Paleoenvironmental Change in Central California in the Late Pleistocene and Holocene: Impacts of Climate Change and Human Land Use on Vegetation and Fire Regimes

By

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Abstract

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Dramatic environmental changes have occurred in the last 50,000 years in California due both to changes in climate and anthropogenic impacts. Analyses of pollen and microscopic charcoal from sediment cores from three wetland sites in central California record changes in vegetation and fire frequencies during the late Pleistocene and Holocene at different temporal resolutions. A long-term record with a basal date of ca. 50,000 cal yrs BP from a coastal wetland north of Santa Cruz shows important vegetation shifts between the Last Glacial Maximum, the glacial-interglacial transition, and the mid- to late-Holocene, as well as the introduction of a frequent fire regime in the Holocene. A 3,000-year record from a wetland near Año Nuevo State Park provides evidence of an increase in fire frequency in coastal California from the fifteenth century to the present, and vegetation changes associated with logging after Euro-American settlement. A core that spans the last ca. 700 years from an oxbow lake in the Sacramento Valley records the introduction of non-native plants into the area after European arrival. Together, these records help place the magnitude of anthropogenic impacts in the context of long-term environmental change due to regional or global climatic forcing.

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Chapter 1

INTRODUCTION

In this dissertation, I investigate ecological change along the central coast of California and in the Sacramento Valley in the Holocene and late Pleistocene. The three main topics I address are: 1) the local effects of global climate change along the central coast of California during the late Pleistocene and Holocene; 2) evidence for and effects of anthropogenic fire use in the Holocene; and 3) the importance of environmental changes that occurred with the arrival of Europeans in the late eighteenth and nineteenth centuries. I use proxy evidence from pollen, microscopic charcoal, magnetic susceptibility, particle size analysis, XRF, and loss-on-ignition from three sediment cores to investigate changes in vegetation and fire frequency over long-term timescales. I also incorporate archival research from historical texts and maps.

Study Area

Central California has a Mediterranean-type climate with mild temperatures and seasonal precipitation. The North Pacific high-pressure system delivers frontal storms to this region as it moves south in winter. The amount of precipitation from year to year is variable and has been influenced by the El Niño Southern Oscillation (ENSO) at least since the mid-Holocene (Moy et al., 2002). As the system moves north in summer, central California is affected by descending air from the Hadley cell, bringing dry conditions between May and September. Along the coast, summer temperatures are depressed by the frequent occurrence of marine fog and stratus, which develop from the interaction of subsiding warm air with water-saturated air that passes over cold upwelled water in the eastern Pacific Ocean. Vegetation in California is adapted to this seasonally wet/dry climate, with coastal vegetation being unique due to the influence of marine stratus and fog. For example, the coast redwood (*Sequoia sempervirens*) thrives along the coast due to the increased available moisture and shading brought by frequent fog and stratus occurrence in summer (Dawson, 1998).

Topics

The first topic that I address is the nature of past climate change in central coastal California. While palynologists generally agree that the late Pleistocene was cooler than the Holocene, change in precipitation and seasonality is still uncertain. A pollen study at Point Reyes has shown a transition from conifer forest (Douglas fir, fir, and pine) in the late Pleistocene to coastal scrub and grassland in the Holocene (Rypins et al., 1989), indicating a transition from cool, wet conditions to dryer conditions. Pollen evidence from Clear Lake shows a transition from conifer forest (pine and Cupressaceae/Taxaceae types) to oak woodland at the Pleistocene/Holocene transition, indicating a cool Pleistocene followed by a warmer Holocene (Adam and West, 1983; Adam et al., 1981b). Marine cores document a transition from montane forest (pine, spruce, cedar, hemlock) in the Pleistocene to oak and redwood in the Holocene demonstrating warming conditions and the importance of coastal fog (Heusser, 1998; Heusser et al., 2000). From Santa Barbara basin, pollen studies have revealed a shift from the dominance of pine and CT (Cupressaceae/Taxaceae) types in the Pleistocene to the dominance of chaparral types (Rhamnaceae, Rosaceae, Anacardiaceae) in the Holocene, pointing to a transition from cool, wet conditions to a warmer and dryer climate (Heusser, 1998, 1995). A proposed chronology from a previous study at Laguna de las Trancas suggests a cooler and wetter Last Glacial Maximum (LGM) with a transition to more seasonal climate during the Holocene (Adam et al., 1981a). At Tulare Lake, further inland, a cooler and wetter early Holocene is interpreted from the pollen results, with a transition to warmer and dryer conditions ca. 7000 years BP (Davis, 1999).

The second issue that I address is the importance of anthropogenic fire use. Native Americans, who may have arrived in California as early as 13,000 years ago (Erlandson et al., 2011), were complex hunter-gatherers who used fire to maintain open environments and encourage fire adapted plants to resprout or regenerate. However, there is currently no consensus as to the extent to which people may have modified the environment using fire prior to the arrival of Europeans in California. One leading theory is that anthropogenic fire use fundamentally changed landscape patterns in promotion of a heterogeneous, diverse array of species (Anderson, 2005; Blackburn and Anderson, 1993; Lewis, 1973; Lightfoot and Parrish, 2009; Stewart, 2002). For example, pollen evidence suggests that oak densities increased after the cessation of burning by Native Americans after European arrival (Byrne et al., 1991). Keeley (2002) argues that the alteration of natural fire regimes by humans resulted in more open grasslands and shrublands in central coastal California prehistorically. The opposing position, proposed by Vale (2002) and others, states that native people only burned in small areas surrounding villages, and that most fire regimes were controlled primarily by natural processes rather than by humans.

The third topic addresses the widespread and dramatic ecological changes that occurred with the arrival and subsequent settlement of Europeans in California. This includes the introduction of non-native plants, domesticated livestock, agriculture, logging operations, hydrological alterations, and fire regime changes. Many of these changes occurred simultaneously with the decimation of the Native American population. Therefore, many of these changes can be attributed to a shift in the dominant landscape management practices from that of indigenous people to Euro-Americans. Some parts of California were more affected than others, like the Sacramento Valley, which is one of the most dramatically altered regions in North America. Today, much of the valley has been converted to agriculture, but the remainder has changed significantly in floristic composition with an estimated 80-90% of California valley grassland comprising introduced species (Bartolome, 1979; Heady, 1988). Yet, little scientific evidence for native species composition prior to European contact currently exists. Invasive species from the Mediterranean region were widespread long before the first non-native explorer set foot in the valley, making it particularly difficult to sort out this history based on archival evidence alone (Blumler, 1995; Mensing and Byrne, 1998). Furthermore, the initial invasion of non-native species and their spread in the Sacramento Valley is not well understood (Minnich, 2008; Seabloom et al., 2003).

Chapter Outline

Chapter two covers the paleolimnological record from Laguna de las Trancas, a marsh in coastal California that formed ca. 50,000 years ago. Little is known about long-term climate change along the central coast because few lakes preserving proxy records are older than ~5,000 years in this region. Previous work at Laguna de las Trancas done by Dave Adam and others in 1981 showed significant changes in vegetation composition recorded in the sediments over the last ca. 30,000 years (Adam et al., 1981a). We took a new, longer core from this marsh in 2010 and I have analyzed pollen, microscopic charcoal, loss-on-ignition, particle size, magnetic susceptibility, and geochemistry. I am adding to previous research at this site by including a detailed chronology (24 AMS radiocarbon dates) to the pollen counts and assessing changes in fire frequency. The pollen record clearly shows shifts in vegetation indicating changes in climate in this region. In addition, the charcoal record demonstrates an increase in fire frequency during the Holocene, which may be attributable to human impacts given the density of archaeological sites in the surrounding area.

In the third chapter, I discuss analyses of a core from Skylark Pond, a wetland located near an important archaeological site on the central coast of California. The focus of this study is to assess the impacts of indigenous landscape management practices, especially the use of fire. I analyzed pollen, microscopic charcoal, and loss-on-ignition from this core, which records the last ca. 3,000 years. The pollen record shows the importance of redwood in this area and dramatic changes that occurred with the arrival of Euro-American settlers. Analysis of microscopic charcoal indicates an increase in fire frequency beginning in the fifteenth century, and because lightning is rare along the coast, this increase suggests that Native Americans in the area may have been managing the landscape with the use of fire.

The fourth chapter covers analyses of a sediment core from Little Packer Lake, an oxbow lake that formed ca. 700 years ago in the Sacramento Valley. Little is known about the nature of vegetation change in the Central Valley and this work represents one of the first attempts to scientifically describe prehistoric vegetation and the changes that occurred with Euro-American arrival in this region. I analyzed pollen, magnetic susceptibility, and loss-on-ignition from this core. The pollen record from Little Packer Lake shows significant changes in vegetation after the arrival of Euro-Americans in California, with an increase in invasive species and a decrease in riparian forest.

Chapter five is a summary of findings and conclusions from my work at these three sites. I also outline future work that will add to our understanding of the nature of long-term climate change in central California and the impacts that humans have had on the ecology of this region.

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Chapter 2

CLIMATE CHANGE AND HUMAN IMPACTS IN CENTRAL COASTAL CALIFORNIA DURING THE LATE PLEISTOCENE AND HOLOCENE

Abstract

Analyses of a sediment core from Laguna de las Trancas, a small landslide-dammed pond located 7 kilometers southeast of Point Año Nuevo, show significant changes in vegetation and fire frequency during the last ~50,000 years. The age model for the core is based on twenty-four AMS radiocarbon dates and shows that the record is interrupted by two hiatuses. Analyses include pollen, microscopic charcoal, grain size, and XRF. Major changes in pollen frequencies and charcoal abundance indicate important shifts in climate and vegetation during the Last Glacial Maximum (LGM), the glacial-interglacial transition (GIT) in the late Pleistocene, and the Holocene. The LGM is characterized by cool, dry conditions based on decreases in conifer forest and increases in herbaceous vegetation. Sand content in this section of the core may also indicate increased wind speed during the LGM. An increase in precipitation during the GIT is indicated by the presence of fir pollen, most likely grand fir, whose nearest populations are located 150 km north of the core site. Redwood is absent during the LGM and increases in importance during the GIT and Holocene, probably due to the influence of marine fog. Fire was not important in the region until the Holocene, when both the diversity of pollen types and charcoal concentrations increase. The increase in fire frequency may be due to natural ignition sources and summer drought or to human use of fire. The latter seems likely given the density of archaeological sites in the region and high fire return intervals from the fire scar record.

Introduction

The nature of late Pleistocene/Holocene climate change along the central coast of California is not well known, since most lakes in the region are less than 5,000 years old and few marine records have produced high-resolution chronologies. Terrestrial records have shown important shifts in vegetation at the Pleistocene/Holocene transition (Adam et al., 1981a, 1981b; Rypins et al., 1989) and evidence from marine cores has shown changes in upwelling along the California margin and increased precipitation during deglaciation (Barron et al., 2003; Doose et al., 1997; Gardner et al., 1997; Heusser et al., 2000; Heusser, 1995; Lyle et al., 2010; Ortiz et al., 1997). However, there is considerable uncertainty about the timing of increased precipitation at the end of the Pleistocene and the mechanisms responsible. Different authors have argued conflicting conclusions regarding changes in upwelling strength and this has led to confusion about the effects of fog on coastal vegetation throughout the late Pleistocene and Holocene (Anderson et al., 2008; Doose et al., 1997; Gardner and Hemphill-Haley, 1986; Gardner et al., 1997, 1988; Herbert et al., 2001; Heusser, 1998; Heusser et al., 2000; Kennett and Venz, 1992; Kirby et al., 2013; Lyle et al., 2010). Additionally, little attention has been given to fire in this region, though evidence is mounting that human fire use may have been an important driver of biotic change during the Holocene (Anderson, 2005; Cuthrell et al., 2012; Lightfoot et al., 2013; Stephens and Fry, 2005; Stephens et al., 2007).

Long-term records from coastal California have generally shown cooler conditions during the Pleistocene and warmer conditions during the Holocene, though some uncertainty exists about changes in precipitation. Most studies agree, however, that more severe summer droughts occurred during the Holocene. A study at Coast Trail Pond in Point Reyes demonstrated a cooler, possibly wetter glacial-interglacial transition (GIT) with the dominance of a Douglas-fir, fir, and pine and a transition to dryer conditions at ca. 10,000 BP with an increase in coastal scrub and grassland (Rypins et al., 1989). Pollen evidence from Clear Lake shows a distinct change from cool conditions in the late Pleistocene with the dominance of coniferous species (pine and Cupressaceae/Taxaceae [CT] types) to warmer conditions in the Holocene with the dominance of oak, though precipitation estimates are unclear (Adam and West, 1983; Adam et al., 1981b). Similarly, marine cores off the coast of northern and central California have shown that coniferous forest (pine, spruce, cedar, hemlock) dominated in the Pleistocene, indicating cooler and wetter conditions, while oak and redwood dominated in the Holocene, indicating higher temperatures and the development of coastal fog (Heusser, 1998; Heusser et al., 2000). Further south, a similar story has been developed from marine cores from the Santa Barbara Basin, where pine and CT (Cupressaceae and Taxaceae) types dominated in the Pleistocene and were subsequently replaced by chaparral types (Rhamnaceae, Rosaceae, and Anacardiaceae families) during the Holocene (Heusser, 1998, 1995) indicating a transition from cool, moist to warm, dry conditions. Further inland, pollen evidence from Tulare Lake suggests a cool, wet Pleistocene and early Holocene based on an interpreted pine-oak woodland with a transition to warmer, dryer conditions ca. 7000 BP with increases in Amaranthaceae and charcoal (Davis, 1999).

While several studies along the coast of California record a wet phase during deglaciation in the terminal Pleistocene, there is considerable debate on its timing and the mechanism responsible (Gardner et al., 1997; Heusser, 1998; Kirby et al., 2013; Lyle et al., 2010; Ortiz et al., 1997; Rypins et al., 1989). In Southern California, increased precipitation is recorded for a period between 21,000 and 10,000 years BP from Santa Barbara Basin with a peak at ~14,000 years ago (Heusser, 1995) and 19,000 -14,700 years BP from Lake Elsinore (Kirby et al., 2013). Cores from the central California coast exhibit evidence for a wet period at the Pleistocene/Holocene transition (Lyle et al., 2010; Rypins et al., 1989) and an important shift in atmospheric and oceanic circulation at ~13,500 years ago (Gardner et al., 1997, 1988; McGann, 1990). A marine core from Northern California is interpreted to show a wet period peaking between 12,000 and 11,000 cal yrs BP (Barron et al., 2003).

Previous pollen analysis of a 2.1 m sediment core from Laguna de las Trancas produced a record of vegetation change covering the last ~30,000 years. (Adam et al., 1981a). However, interpretation was hindered by poor chronological control with only one basal radiocarbon date. The authors reported a basal pine zone estimated to be between 30,000-24,000 BP years old, a pine-fir zone thought to be the last full glacial at 24,000-12,000 BP in age, and a redwood zone representing the terminal Pleistocene to mid-Holocene (12,000-5,000 BP). They interpreted the basal pine zone tentatively as cool and dry, the pine-fir zone as a cooler and wetter glacial maximum with increased onshore wind, and the redwood zone as warmer with more severe summer droughts.

Here we report on analyses of a 7 meter sediment core from Laguna de las Trancas taken in 2010. The core has a basal date of ~50,000 cal. yr BP, however there are hiatuses between ca. 43,000 BP - ca. 27,000 BP and ca. 12,900 BP - ca. 6,500 BP. We revise the previous chronology with twenty-four AMS radiocarbon dates that establish the timing for important changes in vegetation composition. As expected, the results of the pollen analysis of this core are similar to those reported in the previous study with only a few exceptions. Additional evidence of environmental change was uncovered by analyses of microscopic charcoal, sediment particle size, and geochemistry. Based on our revised chronology, significant changes in vegetation occurred between the Last Glacial Maximum (LGM), the glacial-interglacial transition (GIT), and the mid- to late-Holocene. The most important change in fire frequency occurs when microscopic charcoal increases substantially ca. 6,500 cal. yrs BP and then continues to be present at high levels throughout the mid- to late-Holocene. These fires were probably the result of human activities in coastal California because it is an area with very few lighting strikes. Major shifts in vegetation appear to be influenced by climate change until the mid-Holocene, when human influence may have been more dominant.

Study Area

Laguna de las Trancas (37˚05'17"N, 122˚15'31"W) is a palustrine wetland located ca. 1 km from the coast and ca. 7 km southeast of Point Año Nuevo. The marsh, which has a maximum diameter of 136 m, was formed by a landslide ca. 50,000 years ago and sits on a marine terrace at an elevation of 180 m above sea level. The landslide was probably caused by tectonic activity within the San Gregario fault zone. Modern climate in this region is governed by the seasonal migration of the North Pacific High and the mid-latitude storm track. Temperatures are mild throughout the year and average from 17°C in September to 9°C in January (Adam et al., 1981a). Average precipitation ranges between 76 and 89 cm per year, falling mostly between November and April (National Atlas of the United States, 2003). Fog and low stratus clouds are frequent in the late spring and summer.

Figure 1 shows a generalized vegetation map of the Laguna de las Trancas area and Table 1 is a list of locally important plant species. Coastal shrub/scrub is dominated by coyote brush (*Baccharis pilularis*) and coastal sage (*Artemisia californica*). Further inland Monterey pine (*Pinus radiata*) and knobcone pine (*Pinus attenuata*), as well as their hybrids, dominate a mixed forest. In the foothills of the Santa Cruz Mountains, coast redwood (*Sequoia sempervirens*) is dominant and grows in

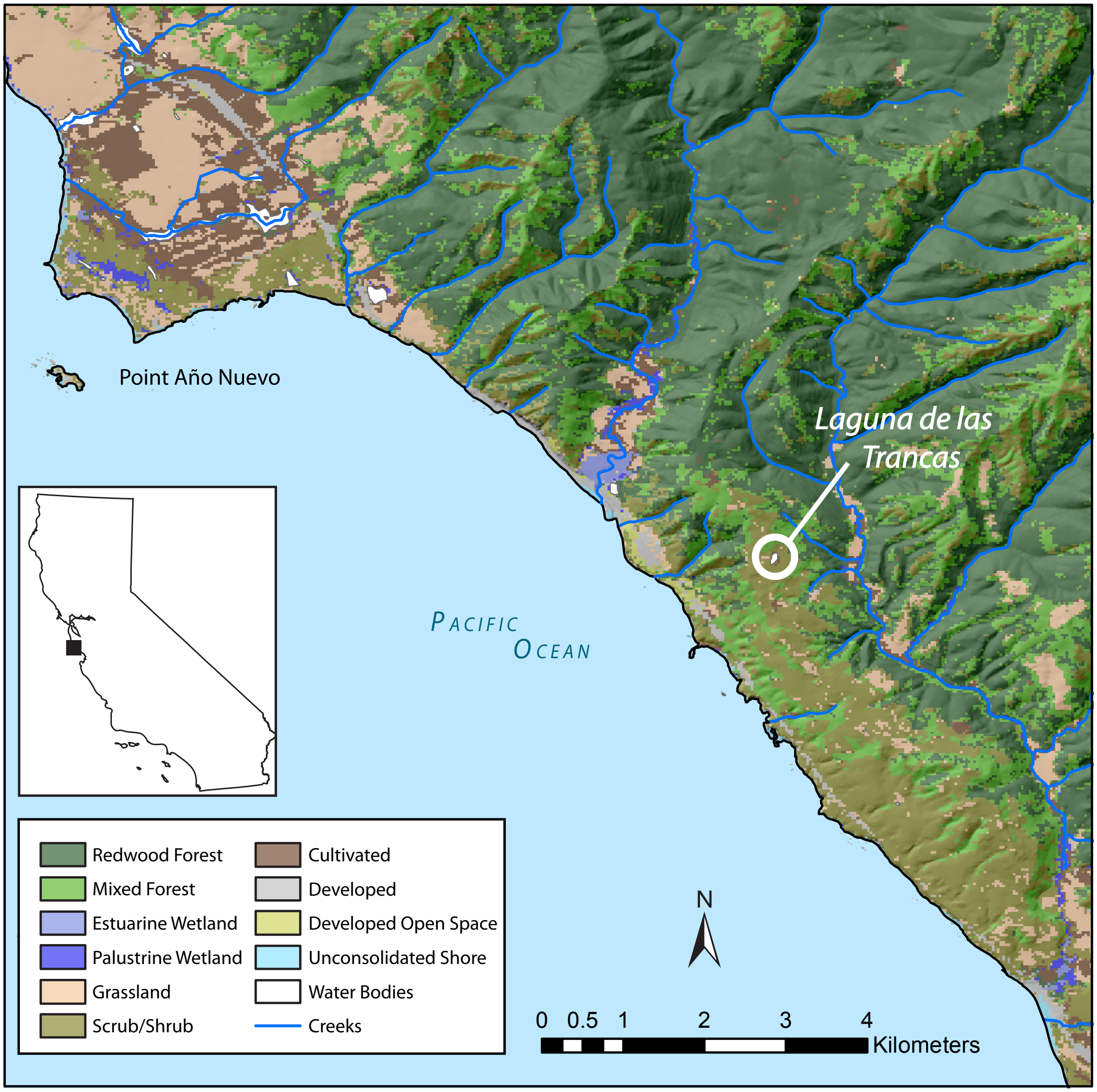

Figure 1. Area map showing location of Laguna de las Trancas and generalized vegetation distribution. Laguna de las Trancas is located between Waddell Creek and Scotts Creek approximately 1 km from the Pacific coast and 6.9 km southeast of Point Año Nuevo. Redwood forest includes coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), tanoak (*Notholithocarpus densiflorus*), and California bay laurel (*Umbellularia californica*). Mixed forest includes Monterey pine (*Pinus radiata*), knobcone pine (*Pinus attenuata*), Douglas-fir (*Pseudotsuga menziesii*), coast live oak (*Quercus agrifolia*), and Pacific madrone (*Arbutus menziesii*). Along streams, redwood and mixed forest also include red alder (*Alnus rubra*), willow (*Salix* spp.), California buckeye (*Aesculus californica*), California nutmeg (*Torreya californica*), big-leafed maple (*Acer macrophyllum*), and box elder (*Acer negundo*). Grasslands include non-native types and various native and non-native herbs. Scrub/Shrub areas are dominated by coyote brush (*Baccharis pilularis*) and coastal sage (*Artemisia californica*), with occasional chamise (*Adenostoma fasciculatum*) and manzanita (*Arctostaphylos* spp.).

Source: USGS National Landcover Dataset & National Hydrography Dataset

Table 1. List of important species near Laguna de las Trancas.

Open prairie / grassland	**Forest**	**Aquatics**
bedstraw (*Galium trifidum*)	**Mixed Forest**	Sedges (Cyperaceae)
California buttercup (*Ranunculus californicus*)	knobcone pine (*Pinus attenuata*)	cattail (*Typha latifolia*)
California figwort (*Schrophularia californica*)	Monterey pine (*Pinus radiata*)	whitewater crowfoot (*Ranunculus aquatilis*)
California hedgenettle (*Stachys bullata*)	Douglas-fir (*Pseudotsuga menziesii*)	yellow cress (*Rorippa* spp.)
California poppy (*Eschscholzia californica*)	coast live oak (*Quercus agrifolia*)	water parsley (*Oenanthe sarmentosa*)
cinquefoil (*Potentilla* spp.)	Pacific madrone (*Arbutus menziesii*)	rushes (*Juncus* spp.)
clarkia (*Clarkia* spp.)		water fern (*Azolla filiculoides*)
goldenrod (*Solidago* spp.)	**Redwood Forest**	duckweed (*Lemna minor*)
gumweed (*Grindelia* spp.)	coast redwood (*Sequoia sempervirens*)	
Lupine (*Lupinus* spp.)	Douglas-fir (*Pseudotsuga menziesii*)	
monkeyflower (*Mimulus* spp.)	tanoak (*Notholithocarpus densiflorus*)	
mugwort (*Artemisia douglasiana*)	California bay laurel (*Umbellularia californica*)	
native plantains (*Plantago erecta*, *Plantago subnuta*)		
oatgrass (*Danthonia californica*)	**Riparian Forest**	
Pacific reed grass (*Calamagrostis nutkaensis*)	red alder (*Alnus rubra*)	
rattlesnake grass (*Briza maxima*)*	willow (*Salix* spp.)	
sheep's sorrel (*Rumex acetosella*)*	California buckeye (*Aesculus californica*)	
smartweed (*Polygonum* spp.)	California nutmeg (*Torreya californica*)	
stinging nettle (*Urtica dioica*)	big-leafed maple (*Acer macrophyllum*)	
sun cup (*Taraxia ovata*)	box elder (*Acer negundo*)	
willowherb (*Epilobium ciliatum*)		
wintercress (*Barbarea orthoceras*)		
	Forest understory	
	California lilac (*Ceanothus thyrsiflorus*)	
Shrubs / scrub	poison oak (*Toxicodendron diversilobum*)	
coyote brush (*Baccharis pilularis*)	toyon (*Heteromeles arbutifolia*)	
manzanita (*Arctostaphylos* spp.)	hazelnut (*Corylus cornuta*)	
canyon live oak (*Quercus chrysolepis*)	bittercress (*Cardamine oligosperma*)	
interior live oak (*Quercus wislizenii*)	vetch (*Vicia spp.*)	
chamise (*Adenostoma fasciculatum*)	California huckleberry (*Vaccinium ovatum*)	
coastal sage (*Artemisia californica*)	soap plant (*Chlorogalum pomeridianum*)	
	pine grass (*Calamagrostis rubescens*)	
	blackberry (*Rubus ursinus*)	
	black elderberry (*Sambucus nigra*)	
	oso berry (*Oemleria cerasiformis*)	
	wood fern (*Dryopteris arguta)*	
	sword fern (*Polystichum* spp.)	
	polypody (*Polypodium* spp.)	

*non-native

association with Douglas-fir (*Pseudotsuga menziesii*). Willows (*Salix* spp.), red alder (*Alnus rubra*), and California buckeye (*Aesculus californica*) are locally common near streams.

The immediate area surrounding the marsh is open grassland currently used as pasture for cattle. Several non-native species occur here, such as rattlesnake grass (*Briza maxima*) and sheep's sorrel (*Rumex acetosella*). Native grasses and forbs are also present (see Table 1). Aquatics, including tule (*Scirpus acutus*), cattail (*Typha latifolia*), and rushes (*Juncus* spp.) grow in and around the marsh with water fern (*Azolla filiculoides*) and duckweed (*Lemna minor*) floating on the open water.

Methods

We extracted a 7 m sediment core from Laguna de las Trancas in 2010 using a narrow gauge (2.5 cm diameter) modified Livingstone corer. Individual core sections were extruded on site, wrapped in plastic wrap, stored in 2.5 cm PVC tubing, transported to UC Berkeley, and stored in a 5°C cold room. The sediment water interface was captured with a 5 cm diameter transparent PVC tube equipped with a piston.

Core sections were scanned with a Bartington Magnetic Sensor MS2C at 1 cm intervals to assess magnetic susceptibility. Fifty-six samples were analyzed for pollen, microscopic charcoal, and loss-on-ignition (LOI). Samples were taken every 5 cm from the top of the surface core at 95 cm to 300 cm (top 2 m of the core), every 10 cm between 300 cm and 350 cm, and every 50 cm from 350 cm to 700 cm. The bottom 90 cm contained little organic material and was not analyzed for pollen and charcoal. Eighty-eight samples were analyzed for particle size at 10 cm intervals, except between 183 cm and 363 cm where samples were analyzed at 5 cm intervals. Samples were taken at 10 cm intervals for geochemical analysis using X-ray fluorescence (XRF).

Pollen was extracted using standard procedures (Faegri and Iversen, 1989). Known quantities of *Lycopodium* spores were added to each sample prior to digestion to calculate pollen concentrations. Sample residues were stored in silicone oil and mounted on slides for counting. Pollen was counted at 400x magnification using a Leitz Dialux microscope. Samples were counted to a minimum of 400 pollen grains and spores per sample, with the exception of 9 samples. Samples at 95 cm, 100 cm, 105 cm, 110 cm, and 176 cm were counted to a minimum of 350 grains and the 180 cm sample was counted to 239 grains due to low pollen concentrations. Three samples (200 cm, 205 cm, and 210 cm) were not counted because pollen concentrations were very low due to extraordinarily high charcoal concentrations. Pollen was identified using the University of California Museum of Paleontology pollen reference collection and published keys (Bassett, 1978; Kapp, 2000; McAndrews et al., 1973; Moore, 1991). Pollen frequencies were plotted on diagrams as a percentage of total non-aquatic pollen for non-aquatics or a percentage of total pollen for aquatics.

All samples were analyzed for microscopic charcoal using the ratio of charcoal concentration to pollen concentration in order to control for taphonomic effects. Microscopic charcoal concentrations were measured by digitally imaging slides at 8,000 dpi (1 pixel = 3.175 micrometers) in a Nikon Coolscan V Ed scanner fitted with a Nikon FH-GI slide holder. Charcoal particles were identified in Adobe Photoshop and verified under the microscope. Particles were selected based on color pixel similarity to known charcoal particles. Particles greater than 20 μm^2 were then counted and measured in ImageJ and included in the charcoal concentration calculation. The microscopic charcoal concentration was calculated by multiplying the total charcoal counts of each slide by the proportion of the slide used in calculating pollen concentration. Microscopic charcoal was then calculated as a ratio of charcoal concentration to pollen concentration by volume for each sample.

Results

Chronology

Twenty-four radiocarbon dates (Table 2) show that the core spans the last approximately 50,000 years. All dates were calibrated using Calib 6.0 (Stuiver et al., 2010). The radiocarbon dates indicate that there are two hiatuses in the core: ca. 43,000 cal yr BP to 27,000 cal yr BP, and ca. 12,900 cal yr BP to ca. 6,500 cal yr BP. For the purposes of discussion, we label the latest Pleistocene phase the glacial-interglacial transition (GIT), which corresponds roughly to the Oldest Dryas (19,000 - 14,700 cal yr BP) and Bølling-Allerød (14,700 - 12,900 cal yr BP) phases from Northern Europe. The basal date of the core is not known since the lower section of the core is nearing the limits of radiocarbon. The oldest date obtained from the core is ca. 46,300 cal yr BP, therefore the basal date is approximated at ca. 50,000 cal yr BP. An age depth model showing radiocarbon dates and sedimentation rate of the upper half of the core is shown in Figure 2. Water depth was 90 cm at the time of coring and all depths are recorded as depth below the water surface, with the top of the core beginning at 90 cm.

Pollen and charcoal results are shown in Figures 3, 4, and 5 with the charcoal to pollen ratio plotted on a log scale. Redwood pollen grains were separated from other CT (Cupressaceae and Taxaceae) types, and were identified based on their thicker exine. Results of the magnetic susceptibility, grain size, and LOI analyses are plotted along with pollen concentration and charcoal in Figure 6. Results from the XRF analysis are shown in Figure 7. For purposes of discussion, the diagrams are divided into four zones and one separate charcoal zone.

Zone 4 (ca. 50,000 - 43,000 cal. yr BP; 700 cm - 350 cm): Zone 4 is characterized by a high sedimentation rate with very little change between approximately 600 cm and 350 cm. Pine (*Pinus*) and CT (Taxaceae and Cupressaceae) pollen are the dominant types in this zone, each comprising up to 40-50% of the pollen rain. Herbs and shrubs are not abundant, with most types comprising less than 5%; however, pollen was poorly preserved in this section of the core. Quillwort (*Isoetes*) is the dominant

Table 2. AMS radiocarbon ages obtained from the Laguna de las Trancas core.
All radiocarbon ages were calibrated using Calib 6.0 (Stuiver et al., 2010).

Depth (cm)	CAMS #	radiocarbon age	error	Calibrated median age (yrs BP)	Calib 2 sigma range lower	Calib 2 sigma range upper	Material dated
125	150143	530	30	540	510	559	plant material or charcoal
143	160130	1750	45	1660	1552	1741	plant material or charcoal
160	150144	1770	50	1689	1564	1819	plant material or charcoal
175	150145	3165	35	3393	3335	3460	plant material or charcoal
191	160123	4470	30	5171	5155	5287	charcoal
200	150146	990	40	902	795	964	plant material or charcoal
209	160124	5645	40	6427	6314	6498	charcoal
234	163700	11570	90	13399	13226	13574	pollen
237	106125	11800	250	13663	13110	14244	charcoal, azolla spores, plant material
250	150147	8005	45	8874	8716	9012	plant material or charcoal
262	163701	12190	90	14081	13768	14452	pollen
267	160126	12870	380	15439	14100	16719	charcoal, azolla spores, plant material
272	160127	12890	620	15421	13618	17048	charcoal, plant material
275	150830	17190	310	20482	19793	21325	plant material or charcoal
292	160091	20700	1640	24806	20879	28624	charcoal, plant material
310	150831	13980	200	17086	16724	17609	plant material
322	153588	22300	700	26814	25014	28451	plant material
337	160092	37120	860	41919	40452	43220	charcoal
350	150190	38150	400	42611	42002	43228	plant material or charcoal
400	150191	40300	520	44203	43268	45025	plant material or charcoal
450	150192	37450	370	42167	41604	42747	plant material or charcoal
500	150193	36960	350	41843	41287	42380	plant material or charcoal
600	150194	33660	770	38420	36655	40371	plant material or charcoal
700	150196	42810	1930	46309	43507	49777	plant material or charcoal

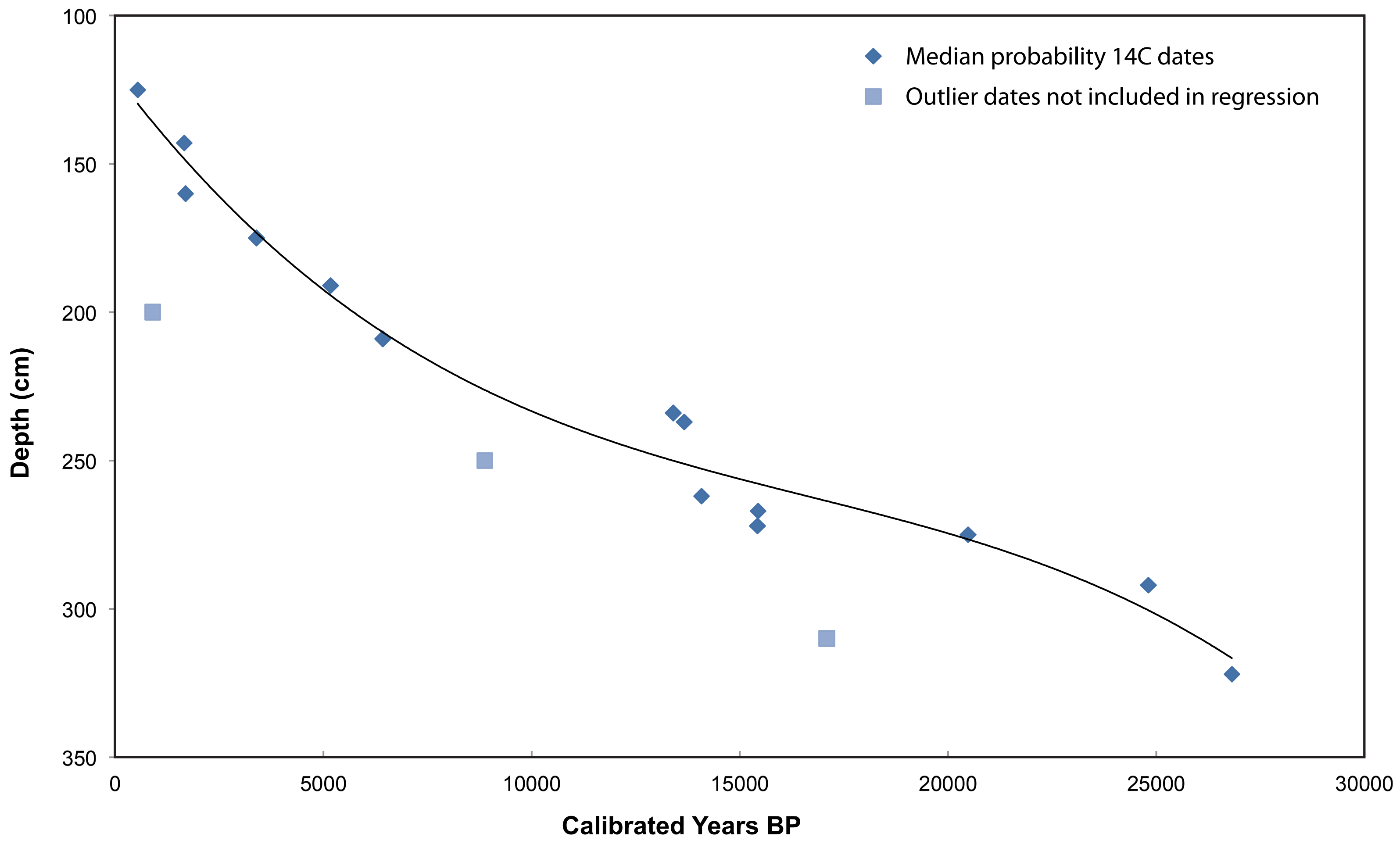

Figure 2. The age depth model shows median ages from the upper 350 cm of the core based on 17 AMS radiocarbon dates. The bottom seven samples exhibited a wide scatter of age estimates due to low radiocarbon content, and are therefore not shown in the age model. A 3rd order polynomial regression was used to construct the age depth curve. Three outliers were isolated from the other dates and not included in the regression analysis.

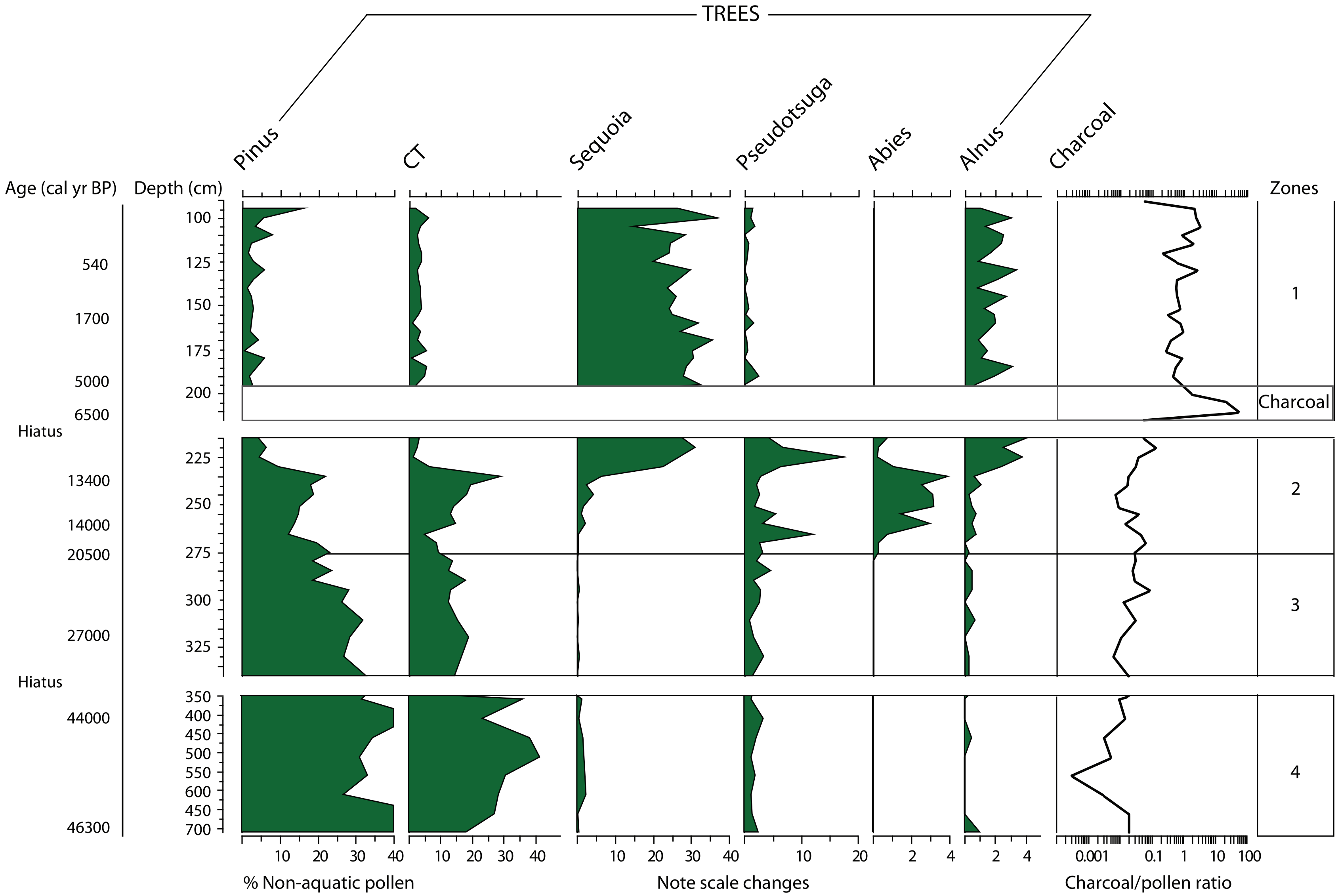

Figure 3. Percent pollen diagram showing selected trees and microscopic charcoal/pollen ratio.

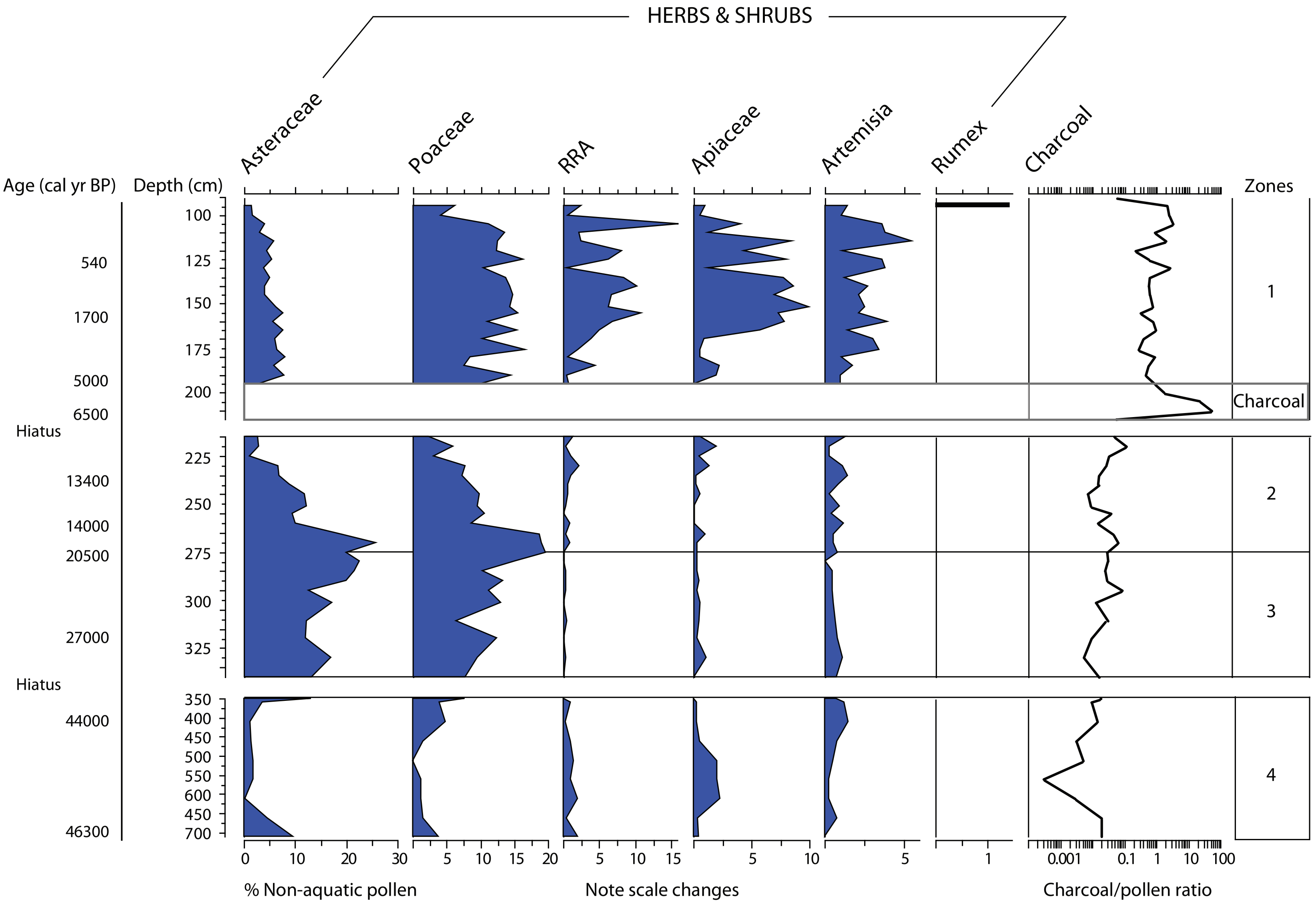

Figure 4. Percent pollen diagram showing selected herbs, shrubs, and microscopic charcoal/pollen ratio.

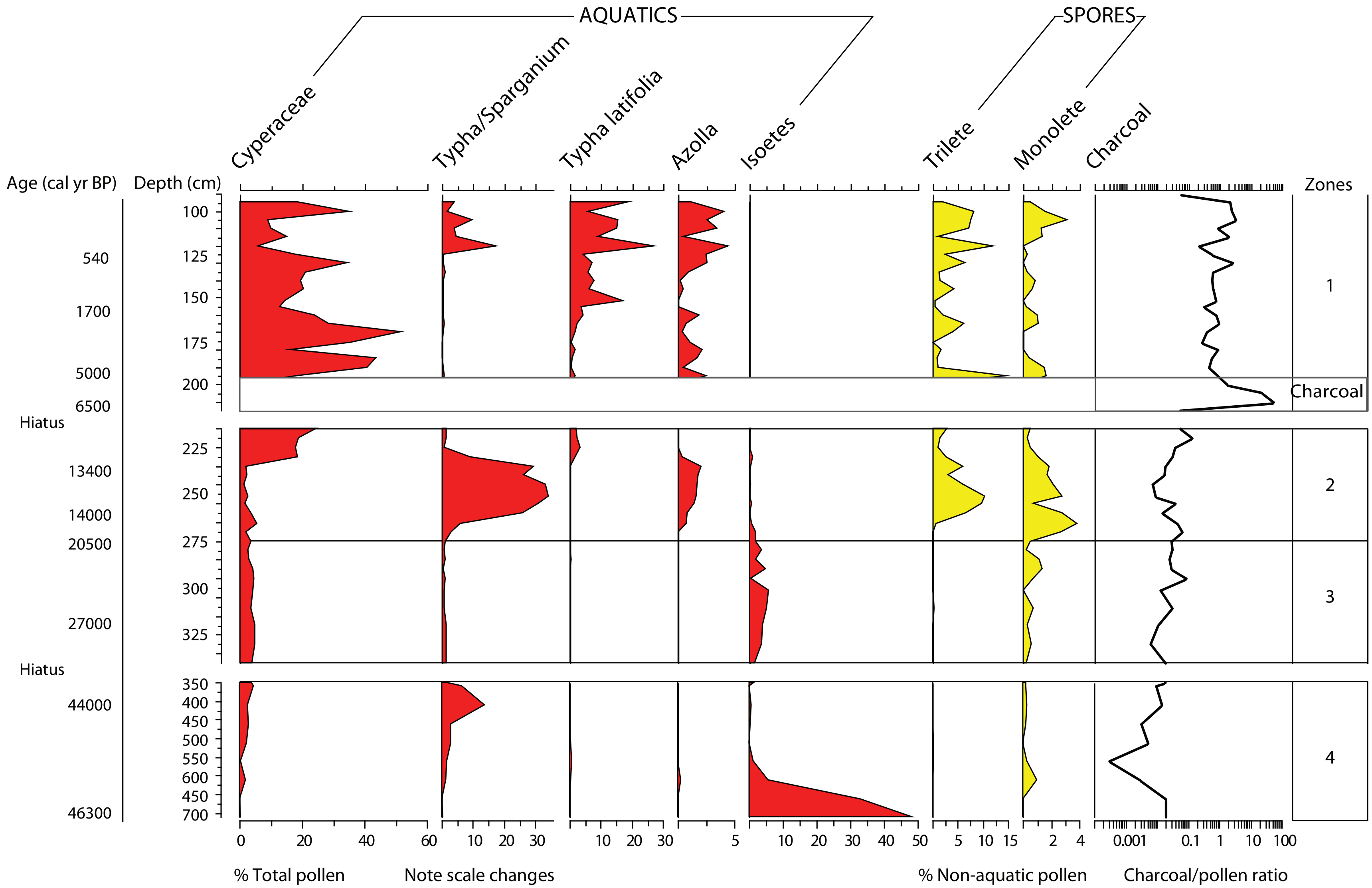

Figure 5. Percent pollen diagram showing selected aquatics, spores, and microscopic charcoal/pollen ratio.

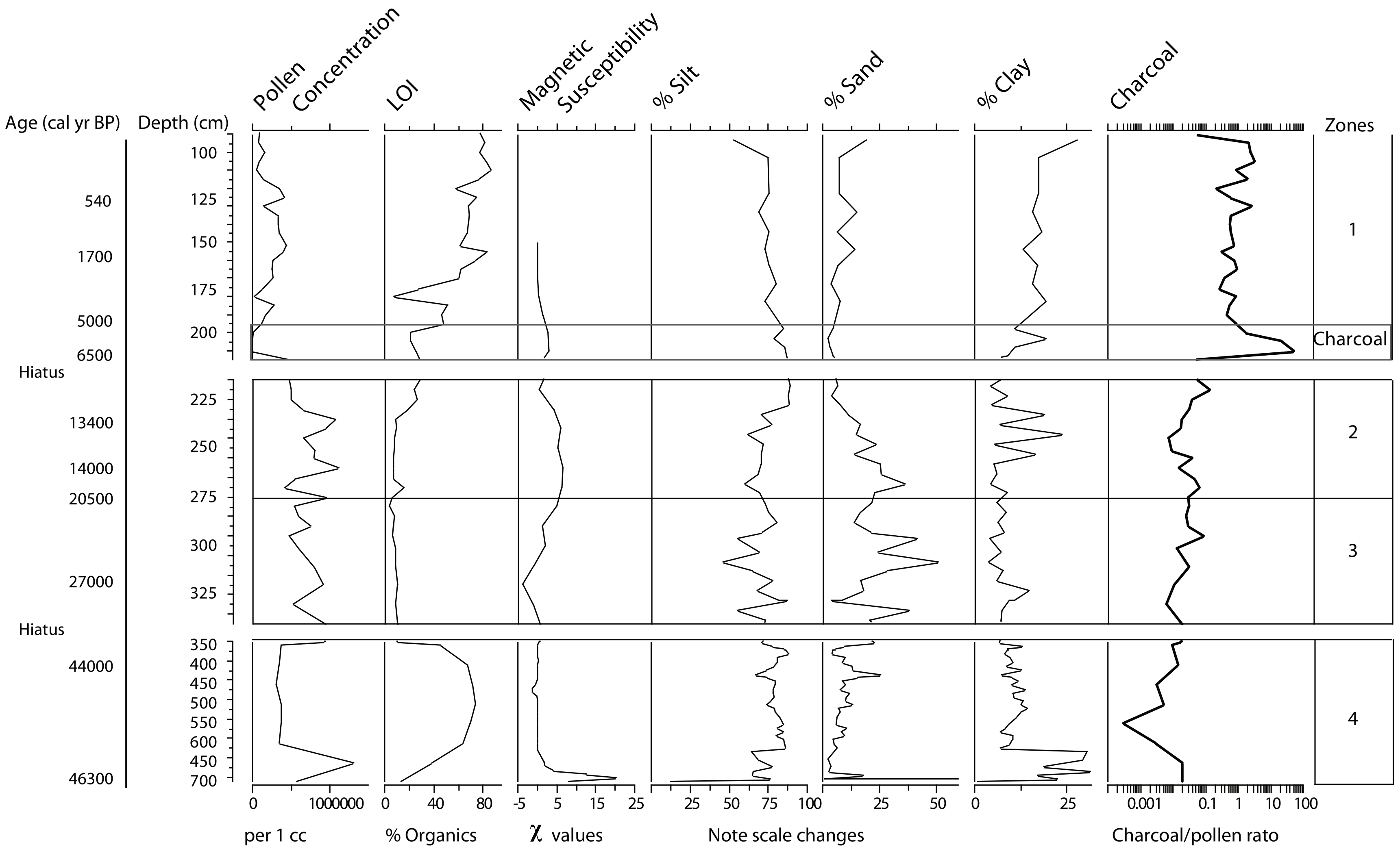

Figure 6. Stratigraphic diagram showing pollen concentration, LOI, magnetic susceptibility, particle size, and microscopic charcoal/pollen ratio.

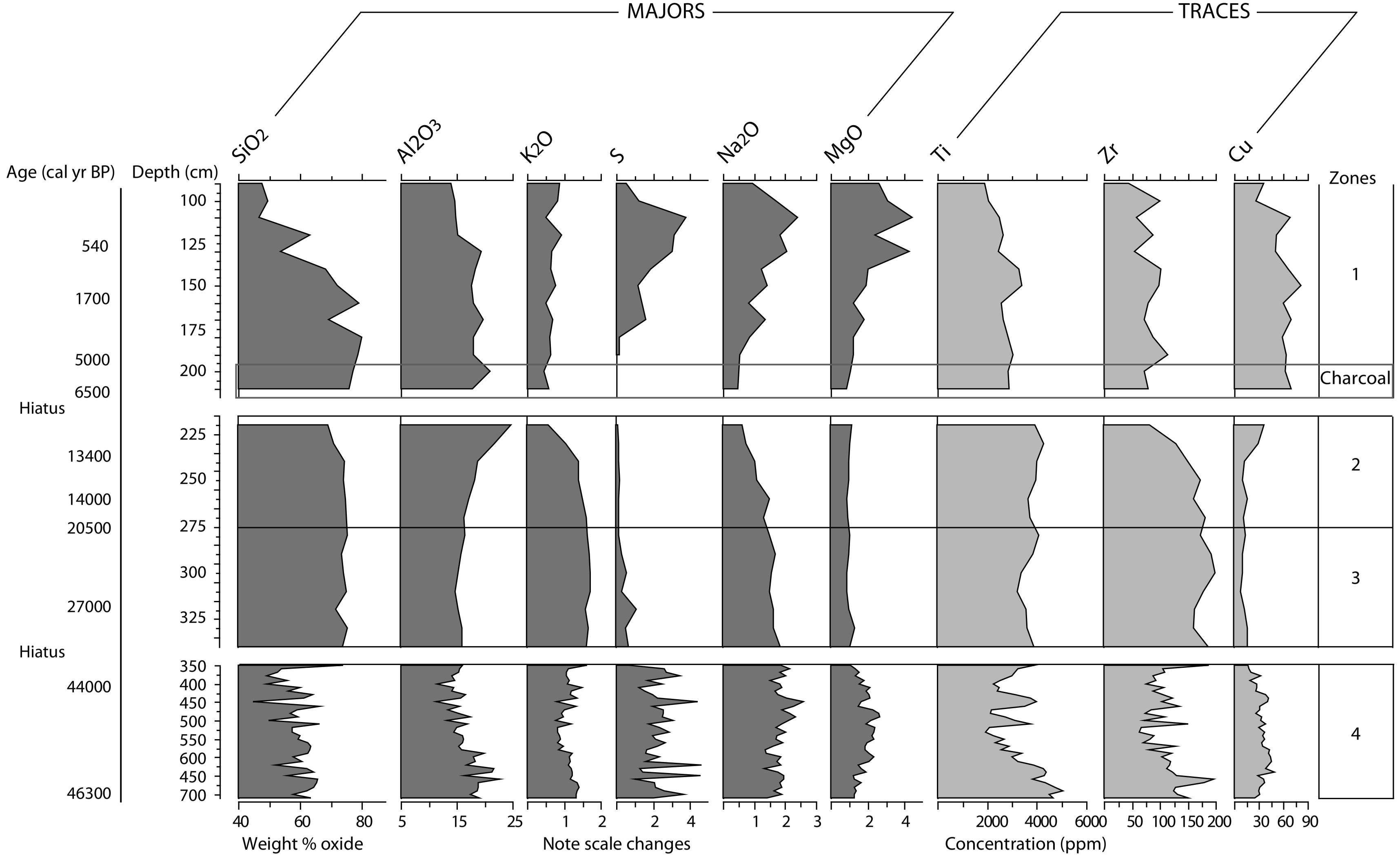

Figure 7. Stratigraphic diagram showing selected major and trace elements.

aquatic at the bottom of the core, making up 50% of the total sum of pollen and spores, and then decreasing to very low levels for the remainder of the zone. Bur-reed (*Typha*/*Sparganium*) increases near the top of the zone and peaks at ~15%. Microscopic charcoal content is very low, with the charcoal to pollen ratio of all samples below 0.1. This zone is organic rich, but with low pollen concentrations, except for levels below 600 cm. A magnetic peak as well as a peak in sand occurs in the basal portion of the core, though the majority of this zone is composed of silt with slightly more clay near the bottom.

Zone 3 (ca. 27,000 - 20,500 cal. yr BP; 350 cm - 275 cm): CT (~20%) and Pine (~35%) begin to decrease in importance in this zone. Grasses (Poaceae) and members of the sunflower family (Asteraceae) start at very low levels (less than 5%) and then increase substantially, peaking at 20-25%. Quillwort appears again in this zone, comprising about 10% of the total. The ratio of microscopic charcoal to pollen remains low in this section of the core at below 0.1. Pollen concentrations increase but organic content is low. This zone is distinctive for its high sand content, which is indicated both by particle size and increases in silica (SiO_2), potassium (K_2O), zirconium (Zr), and titanium (Ti). Magnesium (MgO) and sulphur (S) decrease in this zone.

Zone 2 (ca. 20,500 - ca. 12,900 cal. yr BP; 275 cm - 210 cm): CT and pine are important (~30%) in this zone, fir (*Abies*) appears (up to 4%), and two peaks in Douglas fir (*Pseudotsuga*) (15-20%) indicate its presence close to the marsh. Redwood (*Sequoia sempervirens*) (30%) and alder (*Alnus*) (4%) increase in importance near the top of this zone, just as fir, pine, and CT decrease, indicating a significant shift in vegetation. Grasses and Asteraceae start at high levels (~20%) and decrease substantially in this zone to ~5%. Bur-reed is the dominant aquatic, peaking at ~35% of total pollen. Trilete spores begin to appear at about 10% and monolete spores decrease. Water fern (*Azolla*) is present at the same time as bur-reed. At the top of the zone, sedge (Cyperaceae) pollen increases from less than 5% to ~25%. Microscopic charcoal remains low in this zone until it increases near the top with a charcoal to pollen ratio greater than 0.1. Sand content decreases, along with decreases in sodium (Na_2O), potassium (K_2O), zirconium (Zr), titanium (Ti), and a slight decrease in silica (SiO_2). Silt and clay increase, along with increases in aluminum (Al_2O_3) and copper (Cu).

Charcoal zone (210 cm - 200 cm): Samples in this zone exhibit high charcoal abundances and very low pollen concentrations. The charcoal to pollen ratio is as high as 50, and is greater than 1 in all samples. Macroscopic charcoal ($> 125\ \mu m^2$) was observed visually, and determined to be rhizome material from aquatic plants, such as tule (*Scirpus acutus*).

Zone 1 (ca. 6,500 cal. yr BP - present; 200 cm - 95 cm): Redwood is dominant in this zone, comprising up to 40% of the total pollen. Grasses are also important at ~15-20% together with Asteraceae (~10%), Apiaceae (up to 10%), and the Rhamnaceae, Rosaceae, and Anacardiaceae type (up to 16%), and Artemisia (up to 5%). Sheep's sorrel (*Rumex acetosella*), a non-native species, is present in the top level. Sedge pollen is present at high levels (up to ~50%), while cattail (*Typha latifolia*) and water fern also increase. Trilete and monolete spores are present at ~5-12%. Microscopic charcoal is present at high levels in this zone, with the charcoal to pollen ratio being greater than 0.1 in all levels except the top level and is greater than 1 in some levels. Pollen concentrations are slightly lower, while organic content is slightly higher than Zone 2. This portion of the core is mainly silt, with clay and sand increasing slightly near the top. Silica (SiO_2), aluminum (Al_2O_3), zirconium (Zr), and titanium (Ti) decrease gradually in this zone, along with sharp increases in sodium (Na_2O), magnesium (MgO), and sulphur (S).

Discussion

The Laguna de las Trancas pollen record reflects changes from glacial to interglacial climate during the late Pleistocene and Holocene along the central coast of California. Marine records along the California coast have shown that similar changes have occurred cyclically over the last 600,000 years, with pine, herbs, and shrubs dominating in glacials and alder and redwood increasing during glacial-interglacial transitions. These changes occur cyclically with changes in ice volume associated with Milankovitch cycles (Heusser, 1998; Heusser et al., 2000; Lyle et al., 2010; White et al., 2013).

Glacial-Interglacial Transition Wet Phase

Marine core pollen data show that over the last 500,000 years, pronounced wet events occurred during each glacial to interglacial transition (Heusser et al., 2000; Lyle et al., 2010). The Laguna de las Trancas record shows a wet event during the Pleistocene/Holocene transition with the presence of fir pollen. Fir percentages are high from ca. 20,000 to ca. 12,900 cal yr BP, with a peak between 14,000 and 13,000 cal yr BP. Dates for the peak are reliable from this core because two radiocarbon dates were derived directly from concentrated pollen at levels where fir is important (see Table 2). The timing of this event is earlier than that reported by Lyle et al. (2010), who described a wet event from 13,000 to 6,000 years BP. The discrepancy in timing may be due to a lack of detailed chronological control on the marine core. In our study, the end of the wet phase is difficult to constrain due to the unconformity in the core between about 12,900 cal yr BP and 6,500 cal yr BP. However, the sudden increase in redwood pollen at the top of Zone 2 may indicate the end of the wet phase, with the establishment of higher summer temperatures and increased importance of coastal fog as a moisture source during summer drought. Coastal upwelling may have declined during glacial to interglacial wet phases, while SSTs rapidly increased allowing more storms to reach the California coast. These wet phases probably ended when SSTs cooled (Lyle et al., 2010).

The argument that a wet climate transient progressed from south to north along the California coast during deglaciation is not supported due to the lack of chronological control on many of these records (Gardner et al., 1988; Heusser et al., 2000; Lyle et al., 2010). More likely than a latitudinal change in the jet stream is an increased number of winter storms which occurred during this period due to warming SSTs all along the California margin (Barron et al., 2003; Doose et al., 1997; Lyle et al., 2010). Several studies have shown that the southward displacement of the polar jet during the last full glacial was limited (Gardner et al., 1997; Heusser, 1998; Ortiz et al., 1997). Lyle et al. (2010) ascribe changes to the strengthening and warming of the North Pacific gyre and the westerly storm track at ~12,000 years BP. However, the issue of timing is still uncertain as our record shows that the wet phase in central California peaked between 14,000 and 13,000 years ago.

Upwelling and Marine Fog

There is some uncertainty as to whether the California current was weaker during the late Pleistocene than it is today, and this has significance for marine fog and stratus formation along the coast during summer drought. Low stratus clouds form when surface air that passes over cold ocean water encounters subsiding warm air from the eastern arm of the North Pacific high-pressure cell, producing a temperature inversion. This inversion layer then stops the humid marine air from rising into the atmosphere. Without upwelling along the coast, marine fog and stratus are not likely to form. Evidence for a weaker California current at the LGM comes from alkenones from marine cores along the California margin (Doose et al., 1997; Herbert et al., 2001), while others suggest that upwelling along the California coast was just as strong in the Pleistocene as it is today (Gardner and Hemphill-Haley, 1986; Gardner et al., 1997; Kennett and Venz, 1992). The different interpretations may be due to the seasonal change in SSTs, which may have produced significant cooling during times of upwelling, but on average SSTs may have been only a few degrees cooler (Doose et al., 1997). Alternatively, greater upwelling along the central California coast during deglaciation (18,000-10,000 years BP), may indicate a change from continuous upwelling, persisting throughout this period and into the early Holocene, to seasonal upwelling at approximately the mid-Holocene (Gardner and Hemphill-Haley, 1986).

Marine fog and stratus are important for coastal terrestrial vegetation, providing moisture during summer drought. Numerous endemic species, such as coast redwoods (*Sequoia sempervirens*), survive within this "fog belt" due to decreased evaporative demand from shading, increased available moisture from fog drip, and in some cases, direct foliar uptake (Dawson, 1998; Fischer et al., 2009). However, whether fog and stratus were important ecological factors within the Pleistocene is unknown. Evidence that the California Current slowed during the LGM (Doose et al., 1997; Herbert et al., 2001) could explain the paucity of redwood forests during glacial periods due to a lack of upwelling induced coastal fog in the summer months, but some evidence points to *more* coastal fog in the late Pleistocene at ca. 16,600 BP (Anderson et al., 2008).

Since temperatures were lower during glacial phases, the possibility of winter frost may have reduced the extent of redwood forests even if fog during the summer months provided enough moisture. Since the pollen record indicates that redwood trees were at least present during glacial phases, if to a much lesser extent, they may have survived in protected valleys within the Santa Cruz Mountains where frost and high wind speeds were less likely.

Comparison with other records

Other long-term pollen records from the central coast exhibit similar trends to those of the Laguna de las Trancas core. In general, a decrease in pine and an increase in redwood and alder indicate the shift between glacial and interglacial conditions (Heusser, 1998; Heusser et al., 2000; Lyle et al., 2010).

A marine core (V1-80_P3) recovered near the outlet of the Russian River records an increase in redwood at about 12,000 BP, a peak in CT at about 15,000 to 12,500 BP, and an increase in alder from about 16,000 - 7,000 years BP. Pine declines in importance from glacial to interglacial periods (Gardner et al., 1988). The interglacial mode in this study is described as post-13,500 years BP, which matches well with Laguna de las Trancas. Foraminifera indicative of cold water upwelling appear at 13,500 to 14,000, which fits with the increase in redwood at about 13,300 BP in the Laguna de las Trancas core.

A marine core from the Monterey fan shows a similar trend, with abundant pine in the last full glacial with some redwood and fir, followed by a possible wet phase associated with a transitional mode from 18,000 to 13,500 years BP. In the Holocene, redwood and oak are abundant, pine has decreased, and fir is not present (McGann, 1990).

While marine pollen diagrams (Heusser, 1998; Heusser et al., 2000; Lyle et al., 2010; McGann, 1990) and the Clear Lake record (Adam et al., 1981b) show an increase in oak during the Holocene, oak is surprisingly rare in the Laguna de las Trancas samples. Oak is not displayed on the pollen diagrams as it never represents more than 3% of the total pollen. This may be due to the much smaller area represented by the Laguna de las Trancas pollen record. It has also been noted that while oak is the dominant Holocene pollen type at Clear Lake, it is a relatively minor pollen producer in other parts of the Coast Ranges (Gardner et al., 1988).

Zone 4 (ca. 50,000 - 43,000 cal. yr BP; 700 cm - 350 cm):

Pine and cypress and/or juniper were the dominant trees at Laguna de Las Trancas around 40,000 years ago. The Monterey pines at Point Año Nuevo represent the northernmost natural population of this species on the California coast. Hybrids of Monterey pine and knobcone pine grow near Laguna de las Trancas today. A previous study at this site recovered a knobcone pine cone from the basal pine zone of the core, so we can be certain that this species was growing in the vicinity (Adam et al., 1981a).

Unfortunately, the pollen of Cupressaceae and Taxaceae types cannot be identified to genus or species under light microscopy. Possibilities within these families include California juniper (*Juniperus californica*), Santa Cruz cypress (*Cupressus abramsiana*), Gowen cypress (*Cupressus goveniana),* Monterey cypress (*Cupressus* *macrocarpa*), or California nutmeg (*Torreya californica*). Both California nutmeg and Santa Cruz cypress grow in the hills surrounding the marsh today, though the Santa Cruz cypress is an endangered species restricted to just five populations in the Santa Cruz Mountains. Monterey cypress is similarly rare, with only two small populations at Point Lobos and Cypress Point, about 65 km to the south. Gowen cypress is also a rare tree that grows in only two groves in Monterey county (Stuart and Sawyer, 2001). Its distribution appears to have been more widespread in the past, however, as fossil cones of Pleistocene age were found in Southern California on the Channel Islands and the Rancho La Brea and Carpinteria tar pits, as well as further north at Little Sur and Tomales (Johnson, 1977). Fossil cones of Monterey pine and Monterey cypress, also species with limited distributions today, were found in many of these same locations. Several paleobotanists who analyzed these fossil floras hypothesized that coastal California was dominated by a closed-cone conifer forest in the Pleistocene, and interpreted this to mean that the Pleistocene featured more precipitation than today (Axelrod, 1980; Chaney and Mason, 1930; Raven and Axelrod, 1978). However, if at 40,000 years ago, fog and stratus were at least as important along the coast as they are today, and if low summer temperatures prevented significant evapotranspiration, this would provide enough moisture for these trees to survive along the coast until reduced winter precipitation and frost during the LGM limited their distribution.

If the CT pollen represents California juniper, then this would indicate a very different environment than today. The juniper forests in Southern California may have extended further north if conditions were sufficiently dry. There are currently isolated stands of juniper in central California, as for example at Mt. Diablo, which may indicate more widespread distribution in the past.

Herbs and shrubs are not well represented in the pollen record from this time period. This may be due to a relatively dense forest surrounding Laguna de las Trancas during this time, or to the poor preservation of these pollen types. The abundance of quillwort at the bottom of the core may reflect local conditions of the lake as it formed.

Charcoal abundance is very low in zone 4, and in some levels there is virtually no charcoal. This indicates that fire was not important during this time.

Zone 3 (ca. 27,000 - 20,500 cal. yr BP; 350 cm - 275 cm):

The period leading up to the LGM is characterized by an opening of the forest to a grassland environment with major increases in grasses and herbaceous vegetation. This could be due to a drying of the climate and to stronger winds due to increased pressure gradients and intensified atmospheric circulation during the full glacial. When sea level was at its lowest point, a broad coastal plain covered with beach ridges and sand dunes extended for about 16 km southwest of Point Año Nuevo (Weber, 1981). The high sand content in the core may have been blown in from these nearby dune fields. Currently, there is a dune field at Año Nuevo, which is thought to be only 3,000-6,000 years in age at its present location (Weber, 1981), but that may have been more extensive in the past. Sand dunes are also present at the mouth of nearby Waddell Creek (Thomas, 1961), which may have been part of a much broader dune field at the LGM. Quillwort is an important aquatic at this time, and may indicate a seasonally wet/dry environment. Charcoal is present but rare, indicating fires were not important during this time period.

Zone 2 (ca. 20,500 - ca. 12,900 cal. yr BP; 275 cm - 210 cm):
The GIT appears to be a wetter period than either the LGM or the Holocene, as grasses and other herbaceous types decrease, while trees including Douglas-fir and fir increase in importance. Fir does not currently grow in the area, and previous studies proposed that this pollen type is likely grand fir (*Abies grandis*). Today, grand fir reaches its southernmost limit approximately 150 km to the north of Laguna de las Trancas (Adam et al., 1981a; Griffin and Critchfield, 1972). Fir and Douglas-fir pollen was also found from a core dating to the GIT (ca. 14,000-11,000 cal yr BP) from Point Reyes, an area which is about 50 km south of the current distribution of grand fir. The Point Reyes study also has evidence for greater rainfall and high intensity storms which begin at about 14,000 cal yr BP (Rypins et al., 1989). Bur-reed and water fern increase at this time at Laguna de las Trancas, also indicating wetter conditions. Decreasing sand content may be due to a decrease in wind and less extensive dune fields as sea level rose. An important change in vegetation occurs at ca. 13,000 BP when redwoods become more important, while fir, pine, and CT declined. Charcoal also increases at the top of the zone, and fire may have been at least partially responsible for the decline in Douglas-fir and fir, as these trees are generally not fire-tolerant (Starker, 1934). The onset of hot, dry summers in the Holocene is also likely responsible for the extirpation of grand fir in the area.

Charcoal zone (210 cm - 200 cm):
The abundance of both microscopic and macroscopic charcoal in this zone indicates that the marsh experienced one or more fires. The early Holocene is absent in the core, and the hiatus between ca. 12,900 cal yr BP and ca. 6,500 cal yr BP may be due to the marsh fire burning down into the sediment and destroying the record. Another possibility is that the early- to mid-Holocene was significantly dry and the marsh may have dried up.

Zone 1 (ca. 6,500 cal. yr BP - present; 200 cm - 95 cm):
The importance of redwoods near Laguna de las Trancas in the Holocene indicates the prevalence of fog and stratus formation along the coast. Coast redwoods (*Sequoia sempervirens*) are currently distributed along a narrow belt from ~42°N to 36°N within about 50 km of the coast (Johnstone and Dawson, 2010). The coastal mountains restrict inland movement of fog and stratus, which redwoods depend on for moisture in the dry summer months, and in general the inland limit of summer coastal fogs defines the inland limit of well-developed redwood forests (Dawson, 1998; Thomas, 1961). The tops of marine stratus clouds generally correspond with the base of the inversion layer at about 400-500 m in California, and vegetation below this elevation benefits from shading and/or fog drip (Fischer et al., 2009; Leipper, 1994).

Redwoods tolerate low-severity fire and often resprout once burned. Therefore, the introduction of recurring fires may have been a factor in allowing redwoods to thrive, while limiting other trees like fir and Douglas-fir. The higher percentages of alder pollen may be indicative of local conditions surrounding the marsh, suggesting more precipitation.

This zone shows an increase in shrubs and weedy plants such as members of the Asteraceae family, Apiaceae family, Rhamnaceae & Rosaceae families, and Artemisia making up ~5-20% of the non-aquatic pollen total. Increases in herbaceous and shrubby vegetation indicate an open environment, with the possibility that the immediate area surrounding the marsh was open grassland and coastal scrub as it is today. Artemisia probably represents the coastal sage (*Artemisia californica*) and native grasses like Pacific reed grass (*Calamagrostis nutkaensis*) and California oatgrass (*Danthonia californica*) would likely have been important members of the coastal grassland. The appearance of sheep's sorrel (*Rumex acetosella*) at the top of the core indicates that at least part of the historic period is preserved. This non-native currently grows near the marsh.

Charcoal increases by an order of magnitude in this zone as compared to previous zones. Whether this is due to changes in climate or human influence is uncertain. Fires may have become more frequent during the Holocene when summer temperatures increased and summer drought became more pronounced, and the wet phase in the GIT may have enabled a buildup of fuels (Edlund and Byrne, 1991). However, fires cannot start without an ignition source, and natural lightning is very rare along the coast of California, especially during the dry season (Keeley, 2002; van Wagtendonk and Cayan, 2008). Because of the relatively low frequency of natural ignitions in the region, as well as the presence of redwood, alder, and aquatics indicating moist conditions, the increase in fire frequency could be a signal of human presence. The coastal region of Santa Cruz and San Mateo Counties has a high density of archaeological sites, some dating to as early as 6,700 cal yr BP (Hylkema, 1991).

A fire scar dendrochronology study in the Whitehouse Creek, Waddell Creek, and Scotts Creek watersheds shows a mean fire return interval of approximately 7.6 years prior to the logging period (Johnson et al., 2013). Another study in the Santa Cruz Mountains has shown evidence for a mean fire return interval of approximately 12 years prior to the advent of suppression policies in the early twentieth century (Stephens and Fry, 2005). Both of these studies indicate that fires were occurring much more frequently than the predicted fire return interval of about 135 years under natural ignition scenarios in the Santa Cruz Mountains (Greenlee and Langenheim, 1990). This suggests that indigenous people in California had an important influence on the vegetation near Laguna de las Trancas with their frequent use of fire, which may have encouraged herbaceous plants to regenerate. Increases in herbs and shrubs like grasses, RRA, Apiaceae, and Artemisia may indicate an increase in species diversity and the encouragement of fire-adapted plants that regenerate with frequent, low-severity fire. A decrease in charcoal at the very top of the core, when a non-native pollen type also appears, may indicate changes in fire frequency with the arrival of Europeans.

Conclusion

The record from Laguna de las Trancas shows clear shifts in dominant vegetation at the LGM, during the GIT, and mid- to late-Holocene along the central coast of California. A pine and cypress or a pine and juniper forest dominated between ca. 50,000 years ago and ca. 43,000 years ago. During the LGM, the climate was likely dry with strong winds. During the GIT, an important shift to wetter conditions is evident in the pollen record, peaking ca. 14,000-13,000 years ago. The dominance of redwood in the Holocene indicates higher temperatures and the prevalence of coastal fog throughout this period.

The charcoal peak at ~6,500 cal yr BP indicates the beginning of regular fires in the region, as charcoal content remains high throughout the mid- to late-Holocene. While a drier climate may have contributed to the increase in fire frequency in the Holocene, humans may have also had an important influence on the environment. Since redwoods and other indicators of summer moisture are prevalent in the record, and the fire scar record exhibits frequent fire return intervals, it is probable that the high fire frequency in the Holocene is due to human ignition.

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Chapter 3

A PALEOLIMNOLOGICAL RECORD OF LATE HOLOCENE VEGETATION CHANGE FROM THE CENTRAL CALIFORNIA COAST

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Abstract

In this paper, we present results of the analysis of the pollen and microscopic charcoal content of a sediment core from Skylark Pond near Point Año Nuevo in Santa Cruz County, California. The core covers approximately the last 3,000 years and is of interest because Skylark Pond is located only 1.8 km from Quiroste Valley State Cultural Preserve, an important ceremonial and habitation location for the historic Quiroste tribe containing numerous late Holocene archaeological sites. The results show an increase in fire activity from the fifteenth century to the present. Peaks in charcoal at ca. A.D. 1425 along with subsequent high charcoal abundance indicate either small, frequent fires ignited by humans or large natural conflagrations. Significant changes after European colonization include increases in grass, oak, and bracken fern, all of which indicate the opening of the redwood forest by logging and ranching. Historic period charcoal peaks can be attributed to the burning of logging slash.

Introduction

The use of fire by Native Americans as a tool for managing landscapes for a variety of purposes is well documented in historical and ethnographic accounts (Anderson 2005; Brown 2001; Lewis 1973; Stewart 2002). Less certain, however, is the spatial extent of indigenous fire use and variability in fire frequencies through time. One leading theory is that frequent low-severity fires set by humans fundamentally changed landscape patterns to promote a heterogeneous, diverse array of species (Anderson 2005; Blackburn and Anderson 1993; Lewis 1973; Lightfoot and Parrish 2009; Stewart 2002). For example, changes in oak density have been attributed to cessation of burning by Native Americans after the arrival of Europeans (Byrne et al. 1991). Keeley (2002) argued that prehistoric human alteration of natural fire regimes resulted in more grasslands and shrublands in central coastal California, as this distribution has no other climatic or edaphic explanation. The opposing position by Vale and others (2002) is that native people only burned small areas surrounding villages, and therefore did not change vegetation significantly. They pointed out that in many parts of California, such as in the Sierra Nevada Mountains, natural fires were so frequent that human fire use would not be necessary to explain pre-European vegetation composition.

Paleoecological study of indigenous burning practices and their effects on vegetation is only now beginning to take place. The most direct evidence for indigenous fire use in central coastal California comes from fire scars which show a more frequent fire regime (~8-12 year mean fire return interval) prior to suppression policies in the early twentieth century (Brown et al. 1999; Stephens and Fry 2005). Coastal California also has a low occurrence of lightning-ignited fire (Keeley 2002; van Wagtendonk and Cayan 2008), so most prehistoric fires in this region were likely due to human ignition. However, fire scar evidence is generally only available for the last few centuries, and this time period includes the relatively cool and moist "Little Ice Age." Untangling the various factors that could have affected fire regimes and brought about vegetation change requires a long-term perspective. For example, in other parts of California climate changes have been shown to have an effect on fire regimes, with more frequent fire occurring at the end of wet phases and beginning of dry periods (Edlund and Byrne 1991; Mensing et al. 1999).

Here we present pollen and charcoal evidence of prehistoric fire frequencies from Skylark Pond, which is located 1.8 km from site CA-SMA-113, the focus of our research team's archaeological research. Archaeologists believe CA-SMA-113 to be the probable location of "Casa Grande," a large native settlement that was described in journals from the Portolá expedition of 1769 (Cuthrell et al. 2012; Cuthrell et al., 2013). The pollen and charcoal record from Skylark Pond indicates an increase in burning after ca. A.D. 1425 and again after American settlement in the mid-nineteenth century due to logging activity in the area and the unmonitored burning of logging slash. A parallel study from Laguna de las Trancas, a marsh located ca. 10 km south of Quiroste Valley, has produced a long-term record of vegetation and fire regime change that will cover much of the Holocene and late Pleistocene. Findings from Laguna de las Trancas are reported in Chapter 2.

Study Area

Skylark Pond (37°10'26"N, 122°18'52"W; Figure 1) is a small 15 m diameter sag pond formed by a landslide. It is located at an elevation of 268 m.a.s.l. approximately 1.8 km northeast of CA-SMA-113 and 4.5 km from the Pacific coast. The pond was filled in with gravel as part of a reclamation project during the historic period. Modern climate in this region is governed by the seasonal migration of the North Pacific High and the mid-latitude storm track. Seasonal temperatures range from 10ºC to 14ºC in winter and 13ºC to 20ºC in summer (Thomas 1961). Average precipitation is approximately 76-89 cm per year (National Atlas of the United States 2003) with two-thirds falling from December through March. Fog is frequent in the late spring and summer. The pond is located within the San Gregorio fault zone, which comprises seven or eight faults along which movement has occurred within the last 105,000 years (Weber 1981).

Currently, the vegetation around the pond is redwood forest with redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), tanoak (*Notholithocarpus densiflorus*), canyon live oak (*Quercus chrysolepis*), and coast live oak (*Quercus agrifolia*). Aquatic plants, including tule (*Schoenoplectus acutus* var. *occidentalis*), grow in and around the pond. The immediate area surrounding the pond is open grassland dominated by non-native grasses and forbs. It is not known whether the

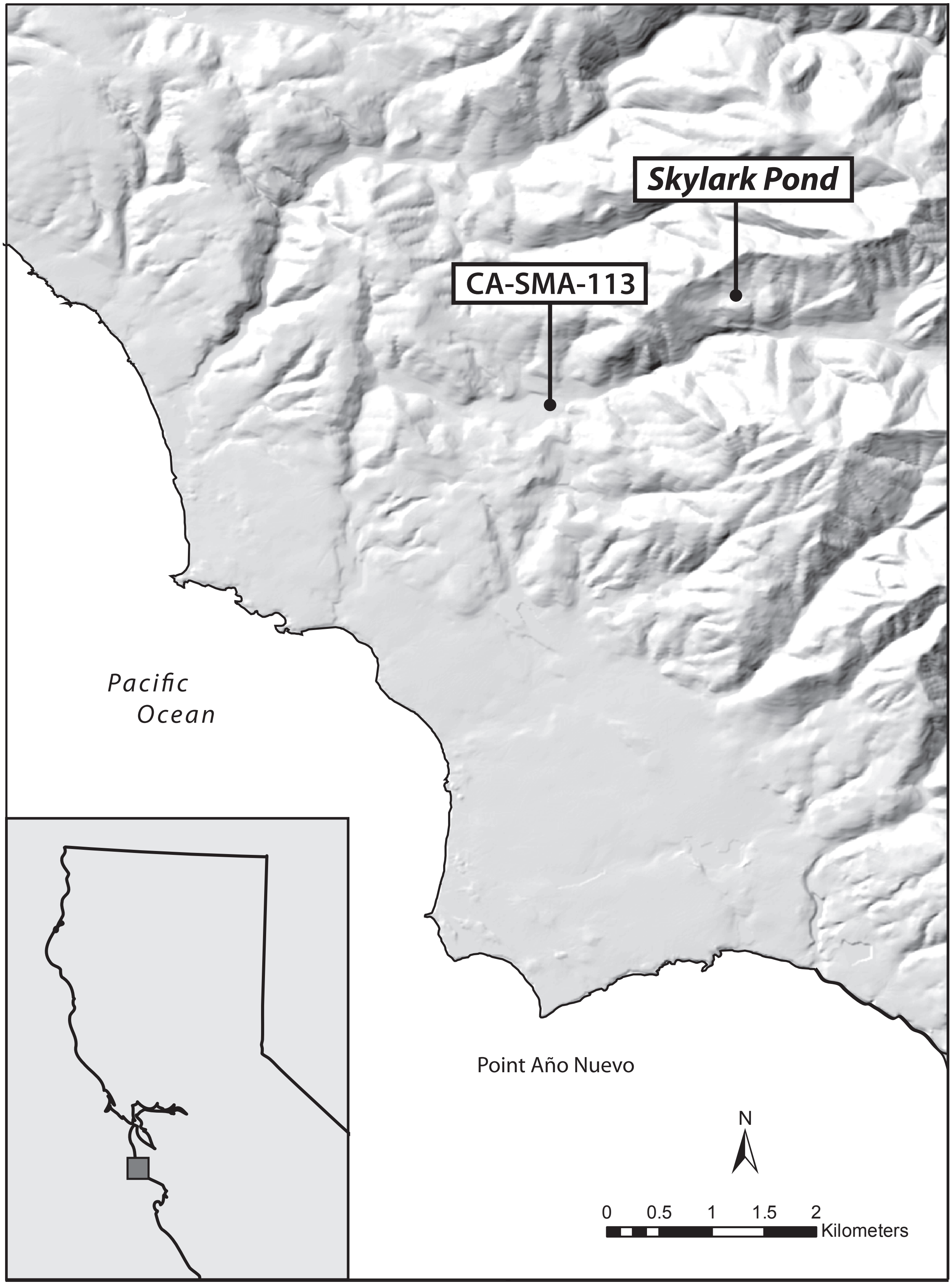

Figure 1. Area map showing location of Skylark Pond and CA-SMA-113.

forest would naturally grow to the edges of the pond, but historical aerial photographs show that the forest has encroached in the last ca. 60 years (Aero Service Corporation 1943). The forest understory is largely composed of ferns, such as bracken fern (*Pteridium aquilinum*) and Western sword fern (*Polystichum munitum*), and herbaceous plants. On dry sites, species include knobcone pine (*Pinus attenuata*), chinquapin (*Chrysolepis chrysophylla*), coyote bush (*Baccharis pilularis*), blackberry (*Rubus ursinus*), madrone (*Arbutus menziesii*), manzanita (*Arctostaphylos* spp.), interior live oak (*Quercus wislizeni*), and toyon (*Heteromeles arbutifolia*).

Common species in the area around CA-SMA-113 on the floor of Quiroste Valley include coast tarweed (*Madia sativa*), poison oak (*Toxicodendron diversilobum*), California coffeeberry (*Frangula californica*), California lilac (*Ceanothus* spp.), toyon, blackberry, cow parsnip (*Heracleum maximum*), elderberry (*Sambucus* spp.), sedges (Cyperaceae), rushes (*Juncus* spp.), and many non-native grasses and forbs. In riparian areas near Whitehouse Creek, redwood and alder (*Alnus rhombifolia*) grow with understory vegetation including Western sword fern, bittercress (*Cardamine californica*), salmonberry (*Rubus spectabilis*), gambleweed (*Sanicula crassicaulis*), stinging nettle (*Urtica dioica*), and nightshades (*Solanum* spp.).

Vegetation on the near-coastal terraces west of Skylark Pond and CA-SMA-113 includes coyote bush, poison oak, coast buckwheat (*Eriogonum latifolium*), lupine (*Lupinus albifrons*), gumplant (*Grindelia* spp.), sage (*Artemisia californica*), Pacific wax myrtle (*Morella californica*), and willow (*Salix* spp.).

Methods

We extracted a 163 cm sediment core from Skylark Pond in 2009 using a modified Livingston coring system equipped with a 6 cm diameter polycarbonate tube that was driven into the sediments with a sledgehammer. The core was raised with the aid of a winch and pulley. The core was brought to UC Berkeley and stored in a 5°C cold room. The upper meter consisted of historic sand and gravel fill and was not analyzed. A 63 cm segment of the sediment core below the gravel fill was analyzed for pollen and microscopic charcoal.

Samples for pollen and microscopic charcoal analysis were taken at 1-2 cm intervals and pollen extracted using standard procedures (Faegri and Iversen 1989). Known quantities of *Lycopodium* spores were added to each sample prior to digestion to calculate pollen concentrations and accumulation rates. Sample residues were stored in silicone oil. Pollen was counted at 400x magnification using a Leitz Dialux microscope. A total of 36 samples were analyzed, with 33 samples counted to a minimum of 400 grains per sample. Pollen in the remaining three samples (126 cm, 128 cm, and 129 cm) was not counted due to very low concentrations. All 36 samples were analyzed for microscopic charcoal. Pollen and spores were identified using the University of California Museum of Paleontology pollen reference collection and published keys (Bassett 1978; Kapp 2000; McAndrews et al. 1973;

Moore et al. 1991). Pollen and spore frequencies were plotted on diagrams as a percentage of total non-aquatic pollen for non-aquatics or a percentage of total pollen for aquatics.

We used the charcoal/pollen and spore ratio as a means of controlling for taphonomic effects. Since pollen, spores, and charcoal of the same approximate size are deposited by the same mechanisms (e.g. wind and water), comparing the concentration of microscopic charcoal to the concentration of pollen and spores allows us to determine when fires were occurring in the area. Microscopic charcoal concentrations were measured by digitally imaging slides at 4,000 dpi (1 pixel = 6.35 micrometers) with a Nikon Coolscan V Ed scanner fitted with a Nikon FH-GI slide holder. Charcoal particles were identified in Adobe Photoshop and then counted and measured in ImageJ. Particles smaller than 20 μm^2 or those with large standard deviations of the grey scale value were not included in the count. The microscopic charcoal concentration was calculated by multiplying the total charcoal counts of each slide by the proportion of the slide used in calculating pollen and spore concentration. Microscopic charcoal was then calculated as a ratio of charcoal concentration to pollen and spore concentration by volume for each sample. Initial assessment of size-based analyses did not show significant variation between samples and is therefore not reported here.

Results

Chronology
Five AMS radiocarbon dates (Table 1; Figure 2) obtained for the lower section of the core show a very low sedimentation rate averaging only 0.5 mm per year. All dates are calendar dates and were calibrated using Calib 6.0 (Stuiver et al. 2010). The core has a basal date of ca. 3200 cal. B.P (ca. 1250 B.C.). Both the presence of *Rumex acetosella*, a non-native pollen type, and the two youngest radiocarbon dates indicate that the upper portion of this section of the core was deposited in the historic period.

The pollen and charcoal results are shown in Figures 3 and 4. For purposes of discussion, the diagrams are divided into three zones:
Zone 3 (163 cm – 132 cm; 3190 cal. B.P. [1240 B.C.] – ca. 550 cal. B.P. [A.D. 1400]): Redwood pollen is the dominant pollen type in Zone 3, comprising 25-50% of total non-aquatic pollen. Aquatic pollen types, particularly the sedge type, are ca. 40% of total pollen at the bottom of the core. Bracken fern (1-15%) and Asteraceae (5-15%) fluctuate in this zone. Members of the three families Rhamnaceae, Rosaceae, and Anacardiaceae (RRA) total ca. 13% at the bottom of the core and decline through time. Brassicaceae pollen is present here at ca. 4-8% of the total. A peak in canyon live oak occurs at 142 cm depth. Organic content (LOI) is relatively low in this zone but increases gradually. Microscopic charcoal is present at low levels, with one peak at 154 cm depth.

Table 1. AMS radiocarbon ages obtained from the Skylark Pond core. All radiocarbon ages were calibrated using Calib 6.0 (Stuiver et al. 2010).

Depth (cm)	**Laboratory Sample #**	**Radiocarbon Age (yrs B.P.) and Error**	**Calibrated Age (yrs B.P.) 2-σ**	**Calibrated Median Age (yrs B.P.)**	**Material**	**Sedimentation Rate (mm/yr)**
115	USGS WW7667	170 ± 35	131 – 230	176	uncharred botanical	0.86
120	CAMS #155451	230 ± 70	123 – 232	234	charred botanical	0.86
130	CAMS #155452	495 ± 30	501 – 549	525	charred botanical	0.34
146	CAMS #155453	1325 ± 45	1171 – 1318	1255	charred botanical	0.22
163	USGS WW7666	2995 ± 30	3077 – 3266	3190	uncharred botanical	0.09

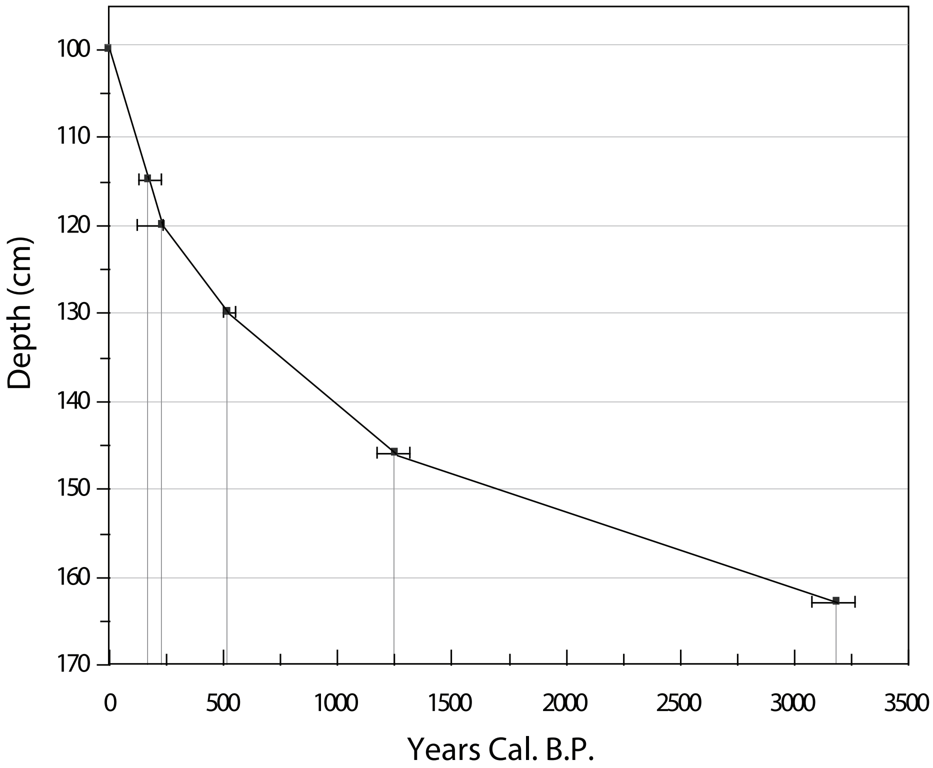

Figure 2. Age model. Solid line represents linear sedimentation rate between calibrated median probability ages listed in Table 1. Error bars indicate the 2-sigma range.

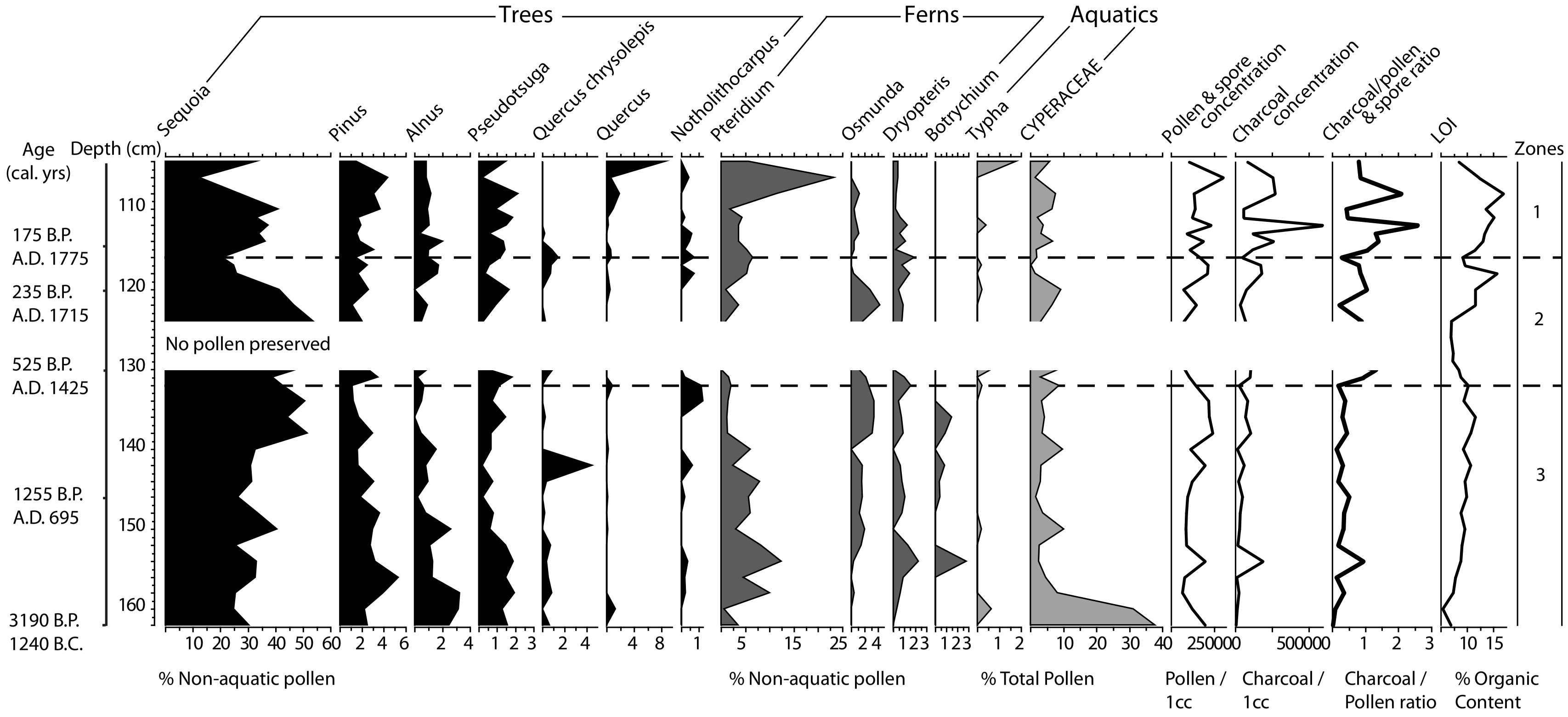

Figure 3. Percent pollen diagram of selected trees, ferns, and aquatics with charcoal concentration, pollen and spore concentration, charcoal/pollen and spore ratio, and loss-on-ignition (LOI). Note scale changes along x-axes.

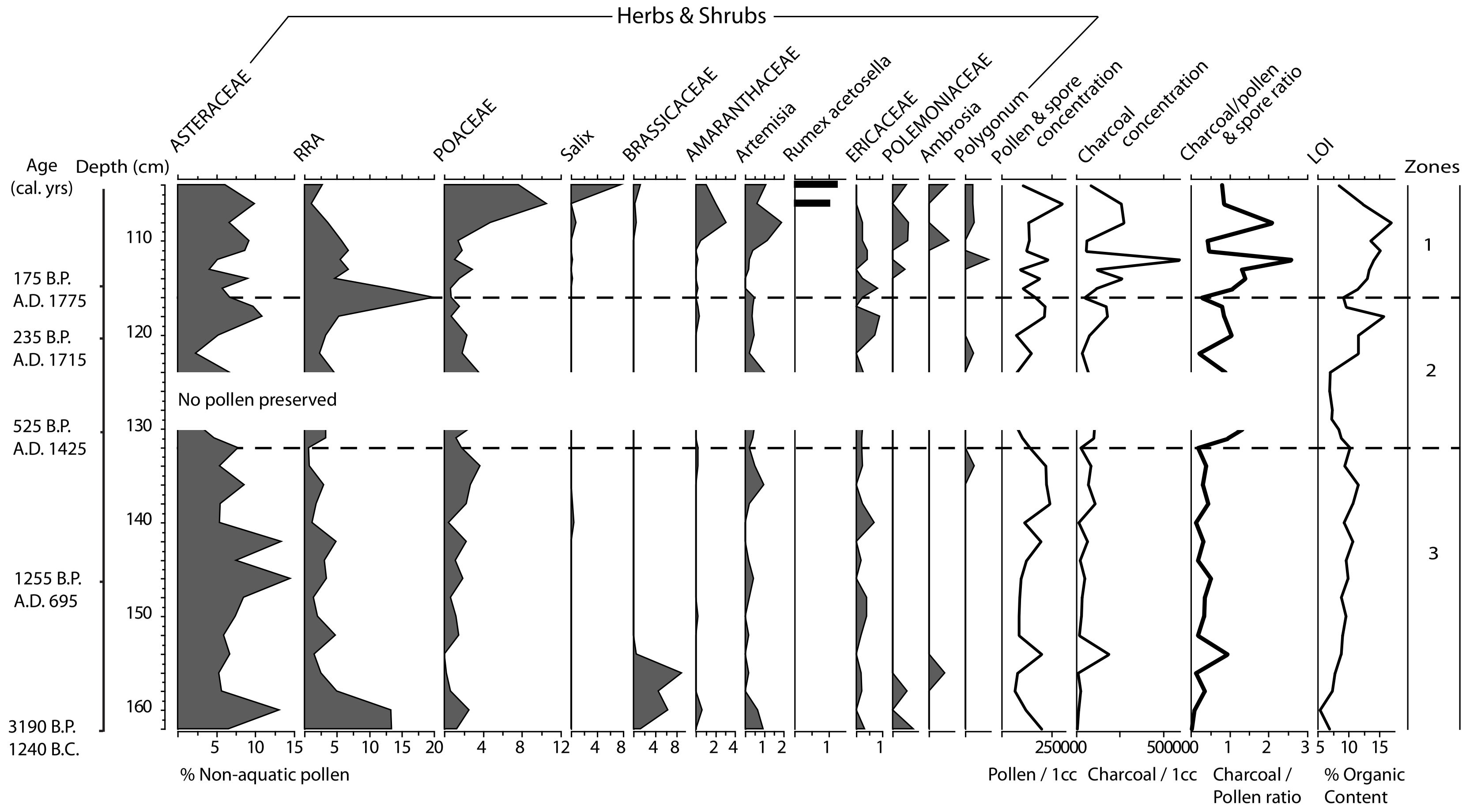

Figure 4. Percent pollen diagram of selected herbs and shrubs with charcoal concentration, pollen and spore concentration, charcoal/pollen and spore ratio, and loss-on-ignition (LOI). Note scale changes along x-axes.

Zone 2 (132 cm – 116 cm; ca. 550 cal. B.P. [A.D. 1400] – ca. 200 cal. B.P. [A.D. 1750]): This zone includes a section of low organic content from 129-125 cm in which little pollen is preserved. Redwood is present at high levels from 40-55%, with a sharp decline near the top of the zone to ca. 20%. Asteraceae decreases to its lowest level at less than 3%, but then increases to greater than 10%. The RRA type increases substantially at the top of this zone to almost 20%. Microscopic charcoal increases in this zone with two peaks at 131 and 130 cm just before the section with little organic content. Other samples with higher than average charcoal include samples at 124, 120, 118, and 117 cm.

Zone 1 (116 cm – 104 cm; ca. 200 cal. B.P. [A.D. 1750] – ca. 0 cal. B.P. [A.D. 1950]): Organic content increases in this zone. Redwood increases to 40% then drops to ca. 10%, but again increases near the top of the core. Pine increases slightly and oak and willow increase to 8% at the top. Bracken fern increases dramatically at the top of the core to ca. 23%. Members of the RRA families decrease to ca. 5%. Grasses increase at the top to greater than 10%. Sheep's sorrel (*Rumex acetosella*), a non-native species, is present at 106 cm and 104 cm. The highest peaks in charcoal occur in this zone at 112 cm and 108 cm. Both 115 cm and 114 cm samples also contain comparatively high levels of charcoal.

Discussion

Due to the low sedimentation rate, individual years or fire events are not distinguishable in the 1 cm^3 samples analyzed. However, the relative change in the abundance of microscopic charcoal enables us to assess when fires were more frequent. Due to the dominance of redwood in the core, we believe that most of the pollen and charcoal in the Skylark Pond sediments is of local origin. Redwood trees around the pond would have acted as a screen to filter out most extra-local pollen and charcoal (Tauber 1967). In this case, microscopic charcoal records counted on pollen slides can indicate low-intensity fires within a few kilometers (Pitkänen et al. 1999).

Zone 3 (163 cm – 132 cm; 3190 cal. B.P. [1240 B.C.] – ca. 550 cal. B.P. [A.D. 1400]): The high redwood percentages indicate that Skylark Pond was surrounded by redwood forest throughout this time period. Low Douglas-fir percentages show that it was also locally present. High levels of sedge at the basal levels of the core indicate a marsh developed when the pond first established. Since a tectonically induced landslide created the pond, it is not surprising that plants characteristic of disturbed environments are present at moderate levels, such as members of the Rhamnaceae, Rosaceae, Anacardiaceae, Asteraceae, and Brassicaceae families. Species in these families that currently grow nearby include California coffeeberry (Rhamnaceae), California lilac (Rhamnaceae), blackberry (Rosaceae), toyon (Rosaceae), poison oak (Anacardiaceae), coyote bush (Asteraceae), and bittercress (Brassicaceae). With the exception of a single peak at 154 cm, low values of the charcoal to pollen and spore ratio indicate that fire was not important during this period.

Zone 2 (132 cm – 116 cm; ca. 550 cal. B.P. [A.D. 1400] – ca. 200 cal. B.P. [A.D. 1750]): An increase in shrubby and herbaceous plants surrounding the pond is indicated by the increase in RRA and Asteraceae pollen at the top of this zone. Redwood is at its highest percentages at the bottom of this zone, but then appears to decline near the top. This decline may be due to the relative abundance of redwood pollen in a percentage diagram, rather than a decline in the actual number redwoods in the area. Because microscopic charcoal increases in this zone, the increase in RRA and Asteraceae pollen could be a result of more frequent low-severity fires in the area. Species in these families that vigorously regenerate after fire include California coffeeberry, California lilac, toyon, chaparral cherry (*Prunus ilicifolia*), and poison oak. Another possible explanation is a large conflagration that could have reduced the area of redwoods surrounding the pond, allowing fire-adapted plants to colonize the newly opened environment.

An interesting aspect of this zone is the section with decreased organic content. Since two large charcoal peaks occur just before this section, it is probable that a fire reduced vegetative cover around the pond and allowed erosion to significantly increase. Since redwood pollen continues to be present at high levels just after this section, the fire event was likely low-severity. Alternatively, tectonic activity and subsequent landslides could be an explanation.

A radiocarbon date obtained from the 130 cm depth indicates that the first two major charcoal peaks date to the mid-fifteenth century (see Table 1). Subsequent levels with higher than average charcoal content may indicate regular burning in the area. The intact portion of the nearby archaeological site CA-SMA-113 was occupied ca. A.D. 1000-1300 and may have been occupied up to ca. A.D. 1770. Radiocarbon dates from other nearby archaeological sites in the Point Año Nuevo area indicate settlement at various times over the last two thousand years, with several dating to the thirteenth through sixteenth centuries (Hylkema and Cuthrell 2013: Table S1).

Although natural fire due to changes in climate cannot be ruled out as a reason for the increase in charcoal in this zone, we believe that this is unlikely for a number of reasons. The pollen frequencies show no evidence of drought, which would be expected to increase natural fire frequency. In fact, redwood pollen is at its highest levels in this zone. If a landslide were responsible for the erosive event rather than a fire, this could indicate a period of increased precipitation along with a tectonic event (Adam 1975). Few studies have addressed climatic changes along the Central California Coast during this time period, but studies from the San Francisco estuary report increased precipitation over Central California from approximately A.D. 1200 to 1930 (Byrne et al. 2001) and a major flood deposit from ca. A.D. 1420 (Goman and Wells 2000). Finally, the upper portion of this zone is within the “Little Ice Age” (sixteenth through nineteenth centuries), which numerous studies have shown was a period of cooler and wetter climate in California (Malamud-Roam et al. 2006), yet microscopic charcoal is present at relatively high levels. Though natural fire return intervals of around 135 years would be expected for redwood forest in the Santa Cruz Mountains (Greenlee and Langenheim 1990), the low charcoal abundance prior to this period in Zone 3, with the exception of a single peak at 154 cm, indicates that natural fires occurred even less frequently. Therefore, the increase in charcoal in Zone 2 represents an important shift in fire regime for the local area.

Zone 1 (116 cm – 104 cm; ca. 200 cal. B.P. [A.D. 1750] – ca. 0 cal. B.P. [A.D. 1950]): Zone 1 includes the historic period during which the most obvious changes in vegetation occur. The decrease in redwood near the top, along with the dramatic increases in grass and bracken fern and modest increases in oak, willow, Amaranthaceae, and *Artemisia* indicate significant changes in vegetation. The most probable explanation is the establishment of logging operations in the area after American settlement in the mid-nineteenth century. The first sawmill in the Santa Cruz Mountains was established in 1842 near the town of Felton (Thomas 1961). From 1867 to 1880, a large sawmill called Glen Mills was in operation less than a kilometer from Skylark Pond. A ranch was also established in the area around the same time. In 1892, Glen Mills shut down as all the large redwoods in the area had been cut, while farming and ranching continued (Mowry 2004). Large conflagrations often accompanied logging operations because of the burning of logging slash (Greenlee and Langenheim 1990). The highest charcoal peaks in the Skylark Pond core probably indicate large, uncontrolled fires in the late nineteenth century.

Conclusion

When members of the Portolá expedition left the "Casa Grande" village on October 24, 1769, Juan Crespí reported passing over hills that were "all burnt off, having very good soil, all of them bare of trees" (Brown 2001). Numerous reports from this expedition described burned vegetation in the area along the coast. The microscopic charcoal record from Skylark Pond provides evidence of regular fires from the fifteenth century to the present near Quiroste Valley, the probable location of "Casa Grande." We propose that at least some of these fires were ignited by humans because of the evidence of large settlements in the area. However, due to the limitations of low-resolution data and without fire scar evidence to calibrate the charcoal record, we cannot conclusively state whether the increase in charcoal from the fifteenth century to the present can be attributed to frequent low-severity fires ignited by humans or perhaps more frequent or more severe natural fires. The spatial scale of past fires is also difficult to determine without fire scar evidence or more paleoecological studies in the area. Ongoing fire scar research in Quiroste Valley, along with results from nearby Laguna de Las Trancas, will enable a more definitive conclusion. However, it is clear from the Skylark Pond record that the most dramatic changes in vegetation and fire regimes occurred after American settlement, when logging, farming, and ranching became widespread.

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Chapter 4

A PALYNOLOGICAL PERSPECTIVE ON NON-NATIVE PLANT INVASIONS IN THE SACRAMENTO VALLEY, CALIFORNIA

Abstract

The transformation of the vegetation of California's Sacramento Valley during the last 250 years involves some of the most dramatic examples of successful plant invasions. However, historical evidence regarding the timing and mechanism of these invasions is limited. Here we report the results of pollen analysis of sediment cores recovered from Little Packer Lake, an oxbow lake in the Sacramento Valley. The cores cover approximately the last 700 years and provide clear evidence of dramatic changes in vegetation during the nineteenth and twentieth centuries. Our results document the sequence of non-native invasions and introductions. We find that *Brassica* and *Erodium* were important early invaders; that agriculture and arboriculture were major sources of non-native plant introductions during the early years of Euro-American settlement; and that grass pollen was not important prehistorically.

Introduction

During the last century and a half, the vegetation of the Sacramento Valley has been in a large part coverted to agricultural land use, and those areas that have not been cultivated have been significantly modified by grazing and changes in fire frequency. Numerous non-native species have become established, so much so that in some areas they make up more than 90% of the present plant cover (Bartolome, 1979; Heady, 1988). This replacement of native species by invasives provides an extreme example of "ecological imperialism" (Crosby, 1986). However, the details of this transformation are not well understood. Many non-native species became established during the early years of Spanish settlement and the history of their arrival and spread is poorly documented (Blumler, 1995; Mensing & Byrne, 1998; Seabloom et al., 2003; Minnich, 2008).

In view of the limitations of the historical record, it is not surprising that ecologists and biogeographers have reached different conclusions as to the nature of the pre-contact vegetation and its subsequent transformation. The influential ecologist Frederic Clements first proposed his "perennial grassland thesis" in 1920 where he argued that the Central Valley was prehistorically dominated by perennial bunchgrasses, and later specified that *Stipa pulchra* (purple needlegrass) was the most important species (Clements, 1920; Clements, 1934). Despite the lack of evidence, his ideas have remained at the forefront of California ecology (Burcham, 1957; Bartolome, 1979; Heady, 1988; Hamilton, 1997; Holstein, 2001; Seabloom, 2003). Alternative hypotheses for prehistoric composition have included chaparral dominated by sclerophyllous shrubs (Cooper, 1922), a grassland composed mostly of annual grasses (Jepson, 1925; Frenkel, 1970; Wester, 1975), or a prairie dominated by annual forbs (Blumler, 1992; Minnich, 2008).

While most ecologists agree that *Avena fatua* (wild oats) and *Brassica nigra* (black mustard) were "probably" the first non-natives in the area (Heady, 1988), there is little conclusive evidence to prove this true. Furthermore, the extent to which overgrazing played a role in the spread of invasive species during the early settlement years is still unclear. Burcham (1957) argued that many non-natives were able to establish when the area was overgrazed by introduced livestock. However, some ecologists argue that the adaptation of the plants themselves, rather than grazing pressure, is sufficient to explain the rapid expansion of non-native plants that are well-adapted to a Mediteranean climate (Heady, 1988; Blumler, 1992; Blumler 1995; Mensing & Byrne, 1998).

Here we report on the fossil pollen content of a sediment core recovered from Little Packer Lake, an oxbow of the Sacramento River in Glenn County (Fig. 1). A previous study has shown that the Little Packer Lake is approximately 800 years old (Sullivan, 1982). Our pollen record documents the invasion of several non-native weedy taxa (*Erodium cicutarium, Brassica* spp*., Centaurea solstitialis, Rumex acetosella, Plantago lanceolata*) coincident with declines in native riparian taxa (*Quercus*, *Platanus*, and *Alnus*). The results also show the establishment of walnut orchards (*Juglans*) near the lake and the planting of *Eucalyptus* trees. *Brassica* was an important early invader and agriculture and arboriculture brought in numerous invasive plants after European settlement.

Study Area

Little Packer Lake (39°27'19" N, 122°00'43"W; Fig. 1) is an oxbow lake located on the western side of the Sacramento River in Glenn county, California. The lake formed approximately 700 years ago when it was cut off from the main channel of the river. Packer Lake, a younger oxbow located to the southeast of Little Packer Lake, was cut off in the late nineteenth century (Sullivan, 1982). At present there is a walnut orchard (*Juglans*) next to the lake and an abandoned field dominated by *Centaurea solstitialis* (yellow starthistle). Riparian vegetation includes *Quercus lobata* (valley oak), *Acer negundo* (box elder), *Toxicodendron diversiloba* (poison oak), *Cephalanthus occidentalis* (buttonbush), *Vitis californica* (wild grape), and several species of *Salix* (willow). *Lemna* (duckweed) covered the surface of the lake when cores were taken in 2008.

As the Sacramento River overflows its banks in the winter, alluvial deposits have built up over time to create natural levees which flank the river on both sides, becoming wider and more continuous as the river flows south. In the Little Packer Lake area, the river flows on an alluvial ridge up to 3.3 meters above the flood basins to the east and west. Tree species with different levels of flood tolerance occupy different parts of the riparian landscape. Young stands of *Populus fremontii* (Fremont cottonwood) and *Salix* spp. (willow) are predominate on the low terraces

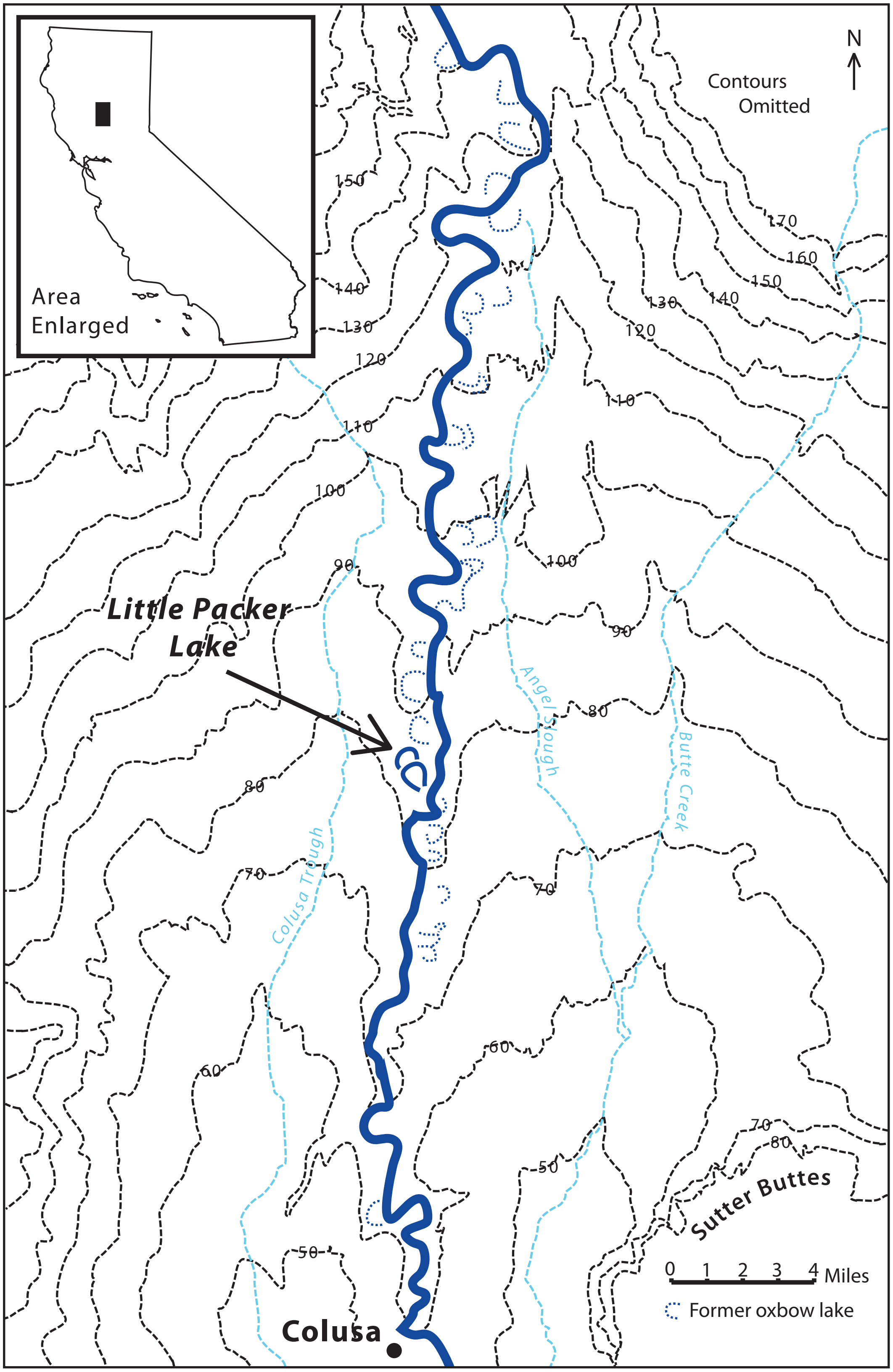

Figure 1. Area map showing location of Little Packer Lake and the Sacramento River, with elevation contours in feet (after Brice, 1977).

near the river. Further away, *Fraxinus oregana* (Oregon ash) and *Acer negundo* (box elder) become important, as well as *Juglans nigra* (black walnut), though it is not believed to have grown here before European settlers brought its rootstock to the area to produce orchards. Mature oaks (*Quercus* spp.) and sycamore (*Platanus racemosa*) grow on high terraces (Strahan, 1984).

Before extensive European settlement in the Sacramento Valley began in the 1850s, riparian woodland extended from one to five miles from the river and channels on the natural levees. Dominant trees were *Quercus lobata* (valley oak), *Quercus wislizenii* (interior live oak), *Populus fremontii* (Fremont cottonwood), *Salix* spp. (willow), *Platanus racemosa* (California sycamore), *Alnus rhombifolia* (white alder), and *Fraxinus oregana* (Oregon ash). These species still occur today along the river, but the total area of woodland is significantly reduced (Thompson, 1961). Losses of riparian habitat are attributable to land use changes after European settlement, such as the conversion to orchard and field crops, logging for wood chips, reduction of water flow by dams and irrigation, channelization and streambank stabilization, gravel and gold mining, grazing, and water pollution (Roberts et al., 1980).

With the exception of Sutter Buttes, the Sacramento Valley is flat and almost featureless. This flat land has been called “California grassland” by taxonomists Munz and Keck (1959), Heady (1988), and Küchler (1964), but has been so altered by land use changes and invasion of non-native species that it is unclear what types of vegetation dominated prehistorically. This area today includes seasonally inundated marshes and alkali flats with vernal pools. Since the river runs through an alluvial ridge, small distributary streams flow into flood basins in winter as the river overflows, creating marshes that were much more extensive historically than they are today.

Invasive annual grasses are now prevalent in the non-cultivated sections of the flood basins. They include *Avena barbata* and *Avena fatua* (wild oats), *Bromus mollis* (soft brome), and *Lolium multiflorum* (annual ryegrass) (Jackson, 1985). Marshes are dominated by *Scirpus acutus* (tule) (Thompson, 1961). Native wildflowers include *Eschscholzia californica* (California poppy), *Lupinus spp.* (Lupine), *Lasthenia gracilis* (Goldfields), *Orthocarpus erianthus* (owl's clover), *Nemophila menziesii* (baby blue eyes), and many others (Minnich, 2008).

The alkali flats and vernal pools which form in winter covered thousands of acres prehistorically. This landscape has virtually disappeared due to extensive rice cultivation, but at the Sacramento National Wildlife Refuge, a few thousand acres of uncultivated alkali land are preserved. Here, spectacular wildflower displays occur in spring in an area that appears barren and dry later in the year. Species include *Eryngium vaseyi* (button-celery), *Plagiobothrys spp.* (popcornflower), *Lasthenia fremontii* (Fremont’s goldfields), *Downingia spp.*, *Grindelia camporum* (Great Valley gumplant), *Hemizonia spp*. (spikeweed), *Sidalcea spp*. (mallow), and *Clarkia spp.* (Silveira, 2000).

The Sacramento Valley, like most of California, has a Mediterranean climate with drought in the summer due to subsidence in the eastern portion of the subtropical high and winter rain from mid-latitude cyclones in the westerlies. Sacramento River flow is affected by snow melt from the mountains to the north and east, which contributes substantially to runoff in the spring. Precipitation varies widely from year to year, and snow melt runoff affects the degree to which the river overflows its banks in the winter. Although the Sacramento River experiences seasonal and interannual changes in flow volumes, the flow has been regulated since the contruction of Shasta Dam in 1945. Little Packer Lake is located within man-made levees, which were constructed beginning in the second half of the nineteenth century (Kelley, 1972).

Methods

Two seven meter long cores were recovered from the central area of Little Packer Lake in September 2008 with a 5 cm diameter Livingstone piston corer equipped with butyrate liners. Water depth was only 20 cm at the time of coring, and subsequent trips have revealed that the lake was dry in 2013. The sediment-water interface was captured with a plastic tube fitted with a piston. Cores were brought back to UC Berkeley and stored in a 5°C cold room.

Pollen samples were extracted using standard procedures (Faegri & Iverson, 1975). Known quantities of *Lycopodium* spores were added to each sample prior to digestion to calculate pollen concentrations and accumulation. Samples for pollen analysis were taken from the cores at 10 cm intervals from 0 cm to 320 cm and at approximately 20 cm intervals from 320 cm to 680 cm. Samples were mounted in silicone oil on slides and pollen was counted at 400x magnification using a Leitz Dialux microscope. Forty-eight samples were analyzed, with 37 samples counted to approximately 400 grains per sample. Due to low pollen concentrations, 3 samples were counted to a minimum of 300 grains, 7 samples to a minimum of 200 grains, and 1 sample to 160 grains. Variability in pollen concentrations may be related to changes in hydrology associated with occasional flooding from the Sacramento River. Pollen was identified using the University of Calfornia Museum of Paleontology pollen reference collection and published keys (McAndrews *et al.*, 1973; Bassett *et al.,* 1978; Kapp *et al.*, 2000). Pollen frequencies were plotted as a percentage of total non-aquatic pollen (Fig. 2 & 3).

Chronology

Chronology for the core was established using three AMS radiocarbon dates and one assigned date (see Table 1). The assigned date is based on matching significant peaks in magnetic susceptibility with the historic flood record of the Sacramento River (Fig. 4). Peaks in magnetic susceptibilty are probable flood events, as these peaks indicate a high influx of mineral material in the lake. We matched peaks in magnetic susceptibility to known historic floods in 1862, 1907, 1909, 1940, 1955, and 1970 (Leach & Van Woert, 1968; Kelley, 1972). We determined the peak at 200 cm depth was likely the 1862 flood, and used this date as a chronological marker for

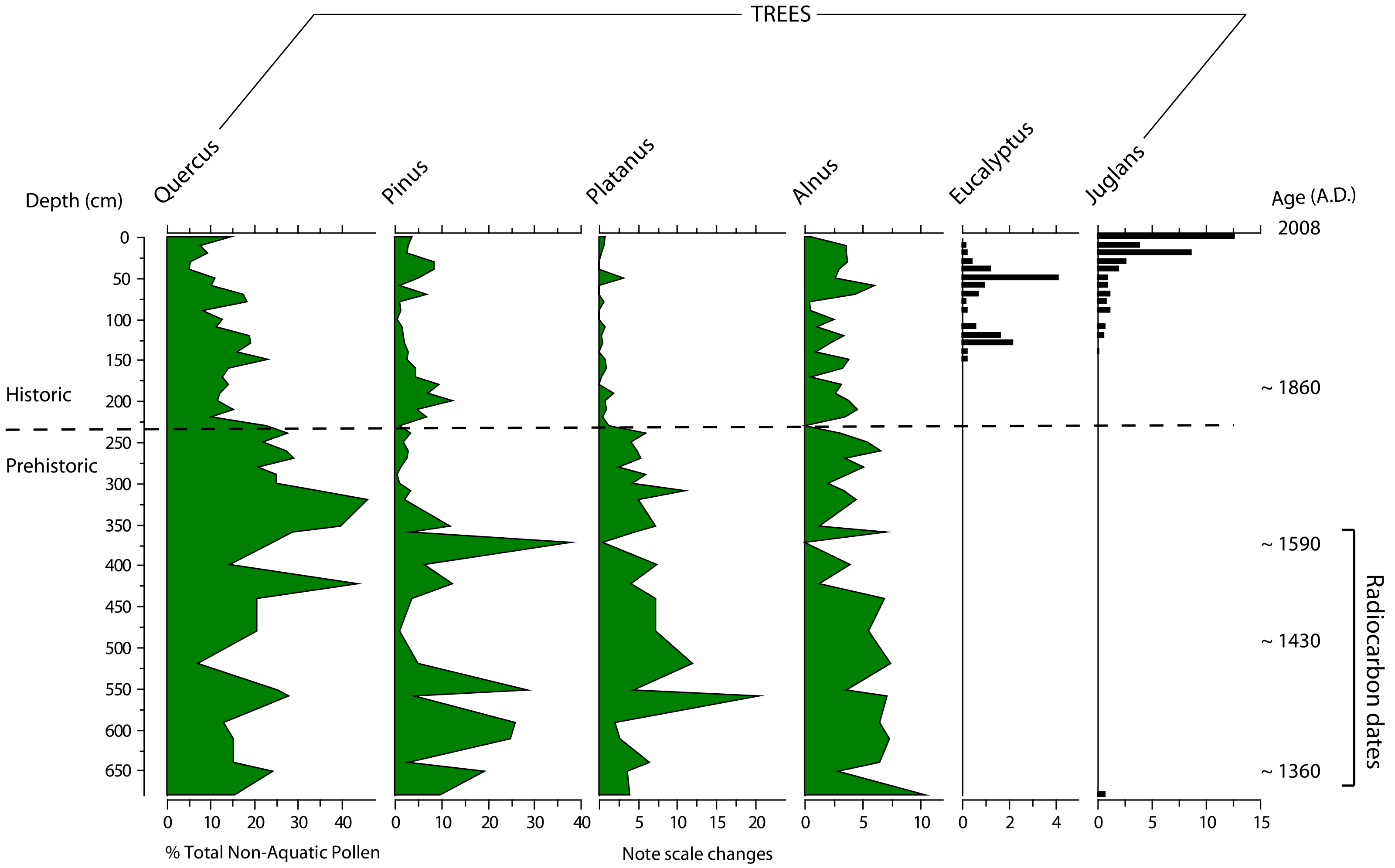

Figure 2. Percent pollen diagram showing selected trees. Non-native trees are depicted with the bar symbol.

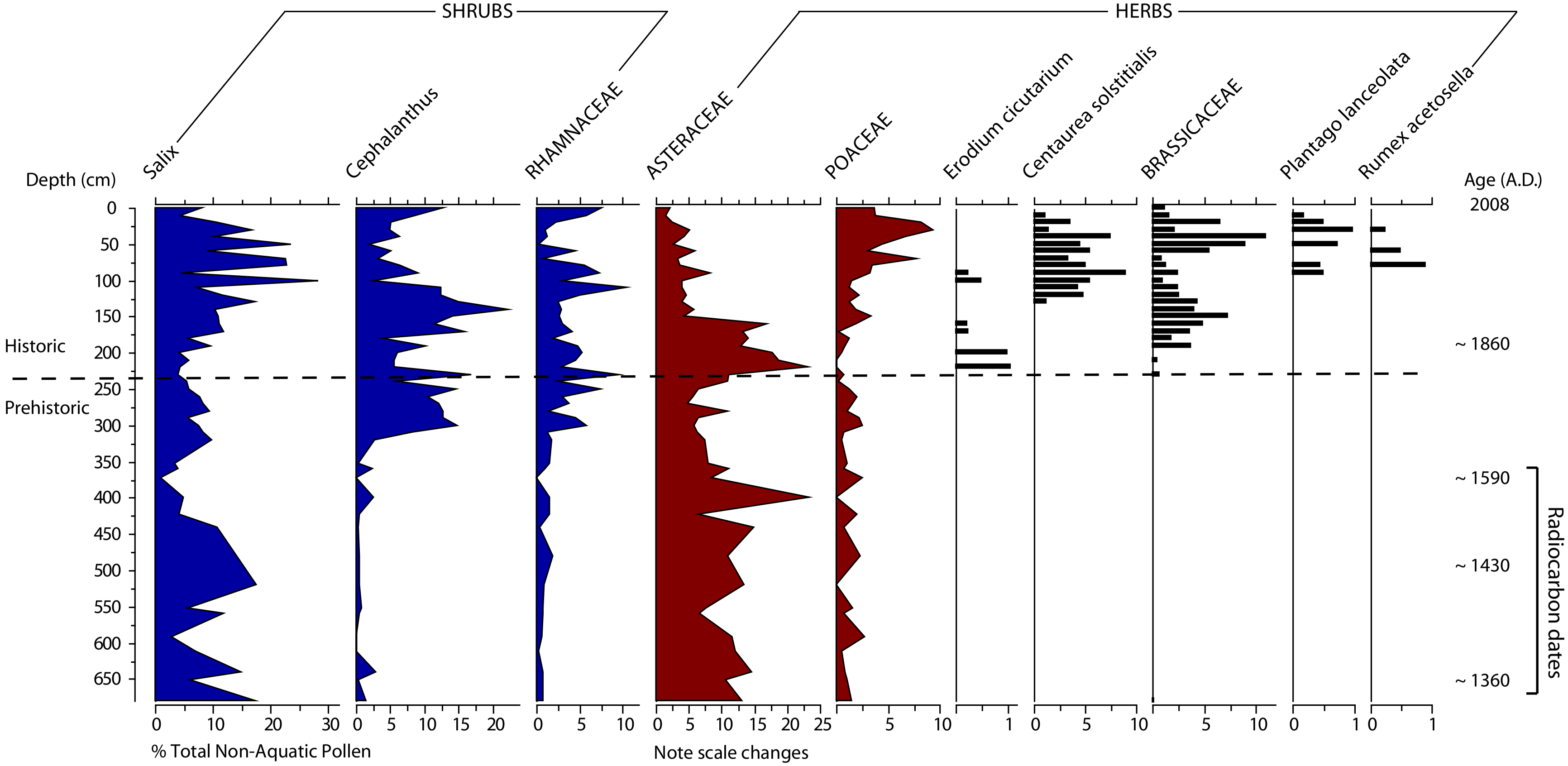

Figure 3. Percent pollen diagram showing selected herbs and shrubs. Non-native herbs are depicted with the bar symbol.

Table 1. AMS radiocarbon dates and assigned date for Little Packer Lake

Depth (cm)	Historic Flood (yr A.D.)	Lab No.	Radiocarbon age (^{14}C yr B.P.)	Calibrated age[1] median probability (cal yr A.D.)	Age range 2 sigma (cal yr A.D.)
200	1862				
370		CAMS-150140	275 ± 30	1591	1513-1600
510		CAMS-150141	490 ± 30	1427	1405-1449
650		CAMS-150142	560 ± 60	1362	1295-1439

[1] Calibrated ages were calculated using the Calib 6.0 program (Stuiver *et al.*, 2010)

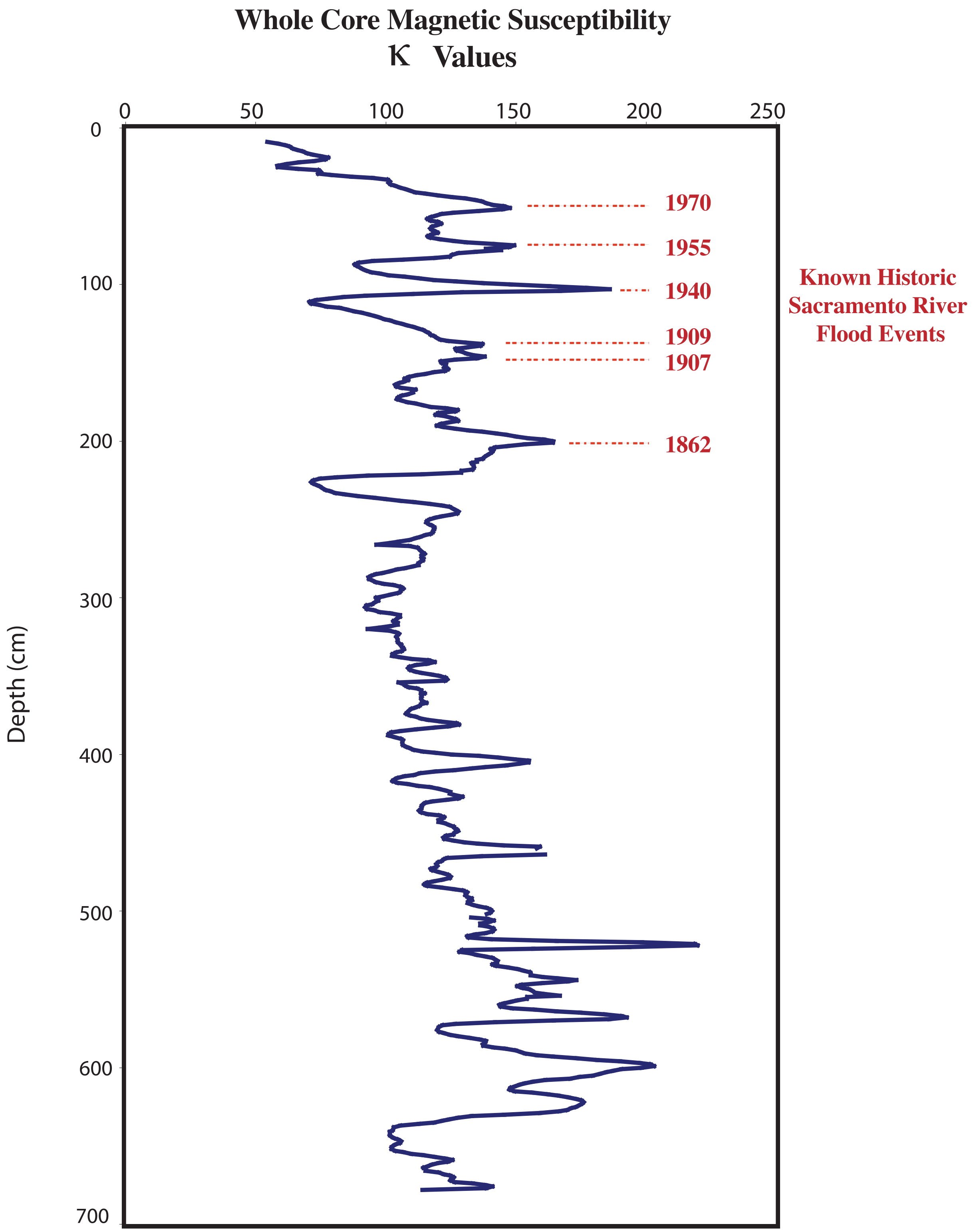

Figure 4. Magnetic susceptibility peaks matched with known historic Sacramento River flood years.

the upper portion of the core. Loss on ignition (LOI) shows a similar inverse pattern to the magnetic susceptibility data since periods of flooding are lower in organic content, and therefore have a low LOI value (Fig. 5). For the age-depth model, sedimentation rate was calculated using a 3rd order polynomial regression with the three calibrated radiocarbon dates and assigned date for the magnetic susceptibility peak at 200 cm (Fig. 6).

Results

Pollen results are presented as percentage diagrams in Figures 2 and 3. For purposes of discussion, the diagrams are divided into two zones: Prehistoric and Historic. The zone boundary is set at ca. A.D. 1800 based on our age model, which is just prior to the first Spanish explorations in the Sacramento Valley and marks the beginning of important ecological changes in this part of California.

Prehistoric Zone (A.D. 1230 – A.D. 1800; 680 cm – 235 cm) **–** Pollen in the prehistoric zone is dominated by riparian taxa *Quercus* (oak), *Platanus* (sycamore), *Alnus* (alder), and *Salix* (willow), as well as extra-local *Pinus* (pine) and members of the Asteraceae (sunflower) family. Poaceae (grass) pollen is not important in this zone, making up only about one to three precent of non-aquatic pollen. *Cephalanthus occidentalis* (button bush) and the Rhamnaceae-type (buckthorns) increase at the top of this zone. The small amounts of *Juglans* and Brassicaceae found in the bottom level of the core are believed to be due to contamination.

Historic Zone (ca. A.D. 1800 – Present; 235 cm – 0 cm) **–** The first non-native pollen types to appear are *Brassica* and *Erodium* at ca. A.D. 1830. Riparian trees (*Quercus*, *Platanus*, *Alnus*) decline in importance. A second wave of non-native species including *Juglans* (walnut), *Eucalyptus*, *Plantago lanceolata* (English plantain), *Rumex acetosella* (sheep's sorrel), and *Centaurea solstitialis* (yellow starthistle) appear after ca. A.D. 1900. Asteraceae pollen declines, while Poaceae pollen increases near the top of the core.

Discussion

The arrival of the Spanish missionaries in San Diego in 1769 marked the beginning of significant ecological changes in California, although some evidence indicates that non-native plants may have spread into California even earlier (Hendry, 1931; Mensing & Byrne, 1998). By 1834, there were twenty-one missions along the coast from San Diego to Sonoma. Meanwhile, Russian merchants were establishing settlements along the coast north of San Francisco. Many non-native plants were introduced by the missions and Russian settlements during this time period, either intentionally or as impurities in crop plants (Burcham, 1957).

Prior to Spanish arrival in California, large populations of California Indians living along the Sacramento River likely altered local vegetation through the use of fire (Lewis, 1973). Though it is impossible to know exactly how many people lived in the

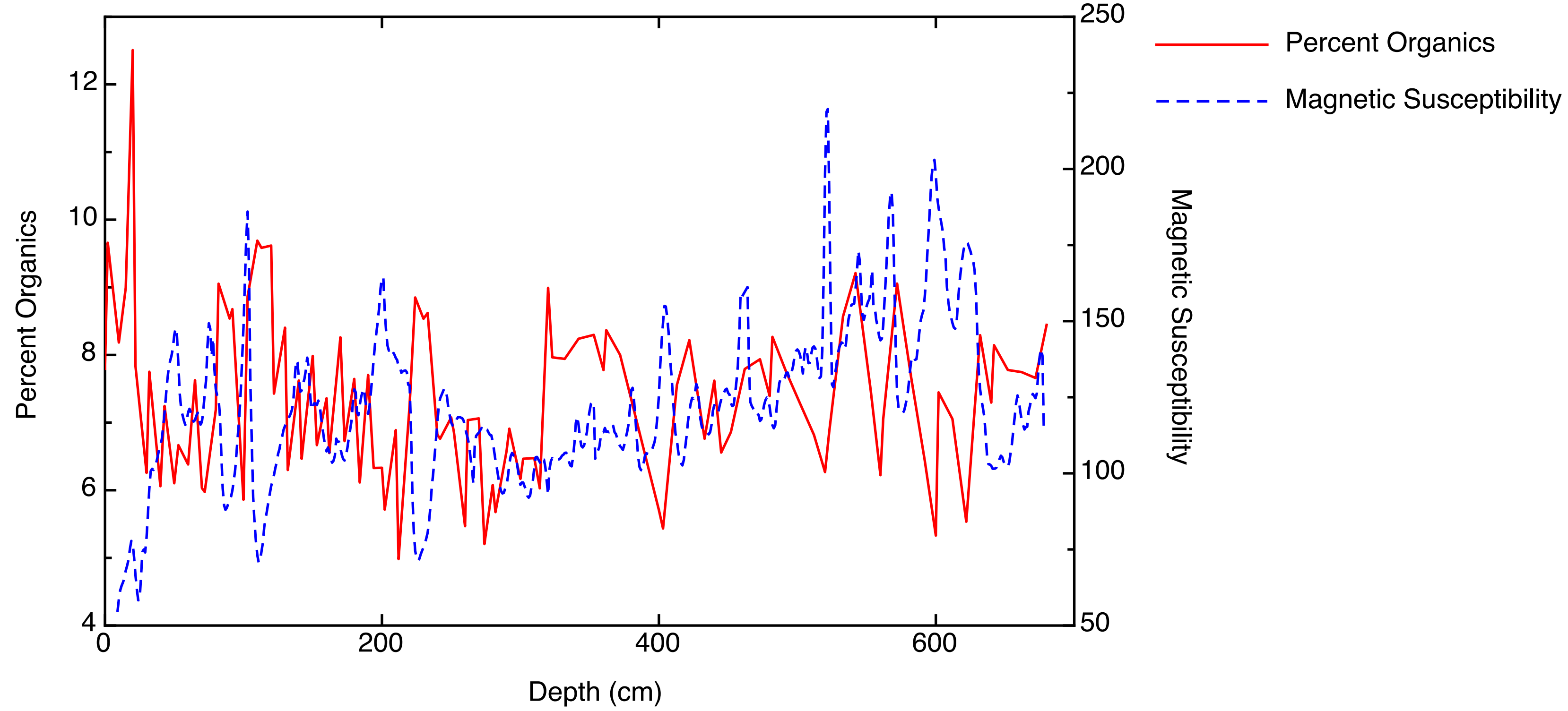

Figure 5. Loss-on-ignition and magnetic susceptibility data show an inverse relationship related to periodic flooding of Little Packer Lake from the Sacramento River.

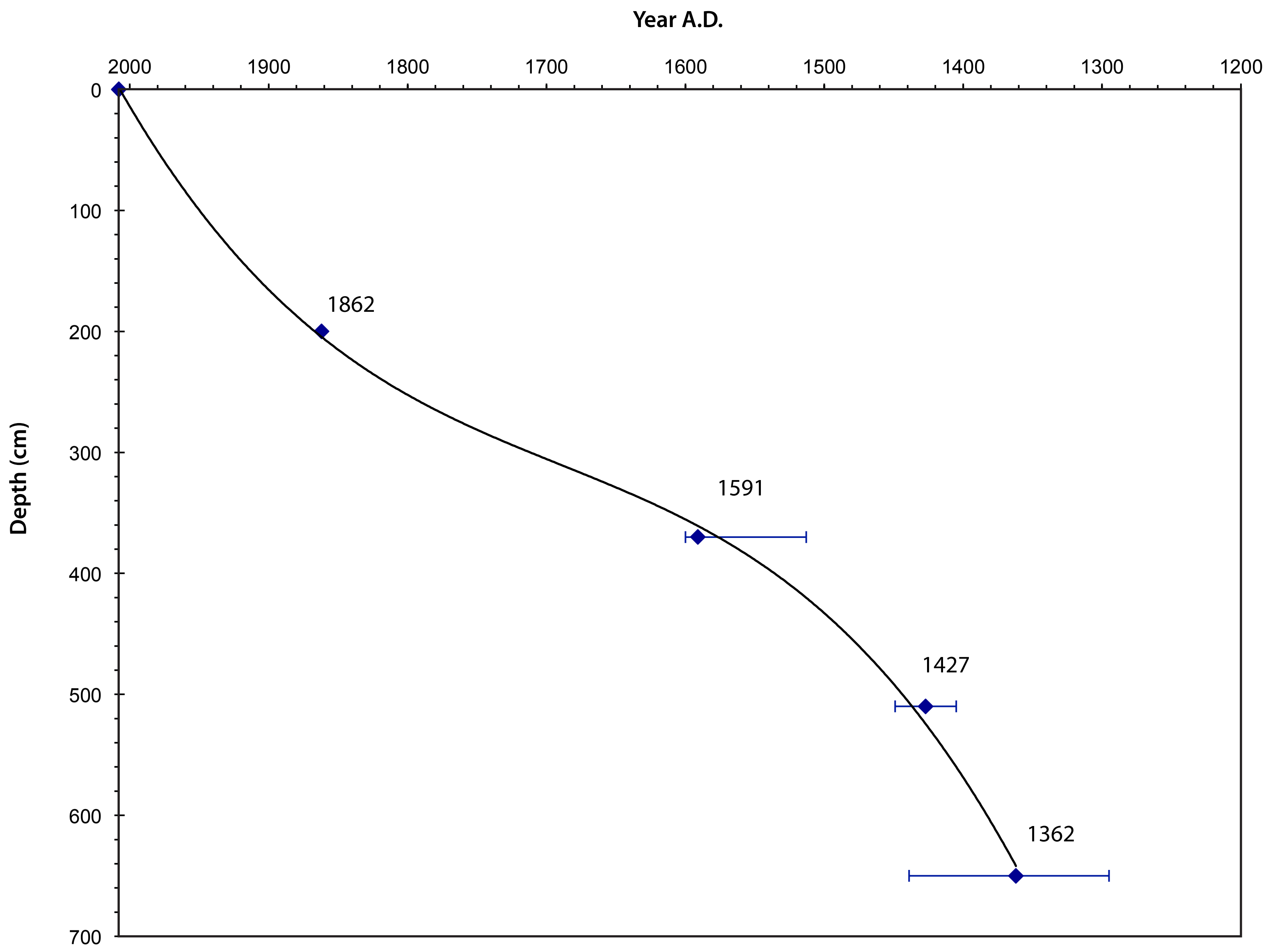

Figure 6. Age-depth curve calculated from 3 radiocarbon dates and 1 assigned date using a 3rd order polynomial regression.

valley prior to European arrival, archaeological evidence suggests that it was one of the most densely populated regions in the state (White, 2003). Cook (1976) estimated that approximately 105,000 people lived in the Central Valley in the eighteenth century, and roughly 53,500 lived in the Sacramento Valley. John Bidwell estimated in 1844 that approximately ten thousand Native Americans lived in the territory that would later become Colusa and Glenn Counties, though a plague in 1833 had severely reduced their numbers (Green, 1950; Gudde, 1936). California Indian populations drastically declined during the nineteenth century due to epidemics and harsh living conditions at missions (Lightfoot, 2005).

Spanish explorers entered the Sacramento Valley for the first time in 1808, but settlement did not begin until the 1830s. The valley was divided into ranchos during the Mexican Period (1821-1848), when early settlers maintained small-scale farms and ranches. After gold was discovered in 1848 and California became part of the United States, the population of new settlers in the valley increased substantially and drastic changes in land use followed. Farming and ranching became major industries and manmade levees began to alter the flooding patterns of the Sacramento River.

The area around Little Packer Lake has been important agriculturally since the mid-nineteenth century. Wheat farming began in earnest in the 1850s, but was replaced by cattle ranching after a series of droughts in the early 1860s. Very few livestock were brought to the area before 1850, when people flocked to the valley during the gold rush. Rice was planted starting in 1911 and is currently one of the major crops in the region (McComish & Lambert, 1918).

Prehistoric Zone (A.D. 1230 – A.D. 1800; 680 cm – 235 cm) - High percentages of riparian tree pollen types indicate that dense riparian woodland grew near Little Packer Lake prior to European arrival and settlement. The pollen record from Little Packer Lake does not provide conclusive evidence of the plants that dominated the “valley grassland” prehistorically. While members of the Asteraceae family are far more important than members of the Poaceae family, we cannot rule out the possibility that the sediments have only captured a local pollen signal dominated by riparian vegetation and that pollen from plants growing in the surrounding flood basins may have been only infrequently deposited in the lake. However, the relative unimportance of Poaceae pollen suggests grasses may not have been the dominant vegetation type.

John Muir called the Central Valley a “rich sheet of golden compositae [Asteraceae]” (Muir, 1894). High levels of Asteraceae pollen suggest that flowering annuals were an important component of the Sacramento Valley prehistorically. It is feasible that the “California grassland” was dominated by forbs rather than perennial bunchgrasses, an idea which has gained attention in recent years (Minnich, 2008; Blumler, 1992). Phytolith evidence also indicates that California grasslands, which are currently dominated by non-native annual grasses, were not dominated by grasses prehisotrically (Evett & Bartolome, 2013). Since most flowering annuals are insect pollinated, it is not surprising that there is little evidence of other forbs in the pollen record. Some members of the Asteraceae family are at least partially wind pollinated and therefore more prevalent in lake sediments. Species in this family tend to have showy flowers and native species include *Eriophyllum lanatum* (woolly sunflower), *Lasthenia gracilis* (goldfields), and *Layia platyglossa* (tidy tips). Wildflowers found at the vernal pools or in the alkali meadows at nearby Sacramento Valley Wildlife Refuge include several species in the Asteraceae family, such as *Grindelia camporum* (Great Valley gumplant), *Psilocarphus brevissimus* (dwarf woolly-heads), *Psilocarphus oregonus* (Oregon woolly-heads), *Lasthenia fremontii* (Fremont's goldfields), *Hemizonia pungens* (common spikeweed), and *Hemizonia parryi ssp. rudis* (pappose spikeweed) (Silveira, 2000).

Richard Minnich (2008) argues that the valley was a carpet of wildflowers during the spring, which subsequently became a barren land in the summer. He maintains that native annuals would have completed their growth cycle by the end of spring and left the land without vegetative cover unless surrounded by a wetland. Early settlers in the region noted, "everywhere, especially in the spring and early summer there was a profusion of wildflowers. Great patches of color- blue, purple, white, yellow- often acres in extent, were set in the green carpet of the valley" (McComish & Lambert, 1918). Though much of the Central Valley has now been converted to agriculture, some areas still preserve spectacular native wildflower displays, such as at the Sacramento National Wildlife Refuge and Bear Valley in Colusa County.

The increase in *Cephalanthus occidentalis* and other shrubs at ca. A.D. 1670 is likely related to the gradual infilling of the oxbow lake. *Cephalanthus* is known to thrive in areas where still water stands throughout the year (Holstein, 1984), so the shallow edges of the lake probably became prime habitat for this shrub as the water slowly receded.

Historic Zone (A.D. 1800 – Present; 235 cm – 0 cm) - *Erodium cicutarium* has been identified as one of the earliest non-native species to arrive in California and is often the first non-native species to appear in pollen records from California (Mensing & Byrne, 1998). Some evidence indicates that *Erodium cicutarium* spread prior to the introduction of livestock from the California missions, and may have spread north from Baja without the need for disturbance by domesticated livestock (Mensing & Byrne, 1998). It was present in northern California at least by 1827 (Hooker & Arnott, 1841) and was widespread in the Central Valley as early as 1844, when the explorer Frémont wrote, "instead of grass, the whole face of the country is closely covered with *erodium cicutarium*" (1845). The age model suggests that the first appearance of *Erodium cicutarium* at Little Packer Lake dates to ca. A.D. 1830.

The sudden appearance and rapid increase in Brassicaceae pollen in this zone suggests that an invasive species in this family, likely *Brassica nigra* (black mustard) or *Brassica rapa* (field mustard), was an early invader in the Sacramento Valley. *Brassica nigra* is well-known to have escaped mission gardens and spread quickly along the coast (Minnich, 2008). Though there are native species in the Brassicaceae family, the absence of Brassicaceae pollen in the lower sections of the core relative to its importance coincident with other non-natives indicates that it is an invasive type. Little is known about the expansion of mustard into the Sacramento Valley, as most references only note its coastal distribution. It had already invaded mission grounds by the 1770s and preserved specimens were discovered in mission bricks in Baja, California and at mission Soledad built in the 1790s, suggesting that this non-native was present before these mission buildings were constructed (Minnich, 2008). Since the seeds of *Brassica nigra* are dispersed by birds, this species may have been concurrent with the early invasion of *Erodium cicutarium*, which preceded Europeans in California, invading from the southern missions in Baja California (Mensing & Byrne, 1998).

Wild oats (*Avena fatua*) and mustard were often associated and tended to be dominant in large areas at the same time, such as in floodplains and fertile valleys. Russians may have been the first to introduce mustard and wild oats as impurities in crop plants north of San Francisco Bay (Burcham, 1957). Black mustard had spread over thousands of acres by the 1830s, and in the 1840s Edwin Bryant wrote that oats and mustard grew so thickly as to become a nuisance between the Sierra Nevada and Pacific (Minnich, 2008).

In *California Range Land*, Burcham (1957) outlines a sequence of non-native species dominance in California in the nineteenth century. He argues that the first phase of non-native dominance was characterized by wild oats and mustard from 1845 to 1855 and the second by *Erodium* (filaree), *Hordeum murinum* (mouse barley), and *Gastridium ventricosum* (nitgrass) in 1855-1870. While it is unclear what evidence his argument is based on, our pollen results appear to coincide only partially with the first two phases of his sequence.

We do not see evidence of an increase in grasses in the early Historic Zone, which is unexpected given the proliferation of *Avena fatua* in the early years of settlement. This may be due to the relatively short distance that *Avena fatua* pollen travels from the parent plant or to the possibility that the success of this species is related to its ability to self-pollinate (Allard, 1965). The slight decrease in riparian trees in this zone may be indicitive of the dominance of invasive species or to the beginnings of deforestation in the mid-nineteeth century.

The pollen of *Eucalyptus* and *Juglans* first appears ca. A.D. 1900-1910. Both trees were intentionally planted by settlers in the valley during this time period. *Eucalyptus* was introduced to California in 1856 in San Francisco and plantings increased after 1870 around the state (Butterfield, 1935). They were planted in the Sacramento Valley to serve as wind breaks and a cheap source of timber in the late-nineteenth and early twentieth centuries. *Juglans* pollen indicates the beginning of the walnut orchard next to the lake. While there is a native *Juglans* in northern California, ecologists believe that the riparian corridors of the Sacramento Valley were not part of its natural habitat prior to European settlement. The absence of *Juglans* pollen in the prehistoric section of the diagram supports this idea. Settlers started walnut orchards in the region, and crossed *Juglans nigra* (black walnut) rootstock with *Juglans regia* (English walnut) (Strahan, 1984). Historical sources confirm that native *Juglans nigra* trees were first planted in 1907 near Little Packer Lake, and were then grafted with *Juglans regia* buds two years later (McComish & Lambert, 1918). There is a walnut orchard currently next to the lake, and not surprisingly *Juglans* is an important component of the pollen record in the top portion of the core.

Centaurea solstitialis (yellow starthistle), an invasive weed, appears in the record at ca. A.D. 1920 and continues to be an important component to the present. *Centaurea solstitialis* was introduced unintentially as an impurity in alfalfa seed, which was grown for stock grazing on natural river levees beginning in the 1850s and 1860s in the Sacramento Valley (Gerlach, 1997). By 1918, there were approximately 20,000 acres of alfalfa in Colusa and Glenn Counties (Rogers, 1891; McComish & Lambert, 1918).

Rumex acetosella and *Plantago lanceolata*, non-natives which appear near the top of the core, are indicators of disturbance. According to historical evidence, *Rumex acetosella* arrived in northern California during the Mission period, and *Plantago lanceolata* is first reported during the Gold Rush (Frenkel, 1970). After significant deforestation and disturbance from farming and ranching, these two non-natives were able to colonize newly opened habitat. The slight increase in members of the Poaceae family near the top of the core is likely due to the introduction of agriculture or to the dominance of invasive grasses in the face of deforestation and increasing disturbance. Cultivated wheat and rice may be responsible for the increase in Poaceae pollen in the top portion of the core.

Whether overgrazing played a role in the early spread of non-native plants in California is a subject of debate (Burcham, 1957; Blumler, 1992; Minnich, 2008). Though Burcham claimed that herds of wild cattle were in much of the Central Valley prior to the Gold Rush, he also noted that cattle on mission lands along the coast accounted for a large proportion of livestock in California before 1840. Minnich and Blumler argue that biological invasion theory and competitive exclusion are sufficient to explain the transformation of California vegetation in the mid-nineteenth century and need not require such explanations as overgrazing since *Brassica* spp., *Erodium cicutarium*, and *Avena fatua* spread into the area before the period of intensive grazing by cattle in the late 1850s and early 1860s.

If large herds of feral livestock roamed the valley prior to the 1850s, it seems unlikely that their influence would outweigh that of native grazing herbivores since accounts of early explorations document significant numbers of native elk, deer, and antelope. For example, during the Belcher expedition, “whenever anybody had an opportunity of penetrating the thick, dense barriers of trees and shrubs that lined the banks, he arrived upon a vast plain almost without an inequality covered with the richest pasture and interspersed with parklike groups of trees, on which large herds of elk, consisting sometimes of several hundreds, were constantly grazing.”

(Pierce & Winslow, 1969). Another account is that of Green from "The Sacramento Valley as Will S. Green saw it in 1850": “Over this vast plain roamed tens of thousands of antelope; skirting the timber and the foothills were great bands of elk; in the hills and along the river were an abundance of deer…” (Green 1950, supplement VII). A map by George Derby dating to 1849 shows feral livestock in the Sacramento Valley, and also indicates that native grazers were abundant in the same area (Thompson, 1961).

Our pollen evidence shows a primary invasion of *Erodium cicutarium* and *Brassica* spp., which preceded the overgrazing period of the late 1850s and early 1860s, was followed by a secondary invasion by weeds associated with agriculture around the turn of the twentieth century. Therefore, livestock grazing does not appear to be a causal factor in the initial spread of invasive species at our site. Even if feral cattle and horses were grazing parts of the Sacramento Valley prior to extensive settlement, it seems unlikely that their influence would be more intensive than the grazers that were already present prior to European arrival. While grazing may have contributed to the dispersal of some non-native plants, overgrazing was not required for non-natives to successfully invade. Minnich notes, “the novelty of the Hispanic period was not the introduction of livestock, but the introduction of herbaceous annual species from Europe” (Minnich, 2008).

Conclusion

The Little Packer Lake pollen record reflects the dramatic changes that occurred with European exploration and settlement of the Sacramento Valley. It demonstrates that *Erodium cicutarium* and *Brassica* spp. were the earliest non-native invaders in the region, and subsequent invasions and introductions were the result of agriculture and arboriculture. Several non-native taxa are recorded in the upper levels of the core and riparian taxa decrease, both because of the dominance of non-native weeds and due to clearing for farms and orchards. There is no evidence that overgrazing played a signficant role in the spread of invasive species in this study.

Also, there is no evidence for a Sacramento Valley dominated by grasses. However, as the dense riparian woodland surrounding the lake may have acted as a screen and filtered out extra-local pollen, it is not certain that grasses were not important. The limited pollen production of native grasses may also account for the low grass pollen percentages prior to European contact. However, given the significance of Asteraceae pollen, we can be certain that herbaceous plants were important prehistorically.

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Chapter 5

CONCLUSION

Both changes in land use and the introduction of invasive plants have transformed the landscape of central California since the arrival of Europeans in the late eighteenth and early nineteenth centuries. Important changes in vegetation and fire frequency occur during and after the time of European arrival in all three studies in this dissertation. At Little Packer Lake, a detailed sequence of non-native species is documented in the pollen record, with the early arrival of redstem filaree (*Erodium cicutarium*) and mustard (*Brassica* spp.). More non-native plants (*Eucalyptus*, *Juglans*, *Centaurea solstitialis*, *Plantago lanceolota*, and *Rumex acetosella*) appear later in the pollen record after the Sacramento Valley was settled by Euro-Americans in the mid-nineteenth century, appearing in association with the establishment of agriculture and arboriculture in the valley. At Skylark Pond, decreases in redwood (*Sequoia sempervirens*) pollen and increases in grass (Poaceae) and bracken fern (*Pteridium aquilinium*) pollen at the top of the core indicate an opening of the redwood forest due to the establishment of logging operations in the Santa Cruz Mountains. The increase in fire frequency or severity is likely due to the burning of logging slash in this region. Sheep's sorrel (*Rumex acetosella*), a non-native plant, appears at the top of both the Skylark Pond core and the Laguna de las Trancas core.

Native Americans may have had an important influence on the environment in central California with the frequent use of fire, but untangling human influence from climate is difficult in pollen studies. Microscopic charcoal evidence from both Laguna de las Trancas and Skylark Pond imply that people may have been setting fires along the coast from the mid-Holocene until present, opening up the surrounding forest to more herbaceous and shrubby plants that regenerate after low-severity fire. Increases in charcoal are tentatively interpreted as fires set by humans since lightning ignition is rare along the coast and fire scar studies in this region have shown a prehistoric fire regime that is more frequent than would be expected from naturally occurring fires. This conclusion is made with some caution, however, because of the need for other lines of evidence that rule out climate as a factor.

The pollen record from Laguna de las Trancas indicates important shifts in climate along the central coast of California during the late Pleistocene and Holocene. Prior to the LGM (Last Glacial Maximum), a cypress and pine or juniper and pine forest dominated the region. Interpretation of climate during this period is hindered by the difficulty in identifying species within the Cupressaceae and Taxaceae families with light microscopy. The LGM is characterized by cool, dry conditions based on increases in grasses and herbaceous vegetation. Winds may have been stronger along the coast, blowing sand from coastal dunes into the marsh. A wet phase occurs during the glacial-interglacial transition, indicated by the presence of grand fir (*Abies grandis*) pollen at this site. The early Holocene is missing in the sediment core, but a significant peak in microscopic charcoal at the mid-Holocene shows that the marsh likely caught fire during this time. Subsequent high charcoal abundance in the core indicates the importance of regularly occurring fires in this region in the mid- to late-Holocene. The importance of redwood (*Sequoia semprevirens*) suggests that marine fog and stratus have been present in this region during the Holocene. Climate appears to have been relatively stable throughout the Holocene, with frequent fire and the prevalence of marine fog and stratus in the summer months.

Future work will need to further address the extent to which Native Americans may have had an influence on the environment with the use of fire, as well as address the nature of early Holocene climate in this region. A comparison with the new pollen and charcoal record from Clear Lake, a study which is currently underway, will aid in sorting out regional versus local impacts of climate change along the central coast. This high-resolution record will also better establish a chronology for important climate shifts in central California, such as the wet phase during the glacial-interglacial transition. Additionally, more fire scar records in the region will lend further evidence to the hypothesis that humans created a more frequent fire regime prehistorically. Ideally, a comparison with the charcoal record from the last interglacial, when humans were not present in North America, would shed light on whether the increase in fire frequency in the Holocene is human-induced or related to a more seasonal climate.