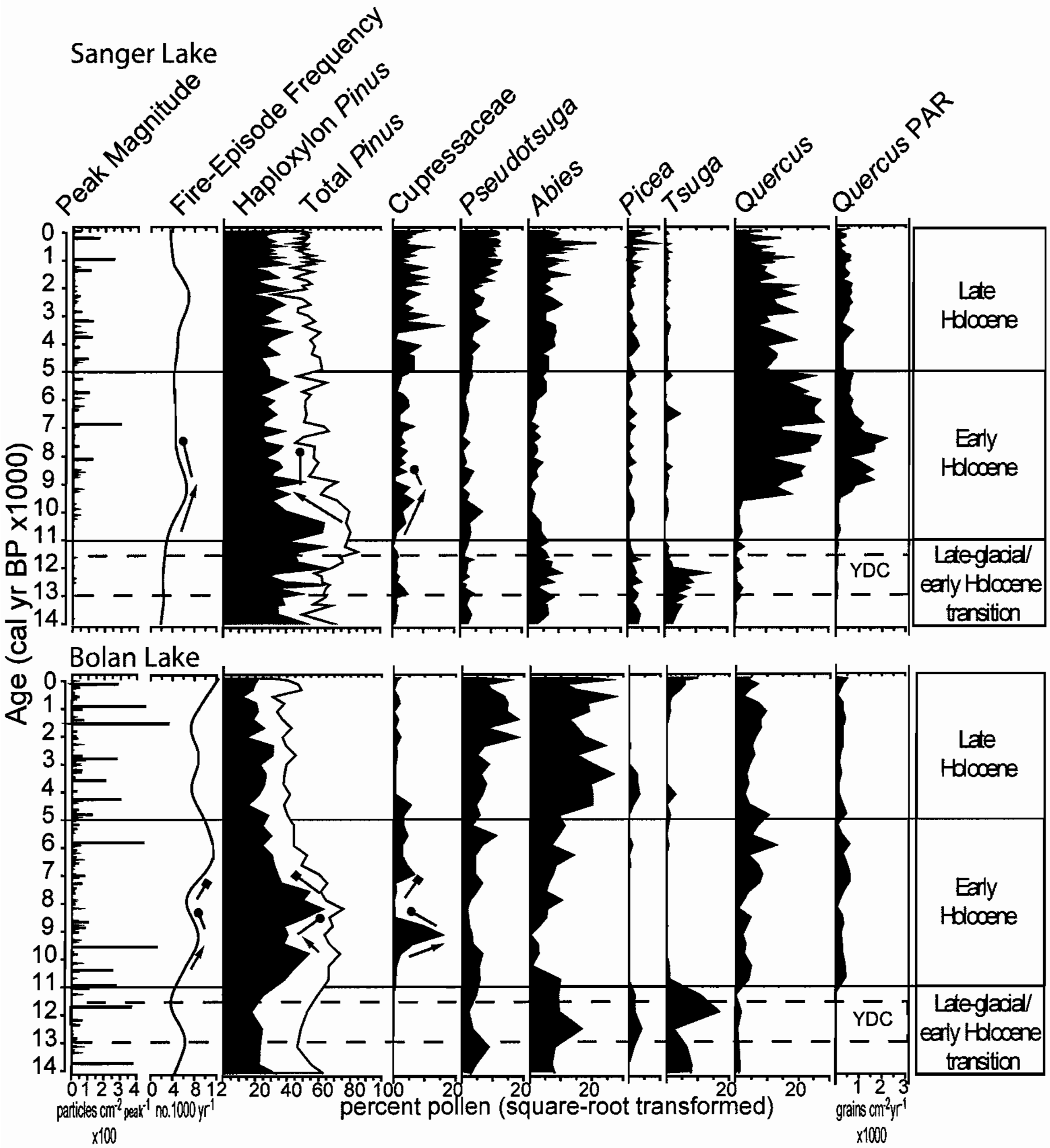


Figure 2.6. Fire episodes, peak magnitude, and frequency, and pollen percentages for Sanger and Bolan lakes. *Quercus* pollen accumulation rates (PAR) are also included. The arrows show the relationship between fire-episode frequency, Cupressaceae, and haploxylon *Pinus* (likely *Pinus monticola*) at the two sites. Increased fire-episode frequency (triangle and square arrows) is followed by a period of increased Cupressaceae and decreased *Pinus monticola*. The opposite occurs when fire-episode frequency decreases (circle arrow). The Younger Dryas chronozone (YDC) is defined by the dashed line.

from climate model simulations and ocean and terrestrial paleoclimate records (Bartlein et al, 1998; Barron et al., 2003; Vacco et al, 2005).

Late-glacial/Early Holocene Transition Period (>11,000 cal yr BP)

Paleoclimate model simulations for 14,000 cal yr BP suggest that increasing summer insolation resulted in summers that were warmer than before in the PNW, but still cooler and drier than present (Bartlein et al., 1998). Core ODP 1019 (Barron et al, 2003), located at the same latitude as Sanger Lake and ~50 km offshore, recorded sea surface temperatures (SST) that were 1°C less than the present day (12°C) using alkenone-derived mean annual SST estimates between 15,000 and 13,000 cal yr BP. An abundance of diatoms between 14,600 to 12,900 cal yr BP from ODP 1019 suggests upwelling of colder bottom ocean waters (Barron et al., 2003). *Pinus* and *Artemisia* pollen found in marine ocean cores declined, and *Alnus* increased, suggesting that conditions were becoming warmer and wetter on land than before.

Sanger and Bolan lakes were colonized by a subalpine parkland between 14,000 and 12,000 cal yr BP, and this vegetation was widespread across the region (Figure 2.6; Daniels et al., 2005; Mohr et al., 2000). The lack of a tundra period prior to this forested period is consistent with rapid warming conditions following deglaciation. *Tsuga*, *Abies*, *Picea* and haploxlyon *Pinus* (likely *Pinus monticola*) were the dominant forest species. The gradual increase in percentages of *Tsuga*, *Abies* and in PAR suggests a closing of the forest at this time. *Tsuga* would have been favored by deep spring snowpacks and a short mild growing season (Peterson and Peterson, 2001). Fire-episode frequency and peak magnitudes were higher at Bolan Lake than Sanger Lake at this time, suggesting that fires may have been larger and/or more intense at Bolan Lake and/or produced more charcoal.

Between 12,900 and 11,600 cal yr BP (i.e., during the Younger Dryas chronozone, Alley, 1993), alkenone-derived mean annual SST estimates from ODP 1019 abruptly dropped to <8°C and diatom production decreased suggesting reduced coastal upwelling (Barron et al., 2003). After 11,600 cal yr BP, mean annual SSTs increased more than 5°C within a 500-year period and diatom abundances remained low. Barron et al. (2003) attribute these changes to the Younger Dryas cool period (11,500 to 12,900 cal yr B.P.; Alley, 1993). This eastern Pacific cool event and subsequent abrupt warming are recorded in ocean records to the north and south of ODP 1019 (Kienast and McKay, 2001; Mortyn, 1996). An isotopic record from speleothems from the Oregon Caves National Monument (~20 km north of Bolan Lake) suggests that land atmospheric temperatures dropped more than 3°C after 13,000 cal yr BP for a 1200-year period and then abruptly increased (Vacco et al., 2005).

No distinctive or synchronous vegetation or fire change has been detected during the YD chronozone in the PNW region (Daniels et al, 2005; Mohr et al., 2000; Grigg and Whitlock, 1998). Bolan and Sanger lakes show increasing *Tsuga* suggesting that conditions were becoming warmer and wetter than before. *Tsuga* declined after 12,000 cal yr BP at Sanger Lake, but was in greatest abundance at Bolan Lake until 11,500 cal yr BP. Haploxylon *Pinus* (and total *Pinus*) increased at Sanger Lake at 12,000 cal yr BP and around 500 years later at Bolan Lake. The fire regimes at the two sites were also different after 12,500 cal yr BP. Fire-episode frequency at Sanger Lake increased slowly and peak magnitudes were low through the period, whereas at Bolan Lake, frequency was high until 12,500 cal yr BP, declined to the lowest levels of the record at 11,500 cal yr BP and increased thereafter. Peak magnitudes also increased after 11,500 cal yr BP at Bolan Lake indicating that fires were large and/or intense. Increasing fire activity at Sanger Lake after 12,000 cal yr BP was likely responsible for the abundance of haploxylon *Pinus* (likely *Pinus monticola*). *P. monticola* is a seral species that relies on disturbances to remove competing vegetation for regeneration (Burns and Honkala, 1990).

Reduced upwelling that resulted in warmer conditions at Sanger Lake after 12,000 cal yr BP, is likely responsible for the loss of *Tsuga* and establishment of a forest with more *Pinus monticola* and increasing fire activity. Sanger Lake became more productive, as evidenced by increased organic content, whereas Bolan Lake remained relatively unproductive until 11,000 cal yr BP (Briles et al., 2005). At Bolan Lake, clastic minerals and the presence of pebbles in gyttja suggest more avalanche or glacial activity in the watershed. Therefore, the more inland location of Bolan Lake may have permitted cooler wetter conditions to persist 500 to 1000 years longer than at Sanger Lake.

Early and Middle Holocene (11,000 to 5,000 cal yr BP)

Paleoclimate simulations for 11,000 cal yr BP suggest that higher-than-present summer insolation in the early Holocene led to the expansion and intensification of the northeastern Pacific subtropical high pressure system, and continental heating and drying in the Pacific Northwest (Bartlein et al., 1998). From 11,000 to 8200 cal yr BP, alkenone-derived mean annual SSTs from ODP 1019 were up to 1°C above modern levels, and then decreased to 1°C below modern conditions between 8200 and 3300 cal yr BP (Barron et al., 2003). In addition, warm-water diatoms between 11,600 and 8200 cal yr BP, suggest a weak California Current and reduced upwelling. Cool-water diatoms increased between 8200 and 3300 cal yr BP reflecting a stronger California Current and increased upwelling.

Major changes in vegetation and fire activity were registered at Bolan and Sanger lakes during the early Holocene (Figure 2.6). Both sites show a decrease in the abundance of *Abies* at 11,000 cal yr BP and *Pseudotsuga* at 10,000 cal yr BP. *Abies* and *Pseudotsuga* occur in lowest abundance during the summer insolation maximum between 10,000 and 9000 cal yr BP, which is not surprising since the species do best in wetter environments today. As summer insolation decreased, between 9000 and 5000 cal yr BP, *Abies* and *Pseudotsuga* increased in abundance, responding to the cooler and wetter summer conditions than before. The changes in *Abies* during the early Holocene are similar to those found at other sites in the Klamath Mountains (Daniels et al, 2005; Mohr et al, 2000).

Understory shrubs, *Quercus* and *Ceanothus*, became abundant at Bolan and Sanger lakes and at other sites in the Klamath region during the early Holocene (Daniels et al, 2005; Mohr et al, 2000). *Ceanothus* increased after 11,000 cal yr BP, and *Quercus* increased at Bolan Lake ca. 11,000 cal yr BP and at Sanger Lake ca. 9500 cal yr BP. *Ceanothus* species favor warm dry conditions and require fire to regenerate. *Quercus* is a shrub that does well in warm and especially dry conditions, has resinous leaves that carry fire from the understory into the forest canopy, and sprouts from the root crown following fire (Burns and Honkala, 1990). The presence of these species at both sites is consistent with a period of high fire-episode frequency.

The delayed expansion of *Quercus* in the early Holocene at Sanger Lake, compared with Bolan Lake, is likely the result of wetter conditions there compared with drier inland conditions resulting from intensified summer heating. Interestingly, PAR of *Quercus* increased abruptly, and fire was frequent at Sanger Lake around 9200 cal yr BP, the summer insolation maximum. Both *Quercus* PAR and fire activity declined until 7000 cal yr BP, during a period when SSTs dropped and upwelling increased (Barron et al., 2003). In contrast, PAR of *Quercus* at Bolan Lake peaked ca. 7000 cal yr BP, when fire-episode frequency was highest, and decreased after 5500 cal yr BP, suggesting that warm dry conditions and high fire activity persisted for a longer period at Bolan Lake.

The trade-offs between Cupressaceae (likely incense cedar) and haploxylon *Pinus* (likely *Pinus monticola*) recorded at Bolan Lake are less evident at Sanger Lake (Figure 2.6). At Bolan Lake, haploxylon *Pinus* increased at 11,000 cal yr BP when fire-episode frequency was low, decreased between 10,000 and 9000 cal yr BP, and was replaced by Cupressaceae when fire-episode frequency increased. Haploxylon *Pinus* then increased between 9000 and 8000 cal yr BP at the expense of Cupressaceae, as fire-episode frequency decreased, and dropped after 8000 cal yr BP as Cupressaceae increased and fire-episode frequency increased. It was suggested by Briles et al (2005) that centennial-scale climate variations and fire might be responsible for these variations (i.e., cooler climate and decreasing fire favored haploxylon *Pinus*, whereas a warmer climate and increasing fire maintained more Cupressaceae). At Sanger Lake, haploxylon *Pinus* was abundant between 11,000 and 10,000 cal yr BP when fires were infrequent but increasing, and Cupressaceae (likely incense cedar and/or Port-Orford cedar) was not abundant. After 10,000 cal yr BP, Cupressaceae increased slightly at the expense of haploxylon *Pinus* as fire frequency increased until 9200 cal yr BP. After 9200 cal yr BP, fire frequency and Cupressaceae decreased slightly with little change in haploxylon *Pinus* abundance. Unlike Bolan Lake, no additional trade-offs in the two species are recorded at Sanger Lake after 9200 cal BP. Apparently, the more xeric conditions and greater incidence of fire at Bolan Lake allowed the trade-offs between haploxylon *Pinus* and Cupressaceae to persist longer than at Sanger Lake. Given that there is a short-lived and subdued response of haploxylon *Pinus* and Cupressaceae at Sanger Lake, the trade-off in the two species at Bolan Lake and the associated changes in fire cannot be attributed to centennial-scale climate variations based on these two records alone.

Late Holocene (5000 cal yr BP to present)

Paleoclimate simulations for 6000 cal yr BP indicate that decreasing summer insolation likely resulted in cooler wetter summers than before, and a weaker northeastern Pacific subtropical high-pressure system in summer than previously (Bartlein et al., 1998). In the winter, increasing solar radiation resulted in warmer and likely wetter winters than before. Alkenone-derived mean annual SSTs from ODP 1019 were initially low (~11°C) at 5000 cal yr BP, and then increased by 1°C after 3300 cal yr BP (Barron et al., 2003). The abundance of *Sequoia* pollen found in the ocean sediments from ODP 1019 suggests more upwelling and increased fog production in spring and summer than before.

Abies and *Pseudotsuga* were found in abundance in the Sanger and Bolan records, and had very similar histories at the two sites through the late Holocene (Figure 2.6). Between 5000 and 2500 cal yr BP, *Abies* reached late-glacial abundances at both sites and then decreased after 2500 cal yr BP. *Pseudotsuga* reached its greatest abundance at both sites within the last 2500 years. This is consistent with gradual warming though the late Holocene and suggests wetter conditions occurred in the earlier part and drier during the latter part of the late Holocene. Fire-episode frequency also increased at both sites, approaching (Sanger Lake) or exceeding (Bolan Lake) frequencies of the early Holocene. The increase in *Pseudotsuga* in the last 2500 years is consistent with the high fire frequency and peak magnitudes at both sites.

Both sites show an abundance of haploxylon *Pinus*, *Pseudotsuga*, and *Quercus* between 2000 and 1200 cal yr BP, and a drop in abundance of these taxa and replacement of *Abies* after 1200 cal yr BP. Within the last 300 years, a significant increase in *Picea* occurred in the forest at Sanger Lake, whereas *Tsuga* increased at Bolan Lake, perhaps in response to Little Ice Age cooling (500-100 cal yr BP; Taylor, 1995). The higher snowpack and proximity of high-elevation peaks around Bolan Lake may account for the increase in *Tsuga* instead of *Picea breweriana.* Today, the high peaks in the Bolan Lake watershed support more *Tsuga*, whereas Sanger Lake has a minor component of *Tsuga*, but abundant *Picea breweriana.* One of the longest periods without fire occurred in the last 1000 years at Sanger Lake, while fire activity at Bolan Lake declined slightly between 2500 and 1700 cal yr BP and then increased toward the present day. Sanger Lake also maintained an abundance of Cupressaceae (likely *Chamaecyparis lawsoniana*) over the last 5000 cal yr BP, while at Bolan Lake it was a minor component of the forest and more likely *Calocedrus decurrens*. A detailed macrofossil study is needed to determine the exact species in the watersheds. The abundance of *Picea breweriana*, Cupressaceae, and infrequent fires are likely due to Sanger Lake's more maritime climate. The peak abundances of *Sequoia* pollen in ODP 1019, especially in the last 1000 years, suggests an increase in wetter conditions than before, and may account for the drop in fire-episode frequency at Sanger Lake. However, at Bolan Lake, peak fire-episode frequency suggests that this shift to wet conditions was restricted to the coastal regions. In addition, within the last 1000 years, several clay layers and peaks in magnetic susceptibility at Sanger Lake may represent erosional episodes as a result of increased heavy precipitation events resulting in debris flows, and these were not apparent at Bolan Lake. Today, the southeast side of the Sanger Lake watershed has an active debris flow channel that terminates 100 meters from the shore of the lake, suggesting that debris flow have occurred recently.

Conclusions

In this study, large-scale controls in climate, namely variations in seasonal insolation, have been shown to influence postglacial vegetation and fire activity. For example, the abundance of forest taxa, such as *Abies* and *Pseudotsuga,* showed similar trends at Sanger Lake and Bolan Lake when conditions were cooler and wetter than today during the late-glacial/early Holocene transition period. These species reached their lowest abundances during the early Holocene when conditions were warmer and drier than present. Both sites also experienced peak fire frequency when summer insolation was higher than today ~9000 cal yr BP. Both *Abies* and *Pseudotsuga* increased in abundance, comparable to the late-glacial/early Holocene transition, as climate conditions became cooler and wetter in the late Holocene. In the last 2500 years, both sites record synchronous increases in *Pseudotsuga* and high fire frequency.

It is also clear that different microclimates at Sanger and Bolan lakes account for asynchronous responses and different sensitivities of species to these large-scale climate changes. For example, reduced costal upwelling and warmer SSTs after 12,000 cal yr BP resulted in the registration of warmer temperatures 1000 years earlier at Sanger Lake than at Bolan Lake. These warmer conditions at Sanger Lake resulted in the loss of *Tsuga, Picea, Artemisia,* and *Poaceae* and the early establishment of *Pinus monticola*. Later, trade-offs between Cupressaceae and haploxylon *Pinus*, that are associated with changes in fire-episode frequency, were strongly evident at Bolan Lake between 11,000 and 7000 cal yr BP, but they were shorter-lived and subdued at Sanger Lake (occurring between 11,000 and 9000 cal yr BP). It is likely that the warmer drier conditions at Bolan Lake increased the flammability of the vegetation, while the more mesic setting at Sanger Lake, resulting from increased ocean upwelling and coastal fog production, reduced flammability and fire occurrence. Increased spring and summer coastal upwelling and warmer winter conditions than before, created conditions at Sanger Lake that were wetter and milder than at Bolan Lake during the last 1000 years, and resulted in fewer fires at

Sanger Lake than at Bolan Lake. Endemic species, *Picea breweriana* and *Chamaecyparis lawsoniana,* likely have been in the Sanger Lake watershed since the last ice age, whereas at Bolan Lake conditions were drier, and their presence was sporadic and short-lived. The drier conditions at Bolan Lake relative to those at Sanger Lake were persistent through the Holocene, with Sanger Lake supporting fewer fires with smaller peak magnitudes, and Bolan Lake registering more fires and larger peak magnitudes. However, both sites record peak fire-episode frequency at ~9200 cal yr BP and 2500 cal yr BP.

It is becoming increasingly apparent that local controls can have a strong influence on vegetation and fire history in mountainous regions and account for differences in closely-spaced sites that experienced the same large-scale controls. In a similar comparison of the vegetation history along a steep coastal-to-inland moisture gradient on Vancouver Island, British Columbia, Brown et al. (2006) found dry conditions were registered inland during the early Holocene, while more coastal sites remained wet. Fire history reconstructions from two closely spaced sites in central British Columbia showed asynchronous patterns in fire episodes and different fire intervals in the middle Holocene, but more synchrony in the late Holocene (Gavin et al., 2006). The temporal differences in fire activity were attributed to shifts in the importance of local controls (i.e., aspect and topography) versus large scale controls under different configurations of regional climate. A similar comparison of two sites with different aspects and elevations in the eastern Klamath Mountains showed that a high-elevation site with a north-facing aspect (Crater

Lake) supported a more mesic forest through the Holocene than a lower-elevation site with a south-facing aspect (Bluff Lake) (Mohr et al., 2000).

The comparison of Bolan and Sanger lakes vegetation and fire history in the Siskiyou Mountains suggests delays in the response of vegetation and fire response to long-term climate change can be on the order of centuries to millennia. Periods of contrasting vegetation and fire in the Siskiyou Mountain region need further study to better evaluate how local factors (i.e., topography, aspect, ocean, edaphic controls) either enhance or suppress regional climate patterns on multiple time scales.

CHAPTER III

HOLOCENE VEGETATION AND FIRE HISTORY ON DIFFERENT SUBSTRATES FROM THE KLAMATH MOUNTAINS, NORTHERN CALIFORNIA, USA

Introduction

The Klamath Mountains, of northern California, contain one of the most diverse temperate coniferous forests in the world. Of the 39 conifer species that occur in the region, seven are endemic and 17 can be found in a 2.59 km^2 area in the Russian Wilderness in the eastern Klamath Mountains (Vance-Borland et al., 1995). Several explanations have been proposed for this high floristic diversity, including the fact that the region's complex geology affects soil fertility, the steep elevational gradients at present create strong environmental contrasts, the spatially variable disturbance regime maintains vegetation in multiple successional stages, and the late-Cenozoic climate history has been fairly stable, which may have enabled the region to serve as a long-term refugium (DellaSala et al., 1999; Ricketts et al., 1999; Coleman and Kruckeberg, 1999; Kruckeberg, 2002; Whittaker, 1960; Skinner et al., 2006, Axelrod, 1978). Little information exists to evaluate the relative importance of such historical and non-historical factors in influencing present diversity patterns in the Klamath Mountains (Whittaker, 1960; Kruckeberg, 2002; Harrison et al., 2006; Safford and Harrison, 2004; Harrison et al., 2000; Mohr et al., 2000; Briles et al., 2005).

This study examines one of the possible explanations, namely how Holocene climate variability and substrate differences influence forests and fire regimes over millennia. Soil fertility in the Klamath Mountains has a significant influence on plant communities, especially those derived from ultramafic bedrock. Ultramafic substrates (UMS) are poorly developed, rocky, and excessively drained. Soil chemistry of UMS is high in iron, magnesium, chromium, nickel, and cobalt, and low in calcium, nitrogen, phosphorous, and potassium (Alexander et al., 2007). These nutrient deficiencies restrict many plant species because of the low Ca:Mg ratios (Kruckeburg, 1984; Brooks, 1987). Several plants growing on UMS are neoendemics, having evolved from ancestors on neighboring non-ultramafic soils, and are capable of withstanding the nutrient deficiencies and heavy metals (Kruckeburg, 1984; Stebbins and Major, 1965). At mid-to-high elevations, these substrates tend to support open forests with *Pinus jeffreyi* (Jeffrey pine) and *Calocedrus decurrens* (incense cedar) as the dominant tree species, and a well-developed shrub understory of *Quercus vaccinifolia* (huckleberry oak; referred hereafter as *Quercus*), *Arctostaphylos* (manzanita) and a diverse array of herbaceous species (Alexander et al., 2007). Because of the open structure of these forests, fires tend to be small, frequent surface fires (Whitlock et al., 2004; Skinner et al., 2006).

Non-ultramafic substrates (NUMS), underlain by diorite, granodiorite, basalt and sedimentary rocks, have varying degrees of soil permeability, pH, and fertility, and tend to be well-developed. Plant species on NUMS at mid-to-high elevations include *Abies concolor* (white fir), *Abies magnifica* (Shasta red fir), *Pseudotsuga menziesii* (Douglas-fir), *Pinus monticola* (western white pine), and *Pinus lambertiana* (sugar pine), and forests are often closed (Alexander et al., 2007; Kruckeburg, 2002). Fires are less frequent than on UMS and tend to be low-to-moderate surface fires; however, crown fires can occur where ladder fuels are abundant (Skinner et al., 2006).

In his classic study of vegetation patterns along elevational gradients in the Klamath Mountains, Robert Whittaker suggested that plant communities at similar elevations are different because UMS tend to be warmer and drier, have higher evapotranspiration rates than NUMS and, therefore, allow more xeric vegetation types to grow further upslope (Whittaker, 1960). Species that reside on both UMS or NUMS, known as bodenvag taxa, have the ability to extend their ranges farther up or down slope on UMS than they do on NUMS.

The paleorecord provides an opportunity to examine the extent to which substrate influences changes in species distribution along elevational gradients in response to climate change. By building on previous research in the Klamath Mountains that established the general sequence of Holocene climate changes, I specifically address the synergistic effects of climate change and substrate as a driver of vegetation diversity and fire regimes. A network of eight vegetation and fire records, reconstructed from microscopic pollen and macroscopic charcoal preserved in mid-to-high elevation lake sediments on NUMS and UMS in the Klamath Mountains were compared to examine how Holocene climate variations influenced forests in different geological settings. This study specifically addresses the following questions: (1) Have long-term changes in climate led to similar responses in vegetation and fire on different substrates, and (2)

Have UMS consistently supported different plant communities and fire regimes than NUMS?

The paleoecologic data for the comparison come from three new sites, Taylor, Campbell and Cedar lakes (fully described below; see Figure 1.1, Table 3.1; sites are bolded), published data from Bolan, Bluff, Crater and Mumbo lakes (Briles et al., 2005; Daniels et al., 2005; Mohr et al., 2000; not bolded), and unpublished data from Sanger Lake (described in chapter 2; underlined). The sites were divided into two categories based on substrate type: sites on UMS (Bluff, Crater, Cedar lakes) and those on NUMS (Taylor, Campbell, Bolan, Sanger, Mumbo lakes). Sites were selected to have similar environmental characteristics (other than their differences in substrates), to minimize other variables that might influence their vegetation and fire history. For example, sites were located in cirque basins with similar elevations, modern climates, and watershed sizes. In addition, sites on both NUMS and UMS in the southeastern Klamath Mountains were within 30 km of each other. Based on our understanding of modern UMS and NUMS plant communities, we would expect that NUMS plant communities would be more sensitive to Holocene climate changes than UMS plant communities and would have supported more closed mesic forests over the Holocene.

It was not possible to reconstruct detailed plant communities because of two inherent limitations that constrain paleoecological studies in this region. First, several of the dominant conifer species in the Klamath Mountains can only be identified to the genus or sub-genus level. Other pollen types are only identifiable to family level (e.g., Cupressaceae, Poaceae). Thus, several of the species identifications were inferred based

Table 3.1

Site descriptions

Site (lat, long, elev., size, water depth)	**Local Vegetation**	**Climate[a,b]**	**Geology**
Sites on Non-ultramafics (NUMS)			
Bolan Lake (42.0225, -123.4583, 1637 m, 5 ha,)	*Abies concolor, Pinus monticola, Abies magnifica, Pseudotsuga menziesii, Calocedrus decurrens*	Avg. annual ppt (mm): 1139 Avg. Jan, July ppt (mm): 202, 11 Mipt: 0.58 Avg. Jan., July temp (°C): -1,14.7	Diorite substrates with minor serpentine outcrops in the watershed
Sanger Lake (41.9021, -123.6465, 1547m, 4 ha, 7.19m)	*Picea breweriana, Chamaecyparis lawsoniana , Abies concolor, Pinus monticola*	Avg. annual ppt (mm): 1328 Avg. Jan, July ppt (mm): 234, 12 Mipt: 0.62 Avg. Jan., July temp (°C): 0, 13.9	Diorite substrates with minor serpentine outcrops in the watershed
Campbell Lake (41.5333, -123.1050 1750m, 12 ha, 7.12m)	*Pinus monticola, Abies concolor, A. magnifica, Pseudotsuga menziesii*	Avg. annual ppt (mm): 1155 Avg. Jan, July ppt (mm): 202, 12 Mipt: 0.64 Avg. Jan., July temp (°C): -1.3, 14.4	Metamorphic substrates from schist, shale, and mudstone and diorite
Taylor Lake (41.3614, -122.9675, 1979 m, 5 ha, 9.45 m)	*Abies concolor, A. magnifica Pinus monticola, Tsuga mertensiana, Amelanchier alnifolia*	Avg. annual ppt (mm): 1099 Avg. Jan, July ppt (mm): 194, 12 Mipt: 0.67 Avg. Jan., July temp (°C):-2.7, 14.5	Granodiorite substrates
Sites on Ultramafics (UMS)			
Crater Lake (41.3836, -122.5797, 2288m, 6 ha, 12.15m)	*Pinus albicaulis, P. monticola, P. contorta, Abies magnifica, Tsuga mertensiana*	Avg. annual ppt (mm): 989 Avg. Jan, July ppt (mm): 169, 13 Mipt: 0.58 Avg. Jan., July temp (°C): -4.6, 14.3	Peridotite substrates
Bluff Lake (41.3466, -122.5598, 1926m, 3 ha, 1.7m)	*Pinus jeffreyi, P. contorta, Calocedrus decurrens, Quercus vaccinifolia*	Avg. annual ppt (mm): 1048 Avg. Jan, July ppt (mm): 180, 11 Mipt: 0.62 Avg. Jan., July temp (°C):-2.6, 15.2	Peridotite substrates
Cedar Lake[c] (41.2075, -122.4954, 1742 m, 4 ha, 2.6 m)	*Pinus jeffreyi, P. contorta, Chamaecyparis lawsoniana, Quercus vaccinifolia*	Avg. annual ppt (mm): 1120 Avg. Jan, July ppt (mm): 196, 10 Mipt: 0.59 Avg. Jan., July temp (°C): -1.5, 15.9	Peridotite substrates
Mumbo Lake (41.1913, -122.5092, 1860 m, 4 ha 3.2 m)	*Abies concolor, A. magnifica, Tsuga mertensiana, Pinus monticola, P. contorta, Quercus vaccinifolia*	Avg. annual ppt (mm): 1096 Avg. Jan, July ppt (mm): 192, 10 Mipt: 0.60 Avg. Jan., July temp (°C) :-2.2, 15.7	Diorite substrates with extensive peridotite outcrops nearby and in watershed

[a] Elevationally adjusted interpolations of nearby weather station data (Bartlein and Shafer, unpublished data, 2007).

[b] Mipt--Priestley-Taylor (alpha) parameter (actual evaporation/potential evaporation)

[c] J.A. Mohr, T. Minckley, and C.Whitlock, unpublished data

on modern plant communities and species affinities. For example, *Pinus jeffreyi* pollen cannot be distinguished from *P. ponderosa* or *P. contorta*, but *P. jeffreyi* is primarily found on UMS, while the other taxa have broader distributions on NUMS. In the case of Cupressaceae, ecologic, climatic and bioclimatic parameters of modern species distributions were used to infer which species might have grown in a location in the past (Thompson et al., 1999). Another limitation is that several species in the Klamath Mountains are animal pollinated and poorly represented in lake sediments. The lack of pollen evidence for these taxa constrains our ability to study the history of many plant species. For example, *Arctostaphylos* (manzanita) is an abundant understory shrub at many of the lakes; however, it is pollinated by insects and not well recorded in the pollen record. Despite these limitations, pollen data do provide information on the dominant trees (e.g., *Abies*, *Pseudotsuga*, *Tsuga, Picea*) and shrubs (*Quercus vaccinifolia*, *Artemisia* (sagebrush), *Lithocarpus*), as well as openness of the vegetation.

Site Description

Taylor, Campbell, Sanger, Bolan, Bluff, Mumbo, Crater and Cedar lakes all occupy late-Pleistocene cirques (Figure 1.1; Table 3.1). The sites lie in the *Abies concolor* Vegetation Zone or in the transition between this zone and the higher elevation *Abies magnifica* (Shasta red fir) Vegetation Zone (1500 to 2200 meters elevation) (Franklin and Dyrness, 1988 and Sawyer and Thornburg, 1988) (all botanical nomenclature is based on Hickman, 1993).

Bolan and Sanger lakes are discussed in chapter 2 and Bolan Lake was also described in Briles et al. (2005). Bolan Lake lies on the border of southwest Oregon and northern California and Sanger Lake is located in more mesic forest 20 km to the southwest of Bolan Lake in California. Both locations are influenced by diorite (non-ultramafic) soils but small isolated serpentine (ultramafic) outcrops are nearby. The forests at Bolan and Sanger lakes are primarily composed of *Abies concolor* and *Pinus monticola* (including *Picea breweriana* (Brewer spruce) and *Chamaecyparis lawsoniana* (Port-Orford cedar) at Sanger Lake), with minor amounts of *Pseudotsuga* and *Calocedrus*. The dominant shrubs around the lakes include *Quercus, Chrysolepis chrysophylla* (golden chinquapin), *Lithocarpus densiflora* (tanoak), *Arctostaphylos* and *Ceanothus velutinus* (snow brush).

Taylor Lake, which is located in the Russian Wilderness Area in the southeastern Klamath Mountains, is underlain by Jurassic granodiorite (similar to granite with higher amounts of plagioclase feldspar). The closed forest is composed of *Abies concolor*, *A. magnifica, Tsuga mertensiana* (mountain hemlock), and *Pinus monticola,* with more minor components of *Calocedrus*, *Pseudotsuga*, and *Pinus contorta* (lodgepole pine). The forest opens on steep rugged slopes on the north side of the lake, and shrubs such as *Amelanchier pallida* (western serviceberry), *Chrysolepis chrysophylla* (golden chinquapin), *Spiraea douglasii* (Douglas spirea), *Ceanothus velutinus* (snowbrush), and *Salix* (willow) grow on the slopes and lake margin. *Artemisia tridentata* (bigleaf sagebrush), *Cercocarpus spp.* (mountain mahogany), and minor amounts of *Quercus* are found on dry slopes.

Campbell Lake lies on the eastern border of the Marble Mountains Wilderness in the southeastern Klamath Mountains. The geology consists of Jurassic slate, schist, mudstone, and diorite. The forests are closed and dominated by *Abies concolor*, *A. magnifica*, *Pinus monticola* and *Pseudotsuga,* with minor components of *Calocedrus* and *P. contorta. Tsuga* is present in the forest as mature (300+ years) trees. A minor shrub component of *Amelanchier, Acer circinatum* (vine maple), *Corylus cornuta* (western hazelnut), *Salix* (willow), *Arctostaphylos,* and *Symphoricarpos albus* (snowberry) is present around the lake and in wet forest openings.

Bluff, Crater, and Cedar lakes are located on the Trinity Ultramafic sheet (Irwin, 1981) in the southeastern Klamath Mountains, which is one of the largest outcrops of ultramafic rock (of Paleozoic age) in the region. At Bluff Lake (Mohr et al., 2000), which lies in a southeast-east facing valley of South China Mountain, *Pinus jeffreyi* and *Calocedrus* are the dominants in open forest with a sparse understory of *Quercus*, *Ceanothus prostratus* (squaw carpet) and Poaceae (grass). Cedar Lake is surrounded by a margin of *Chamaecyparis lawsoniana.* The drier slopes around the watershed support stands of *Pinus jeffreyi*, *P. monticola*, *P. contorta, P. lambertiana,* and *Calocedrus,* and *Abies concolor* and *Pseudotsuga* on wetter slopes. The understory includes shrubs, such as *Quercus*, *Ceanothus prostratus*, *C.velutinus*, *Arctostaphylos*, *Amelanchier*, and *Holodiscus discolor* (ocean spray). Crater Lake is the highest elevation lake (Mohr et al., 2000), and *Pinus albicaulis* (whitebark pine), *P. monticola*, *P. contorta*, *Abies magnifica* and *Tsuga* are major components of the forest. *Quercus, Ceanothus prostratus* and *Arctostaphylos* are the dominant shrubs in the understory.

Mumbo Lake is located on diorite bedrock in a small west-facing cirque not far from Cedar Lake, but extensive peridotite outcrops are nearby. The closed forest is composed of *Abies concolor*, *A. magnifica, Pinus contorta, P. monticola* and open slopes support *Quercus*, *Arctostaphylos*, *Amelanchier,* and *Spiraea douglasii* (Daniels et al., 2005).

Bolan, Sanger, Campbell, Taylor, Crater, Bluff, Cedar and Mumbo lakes have similar modern climates with cool winters (average temperatures ranging between -5 and 0°C) and mild summers (average temperatures ranging between 14 and 16°C; see Table 3.1)). Half of the annual precipitation (~1100 mm) falls in winter (approximately 500-550 mm) as snow and approximately 15% in the summer (55-60 mm) from thunderstorms (Bartlein and Shafer, unpublished data, 2007). Sanger Lake receives the most precipitation (1328 mm average annual) and is the warmest site in the winter. Crater Lake receives the least precipitation (989 mm average annual) and has the coldest winters.

Methods

Methods used for the analysis of the Taylor, Campbell and Cedar lake sediment cores are presented below. Methods employed at Bluff and Crater lakes were described in Mohr et al. (2000), those for Mumbo Lake are in Daniels et al (2005), those for Bolan Lake in Briles et al. (2005) and chapter 2, and those for Sanger Lake in chapter 2. New age-depth models were constructed for Bluff, Crater and Mumbo lakes to account for the new calibration curve (Reimer et al., 2004) and modeling techniques (Higuera et al., in prep). Charcoal concentrations were reanalyzed for all sites to standardize the results. Mumbo Lake charcoal data were not included in the charcoal comparison as deposition times were too slow (40-80 years/cm) to provide a good comparison with other sites. Chronological results were not different enough to warrant reinterpretation of pollen data; however, reanalysis of charcoal data did produce different results and are described below.

Field

Long cores, taken with a modified Livingstone piston sampler (Wright et al., 1983), and short cores, obtained with a Klein piston corer, were retrieved from each lake from an anchored platform in the deepest part of each basin. At Campbell Lake, sediment cores were taken in the deepest water in the northern sub-basin of the lake. Core recovery ranged from 5.86 m at Taylor Lake, 5.20 m at Campbell Lake, and 3.67 m at Cedar Lake. The cores were wrapped in cellophane and aluminum foil and transported back to the lab where they were refrigerated.

Lithologic

Cores were cut in half, described, and subsampled at 1-cm intervals in the lab and placed in plastic bags for further analyses. Magnetic susceptibility was measured at 1-cm intervals to determine inorganic allochthonous sediment inputs (i.e., clastic minerals) to the lakes and reported in cgs units (Gedye et al., 2000). Organic content of the sediments was measured in each sample as the weight loss after ignition at 550°C for 2 hours (Dean, 1975). This information was used to assess changes in lake productivity through time.

Loss-on-ignition analysis was performed at 4-cm intervals for Taylor and Campbell lakes and at 1-cm intervals for Cedar Lake.

Chronology

Radiocarbon dates were obtained on plant macrofossils (seed, twigs, leaves, etc.) and sediment (only where necessary) for Taylor, Campbell and Cedar lakes. Similar material was dated for Bluff, Crater, and Mumbo lakes (Mohr et al., 2000 and Daniels et al., 2005). Dried sediment was ^{210}Pb dated on the upper 18 cm of the Taylor Lake short core and the upper 10 cm of the Campbell Lake short core at the USGS-Denver. The top 26 cm of the Cedar Lake short core was ^{210}Pb dated by the University of Wisconsin-Milwaukee, Center of Great Lake Studies (Whitlock et al., 2004).

Age-depth models were constructed based on ^{14}C and ^{210}Pb dating, and tephrochronology from both long and short cores for Taylor, Campbell and Cedar lakes, and ^{14}C dating and tephrochronology from the long cores of Bluff, Crater and Mumbo lakes (Mohr et al. 2000; Daniels et al., 2005). The top of the Taylor, Campbell, Cedar, Bluff and Crater lake sediment cores (0 cm) were assigned the year that the core was taken (-53,-54, -46, -45, -46 cal yr BP, respectively) and included in the age model. The uppermost sediments were not recovered in the long core at Mumbo Lake, and charcoal stratigraphy from the long and short core (Wick, 1989) were used to estimate the top of the long core at 25 cal yr BP (Daniels et al., 2005). Radiocarbon ages were calibrated using Calib 5.0.2 (Stuiver et al., 2005), and an age-depth models were constructed using a cubic smoothing spline and bootstrap approach that allowed each date to influence the age model through the probability density function of the calibrated age (Higuera et al.,in prep; Reimer et al., 2004). The smoothing parameter for each spline was selected based on the assumption that the predicted ages of each sample must fall within the confidence intervals of the calibrated ^{14}C ages. The overall uncertainty of each age estimate (i.e., two standard deviations) was used to weight the influence of each calibrated age in the age-depth model (e.g., Telford et al., 2004), and confidence intervals, reflecting the combined uncertainty of all age estimates in the model, were derived from 10,000 bootstrap-estimated chronologies. For each bootstrap chronology, the specific ages used to develop the chronology were selected randomly based on the probability distribution of the ^{210}Pb or calibrated ^{14}C date. The final chronology represents the median age of each depth from the 10,000 bootstrap-estimated chronologies.

Pollen

Pollen analyses provided information on the regional and local vegetation history. Pollen was sampled every 50-100 years for the last 2000 years, and every 100-200 years for the remainder of the Taylor and Campbell lake records. At Cedar Lake, pollen was sampled approximately every 300 years. A total of 95 pollen samples for Taylor Lake, 84 samples for Campbell Lake, and 34 samples for Cedar Lake were processed, using methods of Bennett and Willis (2002); however, the Schulze procedure was used in place of acetolysis to oxidize organics for Taylor and Campbell lakes (Doher, 1980). A *Lycopodium* tracer was added to calculate pollen concentration (grains cm^{-3}).

Pollen grains were identified at magnifications of 500 and 1250x, and counts were at least 300 terrestrial grains per sample, with at least 100 non-*Pinus* grains. Pollen was identified to the lowest taxonomic level possible using reference collections, atlases (e.g., Kapp et al., 2000; Moore and Webb, 1978), and other publications (Jarvis et al., 1992; Hebda et al., 1988a, b). The assignment of pollen taxa was based on modern phytogeography. Haploxylon-type *Pinus* pollen was attributed to *Pinus monticola* but contributions from *P. lambertiana* (sugar pine) and/or minor amounts of *P. balfouriana* (fox tail pine) and *P. albicaulis* (whitebark pine) may also have been included. Diploxylon-type *Pinus* pollen was attributed to *P. jeffreyi, P. ponderosa* and/or *P. contorta.* On UMS, the major contribution was likely from *P. jeffreyi* and *P. contorta. Pinus* grains missing a distal membrane were identified as undifferentiated *Pinus,* which was assumed to contain the same proportions of haploxylon-type and diploxylon-type pine as the identified fraction. *Abies* pollen grains were from *A. concolor* and *A. magnifica* and possibly *A. procera* (although its range is limited in northern California and it does not occur near any sites today). *Picea* pollen was attributed to *P. breweriana* or *P. engelmannii* (Engelmann spruce). Cupressaceae grains may have come mostly from *Calocedrus* or *Chamaecyparis lawsoniana* and *Juniperus occidentalis* (western juniper) is also in the region but not near the sites today. *Quercus vaccinifolia*-type pollen was distinguished from *Quercus garryana*-type (Oregon white oak) based on coarseness of the sculpturing elements and differences in the apertures (Jarvis et al., 1992). Pollen grains that were broken, corroded, hidden or otherwise damaged were counted as 'Indeterminate', and those that were unidentifiable counted as 'Unknown.'

Pollen, including total arboreal and nonarboreal, percentages and accumulation rates (PAR; grains cm^{-2} yr^{-1}) were used to reconstruct past vegetation. Percentages of terrestrial upland taxa were based on a sum of pollen from all trees, shrubs, herbs, and pteridophytes. The pollen-percentage records were divided into zones by use of a constrained cluster analysis (CONISS; Grimm, 1988). PAR were determined by dividing pollen concentrations by deposition time (yr cm^{-1}).

Charcoal

Macroscopic charcoal samples were prepared following methods described by Whitlock and Larsen (2001) for long cores from Taylor, Campbell, and Cedar lakes and short cores from Taylor and Campbell lakes, and the data was used to reconstruct past fire activity. Sediment samples of 2 cm^3 were taken at contiguous 1-cm intervals and soaked in 5% sodium hexametaphosphate and bleach for 24 hours. They were washed through 250- and 125-micron-mesh screens. Particles in each size class were counted in gridded petri dishes under a stereomicroscope at 50-100x magnification. Charcoal concentrations (number of particles cm^{-3}) from the two size fractions showed similar trends and were combined. At Taylor and Campbell lakes, long and short core data were merged based on correlation of the charcoal stratigraphy, magnetic susceptibility profiles, and other lithologicial markers. Charcoal concentrations and deposition times were interpolated to the highest sample resolution of all records (i.e., 50 years sample^{-1}), including Bluff, Crater, Mumbo, Sanger and Bolan lakes, to produce equally spaces intervals within and between records. Charcoal accumulation rates (CHAR, particles cm^{-}

^{2} yr^{-1}) were determined by multiplying the interpolated charcoal concentrations by the interpolated sedimentation rate (cm yr^{-1}) using CharAnalysis software (http://www.charanalysis.googlepages.com; Higuera et al., 2008).

To identify peaks in CHAR likely related to local fire occurrence, the CHAR time series was decomposed into two components: 1) a *background component* and 2) a *peaks component*. The background component represents long-term variations in charcoal production, secondary transport, sediment mixing, and sediment sampling (Long et al. 1998, Higuera et al. 2007) and was defined by a locally-weighted regression using the tricube weight function with a 700-year window, robust to outliers (Cleveland, 1979; 5 robustness steps). The peaks component represents high-frequency variability around background and was defined as the residuals after the background component was subtracted. The peaks component can be further separated into two sub-components: non-fire-related variability in CHAR (i.e. analytical and natural noise, assumed to follow a normal or Gaussian distribution) and fire-related CHAR peaks (i.e. signal). A Gaussian mixture model was used to identify the noise component (Gavin et al., 2006, Higuera et al., 2008), and the 95th percentile of this distribution was taken and the threshold value separating fire-related signal from noise in the peaks component (Higuera et al., 2008). The procedure was done on each 700-yr, overlapping portion of the CHAR record, producing a unique threshold for each sample. The individual threshold values were smoothed with a 700-yr tricubic locally-weighted regression to produce the final threshold values for the record. Finally, all peaks exceeding the locally-defined threshold were screened using the original charcoal counts contributing to each peak. If the maximum count in a CHAR peak had a > 5% chance of coming from the same Poisson-distributed population as the minimum charcoal count within the proceeding 75 years, then the "peak" was rejected (e.g. Charster user's guide, accessed March 2007, http://geography.uoregon.edu/gavin/charster/Analysis.html). Statistical treatment of the charcoal records was done using the program CharAnalysis (PEH, available online at http://www.charanalysis.googlepages.com). Fire activity was reported as mean fire return intervals (MFI) and represents the number of years between individual fire events/episodes. MFI were smoothed with a locally weighted mean (1000 years) to visually represent long-term trends in the data.

Results

Chronology

Age determination based on ^{210}Pb and ^{14}C AMS dates and tephrachronology are presented in Table 3.2 for Taylor Lake, Table 3.3 for Campbell Lake and Table 3.4 for Cedar Lake. Those previously published for Bluff, Crater and Mumbo lakes are presented in Table 3.5, and were used to develop new age models for those sites. The Taylor Lake chronology was developed from 22 ^{14}C AMS determinations, the Campbell Lake chronology from 15 ^{14}C AMS determinations, the Cedar Lake chronology from 6 ^{14}C AMS determinations, the Bluff Lake chronology from 8 ^{14}C AMS determinations, and the Crater and Mumbo Lake chronologies from 5 ^{14}C AMS determinations (Figure 3.1). The Taylor, Campbell and Cedar Lake chronologies also included ^{210}Pb age

Table 3.2

Uncalibrated ^{14}C dates, calibrated ages, and ^{210}Pb dates for Taylor Lake.

Depth (cm)[a]	Predicted age (cal yr BP; med. prob.)[b,d,e]	Upper age range (cal yr BP)[c]	Lower age range (cal yr BP)[c]	^{14}C age BP	±	Material dated	Reference
1	-51					gyttja ^{210}Pb	
2	-43					gyttja ^{210}Pb	
3	-35					gyttja ^{210}Pb	
4	-29					gyttja ^{210}Pb	
5	-22					gyttja ^{210}Pb	
6	-14					gyttja ^{210}Pb	
7	-5					gyttja ^{210}Pb	
8	6					gyttja ^{210}Pb	
9	19					gyttja ^{210}Pb	
10	29					gyttja ^{210}Pb	
32	454	483	424	365	35	needle	CAMS118765
40	601	632	568	590	35	seed	CAMS112999
47	726	760	692	945	30	needle	CAMS119615
65.5	1037	1076	999	1115	35	needles	CAMS113000
78.5	1257	1301	1215	1085	35	needle	CAMS112976
95	1549	1600	1500	1580	35	needle	CAMS119616
125.5	2091	2156	2030	2155	35	needle	CAMS112977
179.5	3120	3181	3059	2940	35	cone scale	CAMS112978
203.5	3583	3638	3524	3375	30	needles	CAMS119618
247	4460	4522	4394	3965	35	cone scale	CAMS112984
255.5	4659	4723	4594	4060	45	twig	CAMS112979
287	5405	5461	5347	4620	35	wood	CAMS112980
307.5	5955	6005	5906	5195	35	wood	CAMS113001
334	6673	6718	6632	5955	40	wood	CAMS112981
354	7254	7295	7216	6365	35	needles	CAMS118768
367	7654	7692	7617	6845	50	Mazama Ash	Bacon, 1983
391.5	8503	8539	8471	7655	40	twig	CAMS112982
417	9484	9518	9449	8485	35	gyttja	CAMS118769
443	10655	10700	10614	9330	60	twig	CAMS112983
458	11405	11455	11361	9915	35	gyttja	CAMS118770
474	12261	12317	12207	10305	40	isoetes	CAMS113002
483.5	12819	12881	12755	10715	40	needle	CAMS113003
498	13615	13694	13531	12140	70	gyttja	CAMS112992
534	Too old	Too old	Too old	14490	650	organic clay	CAMS112991

[a] Depth below mud surface.

[b] ^{14}C calibrated ages derived using a Monte Carlo approach based on the probability distribution function of each ^{14}C age (Calib 5.0.2; Stuiver et al., 2005). The median calibrated age is given and based on 10,000 runs.

[c] 95% confidence interval based on 10,000 runs.

[d] ^{210}Pb dates were adjusted for the year cores were taken since 1950 A.D. before being considered with the radiocarbon dates.

[e] ^{210}Pb ages and errors from USGS-Denver

Table 3.3

Uncalibrated ^{14}C dates, calibrated ages, and ^{210}Pb dates for Campbell Lake.

Depth (cm)[a]	Predicted age (cal yr BP; med. prob.)[b,d,e]	Upper age range (cal yr BP)[c]	Lower age range (cal yr BP)[c]	^{14}C age BP	±	Material dated	Reference
0	-54					gyttja ^{210}Pb	
1	-43					gyttja ^{210}Pb	
2	-34					gyttja ^{210}Pb	
3	-22					gyttja ^{210}Pb	
5	-10					gyttja ^{210}Pb	
6	2					gyttja ^{210}Pb	
7	13					gyttja ^{210}Pb	
8	21					gyttja ^{210}Pb	
9	30					gyttja ^{210}Pb	
10	58					gyttja ^{210}Pb	
30	467	497	446	630	35	gyttja	CAMS119610
47	778	821	749	765	35	gyttja	CAMS119614
73	1262	1331	1210	1480	80	gyttja	CAMS112985
109	1841	1912	1768	1930	40	gyttja	CAMS112987
169.5	2871	2931	2833	2685	35	gyttja	CAMS112988
209	3874	3961	3799	3770	40	gyttja	CAMS112986
255.5	5128	5229	5077	4380	40	wood	CAMS112962
288	6355	6401	6321	5590	35	needles	CAMS119611
289.5	6399	6445	6366	5555	35	wood	CAMS112963
317	7754	7797	7716	6845	50	Mazama Ash	Bacon, 1983
324	8098	8145	8052	7675	35	needle	CAMS119613
348	9194	9261	9100	8045	45	cone scale	CAMS112964
380	10729	10807	10585	9195	50	wood	CAMS112961
388	11140	11218	10994	9655	40	twig	CAMS112997
414	12545	12623	12426	10520	45	needle	CAMS112998
440.5	14013	14122	13915	13290	80	gyttja	CAMS112989
491.5	Too old	Too old	Too old	18260	730	organic clay	CAMS112990

[a] Depth below mud surface.

[b] ^{14}C calibrated ages derived using a Monte Carlo approach based on the probability distribution function of each ^{14}C age (Calib 5.0.2; Stuiver et al., 2005). The median calibrated age is given and based on 10,000 runs.

[c] 95% confidence interval based on 10,000 runs.

[d] ^{210}Pb dates were adjusted for the year cores were taken since 1950 A.D. before being considered with the radiocarbon dates.

[e] ^{210}Pb ages and errors from USGS-Denver.

Table 3.4

Uncalibrated ^{14}C dates, calibrated ages, and ^{210}Pb dates for Cedar Lake.

Depth (m)[a]	Predicted age (cal yr BP; med. prob.)[b,d,e]	Upper age range (cal yr BP)[c]	Lower age range (cal yr BP)[c]	^{14}C age BP	±	Material dated	Reference
1	-46					gyttja ^{210}Pb	
5.5	-39					gyttja ^{210}Pb	
6.5	-32					gyttja ^{210}Pb	
7.5	-25					gyttja ^{210}Pb	
8.5	-18					gyttja ^{210}Pb	
9.5	-12					gyttja ^{210}Pb	
10.5	-5					gyttja ^{210}Pb	
12.5	9					gyttja ^{210}Pb	
14.5	24					gyttja ^{210}Pb	
16.5	37					gyttja ^{210}Pb	
18.5	51					gyttja ^{210}Pb	
20.5	64					gyttja ^{210}Pb	
22.5	78					gyttja ^{210}Pb	
24.5	92					gyttja ^{210}Pb	
26.5	106					gyttja ^{210}Pb	
43	1032	1034	1030	1065	90	Little Glass Mountain Ash	Heiken, 1978
82	2469	2625	2344	2445	100		AA33634
137	4283	4460	4135	3910	100		AA34319
186	5888	6004	5770	5095	120		AA33635
234	7560	7615	7494	6845	50	Mazama Ash	Bacon, 1983
263	8338	8413	8233	7580	130		AA33636
314	9513	9600	9382	8395	110		AA34319
367	11393	11980	10893	10000	360		AA33637

[a] Depth below mud surface.

[b] ^{14}C calibrated ages derived using a Monte Carlo approach based on the probability distribution function of each ^{14}C age (Calib 5.0.2; Stuiver et al., 2005). The median calibrated age is given and based on 10,000 runs.

[c] 95% confidence interval based on 10,000 runs.

[d] ^{210}Pb dates were adjusted for the year cores were taken since 1950 A.D. before being considered with the radiocarbon dates.

[e] ^{210}Pb ages and errors from USGS-Denver.

Table 3.5

Uncalibrated radiocarbon dates and calibrated ages for published sites in the Klamath Mountains.

Depth (m)[a]	Predicted age (cal yr BP; med prob.)[b]	Lower age range (cal yr BP)[c]	Upper age range (cal yr BP)[c]	^{14}C age BP	±	Material dated	Reference
Bluff Lake							
37	1657	1761	1582	1720	50	needles	AA20622
66	2809	2918	2743	2720	60	needles	AA23317
113	4842	4948	4732	4220	55	wood	AA20623
141	6381	6506	6273	5675	55	needles	AA23318
193	8881	9053	8692	7960	100	wood	AA22157
227	10084	10212	9862	9025	70	wood	AA20624
313	11515	11803	11367	9940	75	wood	AA20625
364	13352	13582	13207	11550	90	needles	AA22158
Crater Lake							
62	1370	1455	1291	1585	45	conifer needles	AA23312
159	2652	2777	2489	2500	45	wood	AA23313
261	5660	5772	5547	5130	55	conifer needles	AA23314
337	6592	6705	6492	5650	50	pine needles	AA23315
407	8041	8334	7750	7355	175	conifer needles	AA23316
Mumbo Lake							
28.5	1025	1761	1582	1065	90	Little Glass Mountain Ash	Heiken, 1978
51.5	1869	1992	1738	1925	75	pine needles	AA38221
133.5	5228	5360	5127	4670	55	pine needles	AA33507
174.5	7302	7440	7206	6085	56	pine needles	AA38222
207.5	9556	9748	9462	8629	69	pine needles	AA38223
260.5	13829	14270	13631	12210	100	wood fragments	AA33508

[a] Depth below mud surface.

[b] ^{14}C calibrated ages derived using a Monte Carlo approach based on the probability distribution function of each ^{14}C age (Calib 5.0.2; Stuiver et al., 2005). The median calibrated age is given based on 10,000 runs.

[c] 95% confidence interval is based on 10,000 runs.

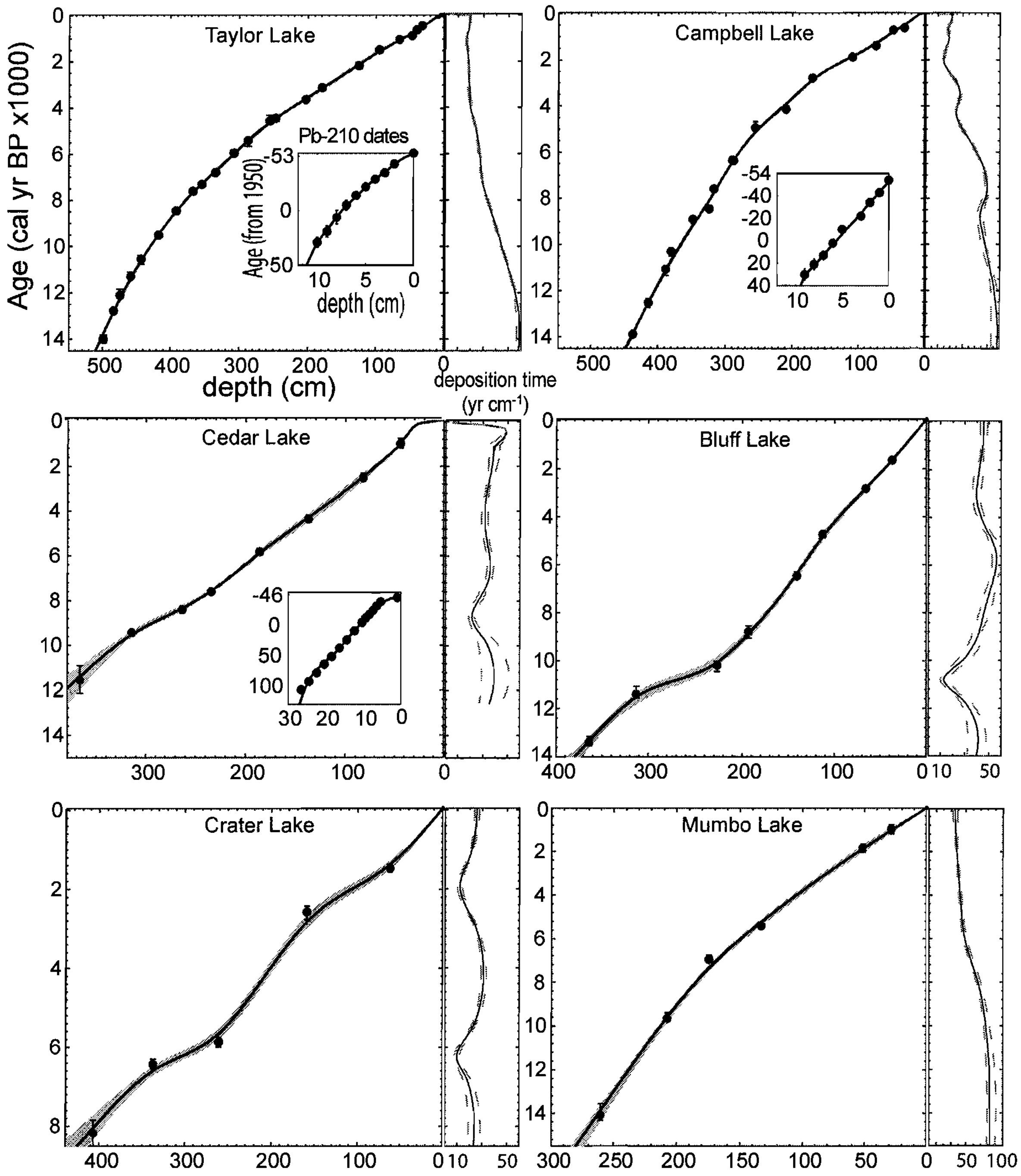


Figure 3.1. Age-versus-depth curves and deposition times based on radiocarbon and ^{210}Pb dates, and tephrochronology. The gray band reflects the range of dates and deposition times and black line the 50th (i.e., median age) percentile of all runs. Circles and bars reflect the 50th, 2.5th (i.e., lower age) and 97.5th (i.e., upper age) percentiles of the probability distribution function of calibrated dates. See Tables 3.2 to 3.5 for ages.

determinations (ten, nine, and fifteen, respectively) on the upper sediments of the short cores.

Mazama ash was present at 367 cm depth at Taylor Lake, 317 cm depth at Campbell Lake, and 234 cm depth at Cedar Lake, and assigned an age of 6845±50 ^{14}C BP (Bacon, 1983). Mazama ash was not found at the other sites. Cedar and Mumbo Lake chronologies also included the Little Glass Mountain ash layer (1065±90 ^{14}C BP; Heiken, 1978) at 43 cm and 28.5 cm depth, respectively. Radiocarbon dates on inorganic clay at the bottom of the Taylor Lake and Campbell Lake long cores (534, 491.5 cm depth, respectively) yielded old calibrated ages with large errors (~18,000 and 21,000 cal yr BP, respectively) beyond the timing of deglaciation in the Pacific Northwest (after 17,000 cal yr BP) (Porter & Swanson 1998; Clark & Gillespie 1997). They were left out of those chronologies.

The average deposition time of the NUM sites (Taylor and Campbell lakes) gradually decreased from 50 to 15 years cm^{-1} at the top. Radiocarbon dates on gyttja at 498 cm depth at Taylor Lake and 440 cm depth at Campbell Lake suggest that the sites were at least 14,000 years old. Mumbo Lake had a substantially slower average deposition time of 80 years cm^{-1} between 267 cm (14,400 cal yr BP) and 175 cm (7000 cal yr BP) depth and then decreased to 40 year cm^{-1} toward the top of the record.

Sediment accumulated more evenly at sites on UMS. The average deposition time at Bluff Lake between 310 cm (11,500 cal yr BP) and 431 cm (14,800 cal yr BP) depth was 40 year cm^{-1}. Several sedimentological events in the watershed resulted in an average deposition time of 18 years cm^{-1} between 310 and 230 cm (10,000 cal yr BP) depth;

thereafter, deposition increased to 44 years cm^{-1} toward the top of the record. The average deposition time at Crater Lake (434 cm depth spanning 8700 cal yr) was the lowest of the UMS sites at 20 years cm^{-1} and Cedar Lake (367 cm depth in 11,400 cal yr) was intermediate at 31 year cm^{-1}. In general, the basal age of the records suggests that most lakes formed in the Klamath Mountains between 15,000 and 14,000 cal yr BP, marking a minimum age for deglaciation in the region.

Lithology

The lithologic results from Bluff, Crater and Mumbo lakes were described in Mohr et al. (2000) and Daniels et al. (2005). Below we present only new results from Taylor, Campbell and Cedar lakes.

Lithological analyses revealed similar stratigraphy at Taylor, Campbell and Cedar lakes. The Taylor Lake and Campbell Lake lithologies were divided into two units, and the Cedar Lake long core contained the upper unit (Figure 3.2). The first unit (4.42 to 5.20 m depth at Campbell Lake and 5.05 to 5.86 m depth at Taylor Lake; >~14,000 cal yr BP) was composed of inorganic clay with layers of sand (<4% organic matter, $>100 \times 10^{-6}$ cgs magnetic susceptibility values). These sediments contained little to no pollen and charcoal.

The second unit in all three cores consisted of gyttja, with varying amounts of plant detritus and abundant well-preserved pollen and charcoal. At Taylor Lake, percent organics increased (4 to 30%) and magnetic susceptibility decreased ($>100 \times 10^{-6}$ to $\sim 5 \times 10^{-6}$ cgs) between 505 and 400 cm depth (14,000 to 9000 cal yr BP). The sediment

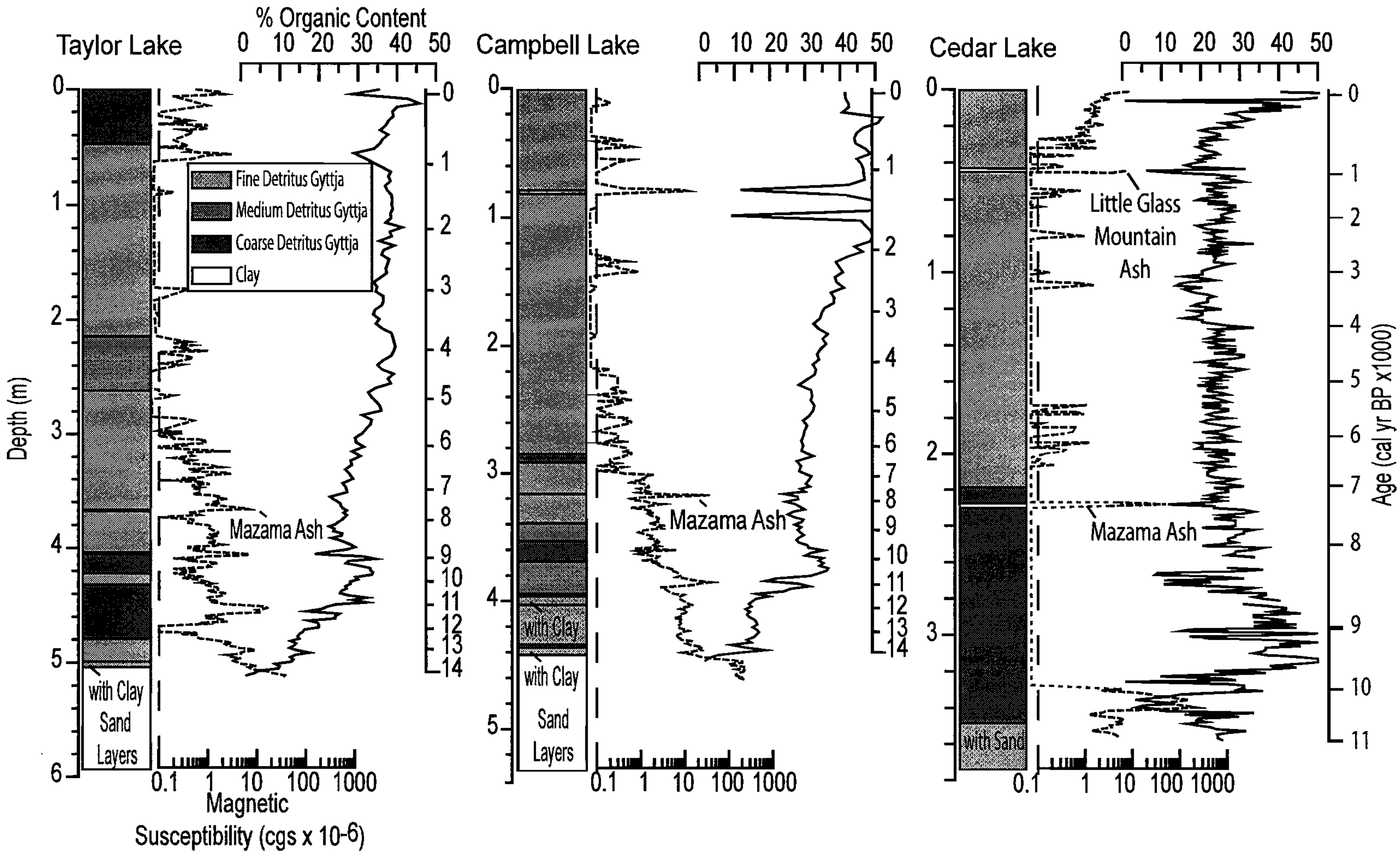


Figure 3.2. Lithology, magnetic susceptibility (dashed line) and percent organic content (solid line) for Taylor, Campbell and Cedar lakes.

during this period contained an abundance of plant detritus. Percent organics and magnetic susceptibility decreased (to 25% and to $1x10^{-6}$ cgs, respectively), and plant detritus was less abundant between 400 and 350 cm depth (9000 to 6800 cal yr BP) than below. Magnetic susceptibility continued to decrease to very low values (from $1x10^{-6}$ to ~0 cgs) between 350 and 68 cm depth (6800 to 1000 cal yr BP) and then increased to the present (back to $1x10^{-6}$ cgs). Percent organics increased (to 40%) until 260 cm depth (4800 cal yr BP), after which plant detritus became moderately abundant until 216 cm depth (3800 cal yr BP), and percent organics remained comparable to the first unit until 50 cm depth (600 cal yr BP) then increased (to 45%) along with plant fragments in the sediment.

Similar to Taylor Lake, percent organics at Campbell Lake increased (4 to 30%) and magnetic susceptibility decreased (>$100x10^{-6}$ to ~$5x10^{-6}$ cgs) between 442 and 356 cm depth (14,000 and 9500 cal yr BP). Two clay layers were present at 418 and 398 cm depth (12,800 and 11,600 cal yr BP respectively), and clay was mixed with gyttja until 398 cm depth. Above the clay layer at 398 cm depth, plant detritus increased, especially between 365 and 356 cm depth (10,000 to 9500 cal yr BP). Percent organics, magnetic susceptibility, and plant detritus in the sediment decreased (to 25% and to $1x10^{-6}$ cgs, respectively) between 356 and 290 cm depth (9500 to 6800 cal yr BP). Percent organics increased (to 50%) between 290 and 120 cm depth (6800 and 2000 cal yr BP), with abundant plant detritus between 290 and 283 cm depth (6800 to 6300 cal yr BP), and then remained unchanged until 20 cm and dropped (to 40%; last 400 years). Magnetic susceptibility continued to decline (to 0 cgs) until 80 cm depth (1200 cal yr BP) and then increased in a 1-cm thick clay layer (to 10×10^{-6} cgs) and was very low ($>1 \times 10^{-6}$ cgs) for the rest of the record.

Cedar Lake recorded high magnetic susceptibility values between 367 and 330 cm depth (11,800 to 10,000 cal yr BP). The lower part of the unit, between 367 to 350 cm depth (10,800 cal yr BP), was gyttja with sand, which changed to gyttja with abundant plant detritus in the upper part of the unit where organic content was moderate (at 20%). Organic content increased (to 50%) between 330 and 280 cm depth (10,000 to 8500 cal yr BP) and the sediment had abundant plant detritus. Magnetic susceptibility was low (~0 cgs) between 330 and 40 cm depth (10,000 to 1000 cal yr BP) and then increased toward the present (5×10^{-6} cgs). Percent organics dropped between 280 and 20 cm depth (to 25%; 8500 and 400 cal yr BP) and then increased toward surface (to 50%).

The similarity in the lithological records suggests that lakes were unproductive with high clastic inputs prior to ~14,000 cal yr BP. Lake productivity increased substantially after that and was high until ~9000 cal yr BP and then decreased slightly and remained unchanged until 6800 cal yr BP at Taylor and Campbell lakes and 400 cal yr BP at Cedar Lake. Clastic inputs into the system decreased until 6800 cal yr BP at Taylor and Campbell lakes and 10,000 cal yr BP at Cedar Lake, and very minor inputs into the system occurred until 1000 cal yr BP, after which inputs increased, except at Campbell Lake. After 6800 cal yr BP, lake productivity increased and peaked at 4800 cal yr BP at Taylor Lake and at 2000 cal yr BP at Campbell Lake.

Charcoal Record

Charcoal accumulation rates (CHAR) and mean fire episode return interval (MFI)) for Campbell, Taylor, Sanger, Bolan, Bluff, Crater and Cedar lakes are presented in the following section (Figure 3.3). A comparison of fire reconstructions based on tree-rings and lake sediment charcoal from Bluff, Crater, and Cedar lakes indicated that the charcoal data was not resolved enough to register individual fires, but instead captured broad periods of high fire activity (Whitlock et al., 2004). This insensitivity arises as a result of the slow sedimentation rates at these sites (see chronology results) and the likelihood that multiple fires were recorded in a single sample, a consequence of the relatively short median fire return interval of 35 years (range of 25 and 64 years) in modern mid-to-high elevation forest on UMS (Whitlock et al., 2004).

In addition to the effect of slow sedimentation rates on peak detection, differences in vegetation and fuels on NUMS and UMS likely also influenced the amount of charcoal produced during individual fire events. Therefore, only comparisons of peaks (fire episodes) from sites within each substrate-type are warranted because background is strongly influenced by available fuel biomass. For the purposes of comparing sites on UMS and NUMS over the last 14,000 years, the longest deposition time of sites on each substrate type (50 years cm^{-1} for both NUMS and UMS, Campbell and Bluff lakes) was selected to resample charcoal concentrations and deposition times. CHAR were smoothed at 700 years to determine background CHAR. Standardizing all records in this way produced different results than those previously published (Mohr et al., 2000; Daniels et al, 2005; Briles et al., 2005).

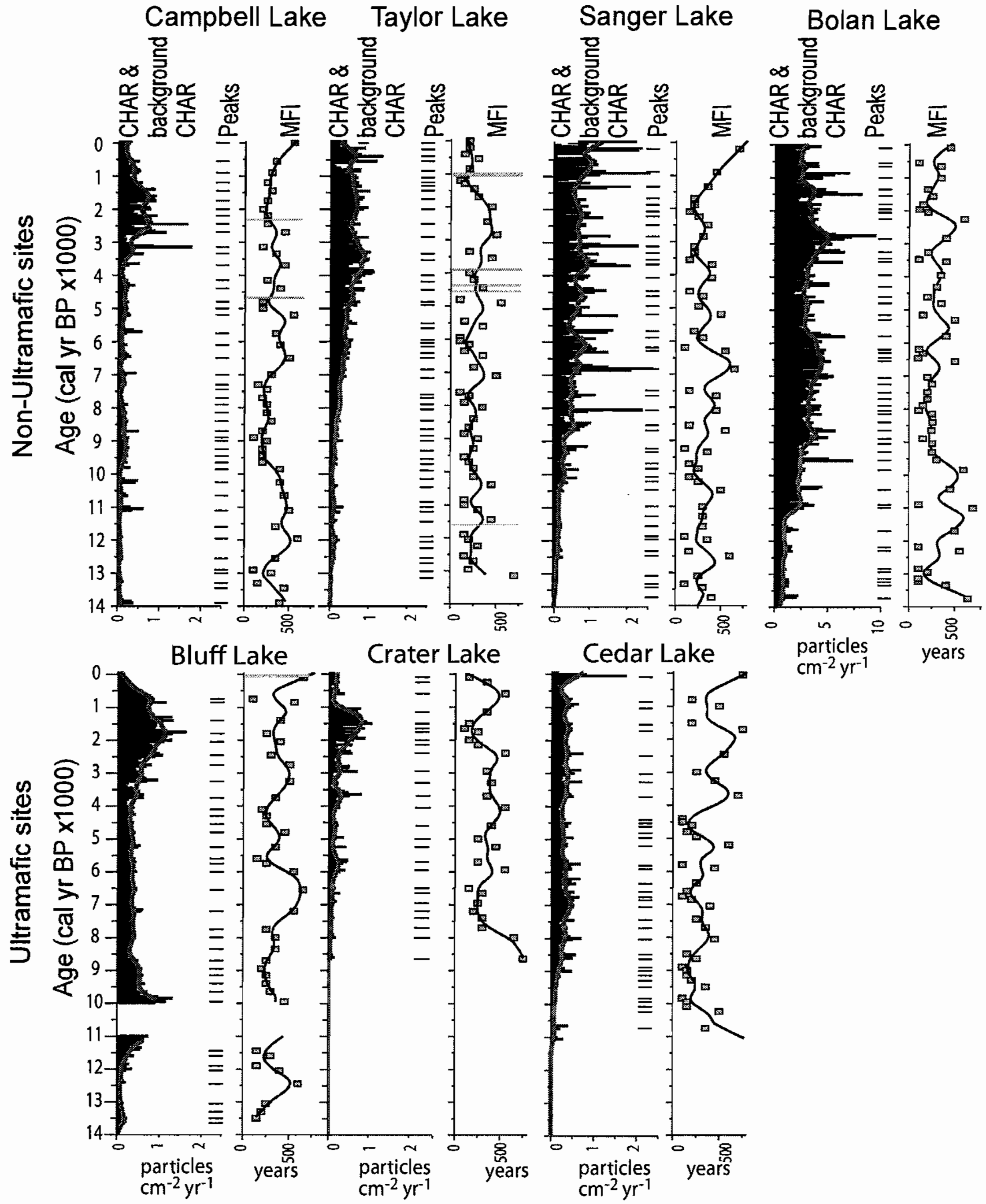


Figure 3.3. Charcoal accumulation rates (CHAR) for the last 14,000 cal yr for sites discussed in the dissertation. Accumulation rates were decomposed into background CHAR (gray slowly varying curve overlying the CHAR curve; window-width = 700 yr) and peaks or fire episodes. The mean fire return interval (MFI) shows the number of years between fire epiosodes (gray boxes) and is smoothed with a 1000-year window.

Campbell Lake had very low background CHAR levels (<0.1 particles $cm^{-2} yr^{-1}$) until 3500 cal yr BP, increased significantly after 3500 cal yr BP to 0.8 particles $cm^{-2} yr^{-1}$ and then dropped after 2000 cal yr BP to low levels (0.2 particles $cm^{-2}yr^{-1}$). Fire episodes were frequent (100 to 300 yr MFI) between 14,000 and 12,500 cal yr BP and became infrequent (~500 yr MFT) until 10,000 cal yr BP. Fire episodes were more frequent between 10,000 and 7000 cal yr BP (~200 yr MFI), infrequent (~450 yr MFI) between 7000 and 5000 cal yr BP, and variable (~200 to 300 yr MFI) between 5000 and 2500 cal yr BP. Fire episodes were frequent (250 yr MFI) until 1000 and then decreased (MFI >500 yrs).

Taylor Lake had very low background CHAR levels (<0.1 particles $cm^{-2} yr^{-1}$) until 9000 cal yr BP. Background CHAR gradually increased from 0.1 to 0.86 particles $cm^{-2} yr^{-1}$ until 3500 cal yr BP, declined to 0.6 particles $cm^{-2} yr^{-1}$ until 2500 cal yr BP and then remained unchanged until present. MFI ranged between 150 to 450 years between 14,000 and 10,000 cal yr BP, suggesting that fire occurrence was variable. Fire-episode occurrence became more consistent between 10,000 and 7000 cal yr BP with a MFI of 250 years. Between 7000 and 3000 cal yr BP MFI were more variable (ranged between 100 to 500 yrs). Fire episodes were infrequent (450 yr MFI) between 3000 and 1000 cal yr BP and frequent (150 yr MFI) in the last 1000 years.

The results of background CHAR for Sanger Lake are discussed in chapter 2. A median sample resolution at both sites (of 20 years) was used to compare the Bolan and Sanger lake charcoal data; and this approach produced 103 and 67 fire events/episodes, respectively, over the last 14,000 years. In order to compare these records with sites that had even slower sedimentation rates, the charcoal data were resampled to 50 year intervals. This coarser-resolution analysis yielded only 51 and 44 episodes at Bolan and Sanger lakes, respectively. The trends in fire occurrence were unchanged for Sanger Lake (i.e., fires were combined equally across the record), but the reanalysis of Bolan Lake indicated frequent fires between 7500 and 6000 cal yr BP and fewer fires in the last 1000 years (Briles et al., 2005). During these periods of frequent fire at Bolan Lake, the 50-year resampling interval captured as many as 3 fire episodes. Resampling the Bolan and Sanger lake records highlights the effects of sedimentation rate when reconstructing fire episodes from charcoal data, because the sedimentation influences whether or not an individual fire can be resolved in the lake sediment record.

Bluff Lake had moderate background CHAR levels between 14,000 and 9000 cal yr BP (0.1 to 1.5 particles $cm^{-3}yr^{-1}$), that dropped to 0.3 particles $cm^{-2}yr^{-1}$ until 4000 cal yr BP, increased to 1.1 particles $cm^{-2}yr^{-1}$ at 2000 cal yr BP and then declined to 0.1 particles $cm^{-2}yr^{-1}$ to the present. Charcoal was not evaluated during the mass-wasting events that occurred at Bluff Lake between 11,000 and 10,000 cal yr BP (Mohr et al., 2000). Fire-episode occurrence was variable (with MFIs between 250 and 500 yrs) initially between 14,000 and 11,000 cal yr BP. Between 10,000 and 7500 cal yr BP, fire episodes were frequent (MFI ~200 yrs) and infrequent (~550 yrs) until 6000 cal yr BP. Fire-episode occurrence was also variable between 6000 and 500 cal yr BP (with MFI between 250 and 500 yrs).

At Crater Lake, background CHAR ranged between 0.1 and 0.2 particles $cm^{-2}yr^{-1}$ between 8500 and 2500 cal yr BP, increased to 0.75 particles $cm^{-2}yr^{-1}$ by 1500 cal yr BP, and then dropped back to 0.2 particles $cm^{-2}yr^{-1}$. Fire episodes were frequent between 8000 and 6500 cal yr BP, became more variable between 6500 and 2000 cal yr BP (with MFIs between 300 and 500 yrs), frequent between 2000 and 1000 cal yr BP, and again variable over the last 1000 years (with MFIs between 300 to 500 yrs).

Cedar Lake had low background CHAR levels (<0.1 particles cm^{-2} yr^{-1}) until 9000 cal yr BP. Background CHAR gradually increased to 0.6 particles $cm^{-2}yr^{-1}$ at the present day. Fire episodes were infrequent between 11,000 and 10,000 cal yr BP (400 yr MFI), frequent (150 yr MFI) between 10,000 and 4000 cal yr BP, and more variable until present (with MFIs between 150 and 500 yrs).

In summary, all sites had low background CHAR levels over the last 14,000 years, except Bolan Lake in the northern Klamath Mountains, suggesting low-to-moderate severity surface fires and low charcoal production (Taylor and Skinner, 1998; 2003). At most sites, a slight increase in background CHAR occurred after 11,000 cal yr BP, indicating increased fuel biomass. Background CHAR peaked at Campbell, Bluff and Crater lakes between 3000 and 2000 cal yr BP, implying that fuels became better developed than before at this time.

Fire episodes on NUMS (Bolan, Sanger, Campbell and Taylor Lakes) showed variability in MFIs from 14,000 to 10,000 cal yr BP. Between 10,000 and 7000 cal yr BP, fire episodes were more frequent than before and MFIs were similar at and among sites. Fire episodes were infrequent between 7000 and 5000 cal yr BP, and slightly more frequent than before between 5000 and 3000 cal yr BP. MFIs were variable between

3000 and 1000 cal yr BP. At mid-elevation sites, MFIs increased in the last 1000 cal yr, except at Taylor Lake which remained unchanged from before.

Only one charcoal record on UMS, from Bluff Lake, extended back to 14,000 cal yr BP and MFIs were variable until 10,000 cal yr BP. Fire episodes were frequent between 10,000 and 7500 cal yr BP at Cedar and Bluff lakes, and then MFIs were variable until 500 cal yr BP at Cedar, Crater and Bluff lakes, showing few common trends. MFIs then increased at the sites on UMS to the present, with the exception of Crater Lake, where it decreased over the last 500 years.

Pollen Record

Pollen data for Cedar, Taylor, and Campbell lakes are presented in Figure 3.4 and 3.5. Those from Bluff, Crater and Mumbo lakes were described in Mohr et al. (2000) and Daniels et al. (2005) and will be discussed later as a comparison. The Taylor and Campbell (NUMS) pollen records show remarkable similarities over the last 14,000 cal yr BP, except for the abundance of *Picea* at Campbell Lake between 14,000 and 10,000 cal yr BP that is not present at Taylor Lake. The dominant pollen types in both records include haploxylon *Pinus* (likely *P. monticola* but possibly some *P. lambertiana), Abies* (likely *Abies concolor* or *Abies magnifica*), and *Amelanchier*. In contrast, the pollen record from Cedar Lake (UMS) is dominated by species of diploxylon *Pinus* (likely *P. jeffreyi* but possibly some *P. contorta*), Cupressaceae, and *Quercus*.

At the beginning of the Cedar Lake record (11,000 cal yr BP) percentages of diploxylon *Pinus* (likely *Pinus jeffreyi/contorta*) were high (up to 20%) and decreased (to

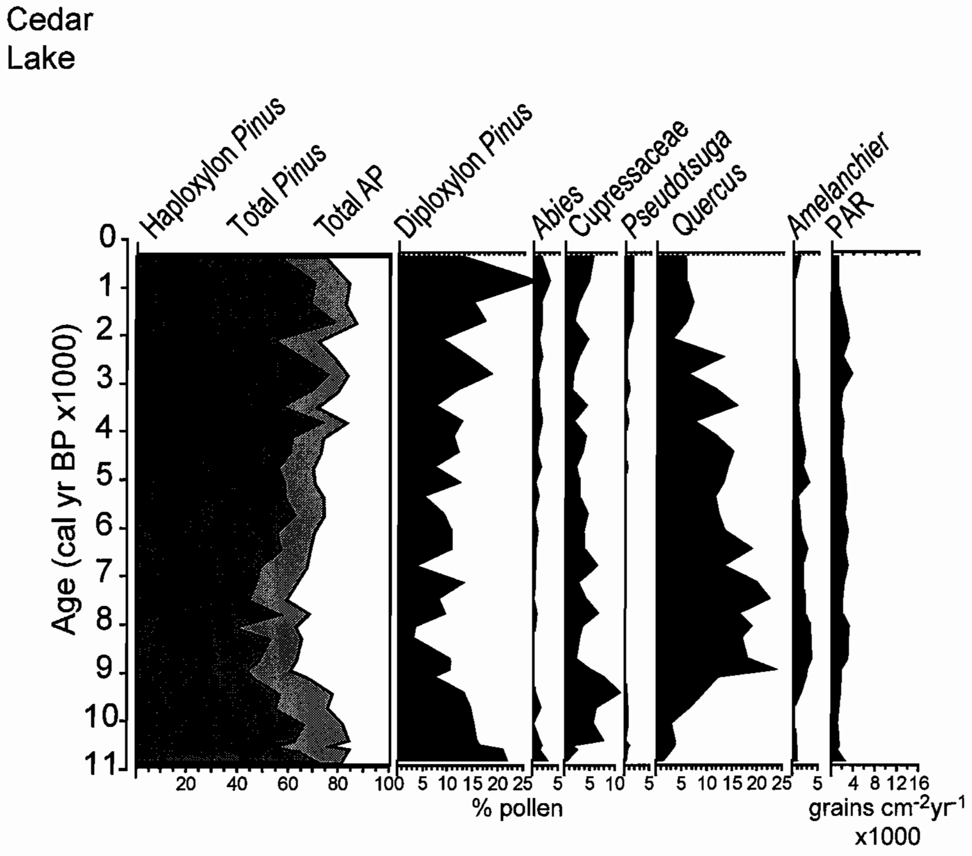


Figure 3.4. Pollen percentages for selected taxa for Cedar Lake on UMS. Arboreal pollen (AP) percentages and total pollen accumulation rates (PAR) are also included.

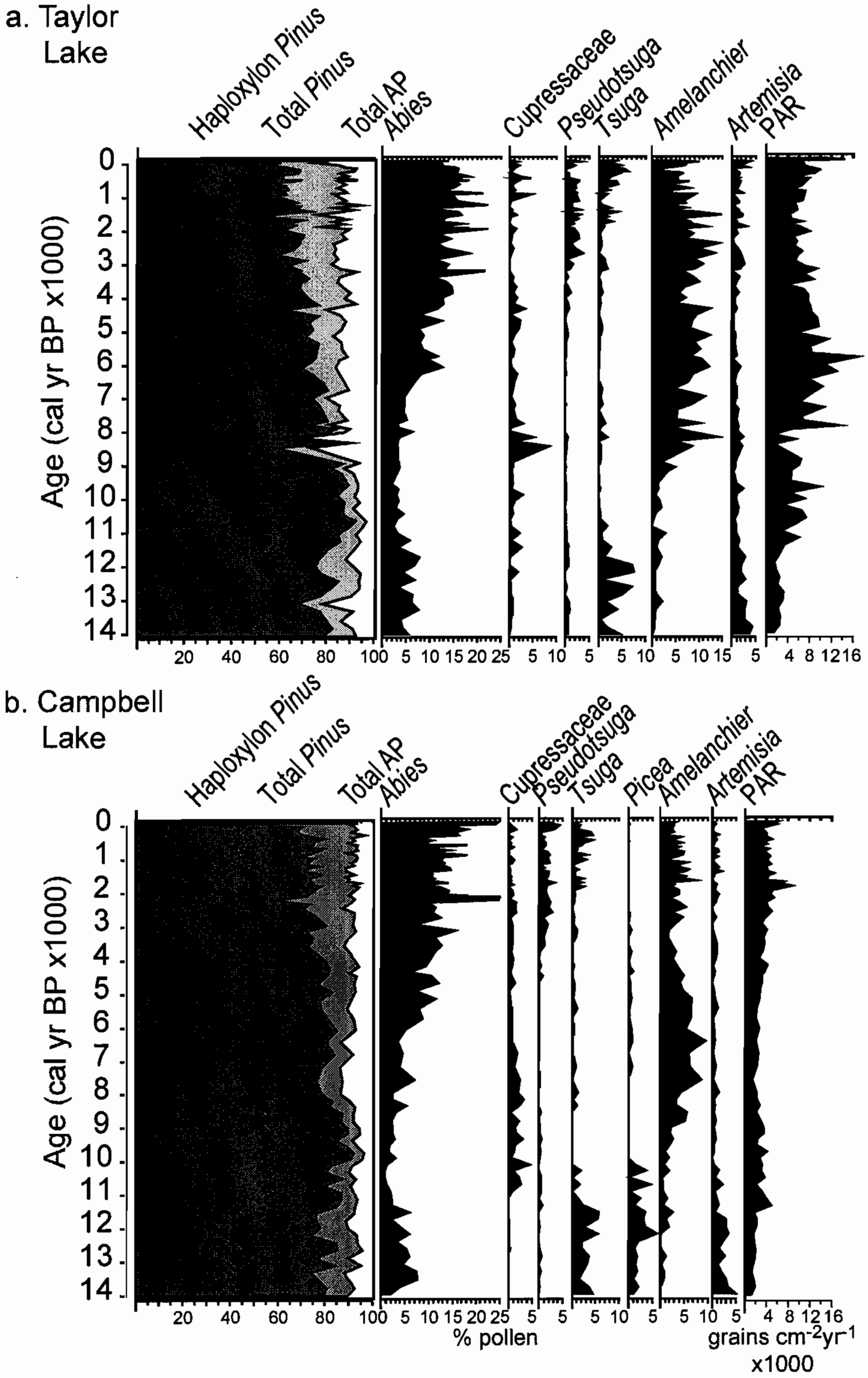


Figure 3.5. Pollen percentages for selected taxa for sites (a) Taylor Lake and (b) Campbell Lake on NUMS. Arboreal pollen (AP) percentages and total pollen accumulation rates (PAR) are also included for each site.

10%) until 9000 cal yr BP (Figure 3.4). Nonarboreal taxa were abundant (20-35%) through the record, especially between 9000 and 7000 cal yr BP (30-35%). After 9000 cal yr BP, the percentages of diploxylon *Pinus* remained unchanged until 3000 cal yr BP and then increased (to 15-20%). *Quercus* and *Amelanchier* increased (from 3 to 20% and >1% to 3%, respectively) between 10,000 and 9000 cal yr BP and gradually decreased (to 5% and >1%) toward the present. Cupressaceae was high (10%) between 11,000 and 9000 cal yr BP and then decreased (to 5%) until present. *Abies* was low (1-2%) throughout the record but was highest (~2%) between 11,000 and 9000 cal yr BP and after 5000 cal yr BP. *Pseudotsuga* was present after 2000 cal yr BP (~2%). Total PAR ranged between 2000 and 3000 grains cm^{-2} yr^{-1} suggesting that the forest was open (Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967). The vegetation at Cedar Lake during the last 11,000 was similar to that found on UMS today (i.e., *Pinus jeffreyi*, *Calocedrus decurrens* and *Quercus vaccinifolia*); however the abundances of diploxylon *Pinus*, Cupressaceae and *Quercus vaccinifolia* in the forest fluctuated.

Prior to 11,000 cal yr BP, Taylor Lake was characterized by an open forest of haploxylon *Pinus, Abies,* and *Tsuga,* and nonarboreal taxa (mostly *Artemisia*) indicated by pollen percentages of those taxa (45%, 6%, ~6%, ~10% respectively) and low total pollen accumulation rates (PAR) (~3000 grains cm^{-2} yr^{-1}) (Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967) (Figure 3.5a). After 11,000 cal yr BP, the forest was dominated by haploxylon *Pinus* (pollen percentages of the species increased to 55-60%) and total PAR (to 4500-5000 grains cm^{-2} yr^{-1}) increased, which implies the forest became more closed. Cupressaceae was a minor component of the forest with low percentages (<1%) between 14,000 and 9000 cal yr BP and between 8000 cal yr BP and present; with a brief increase (6%) for 1000 years after 9000 cal yr BP. At the height of the Cupressaceae percentages, between 9000 and 8000 cal yr BP, there was a decline in haploxylon *Pinus* in the forest (pollen percentages dropped to 40%). Nonarboreal taxa percentages declined (from 10% to 2%) between 13,000 and 9000 cal yr BP, indicating a sparse understory. After 9000 cal yr BP, nonarboreal taxa increased in the forest (pollen percentages increased to 15%) and remained unchanged, suggesting a more developed understory than before. *Amelanchier* was a part of the forest understory between 9000 and 2000 cal yr BP (pollen percentages of were up to 7-8%) and then declined slightly (decreased pollen percentages to 6%) at present. *Abies* and *Tsuga* were minor components of the forest after 11,000 cal yr BP as indicated by low pollen percentages of *Abies* (3%) until 6000 cal yr BP and *Tsuga* (<1%) until 2000 cal yr BP. Total PAR were the highest at Taylor Lake, between 8000 and 4000 cal yr BP (8000-10,000 grains cm^{-2} yr^{-1}), which suggests that the forest was relatively closed during this period ((Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967). However, the presence of shrubs and nonarboreal pollen suggest forest openings within closed patches of forest. *Abies* increased in abundance in the forest after 6000 cal yr BP (pollen percentages increased to 12%). Haploxylon *Pinus* decreased gradually in the forest (pollen percentages declined to <40%) until ca. 1000 cal yr BP, decreased significantly (pollen percentages dropped to <30%) until 500 cal yr BP, and then increased (pollen percentages increased to 50%) toward the present. *Pseudotsuga* pollen appeared in small amounts (2%) by 3000 cal yr BP and *Tsuga* (2%) by 2000 cal yr BP, suggesting that these species were only minor components of the forest. *Tsuga* percentages were moderate (up to 4%), indicating that the species attained late-glacial period abundances in the forest over the last 550 years. *Pseudotsuga* and *Abies* were less abundant than before in the forest as indicated by decreased percentages (<1% and 10%, respectively) between 550 and 200 cal yr BP. After 200 cal yr BP, *Pseudotsuga* increased (pollen percentages up to 5%) and *Abies* remained unchanged in the forest.

The pollen record Campbell Lake indicates open forest of haploxylon *Pinus, Abies,* and *Tsuga, Picea* and nonarboreal taxa (mostly *Artemisia*) prior to 11,000 cal yr BP as evidenced by the percentages of pollen of those species (45%, 7%, 4%, 10%, 4%, respectively) (Figure 3.5b). Total PAR (~2000 grains cm^{-2} yr^{-1}) was low suggesting that forests were open (Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967). *Artemisia* declined in the forest (pollen percentages decreased to 2%) after 11,500 cal yr BP and remained unchanged for the rest of the record. After 11,000 cal yr BP, the forest was dominated by haploxylon *Pinus* (pollen percentages of the sub-genus increased to 50-55%). Cupressaceae was a minor component of the forests indicated by low pollen percentages (~3%) between11,000 cal yr BP and 8000 cal yr BP, and then declined to very low abundances (pollen percentages decreased to 1%) by 6500 cal yr BP. *Amelanchier* was abundant in forest openings between 9000 and 5000 cal yr BP (pollen percentages up to 7-8%) and then declined (pollen percentages decreased to 2%) to the present. *Abies* and *Tsuga* were minor components of the forest after 11,000 cal yr BP, as indicated by low pollen percentages of *Abies* (2-5%) until 6000 cal yr BP and of *Tsuga* (<1%) until 2000 cal yr BP. *Abies* increased in abundance in the forest after 6000 cal yr

BP to the present (pollen percentages increased to 12%). Haploxylon *Pinus* percentages dropped after 11,000 cal yr BP (to 40%), remained unchanged until 2500 cal yr BP, dropped (to 35%) until 2000 cal yr BP and then increased to the present (to 40%), indicating the gradual replacement of haploxylon *Pinus* with *Abies* in the forest. PAR increased to 4000 grains cm^{-2} yr^{-1} between 11,000 and 9000 cal yr BP, decreased until 5000 cal yr BP to late-glacial period values, and then increased to 5000 grains cm^{-2} yr^{-1} at the present, suggesting that the forest, unlike Taylor Lake, was open between 9000 and 5000 cal yr BP, and then gradually became more closed (Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967). *Pseudotsuga* was present in the forest by 4000 cal yr BP and *Tsuga* by 2000 cal yr BP as indicated by the small percentages of those species (2 and 3%, respectively). During the height of *Tsuga* percentages between 550 and 200 cal yr BP, those of *Pseudotsuga* and *Abies* were low (>1% and 10%, respectively). After 200 cal yr BP, *Pseudotsuga* and *Abies* increased (up to 5% and 15%, respectively). The trade-offs in these pollen-types over the last 1000 years, suggests that the forest was experiencing significant changes in composition.

Discussion

Environmental History of the Klamath Mountains

The vegetation and fire history of the Klamath Mountains is reconstructed from a network of sites from southern Oregon to the northern extent of the Sacramento Valley in northern California (Figure 3.6 and 3.7). Vegetation and fire histories from Taylor Lake (Figure 3.6a), Campbell Lake (Figure 3.6b), Bolan Lake (Figure 3.6c), Sanger Lake

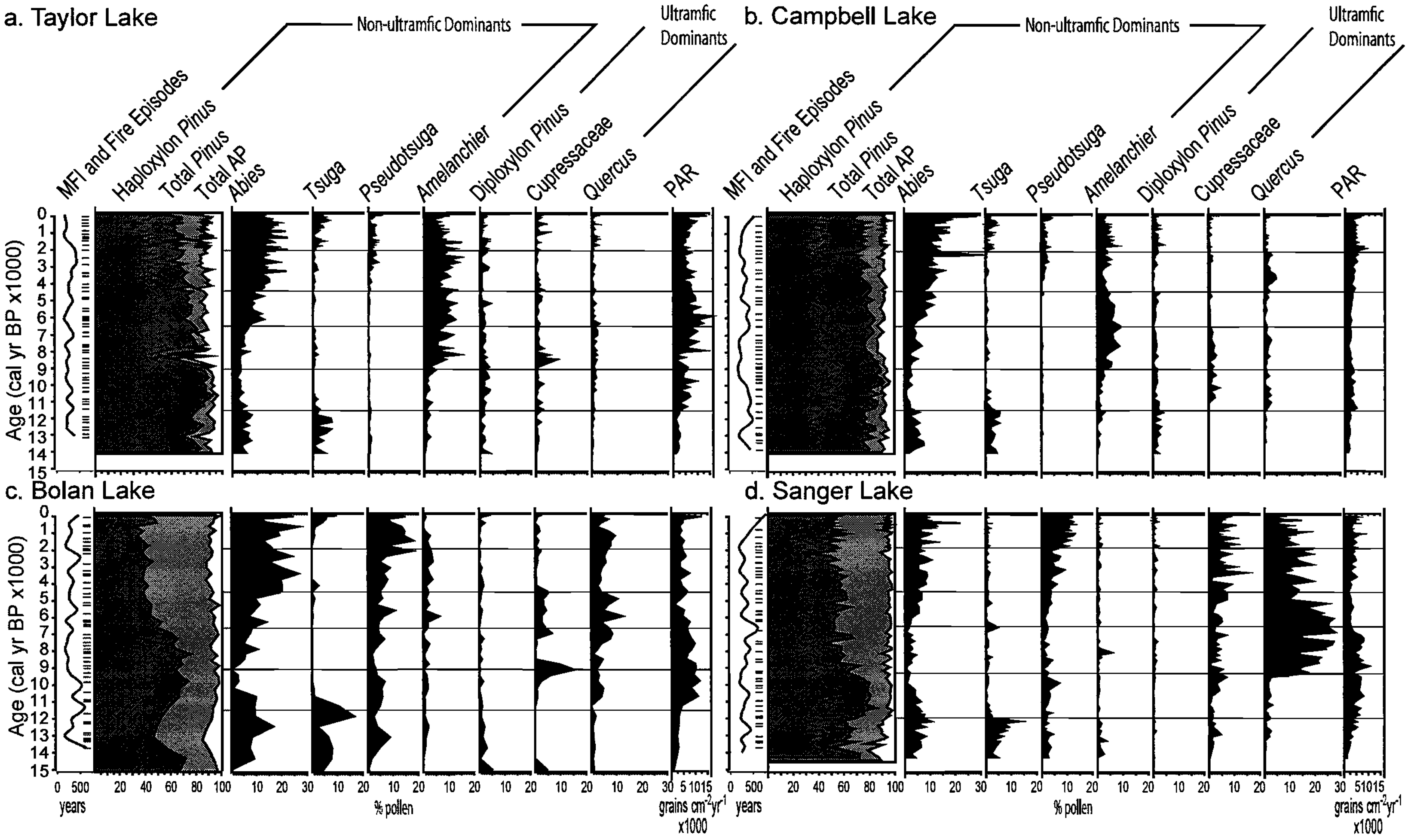


Figure 3.6. Pollen percentages and total pollen accumulation rates (PAR) for sites on NUMS (Taylor, Campbell, Bolan and Sanger lakes). Horizontal lines represent zones that identify major changes in species composition and/or abundance at the sites.

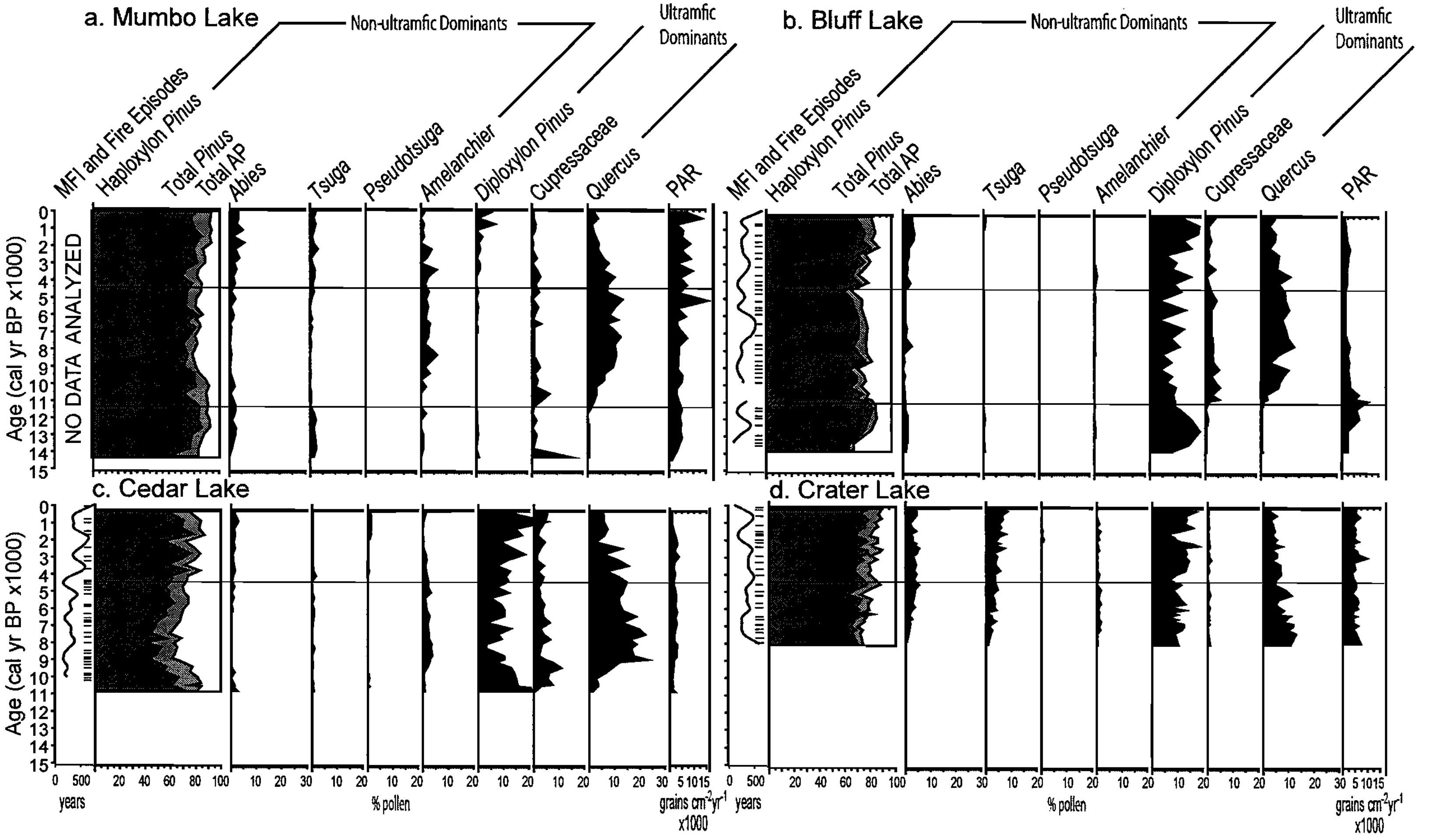


Figure 3.7. Pollen percentages and total pollen accumulation rates (PAR) for sites on NUMS (Mumbo Lake) and UMS (Bluff, Cedar and Crater lakes). Horizontal lines represent zones that identify major changes in species composition and/or abundance at the sites.

(Figure 3.6d), Mumbo Lake (Figure 3.7a), Bluff Lake (Figure 3.7b), Cedar Lake (Figure 3.7c), and Crater Lake (Figure 3.7d) are included in the reconstruction (Mohr et al., 2000, Daniels et al., 2005). Bluff, Crater, and Cedar lakes will be referred to collectively as sites on UMS, and Bolan, Sanger, Taylor and Campbell lakes are located on NUMS. The pollen record from Mumbo Lake showed extralocal forest responses on UMS as well as local changes on NUMS, suggesting that Mumbo Lake was capturing pollen beyond the watershed. The vegetation and fire reconstruction at these eight sites is also compared with independent climate data (alkenone-derived SSTs, speleothem $\delta^{18}O$-dervied temperatures, and climate simulations) from the region (Figure 3.8).

Late-glacial Period (>11,500 cal yr BP)

During this late-glacial period, summer insolation was increasing from near-modern levels in the full-glacial period, causing increased continental heating and warmer conditions than before, as suggested by paleoclimate model simulations at 14,000 cal yr BP (Bartlein et al., 1998; Bartlein and Hostetler, 2004). These simulations also suggest that the decrease in size and elevation of the North American ice sheets resulted in the northward shift in the northern hemisphere jet stream at this time (relative to earlier), which brought wetter conditions to the Pacific Northwest. Ocean record ODP 1019, located off the coast of northern California, indicates that sea-surface temperatures (SST) were 1-2°C less than present between 15,000 and 13,000 cal yr BP based on alkenone data (Barron et al., 2003).

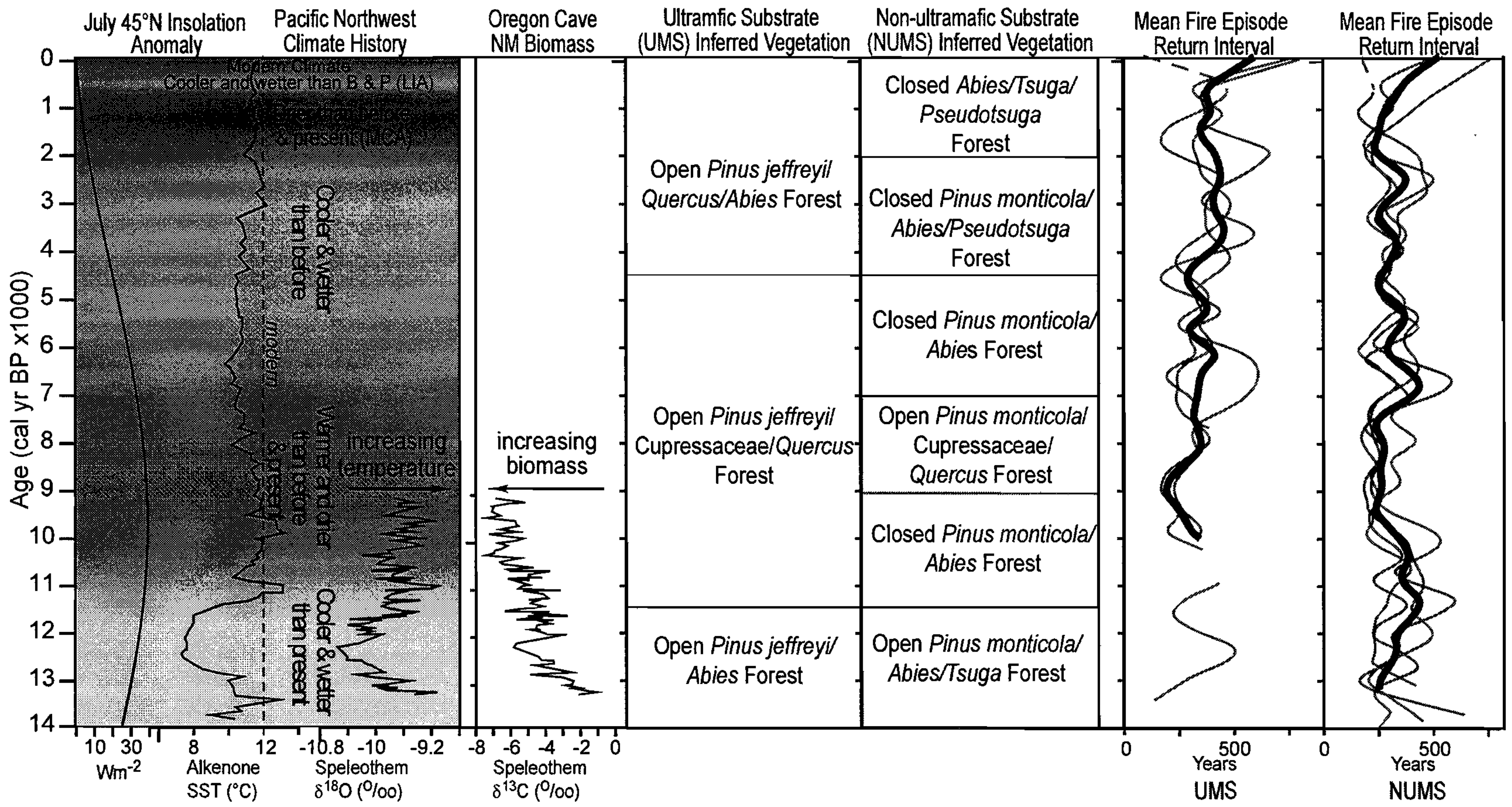


Figure 3.8. Climate, vegetation and fire history (based on pollen and charcoal data) from the Klamath Mountains. July 45°N insolation anomaly, PNW climate history and terrestrial biomass production inferred from alkenone-derived sea-surface temperatures, speleothem δ^{18}O-derived temperatures and δ^{13}C-derived biomass production, and climate simulations (Barron et al., 2003; Vacco et al., 2005; Bartlein et al., 1998). MFIs (gray curves) for sites on UMS and NUMS are averaged (black curve). High-elevation sites on UMS and NUMS that showed a decrease in MFI in the last 1000 years are dashed.

The late-glacial lithology and pollen data from on both NUMS and UMS in the Klamath Mountains are consistent with cool wet conditions inferred from the late-glacial simulations (Bartlein et al., 1998). Following deglaciation, the lakes were initially unproductive and had a high input of clastic material (clay-to-sand sized particles) from unstable slopes. They became more productive around 14,000 cal yr BP based on radiocarbon dates from gyttja.

On NUMS (i.e., Campbell, Taylor, Bolan and Sanger lakes), subalpine parkland was widespread at middle and high elevations. Nonarboreal taxa (i.e., *Artemisia* and herbaceous taxa) were moderately abundant and low total PAR suggest sparse vegetation cover. *Abies* (most likely *A. magnifica* and *A. concolor*), *Tsuga*, *Pseudotsuga,* and haploxylon *Pinus* (most likely *Pinus monticola* and possibly *P. lambertiana*) were growing near the sites on NUMS. The vegetation composition was most similar to modern associations in the *Tsuga mertensiana* Zone (Franklin and Dyrness, 1988), suggesting that species were growing 500 m lower in elevation than their present range.

In contrast, UMS (i.e., Bluff Lake) supported open forests of diploxylon *Pinus* (most likely *P. jeffreyi* and possibly *P. contorta*), *Abies* (most likely *A. magnifica* and *A. concolor*), and a substantial shrub and herbaceous understory. The abundance of *Pinus* and nonarboreal taxa on UMS through the late-glacial period suggests open plant communities and low soil moisture. The vegetation was comparable to that of higher elevation forests on UMS today (Whittaker, 1960). Fire-episode occurrence was variable and likely as surface fires, as evidenced by the small amounts of charcoal in the sediments.

An abrupt cooling of 3°C during the Younger Dryas chronozone (YDC; 12,900 to 11,500 cal yr BP) has been inferred from a speleothem $\delta^{18}O$ record from Oregon Caves National Monument, southwestern Oregon (OCNM; Vacco et al., 2005) and from alkenone-derived SST estimates (Barron et al., 2003). Lake sediment records from the Klamath Mountains show an increase in *Tsuga* in forests on NUMS, in addition to an increase in *Picea* at Campbell and Bolan lakes (see Figure 3.5b and Figure 2.6 in Chapter 2) that occurred during the later part of the YDC (12,500 to 11,500 cal yr BP). This shift from subalpine parkland to a forest of *Tsuga* and *Picea* is likely the result of the development of warmer wetter conditions. During the same period, *Abies* increased slightly in forests on UMS (i.e., Bluff Lake), again suggesting that conditions were warmer and wetter than before. Nonarboreal taxa declined from 14,000 to 11,000 cal yr BP at all sites, suggesting that the forests were becoming more closed. Similarly, the $\delta^{13}C$ OCNM speleothem record also implies a closing of forests as terrestrial biomass gradually increased through the YDC (Figure 3.8). Periods without fire are noted at Bolan, Campbell and Bluff lakes, and this is likely the result of wetter conditions than before, whereas other sites show little change in fire frequency through the YDC. Finally, most sites show an increase in organic content and a decrease in clastics during the YDC, with the exception of Bolan Lake, where clastic content increased.

After 11,500 cal yr BP, an abrupt warming of 4 to 5°C is recorded in the speleothem and ocean data (Barron et al., 2003; Vacco et al., 2005). This warming is also evidenced by the decline in *Tsuga*, *Picea*, *Pseudotsuga* and *Abies*, and the increase in *Pinus monticola/lambertiana*, Cupressaceae and *Quercus* on NUMS. Fire-episode occurrence remained variable on NUMS. Higher overall charcoal and pollen abundance (background CHAR and PAR) on NUMS than before, suggests closed forests and increased fuel biomass after 11,500 cal yr BP. In forests on UMS, *Pinus jeffreyi/contorta* and *Abies* declined, Cupressaceae and *Quercus* became abundant in the forest, and fire occurrence remained unchanged from before. Background CHAR and PAR were low on UMS, suggesting that forests were open and fires were small. Lake productivity, as evidenced by sediment organic content, increased substantially after 11,500 cal yr BP at sites on both NUMS and UMS.

The Early and Middle Holocene (11,500 cal yr BP to ca. 5000 cal yr BP)

During the early Holocene, higher-than-present summer insolation led to the expansion and intensification of the northeastern subtropical high pressure system, and increased continental heating and aridity in the Pacific Northwest, as suggested by paleoclimate simulations of 11,000 cal yr BP (Bartlein et al., 1998). From 11,000 to 8200 cal yr BP, alkenone-derived SSTs temperatures were up to 1°C above modern conditions, and then decreased to 1°C below modern conditions between 8200 and 3300 cal yr BP (Barron et al., 2003). Similar early-Holocene conditions are recorded in the speleothem record from Oregon Caves National Monument (Vacco et al., 2005).

On NUMS (i.e., Campbell, Taylor, Bolan and Sanger lakes), *Abies, Pseudotsuga* and *Tsuga* were reduced in abundance after 11,500 cal yr BP. *Pinus monticola/lambertiana* remained the dominant species, and increased between 11,500 and 9000 cal yr BP. Cupressaceae and *Quercus* were abundant in most forests on NUMS after 9000 cal yr BP, except near Campbell Lake. *Amelanchier* increased and was more abundant in open forests (e.g., at Taylor and Campbell lakes) between 9000 and 6000 cal yr BP in the southeastern Klamath Mountains. *Amelanchier* does well on NUMS where fire is frequent and forests are open today (Alexander et al., 2007). A similar increase in *Quercus* occurred at 11,000 cal yr BP at Bolan Lake and at 9000 cal yr BP at Sanger Lake, and it decreased at both sites at 5000 cal yr BP. *Quercus* abundance at Sanger and Bolan lakes suggests forest openings around the lakes. Fire episodes were frequent in forests on NUMS after 10,000 cal yr BP. The increase in background CHAR suggests fires were consuming more biomass.

On UMS (i.e., Bluff and Cedar Lake), *Pinus jeffreyi/contorta* continued to dominate forests between 11,500 and 8000 cal yr BP. The pollen data also suggests an abundant shrub and herbaceous understory. *Quercus* increased after 11,500 cal yr BP and was high until 5000 cal yr BP. Cupressaceae was also well represented by 11,000 cal yr BP. The association of *Pinus jeffreyi/contorta, Quercus,* and Cupressaceae apparently developed as early as 11,000 cal yr BP. Fire episodes were frequent at Bluff and Cedar lakes after 10,000 cal yr BP, and increased background CHAR, suggests that fires were consuming more biomass.

On NUMS (i.e., Campbell, Taylor, Bolan and Sanger lakes), *Abies* (likely *A. concolor*) increased in forests after 7000 cal yr BP and was abundant by 6000 cal yr BP. The increase in *Abies* in the forests was likely a response to increasingly cooler and wetter conditions than before. *Pinus monticola/lambertiana* decreased between 9000 and 8500 cal yr BP in forests, and remained unchanged until 2000 cal yr BP. Interestingly, at

Bolan Lake an increase in *Pinus monticola/lambertiana* occurred between 8500 and 7500 cal yr BP, in addition to an increase in Cupressaceae and *Quercus* between 8500 and 6000 cal yr BP. These short-term fluctuations are attributed to increases in temperature, xeric conditions, and frequent fires (11 fires/1000 years; see chapter 2). Background CHAR and fire-episode occurrence either increased (e.g., Sanger, Taylor, and Bolan lakes) or remained unchanged (e.g., Campbell Lake) from before. The similarity of the past vegetation composition with modern compositions in the Mixed-Evergreen Zone (i.e., *Pinus monticola/lambertiana*, Cupressaceae, and *Quercus*; occurring 500 m in elevation below the sites today) on NUMS, suggests that species ranges shifted upslope in response to warmer drier conditions than before and at present.

On UMS (i.e., Crater, Bluff and Cedar lakes), *Pinus jeffreyi/contorta* increased slightly after 8000 cal yr BP, but remained in moderate abundance until 5000 cal yr BP. *Abies* also increased slightly in the last 7000 cal yr BP. Background CHAR remained moderate-to-low on UMS. Fire episodes occurred irregularly (MFIs were variable) across the region on both substrate types between 7000 and 5000 cal yr BP.

Late Holocene (ca. 5000 cal yr BP to present)

Decreasing summer insolation resulted in a weaker northeastern Pacific subtropical high pressure system, and cooler wetter summers than before, as suggested by paleoclimate model simulations at 6000 cal yr BP (Bartlein et al., 1998). Alkenone-derived SSTs were initially cool at 5000 cal yr BP and then warmed 1°C after 3300 cal yr BP (Barron et al., 2003). Speleothem data are not available for this time period.

On NUMS (i.e., Campbell, Taylor, Bolan and Sanger lakes), *Abies* increased after 6000 cal yr BP and reached peak abundances after 4000 cal yr BP through present day. *Pseudotsuga* increased after 4500 cal yr BP and *Tsuga* increased and reached late-glacial abundances after 2000 cal yr BP. Cupressaceae reached low abundances after 5000 cal yr BP. The forest at Sanger Lake maintained high abundances of Cupressaceae, possibly suggesting that *Chamaecyparis lawsoniana*, which dominates the watershed today, was present through the Holocene (see chapter 2). *Amelanchier* and *Quercus* declined and were moderately abundant after ca. 4500 cal yr BP. Background CHAR reached peak levels within the last 5000 cal yr BP in forests on NUMS. Fire episodes occurred more regularly than before and were moderately frequent. Fire episodes were infrequent at all mid-elevation sites after 1000 cal yr BP, which may be in part related to Little Ice Age (500-100 cal yr BP; Taylor, 1995) cooling and/or fire suppression. At Taylor Lake, at higher elevations, fire episode occurrence remained unchanged.

On UMS (i.e., Crater, Bluff and Cedar lakes), *Pinus jeffreyi/contorta* increased in the forests, reaching percentages of the late-glacial period, while Cupressaceae and *Quercus* were less abundant in the forest than before. Forests on UMS maintained xerophytic plant communities that changed little in composition; however, the mild wet conditions of the late Holocene were likely responsible for an increase in *Pinus jeffreyi/contorta* and *Abies* (slight increase) and a decrease in *Quercus* and *Amelanchier*. At higher elevations, *Tsuga* and *Abies* were more abundant at Crater Lake after 5000 cal yr BP than at Cedar and Bluff lakes, suggesting that these species did better in high-elevation forests, where conditions were effectively wetter. In contrast, *Tsuga* and *Abies* were well represented in forests on NUMS at similar elevations as Cedar and Bluff lakes. Increased background CHAR corresponded with increased *Abies* in forests on UMS starting at 5000 cal yr BP, suggesting that the forests produced more charcoal. Crater and Bluff lakes show a significant increase in background CHAR after 3000 cal yr BP, that declined in the last 600 years, again suggesting fires were more severe in the late Holocene. Fire episodes occurred irregularly in forests on UMS until 1000 cal yr BP, and then became infrequent at mid-elevation sites.

During the last 2000 years, Taylor and Campbell lakes on NUMS show periods of increased *Tsuga* and decreased *Abies* from 2000 to 1100 cal yr BP and 700 to 200 cal yr BP, and increased *Abies* and decreased *Tsuga* between 1100 to 700 cal yr BP and after 200 cal yr BP to the present. In addition, *Pseudotsuga* was significantly reduced between 700 and 200 cal yr BP, and increased to the highest abundance of the record in the last two centuries. Periods of high *Tsuga* likely signal cool wet periods, such as the Little Ice Age (600-100 cal yr BP; Graham et al., 2007; Taylor, 1995), and periods of high *Abies* and *Pseudotsuga* indicate warmer drier periods, such as the Medieval Climate Anomaly (1450-600 cal yr BP; Graham et al., 2007).

Historical Factors Influencing Floristic Diversity

The Klamath Mountains have been a long-term refuge for once widespread flora of the western US throughout the cooling and drying of the Cenozoic (see chapter 1) and this provides one historical explanation for the present diversity. However, the explanation must be tempered in light of what we know about Quaternary climate change (i.e., glacial/interglacial cycles resulting from fluctuations in solar radiation), and especially the changes since the last glaciation (i.e., higher than present summer insolation during the early Holocene and centennial variations in climate in the late Holocene including the MCA and LIA). This study suggests that geology plays an important role in the floristic diversity of the region over the Holocene and it seems that edaphic controls have maintained differences in forest composition (as can be detected in the pollen record) in the face of Holocene climate fluctuations. The vegetation association of *Pinus jeffreyi*, Cupressaceae, and *Quercus* on UMS today has persisted for at least 11,500 years and withstood climate fluctuations, such as the early-Holocene arid period, MCA, and LIA, with little change. In contrast, plant communities on NUMS have been more sensitive to climate change and species have responded by adjusting their ranges up or down slope. For example, at middle and high elevations in the Klamath Mountains, an abrupt change in species composition occurred at 11,500 cal yr BP on NUMS when conditions became warmer (~5°C) and drier than before. *Abies*, *Picea*, and *Tsuga* decreased and *Pinus monticola/lambertiana*, Cupressaceae and *Quercus* were abundant in early- and middle-Holocene forests. In the late Holocene, *Abies*, *Tsuga* and *Pseudotsuga* became more abundant in forests on NUMS as conditions became cooler and wetter than before, and elevation ranges were lowered in response to LIA cooling or higher during more xeric conditions in the MCA. Sampling resolution was not high enough in this study to evaluate comparable responses on UMS to late-Holocene climate variability.

Vegetation on NUMS during the late-glacial period was similar to that of the *Tsuga mertensiana* Zone (Franklin and Dyrness, 1988), which occurs 200 to 500 m above the sites today. The forest composition in the early and middle Holocene has modern affinities with the Mixed-Evergreen Zone, which occurs 200 to 500 m below the sites today. The similarity of past assemblages with present forest types implies that elevational adjustment on NUMS was one way for plant species to respond to climate change, and little reorganization of plant communities occurred during these shifts.

Forests on UMS seem to have been more tolerant of climate change, probably because the communities are already constrained by nutrient and moisture limitations and are therefore adapted to the stressed conditions. Species and even forest associations were able to survive large changes in climate intact, as long as the elevational gradients allowed ranges to shift through seed dispersal and seedling establishment to higher or lower elevations. As a result of these range shifts, phenotypes that were better adapted for the new climate survived in the population (Davis and Shaw, 2001). The combination of the two methods of survival to climate change (i.e., range adjustments and in-situ adaptation) likely contributes to the high floristic diversity in the Klamath Mountains.

The paleoecological data from the Klamath Mountains also suggest that UMS communities have supported more xerothermic vegetation types than NUMS communities during the Holocene. On UMS, forests at higher elevations (i.e., Crater Lake) supported more *Abies* and *Tsgua* throughout the Holocene than the lower elevation forests (e.g., Bluff and Cedar lakes). In contrast, forests on NUMS consistently supported more *Abies* and *Tsuga* than those on UMS. This suggests that low effective moisture limited *Abies* and *Tsuga* from UMS at lower elevations. Interestingly, at no time in the last 14,000 years did forests on UMS and NUMS have similar compositions.

Fires are an important disturbance agent in the Klamath forests, creating multiple-aged stands of varying composition. The complex mosaic of fire patterns in the Klamath Mountains today (Skinner et al., 2006, Taylor and Skinner, 2004; 1998) is related to the varying topography, substrate and microclimates. For example, tree-ring studies show small isolated areas record uniform fire dates, whereas at larger scales, fire occurrence is asynchronous (Taylor and Skinner, 2003). The rugged, complex terrain in the Klamath Mountains creates fire patterns that are spatially complex resulting in fires of different sizes and intensities with generally open forests (Taylor and Skinner, 1998).

The charcoal data suggest that fire was important at all sites during the last 14,000 years, but the fire history at each site was fairly unique. Only during the early Holocene did all sites show a common period of frequent fire episodes. Sites on NUMS experienced frequent fire episodes in the early Holocene, which helped support xerophytic and fire-tolerant taxa including *Pinus monticola/lambertiana,* Cupressaceae, *Amelanchier* and *Quercus*. Cooler, wetter periods in the late-glacial and late Holocene featured more mesophytic/fire-intolerant species, including *Abies*, *Tsuga*, and *Picea* and more variable fire regimes. On UMS, forests also experienced frequent fires during the early Holocene (i.e., between 10,000 and 7000 cal yr BP) and xerophytic and fire-tolerant species (i.e., *Pinus jeffreyi*, Cupressaceae, and *Quercus*). Fire regimes on UMS were highly variable after 7000 cal yr BP and forests continued to support fire-tolerant species. Thus, like the vegetation, fire activity on NUMS changed with climate variations more than it did on UMS. The persistent high levels of fire on UMS likely added to the stability of plant communities there by maintaining a consistent disturbance regime. The different fire and vegetation responses through the Holocene on NUMS and UMS contribute to the complexity of vegetation patterns at present.

Conclusions

This study highlights a range of factors that have been important in determining vegetation composition and fire activity during the Holocene in the Klamath Mountains of northern California. Distinct shifts in vegetation occurred at approximately 11,500, 9000, 7000, 4500 and 2000 cal yr BP in forests on NUMS and at 11,500 and 4500 cal yr BP in forests on UMS. Prior to 11,500 cal yr BP, when the climate was cooler and wetter than today, open forests of *Pinus monticola/lambertiana*, *Abies*, *Pseudotsuga* and *Tsuga* grew on NUMS, whereas open forests of *Pinus jeffreyi/contorta* and *Abies* were present on UMS. Fire activity varied on both substrate types with alternating periods of frequent and infrequent fire episodes.

After 11,500 cal yr BP, as summer insolation increased and conditions became warmer and drier than today, UMS continued to support open forests of *Pinus jeffreyi/contorta*, and Cupressaceae and *Quercus* were abundant in the forest for the first time. On NUMS, *Tsuga* and *Pseudotsuga* declined, *Abies* was significantly reduced, and *Pinus monticola/lambertiana*, Cupressaceae, *Amelanchier*, and *Quercus* were abundant after 11,500 cal yr BP. Fire episodes were frequent on both NUMS and UMS during the early Holocene. Warmer drier climate conditions resulted in more frequent fire than before and fires were likely of low severity.

The modern forest composition on NUMS did not become established until the late Holocene with the expansion of *Pseudotsuga* at 4500 cal yr BP and *Tsuga* at 2000 cal yr BP. Fire occurred less frequently under cooler and wetter conditions than before at sites on NUMS. In contrast, forests on UMS continued to support a *Pinus jeffreyi/contorta*, Cupressaceae, *Quercus* forest after 11,500 cal yr BP with little change from before. Fire at UMS sites occurred at variable frequencies after 7000 cal yr BP.

In conclusion, forests in the Klamath Mountains coped with climate change in at least two ways. First, plant species dominant on UMS have adapted to tolerate nutrient and moisture limitations, and were apparently fairly unresponsive to Holocene climate variations. UMS were more xeric and supported more drought-tolerant species than exist on NUMS. Thus, UMS forests have changed little and have tolerated a wide range of environmental conditions during the Holocene in situ. The second strategy occurs on NUMS where species have adjusted their distribution by moving up or downslope in response to climate change. At any given location in the Klamath Mountains, this strategy has resulted in vegetation associations moving up and downslope relatively intact. These different methods of surviving climate change, along with the variety of fire regimes, results in a diversity of plant communities in the Klamath Mountain region.

The results of this research suggest that edaphic differences have been important in the vegetation and fire history of the Klamath Mountains region during the last 14,000 years. Vegetation on NUMS has been particularly sensitivity to climate change and responded to abrupt and gradual shifts in climate through elevation adjustments. For example, the abrupt 5°C warming at the late-glacial/early Holocene transition resulted in the loss of subalpine parkland and the replacement of more drought-tolerant species such as haploxylon *Pinus* (likely *Pinus monticola*), Cupressaceae (*Calocedrus decurrens*) and *Quercus vaccinifolia.* In the late Holocene, as conditions became cooler and wetter than the early Holocene, more mesophytic species such as *Abies* and *Tsuga* moved downslope. Two species, *Tsuga* and *Pseudotsuga,* have been particularly sensitive to Holocene climate on NUMS. Both species were restricted under warmer drier conditions in the early Holocene, especially in the southeastern Klamath Mountains, and show considerable fluctuations in response to late Holocene climate variability.

Plant communities on NUMS, as compared with those on UMS, will likely experience the greatest amount of change with projected warmer conditions in the next century (IPCC, 2007). Plant species will track their ideal conditions up and down slope as they have in the past to changes in climate. In contrast, vegetation on UMS has shown little change in the Holocene to climate change as a result of nutrient and moisture deficiencies. These communities may well show the least amount of response to future warming.

CHAPTER IV

SUMMARY

The Klamath Mountains of northern California support some of the most diverse conifer forests in the world, including several species that occur nowhere else. This investigation of the postglacial history of vegetation and fire, reconstructed using pollen and charcoal preserved in lake sediments, provides a better understanding of the development of these forests and their sensitivity to past environmental change. In particular, it uses the unique diversity of geology and spatial variability of climate in the region to determine the role of climate change on plant communities and fire regimes during the Holocene. Previous paleoecological studies from the region (Daniels et al., 2005; Briles et al., 2005 Mohr et al., 2000) have focused on establishing basic trends in the vegetation and climate history, but none have specifically examined the influence of environmental gradients and substrate on this history. The investigation took two approaches.

1) Two nearby sites (Bolan and Sanger lakes) situated along a coastal-to-inland (wet to dry) moisture gradient, at similar elevations, were compared to determine whether the present differences in forest composition arise from distinct vegetation, fire, and climate histories or merely reflect local site differences.

2) Three sites on ultramafic substrates (UMS; Crater, Cedar and Bluff lakes) and five sites non-ultramafic substrates (NUMS; Taylor, Campbell, Mumbo, Bolan and Sanger lakes) were compared to examine how Holocene climate variations influenced vegetation and fire on different substrates. Due to the striking differences in forest composition and structure today on the different substrate-types, it was of interest to understand if the forests remained consistently different over the Holocene as a result of soil characteristics.

Comparison of the vegetation and fire histories of the two sites along the coastal-to-inland moisture gradient suggested that the histories differed as a result of the persistence differences in climate along this gradient. At both sites, the late-glacial period (>11,500 cal yr BP) was characterized by subalpine parkland and infrequent fire. Subalpine parkland was replaced by closed forest of *Pinus* (likely *Pinus monticola* and/or *P. lambertiana*), Cupressaceae (likely *Calocedrus decurrens* and/or *Chamaecyparis lawsoniana*), *Abies* (likely *Abies concolor* and/or *A. magnifica*) and *Pseudotsuga menziesii* and more frequent fires at both sites. The shift occurred 1000 years earlier at the wetter coastal site (Sanger Lake), than at the drier more inland site (Bolan Lake). The earlier coastal response is attributed to the influence of reduced Pacific Ocean upwelling, between 12,000 and 11,000 cal yr BP, which created warmer drier conditions at the coast. The inland site, in contrast, was influenced more by locally retreating glaciers and cooler conditions. In the early Holocene (11,500 to ~5000 cal yr BP), *Pinus* was less abundant and fire activity was less frequent than before at the coastal site, whereas *Pinus* and higher fire frequencies predominated at the inland site. In addition, *Quercus vaccinifolia* became abundant at the inland site ~2000 years earlier than at the coastal site in the early Holocene. The coastal site was likely influenced by increased coastal upwelling and fog production at this time, whereas hot dry conditions may have affected the more inland site. In the late Holocene (5000 cal yr BP to present), *Abies* and *Pseudotsuga* increased and *Pinus* and *Quercus* decreased in the forest at both sites, suggesting a widespread response to cooler and wetter conditions than before. Wetter conditions than before at the coastal site, also allowed more Cupressaceae to occupy the site. Fewer fires within the last 1000 years may also account for the abundance of *Picea* (likely *P. breweriana)* at the wetter site. The inland site supported more *Tsuga* in the late Holocene, which is likely the result of higher snowpack and proximity of high-elevation peaks, where the species is most abundant today.

The comparison of the two records implies that large-scale controls in climate over the Holocene resulted in major changes in vegetation and fire regime at both sites, but the mesoscale contrast between coastal and inland locations resulted in somewhat different timing of climate change and ecosystem response. Thus, variations in the timing of changes in effective moisture and temperature, ultimately resulting from the influence of ocean upwelling and inland heating, are important in creating different vegetation histories and consequently different plant communities at present.

Across the western US differences in the timing of responses of vegetation and fire at nearby sites has been attributed to a variety of controls including topography and aspect that create a diversity of microclimates, spatial variability of precipitation in mountainous regions, and the autecology of individual species that governs their responses to climate change (Gavin et al., 2006, Brunelle et al., 2005, Heinrichs et al., 2002, Clark et al., 1998, Whitlock and Bartlein, 1993). Although several studies have noted asynchrony in vegetation response among nearby sites (Hebda, 1995; Matthews, 1985), only a few discuss controls. In the Rocky Mountain region, locations can be separated into summer-wet and summer-dry based on the relative importance of summer and winter precipitation. Whitlock and Bartlein (1993) proposed that the contrasts between adjacent sites were stronger in the early Holocene as a result of the influence of greater-than-present summer insolation. Studies in western Montana and eastern Idaho (northern Rocky Mountains) by Brunelle et al (2005) and in Yellowstone by Millspaugh et al. (2004) show that during the early Holocene, summer-dry sites were effectively drier than today, while summer-wet sites were effectively wetter than today (Mock and Bartlein, 1995). Summer-wet areas became wetter because of strengthened onshore flow of moisture from the Gulf of Mexico and Gulf of California which likely enhanced convective thunderstorms in summers during the early Holocene leading to wetter summers conditions. The increase in precipitation in the early Holocene resulted in fewer fires in the northeastern Rocky Mountains. A stronger subtropical high pressure system over the eastern Pacific Ocean during the early Holocene would have suppressed precipitation, and created suitable conditions for fires in the northwestern Rocky Mountains. In the intermountain west, the juxtaposition of two precipitation regimes is responsible for different responses at nearby sites (Fall et al., 1995).

In southern British Columbia, differences in the paleoenvironmental histories of different sites during the Holocene are attributed to the influence of the west-to-east moisture gradient. Heinrich et al. (2002) compared the vegetation response to Holocene climate change for four sites at similar elevations along a climate gradient east of Vancouver, B.C. They found in the late Holocene that cool-wet sites responded earlier to cooling and the development of more mesic conditions than did sites at warmer and drier locations because plant species reached environmental thresholds that allowed for an earlier response at the cool sites. On Vancouver Island, B.C., Brown et al. (2006) reconstructed variations in Holocene precipitation in a series of sites along an east to west transect. Vegetation and fire histories from sites on the eastern side of the island suggest consistently dry conditions through the Holocene and the western sites suggest consistently wet conditions on Vancouver Island, B.C. The central sites histories, however, recorded drier conditions than today during the early Holocene, suggesting a steep precipitation gradient from the coast-inland. The central sites became wetter in the late Holocene, resulting in a more homogenous climate regime across the island. Both Heinrich et al. (2002) and Brown et al. (2006) provide evidence for a coastal-to-inland moisture gradient during the Holocene that caused differential responses in vegetation and fire over short distances.

The results from the Klamath Mountains and southern B.C. suggest that the coastal-to-inland moisture gradient can either enhance or subdue the response of vegetation and fire to larger-scale climate variations over the Holocene by influencing both effective moisture and temperature. In the Klamath Mountains, Sanger Lake, on the coastal side of the Siskiyou Mountains, has lower summer temperatures and higher effective moisture than the more inland location, Bolan Lake, in the interior Siskiyou Mountains. Sanger

Lake maintained more *Picea* and Cupressaceae and experienced fewer fires than Bolan Lake during the Holocene. In contrast to the study on Vancouver Island, the difference in forest composition at the two sites suggests a steep moisture gradient prevailed through the entire Holocene. In addition, vegetation and fire at Sanger Lake responded 1000 years sooner than at Bolan Lake to warmer conditions during the late-glacial/early Holocene transition as a result of warmer coastal conditions (reduced ocean upwelling) and cooler inland conditions that developed during this time. Further, increased summer insolation during the Early Holocene and enhanced continental heating resulted in a greater abundance of xerophytic species and a greater incidence of fire at Bolan Lake than at Sanger Lake. The significant difference between the environmental histories presented in the dissertation and those described in southern B.C., is the influence of ocean upwelling and associated moisture differences between Bolan and Sanger lakes (besides those attributed to the coastal-to-inland moisture gradient) that resulted in asynchronous responses in plants at the two sites.

The third chapter examined the response of vegetation and fire to Holocene climate fluctuations on different substrates, specifically ultramafic substrates (UMS) and non-ultramafic substrates (NUMS). Lakes were located in mixed-conifer forests at similar elevations (between 1600-2100 meters) and had similar modern climates. In the southeastern Klamath Mountains, sites on UMS (Crater, Ceder and Bluff lakes) were located on an extensive peridotite outcrop, two sites on NUMS (Taylor and Campbell lakes) were located on granodiorite and sedimentary bedrock, and Mumbo Lake was located on diorite bedrock, surrounded by extensive peridotite outcrops. Sites discussed in chapter 2 (Sanger and Bolan lakes) located on diorite bedrock were also included in the comparison with other NUMS sites, because their modern climates and vegetation were similar to those in the southeastern Klamath Mountains.

During the late-glacial period (>11,500 cal yr BP), summer insolation increased from near-modern values and conditions became warmer and wetter than before. NUMS supported an open forest of *Pinus monticola* and/or *P. lambertiana*, *Abies* (either *A. concolor* or *A. magnifica*), *Tsuga,* and *Pseudotsuga,* whereas UMS supported open forest of *Pinus jeffreyi* and/or *P. contorta* and *Abies.* This implies that UMS supported a more open forest of xerophytic taxa than NUMS during a period of cooler and wetter conditions than today. Charcoal data suggest that fire episodes (periods of fire) occurred irregularly at all sites, indicating no widespread control on fire, and low charcoal accumulation rates indicate surface fires.

Vegetation changed significantly on both substrates after 11,500 cal yr BP in response to increased summer insolation and warmer and drier conditions than before. On NUMS, closed forests with mesophytic species, between 11,500 and 9000 cal yr BP, gave way to open forest of xerophytic taxa, such as *Pinus monticola/lambertiana,* Cupressaceae, *Quercus* and *Amelanchier*, between 9000 and 7000 cal yr BP. On UMS, open forests of Cupressaceae and *Quercus* with less abundant *P. jeffreyi/contorta* developed after 11,500 cal yr BP, and the composition has remained unchanged until present. This implies that climate had little influence on forest composition after 11,500 cal yr BP on UMS. Fire episodes were more frequent than before on NUMS and UMS during the early Holocene, suggesting that warm dry conditions had a widespread influence on fire regimes at this time. Warmer and drier conditions than today in the early Holocene apparently also had a significant and widespread impact on vegetation on both substrate-types, with forests on UMS supporting mostly shrubs with a few scattered trees and forests on NUMS an open woodland.

After 7000 cal yr BP, *Abies* increased and was abundant by 6000 cal yr BP in forests on NUMS as summer insolation decreased and conditions became cooler and wetter than before, indicating that the forests were becoming more closed. Fire episodes were less frequent than before in forests on NUMS, between 7000 and 5000 cal yr BP, suggesting more mesic conditions were limiting fires. In contrast, fire occurred more variably in forests on UMS, between 7000 and 1000 cal yr BP, indicating climate had little influence on fire regimes. *Pseudotsuga* returned to the forests on NUMS after 5000 cal yr BP, during a period of frequent fire episodes, and *Tsuga* was present after 2000 cal yr BP, during a period of fewer fire episodes, indicating a transition from xerophytic fire-tolerant species to mesophytic fire-intolerant species in the forest. On UMS, forest composition remained the same, however, abundances of Cupressaceae and *Quercus* declined and *P. jeffreyi/contorta* dominated after 5000 cal yr BP. Over the last 1000 years, fire activity decreased to historical lows at mid-elevation sites, while it increased at higher elevations in forests on UMS and NUMS.

The different substrates in the Klamath Mountains have supported distinct plant communities over the Holocene, and these communities responded differently to climate variations. On UMS, plant species (at least those identified in the pollen record) and fire regimes were fairly unresponsive to changes in climate during the Holocene. On NUMS, in contrast, plant species were very responsive to climate change, resulting in a progression of different vegetation assemblages over time. Fire regimes on NUMS were similar among sites and tracked large-scale climate changes resulting from variations in summer insolation.

Thus, plant diversity in the Klamath Mountains has been, in part, maintained by substrate differences that influence forest structure and composition. Plants on UMS are able to withstand nutrient deficiencies, and this adaptation to edaphic conditions seems to limit the sensitivity of UMS plant communities to climate change. In contrast, plants on NUMS have shifted their elevational ranges up and downslope in response to climate change and plant communities have remained relatively intact.

The role of substrate on historical plant communities and fire regimes has been addressed in other studies over the last three decades (Oswald, 2003; Whitlock, 1993; Millspaugh et al., 2000; and Brubaker, 1975). Brubaker (1975) compared the vegetation history on glacial till and outwash in upper Michigan to determine how substrate differences influence past vegetation. Soil texture affected soil moisture, with till holding more moisture than outwash. High infiltration rates on outwash also resulted in greater nutrient leaching and infertile soils than till. Pollen records from lakes on the different substrates indicated that the vegetation history on dry outwash sites supported open jack pine (*Pinus banksiana*) woodland for the last ~10,000 radiocarbon years. More-mesic sites on till showed a more dynamic and diverse vegetation history, including shifts from a jack pine forest following deglaciation to a white pine (*Pinus strobus*), deciduous tree forest after 8000 radiocarbon years. Brubaker (1975) showed that soil texture had a overriding influence on long-term climate conditions over the Holocene, in particular, creating much drier conditions on coarser-grained outwash than on till and a stable plant community dominated by jack pine.

The vegetation and fire history of Grand Teton and Yellowstone National Parks also shows the long-term influence of substrate on vegetation dynamics (Whitlock, 1993). Well-drained, infertile rhyolite soils in central Yellowstone have supported *Pinus contorta* (lodgepole pine) through the Holocene. In contrast, more fertile andesite and nonvolcanic substrates in Grand Teton NP maintained a diversity of species and communities including *Picea*, *Abies,* and *Pinus albicaulis* (white bark pine) during the late-glacial period, *Pinus contorta, Pseudotsuga and Populus* in the early Holocene, and *Pinus albicaulis, Picea*, and *Abies* during the late Holocene. These vegetation changes on andesite soils correspond with long-term variations in climate. The fire history on well-drained rhyolite substrates showed a response to large-scale changes in climate during the Holocene (Millspaugh et al., 2000). For example, fire frequency was highest during the early Holocene when summer radiation was higher that today, and decreased through the late Holocene as summer insolation decreased. Thus, it seems that drier summer conditions in the early Holocene were responsible for higher fire activity than at present, but edaphic conditions maintained stable plant communities despite these climate variations.

Another study from the central Arctic Foothills of northern Alaska showed that the edaphic diversity in the region supported different tundra communities through the Holocene (Oswald et al., 2003). Flat surface with fine-textured soils were dominated by dwarf-shrub tundra throughout the Holocene, whereas coarse-textured soils have supported a sparser, shorter canopy with non-tussock sedges, prostrate shrubs and non-Sphagnum mosses. Oswald et al. (2003) suggests that even in harsh tundra environments substrate differences influence the response of plants to long-term climate change.

The studies in upper Michigan, Yellowstone National Park and Alaska, focus on differences in soils moisture and fertility to explain the long-term differences in vegetation history. In contrast, an analysis of available water-holding capacities in the Klamath Mountains revealed no significant differences between UMS and NUMS (Alexander et al., 2007). However, studies have shown that plants on UMS have plant traits (e.g., reduced root growth, sclerophyllous/hairy leaves) that suggest that the environment is moisture limiting (Alexander et al, 2007; Poshenrieder and Barcelo, 2004). Studies also show that plants on UMS are limited by low calcium and high magnesium and nickel concentrations contained in the parent rock (Vlamis, 1949; Proctor 1970; White, 1971; Alexander et al., 1989; Kruckeberg, 1984). The calcium deficiency results in sparse shrub and herb communities with few species (many of which are endemic) that can tolerate the harsh environments. The openness of UMS communities likely results in higher evapotranspiration rates than in NUM communities, creating drier conditions on UMS. Unlike most soils, UMS become more fertile (i.e., open shrub herbaceous communities become dense forests) over millions of years as excess magnesium is leached from soils (Alexander, 2004; Kronberg and Nesbitt, 1981). Therefore, mineral deficiencies (calcium) and heavy metals (magnesium and nickel) of UMS, as opposed to soil texture that results in leaching of nutrients mentioned in the other studies, hinder plant growth and create sparser communities than on NUMS. In addition, the openness of forests on UMS results in increased loss of moisture, which further limits plant growth (Alexander, 2007; Kruckeburg, 1984). The corresponding effect of mineral deficiencies, heavy metals and limited moisture on UMS likely created local conditions that exceeded more regional conditions imposed by Holocene climate variability and resulted in minor vegetation changes in the Klamath Mountains.

Species on NUMS responded to long-term climate change by adjusting their ranges along elevational gradients. The vegetation reconstructions on NUMS have modern analogs that can be found at different elevations today. For example, during the early Holocene when conditions were warmer that today, xerophytic species that occur 500 meters downslope in the Mixed-Evergreen zone today were likely abundant at higher elevations in the Klamath Mountains (Franklin and Dyrness, 1988). These adjustments involved species that currently grow in the Klamath Mountains and there is no evidence of large-scale biogeographic range changes, such as those observed in the eastern US (Webb et al., 1988).

Elevational adjustments of similar magnitude are part of the vegetation history of other mountain ranges in the western U.S (Jackson et al., 2005; Anderson, 1990; Whitlock, 1993; Petersen and Mehringer, 1976). For example, at mid-elevations on the Colorado Plateau, an *Artemisia, Picea* forest, found at higher elevations today, was replaced by a forest dominated by *Pinus ponderosa* from lower elevations as conditions became warmer and drier than before in the early Holocene (Bentancourt, 1984; Anderson et al., 2000). In the Klamath Mountains, elevational adjustments on NUMS provide a localized way for plant species to persist during periods of climate change. In contrast, UMS are characterized by relatively stable vegetation communities resulting from soil conditions that dampen the response of vegetation to variations in climate.

The high-resolution pollen and charcoal analysis of three new sites in the Klamath Mountains extends the network of vegetation and fire histories in the region, making it possible to address how spatial variations in climate and substrate influence vegetation and fire response to insolation-driven climate change occurring on time scales of centuries to millennia. The results of this research suggest that the topography in the region and ocean influences create a steep moisture gradient that affects the timing of response of plant communities and fire regimes (and consequently forest composition) to long-term climate change over the last 14,000 years. The range of edaphic conditions in the region has supported different plant communities over the Holocene. Communities on UMS showed less sensitivity to Holocene climate changes, whereas communities on NUMS adjust their ranges up and downslope. In conclusion, the study provides new information on how different environmental factors have influenced the Holocene vegetation history of the Klamath Mountains.

APPENDIX A

SANGER LAKE POLLEN DATA

Depth (m)	Age (cal yr BP)	Haploxylon Pinus	Diploxylon Pinus
0	-53.00	128	3
0.05	-13.65	95	2
0.09	28.50	82	0
0.13	79.81	95	4
0.17	131.30	85	2
0.21	183.12	83	3
0.25	235.34	90	0
0.29	288.14	97	5
0.35	368.78	87	0
0.37	396.01	82	1
0.41	451.43	107	1
0.45	507.74	76	0
0.49	565.26	83	1
0.53	623.99	98	2
0.57	684.01	85	3
0.61	745.41	101	0
0.65	807.92	74	1
0.69	870.87	119	0
0.73	934.29	96	1
0.77	997.46	100	2
0.81	1059.92	112	1
0.85	1121.60	124	0
0.95	1272.98	52	0
1.03	1391.20	91	2
1.11	1506.90	103	0
1.19	1619.99	114	0
1.27	1731.37	65	6
1.35	1840.96	79	0
1.39	1895.50	92	0
1.49	2030.62	120	0
1.61	2192.50	37	1
1.73	2356.32	98	2
1.88	2568.93	124	5
1.97	2701.30	103	0

2.05	2824.64	92	1
2.13	2952.34	78	1
2.25	3155.43	109	4
2.33	3301.46	61	2
2.45	3541.18	133	0
2.57	3809.55	99	1
2.65	4004.50	86	0
2.77	4319.71	108	4
2.81	4429.84	69	1
2.97	4886.15	90	0
3.05	5120.26	91	0
3.13	5354.87	128	3
3.25	5702.08	94	1
3.29	5815.82	67	1
3.37	6039.08	103	0
3.45	6255.97	104	0
3.57	6566.49	110	1
3.69	6856.27	88	0
3.77	7036.28	76	0
3.85	7203.29	117	0
3.95	7394.45	78	5
4.07	7598.70	91	2
4.15	7725.63	169	2
4.23	7850.41	117	2
4.37	8076.20	78	0
4.45	8214.87	123	3
4.53	8363.61	133	0
4.61	8522.69	111	4
4.68	8672.48	107	3
4.77	8878.49	176	1
4.85	9075.66	98	2
4.93	9287.68	123	0
5.01	9517.53	100	2
5.13	9901.00	125	1
5.25	10334.95	285	0
5.33	10654.37	296	0
5.41	10998.19	125	1
5.45	11180.19	219	0
5.49	11368.06	157	1
5.53	11561.72	161	1
5.55	11660.20	171	1
5.57	11760.15	166	0
5.61	11963.76	241	0
5.65	12172.03	107	2

5.67	12277.62	94	0
5.71	12490.88	121	1
5.73	12598.60	344	0
5.75	12707.09	105	3
5.79	12924.85	232	0
5.81	13034.19	117	0
5.84	13198.66	117	0
5.87	13364.11	107	0
5.93	13694.89	135	0
6.00	14080.94	192	0
6.04	14301.50	123	1

Pinus undifferentiated	Total Pinus	Picea	Abies	Pseudotsuga
32	163	12	20	36
64	161	7	25	36
63	145	19	27	35
89	188	18	31	41
87	174	7	24	27
55	141	6	21	15
74	164	6	30	36
52	154	16	24	38
47	134	26	67	37
85	168	4	49	34
51	159	4	34	37
67	143	0	27	20
65	149	14	38	31
47	147	6	23	34
68	156	7	32	31
64	165	9	11	35
112	187	6	18	37
54	173	5	11	11
95	192	4	28	30
98	200	1	36	43
57	170	11	17	42
57	181	2	28	39
82	134	11	17	25
90	183	6	21	36
60	163	5	40	29
36	150	6	22	23
106	177	8	22	33
99	178	4	15	12
68	160	7	18	20
44	164	2	23	12
35	73	2	10	10
57	157	4	24	23
49	178	6	34	21
47	150	4	27	13
54	147	0	17	15
87	166	4	17	15
69	182	5	17	28
89	152	8	26	22
61	194	4	28	13
81	181	10	26	11
100	186	12	27	19

62	174	5	13	10
108	178	0	19	11
106	196	5	21	10
57	148	8	14	12
77	208	1	18	8
72	167	4	19	8
101	169	4	14	5
66	169	1	8	4
93	197	1	9	7
62	173	9	6	8
86	174	0	2	7
118	194	7	9	5
90	207	3	5	4
78	161	2	12	1
61	154	2	5	9
91	262	8	12	8
78	197	1	10	2
92	170	3	4	4
84	210	9	16	6
77	210	0	11	3
78	193	2	8	14
80	190	5	10	11
79	256	4	4	8
111	211	0	2	1
61	184	2	6	8
134	236	6	5	6
124	250	7	3	22
63	348	2	18	12
86	382	2	19	15
120	246	3	20	8
47	266	3	12	7
122	280	5	18	4
98	260	7	23	4
104	276	14	16	14
101	267	4	27	8
17	258	8	27	8
78	187	9	34	5
106	200	7	15	8
72	194	14	25	0
15	359	9	23	9
105	213	5	10	4
69	301	16	31	21
89	206	10	26	9
55	172	4	14	6

105	212	8	19	6
61	196	16	25	14
61	253	12	9	8
123	247	19	14	9

Cupressaceae	Tsuga mertensiana	Quercus vaccinifolia	Amelanchier
31	0	29	3
22	2	10	1
20	3	13	2
17	1	16	4
19	0	26	2
14	0	44	1
11	1	28	1
15	1	15	1
13	1	11	0
10	4	18	4
20	0	20	2
34	0	32	0
16	2	20	0
22	1	25	1
17	5	19	0
11	0	42	1
21	3	28	0
10	3	57	2
10	4	48	1
14	0	23	1
7	2	42	1
10	3	22	1
31	2	30	2
16	3	29	1
19	3	36	1
35	1	42	1
17	5	26	5
32	0	25	2
15	2	59	0
10	1	43	2
19	2	43	2
16	0	39	1
11	0	43	0
19	4	51	2
13	0	60	4
32	2	30	3
8	1	34	0
44	5	20	0
5	3	42	0
2	2	63	1
28	2	31	0

14	2	42	2
21	3	39	1
22	2	30	2
9	7	79	0
7	0	52	1
4	0	77	2
10	1	64	1
16	0	89	0
19	3	97	4
7	16	83	0
7	1	96	0
20	1	45	0
10	1	47	0
8	3	87	2
12	3	90	0
7	4	109	0
15	0	83	4
7	1	32	17
13	0	56	3
5	8	80	5
14	1	71	0
2	4	75	2
2	3	55	0
17	2	43	1
9	0	53	0
22	3	8	2
9	3	4	1
18	0	7	3
5	2	11	1
2	0	2	0
0	4	10	0
4	3	2	2
6	6	1	1
4	4	5	0
5	7	4	0
5	10	9	1
3	43	0	2
7	22	2	5
4	28	2	3
12	31	9	0
11	26	8	4
22	17	7	4
4	21	6	0
3	8	0	10

5	17	1	2
5	15	2	3
2	8	0	9
1	16	0	0

Ceanothus	Chrysolepis-type	Poaceae	Artemisia	Chenopodiineae
2	5	2	4	0
2	9	2	3	0
2	0	3	3	1
1	1	4	4	1
4	1	5	4	2
3	6	1	7	2
1	5	1	7	0
2	5	5	6	0
0	1	0	1	2
0	2	2	2	0
2	3	2	2	1
7	6	8	2	2
1	0	1	3	0
8	4	6	0	2
5	1	4	6	0
2	9	2	2	0
1	0	5	6	0
5	6	14	2	2
3	2	9	4	0
1	2	1	2	0
4	10	0	3	0
1	3	3	4	2
3	3	8	2	0
2	0	5	4	3
2	3	2	6	2
3	2	7	8	0
6	2	2	3	0
6	4	3	4	1
5	3	4	3	0
6	4	8	4	1
3	3	5	7	2
3	9	3	6	3
4	3	2	2	1
1	11	3	2	2
6	8	5	1	1
1	1	4	2	3
5	3	1	3	0
0	1	4	2	0
0	3	3	4	2
3	4	5	2	0
2	0	2	5	0

1	3	1	2	0
2	1	6	1	1
2	2	0	11	1
7	0	3	2	1
2	0	2	2	1
6	6	2	7	0
2	2	1	2	0
4	6	2	2	0
2	4	5	2	1
1	0	2	5	0
3	1	0	5	0
3	0	2	5	1
0	3	4	5	1
3	1	3	3	1
4	4	8	2	0
3	3	2	5	1
4	1	1	3	1
4	3	3	9	1
1	0	2	2	2
2	2	4	4	1
2	0	3	2	0
3	1	6	1	3
0	1	0	3	2
3	1	1	9	0
3	1	1	3	0
3	1	4	6	2
0	1	1	4	0
1	0	6	2	0
4	0	3	2	0
0	2	1	2	0
0	0	4	2	3
0	0	1	1	0
0	4	3	3	0
0	1	4	1	0
0	0	1	2	0
0	0	2	1	1
1	0	5	8	0
0	1	9	5	2
0	0	6	3	1
0	2	14	11	1
3	0	7	5	2
1	7	8	5	1
0	1	3	8	0
0	8	6	26	3

0	1	4	5	1
1	4	14	16	4
1	0	2	5	2
0	0	14	4	1

Total Pollen Sum	Spike Count (13911)
330	257
299	112
287	122
348	110
322	69
297	115
313	84
302	157
305	60
313	100
304	82
310	89
286	80
312	126
310	78
325	107
328	84
343	84
351	73
329	40
328	67
315	53
305	85
323	74
331	66
332	87
334	114
319	50
319	90
313	75
229	69
316	71
323	61
318	87
313	98
310	58
313	88
300	125
316	37
328	82
320	118

311	71
292	145
314	105
317	52
319	41
333	67
306	63
325	65
381	86
329	64
341	52
303	61
309	28
318	33
338	48
453	58
341	45
297	57
348	43
360	44
341	29
350	39
354	19
322	27
297	39
326	21
313	18
446	25
473	19
313	21
344	29
329	14
351	19
365	18
351	15
375	39
322	16
320	31
309	15
531	32
326	29
472	48
316	24
300	64

308	30
390	48
350	78
343	80

APPENDIX B

TAYLOR LAKE POLLEN DATA

Depth (m)	Age (cal yr BP)	Haploxylon Pinus	Diploxylon Pinus
0.00	-53.00	102	7
0.04	-29.00	133	5
0.08	6.00	90	8
0.12	81.72	157	7
0.16	156.60	141	0
0.17	175.33	257	7
0.21	250.16	183	5
0.24	306.05	123	4
0.25	324.68	132	0
0.29	399.04	110	5
0.32	454.56	109	0
0.33	473.03	122	2
0.36	528.12	119	2
0.37	546.42	98	9
0.43	655.24	131	6
0.49	761.92	131	1
0.53	831.87	100	4
0.57	900.84	124	1
0.59	935.13	119	3
0.71	1138.71	172	2
0.75	1206.45	136	1
0.79	1274.38	158	2
0.83	1342.32	139	10
0.87	1410.90	157	3
0.91	1480.01	178	14
0.95	1549.81	115	6
0.99	1620.29	159	9
1.03	1691.55	179	8
1.07	1763.26	125	3
1.11	1835.69	173	6
1.15	1908.45	131	10
1.19	1981.47	135	7
1.27	2128.39	130	8
1.35	2276.15	191	6

1.43	2424.51	210	2
1.51	2573.64	187	2
1.59	2723.47	104	1
1.67	2874.17	159	6
1.75	3025.62	155	13
1.83	3178.07	180	11
1.87	3254.68	140	3
1.95	3409.00	160	3
2.03	3564.10	164	3
2.11	3720.64	110	2
2.19	3879.13	174	3
2.27	4040.21	178	3
2.35	4204.73	157	3
2.43	4373.79	112	3
2.51	4547.99	202	1
2.59	4728.27	186	2
2.69	4962.33	204	3
2.77	5155.98	186	16
2.85	5355.25	236	5
2.93	5559.38	251	4
3.01	5768.63	214	7
3.05	5874.74	165	6
3.13	6090.38	190	7
3.21	6309.77	204	8
3.29	6532.83	315	9
3.37	6758.99	336	3
3.45	6989.10	232	10
3.53	7224.38	258	9
3.58	7374.86	234	9
3.67	7654.04	330	5
3.71	7782.23	204	4
3.75	7913.04	418	11
3.78	8013.15	266	10
3.83	8183.55	140	3
3.87	8323.55	372	17
3.91	8466.95	164	5
4.03	8917.97	375	22
4.07	9075.53	332	11
4.11	9236.52	382	18
4.19	9569.03	468	25
4.23	9740.86	468	12
4.27	9916.14	451	13
4.31	10095.37	439	10
4.35	10278.20	336	22

4.39	10464.86	409	22
4.43	10655.56	685	17
4.47	10850.28	552	8
4.51	11048.76	346	14
4.55	11251.24	522	14
4.59	11457.53	332	8
4.65	11773.81	208	8
4.69	11988.97	201	1
4.73	12207.02	221	1
4.77	12427.63	360	11
4.81	12650.62	320	7
4.85	12875.65	260	2
4.89	13102.21	162	6
4.925	13329.78	211	8
4.97	13615.10	276	2
5.01	13843.23	253	4
5.05	14071.04	226	16

Pinus undifferentiated	Total Pinus	Picea	Abies	Pseudotsuga
53	162	1	41	6
48	186	0	20	10
68	166	0	40	1
43	207	0	42	7
76	217	0	50	4
129	393	0	92	2
89	277	1	64	0
95	222	0	42	1
99	231	0	58	3
143	258	3	77	3
69	178	0	31	0
176	300	4	52	4
78	199	0	56	9
109	216	1	57	11
133	270	3	70	9
115	247	1	57	9
131	235	1	44	6
112	237	0	80	9
61	183	0	47	7
85	259	3	61	11
80	217	0	63	1
119	279	0	90	6
80	229	0	37	5
103	263	1	45	11
75	267	0	68	0
54	175	0	55	10
68	236	2	52	6
75	262	1	48	10
66	194	0	39	4
72	251	0	63	7
59	200	0	36	1
58	200	0	72	6
68	206	0	34	8
109	306	1	63	13
69	281	0	48	5
63	252	0	51	8
53	158	2	49	10
55	220	1	35	1
66	234	0	51	6
68	259	0	49	4
67	210	1	66	0

100	263	0	39	2
72	239	0	47	0
127	239	0	51	2
60	237	0	50	4
117	298	0	52	0
119	279	0	47	2
56	171	1	32	2
152	355	0	36	1
98	286	0	49	0
111	318	0	33	2
74	276	0	34	2
92	333	0	34	1
90	345	0	39	1
76	297	0	46	1
107	278	1	36	0
88	285	0	52	0
75	287	0	31	1
94	418	0	36	0
103	442	0	32	0
103	345	0	22	0
106	373	0	23	1
122	365	1	21	0
134	469	1	30	0
86	294	0	13	0
135	564	0	23	0
131	407	0	33	0
38	181	0	12	2
170	559	0	21	2
54	223	0	12	1
142	539	6	21	0
201	544	0	24	1
199	599	0	22	0
134	627	1	14	1
127	607	0	24	3
144	608	1	22	1
155	604	0	24	1
148	506	0	17	0
151	582	0	30	1
291	993	1	34	1
200	760	0	20	1
150	510	1	20	2
217	753	3	50	3
133	473	0	20	5
138	354	2	36	3

118	320	1	29	3
118	340	6	19	0
186	557	0	44	0
175	502	0	20	2
157	419	1	35	0
66	234	1	21	3
126	345	0	34	4
96	374	1	18	3
172	429	0	23	3
92	334	10	24	3

Cupressaceae	Tsuga mertensiana	Quercus vaccinifolia	Amelanchier
2	13	2	12
5	10	6	31
1	8	1	24
7	16	3	23
4	10	0	14
6	31	2	13
2	26	2	10
0	10	0	20
3	17	3	24
10	12	0	23
13	7	5	15
1	10	1	24
6	3	0	10
6	14	2	30
3	18	4	16
3	4	5	31
5	9	2	17
2	0	2	15
15	6	2	29
1	0	4	26
1	2	8	24
0	3	2	17
0	9	9	25
2	2	3	16
2	17	6	40
5	4	0	49
1	8	3	36
1	4	9	22
0	9	3	25
0	4	0	32
2	4	3	37
5	3	3	22
2	1	1	26
2	2	2	32
1	3	2	59
3	2	1	38
1	0	0	36
0	4	4	28
0	6	4	40
0	7	3	34
0	2	0	20

3	0	3	32
2	2	1	35
5	2	0	25
3	3	2	19
7	1	2	29
3	2	2	19
9	1	4	34
1	0	4	45
9	2	0	34
9	4	2	35
4	2	7	48
2	1	1	39
5	1	4	47
3	0	1	33
1	0	5	39
2	0	1	50
6	0	12	34
6	1	8	41
5	5	12	27
2	2	11	53
6	4	1	41
4	0	8	25
8	6	3	31
12	6	5	41
3	4	13	31
1	1	5	38
17	6	7	45
9	0	4	34
32	3	7	32
5	3	5	13
5	0	11	33
4	2	8	23
6	2	12	9
3	3	3	11
21	1	9	6
9	2	4	12
3	2	9	12
5	3	3	6
2	6	4	5
3	16	3	1
14	4	4	18
3	8	5	13
16	16	7	6
1	6	1	10

0	30	4	6
8	33	1	3
1	5	2	6
3	44	0	4
2	28	1	6
3	5	0	8
4	18	2	4
2	2	2	3
2	10	0	3
0	20	1	1

Ceanothus	Chrysolepis-type	Poaceae	Artemisia	Chenopodiineae
1	3	6	6	1
4	2	2	12	1
5	2	6	11	2
0	3	0	6	0
0	0	3	11	0
3	1	3	5	1
2	0	2	4	0
0	3	2	5	2
3	1	4	6	0
2	0	1	6	3
1	4	4	3	0
4	1	0	7	1
1	0	0	3	0
3	1	3	7	0
2	1	2	7	3
1	2	2	5	2
2	1	6	4	0
1	1	0	9	4
1	4	3	1	1
0	2	0	6	1
0	0	0	5	1
0	0	0	2	1
2	2	1	3	2
1	0	0	5	1
2	2	0	6	1
5	3	0	8	1
1	5	0	8	1
0	1	0	2	0
5	1	0	3	1
0	0	1	5	1
1	0	0	10	1
2	1	0	2	0
1	0	0	4	0
3	5	0	1	3
1	0	0	2	0
3	2	0	5	2
0	0	0	5	0
3	0	1	7	0
3	1	1	10	1
3	0	0	6	1
1	0	0	0	0

2	2	0	6	0
1	1	1	4	1
1	2	2	2	0
1	1	0	5	0
4	3	0	3	2
1	1	0	2	0
1	1	4	3	0
2	0	3	2	1
0	1	0	2	2
2	2	1	2	2
1	2	0	3	0
1	2	1	3	0
1	1	1	4	0
0	0	0	4	0
1	0	0	1	0
0	2	0	8	0
0	0	0	4	0
1	1	3	4	1
0	2	2	6	0
2	3	1	5	1
2	7	0	3	1
2	6	6	7	0
0	9	4	6	1
1	4	2	5	3
1	6	3	10	0
1	1	1	7	1
2	14	0	8	0
4	3	0	10	1
2	21	1	9	1
3	3	0	5	0
3	6	0	5	0
1	4	0	3	3
2	1	0	7	1
2	1	2	18	4
2	7	0	8	0
1	5	0	7	0
1	4	0	9	2
0	2	5	9	0
2	5	0	6	2
1	0	6	9	4
4	1	0	6	1
2	0	1	14	2
5	1	1	8	0
6	3	0	14	0

0	5	1	9	1
0	0	0	8	0
4	2	0	19	0
0	9	0	8	0
0	3	4	7	2
3	0	1	11	0
0	1	0	12	2
4	1	0	13	3
2	0	3	23	0
0	0	0	16	0

Total Pollen Sum	Spike Count (27822)
294	394
305	173
319	146
330	101
324	73
571	132
405	72
331	124
371	61
420	75
283	155
429	106
303	93
372	76
430	99
385	100
378	120
375	111
315	76
382	98
338	89
404	142
340	111
359	112
421	128
329	113
377	150
373	142
303	115
374	95
312	130
323	87
292	59
440	143
410	118
381	118
266	64
310	88
365	107
374	80

304	50
361	81
345	60
347	148
336	71
410	76
363	67
273	46
462	73
393	53
427	54
387	86
432	44
454	63
392	52
374	24
407	41
384	31
530	72
548	54
466	58
482	79
464	42
582	85
401	52
667	44
507	94
319	132
661	108
375	126
617	73
659	80
692	109
700	110
698	48
716	116
687	64
580	136
665	63
1076	89
848	96
598	136
874	85
584	104

458	118
422	189
438	152
652	159
611	177
540	94
343	63
447	120
466	104
519	122
423	194

APPENDIX C

CAMPBELL LAKE POLLEN DATA

Depth (m)	Age (cal yr BP)	Haploxylon Pinus	Diploxylon Pinus
0	-53.19	141	5
0.04	-15.44	129	1
0.08	21.31	163	3
0.14	138.75	136	4
0.18	223.70	158	4
0.22	307.19	210	6
0.26	388.56	265	9
0.3	467.15	163	9
0.34	542.58	146	4
0.38	615.68	189	4
0.42	687.67	195	12
0.46	759.75	216	3
0.5	833.05	156	1
0.54	907.62	155	2
0.58	982.91	192	9
0.62	1058.33	141	7
0.66	1133.29	201	2
0.7	1207.23	252	11
0.74	1279.56	158	7
0.78	1349.90	189	7
0.82	1418.33	179	6
0.86	1485.00	222	9
0.9	1550.05	147	12
0.94	1613.61	142	13
0.98	1675.85	201	5
1.02	1736.89	183	3
1.06	1796.89	218	8
1.1	1855.98	230	7
1.18	1972.45	137	9
1.26	2089.12	159	8
1.34	2209.03	132	5
1.42	2335.24	147	3
1.5	2470.79	119	1
1.58	2618.74	193	4

1.66	2782.14	331	9
1.74	2963.77	265	3
1.82	3161.80	154	0
1.9	3370.45	165	2
1.98	3583.82	163	1
2.06	3796.03	235	0
2.14	4001.59	226	0
2.22	4201.46	300	3
2.3	4401.64	259	1
2.34	4503.75	274	14
2.42	4715.85	209	3
2.5	4943.55	205	11
2.58	5192.95	147	4
2.66	5467.84	196	4
2.74	5768.27	256	6
2.82	6093.94	306	5
2.9	6444.55	229	1
2.98	6818.28	305	7
3.06	7207.90	211	6
3.14	7605.01	191	7
3.22	8000.70	225	4
3.26	8193.14	236	10
3.3	8380.31	251	5
3.34	8563.53	441	1
3.4	8834.08	420	5
3.44	9013.65	535	19
3.48	9194.25	459	12
3.52	9377.07	345	10
3.56	9562.37	427	14
3.6	9750.21	615	18
3.64	9940.62	569	12
3.68	10133.65	294	5
3.72	10329.35	225	2
3.76	10527.76	430	10
3.8	10728.91	192	0
3.84	10932.87	415	16
3.88	11139.66	354	15
3.92	11349.30	398	14
3.96	11561.61	133	14
4	11776.41	188	2
4.04	11993.47	188	13
4.08	12212.61	133	0
4.12	12433.62	258	20
4.16	12656.28	295	11

4.2	12880.37	183	15
4.24	13105.62	294	9
4.28	13331.75	190	7
4.32	13558.49	190	9
4.36	13785.57	252	2
4.4	14012.72	219	11
4.65	11773.81	208	8
4.69	11988.97	201	1
4.73	12207.02	221	1
4.77	12427.63	360	11
4.81	12650.62	320	7
4.85	12875.65	260	2
4.89	13102.21	162	6
4.925	13329.78	211	8
4.97	13615.10	276	2
5.01	13843.23	253	4
5.05	14071.04	226	16

Pinus undifferentiated	Total Pinus	Picea	Abies	Pseudotsuga
48	194	0	93	9
68	198	1	79	11
65	231	0	45	14
74	214	0	57	10
94	256	0	58	2
103	319	0	69	2
172	446	0	44	7
99	271	0	39	3
190	340	1	36	6
99	292	0	76	6
149	356	0	40	4
143	362	0	68	3
151	308	0	45	8
77	234	0	62	8
156	357	0	63	9
103	251	0	43	7
119	322	0	60	10
130	393	0	65	1
118	283	0	57	5
85	281	0	57	1
168	353	0	43	9
184	415	0	58	11
160	319	0	46	8
87	242	0	37	5
119	325	0	45	8
147	333	0	65	15
158	384	0	43	10
124	361	0	58	8
165	311	0	59	6
132	299	0	58	7
143	280	0	153	10
123	273	0	38	9
84	204	0	33	6
88	285	1	41	11
97	437	1	71	4
147	415	0	37	9
101	255	2	55	5
147	314	0	47	4
124	288	0	51	5
173	408	4	60	1
178	404	1	53	0

235	538	1	62	2
227	487	6	37	0
178	466	0	62	5
156	368	2	58	0
233	449	3	39	1
182	333	3	49	0
159	359	1	36	1
193	455	1	49	1
272	583	4	36	0
215	445	5	19	1
273	585	1	32	0
200	417	5	21	0
144	342	0	31	2
153	382	0	12	0
212	458	1	13	0
239	495	2	32	0
269	711	0	25	3
239	664	0	17	0
282	836	0	23	1
348	819	0	23	1
194	549	0	19	4
329	770	2	15	1
341	974	0	18	3
343	924	1	31	1
169	468	8	7	0
232	459	22	4	0
176	616	1	6	4
170	362	21	5	2
177	608	2	14	4
233	602	17	15	0
199	611	10	16	5
121	268	13	21	0
158	348	14	10	0
179	380	17	20	1
178	311	26	25	0
258	536	13	21	0
259	565	8	35	1
221	419	11	33	3
259	562	10	30	0
166	363	9	37	2
165	364	5	36	0
244	498	13	24	1
172	402	5	10	0
138	354	2	36	3

118	320	1	29	3
118	340	6	19	0
186	557	0	44	0
175	502	0	20	2
157	419	1	35	0
66	234	1	21	3
126	345	0	34	4
96	374	1	18	3
172	429	0	23	3
92	334	10	24	3

Cupressaceae	Tsuga mertensiana	Quercus vaccinifolia	Amelanchier
0	5	1	11
1	2	5	8
2	6	2	10
5	4	1	8
1	15	2	11
0	19	0	5
4	5	2	25
0	16	1	9
3	12	0	21
1	9	2	10
5	5	1	19
0	5	2	14
1	2	2	21
0	11	1	17
3	6	1	17
4	10	5	4
4	6	2	25
0	1	7	20
1	2	2	18
2	5	2	24
2	2	2	24
1	4	7	16
3	3	6	24
1	8	2	16
3	3	1	33
2	10	1	13
5	2	1	16
0	12	5	12
3	2	4	17
4	3	11	17
1	2	15	10
6	2	7	15
4	0	5	16
6	1	5	10
2	3	6	28
4	2	11	16
3	4	7	7
4	4	18	7
3	0	19	10
3	0	18	18
5	0	7	14

6	3	9	23
3	1	15	26
3	1	5	29
7	2	8	20
1	3	3	26
2	1	2	29
3	5	5	30
3	1	1	36
5	4	1	37
4	0	7	53
13	2	4	43
7	5	15	34
11	0	7	39
10	7	5	22
18	2	12	19
15	7	5	20
4	1	9	46
17	0	4	41
14	0	9	22
15	1	10	20
20	0	12	18
12	1	3	19
14	4	4	11
7	1	5	19
26	0	13	5
6	11	8	11
16	0	18	3
12	8	4	3
6	0	18	5
0	10	13	10
0	17	7	5
0	20	0	10
1	25	2	6
1	13	4	9
1	23	1	1
1	14	4	0
3	14	1	1
0	20	1	7
1	21	2	2
0	12	3	4
0	7	0	4
1	23	2	1
0	23	0	1
1	6	1	10

0	30	4	6
8	33	1	3
1	5	2	6
3	44	0	4
2	28	1	6
3	5	0	8
4	18	2	4
2	2	2	3
2	10	0	3
0	20	1	1

Ceanothus	Chrysolepis-type	Poaceae	Artemisia	Chenopodiineae
1	1	0	2	1
1	2	0	3	0
2	2	0	2	1
2	4	0	1	1
1	2	1	1	0
0	0	1	6	0
1	3	0	4	0
1	5	0	4	0
3	9	1	2	0
1	1	1	2	1
1	3	0	0	0
0	2	0	6	1
6	1	0	6	1
0	1	0	1	0
3	1	0	6	0
1	2	0	1	2
2	2	1	2	0
2	3	0	4	0
1	9	1	6	0
2	2	0	3	1
3	3	0	10	0
2	2	3	3	4
3	8	1	2	2
2	4	0	0	3
2	2	0	1	0
1	1	2	2	0
1	4	0	5	2
1	2	0	4	1
0	1	0	3	1
1	0	0	6	2
2	1	0	5	2
1	3	3	3	0
3	1	3	0	0
2	4	2	1	0
1	2	1	5	0
6	3	0	0	0
1	1	0	1	0
3	1	1	3	0
2	1	0	4	1
1	4	1	6	0
4	0	1	4	1

0	0	0	1	0
3	1	0	4	1
1	0	0	2	0
3	1	0	0	1
1	1	0	2	0
1	0	0	3	1
2	1	0	6	0
0	0	0	1	1
1	0	0	3	0
2	0	0	4	1
1	0	0	1	1
0	1	1	5	3
3	1	0	1	2
2	4	1	7	8
2	1	1	3	1
1	3	0	4	0
5	1	1	3	0
3	0	0	7	4
2	1	0	5	2
4	1	2	6	0
3	0	1	5	1
2	0	0	3	5
0	2	1	4	1
5	2	1	1	3
1	2	0	3	4
3	1	0	8	2
3	0	0	4	2
2	2	0	11	1
3	0	0	4	5
2	1	0	8	1
1	2	0	11	3
0	4	0	2	1
3	6	0	13	2
2	2	0	14	1
0	0	0	15	1
0	3	1	15	1
2	0	1	10	1
0	2	1	15	1
2	2	0	9	3
6	4	0	9	3
2	1	0	14	3
0	3	0	21	2
0	0	0	26	1
6	3	0	14	0

0	5	1	9	1
0	0	0	8	0
4	2	0	19	0
0	9	0	8	0
0	3	4	7	2
3	0	1	11	0
0	1	0	12	2
4	1	0	13	3
2	0	3	23	0
0	0	0	16	0

Total Pollen Sum	Spike (27822)
323.0	327
326.0	267
327.0	227
312.0	133
368.0	133
426.0	141
554.0	197
359.0	106
451.0	194
416.0	157
445.0	289
471.0	165
414.0	174
343.0	122
472.0	150
342.0	121
447.0	153
504.0	161
398.0	161
393.0	153
458.0	179
532.0	170
430.0	171
329.0	138
433.0	266
456.0	115
488.0	135
469.0	105
416.0	152
414.0	167
486.0	166
370.0	157
288.0	108
381.0	110
566.0	192
514.0	194
353.0	95
418.0	127
398.0	115
533.0	175
506.0	215

657.0	178
598.0	182
580.0	201
477.0	153
538.0	183
429.0	135
457.0	160
558.0	204
687.0	172
551.0	172
694.0	162
531.0	135
446.0	189
485.0	131
550.0	149
601.0	134
815.0	248
763.0	166
934.0	170
914.0	161
650.0	178
861.0	236
1057.0	156
1017.0	227
567.0	103
569.0	110
701.0	108
458.0	127
699.0	123
693.0	96
720.0	78
353.0	108
454.0	105
485.0	117
420.0	140
631.0	187
661.0	169
550.0	145
666.0	215
491.0	205
469.0	143
617.0	164
506.0	200
458	118

422	189
438	152
652	159
611	177
540	94
343	63
447	120
466	104
519	122
423	194

APPENDIX D

CEDAR LAKE POLLEN DATA

Depth (m)	Age (cal yr BP)	Haploxylon Pinus	Diploxylon Pinus
0.34	401	53	73
0.42	896	28	119
0.52	1342	25	56
0.62	1727	44	76
0.72	2104	49	59
0.82	2469	45	65
0.92	2820	70	155
1.02	3159	33	51
1.12	3487	35	32
1.22	3808	63	61
1.32	4125	37	48
1.42	4441	40	64
1.52	4759	44	42
1.62	5081	38	65
1.71	5376	37	29
1.82	5749	55	46
1.92	6101	25	66
2.02	6461	26	54
2.12	6821	55	21
2.22	7169	21	60
2.32	7498	46	34
2.42	7798	55	40
2.52	8069	17	19
2.62	8315	34	16
2.82	8754	21	45
2.92	8970	21	26
2.99	9129	19	19
3.12	9458	41	43
3.22	9751	38	44
3.32	10080	80	49
3.42	10436	25	52
3.45	10546	45	74
3.47	10621	46	73
3.53	10849	47	132

Pinus undifferentiated	Total Pinus	Picea	Abies	Pseudotsuga
198	324	0	8	8
156	303	0	13	6
176	257	0	5	5
225	345	0	7	6
261	369	0	7	3
194	304	1	7	1
408	633	0	7	2
215	299	0	4	3
178	245	0	5	0
230	354	0	8	3
182	267	0	4	0
218	322	0	3	0
238	324	0	8	2
210	313	0	2	0
265	331	0	6	0
216	317	0	1	0
258	349	1	5	0
213	293	0	2	0
218	294	0	1	1
138	219	0	2	0
106	186	0	0	1
147	242	0	2	0
182	218	0	2	0
220	270	0	0	0
146	212	0	1	0
64	111	0	0	0
85	123	0	0	0
102	186	0	1	1
87	169	0	4	1
87	216	0	0	2
131	208	0	4	0
129	248	0	7	4
106	225	0	4	1
256	435	0	16	1

Cupressaceae	Tsuga mertensiana	Quercus vaccinifolia	Amelanchier
31	4	32	7
20	2	25	1
9	1	27	0
7	2	26	0
30	4	19	2
12	3	60	1
12	0	50	9
5	0	51	6
18	2	67	4
8	3	35	6
17	7	51	7
18	0	80	12
12	1	81	11
14	1	71	17
15	5	65	5
22	1	61	6
22	6	84	9
19	4	96	14
38	3	79	12
12	1	92	9
17	0	94	10
28	0	69	10
19	1	105	19
14	5	86	17
9	0	78	16
12	0	59	7
20	1	32	7
36	1	30	5
19	0	20	1
18	0	9	1
25	2	12	2
6	1	16	3
8	2	10	2
3	5	7	5

Ceanothus	Chrysolepis-type	Poaceae	Artemisia	Chenopodiineae
5	3	18	13	4
1	0	6	10	5
1	3	8	7	2
1	1	2	10	1
2	3	9	8	7
1	1	9	9	1
6	5	8	12	1
2	2	2	5	0
3	4	3	8	6
0	0	4	6	1
1	0	8	5	4
4	4	3	4	0
3	4	10	10	1
3	1	9	10	6
0	2	5	18	0
5	2	9	8	1
5	3	7	14	4
1	1	9	5	0
1	4	9	15	2
1	1	8	10	1
5	2	5	13	1
3	2	3	5	5
4	2	7	12	1
6	2	6	6	0
4	0	7	5	2
0	2	1	4	2
1	2	2	9	0
4	6	2	5	4
0	0	8	7	2
1	0	9	8	3
1	1	1	6	3
4	3	8	10	8
0	5	3	6	0
2	6	6	12	3

Total Pollen Sum	Spike (12542)
571	119
432	72
375	68
441	53
679	73
464	79
838	80
435	80
428	102
481	86
435	88
531	120
578	98
535	80
566	79
505	76
630	72
514	73
600	71
465	75
422	85
426	95
562	87
515	93
438	88
253	85
265	84
330	93
309	95
328	108
335	87
459	101
352	107
610	82

APPENDIX E

SANGER LAKE LITHOLOGICAL AND CHARCOAL DATA

Depth (m)	Age (cal yr BP)	Magnetic susceptibility (cgs x10^{-6})	Percent Organic Matter	Charcoal Concentrations (particles cm^{-3})
0	-53	1.2	43	8
0.01	-47.57	0.4	NaN	16.5
0.02	-39.55	0.7	NaN	23.5
0.03	-31.1	0.4	NaN	17.5
0.04	-22.37	0.6	NaN	9.5
0.05	-13.48	0.6	42	6
0.06	-4.53	0.5	NaN	6.5
0.07	8.06	0.7	NaN	3.5
0.08	21.09	1.2	NaN	2.5
0.09	34.13	0.9	NaN	1
0.1	47.17	1.7	NaN	2
0.11	60.22	1.9	40	2
0.12	73.26	2	NaN	1
0.13	86.32	2	NaN	4.5
0.14	99.39	2.9	NaN	12.5
0.15	112.47	3	NaN	10
0.16	125.56	2.8	20	11.5
0.17	138.67	2.7	NaN	13.5
0.18	151.8	3.5	NaN	30.5
0.19	164.95	2.8	NaN	34
0.2	178.11	2.3	NaN	34
0.21	191.28	1.6	45	36
0.22	204.5	1.6	NaN	52.5
0.23	217.71	2	NaN	34
0.24	230.94	1.3	NaN	5.5
0.25	244.21	1	NaN	8
0.26	257.51	1.8	40	18
0.27	270.83	1.6	NaN	10.5
0.28	284.17	1.6	NaN	10
0.29	297.58	2.3	NaN	11
0.3	311	2	NaN	11
0.31	324.45	4.3	13	14

0.32	337.94	16.1	NaN	2.5
0.33	351.48	27.6	NaN	3
0.34	365	32.5	NaN	0
0.35	378.58	76.7	NaN	0
0.36	392.24	173.8	17	0.5
0.37	405.92	174.1	NaN	2
0.38	419.66	203.5	NaN	0.5
0.39	433.43	161.5	NaN	0.5
0.4	447.22	53.9	NaN	20
0.41	461.1	60.1	23	13.5
0.42	475.01	49.1	NaN	7
0.43	488.96	47.7	NaN	7.5
0.44	502.96	51.8	NaN	14.5
0.45	517.01	88	NaN	15.5
0.46	531.1	87.5	19	18
0.47	545.24	76.9	NaN	18.5
0.48	559.48	75.1	NaN	14.5
0.49	573.72	58.5	NaN	17.5
0.5	588.09	46.4	NaN	13.5
0.51	602.44	51.8	22	9.5
0.52	616.87	56.3	NaN	18.5
0.53	631.4	71.4	NaN	16.5
0.54	645.92	55.1	NaN	21
0.55	660.55	69.3	NaN	17
0.56	675.26	54.4	23	15
0.57	690.01	81.5	NaN	16
0.58	704.81	59.7	NaN	6.5
0.59	719.64	4.1	NaN	7.5
0.6	734.57	1.8	NaN	6.5
0.61	749.48	1.9	32	14.5
0.62	764.52	1.3	NaN	15
0.63	779.62	1.6	NaN	14.5
0.64	794.73	1.6	NaN	14
0.65	809.9	1.6	NaN	12.5
0.66	825.02	2	46	12
0.67	840.17	1.8	NaN	12
0.68	855.29	2.3	NaN	14
0.69	870.56	2.8	NaN	17.5
0.7	885.75	2.8	NaN	43
0.71	900.99	3.1	35	57.5
0.72	916.21	2.4	NaN	114
0.73	931.5	2.7	NaN	48
0.74	946.72	2.3	NaN	26.5
0.75	962	1.9	NaN	24

0.76	977.28	0.9	44	10
0.77	992.48	0.8	NaN	5.5
0.78	1007.6	0.8	NaN	10
0.79	1022.7	0.7	NaN	14
0.8	1037.73	-0.1	NaN	9
0.81	1052.84	1	43	12
0.82	1067.81	1.2	NaN	12
0.83	1082.98	1.5	NaN	4.5
0.84	1097.91	1.7	NaN	4
0.85	1112.94	2.3	NaN	5
0.86	1127.85	2.7	44	8
0.87	1142.74	1.8	NaN	5
0.88	1157.67	NaN	NaN	0
0.89	1172.61	NaN	NaN	0
0.9	1187.44	NaN	NaN	0
0.91	1202.18	106.6	18	8.5
0.92	1216.97	76.2	NaN	15.5
0.93	1231.67	52.5	NaN	23.5
0.94	1246.37	29.9	NaN	15
0.95	1261.04	8.5	NaN	11.5
0.96	1275.67	42	12	1.5
0.97	1290.4	58.9	NaN	7.5
0.98	1304.96	25.6	NaN	25.5
0.99	1319.56	15.5	NaN	31.5
1	1334.21	9.5	NaN	48
1.01	1348.78	2.7	36	36
1.02	1363.28	2.4	NaN	17.5
1.03	1377.66	2.3	NaN	8.5
1.04	1392.24	1.2	NaN	9.5
1.05	1406.61	1	NaN	3.5
1.06	1421.01	0.8	43	4.5
1.07	1435.43	0.8	NaN	5.5
1.08	1449.78	0.4	NaN	8.5
1.09	1464.12	-0.1	NaN	10
1.1	1478.47	-0.1	NaN	9
1.11	1492.81	0.4	40	7.5
1.12	1507.04	1.2	NaN	8.5
1.13	1521.34	1.1	NaN	6.5
1.14	1535.51	1.2	NaN	3
1.15	1549.67	1.4	NaN	3.5
1.16	1563.92	0.9	38	2
1.17	1578.1	0.8	NaN	6
1.18	1592.23	0.5	NaN	6.5
1.19	1606.34	0.6	NaN	6.5

1.2	1620.42	0.5	NaN	15.5
1.21	1634.49	1	35	5
1.22	1648.51	0.5	NaN	8
1.23	1662.61	0.2	NaN	8.5
1.24	1676.6	0.5	NaN	8.5
1.25	1690.55	0.7	NaN	7.5
1.26	1704.51	1.1	39	9.5
1.27	1718.46	1.2	NaN	13.5
1.28	1732.36	1.4	NaN	15.5
1.29	1746.24	1.3	NaN	8.5
1.3	1760.1	0.8	NaN	9.5
1.31	1774	1	39	5
1.32	1787.87	0.6	NaN	3.5
1.33	1801.68	0.9	NaN	8
1.34	1815.49	0.6	NaN	13
1.35	1829.31	0.8	NaN	11
1.36	1843.25	0.6	41	6
1.37	1857.07	0.6	NaN	6
1.38	1870.86	0.9	NaN	3
1.39	1884.59	0.7	NaN	5
1.4	1898.3	1.1	NaN	4
1.41	1912.05	1.3	37	16
1.42	1925.77	1.6	NaN	17
1.43	1939.41	1.2	NaN	14.5
1.44	1953.09	1.1	NaN	9.5
1.45	1966.74	0.7	NaN	3
1.46	1980.42	1.1	36	2
1.47	1994.08	1.7	NaN	6
1.48	2007.74	2.1	NaN	7
1.49	2021.37	2.1	NaN	14
1.5	2035.08	2.7	NaN	8.5
1.51	2048.76	2.3	32	12
1.52	2062.5	1.6	NaN	14
1.53	2076.25	1.7	NaN	8
1.54	2089.91	1.6	NaN	6.5
1.55	2103.6	1.8	NaN	15.5
1.56	2117.29	1.5	37	19.5
1.57	2131.01	2	NaN	10
1.58	2144.68	2.1	NaN	6
1.59	2158.37	1.3	NaN	2
1.6	2172.22	1.6	NaN	4
1.61	2186.02	1.6	33	5
1.62	2199.77	2	NaN	7
1.63	2213.62	2.3	NaN	11

1.64	2227.42	2.6	NaN	21
1.65	2241.19	2.2	NaN	16.5
1.66	2254.98	1.6	37	15
1.67	2268.79	1.8	NaN	22.5
1.68	2282.7	1.5	NaN	18.5
1.69	2296.6	1.9	NaN	10.5
1.7	2310.51	1.3	NaN	6
1.71	2324.46	1.1	33	6.5
1.72	2338.51	1.4	NaN	12.5
1.73	2352.58	1.7	NaN	19.5
1.74	2366.69	2	NaN	5.5
1.75	2380.89	1.8	NaN	3
1.76	2394.96	2.5	31	8
1.77	2409.13	2.4	NaN	3.5
1.78	2423.39	2.6	NaN	5
1.79	2437.75	2.6	NaN	6.5
1.8	2452.04	2.1	NaN	7
1.81	2466.37	2.2	33	22.5
1.82	2480.78	1.6	NaN	9
1.83	2495.32	1.7	NaN	11.5
1.84	2509.79	1.3	NaN	6.5
1.85	2524.32	1.6	NaN	16.5
1.86	2538.96	1.7	35	17.5
1.87	2553.61	1.4	NaN	4.5
1.88	2568.29	1.1	NaN	3.5
1.89	2583	2	NaN	10.5
1.9	2597.79	2	NaN	7
1.91	2612.79	39.3	22	15
1.92	2627.74	43.5	NaN	7
1.93	2642.73	17	NaN	8.5
1.94	2657.89	4.2	NaN	9
1.95	2673.14	1.5	NaN	7.5
1.96	2688.39	1.1	37	5
1.97	2703.66	1.1	NaN	6
1.98	2719.07	1.4	NaN	13.5
1.99	2734.63	2.1	NaN	9.5
2	2750.25	2.2	NaN	7.5
2.01	2765.89	2.5	30	15
2.02	2781.66	2.2	NaN	12.5
2.03	2797.41	2.1	NaN	50
2.04	2813.32	1.9	NaN	7
2.05	2829.18	1.2	NaN	16.5
2.06	2845.36	1.3	36	23
2.07	2861.51	1.2	NaN	14

2.08	2877.7	0.7	NaN	8.5
2.09	2894	1	NaN	7
2.1	2910.38	1.1	NaN	7.5
2.11	2926.95	4.8	26	14.5
2.12	2943.58	13.6	NaN	11.5
2.13	2960.28	3.4	NaN	4.5
2.14	2977.12	2.1	NaN	5.5
2.15	2994.02	1.7	NaN	6.5
2.16	3010.96	1.4	36	3.5
2.17	3028.07	1.4	NaN	9.5
2.18	3045.37	1.5	NaN	18
2.19	3062.72	1.3	NaN	13.5
2.2	3080.19	1.6	NaN	33.5
2.21	3097.81	1.6	32	43.5
2.22	3115.51	2.1	NaN	47.5
2.23	3133.45	1.7	NaN	29
2.24	3151.42	1.2	NaN	12.5
2.25	3169.54	1.4	NaN	19.5
2.26	3187.82	0.8	38	15
2.27	3206.24	1	NaN	12.5
2.28	3224.8	1.3	NaN	6
2.29	3243.51	1.6	NaN	5.5
2.3	3262.36	1.2	NaN	5
2.31	3281.37	0.8	36	12.5
2.32	3300.52	0.9	NaN	13
2.33	3319.83	0.8	NaN	9.5
2.34	3339.28	0.9	NaN	26.5
2.35	3358.89	0.8	NaN	35.5
2.36	3378.77	0.7	38	9.5
2.37	3398.69	0.8	NaN	9.5
2.38	3418.82	1.3	NaN	12.5
2.39	3439.12	1.4	NaN	18.5
2.4	3459.58	2.3	NaN	17.5
2.41	3480.22	1.9	35	11
2.42	3501.1	1.8	NaN	9.5
2.43	3522.07	2.7	NaN	13
2.44	3543.29	2.7	NaN	11
2.45	3564.66	3.7	NaN	28
2.46	3586.31	3.5	34	41.5
2.47	3608.05	2.6	NaN	15
2.48	3630	2.8	NaN	18
2.49	3652.15	3.5	NaN	27.5
2.5	3674.48	2.2	NaN	52.5
2.51	3697.08	4.6	30	49.5

2.52	3719.79	5.1	NaN	48.5
2.53	3742.6	4.1	NaN	27
2.54	3765.74	4.8	NaN	20.5
2.55	3788.96	3.3	NaN	9.5
2.56	3812.35	3.1	32	5.5
2.57	3835.96	3.4	NaN	14
2.58	3859.72	3.1	NaN	16
2.59	3883.65	3.5	NaN	24.5
2.6	3907.8	3	NaN	8
2.61	3932.07	2.9	34	5.5
2.62	3956.51	2.2	NaN	9.5
2.63	3981.12	2.4	NaN	11.5
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2.67	4081.55	1.1	NaN	23.5
2.68	4107.01	1.9	NaN	24
2.69	4132.67	0.6	NaN	13.5
2.7	4158.45	0.7	NaN	14.5
2.71	4184.48	0.9	38	8
2.72	4210.65	0.6	NaN	10.5
2.73	4236.89	1.2	NaN	7
2.74	4263.25	0.7	NaN	8.5
2.75	4289.71	1.6	NaN	12.5
2.76	4316.34	1	36	9
2.77	4343.1	0.7	NaN	11
2.78	4369.79	1	NaN	18
2.79	4396.72	1.3	NaN	23.5
2.8	4423.75	1.9	NaN	35.5
2.81	4451.05	1.7	29	34.5
2.82	4478.21	1.8	NaN	45
2.83	4505.59	2.7	NaN	32.5
2.84	4532.93	2.8	NaN	16
2.85	4560.5	2.8	NaN	4
2.86	4587.98	2.8	32	5.5
2.87	4615.75	10	NaN	26
2.88	4643.44	15.6	NaN	41.5
2.89	4671.25	0.6	NaN	9.5
2.9	4699.05	1.5	NaN	19.5
2.91	4726.85	2.6	34	31
2.92	4754.92	3.7	NaN	23
2.93	4782.97	3.6	NaN	17.5
2.94	4811.04	-1.1	NaN	7
2.95	4838.99	-0.2	NaN	11

2.96	4867.11	1.4	33	11.5
2.97	4895.13	1.2	NaN	15
2.98	4923.3	1.5	NaN	15.5
2.99	4951.5	1.1	NaN	29.5
3	4979.69	1	NaN	26
3.01	5007.95	1.1	32	8
3.02	5036.27	1.3	NaN	15.5
3.03	5064.53	0.1	NaN	24.5
3.04	5092.77	0.7	NaN	22.5
3.05	5120.86	1	NaN	11.5
3.06	5149.14	1.3	33	18.5
3.07	5177.36	1.2	NaN	26
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3.09	5233.7	1.7	NaN	30
3.1	5261.77	1.2	NaN	7
3.11	5289.89	0.6	37	10.5
3.12	5317.97	1.2	NaN	20.5
3.13	5345.96	0.5	NaN	5
3.14	5373.9	0.8	NaN	3.5
3.15	5401.82	0.6	NaN	6
3.16	5429.57	1.2	37	10.5
3.17	5457.43	0.9	NaN	11.5
3.18	5485.22	0.7	NaN	8.5
3.19	5512.85	1.1	NaN	9
3.2	5540.38	0.4	NaN	13.5
3.21	5567.78	0.8	37	13
3.22	5595.16	0.7	NaN	12.5
3.23	5622.54	1	NaN	16
3.24	5649.93	1.3	NaN	36
3.25	5677.1	2.4	NaN	57.5
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3.27	5731.04	0.4	NaN	13
3.28	5757.86	0.5	NaN	11
3.29	5784.51	0.7	NaN	9.5
3.3	5811.06	0.5	NaN	5
3.31	5837.53	1	38	6.5
3.32	5863.83	1.2	NaN	25
3.33	5890.16	2.6	NaN	39
3.34	5916.42	2.6	NaN	24.5
3.35	5942.41	1.5	NaN	19.5
3.36	5968.36	1.8	34	19
3.37	5994.21	2.3	NaN	9
3.38	6019.96	3.7	NaN	18.5
3.39	6045.53	2.5	NaN	22

3.4	6071.02	1.9	NaN	24
3.41	6096.44	2.3	37	27.5
3.42	6121.69	2.6	NaN	22
3.43	6146.7	4	NaN	14.5
3.44	6171.56	4.3	NaN	36
3.45	6196.38	4.7	NaN	34.5
3.46	6221.11	3.4	34	24
3.47	6245.66	5.8	NaN	7.5
3.48	6270.17	5.9	NaN	14
3.49	6294.57	2.7	NaN	31.5
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3.51	6342.91	3.8	36	29
3.52	6366.82	2.8	NaN	12
3.53	6390.72	1.9	NaN	8
3.54	6414.42	1.8	NaN	4
3.55	6438.03	3	NaN	12.5
3.56	6461.52	2.6	39	14
3.57	6484.82	2.5	NaN	13
3.58	6507.93	4	NaN	14
3.59	6531.14	5.1	NaN	7.5
3.6	6554.05	4.1	NaN	9
3.61	6576.94	3.7	38	11
3.62	6599.78	4	NaN	3.5
3.63	6622.38	2.8	NaN	10.5
3.64	6644.88	2.2	NaN	12
3.65	6667.3	4.9	NaN	16.5
3.66	6689.61	3.5	30	18
3.67	6711.75	5.8	NaN	24.5
3.68	6733.69	4	NaN	26
3.69	6755.45	3.2	NaN	33.5
3.7	6777.2	2.2	NaN	33.5
3.71	6798.77	3.7	28	43
3.72	6820.11	3.6	NaN	57.5
3.73	6841.34	5.8	NaN	116.5
3.74	6862.5	3.1	NaN	12.5
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3.76	6904.22	1.1	39	6
3.77	6924.82	0.8	NaN	16.5
3.78	6945.4	0.6	NaN	27.5
3.79	6965.76	0.9	NaN	9.5
3.8	6986.09	0.9	NaN	4
3.81	7006.3	1.1	38	2.5
3.82	7026.42	0.8	NaN	5
3.83	7046.33	0.9	43	5.5

3.84	7066.05	0.9	NaN	5.5
3.85	7085.73	1.3	NaN	9.5
3.86	7105.36	1.3	39	10
3.87	7124.75	1.3	NaN	9.5
3.88	7144.12	1	40	3
3.89	7163.41	9.4	NaN	13.5
3.9	7182.59	0.8	NaN	6
3.91	7201.8	2.7	32	10
3.92	7220.86	2.8	NaN	11.5
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3.94	7258.61	1.7	NaN	11
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3.97	7314.72	1.8	NaN	6
3.98	7333.22	3.1	30	12.5
3.99	7351.7	3.5	NaN	16
4	7370.13	4	NaN	6.5
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4.02	7406.72	2.9	NaN	6
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4.07	7497.63	2.8	NaN	8
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4.09	7533.71	3	NaN	10.5
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4.11	7569.79	4.1	28	14
4.12	7587.88	2.9	NaN	9.5
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4.16	7659.85	2.3	30	8
4.17	7677.9	4.2	NaN	9.5
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4.23	7785.99	2.3	33	6
4.24	7804.15	2.1	NaN	4
4.25	7822.39	2	NaN	7
4.26	7840.57	2.2	33	19
4.27	7858.73	2.2	NaN	5

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4.3	7913.9	2.1	NaN	4.5
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4.38	8063.45	6.3	24	31.5
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5.68	12338.27	33.8	19	10
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5.83	13123.99	42.3	16	5
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5.85	13230.01	37.4	NaN	3
5.86	13283.02	50.2	17	4.5
5.87	13336.31	58.8	NaN	7
5.88	13389.31	51.8	15	1.5
5.89	13442.48	68.1	NaN	5.5
5.9	13495.64	67.8	14	3.5
5.91	13548.96	NaN	NaN	2
5.92	13602.36	NaN	NaN	0
5.93	13655.67	NaN	NaN	4
5.94	13708.86	NaN	NaN	5
5.95	13762.25	NaN	NaN	3.5
5.96	13815.58	NaN	9	0.5
5.97	13868.92	NaN	NaN	1
5.98	13922.16	NaN	NaN	0.5
5.99	13975.44	NaN	NaN	1
6	14028.56	NaN	NaN	2
6.01	14081.77	NaN	8	2
6.02	14134.99	NaN	NaN	2
6.03	14188.11	NaN	NaN	0.5

6.04	14241.23	NaN	NaN	4.5
6.05	14294.17	NaN	NaN	10.5
6.06	14347.13	NaN	5	4.5

APPENDIX F

TAYLOR LAKE LITHOLOGICAL AND CHARCOAL DATA

Depth (m)	Age (cal yr BP)	Magnetic susceptibility (cgs x10^{-6})	Percent Organic Matter	Charcoal Concentrations (particles cm^{-3})
0	-53.00	0.6	35	0.5
0.01	-48.94	1	NaN	1.5
0.02	-43.00	1.9	NaN	4.5
0.03	-35.00	1.5	NaN	4
0.04	-29.00	2.1	28	0.5
0.05	-22.00	0.8	NaN	5.5
0.06	-14.00	0.2	NaN	1
0.07	-5.00	0	NaN	3
0.08	6.00	-0.3	43	4
0.09	19.00	-0.3	NaN	3.5
0.1	29.00	-0.5	NaN	3.5
0.11	63.01	-0.8	NaN	0.5
0.12	81.72	-0.2	46	1
0.13	100.43	-0.7	NaN	2.5
0.14	119.16	1	NaN	3
0.15	137.85	0	40	10
0.16	156.60	-0.5	NaN	17
0.17	175.33	-0.9	NaN	19
0.18	194.03	-0.4	NaN	19
0.19	212.74	-0.5	39	13
0.2	231.46	0.1	NaN	6
0.21	250.16	0.1	NaN	2.5
0.22	268.79	0.1	NaN	11
0.23	287.40	0.1	39	14
0.24	306.05	-0.4	NaN	7.5
0.25	324.68	-0.5	NaN	10.5
0.26	343.29	-0.1	NaN	11
0.27	361.94	0.4	38	13.5
0.28	380.50	0.2	NaN	19
0.29	399.04	0.4	NaN	29
0.3	417.60	0.1	NaN	27
0.31	436.08	1	37	15.5

0.32	454.56	0.6	NaN	11
0.33	473.03	0.7	NaN	10
0.34	491.43	1	NaN	2.5
0.35	509.81	0.3	36	14.5
0.36	528.12	0.4	NaN	13.5
0.37	546.42	0.5	NaN	26.5
0.38	564.65	-0.2	NaN	17
0.39	582.93	0.4	38	21.5
0.4	601.13	-0.2	NaN	14.5
0.41	619.20	-0.7	NaN	6
0.42	637.26	-0.2	NaN	3
0.43	655.24	-0.5	36	0
0.44	673.15	0.2	NaN	1
0.45	691.02	0	NaN	1
0.46	708.81	-0.2	NaN	2.5
0.47	726.56	-0.4	35	2.5
0.48	744.29	-0.2	NaN	3
0.49	761.92	0.4	NaN	3
0.5	779.47	0.1	NaN	6.5
0.51	797.03	0.3	34	10.5
0.52	814.47	0.4	NaN	24
0.53	831.87	0.5	NaN	5
0.54	849.18	0.4	NaN	8.5
0.55	866.41	1.3	29	8.5
0.56	883.61	3	NaN	26
0.57	900.84	0.9	NaN	5
0.58	918.01	-0.2	NaN	2
0.59	935.13	-0.2	31	4.5
0.6	952.20	0.5	NaN	8.5
0.61	969.28	NaN	NaN	NaN
0.62	986.28	NaN	NaN	NaN
0.63	1003.25	NaN	NaN	NaN
0.64	1020.19	NaN	NaN	NaN
0.65	1037.13	NaN	NaN	NaN
0.66	1054.11	NaN	NaN	NaN
0.67	1071.05	-5.3	NaN	13.5
0.68	1087.98	-2.6	NaN	6.5
0.69	1104.91	-1.5	NaN	13.5
0.7	1121.87	-1.5	NaN	6.5
0.71	1138.71	-0.8	38	5
0.72	1155.63	-0.8	NaN	9.5
0.73	1172.62	-0.6	NaN	12
0.74	1189.55	-0.5	NaN	11.5
0.75	1206.45	-0.6	38	10.5

0.76	1223.45	-0.6	NaN	17
0.77	1240.38	-0.8	NaN	4.5
0.78	1257.41	-0.7	NaN	6
0.79	1274.38	-0.2	38	6
0.8	1291.28	-0.3	NaN	13
0.81	1308.32	-0.2	NaN	9
0.82	1325.30	-0.1	NaN	18.5
0.83	1342.32	-0.4	37	11
0.84	1359.39	-0.1	NaN	11
0.85	1376.51	-0.6	NaN	2.5
0.86	1393.66	-0.4	NaN	5.5
0.87	1410.90	-0.3	37	7.5
0.88	1428.08	0.2	NaN	14
0.89	1445.34	-0.1	NaN	17.5
0.9	1462.67	0	NaN	20.5
0.91	1480.01	-0.5	38	14
0.92	1497.40	-0.2	NaN	10
0.93	1514.81	-0.7	NaN	11.5
0.94	1532.33	-0.8	NaN	9
0.95	1549.81	-0.6	39	5
0.96	1567.36	-0.5	NaN	14
0.97	1584.99	-0.9	NaN	15.5
0.98	1602.68	-0.4	NaN	11
0.99	1620.29	-0.4	39	7.5
1	1638.02	-0.5	NaN	10
1.01	1655.84	-0.4	NaN	20.5
1.02	1673.68	-0.5	NaN	13.5
1.03	1691.55	-0.4	39	13
1.04	1709.41	-0.6	NaN	20.5
1.05	1727.32	-0.2	NaN	10
1.06	1745.26	-0.1	NaN	8.5
1.07	1763.26	-0.5	38	14
1.08	1781.34	-0.8	NaN	16
1.09	1799.40	-0.6	NaN	5
1.1	1817.54	-0.5	NaN	5
1.11	1835.69	-0.7	38	11.5
1.12	1853.88	-0.3	NaN	17.5
1.13	1872.03	-0.5	NaN	8.5
1.14	1890.32	-0.3	NaN	10
1.15	1908.45	-0.6	37	5.5
1.16	1926.68	-0.6	NaN	9.5
1.17	1944.94	-0.7	NaN	7
1.18	1963.20	-0.4	NaN	17.5
1.19	1981.47	-0.5	41	28.5

1.2	1999.77	-0.1	NaN	8
1.21	2018.15	-0.4	NaN	18.5
1.22	2036.55	-0.2	NaN	18.5
1.23	2054.92	-0.6	38	8
1.24	2073.32	-0.6	NaN	17.5
1.25	2091.68	-0.6	NaN	6
1.26	2110.04	-0.5	NaN	3.5
1.27	2128.39	-0.8	38	6.5
1.28	2146.84	-0.7	NaN	13.5
1.29	2165.25	-0.5	NaN	7
1.3	2183.69	-0.3	NaN	15
1.31	2202.11	-0.4	35	11.5
1.32	2220.65	-0.5	NaN	13
1.33	2239.16	-0.7	NaN	9.5
1.34	2257.69	-0.1	NaN	3
1.35	2276.15	-0.5	39	20
1.36	2294.75	-0.6	NaN	22.5
1.37	2313.25	-0.3	NaN	11.5
1.38	2331.77	-0.8	NaN	2.5
1.39	2350.33	-0.6	36	1.5
1.4	2368.85	-0.3	NaN	9
1.41	2387.40	-0.3	NaN	7.5
1.42	2405.93	-0.1	NaN	8.5
1.43	2424.51	-0.3	36	8.5
1.44	2443.08	-0.5	NaN	11.5
1.45	2461.68	-0.1	NaN	13.5
1.46	2480.30	-0.5	NaN	16.5
1.47	2498.93	-0.3	38	4
1.48	2517.52	-0.6	NaN	11.5
1.49	2536.21	-0.4	NaN	4
1.5	2554.86	-0.7	NaN	10
1.51	2573.64	-0.7	37	12
1.52	2592.33	-0.6	NaN	2.5
1.53	2611.15	-0.5	NaN	11.5
1.54	2629.80	-0.4	NaN	13.5
1.55	2648.49	-0.5	37	7.5
1.56	2667.22	-0.4	NaN	15
1.57	2685.94	-0.4	NaN	5.5
1.58	2704.68	-0.5	NaN	8.5
1.59	2723.47	-0.2	37	19.5
1.6	2742.24	-0.6	NaN	12.5
1.61	2761.06	-0.3	NaN	8.5
1.62	2779.88	-0.6	NaN	11.5
1.63	2798.72	-0.2	NaN	15

1.64	2817.53	-0.1	NaN	12.5
1.65	2836.37	-0.2	NaN	6
1.66	2855.27	-0.1	NaN	21.5
1.67	2874.17	-0.3	34	23
1.68	2893.09	-0.3	NaN	6
1.69	2912.08	-0.3	NaN	6.5
1.7	2930.94	0	NaN	18
1.71	2949.90	0.1	35	12
1.72	2968.84	0.4	NaN	14.5
1.73	2987.74	-0.3	NaN	16
1.74	3006.67	-0.2	NaN	10.5
1.75	3025.62	0	34	16.5
1.76	3044.71	0	NaN	8.5
1.77	3063.73	-0.2	NaN	10.5
1.78	3082.71	-0.2	NaN	4.5
1.79	3101.73	-0.2	36	22
1.8	3120.87	-0.2	NaN	6
1.81	3139.88	0.1	NaN	21.5
1.82	3158.98	-0.2	NaN	7.5
1.83	3178.07	0.1	36	19
1.84	3197.17	-0.3	NaN	10.5
1.85	3216.39	-0.9	NaN	9.5
1.86	3235.49	-0.3	NaN	16
1.87	3254.68	-0.2	36	19.5
1.88	3273.86	-0.6	NaN	8
1.89	3293.05	-0.3	NaN	12.5
1.9	3312.43	-0.8	NaN	30
1.91	3331.70	-0.1	34	14.5
1.92	3350.97	-0.2	NaN	16.5
1.93	3370.33	0	NaN	20.5
1.94	3389.67	0.1	NaN	17.5
1.95	3409.00	-0.1	34	15
1.96	3428.29	-0.5	NaN	14.5
1.97	3447.69	-0.3	NaN	14.5
1.98	3467.01	-0.4	NaN	15
1.99	3486.29	-0.2	35	29
2	3505.69	-0.3	NaN	9
2.01	3525.19	-0.5	NaN	26
2.02	3544.67	-0.3	NaN	14
2.03	3564.10	-0.3	34	26
2.04	3583.57	-0.1	NaN	14
2.05	3603.03	-0.5	NaN	24.5
2.06	3622.60	-0.5	NaN	13
2.07	3642.27	-0.3	36	8.5

2.08	3661.80	-0.1	NaN	8
2.09	3681.35	-0.3	NaN	16.5
2.1	3700.99	-0.4	NaN	5.5
2.11	3720.64	-0.1	38	10.5
2.12	3740.30	-0.1	NaN	9
2.13	3760.06	-0.3	NaN	4.5
2.14	3779.83	-0.6	NaN	13.5
2.15	3799.71	-0.2	39	23
2.16	3819.46	0.2	NaN	7.5
2.17	3839.25	0	NaN	9
2.18	3859.12	0.4	NaN	26.5
2.19	3879.13	0.2	NaN	NaN
2.2	3899.02	0	NaN	NaN
2.21	3919.10	0.5	NaN	NaN
2.22	3939.22	-0.2	NaN	20.5
2.23	3959.33	0.2	39	21.5
2.24	3979.59	0.4	NaN	22
2.25	3999.76	0.3	NaN	19
2.26	4020.00	1	NaN	16
2.27	4040.21	0.1	39	16.5
2.28	4060.61	0.1	NaN	8
2.29	4081.02	-0.1	NaN	11
2.3	4101.45	0.3	NaN	8.5
2.31	4122.02	0.4	38	13.5
2.32	4142.59	0.5	NaN	10
2.33	4163.28	0.4	NaN	8.5
2.34	4183.96	-0.2	NaN	7.5
2.35	4204.73	0	36	21.5
2.36	4225.56	0.2	NaN	15
2.37	4246.51	0.1	NaN	9.5
2.38	4267.50	0.3	NaN	11
2.39	4288.61	-0.1	35	11.5
2.4	4309.86	0	NaN	5.5
2.41	4331.12	-0.3	NaN	7
2.42	4352.48	0.1	NaN	6
2.43	4373.79	NaN	36	NaN
2.44	4395.31	NaN	NaN	10
2.45	4416.74	NaN	NaN	27
2.46	4438.47	0	NaN	18.5
2.47	4460.23	-0.2	39	23.5
2.48	4482.04	-0.1	NaN	12
2.49	4503.94	-0.2	NaN	12
2.5	4526.00	-0.2	NaN	14.5
2.51	4547.99	-0.5	38	NaN

2.52	4570.21	-0.2	NaN	9.5
2.53	4592.55	-0.2	NaN	3.5
2.54	4614.99	-0.1	NaN	16
2.55	4637.34	-0.4	38	15
2.56	4659.97	-0.6	NaN	9
2.57	4682.64	-0.3	NaN	10
2.58	4705.41	-0.3	NaN	8
2.59	4728.27	-0.2	34	24.5
2.6	4751.34	0.1	NaN	14.5
2.61	4774.37	-0.2	NaN	11.5
2.62	4797.50	-0.1	NaN	15.5
2.63	4820.78	0.1	33	20.5
2.64	4844.14	0.1	NaN	8
2.65	4867.54	0.2	NaN	5.5
2.66	4891.10	-0.1	NaN	12.5
2.67	4914.80	-0.2	33	22.5
2.68	4938.54	0.1	NaN	6
2.69	4962.33	0	NaN	10
2.7	4986.23	-0.3	NaN	4.5
2.71	5010.17	-0.1	35	6
2.72	5034.22	-0.3	NaN	6
2.73	5058.44	-0.1	NaN	11
2.74	5082.69	-0.1	NaN	20
2.75	5106.93	-0.3	35	6
2.76	5131.37	-0.1	NaN	4.5
2.77	5155.98	0	NaN	13.5
2.78	5180.56	-0.1	NaN	9.5
2.79	5205.27	-0.3	36	14
2.8	5230.08	-0.3	NaN	8
2.81	5254.93	-0.1	NaN	10.5
2.82	5279.84	-0.1	NaN	8.5
2.83	5304.86	0	31	11
2.84	5330.01	-0.1	NaN	10
2.85	5355.25	0.3	NaN	12.5
2.86	5380.47	-0.2	NaN	8.5
2.87	5405.76	0.5	33	9.5
2.88	5431.14	0	NaN	23
2.89	5456.68	-0.5	NaN	20.5
2.9	5482.26	-0.4	NaN	7
2.91	5507.85	-0.4	33	9
2.92	5533.60	-0.2	NaN	10
2.93	5559.38	-0.1	NaN	10
2.94	5585.36	0	NaN	10.5
2.95	5611.35	-0.1	32	12.5

2.96	5637.38	0.1	NaN	11
2.97	5663.48	0.3	NaN	8
2.98	5689.61	0.1	NaN	8
2.99	5715.86	0.2	31	9.5
3	5742.20	-0.1	NaN	8.5
3.01	5768.63	0.1	NaN	8
3.02	5795.08	0.2	NaN	9
3.03	5821.61	0.2	29	7
3.04	5848.17	0.9	NaN	7.5
3.05	5874.74	0.8	NaN	7.5
3.06	5901.45	0.9	NaN	7.5
3.07	5928.25	0.9	29	14
3.08	5955.16	0.3	NaN	15
3.09	5982.10	0.4	NaN	16.5
3.1	6008.99	0.1	NaN	9.5
3.11	6036.04	0.1	31	19
3.12	6063.14	0	NaN	12.5
3.13	6090.38	0.8	NaN	7
3.14	6117.56	2.8	NaN	4
3.15	6144.83	0.4	28	12
3.16	6172.12	0.4	NaN	16
3.17	6199.56	-0.1	NaN	5
3.18	6227.01	0.5	NaN	14.5
3.19	6254.51	0.3	31	11.5
3.2	6282.14	0.2	NaN	11
3.21	6309.77	0.3	NaN	8
3.22	6337.45	0.5	NaN	16.5
3.23	6365.16	0.4	28	12.5
3.24	6393.00	0.3	NaN	8.5
3.25	6420.85	0.4	NaN	8.5
3.26	6448.74	1.1	NaN	3.5
3.27	6476.64	1.3	28	9.5
3.28	6504.71	1.9	NaN	17
3.29	6532.83	-0.2	NaN	7.5
3.3	6560.93	0.4	NaN	6
3.31	6589.19	0.7	27	7
3.32	6617.37	0.6	NaN	11.5
3.33	6645.58	2.6	NaN	3.5
3.34	6673.88	2.8	NaN	13.5
3.35	6702.24	1	28	10.5
3.36	6730.57	0.9	NaN	9
3.37	6758.99	0.8	NaN	11
3.38	6787.49	0.3	NaN	6
3.39	6816.11	0.6	29	10

3.4	6844.75	0.1	NaN	12.5
3.41	6873.52	0.8	NaN	9.5
3.42	6902.31	0.7	NaN	5.5
3.43	6931.13	1.1	26	17.5
3.44	6960.09	0.5	NaN	6.5
3.45	6989.10	0.5	NaN	4
3.46	7018.20	0.7	NaN	10
3.47	7047.41	0.5	27	12
3.48	7076.70	0.7	NaN	11.5
3.49	7106.04	0.7	NaN	8
3.5	7135.47	0.7	NaN	10
3.51	7165.02	0.6	27	7
3.52	7194.67	0.5	NaN	5
3.53	7224.38	1.2	NaN	5
3.54	7254.22	1.7	NaN	6.5
3.55	7284.21	1.5	23	8
3.56	7314.34	2.4	NaN	7
3.57	7344.54	1.6	24	7.5
3.58	7374.86	1.6	NaN	7
3.59	7405.32	1.2	25	6
3.6	7435.93	1.8	NaN	7.5
3.61	7466.55	0.9	25	5.5
3.62	7497.41	2	NaN	6
3.63	7528.38	2.9	26	11
3.64	7559.53	5.7	NaN	6.5
3.65	7590.88	6.9	26	6
3.66	7622.41	1.1	NaN	11.5
3.67	7654.04	0.7	27	7.5
3.68	7685.84	0.4	NaN	8
3.69	7717.80	0.6	26	10
3.7	7749.89	0.7	NaN	6.5
3.71	7782.23	0.3	27	5
3.72	7814.69	0.1	NaN	11
3.73	7847.29	0	26	5
3.74	7880.10	0.5	NaN	12
3.75	7913.04	0.5	26	9
3.76	7946.26	0.4	NaN	7.5
3.77	7979.65	0.4	25	10
3.78	8013.15	0.6	NaN	7
3.79	8046.84	1	24	9.5
3.8	8080.72	1.1	NaN	9
3.81	8114.84	1	23	6
3.82	8149.08	1.1	NaN	7.5
3.83	8183.55	1.2	24	3

3.84	8218.26	1.4	NaN	2.5
3.85	8253.17	1.6	24	9.5
3.86	8288.28	1.6	NaN	6
3.87	8323.55	1.1	26	4.5
3.88	8359.07	1.6	NaN	6
3.89	8394.86	1.2	26	11
3.9	8430.86	1	NaN	6
3.91	8466.95	1.4	23	7
3.92	8503.36	1.4	NaN	1.5
3.93	8539.93	1.4	25	3
3.94	8576.71	1	NaN	8
3.95	8613.74	1.3	27	2.5
3.96	8651.06	2	NaN	8.5
3.97	8688.55	1.4	28	8
3.98	8726.23	0.4	NaN	5
3.99	8764.14	0.4	29	4
4	8802.25	0.9	NaN	7
4.01	8840.62	0.5	27	11.5
4.02	8879.19	0.9	NaN	3.5
4.03	8917.97	2.5	23	2.5
4.04	8957.02	7	NaN	4.5
4.05	8996.31	6.1	19	15
4.06	9035.81	1	NaN	3.5
4.07	9075.53	0.6	31	5
4.08	9115.45	0.2	NaN	2.5
4.09	9155.60	0.6	34	4.5
4.1	9195.91	0.4	NaN	5.5
4.11	9236.52	1	27	5.5
4.12	9277.35	1.6	NaN	5
4.13	9318.38	1.1	27	7.5
4.14	9359.60	1	NaN	3
4.15	9401.05	1.1	30	4.5
4.16	9442.72	0.8	NaN	6.5
4.17	9484.61	0.2	33	2.5
4.18	9526.75	0.3	NaN	9.5
4.19	9569.03	0.6	33	6.5
4.2	9611.67	0.5	NaN	2.5
4.21	9654.55	0.2	34	3
4.22	9697.58	0.3	NaN	9
4.23	9740.86	0	33	2
4.24	9784.34	0.8	NaN	3
4.25	9828.08	0.3	29	2.5
4.26	9872.05	0.5	NaN	4
4.27	9916.14	0.7	30	4

4.28	9960.62	0.9	NaN	1.5
4.29	10005.31	0.7	28	0
4.3	10050.23	1.2	NaN	0.5
4.31	10095.37	0.9	28	1
4.32	10140.74	1.1	NaN	3.5
4.33	10186.35	1.5	27	2.5
4.34	10232.15	1.6	NaN	2
4.35	10278.20	1.6	27	4.5
4.36	10324.56	1	NaN	5
4.37	10371.08	1.2	26	13
4.38	10417.86	2.2	NaN	1.5
4.39	10464.86	2.2	25	2
4.4	10512.13	2.1	NaN	2
4.41	10559.73	1.6	28	2
4.42	10607.51	1	NaN	3.5
4.43	10655.56	1	32	5.5
4.44	10703.91	1	NaN	1
4.45	10752.43	1.6	29	1
4.46	10801.24	1.1	NaN	8
4.47	10850.28	1.7	32	7.5
4.48	10899.50	2.2	NaN	5
4.49	10949.00	6.6	24	7.5
4.5	10998.77	15.2	NaN	17
4.51	11048.76	16.3	22	4.5
4.52	11099.07	14	NaN	6
4.53	11149.62	9.9	21	13.5
4.54	11200.34	11.1	NaN	2
4.55	11251.24	12.3	17	1.5
4.56	11302.51	2.6	NaN	3.5
4.57	11353.88	1.6	25	2
4.58	11405.60	0.9	NaN	10.5
4.59	11457.53	1.6	24	5.5
4.6	11509.69	0.9	NaN	1.5
4.61	11562.01	2	24	2
4.62	11614.75	NaN	NaN	NaN
4.63	11667.53	2.4	17	2
4.64	11720.49	0.7	NaN	3
4.65	11773.81	0.9	20	2
4.66	11827.28	0.3	NaN	3
4.67	11881.07	0.1	20	11
4.68	11934.89	-0.4	NaN	5.5
4.69	11988.97	-0.6	20	13.5
4.7	12043.17	0.1	NaN	9.5
4.71	12097.71	-0.1	16	1.5

4.72	12152.27	0.1	NaN	2.5
4.73	12207.02	0.6	16	4.5
4.74	12261.89	0.3	NaN	10.5
4.75	12317.00	0.6	15	3.5
4.76	12372.25	0.6	NaN	1.5
4.77	12427.63	0.6	14	5
4.78	12483.26	0.7	NaN	4
4.79	12539.05	1.2	15	8
4.8	12594.76	1.7	NaN	5
4.81	12650.62	2.6	13	2.5
4.82	12706.68	3.1	NaN	7.5
4.83	12762.92	2.3	14	0.5
4.84	12819.20	2.5	NaN	0
4.85	12875.65	3.8	13	0
4.86	12932.10	4.2	NaN	2.5
4.87	12988.73	7.5	12	1.5
4.88	13045.30	9.3	NaN	0
4.89	13102.21	5.5	14	3.5
4.9	13159.07	4.7	NaN	1.5
4.91	13215.92	4.7	17	2
4.92	13272.87	2.4	NaN	0.5
4.93	13329.78	3.3	14	1.5
4.94	13386.82	3.1	NaN	1.5
4.95	13443.76	4.6	13	1.5
4.96	13500.91	3.6	NaN	1.5
4.97	13557.96	3.1	13	1
4.98	13615.10	3.7	NaN	0.5
4.99	13672.22	4.2	13	1
5	13729.10	4.6	NaN	3
5.01	13786.17	7.6	9	1.5
5.02	13843.23	9.3	NaN	3.5
5.03	13900.27	6.8	10	5
5.04	13957.13	7.5	NaN	2.5
5.05	14014.12	9	10	2
5.06	14071.04	13.3	NaN	5
5.07	14127.83	19.2	5	3.5
5.08	14184.55	20.6	NaN	0.5
5.09	14241.13	28.8	3	0
5.1	14297.77	37.4	NaN	0

APPENDIX G

CAMPBELL LAKE LITHOLOGICAL AND CHARCOAL DATA

Depth (m)	Age (cal yr BP)	Magnetic susceptibility (cgs x10^{-6})	Percent Organic Matter	Charcoal Concentrations (particles cm^{-3})
0	-53.19	-0.3	NaN	1.5
0.01	-43.61	-0.5	NaN	3
0.02	-34.11	-0.4	NaN	3.5
0.03	-24.71	-0.1	41	6.5
0.04	-15.44	-0.5	NaN	4
0.05	-6.23	-0.5	NaN	7.5
0.06	2.95	-0.1	NaN	3
0.07	12.13	0.1	42	4
0.08	21.31	0	NaN	2
0.09	30.48	-0.1	NaN	1.5
0.1	52.98	-0.1	NaN	1.5
0.11	74.47	0.2	NaN	1.5
0.12	95.93	0.2	43	1
0.13	117.36	-0.1	NaN	3.5
0.14	138.75	-0.3	43	1.5
0.15	160.09	-0.5	NaN	7.5
0.16	181.37	0	NaN	3
0.17	202.58	-0.3	NaN	4.5
0.18	223.70	-0.4	41	2.5
0.19	244.74	-0.9	NaN	4.5
0.2	265.67	-0.3	NaN	2.5
0.21	286.49	-0.5	NaN	6
0.22	307.19	-0.1	52	2.5
0.23	327.76	-0.3	NaN	2
0.24	348.18	-0.3	NaN	1.5
0.25	368.45	-0.7	NaN	3.5
0.26	388.56	-0.2	51	3
0.27	408.49	-0.3	NaN	3
0.28	428.24	-0.4	NaN	9
0.29	447.80	-0.5	NaN	4.5
0.3	467.15	-0.2	47	2.5
0.31	486.29	-0.9	NaN	6.5

0.32	505.23	-0.4	NaN	6
0.33	523.99	-0.2	NaN	6.5
0.34	542.58	-0.4	45	5.5
0.35	561.03	-0.3	NaN	12.5
0.36	579.35	-1	NaN	8
0.37	597.56	-0.7	NaN	6
0.38	615.68	-0.3	44	2.5
0.39	633.73	-0.6	NaN	2
0.4	651.74	0.4	NaN	4
0.41	669.71	0.1	NaN	5
0.42	687.67	-0.2	44	3.5
0.43	705.63	0.2	NaN	5
0.44	723.62	0.5	NaN	8
0.45	741.65	0.7	NaN	8.5
0.46	759.75	0.2	47	5
0.47	777.93	0.1	NaN	10
0.48	796.21	-0.4	NaN	8.5
0.49	814.58	-0.2	NaN	7
0.5	833.05	0.1	49	12.5
0.51	851.59	0	NaN	3.5
0.52	870.21	-0.1	NaN	14.5
0.53	888.89	-0.1	NaN	10.5
0.54	907.62	0.1	45	8.5
0.55	926.40	0.6	NaN	8.5
0.56	945.21	0	NaN	2.5
0.57	964.05	0.3	NaN	2.5
0.58	982.91	-0.1	46	5
0.59	1001.77	-0.4	NaN	5.5
0.6	1020.64	-0.8	NaN	3
0.61	1039.49	-0.7	NaN	7
0.62	1058.33	-0.5	47	6.5
0.63	1077.13	-0.3	NaN	3.5
0.64	1095.90	-0.4	NaN	3
0.65	1114.62	0.1	NaN	6.5
0.66	1133.29	-0.4	47	10.5
0.67	1151.90	-0.4	NaN	12
0.68	1170.43	-0.6	NaN	3.5
0.69	1188.87	-0.6	NaN	3.5
0.7	1207.23	-0.1	47	16.5
0.71	1225.49	-0.3	NaN	8.5
0.72	1243.63	-0.8	NaN	6.5
0.73	1261.66	0.1	NaN	7
0.74	1279.56	-0.5	42	5
0.75	1297.33	0	NaN	6

0.76	1314.98	-0.1	NaN	12.5
0.77	1332.50	0.4	NaN	9.5
0.78	1349.90	8.4	12	3.5
0.79	1367.18	11.9	NaN	2.5
0.8	1384.35	1.8	NaN	11
0.81	1401.40	0.3	NaN	22.5
0.82	1418.33	0.1	41	14.5
0.83	1435.16	-0.1	NaN	5
0.84	1451.88	0.1	NaN	12
0.85	1468.49	0	NaN	8
0.86	1485.00	-0.3	49	18
0.87	1501.41	0.1	NaN	13.5
0.88	1517.72	0	NaN	10.5
0.89	1533.93	-0.7	NaN	6
0.9	1550.05	-0.2	49	4.5
0.91	1566.07	0	NaN	7.5
0.92	1582.00	0.1	NaN	7
0.93	1597.85	-0.4	NaN	22.5
0.94	1613.61	-0.2	49	12.5
0.95	1629.29	-0.4	NaN	9
0.96	1644.89	-0.2	NaN	3.5
0.97	1660.40	-0.3	NaN	21.5
0.98	1675.85	-0.2	9	15
0.99	1691.21	-0.3	NaN	6.5
1	1706.51	-0.2	NaN	6
1.01	1721.73	-0.2	NaN	17
1.02	1736.89	-0.2	46	25
1.03	1751.98	-0.4	NaN	16
1.04	1767.01	-1	NaN	14
1.05	1781.98	-0.7	NaN	6
1.06	1796.89	-0.3	47	9
1.07	1811.74	-0.4	NaN	8
1.08	1826.54	-0.3	NaN	3.5
1.09	1841.28	-0.9	NaN	2.5
1.1	1855.98	-0.5	49	4
1.11	1870.63	-0.5	NaN	4
1.12	1885.25	0	NaN	3.5
1.13	1899.83	-0.3	NaN	5
1.14	1914.38	-0.2	49	4.5
1.15	1928.92	-0.5	NaN	14
1.16	1943.44	-0.6	NaN	16.5
1.17	1957.95	-0.3	NaN	9.5
1.18	1972.45	-0.4	49	10
1.19	1986.96	-0.1	NaN	7.5

1.2	2001.48	-0.4	NaN	7
1.21	2016.02	-0.7	NaN	13.5
1.22	2030.57	-0.2	44	14.5
1.23	2045.15	-0.8	NaN	9
1.24	2059.77	-0.4	NaN	7
1.25	2074.42	-0.3	NaN	1
1.26	2089.12	-0.2	46	3.5
1.27	2103.87	-0.5	NaN	4
1.28	2118.67	-0.8	NaN	4
1.29	2133.54	-0.1	NaN	6.5
1.3	2148.48	-0.2	42	4
1.31	2163.49	0.2	NaN	7
1.32	2178.58	0.1	NaN	7.5
1.33	2193.76	0.3	NaN	12.5
1.34	2209.03	0.5	39	12.5
1.35	2224.40	0.2	NaN	15.5
1.36	2239.87	0.2	NaN	18
1.37	2255.46	0.1	NaN	6
1.38	2271.16	0.3	NaN	8
1.39	2286.98	0.3	NaN	16
1.4	2302.93	NaN	NaN	NaN
1.41	2319.01	0	NaN	11.5
1.42	2335.24	0.9	41	11
1.43	2351.61	0.3	NaN	8
1.44	2368.13	0.2	NaN	11.5
1.45	2384.81	-0.6	NaN	15
1.46	2401.66	0	38	16.5
1.47	2418.67	-0.5	NaN	16.5
1.48	2435.86	-0.2	NaN	5
1.49	2453.23	-0.4	NaN	26
1.5	2470.79	0	39	52
1.51	2488.54	-0.2	NaN	7.5
1.52	2506.50	-0.3	NaN	7
1.53	2524.66	-0.1	NaN	1.5
1.54	2543.03	0.1	41	8
1.55	2561.61	-0.9	NaN	5
1.56	2580.43	-0.5	NaN	8
1.57	2599.47	-0.2	NaN	13.5
1.58	2618.74	-0.4	37	16.5
1.59	2638.26	-0.1	NaN	19
1.6	2658.02	-0.4	NaN	13
1.61	2678.04	-0.1	NaN	21.5
1.62	2698.32	-0.4	38	22
1.63	2718.86	-0.1	NaN	25.5

1.64	2739.68	-0.3	NaN	23.5
1.65	2760.77	-0.4	NaN	10.5
1.66	2782.14	-0.2	38	9
1.67	2803.80	-0.2	NaN	1.5
1.68	2825.76	-0.5	NaN	4
1.69	2848.02	-0.4	NaN	1
1.7	2870.59	-0.7	36	4.5
1.71	2893.46	-0.2	NaN	2.5
1.72	2916.62	-0.5	NaN	6
1.73	2940.06	-0.4	NaN	3
1.74	2963.77	-0.3	35	4.5
1.75	2987.74	-0.2	NaN	3.5
1.76	3011.96	-0.5	NaN	4
1.77	3036.41	-0.2	NaN	6.5
1.78	3061.09	-0.3	34	11
1.79	3085.98	-0.4	NaN	4.5
1.8	3111.07	-0.2	NaN	18
1.81	3136.34	0	NaN	49.5
1.82	3161.80	-0.3	32	54
1.83	3187.42	-0.3	NaN	13.5
1.84	3213.19	-0.2	NaN	8.5
1.85	3239.11	-0.3	NaN	8.5
1.86	3265.16	-0.3	34	8
1.87	3291.33	-0.2	NaN	9.5
1.88	3317.61	0	NaN	8
1.89	3343.98	-0.4	NaN	14
1.9	3370.45	-0.4	36	17
1.91	3396.98	-0.3	NaN	11
1.92	3423.58	0.1	NaN	3.5
1.93	3450.22	-0.1	NaN	1
1.94	3476.91	-0.1	35	7
1.95	3503.62	-0.4	NaN	5
1.96	3530.36	-0.3	NaN	0
1.97	3557.09	-0.4	NaN	2.5
1.98	3583.82	-0.3	36	4.5
1.99	3610.53	-0.1	NaN	4
2	3637.21	-0.3	NaN	10.5
2.01	3663.85	-0.1	NaN	16.5
2.02	3690.44	-0.8	34	6
2.03	3716.96	-0.7	NaN	7.5
2.04	3743.41	-0.5	NaN	1.5
2.05	3769.77	-0.3	NaN	3.5
2.06	3796.03	-0.2	33	1.5
2.07	3822.18	-0.5	NaN	2

2.08	3848.21	-0.3	NaN	2.5
2.09	3874.10	-0.5	NaN	2
2.1	3899.85	-0.5	34	2
2.11	3925.46	-0.2	NaN	0
2.12	3950.95	0	NaN	2
2.13	3976.32	-0.2	NaN	1.5
2.14	4001.59	-0.3	32	1.5
2.15	4026.77	-0.2	NaN	2.5
2.16	4051.87	-0.2	NaN	1.5
2.17	4076.90	-0.1	NaN	1
2.18	4101.87	0.2	33	2
2.19	4126.81	0	NaN	1
2.2	4151.71	0.1	NaN	2.5
2.21	4176.59	0.1	NaN	10
2.22	4201.46	0.1	33	3
2.23	4226.34	0.2	NaN	3
2.24	4251.24	0.3	NaN	4
2.25	4276.17	0	NaN	10
2.26	4301.13	0	30	9
2.27	4326.15	-0.5	NaN	10.5
2.28	4351.23	-0.2	NaN	5.5
2.29	4376.39	-0.1	NaN	5.5
2.3	4401.64	-0.1	28	3
2.31	4426.99	-0.1	NaN	9
2.32	4452.45	0.3	NaN	4.5
2.33	4478.03	0.2	NaN	3
2.34	4503.75	-0.2	32	5.5
2.35	4529.62	0.3	NaN	1.5
2.36	4555.65	0.5	NaN	3
2.37	4581.85	0	NaN	8
2.38	4608.23	0.1	NaN	1.5
2.39	4634.81	NaN	32	NaN
2.4	4661.60	NaN	NaN	NaN
2.41	4688.61	0.4	NaN	4
2.42	4715.85	0.6	32	2.5
2.43	4743.33	0.1	NaN	5
2.44	4771.07	0.4	NaN	3.5
2.45	4799.08	-0.4	NaN	9
2.46	4827.37	-0.3	33	4.5
2.47	4855.95	-0.3	NaN	5
2.48	4884.83	-0.3	NaN	6
2.49	4914.03	0.1	NaN	4
2.5	4943.55	0	32	2
2.51	4973.42	-0.3	NaN	5

2.52	5003.64	-0.4	NaN	8
2.53	5034.22	0.2	NaN	5
2.54	5065.17	-0.1	31	3
2.55	5096.51	0.1	NaN	6
2.56	5128.25	0.5	NaN	4.5
2.57	5160.40	0.4	NaN	9.5
2.58	5192.95	0.4	29	10
2.59	5225.90	0.6	NaN	8.5
2.6	5259.26	0.6	NaN	3
2.61	5293.02	-0.1	NaN	5.5
2.62	5327.18	-0.1	31	3.5
2.63	5361.75	-0.1	NaN	1
2.64	5396.71	0.2	NaN	3
2.65	5432.07	-0.3	NaN	3.5
2.66	5467.84	-0.2	30	1.5
2.67	5504.00	0.1	NaN	3
2.68	5540.56	-0.1	NaN	2
2.69	5577.52	0.3	NaN	6
2.7	5614.88	0.3	30	6
2.71	5652.63	0.3	NaN	13
2.72	5690.78	0.3	NaN	26
2.73	5729.33	-0.3	NaN	14.5
2.74	5768.27	0.2	29	2.5
2.75	5807.60	0.5	NaN	2
2.76	5847.33	0.1	NaN	3
2.77	5887.45	-0.2	NaN	2.5
2.78	5927.97	-0.1	29	2.5
2.79	5968.87	0	NaN	1
2.8	6010.17	0.5	NaN	1.5
2.81	6051.86	0.5	NaN	6
2.82	6093.94	0.5	29	10.5
2.83	6136.41	0.4	NaN	1.5
2.84	6179.26	0.6	NaN	1.5
2.85	6222.51	0.6	NaN	0.5
2.86	6266.15	0.4	32	2
2.87	6310.17	0.4	NaN	5.5
2.88	6354.58	0	NaN	9
2.89	6399.37	0.2	NaN	10.5
2.9	6444.55	0	28	14
2.91	6490.11	0.2	NaN	10.5
2.92	6536.04	0.3	NaN	2
2.93	6582.31	0.2	NaN	2.5
2.94	6628.91	0.1	29	1
2.95	6675.82	0.4	NaN	1.5

2.96	6723.03	0.3	NaN	2.5
2.97	6770.53	0.3	NaN	2
2.98	6818.28	0.1	28	0.5
2.99	6866.29	0.3	NaN	2
3	6914.53	0.4	NaN	9
3.01	6962.98	2	NaN	26
3.02	7011.63	1.2	32	2.5
3.03	7060.46	1.3	NaN	6
3.04	7109.46	1.1	NaN	7
3.05	7158.61	1.2	NaN	2
3.06	7207.90	0.7	31	6.5
3.07	7257.30	0.6	NaN	10.5
3.08	7306.80	1.1	30	8.5
3.09	7356.39	1.4	NaN	2.5
3.1	7406.04	1.5	31	6.5
3.11	7455.75	1.5	NaN	5
3.12	7505.49	0.9	29	0.5
3.13	7555.25	1.1	NaN	1
3.14	7605.01	1.4	30	1
3.15	7654.76	0.9	NaN	2.5
3.16	7704.48	1.4	24	5.5
3.17	7754.15	36.3	NaN	4.5
3.18	7803.75	6	28	2.5
3.19	7853.26	1	NaN	6.5
3.2	7902.61	0.6	28	12
3.21	7951.78	0.7	NaN	5.5
3.22	8000.70	1.3	25	2
3.23	8049.33	1.6	NaN	4
3.24	8097.63	3.1	27	7
3.25	8145.56	1.8	NaN	10.5
3.26	8193.14	1.3	29	6.5
3.27	8240.38	0.6	NaN	3.5
3.28	8287.30	1.2	30	5
3.29	8333.94	1.5	NaN	8.5
3.3	8380.31	1.3	26	10.5
3.31	8426.43	1.9	NaN	11.5
3.32	8472.32	1.5	25	3.5
3.33	8518.02	1.7	NaN	5
3.34	8563.53	2.2	27	7.5
3.35	8608.89	2.5	NaN	9.5
3.36	8654.11	2.5	29	8
3.37	8699.21	2.2	NaN	24
3.38	8744.23	2.5	29	3.5
3.39	8789.18	1.6	NaN	1.5

3.4	8834.08	2	27	2.5
3.41	8878.95	3.4	NaN	14.5
3.42	8923.82	2.6	29	8.5
3.43	8968.72	3	NaN	3.5
3.44	9013.65	1.6	28	14.5
3.45	9058.65	1	NaN	7.5
3.46	9103.73	0.9	29	8.5
3.47	9148.93	1.1	NaN	6.5
3.48	9194.25	1.4	30	12
3.49	9239.72	1.9	NaN	13
3.5	9285.35	1.7	28	3
3.51	9331.13	1.6	NaN	10
3.52	9377.07	2.4	27	5
3.53	9423.16	2.2	NaN	14.5
3.54	9469.40	2.8	28	9
3.55	9515.81	2.2	NaN	3.5
3.56	9562.37	2	31	8.5
3.57	9609.09	2.6	NaN	6.5
3.58	9655.97	1.9	31	11.5
3.59	9703.01	0.7	NaN	4
3.6	9750.21	6.3	35	3
3.61	9797.57	0.9	NaN	14.5
3.62	9845.09	1.3	31	4.5
3.63	9892.77	0.9	NaN	1.5
3.64	9940.62	1.5	30	3.5
3.65	9988.63	2.5	NaN	2
3.66	10036.81	2.3	35	0.5
3.67	10085.15	2	NaN	2.5
3.68	10133.65	1.1	34	3
3.69	10182.33	2.5	NaN	20.5
3.7	10231.17	2.1	35	30.5
3.71	10280.17	2.9	NaN	1
3.72	10329.35	2.6	34	2.5
3.73	10378.70	3	NaN	4.5
3.74	10428.21	4.2	36	3
3.75	10477.90	5.2	NaN	5.5
3.76	10527.76	4.9	36	2
3.77	10577.79	6.3	NaN	6
3.78	10627.99	7	34	15.5
3.79	10678.36	7.5	NaN	5.5
3.8	10728.91	8	32	2
3.81	10779.64	6.5	NaN	2
3.82	10830.54	9.9	22	3.5
3.83	10881.62	12.9	NaN	4

3.84	10932.87	20.2	19	5
3.85	10984.30	37.5	NaN	10.5
3.86	11035.91	20.7	28	34.5
3.87	11087.69	17.9	NaN	20.5
3.88	11139.66	7.5	31	3
3.89	11191.81	2.9	NaN	5
3.9	11244.13	3.5	26	3
3.91	11296.63	3.8	NaN	2
3.92	11349.30	4.2	24	2
3.93	11402.13	4.7	NaN	3
3.94	11455.13	5.6	16	2
3.95	11508.29	9.2	NaN	0
3.96	11561.61	7.9	20	2
3.97	11615.09	7.2	NaN	3.5
3.98	11668.71	7.6	16	1.5
3.99	11722.49	8.5	NaN	2
4	11776.41	9.6	15	4.5
4.01	11830.47	11.9	NaN	3.5
4.02	11884.67	11.9	14	7
4.03	11939.00	15	NaN	5.5
4.04	11993.47	12.4	15	2
4.05	12048.07	8.9	NaN	2
4.06	12102.80	7.7	13	0.5
4.07	12157.64	11	NaN	4
4.08	12212.61	10.9	14	4.5
4.09	12267.70	10.3	NaN	4.5
4.1	12322.89	8.1	13	4.5
4.11	12378.20	8.7	NaN	4
4.12	12433.62	7.3	14	5
4.13	12489.13	5.7	NaN	7
4.14	12544.75	8.8	15	6.5
4.15	12600.47	8	NaN	1.5
4.16	12656.28	7.8	16	0
4.17	12712.18	8.1	NaN	1.5
4.18	12768.17	7.8	16	0.5
4.19	12824.23	6.9	NaN	1.5
4.2	12880.37	7.4	15	5
4.21	12936.59	7.7	NaN	2.5
4.22	12992.87	10.1	16	4
4.23	13049.22	11.9	NaN	2
4.24	13105.62	8.5	17	2.5
4.25	13162.08	8.5	NaN	3
4.26	13218.59	6.9	16	9.5
4.27	13275.15	6.9	NaN	6

4.28	13331.75	6.3	15	2
4.29	13388.39	7.8	NaN	3
4.3	13445.06	8.1	13	4
4.31	13501.76	14	NaN	1.5
4.32	13558.49	13.8	14	1
4.33	13615.24	11	NaN	2
4.34	13672.01	13.6	9	3.5
4.35	13728.78	20.2	NaN	4.5
4.36	13785.57	24.9	13	7
4.37	13842.36	21.2	NaN	19
4.38	13899.15	23.4	18	21.5
4.39	13955.94	14.6	NaN	2.5
4.4	14012.72	9	11	4.5
4.41	14069.49	NaN	NaN	NaN
4.42	14126.23	17.9	5	NaN
4.43	14182.96	20.8	NaN	NaN
4.44	14239.66	31.2	3	NaN
4.45	14296.34	54.8	NaN	NaN
4.46	14352.98	123.3	2	NaN
4.47	14409.58	199.6	NaN	NaN
4.48	14466.13	198.2	NaN	NaN
4.49	14522.64	98.8	NaN	NaN
4.5	14579.10	113.1	NaN	NaN
4.51	14635.51	219.2	NaN	NaN
4.52	14691.86	219.3	NaN	NaN
4.53	14748.14	151.5	NaN	NaN
4.54	14804.35	218.7	NaN	NaN
4.55	14860.49	209.5	NaN	NaN
4.56	14916.56	164.7	NaN	NaN
4.57	14972.54	142.9	NaN	NaN
4.58	15028.44	144.6	NaN	NaN
4.59	15084.25	201.1	NaN	NaN
4.6	15139.97	180.9	NaN	NaN
4.61	15195.59	217.9	NaN	NaN

APPENDIX H

CEDAR LAKE LITHOLOGICAL AND CHARCOAL DATA

Depth (m)	Age (cal yr BP)	Magnetic susceptibility (cgs x10^{-6})	Percent Organic Matter	Charcoal Concentrations (particles cm^{-3})
0.01	-48.06	2.280	41	0
0.02	-46.05	0.774	72	0.2
0.03	-43.81	0.543	66	0.4
0.04	-41.10	0.468	50	0
0.05	-37.71	0.748	45	0.4
0.06	-33.41	0.436	NaN	0.4
0.07	-28.16	0.307	40	0.2
0.08	-22.14	0.250	36	0.4
0.09	-15.61	0.307	46	2.4
0.1	-8.75	0.411	32	2.2
0.11	-1.68	0.153	41	5.8
0.12	5.50	0.395	30	4
0.13	12.71	0.274	27	5.4
0.14	19.85	0.377	30	7.2
0.15	26.84	0.234	30	7.4
0.16	33.60	0.234	33	4.8
0.17	40.12	0.234	31	4.8
0.18	46.38	0.161	25	4.8
0.19	52.35	0.504	27	9
0.2	58.12	0.253	29	15.2
0.21	63.86	0.099	22	15.8
0.22	69.89	0.209	20	18.8
0.23	76.72	0.209	22	17.2
0.24	85.12	0.115	25	7
0.25	96.11	0.178	25	14
0.26	110.82	0.063	21	7.8
0.27	130.46	0.010	25	14.8
0.28	155.48	0.320	20	12.2
0.29	185.59	0.174	19	8.8
0.3	220.48	0.052	22	11.6
0.31	259.83	0.131	19	15.2

0.32	303.32	0.331	20	8.6
0.33	350.63	0.000	21	5.6
0.34	401.44	0.000	24	12.2
0.35	455.43	0.000	24	12
0.36	512.29	0.084	21	16.8
0.37	571.70	0.021	22	10
0.38	633.34	0.000	19	12
0.39	696.89	0.000	20	23.2
0.4	762.03	0.000	18	34.4
0.41	828.44	0.032	16	20.6
0.42	895.81	0.043	18	41.8
0.43	963.81	0.000	31	29.8
0.44	1032.13	2.060	6	10.8
0.45	1070.92	0.982	13	7
0.46	1109.73	0.000	23	14
0.47	1148.53	0.000	27	9
0.48	1187.32	0.000	25	6
0.49	1226.10	0.000	29	14
0.5	1264.85	0.000	31	9
0.51	1303.58	0.000	20	10
0.52	1342.28	0.000	23	14
0.53	1380.95	0.000	27	12
0.54	1419.58	0.000	21	9
0.55	1458.16	0.146	21	15
0.56	1496.71	0.000	25	20
0.57	1535.20	0.032	23	13
0.58	1573.64	0.039	27	16
0.59	1612.02	0.000	20	14
0.6	1650.34	0.000	19	18
0.61	1688.60	0.000	27	19
0.62	1726.78	0.000	21	16
0.63	1764.89	0.000	29	14
0.64	1802.93	0.011	29	16
0.65	1840.88	0.000	25	12
0.66	1878.74	0.000	29	6
0.67	1916.51	0.000	27	13
0.68	1954.19	0.000	25	12
0.69	1991.77	0.000	25	11
0.7	2029.24	0.000	27	13
0.71	2066.61	0.000	23	13
0.72	2103.87	0.000	27	12

0.73	2141.01	0.000	23	8
0.74	2178.03	0.000	19	16
0.75	2214.93	0.000	20	14
0.76	2251.70	0.000	21	12
0.77	2288.34	0.000	27	10
0.78	2324.84	0.000	21	14
0.79	2361.21	0.000	23	16
0.8	2397.42	0.153	23	28
0.81	2433.49	0.015	25	22
0.82	2469.41	0.000	21	11
0.83	2505.17	0.000	23	12
0.84	2540.78	0.000	33	15
0.85	2576.24	0.000	21	12
0.86	2611.55	0.000	25	10
0.87	2646.71	0.000	21	6
0.88	2681.73	0.000	27	12
0.89	2716.62	0.000	19	12
0.9	2751.36	0.000	25	7
0.91	2785.98	0.000	23	7
0.92	2820.46	0.000	24	10
0.93	2854.81	0.000	23	13
0.94	2889.04	0.000	23	21
0.95	2923.15	0.000	27	25
0.96	2957.13	0.000	25	11
0.97	2991.00	0.000	23	21
0.98	3024.76	0.000	21	14
0.99	3058.41	0.000	20	10
1	3091.95	0.022	20	7
1.01	3125.38	0.000	20	10
1.02	3158.71	0.000	15	8
1.03	3191.94	0.000	20	8
1.04	3225.08	0.000	23	6
1.05	3258.12	0.000	17	30
1.06	3291.08	0.132	14	16
1.07	3323.94	0.281	13	10
1.08	3356.72	0.000	20	14
1.09	3389.42	0.000	15	11
1.1	3422.04	0.000	17	13
1.11	3454.58	0.000	18	9
1.12	3487.05	0.000	21	9
1.13	3519.45	0.000	23	9

1.14	3551.78	0.000	21	9
1.15	3584.05	0.000	21	8
1.16	3616.25	0.000	21	16
1.17	3648.40	0.000	19	9
1.18	3680.49	0.000	18	25
1.19	3712.52	0.000	21	12
1.2	3744.51	0.000	25	10
1.21	3776.45	0.000	18	8
1.22	3808.34	0.000	20	8
1.23	3840.20	0.000	20	9
1.24	3872.01	0.000	19	9
1.25	3903.79	0.000	15	8
1.26	3935.53	0.000	20	10
1.27	3967.25	0.000	20	7
1.28	3998.93	0.000	24	8
1.29	4030.60	0.000	27	9
1.3	4062.24	0.000	33	3
1.31	4093.86	0.000	23	2
1.32	4125.47	0.000	25	4
1.33	4157.06	0.000	24	8
1.34	4188.64	0.000	25	12
1.35	4220.22	0.000	23	5
1.36	4251.79	0.000	21	10
1.37	4283.36	0.000	29	6
1.38	4314.93	0.000	21	5
1.39	4346.51	0.000	23	7
1.4	4378.09	0.000	27	7
1.41	4409.69	0.000	21	12
1.42	4441.29	0.000	29	6
1.43	4472.91	0.000	29	6
1.44	4504.55	0.000	23	18
1.45	4536.22	0.000	31	9
1.46	4567.90	0.000	31	7
1.47	4599.62	0.000	29	15
1.48	4631.36	0.000	23	7
1.49	4663.14	0.000	20	9
1.5	4694.95	0.000	27	7
1.51	4726.80	0.000	21	8
1.52	4758.69	0.000	27	9
1.53	4790.63	0.000	31	5
1.54	4822.62	0.000	29	15

1.55	4854.65	0.000	23	8
1.56	4886.74	0.000	25	7
1.57	4918.88	0.000	27	13
1.58	4951.09	0.000	21	20
1.59	4983.35	0.000	25	8
1.6	5015.68	0.000	21	8
1.61	5048.08	0.000	24	10
1.62	5080.54	0.000	19	10
1.63	5113.08	0.000	27	8
1.64	5145.70	0.000	21	15
1.65	5178.40	0.000	21	7
1.66	5211.17	0.000	25	15
1.67	5244.04	0.000	27	6
1.68	5276.99	0.000	20	8
1.69	5310.03	0.000	24	9
1.7	5343.16	0.000	25	5
1.71	5376.39	0.000	27	10
1.72	5409.72	0.000	20	8
1.73	5443.15	0.176	25	5
1.74	5476.68	0.059	20	8
1.75	5510.33	0.022	27	9
1.76	5544.08	0.000	27	6
1.77	5577.95	0.103	23	7
1.78	5611.93	0.169	21	13
1.79	5646.03	0.000	23	13
1.8	5680.26	0.000	27	14
1.81	5714.61	0.000	21	12
1.82	5749.09	0.000	20	26
1.83	5783.69	0.015	21	18
1.84	5818.44	0.000	25	14
1.85	5853.31	0.103	29	7
1.86	5888.33	0.083	27	16
1.87	5923.49	0.000	25	17
1.88	5958.78	0.081	20	6
1.89	5994.19	0.044	25	6
1.9	6029.72	0.000	27	13
1.91	6065.35	0.000	23	8
1.92	6101.08	0.000	27	8
1.93	6136.89	0.000	29	7
1.94	6172.77	0.202	19	15
1.95	6208.72	0.073	20	27

1.96	6244.73	0.000	20	20
1.97	6280.79	0.029	19	9
1.98	6316.88	0.051	27	18
1.99	6353.00	0.044	23	24
2	6389.13	0.015	29	6
2.01	6425.28	0.000	21	5
2.02	6461.42	0.000	25	10
2.03	6497.56	0.015	27	4
2.04	6533.67	0.000	27	11
2.05	6569.75	0.000	20	13
2.06	6605.80	0.029	23	22
2.07	0.00	0.000	27	10
2.08	6677.73	0.000	21	11
2.09	6713.60	0.000	23	10
2.1	6749.39	0.000	21	26
2.11	6785.10	0.000	21	16
2.12	6820.71	0.000	21	15
2.13	6856.21	0.000	23	20
2.14	6891.59	0.000	29	18
2.15	6926.86	0.000	27	12
2.16	6961.98	0.000	23	12
2.17	6996.96	0.000	27	11
2.18	7031.79	0.000	31	35
2.19	7066.46	0.000	23	7
2.2	7100.95	0.000	27	13
2.21	7135.26	0.000	27	14
2.22	7169.37	0.000	24	15
2.23	7203.29	0.000	21	13
2.24	7236.99	0.000	25	14
2.25	7270.48	0.000	21	15
2.26	7303.73	0.000	25	13
2.27	7336.74	1.180	21	11
2.28	7369.51	21.400	11	6
2.29	7402.01	0.781	23	6
2.3	7434.25	0.000	23	22
2.31	7466.21	0.000	31	14
2.32	7497.88	0.000	33	8
2.33	7529.25	0.000	31	2
2.34	7560.32	0.000	25	6
2.35	7591.07	0.000	29	8
2.36	7621.51	0.000	23	8

2.37	7651.64	0.000	29	8
2.38	7681.47	0.000	29	17
2.39	7710.99	0.000	29	9
2.4	7740.22	0.000	29	8
2.41	7769.15	0.000	20	9
2.42	7797.78	0.000	33	10
2.43	7826.13	0.000	31	6
2.44	7854.19	0.000	31	11
2.45	7881.98	0.000	29	6
2.46	7909.48	0.000	29	4
2.47	7936.71	0.000	27	9
2.48	7963.67	0.000	27	11
2.49	7990.36	0.000	29	22
2.5	8016.79	0.000	25	16
2.51	8042.96	0.000	20	13
2.52	8068.87	0.000	36	13
2.53	8094.53	0.000	33	6
2.54	8119.93	0.000	29	11
2.55	8145.09	0.000	29	9
2.56	8170.01	0.000	27	5
2.57	8194.69	0.000	33	6
2.58	8219.13	0.000	NaN	2
2.59	8243.34	0.000	27	2
2.6	8267.32	0.000	NaN	5
2.61	8291.08	0.000	NaN	7
2.62	8314.61	0.000	NaN	2
2.63	8337.93	0.000	27	4
2.64	8361.03	0.000	36	9
2.65	8383.93	0.000	29	1
2.66	8406.64	0.000	8	5
2.67	8429.17	0.000	8	4
2.68	8451.53	0.000	25	10
2.69	8473.74	0.000	31	4
2.7	8495.81	0.000	10	10
2.71	8517.75	0.000	22	17
2.72	8539.57	0.000	10	6
2.73	8561.29	0.000	22	5
2.74	8582.92	0.000	33	4
2.75	8604.46	0.000	31	17
2.76	8625.94	0.000	21	6
2.77	8647.36	0.000	36	9

2.78	8668.74	0.000	36	5
2.79	8690.09	0.000	33	2
2.8	8711.42	0.000	36	3
2.81	8732.74	0.000	40	6
2.82	8754.07	0.000	NaN	3
2.83	8775.42	0.000	31	5
2.84	8796.80	0.000	36	5
2.85	8818.22	0.000	42	5
2.86	8839.70	0.000	42	3
2.87	8861.24	0.000	38	3
2.88	8882.86	0.000	45	3
2.89	8904.58	0.000	33	8
2.9	8926.40	0.000	33	7
2.91	8948.33	0.000	38	1
2.92	8970.40	0.000	42	4
2.93	8992.60	0.000	33	8
2.94	9014.96	0.000	44	16
2.95	9037.48	0.000	33	3
2.96	9060.18	0.000	44	3
2.97	9083.07	0.000	17	1
2.98	9106.17	0.000	14	3
2.99	9129.47	0.000	50	4
3	9153.01	0.000	44	8
3.01	9176.78	0.000	17	2
3.02	9200.81	0.000	22	3
3.03	9225.10	0.000	40	6
3.04	9249.66	0.000	50	2
3.05	9274.52	0.000	40	2
3.06	9299.67	0.000	45	2
3.07	9325.14	0.000	36	7
3.08	9350.93	0.000	36	3
3.09	9377.06	0.000	36	3
3.1	9403.53	0.000	33	1
3.11	9430.38	0.000	36	1
3.12	9457.59	0.000	44	3
3.13	9485.19	0.000	50	2
3.14	9513.19	0.000	50	5
3.15	9541.60	0.000	50	4
3.16	9570.41	0.000	44	2
3.17	9599.61	0.000	37	3
3.18	9629.21	0.000	44	2

3.19	9659.18	0.000	36	2
3.2	9689.53	0.000	23	4
3.21	9720.24	0.000	36	1
3.22	9751.30	0.000	23	3
3.23	9782.72	0.000	9	6
3.24	9814.48	0.000	25	2
3.25	9846.57	0.000	29	4
3.26	9878.98	0.000	0	3
3.27	9911.72	0.000	27	2
3.28	9944.76	0.000	31	4
3.29	9978.11	0.000	31	3
3.3	10011.75	1.388	29	2
3.31	10045.68	0.449	36	1
3.32	10079.88	3.836	23	2
3.33	10114.36	8.885	14	4
3.34	10149.11	10.256	12	2
3.35	10184.10	42.332	7	2
3.36	10219.35	82.125	3	1
3.37	10254.84	31.539	8	4
3.38	10290.56	13.955	13	2
3.39	10326.50	60.313	5	1
3.4	10362.66	128.020	3	3
3.41	10399.03	17.330	9	2
3.42	10435.61	0.586	9	3
3.43	10472.37	0.474	33	2
3.44	10509.32	0.212	15	2
3.45	10546.45	0.482	29	3
3.46	10583.76	1.330	19	3
3.47	10621.22	1.741	19	1
3.48	10658.84	1.189	21	19
3.49	10696.60	1.550	16	2
3.5	10734.51	0.756	19	12
3.51	10772.55	0.815	22	4
3.52	10810.71	0.449	24	2
3.53	10848.99	0.258	31	3
3.54	10887.38	0.665	27	1
3.55	10925.86	1.027	24	2
3.56	10964.44	1.189	24	2
3.57	11003.11	1.376	24	5
3.58	11041.85	0.000	25	13

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