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Holocene Carbon Sequestration and Ecosystems of Wetlands in the San Joaquin Watershed, California

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Holocene Carbon Sequestration and Ecosystems of Wetlands in the San Joaquin Watershed, California

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Geography

by

Scott Edward Lydon

2022

ABSTRACT OF THE DISSERTATION

Holocene Carbon Sequestration and Ecosystems

of Wetlands in the San Joaquin Watershed, California

by

Scott Edward Lydon

Doctor of Philosophy in Geography

University of California, Los Angeles, 2022

Professor Glen Michael MacDonald, Chair

Sediment cores were collected from wetlands along a headwaters-to-estuary gradient within the San Joaquin watershed, California, to examine environmental changes, and carbon (C) storage and sequestration rates over the Holocene. Local hydrogeomorphic conditions were the primary drivers of C sequestration at seven wetland systems analyzed Paleoecological assays of C and multiple paleo-indices were conducted on two cores from the Sacramento-San Joaquin Delta, three cores from Yosemite National Park, and on two cores from Sequoia-Kings Canyon National Park to reconstruct C storage and ecosystem functioning of wetland systems in the watershed over the Holocene. Bayesian age-depth models were developed using cesium 137/lead 210 and radiocarbon dating. Paleo proxies such as loss-on-ignition, pollen, x-ray fluorescence, and charcoal showed that local hydrogeomorphic conditions were the primary drivers of variability in C sequestration at 7 wetland systems analyzed. There is some evidence of C

sequestration responding to past warming by changing vegetation types, altering geochemical concentrations of crustal elements, and varying the frequency of wildfires. A 300 cm sediment core retrieved from Dana Meadow, Yosemite National Park, spans the past 9000 years and indicates carbon storage was ≥ 24 g m^2 yr^{-1} during the Holocene Thermal Maximum (~8000 – 3000 years ago). By the mid-Holocene, terrestrial plants like *Quercus* and *Tsuga mertensiana* expanded upslope amid prolonged warming. Average rates of C sequestration and vertical accretion from the five Yosemite and Sequoia-Kings Canyon wet meadows indicate regional similarities to rates of C storage from subalpine fens in the mountains of western North America as far north as Alberta, Canada. The two cores from the Sacramento-San Joaquin Delta present no clear relationships between C content and climate change. In the Delta, decreases in C content and sedimentation rates occurred after Euro-American settlement in the 19th century, trends that continue during the 21st century. The findings of this dissertation on the whole suggest: 1) no regionally coherent climatic response to past climatic changes was shown in the paleo indices measured for the seven sediment cores from the Delta and Sierra; 2) there is much local variability in the histories of these wetlands and their C sequestration records; 3) local variations in hydrogeomorphology appears to be a primary driver of natural C sequestration and storage for each site; 4) such variability likely reflects differing responses and sensitivities to the impacts past climatic change as well as local hydrogeomorphology; and 5) although this study detected no widespread coherent response of the San Joaquin wetlands C dynamics to past Holocene climatic changes, documenting and helping to understand the potential variability of such environmental systems is arguably just as important in anticipating California’s climate change future and its potential variability of responses.

The dissertation of Scott Edward Lydon is approved.

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2022

A list of people who helped me reach this point would require many more pages than is allowed. I am indebted to Professor MacDonald for his tireless devotion to his students. Brady, Owen, Kalia—this is for you.

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Writing the names of the vast numbers of UCLA undergraduate students that assisted in the field and in the lab could take up an entire page. If I do not list your name here, it is my own oversight. That said, I am particularly grateful for the assistance of: Lisa Martinez; Emily Smith; Cameron Powell; Renate Boronowsky; My Nguyen; Trevor McCracken; Susan Liang; and many others who I worked with in the lab or with field research. I am also grateful for: Marcus Thomson; Katherine Glover; Katherine Willis; Julie Loisel; James Holmquist; Lauren Brown; Elizabeth Fard; Jessie George; Remi Bardou; Mark Ciochina; Jiwoo Han; Benjamin Nauman; Jason Kindinger; Avishesh Neupane; Simona Avnaim-Katav; and several others--thank you.

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California Missions Foundation, 2018, Boronowsky, R., Lydon, S. Illuminating Alta California Culture And Land-Use: A Partnership Between Historical Cartography And 21st Century Geographic Information Systems

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1. Introduction

The natural sequestration of atmospheric carbon (C) in wetlands and forests could be an important C sink globally and in California, drawing scientific and policy interest as a means of addressing anthropogenic climate change (Bonan, 2008; Seddon, 2022; Seddon et al., 2020; Thorslund et al., 2017). Modeled projections indicate by the end of the 21st century, average annual temperatures in California could increase 2.0˚ to 4.0˚C, resulting in enhanced evaporation and aridity (Cayan et al., 2007; Cloern et al., 2011; Dettinger et al., 2016a; Kumar et al., 2013; Taylor et al., 2007; Bedsworth et al., 2018). How such warming will impact C storage and ecosystem functioning in California's freshwater wetlands, forests, and wet meadows remains uncertain (Callaway et al., 2012; Dettinger et al., 2016; Drexler, 2011). It is known that C accumulation occurs in wetlands with water-saturated soils, thus hydroclimatic and geomorphological conditions work in tandem with net primary productivity to determine C storage (Barrow, 1994; Bernal & Mitsch, 2012; Bridgham et al., 2006, 2013; Campbell et al., 1994; Chapin et al., 2006; Craft et al., 2009; Kayranli et al., 2010). Desiccation of wetlands could decrease rates of C sequestration, resulting in emissions of CO_2 and CH_4 (Bridgham et al., 2013; Strachan et al., 2015; Zheng et al., 2020). Wildfires could also lead to C emissions because of vegetation burning (Dettinger et al., 2016; Zhao et al., 2011, 2014). Because of this uncertainty under future conditions, scientists examine the past for baseline C sequestration data for these ecosystems and to understand wetland responses during periods of prolonged aridity and warming throughout the Holocene.

In California, the freshwater wetlands of the San Francisco Bay and Sierra Nevada wet meadows are potentially important stores of C that could be compromised due to climate warming, wetland desiccation, or fires (Gonzalez et al., 2015; Nahlik & Fennessy, 2016).

Roughly 60% of California’s precipitation eventually flows downstream into the San Francisco Bay from the Sacramento-San Joaquin Delta, where several freshwater and estuarine wetlands that sequester C are located (California Department of Water Resources 1995). The Sierra Nevada has many wet meadows and adjacent forests where considerable natural C capture takes place (Lalonde et al., 2018; Norton et al., 2011). Desiccation and decay of organic matter might decrease C content in wetlands while forest fires and vegetation change might decrease C sequestered by forests (Gonzalez et al., 2015; Moomaw et al., 2018) amid climate warming this century. For both the Delta wetlands and Sierra wet meadows, however, important questions remain pertaining to long-term C storage and responses topast climate warming (Blackburn et al., 2021; Norton et al., 2011).

The Delta and Sierra wetlands form two end members of a continuum of California’s wetland C storage and sequestration system at the high and low elevation ranges of the California environment. The Sacramento-San Joaquin Delta’s headwaters are in the Sierra Nevada, where precipitation on the western sloped eventually flows downstream into the Central Valley through one of the many tributaries within the range, or eastward into the Great Basin from the eastern slopes. The San Joaquin River is the main southern tributary for the Delta system, with its headwaters near Devil’s Postpile National Monument, a short hour-long drive from Yosemite National Park and the wet meadows analyzed for this dissertation. The San Joaquin Watershed connects the Sierra wet meadows to the freshwater wetlands of the Delta by hydrology. Hydroclimatic conditions in the Sierra near the river’s headwaters drive C storage in the adjacent wet meadows and forests, and eventually influence C sequestration in the freshwater and estuarine wetlands found downstream in the Delta.

Sediment coring and multi-proxy analyses of the cores provide a means of assessing the current amount of C held in these systems, its long-term rates of sequestration and the response of these systems to past climatic and environmental perturbations over the Holocene. By gathering sediment cores from the 7 wetlands for this dissertation (see Figure 1.1) it is hoped to increase knowledge of C stores in these systems and their responses to climatic and environmental changes. Analytical thermal-chemistry methods were employed to estimate organic content and C sequestration at high resolution (1 cm) for the length of each core (Heiri et al., 2001) and provide ages for events detected in the records. This was possible because the cores were dated using a combination of ^{137}Cs,^{210}Pb210 and ^{14}C dating, then age-depth models were developed using Bayesian modeling to quantify uncertainty associated with the ages for each core (Blaauw & Christen, 2011; Oldfield et al., 1979). To assess ecosystem functioning at each age-depth interval of a core, paleo-indices assessing past fire occurrence (charcoal analysis), vegetation dynamics (fossil pollen), and elemental geochemistry (x-ray fluorescence) were utilized (Brunelle & Anderson, 2003; Fard et al., 2021; MacDonald et al., 1991; Whitlock & Larsen, 2002; Xiao et al., 2020). This sediment coring method in combination with analytical chemistry, age-depth modeling, and paleo-indices provided estimates of C storage for each wetland of this dissertation for about the last 2,000 cal yr BP, and in the case of Dana Meadow (Yosemite; YNP) roughly ~9,000 cal yr BP. Paleoecological studies such as this dissertation provide insights of the impacts of known past climate changes on wetland systems and the responses to past warming and aridity during the Holocene (Brunelle & Anderson, 2003; Fard et al., 2021; J. R. Holmquist et al., 2016; MacDonald et al., 1991; MacDonald et al., 2016; Whitlock & Larsen, 2002; Yu et al., 2011). The specific study sites and questions addressed in this dissertation are outlined below.

In Chapter 2 I will use the multi-proxy analysis of radiocarbon dated sediment cores examine the Browns Island and Bacon Channel Island wetlands and address the following questions:

1. What are the long-term patterns and changes in sediment C content/sequestration rate at BCI and BI over the late Holocene?
2. How did sediment C content/sequestration rates change at BCI and BI during past periods of prolonged higher temperatures, e.g. during the Holocene Thermal Maximum (~3000 cal yr BP to 8000 cal yr BP: calendar years before 1950 CE) and Medieval Climate Anomaly (950 cal yr BP to 1350 cal yr BP)?
3. What is the relationship between sediment C content/sequestration rates at BCI and BI during the prolonged cooling of the Little Ice Age (100 cal yr BP to 600 cal yr BP)?
4. What other changes related to local vegetation cover, local fire or local hydrological conditions that have occurred that could have impacted C content/sequestration rates at BCI and BI?

In Chapter 3 I will use the multi-proxy analysis of radiocarbon dated sediment cores examine the Porcupine Flat (YNP); Tuolumne Meadow (YNP); Dana Meadow (YNP); Dorst Meadow (Sequoia-Kings Canyon National Park; SKCNP); and Log Meadow (SKCNP) wetlands and address the questions of:

1. What are the long-term patterns and changes in sediment C content/sequestration rates at three sampled wet meadow sites in YNP and two sites in SKCNP during the late Holocene?
2. How did sediment C content/sequestration rates change at YNP and SKCNP during past periods of prolonged higher temperatures, e.g. during the Medieval Climate Anomaly (950 cal yr BP to 1350 cal yr BP)?

3. What is the relationship between sediment C content/sequestration rates at YNP and SKCNP during the prolonged cooling of the Little Ice Age (100 cal yr BP to 600 cal yr BP)?
4. Do western mountain regions show the C content and sediment accretion rates rates to the wet meadows sampled at YNP and SKCNP?

In Chapter 4 I will use the multi-proxy analysis of radiocarbon dated sediment cores to examine the past 10,000 years of the sediment core retrieved from Dana Meadow (YNP), and address the questions of:

1. What is the total depth of organic meadow sediment and average % carbon content stored in this meadow system based on the core?;
2. How has the rate of carbon sequestration and storage varied over time?;
3. How have large-scale climatic events such as the Holocene Thermal Maximum (HTM), Medieval Climate Anomaly (MCA) and Little Ice Age Impacted the meadow ecosystem, surrounding forest and rate of carbon sequestration and storage?

Taken as a whole, each study provides data and insights that combined can be used to address the following general over-arching question: Do these wetlands display similar contemporaneous responses to these past climatic variations, or are they more typified by a high degree of site-to-site variability related to localized changes in local vegetation cover, local fire or local hydrological or geomorphological conditions? Chapter 5 will present a brief summation of findings in this context and thoughts on suggestions for future work.

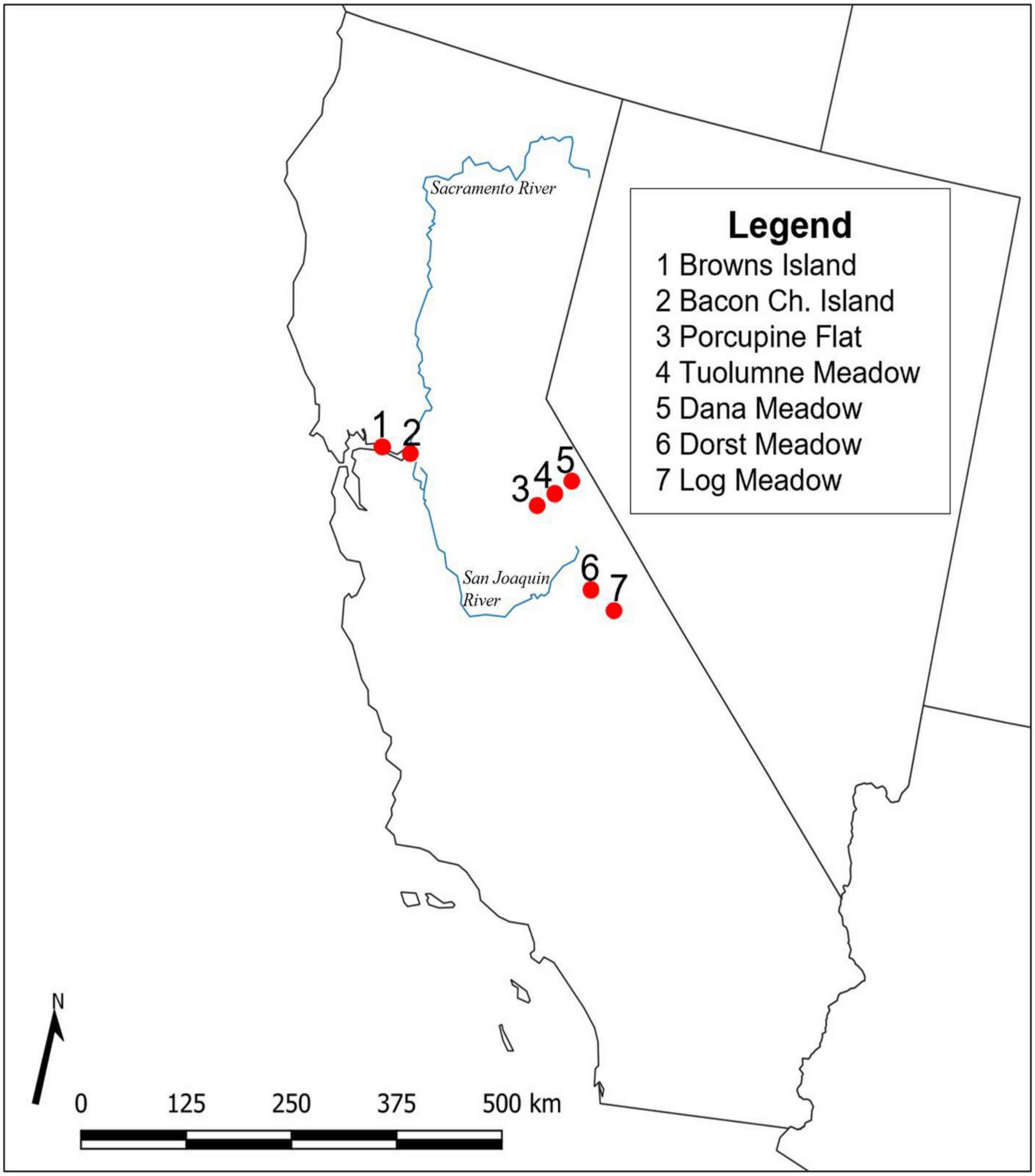

Figure 1.1 Location of study sites discussed in this dissertation that show natural rates of C storage. Sites 1 and 2 are situated in the Sacramento-San Joaquin Delta. Wet meadows 3-5 are in Yosemite National Park, whereas meadows 6 and 7 are in Sequoia-Kings Canyon National Park, California.

2. Paleoecology of the Sacramento-San Joaquin Delta's Freshwater Wetlands

2.1 Abstract

The wetlands located in California's Sacramento-San Joaquin Delta are a vital C pool as warming increases during the 21st century due to anthropogenic climate change. This study presents high-resolution paleoecological data from 2 sediment cores gathered from BCI and BI located in the Delta. The cores were retrieved to answer the following research question: how was C accumulation and ecosystem functioning within two of the Delta's relatively pristine marshes impacted by climate change during the late Holocene? Analysis discusses the key drivers of C accumulation and ecosystem functioning at both marshes during the last ~5,000 years. This baseline data indicates that local hydrogeomorphic factors were the primary drivers of C sequestration and ecosystem functioning during past periods of warming and cool conditions. No clear relationships are shown in the data between C content and climate change between BCI and BI. Decreases in C content and sedimentation rates occurred after Euro-American settlement in the 19th century, and these trends continue in the 21st century. Local hydrogeomorphic factors and land-use history were the main drivers of C accumulation at both marshes during the past 5,000 years.

2.2 Introduction

Anthropogenic climate change during the 21st century poses a significant threat to California's ecosystems (Ackerly et al., 2010; Fard et al., 2021; Holmquist et al., 2011; Lenihan et al., 2007; MacDonald et al., 2016; Parmesan, 2006; Wolf & Cooper, 2015; Bedsworth et al. 2018). Freshwater wetlands throughout the state are now susceptible to desiccation because of higher temperatures and reduced wintertime precipitation (Aber et al., 2012; Cooper et al., 2012;

Drexler et al., 2013). During this century, drought and warmer temperatures may cause freshwater wetlands statewide to decrease in areal extent (Loarie et al., 2008; Parmesan, 2006; Drexler et al., 2013). Such ecosystems constitute one of the world's most important C pools and are key for mitigating methane (CH^4) emissions (Chmura et al., 2003; Mitsch & Hernandez, 2013; Pendea & Chmura, 2012).

It remains uncertain, however, how the C cycle of California's freshwater wetlands will be impacted by climate change (Callaway et al., 2012; Dettinger et al., 2016a; Drexler, 2011). The accumulation of C in water-saturated soils (i.e. hydric soils) is mainly determined by any given wetland's hydrology, and driven by net primary productivity (NPP; i.e. the amount of energy fixed minus the energy lost during respiration) (Barrow, 1994; Bernal & Mitsch, 2012; Bridgham et al., 2006, 2013; Campbell et al., 1994). The storage of C is a balance between NPP and the aerobic-anaerobic zone in a wetland's water table (Chapin et al., 2006; Craft et al., 2009; Kayranli et al., 2010). By 2100, temperatures are projected to increase from 2.0-4.0˚C, leading to enhanced evaporation and a longer dry season in California (Cayan et al., 2007; Cloern et al., 2011; Dettinger et al., 2016a; Kumar et al., 2013; Taylor et al., 2007; Bedsworth et al., 2018). It remains to be seen how increased aridity will alter the C storage of these systems. Desiccation could lead to decreased rates of C sequestration, and emissions of stored C in the form of CO_2 and CH_4 (Bridgham et al., 2013; Strachan et al., 2015; Zheng et al., 2020). Projections of 21st century climate change also indicate that with increased aridity, freshwater wetlands might lose C to the atmosphere from burning and post-fire soil processes (Dettinger et al., 2016a; Zhao et al., 2011, 2014). Future climatic conditions are expected to increase the number of wildfires within California; hence, freshwater wetland vegetation may encounter altered disturbance regimes (Lenihan et al., 2007; Aber et al., 2012; Krawchuk et al., 2012). Given the importance these ecosystems have on the global C cycle--identifying the current types, distributions, and the future challenges that these systems will encounter is an important concern for natural resource managers and state-policy makers.

The wetlands of California's Sacramento-San Joaquin River Delta were once one of the largest freshwater wetland systems on the west coast (Atwater et al., 1979; Byrne et al., 2001; Delusina et al., 2022; Drexler, 2011; Drexler, de Fontaine, & Deverel, 2009; Fard et al., 2021; Goman et al., 2008; Goman & Wells, 2000; Lynn Ingram & DePaolo, 1993; F. P. Malamud-Roam et al., 2006). Much of the delta system is now used for agriculture or has been impacted by human land-use; however, some wetlands in the delta are relatively pristine (Drexler, 2011; Drexler, de Fontaine, & Brown, 2009; Drexler, de Fontaine, & Deverel, 2009). By examining C accumulation and ecosystem functioning of the Delta's wetlands, scientists generate baseline data that informs actionable science that informs California legislators and policy (Ambrose et al., 2007; Callaway et al., 2007, 2012; Fard et al., 2021; MacDonald et al., 2016; Yu et al., 2011, 2012). The data presented here shows high resolution C accumulation rates, vegetation dynamics, and fire history during the late Holocene (i.e. ~4000-5000) at two of the remaining minimally disturbed wetlands in the Delta--Bacon Channel Island (BCI) and Browns Island (BI) (Drexler, de Fontaine, & Brown, 2009; Drexler, de Fontaine, & Deverel, 2009; Goman & Wells, 2000). Paleo-indices used to infer past C concentration and wetland functioning include loss-on-ignition (LOI) derived C estimates, elemental geochemistry, sediment charcoal, and palynology.

2.2.1 Research Questions

1. What are the long-term patterns and changes in sediment C content/sequestration rate at BCI and BI over the late Holocene?

2. How did sediment C content/sequestration rates change at BCI and BI during past periods of prolonged higher temperatures, e.g. during the Holocene Thermal Maximum (~3000 cal yr BP to 8000 cal yr BP: calendar years before 1950 CE)) and Medieval Climate Anomaly (950 cal yr BP to 1350 cal yr BP)?

3. What is the relationship between sediment C content/sequestration rates at BCI and BI during the prolonged cooling of the Little Ice Age (100 cal yr BP to 600 cal yr BP)?

4. What other changes related to local vegetation cover, local fire or local hydrological conditions that have occurred that could have impacted C content/sequestration rates at BCI and BI?

2.3 Study Area

The Sacramento-San Joaquin Delta (Figure 1) is where ~60% off California's freshwater flows into the San Francisco Bay from the Sacramento and San Joaquin rivers (California Department of Water Resources 1995). The Delta is primarily a freshwater system that had increased salinity concentrations during periods of aridity (Byrne et al., 2001; Dettinger et al., 2016b; Goman & Wells, 2000; Lynn Ingram & DePaolo, 1993). California's Mediterranean climate results in 80% of its precipitation occurring in the winter (December, January, February) with dry conditions in the summer (June, July, August), and during the 21st century there has been increasing aridity due to anthropogenic warming (Berg & Hall, 2017; Huang et al., 2018; Swain, 2015). Prior to European arrival the wetlands persisted on numerous vegetated wetland islands in the Delta, but after Euro-American settlement in the mid-18th century much of the Delta was drained for agriculture and the natural wetlands almost completely eradicated (Atwater et al., 1979; Drexler, de Fontaine, & Deverel, 2009; Fard et al., 2021; Goman et al., 2008).

Figure 2.1. Google Earth aerial image of Bacon Channel Island (BCI) and Browns Island (BI) sediment coring locations.

Over 100 islands in the Delta have been drained and used for agriculture, thus very few islands have not been disturbed by Euro-American settlement (Atwater et al., 1979; Drexler, 2011; Drexler, de Fontaine, & Brown, 2009; Drexler, de Fontaine, & Deverel, 2009; Fard et al., 2021; Goman et al., 2008). Two islands that are relatively pristine are BCI and BI and these are the focus of this study. BCI island is predominantly freshwater marsh, has a surface area of about 16 ha, is located at 121°33'21.806" W 38°0'40.816" N and 0 (msl). BI is a mesohaline marsh, has a surface area of about 30 ha, is located at 121°33'24.006" W 38°0'40.816" N and 0 (msl).

Local hydrogeomorphic conditions (e.g. Bay tidal inflow; salinity; land-use history) and vegetation at BI are considerably different from those at BCI, with BI dominated by *Schoenoplectus americanus (*American bulrush) and *Distichlis spicata* (salt grass) (Drexler, de Fontaine, & Brown, 2009; Drexler, de Fontaine, & Deverel, 2009). BCI vegetation, however, is covered by *Salix lasiolepis* (arroyo willow), and the understory isdominated by *Cornus sericea* (red osier dogwood) withsmaller amounts of *Phragmites australis* (common reed) and *Rosa californica* (California wild rose) (Drexler, 2009). Both islands have different species *Schoenoplectus acutus*(hard-stem bulrush), *P. australis*, and *Typha* spp. in abundance.

2.4 Data Collection Methods

2.4.1 Field Work

During the summer of 2015, sediment cores from the two marshes were gathered using a 5-cm diameter Russian peat auger, with 650 cm retrieved from BCI and 1050 cm collected from BI. At both sites, the auger penetrated through the peat until compacted mineral material at the basal depth impeded further drives. Both core drives were extruded in the field, then wrapped longitudinally in cellophane and aluminum foil and placed in core boxes. Subsequently, the cores were transported and placed in cold storage at the UCLA laboratory at ~5°C.

2.4.2 Laboratory Analysis

As there are several earlier paleo studies for BI (Drexler, de Fontaine, & Brown, 2009; Drexler, de Fontaine, & Deverel, 2009; Goman et al., 2008; Goman & Wells, 2000; Lynn Ingram & DePaolo, 1993; F. Malamud-Roam & Ingram, 2001; F. Malamud-Roam & Lynn Ingram, 2004), much of the work reported here focused on BCI. Standard loss on ignition (LOI) procedures were followed during sediment core processing and sub-sampling (Goodsite et al., 2004; Heiri et al., 2001). LOI was analyzed at intervals 1-cm for both BCI and BI. Bulk density was obtained by obtaining wet weight of the sample, drying overnight at 110°C, then weighing again to obtain dry weight (Givelet et al. 2004). Sediment organic C content was assessed by subjecting 1 cm^3 sediment samples placed in crucibles to a furnace for combustion at 550^o for 4 hours. The samples were then weighed and the mass recorded, then the samples underwent a 2-hour furnace combustion at $1000\,^o$ to assess $CaCO_3$ content (Heiri et al., 2001). Plant macrofossil material for radiocarbon dating was selected from macrofossil rich portions of each core. Roots were avoided. The plant macrofossils were radiocarbon dated at the University of California Irvine (UCI) Keck Radiocarbon lab, where a 500 kV accelerator mass spectrometer (AMS) device from National Electrostatics Corporation was used for the analysis. All samples were pretreated following the UCI hydrogen reduction method (Santos et al., 2007). Subsequently, the organic samples were calibrated to calendar years using the IntCal20 calibration curve (Reimer et al., 2020).

Geochemical x-ray fluorescence (XRF)-elemental soil concentrations were analyzed for BCI using a portable XRF (pXRF) handheld device at 5-cm intervals (see also Fard et al., 2021). Fuller geochemical records for BCI are presented in Fard et al (2021). This study presents information on the metals Fe, Rb, Sr, and Zr which are associated with inputs of crustal matter, and Nb which is found in soils, but is also known to bioaccumulate in plant matter (Abbasi, 1988) (Abbasi, 1988). Macroscopic charcoal (i.e. > 250 and > 150 μm) was analyzed for BCI following the procedures of Chipman et al., (2015) and Higuera et al., (2009) at 1-cm intervals then charcoal accumulation rates (CHAR) were modeled in R using the software program CHAR (Higuera et al., 2010, 2011; MacDonald et al., 1991; Vachula et al., 2018; Whitlock & Larsen, 2002). Sediment samples from BCI were collected at 10 cm intervals from 0 cm downcore to 650 cm for fossil pollen analysis. These 65 samples were selected based on the age-depth model for BCI, and to maintain consistency and sampling uniformity. Standard palynological processing protocols were followed during the pollen assay (Faegri & Iversen, 1989). After the chemical treatments were completed, the samples were transferred to archive vials and silicone oil added to preserve and suspend the pollen. Subsequently, microscope slides for each sample were made. Slides were visually inspected using both 200x and 400x magnification, adhering to standard microscopy procedures (Faegri and Iversen 1989). Pollen was identified using a reference collection at UCLA and several identification keys. Pollen sums averaged from 300 to 400 terrestrial pollen grains per sample. After the counts were complete, the software C2 was used to generate the pollen diagram.

2.4.3 Graphing and Statistical Analysis

Graphing and statistical modeling of data was conducted using R and paleocological modeling software C2 (Juggins 2007) and the R the package Bacon (Blaauw & Christen, 2011). Bacon was used to develop the core chronologies and sediment accumulations rates used to reconstruct C sequestration and other paleo proxies. Bacon relies on Bayesian statistics to reconstruct accumulation rates by incorporating radiocarbon dates into an age-depth model (Blaauw & Christen, 2011).

2.5 Results

2.5.1 Chronology

The BCI core length was 650 cm (6.5 m) and the BI core length was 1060 (10 m), with each core consisting of peat throughout the chronology. A total of 20 plant macrofossil samples were gathered from both sediment cores for AMS radiocarbon dating to develop chronologies (Table 2.1). A total of 10 dates were retrieved from BCI, with 1 date at 88 cm being reported as modern. For the BI core 9 dates are reported. There are some minor and unexplained dating inversions at the bases of the two cores. The radiocarbon dates indicate that the cores date back in age approximately 5000 Cal yr BP (Table 2.1 and Fig. 2.3). This is consistent with the initial development of the Delta because of post-glacial sea level rise which reached modern elevations in the mid-Holocene (Atwater and Belknap 1980).

2.5.2 Long-Term Patterns

At BCI a clear long-term pattern is generally decreasing bulk density with a steep drop around 3000 cal yr BP, suggesting this as a period of marsh formation and increasingly low-density organic sediments (Fig. 2.4). The high bulk density, high sediment inorganic matter, and low organic carbon (LOI at 550^{o} C) indicate a low-productivity floodplain type wetland (mudflat) existed shortly after initial formation. The high $CaCO_3$ content and increase after this may reflect San Francisco Bay marine waters influence at the early stage of the marsh. Increasing LOI at 550^{o}C suggests increasing vegetation cover and productivity as the marsh developed. The increasing amounts of *Typha* (cattail) pollen (Fig. 2.4) are consistent with development of a freshwater wetland. This is also consistent with increasing C accumulation rates, particularly in the upper portion of the core. Highest LOI derived organic content and C accumulation rates are at the top of the core. This represents the past 400-500 years. This likely reflects the establishment of the current well-vegetated marsh at BCI. In addition, high amounts of organic matter and C accumulation rates at the top of wetland cores can partially reflect lack of time for decomposition of recent organic material (Young et al., 2019).

Sample Name	UCIAMS Lab #	Depth (cm)	Material	D14C (%)	±	^{14}C age (BP)	±	Cal yr BP
BCI88	191935	88	Plant	250.7	2.1	Modern		1950
BCI190	191936	190	Plant	-44.1	1.3	360	15	1592
BCI205	185588	205	Plant	-48.1	1.8	395	20	1452
BCI-15-01_250	191937	250	Plant	-172.1	1.3	1515	15	552
BCI290	160407	290	Plant	-132.1	1.3	1140	15	886
BCI-15-01_350	185589	350	Plant	-172.1	1.3	1515	15	552
BCI-15-01_450	191918	450	Plant	-225.12	1.5	2050	20	94
BCI-15-01_553	191940	553	Plant	-227.2	3.6	2070	40	151
BCI-603	168457	603	Plant	-453.5	5.5	4850	90	3757
BCI 618	193511	618	Plant	-418	2.1	4350	30	3011
BCI642	168456	642	Plant	-376.2	3.1	3790	45	2291
BI107	185590	107	Plant	-41.6	1.4	340	15	1501
BI197	185591	197	Plant	-110.2	1.4	940	15	1043
BI-15-01_386	191941	386	Plant	-213.5	1.4	1930	15	77
BI-15-01_564	191942	564	Plant	-294.4	1	2800	15	982
BI-15-01_753	191943	753	Plant	-383.5	10.5	3890	140	2571
BI-15-01_950	191944	950	Plant	-392	1.1	4000	15	2565
BI1-1054	168450	1054	Plant	-460.4	0.9	4955	15	3765
BI1-1055	168451	1055	Plant	-461.7	6.3	4980	10	3934
BI1-1061	168452	1061	Plant	-452.1	1	4835	15	3643

Table 2.1. Radiocarbon dates for BCI and BI obtained from UC Irvine Keck Radiocarbon lab.

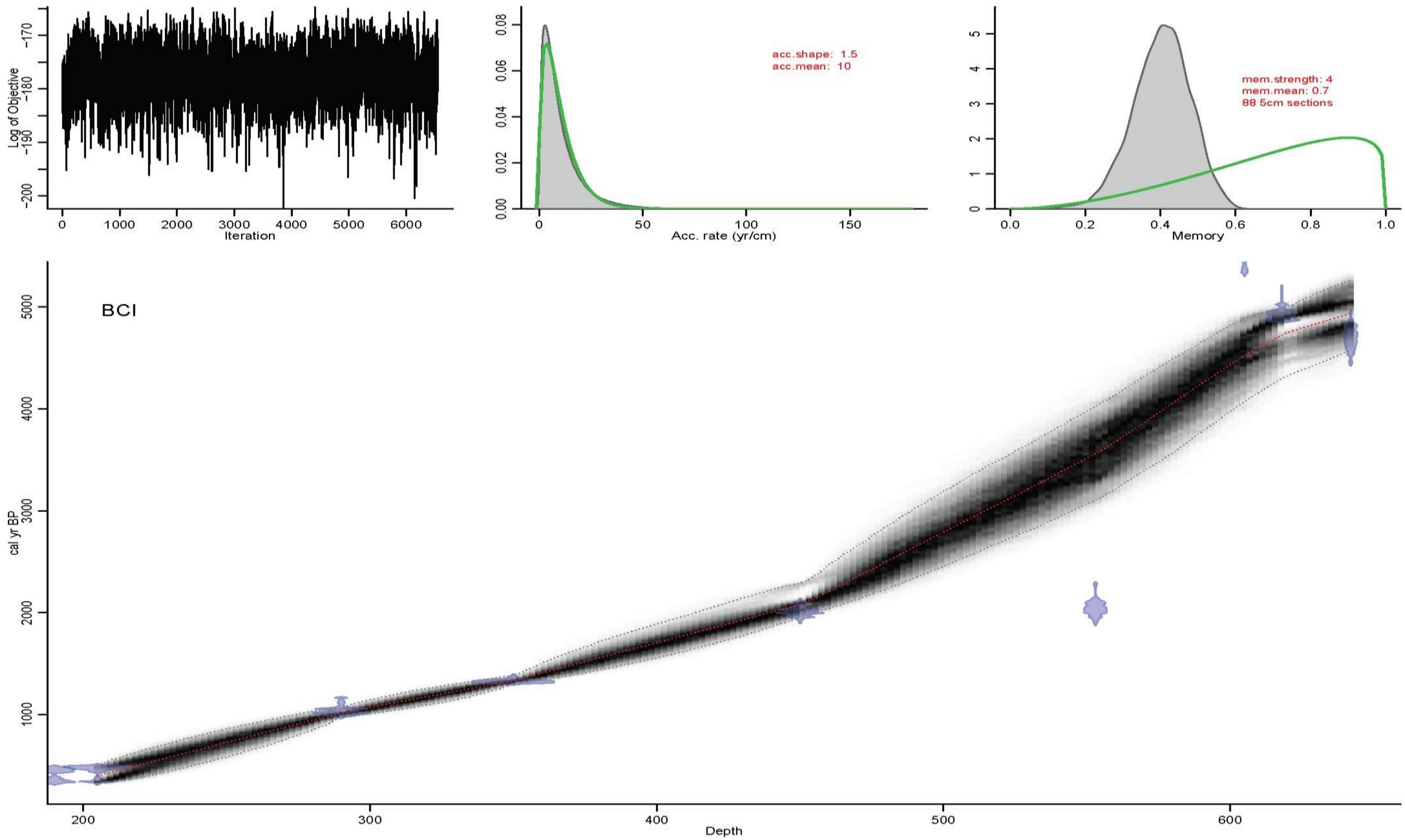

Figure 2.2. Age-depth model for BCI sediment core.

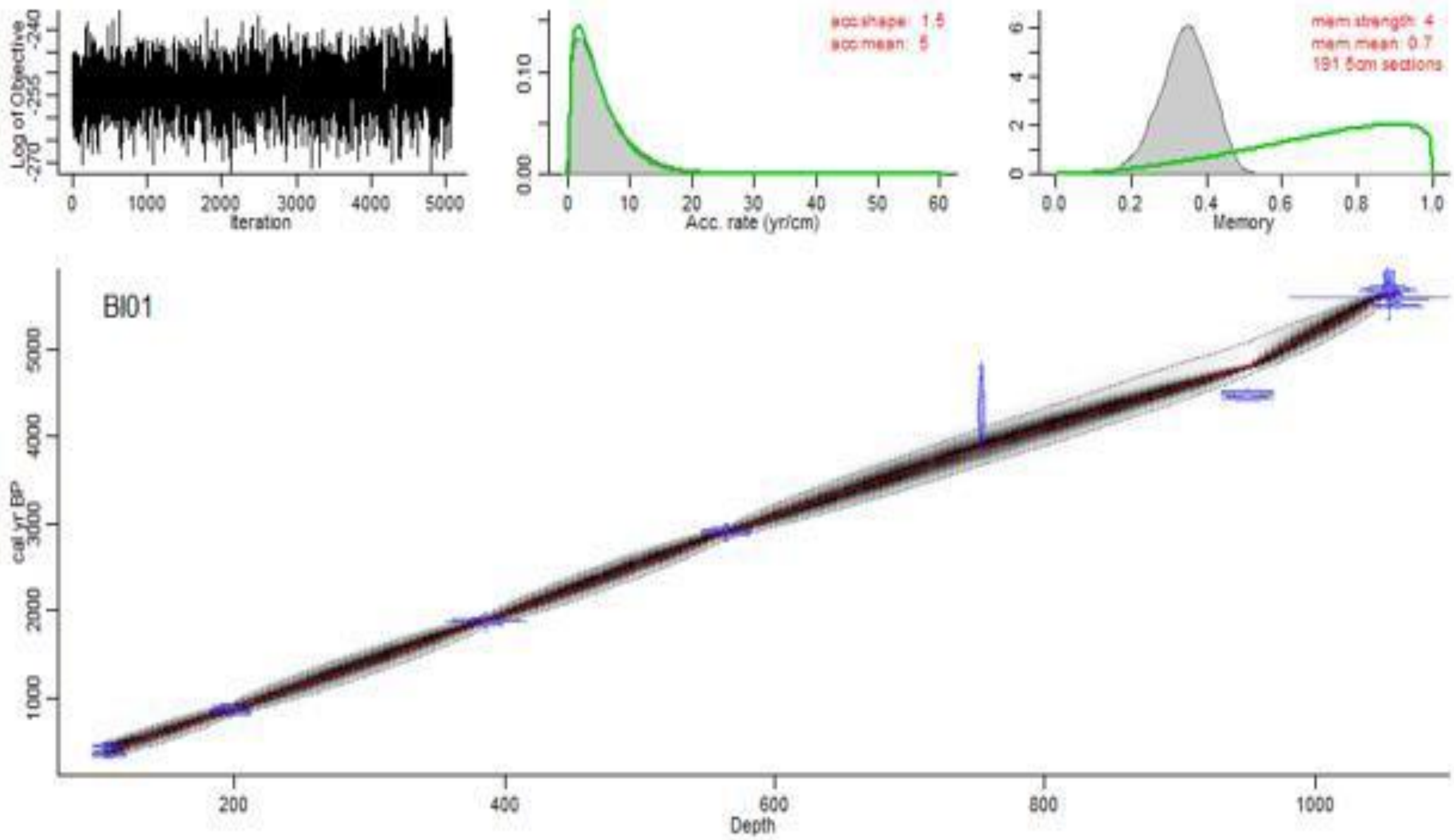

Figure 2.3. Age-depth model for BI sediment core.

The elemental geochemistry record at BCI (Fig. 2.5) shows a general decrease in crustal metals (e.g. Fe, Rb, Sr, Zr) from the basal depth to the top of the core. From ~3100 cal yr BP to 1500 cal yr BP concentrations of crustal elements were relatively high. This period coincides with the initial formation of the BCI marsh. At roughly 1300 cal yr BP, Fe, Rb, Sr, and Zr decreased in concentration. In contrast, Nb increases at this time and remains high. These changes in the elemental chemistry are consistent with the evolution of BCII into a vegetated freshwater marsh. The crustal elements Fe, Rb, Sr, and Zr decreased as OM and C accumulation rates increased, reflecting the development of a well-vegetated freshwater march at BCI. In contrast, Nb is known to bioaccumulate in plant matter and this element increased in abundance as the marsh vegetation increased.

The pollen and charcoal record at BCI (Fig. 2.6) show a dominance of *Alnus* and flowering plants such as *Apiaceae*, *Polygonum*, and *Rhamnaceae* from 3400 cal yr BP until 1300 cal yr BP. The high amount of *Alnus* may reflect its almost complete dominance at the site. This likely is a result of the BCI marsh conditions forming at that time and being locally dominated by this hydric shrub species. The charcoal record shows variability throughout that period and a sharp increase at the start of the MCA. During the MCA at around 1100 cal yr BP a sudden increase in *Typha* pollen occurs, possibly resulting from an interlude of increasing moisture at the coring site, and development of vegetated mash conditions. This appears to have commenced replacement of the *Alnus* cover. The CHAR record slightly increased at 1100 cal yr BP, but for much of the MCA was around 0 particles cm^3yr^{-1}. From 900 cal yr BP to 600 cal yr BP there was minimal change in the proxies, though an increase in Rhamnaceae did occur around 800 cal yr BP. At the onset of the LIA at ~600 cal yr BP the pollen record changes markedly. Alnus declines almost completely and Cyperaceae, *Artemisia*, and Amaranthaceae arise while *Quercus* and *Pinus* appear for the first time in the pollen record. It may be that the decline in local Alnus caused these extra-local taxa to have greater visibility. It may also be that increased incursion of river water to the marsh brought in more pollen from these extra-local taxa. From ~500 cal yr BP to 100 cal yr BP CHAR increased significantly in comparison to the MCA and HTM and showed much variability. Again, this may reflect greater input from river water and suspended loads of extra-local charcoal. Similar trends continued into the recent 20th century warming period, with *Quercus* and *Pinus* dominating the pollen assemblage; Cyperaceae, *Artemisia*, and Amaranthaceae all relatively high in abundance; and the CHAR record peaking again to 13 particles cm^{3}yr^{-1}.

At BI there was a long-term pattern of relatively low and stable bulk density with a decrease at 100 cal yr BP. The low bulk density and high organic carbon (LOI at 550^{o} C) suggest a highly productive brackish wetland existed since the marsh formed during the HTM (Fig. 2.7). The high $CaCO_3$ content reflects a strong San Francisco Bay water influence throughout its lifespan. High LOI at 550^{o} C throughout suggests a stable and productive marsh vegetation cover during much of the late Holocene. This is consistent with high C accumulation rates, particularly in the upper portion of the core. Decreasing sediment accretion and C accumulation at the top of the core may reflect decreased productivity in conjunction with recent 20th century warming and California state water diversions (Callaway et al., 2012; Dorrepaal et al., 2009; Young et al., 2019).

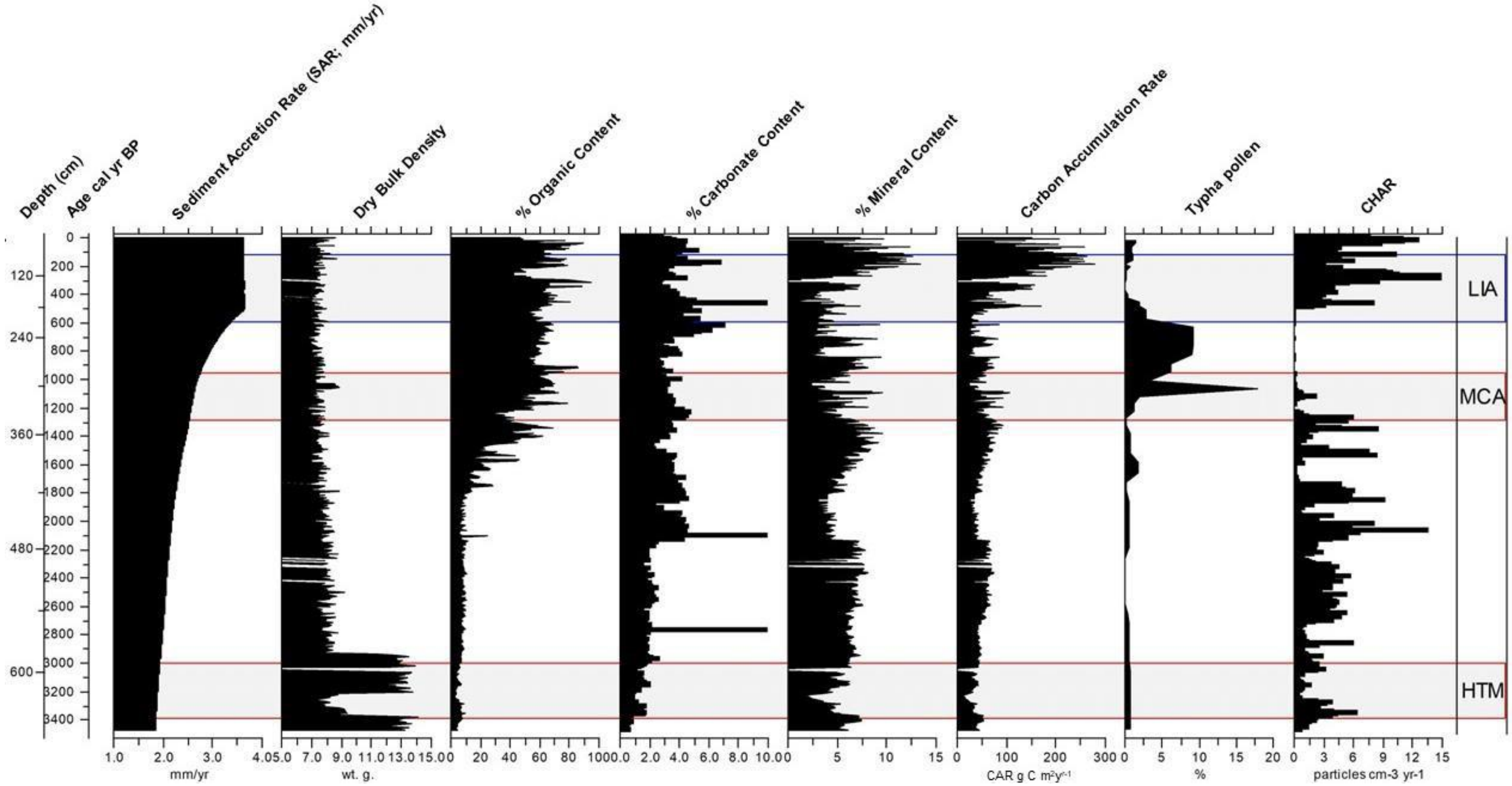

Figure 2.4. Paleoecological diagram showing BCI sedimentology, *Typha* pollen percentage, and CHAR

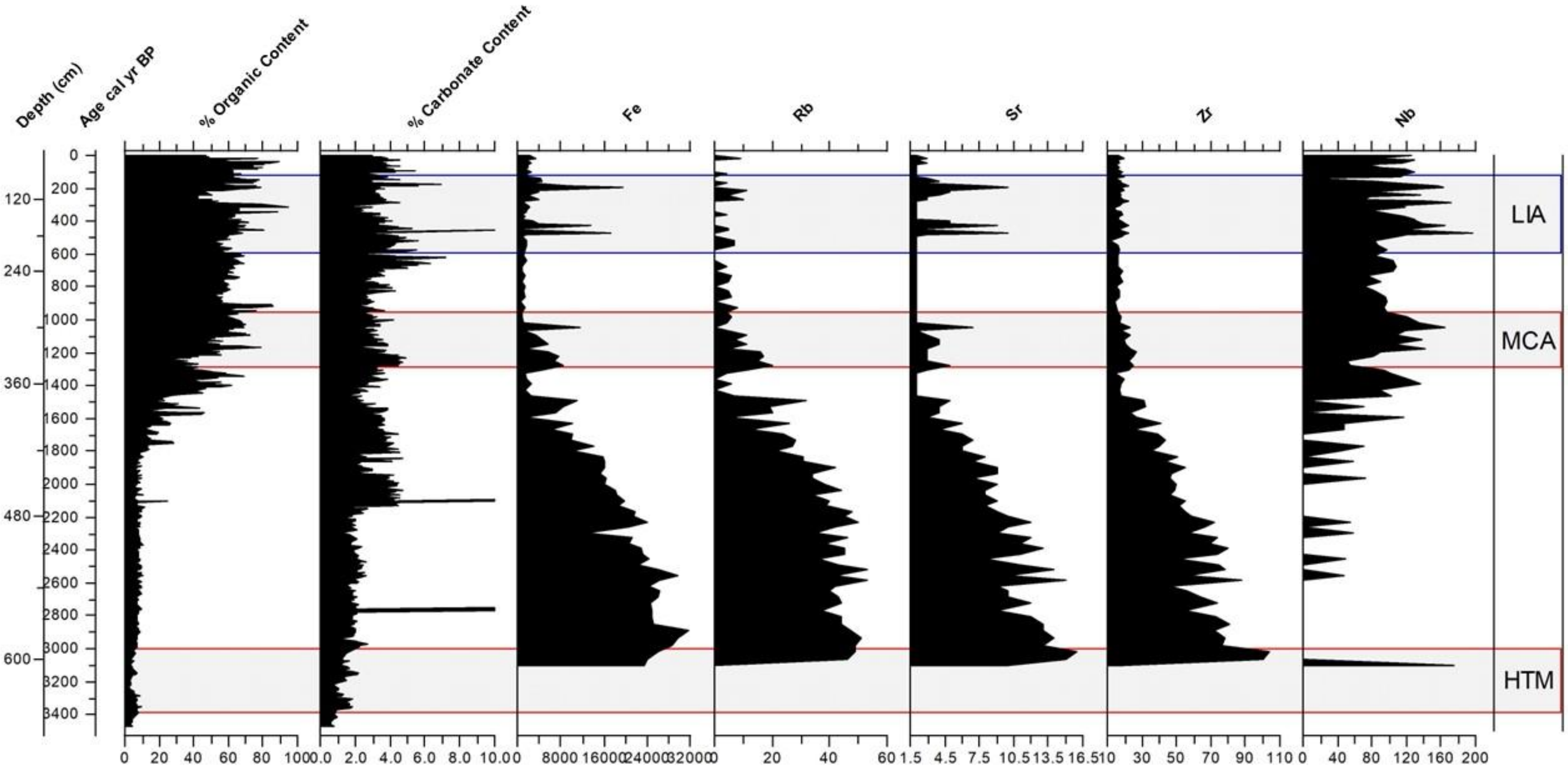

Figure 2.5. Geochemistry record for BCI (see also Fard et al., 2021)

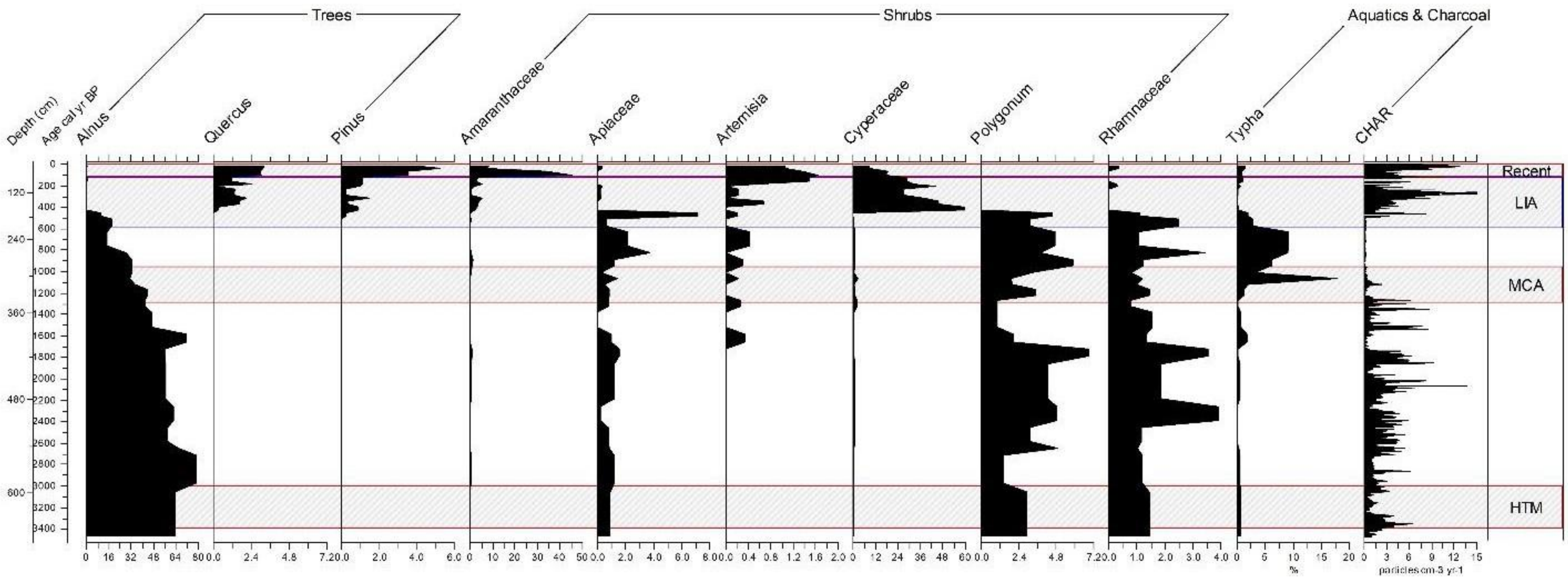

Figure 2.6 Pollen and CHAR record for BCI

The BI geochemistry record shows minimal change throughout much of the core, with exceptions being spikes in Sr and Fe during the HTM as well increases in heavy metals near the top (Fard et al., 2021). Higher levels of Si, Pb, and Cu reported by Fard et al. (2021) near the surface reflect European settlement influences in the Bay-Delta region after ~1850 and the Gold Rush.

A previously published pollen record at BI shows a dominance of *Cyperaceae* throughout the core (Delusina et al., 2020). From 3700 cal yr BP to 3500 cal yr BP *Quercus* and *Pinus* appear in the record, likely reflecting regional influx of pollen from the surrounding area. *Asteraceae* and Cyperaceae were the dominant cover types throughout the HTM, with no change until the MCA. Around 1100 cal yr BP Amaranthaceae suddenly increases, but much of the record did not change. Following the MCA, both *Quercus* and *Pinus* reappear in the record around 600 cal yr BP, coinciding with the start of the LIA. No change occurs in the record until roughly 100 cal yr BP, when the modern vegetation cover of *Salix*, *Quercus*, *Pinus*, *Artemisia*, and other pollen types are shown.

2.5.3 Changes in C Sequestration and Vegetation During the MCA and the Recent Warm Period

Prior to the MCA C accumulation at BCI was relatively low, with DBD ranging from 7.0 g cm^3yr^{-1} to 14.0 g cm^3yr^{-1}, and *Typha* pollen low which indicates that a freshwater marsh was forming. At the onset of the MCA around 1250 cal yr BP. CHAR increased to roughly 8 to 9 particles cm^3yr^{-1} and reflects an increase in occurrence of fire. During most of the MCA, however, CHAR is nearly 0 particles cm^3yr^{-1}, with C accumulation relatively low but with increased variability. During the recent warming period C sequestration reached its highest level in the core chronology with Typha pollen showing a slight increase in comparison to the LIA (Fig. 2.6).

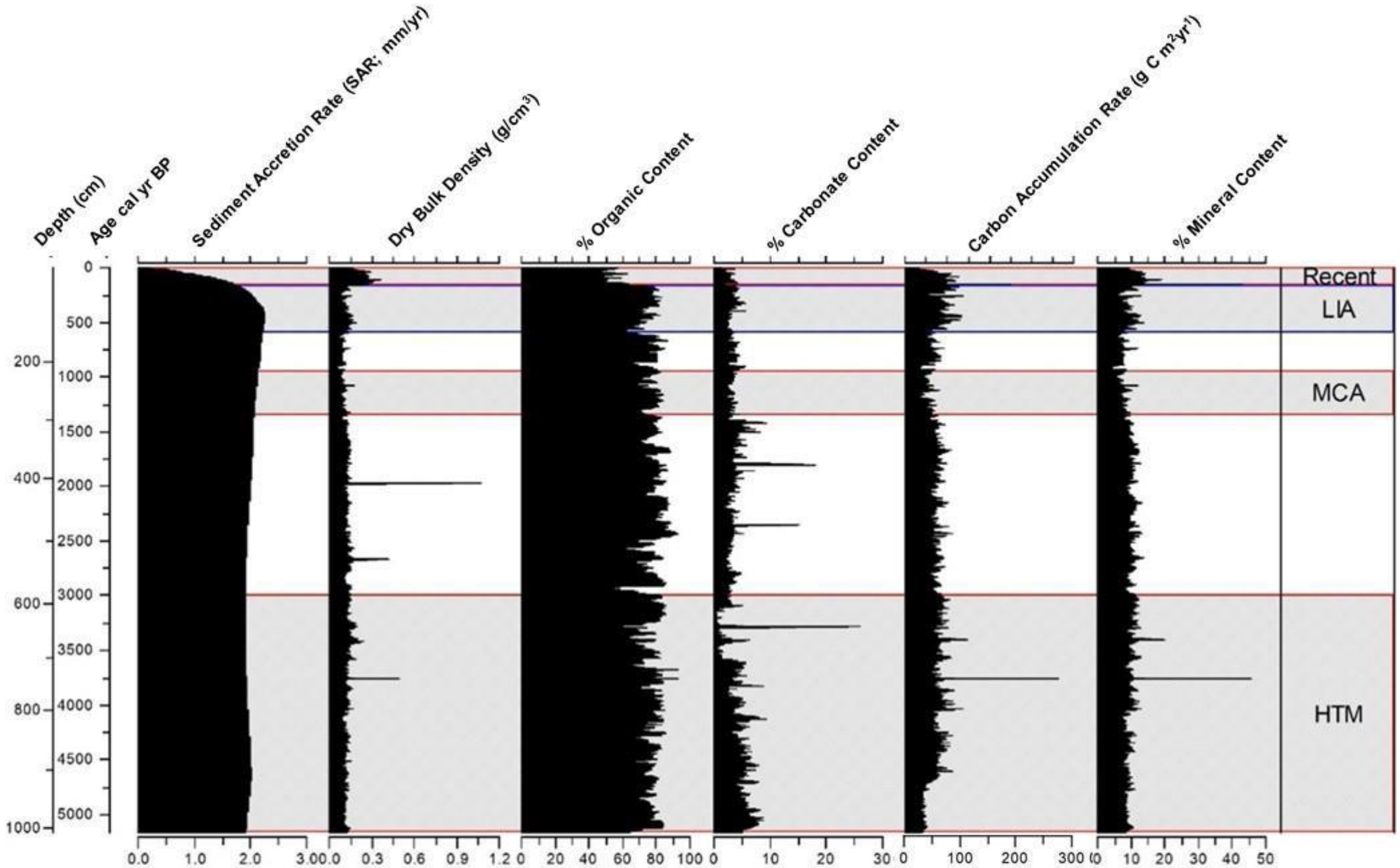

Figure 2.7 Sedimentology record for BI

There are no clear relationships between changes in climate and C accumulation at BCI. Local hydrogeomorphic factors have been the primary drivers of sequestration and ecosystem functioning. The fact that the high abundance of *Typha* pollen corresponds with the paucity of charcoal may indicate that the depositional characteristics of a freshwater *Typha* marsh, isolated from river input, restricted the transport of macrofossil sized charcoal to the site.

At BI the sediment DBD has been stable throughout the lifespan of the core with %LOI generally greater than 50%. This data indicates that BI has accumulated C at a relatively stable rate and been primarily an OC rich marsh during the last ~5,000 years. During the MCA, and LIA %LOI at BI was >50% with sediment accretion ranging from 1.5 to 2.0 mm yr^{-1} (Figure 7). According to the data, the last 100-150 years of the BI core show reduced C accumulation, as well as increased mineral content and sediment density. Not until the recent period that coincides with Euro-American settlement of California did %LOI plunge to ~40% and accretion decreased to below 1.0 mm/yr (Figure 2.7). Similarly to BCI, at BI no clear relationships between warm (MCA) are shown in the data.

2.5.4 Changes in C Sequestration and Vegetation During the LIA Cool Period

The LIA cool period and 20^{th}-21^{st} century warming show increased variability in C sequestration and vegetation changes in the BCI core. At the onset of the LIA around 600 cal yr BP %LOI was about 40%, *Typha* pollen at ~10%, CHAR at 0 particles cm^3yr^{-1}, and C sequestration relatively low. By ~400 cal yr BP %LOI was about 60% but with increased variability, while *Typha* pollen was at 0%, CHAR now near a peak of 9 to 12 particles cm^3yr^{-1}, and C sequestration relatively low but steadily increasing. Such a change in conditions from 600 cal yr BP to 400 cal yr BP reflects an increase in fire occurrence as well as variable wet and dry conditions. During the latter portion of the LIA from ~300 cal yr BP to 100 cal yr BP %LOI peaked at 1.6, while *Typha* pollen was 0%, CHAR decreased to about 0-3 particles cm^3yr^{-1}, and C sequestration increased steadily into the recent warming period. Here the data again shows no clear relationships between changes in C accumulation during the LIA at BCI. It may be that the disappearance of *Typha* signals a more open marsh with inputs of fluvial transported charcoal resuming. Hydrogeomorphic factors unique to the BCI likely are the main factors that drive C sequestration and functioning at the marsh.

The BI core shows no clear changes in %LOI or other paleo proxies during the LIA. . When the LIA began at ~600 cal yr BP %LOI was ~70% and increased to ~80% until Euro-American settlement during the 19th century (Fig. 2.7). There are no clear relationships between conditions during the LIA and changes in %LOI, sediment density, or C sequestration. This data suggests that land-use history and hydrogeomorphic factors drove C sequestration and ecosystem functioning at BI during the LIA into recent times.

2.5.5 Other External Factors Possibly Impacting the Marshes

The BCI CHAR record shows variations in charcoal likely not associated with climatic events. From 3000 cal yr BP to ~1250 cal yr BP CHAR varied between 2 to 12 particles cm3yr-1. CHAR then declines for a prolonged period until approximately 400 cal yr BP when it again increases to values > 12 particles $cm^3yr\text{-}^1$. Similar variability occurred during the preceding HTM, but not in the subsequent MCA. It is possible that some of this variability is associated with Amerindian presence and their use of fire in the region. The Delta was an important fishery and has a strong archaeological record of Amerindian presence (Gobalet et al., 2004; Eerkens and Bartelink, 2019). The decrease in CHAR between 1250 and 400 cal yr BP is associated with a maximum of Typha pollen and may reflect changing depositional environment, perhaps reflecting a period of local ponding and still-water conditions leading to a decrease in the input of charcoal by river flow, and perhaps decreased Amerindian use of the island.   at that time.

European settlement in California, particularly after 1850, resulted in placer mining and agricultural clearance changing sedimentation rates in the Delta and adjacent regions (James, 2011; Fard et al., 2021). This impact is reflected in the top portion of the BI core, where BD increases and OM decreases during the Euro-American period. There is also an increase in crustal elements such as Fe and Sr increase along with Si, Cu, and Pb (see Fard et al., 2021). The fact that this sedimentological and geochemical change is present in the BI record and not BCI may results from the geographic location of BI at the confluence of the San Francisco Bay and Sacramento and San Joaquin rivers and the low, frequently flooded topography of the site. The sedimentological and geochemical record at BI constitutes a regional record of human impact after 1850.

2.6 Discussion

1. What are the long-term patterns and changes in sediment C content / sequestration rate at BCI and BI over the late Holocene?

The current Delta was not formed until 6000 to 5000 cal yr BP. From ~4300 to 1000 cal yr BP (late Holocene), increased sedimentation from river inflow resulted in significant peat accumulation on the nearby Delta marshes at Franks Wetland (FW) and Webb Track Levee (WTL) (Drexler et al., 2009a; Drexler et al., 2009b; Drexler, 2011; Delsunia et al., 2020). The decreased bulk density at BCI and steep decline at 3000 cal yr BP agree with previously published C accumulation findings from FW and WTL and suggest a period of rapid C sequestration at the start of the late Holocene. Differences in C accumulation at BCI, BI, and the previously published marshes at FW and WTL indicate they are significantly influenced by their individual location and hydrological inflow (Delsunia et al., 2020). Differences in C accumulation at BCI and BI are attributable to BCI being situated further upstream and being impacted by fluvial processes, whereas BI predominantly is inundated by a combination of organic and inorganic sediments coming from Bay tidal water as well as the Sacramento-San Joaquin rivers (Goman and Wells, 2000 Drexler, 2011). From ~3000 cal yr BP to 1200 cal yr BP, C accumulation at BCI and BI were relatively low, with variability resulting from changing climatic conditions and river input (Drexler, 2009a; Delsunia, 2020). High amounts of organic matter and C accumulation at the top of cores can partially reflect lack of time for decomposition of recent organic material (Young et al., 2019).

The overall long-term trends at BCI and BI show that there are no clear relationships between changes in past climate and C at either marsh. This suggests the Delta is a dynamic system and C sequestration has been driven by local hydrogeomorphic conditions plus land-use history since the marshes started forming roughly 5,000 years ago. Variations in C accumulation at BCI and BI principally depend on tidal inflow, vegetation cover, past disturbance, and hydrogeomorphic factors (Byrne et al., 2001; Callaway et al., 2012; Drexler, 2011; Drexler, de Fontaine, & Brown, 2009; Drexler, de Fontaine, & Deverel, 2009; Fard et al., 2021; Goman et al., 2008; Goman & Wells, 2000).

How did sediment C content/sequestration rates change at BCI and BI during past periods of prolonged higher temperatures (e.g. Medieval Climate Anomaly (950 cal yr BP to 1350 cal yr BP)? What is the relationship between sediment C content/sequestration rates at BCI and BI community during the prolonged cooling of the Little Ice Age (100 cal yr BP to 600 cal yr BP)?

The primary driver of C sequestration at BCI and other Delta freshwater marshes is high hydrological inflow that promotes hydric soils (Drexler et al., 2009a; Delsunia et al., 2020

(Bridgham et al., 2006; Callaway et al., 2012)). River input into the marsh promotes C accumulation by storing it within anaerobic conditions, thus when river inflow was low during periods of aridity (e.g. MCA). The C content and sequestration generally decreased at BCI (Byrne et al., 2001; Chapin et al., 2006; Craft et al., 2009; Goman et al., 2008; Goman & Wells, 2000; Kayranli et al., 2010). Variability in dry bulk density at BCI at ~3400 cal yr BP and 3200 cal yr BP are consistent with previously reported evidence stating that cool and wet conditions led to pulses of decreased salinity in the Delta between 3800 cal yr BP to 2500 cal yr BP (Byrne et al., 2001; Barron et al., 2003; Malamud-Roam et al., 2006). Because these dates correspond with when BCI formed, these findings provide baseline data for wetland conservationists and restoration scientists today as these ecosystems adapt to changing conditions resulting from 21st century warming and sea-level rise (Malamud-Roam et al., 2006; Drexler 2009a; Delsunia, 2020; Fard et al., 2021).

The BCI sediment core suggests the LIA C sequestration variability. At the onset of the LIA around 600 cal yr BP, organic content was about 40%, and C accumulation relatively low. By ~400 cal yr BP organic content was about 0.6% and highly variable. These findings are consistent with previously published tree-ring based analysis that states the LIA in the west was characterized by highly erratic interannual hydroclimatic variability (Loisel et al., 2017). Because C accumulation and organic content at BCI varies widely, it suggests that the LIA was characterizes by precipitation spikes and increased ecosystem productivity / fuel loading and intermittent aridity that reduced ecosystem functioning. Additionally, C sequestration data from both marshes support the idea that warm and arid conditions of the MCA resulted in low and stationary C accumulation. These high-resolution proxy record findings for BCI are potentially important as they support the plausibility of high precipitation variability during the LIA and a 21st century warm LIA climate scenario (MacDonald et al., 2016; Loisel et al., 2017).

2. What other changes related to local vegetation cover, local fire or local hydrological conditions have impacted C content/sequestration rates at BCI and BI?

The principal factors influencing C sequestration at BCI and BI, other than marsh evolution and local hydrogeomorphology, relate to indigenous land-use in California, Euro-American settlement and placer mining in the Sierra Nevada, and the 20th century development of the state's water conveyance system. Each of these three factors acted independently from one another at different times and are reflected in the BCI and BI sediment records. For example, anthropologists, environmental historians, and geographers have long contested the presence and importance of Native American interactions with the California landscape prior to Euro-American settlement (Anderson et al., 1998; Simmons et al., 1998). Much of this historical narrative derives from qualitative research with descendant communities and documentary sources (Anderson et al., 1998). The BCI CHAR record from this study, however, provides analytical evidence of past fire in the region starting from the late Holocene to the present-day. For example, the spikes in CHAR at BCI around 3400 cal yr BP and 3200 cal yr BP correspond with increased dry bulk density at the marsh and prior research indicating that cool and wet conditions prevailed until 2500 cal yr BP (Byrne et al., 2001; Barron et al., 2003; Malamud-Roam et al., 2006). This suggests that the CHAR record represents regional inflow of extra-local charcoal deposited from further upstream. After the HTM, the CHAR record is consistently high and variable from ~3000 cal yr BP to ~1350 cal yr BP. It is plausible that Native Americans in California utilized fire for landscape management at this time, and that the BCI CHAR record shows this as increased numbers of CHAR particles that likely were deposited from river input.

The BCI charcoal record also illuminates suspected precipitation and fire variability during the LIA, lending support to the notion of precipitation variability in California at the time (Loisel et al., 2017). Based on the CHAR record presented here, there is not a link between C and charcoal concentrations, and changes in sedimentation that brought charcoal to the site did not impact sequestration. Future analysis of both macro- and microscopic charcoal gathered from other California freshwater wetland sediment cores could address this unresolved finding from the BCI CHAR record.

Euro-American settlement also significantly influenced land-use patterns that altered C sequestration at BCI and BI from roughly 1450 cal yr BP onward. For example, placer mining in the Sierra Nevada starting in the 1850s drastically changed the sedimentation regime for both marshes and the Delta more broadly (Isenberg, 2010). Hydraulic mining led to increased inorganic material flowing downstream from the Sierra. This land-use practice altered the ecosystem functioning and productivity of BCI and BI and is reflected by increased dry bulk density and inorganic sedimentation towards the top of the core. The BI geochemistry record shows exceptional spikes in Sr and Fe and other heavy metals near the top of the core resulting from this impact to the Sacramento-San Joaquin watershed in conjunction with agricultural land clearance (Fard et al., 2021). The development of California's Central Valley Project during the 20^{th} century led to water withdrawals from the Delta that changed the salinity gradient at times that likely impacted C accumulation at both marshes in recent years as well. This is reflected in the general decrease of %LOI and sedimentation rate at BI along with increased mineral content, suggesting arid conditions at the marsh since Euro-American settlement.

2.7 Conclusion

The wetlands in the Sacramento-San Joaquin Delta are a vital C pool for the state as warming increases due to anthropogenic climate change. This study presented high-resolution paleoecological data from 2 sediment cores gathered from BCI and BI that are situated in the Delta. The data here underscore the importance of local hydrogeomorphic conditions and land-use history, not solely regional climate, as drivers of C accumulation at BCI and BI during the late Holocene. Examples of some local hydrogeomorphical factors are: 1) the geomorphological evolution of each island; 2) levees along the BCI shoreline that cut it off from river inflow; 3) local-scale flooding; 4) Bay tidal inflow and mesohaline salinity at BI. C accumulation and sediment accretion data from both marshes show that local hydrogeomorphic factors were the primary drivers of C sequestration, variations in organic matter, and ecosystem functioning during the past 5,000 years, rather than climate.

3.2 Introduction

As the present and anticipated impacts from anthropogenic climate change become more frequent and severe during the 21st century, California's montane wet meadows are being viewed as potential C sequestration resources (Drexler et al., 2015; Goss et al., 2020; J. Holmquist et al., 2011; Williams et al., 2019, 2020; Wolf & Cooper, 2015). It is important to develop knowledge on the rates at which these systems sequester carbon at present and on average over the past. As warming increases towards 2100, wet meadows in Yosemite (YNP) and Sequoia-Kings Canyon (SKCNP) will face increased temperatures, more arid conditions, potential desiccation, and elevated wildfire risk as snowmelt occurs earlier in the year along with precipitation variability (Aber et al., 2012; Berg & Hall, 2017; Brunelle & Anderson, 2003; Dong et al., 2019; Drexler et al., 2015; Goss et al., 2020; Huang et al., 2018; Sikes et al., 2013; Williams et al., 2015, 2019). How these meadow systems responded to past climatic changes is also important to know. In general, the rates that these ecosystems sequestered C in the past, however, is unknown beyond the last 100 to 150 years (Drexler et al., 2015; Sikes et al., 2013; Weixelman & Cooper, 2009; Wolf & Cooper, 2015).

The primary drivers of C accumulation within a wet meadow typically are local hydrogeomorphology conditions, the presence of hydric soils, and net primary productivity (NPP; defined as the amount of energy fixed in an ecosystem minus the energy lost during respiration) (Barrow, 1994; Bernal & Mitsch, 2012; Bridgham et al., 2006, 2013; Campbell et al., 1994). The storage of C is a balance between NPP and the aerobic-anaerobic zone within the water table (Chapin et al., 2006; Craft et al., 2009; Kayranli et al., 2010). Modeled projections of 21^{st} century warming show that with increased aridity wet meadows may become a C source, rather than a sink, by emitting CO_2 and CH_4 to the atmosphere by desiccation, wildfire burning, or post-fire soil processes (Dettinger et al., 2016; Strachan et al., 2015; Vile et al., 2003; Zhao et al., 2011, 2014; Zheng et al., 2020). Although these ecosystems are a critical natural resource for California as it expands its C credits program to offset greenhouse gas emissions (GHGs) and tries to meet its clean energy targets by 2035 and beyond (Coignard et al., 2018; Drexler et al., 2015; Froehlich et al., 2019; Lukanov & Krieger, 2019; Matzek et al., 2015; Niemeier et al., 2008; Sanchez et al., 2018; Sovacool, 2011; Yu et al., 2011), their sustainability as C sinks remains a question.

This study quantifies rates of C accumulation and associated ecosystem conditions for montane wet meadows, including periods of past periods of warming and cooling, during the last 3,000 years. The data presented here includes high resolution C-sequestration rates, sediment geochemistry, and fire history from wet meadows located in YNP and SKCNP. Such research establishes baseline information for actionable science that can inform California policy makers as they address climate change through mitigation efforts (Ambrose et al., 2007; Callaway et al., 2007, 2012; Fard et al., 2021; MacDonald et al., 2016; Yu et al., 2011, 2012). Paleo-indices used to infer past C concentration and wetland functioning include loss-on-ignition (LOI) derived C estimates, elemental geochemistry, and sediment charcoal.

3.2.1 Research Questions

1. What are the long-term patterns and changes in sediment C content/sequestration rates at three sampled wet meadow sites in YNP and two sites in SKCNP during the late Holocene?

2. How did sediment C content/sequestration rates change at YNP and SKCNP during past periods of prolonged higher temperatures, e.g. during the Medieval Climate Anomaly (950 cal yr BP to 1350 cal yr BP)?

3. What is the relationship between sediment C content/sequestration rates at YNP and SKCNP during the prolonged cooling of the Little Ice Age (100 cal yr BP to 600 cal yr BP)?

4. Do western mountain regions show the C content and sediment accretion rates to the wet meadows sampled at YNP and SKCNP?

3.3 Study Area

The Sierra Nevada covers an area of roughly 78,000 ha, with Yosemite (YNP) and Sequoia-Kings Canyon (SKCNP) national parks considered two of the crown jewels of wilderness conservation in California (Viers et al., 2013a, 2013b). YNP and SKCNP have a multitude of wet meadows, mostly in designated wilderness areas. At both parks, elevations range from roughly 500 to 4000 m, with montane forest starting at ~1800 m MSL and subalpine forest at 2400 m MSL. A Mediterranean climate with warm and dry summers and moist winters characterizes the parks.

The wet meadows in both parks present a representative sampling of such systems found throughout the Sierra Nevada. The sites sampled for this study are: Porcupine Flat (PF, 3.0 ha, 2472 m MSL, 37°48'21.64"N 119°33'55.35"W), Tuolumne Meadow (TUO, 159.2 ha, 2611 m MSL, 37°52'39.02"N 119°23'18.82"W), Dana Meadow (DM, 350.7 ha, 2964 m MSL, 37°52'48.21"N 119°15'0.20"W), Dorst Meadow (DOM, 3.08 ha, 2113 m MSL, 36°36'57.72"N 118°47'5.41"W), and Log Meadow (LOG, 5.7 ha, 2039 m MSL, 36°33'22.23"N 118°44'52.31"W). These meadows were selected because of their representative nature, relatively undisturbed condition and ease of equipment access. Sediment cores were collected from the sites in 2016 using a Russian peat auger. According to the National Park Service (2014), vegetation at the sample sites is a diverse assemblage of herbs (e.g. *Drosera rotundifolia*), graminoids (e.g. *Carex vesicaria*), and bryophytes (e.g. *Sphagnum subsecundum*).

Dense forest composed primarily of *Pinus* in YNP, and *Sequoiadendron giganteum* at SKCNP, dominate the landscape near the edges of the meadows.

3.4 Materials and Methods

3.4.1 Field Work

During the summer of 2016, sediment cores from the five wet meadows marshes were gathered using a 5-cm diameter Russian peat auger. At all the wet meadow sites, the auger penetrated through the upper peats until compacted mineral material at the basal depth impeded further drives. The core drives were extruded in the field, then wrapped longitudinally in cellophane and aluminum foil and placed in core boxes. Subsequently, the cores were transported and placed in cold storage (~5°C) at the UCLA laboratory.

3.4.2 Laboratory Analysis

Plant macrofossil material for radiocarbon dating was selected from macrofossil rich portions of each core. Roots were avoided. The plant macrofossils were radiocarbon dated at the University of California Irvine (UCI) Keck Radiocarbon lab, where a 500 kV accelerator mass spectrometer (AMS) device from National Electrostatics Corporation was used for the analysis. All samples were pretreated following the UCI hydrogen reduction method (Santos et al., 2007). Subsequently, the organic samples were calibrated using the IntCal20 calibration curve (Reimer et al., 2020).

Standard loss on ignition (LOI) procedures were followed to determine sediment organic matter / C (Goodsite et al., 2004; Heiri et al., 2001). LOI was analyzed at intervals of 1-cm. Bulk density was obtained by obtaining wet weight of the sample, drying overnight at 110°C, then weighing again to obtain dry weight (Goodsite et al., 2004). Sediment organic C content was assessed by weight loss after combusting sediment samples in a muffle furnace at 550 ^{o} C, and $CaCO_3$ by combusting the same samples at 1000^{o} C.

Macroscopic charcoal (i.e. > 250 and > 150 μm) was analyzed for one of the oldest cores (Dana Meadows ~ 8850 years in age) following the procedures of Chipman et al., (2015) and Higuera et al., (2009) at continuous 1-cm intervals. Charcoal accumulation rates (CHAR) were modeled in R using the software program CHAR (Higuera et al., 2010, 2011; Vachula et al., 2018; Whitlock & Larsen, 2002). Elemental geochemistry was also analyzed for Dana Meadow using a portable x-ray fluorescence (pXRF) handheld device at 5-cm intervals. The elements presented and discussed here include Rb, Ti, Sr and Fe.

3.4.3 Statistical Analysis

Data analysis and visualization was done using C2, Microsoft Excel, and R. Statistical modeling was conducted using R and paleocological modeling software C2 (Juggins 2007). In R the package Bacon was used to develop the core chronologies and sediment accumulations rates used to reconstruct C sequestration and other paleo proxies (Blaauw & Christen, 2011). Bacon relies on Bayesian statistics to reconstruct accumulation rates by incorporating radiocarbon dates into an age-depth model (Blaauw & Christen, 2011).

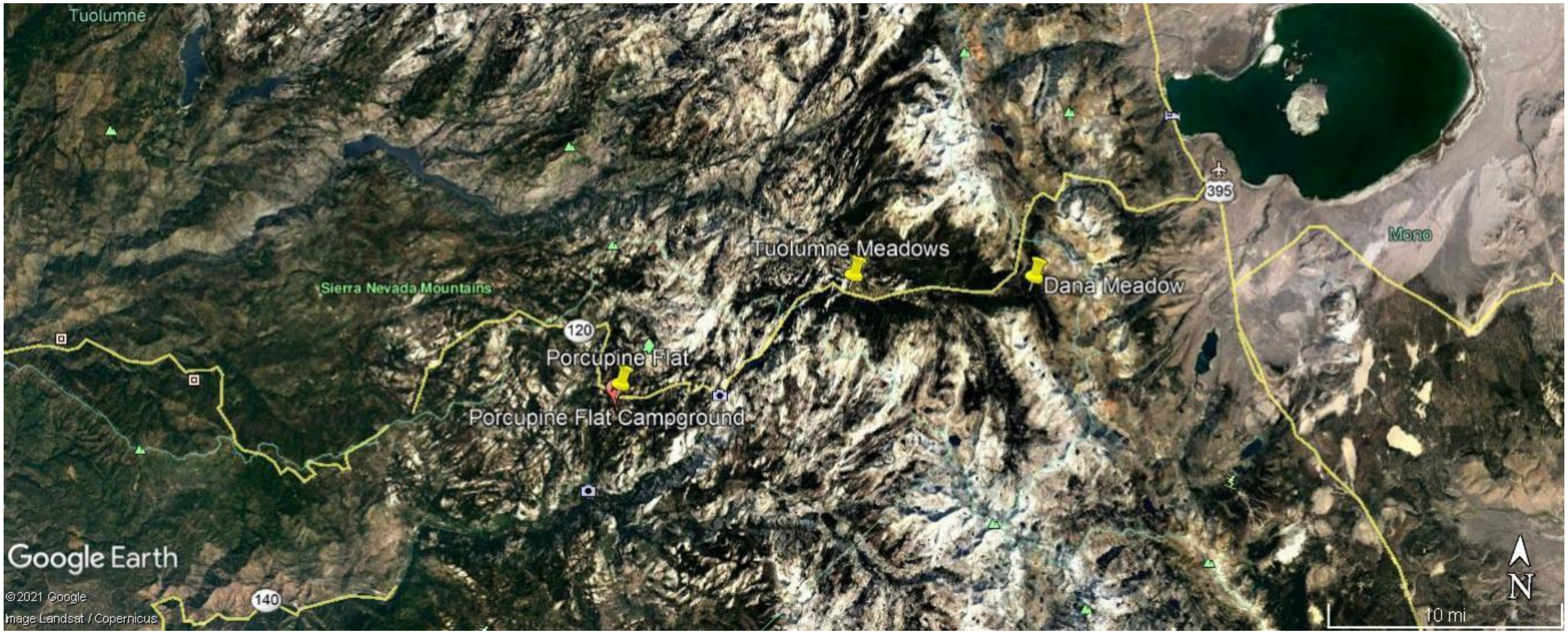

Figure 3.1. Wet meadow sites sampled in Yosemite National Park (YNP) plotted on Google Earth satellite image. Porcupine Flat is located on the western slope of the Sierra. Tuolumne Meadows is situated in the middle of the image. Dana Meadows is near the crest of the Sierra, roughly 16 km west of Mono Lake.

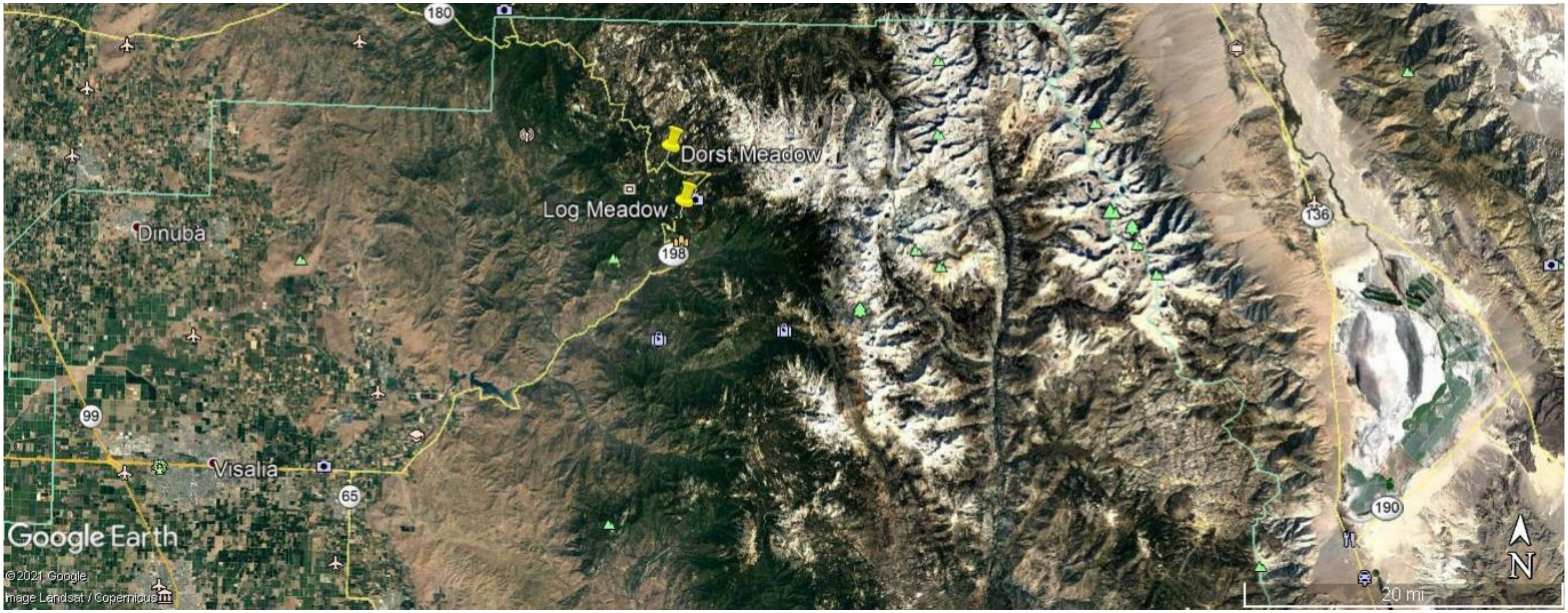

Figure 3.2. Wet meadow sites sampled in Sequoia-Kings Canyon National Park (SKCNP) plotted on Google Earth satellite image. Both wet meadows are located on the west slope of the Sierra Nevada. The Central Valley city of Visalia is shown as a reference point.

3.5 Results

3.5.1 Chronology

The PF core was 100 cm in length (1.0 m); the TUO core was 130 cm (1.3 m); the DM core was 300 cm (3.0 m); the DOM core was 100 cm (1.0 m); and the LOG core was 100 cm (1.0 m). A total of 21 plant macrofossil samples were gathered from the sediment cores to develop chronologies spanning the late Holocene, and in some cases into the early Holocene (Table 1). There is a minor and unexplained dating inversion in the TUO core. The radiocarbon dates indicate that the cores date back in age approximately 8800 cal yr BP for the DM core to approximately 2500 to 2800 cal yr BP for the PF, TUO and LOG cores and 1600 for the DOM core (see Table 3.1; page 42). The focus of subsequent analysis was on the late Holocene (approximately past 3000 years).

Sample Name	UCIAMS Lab #	Depth (cm)	Material	D14C (‰)	±	^{14}C age (BP)	±	Cal yr BP
PF46	191935	46	Plant	250.7	2.1	530	20	1406
PF80	191936	80	Plant	-44.1	1.3	2580	15	792
TUO22	185588	22	Plant	-48.1	1.8	880	15	1164
TUO41	191937	41	Plant	-172.1	1.3	1040	35	979
TUO97	160407	97	Plant	-132.1	1.3	2850	15	1047
TUO127	185589	127	Plant	-172.1	1.3	2840	15	1042
DM34	191918	34	Plant	-225.12	1.5	35	15	Modern
DM60	191940	60	Plant	-227.2	3.6	1630	15	413
DM70	168457	70	Plant	-453.5	5.5	3065	45	1397
DM85	193511	85	Plant	-418	2.1	4810	45	3642
DM228	168456	228	Plant	-376.2	3.1	7800	20	6647
DM282	185590	282	Plant	-41.6	1.4	8480	20	7578
DM299.5	185591	299.5	Plant	-110.2	1.4	8830	20	7572
DM300	191941	300	Plant	-213.5	1.4	8850	20	8171
DOM38	191942	38	Plant	-294.4	1	290	15	1528
DOM64	191943	64	Plant	-383.5	10.5	1210	15	775
DOM99	191944	99	Plant	-392	1.1	1645	15	407
LOG28	168450	28	Plant	-460.4	0.9	310	15	1524
LOG43	168451	43	Plant	-461.7	6.3	1865	15	130
LOG93	168452	93	Plant	-452.1	1	2400	20	511
LOG93.5	168453	93.5	Plant	-452.1	1	2890	20	1112

Table 3.1. AMS radiocarbon dates for Sierra cores from UC Irvine Keck Radiocarbon lab

Age-depth models developed using the BACON software are presented in Figures 3.3 through 3.7. These suggest that at most sites, despite the uniformity of the peaty sediments at their surfaces, there have been appreciable variations in sediment type and/or accumulation rates over time

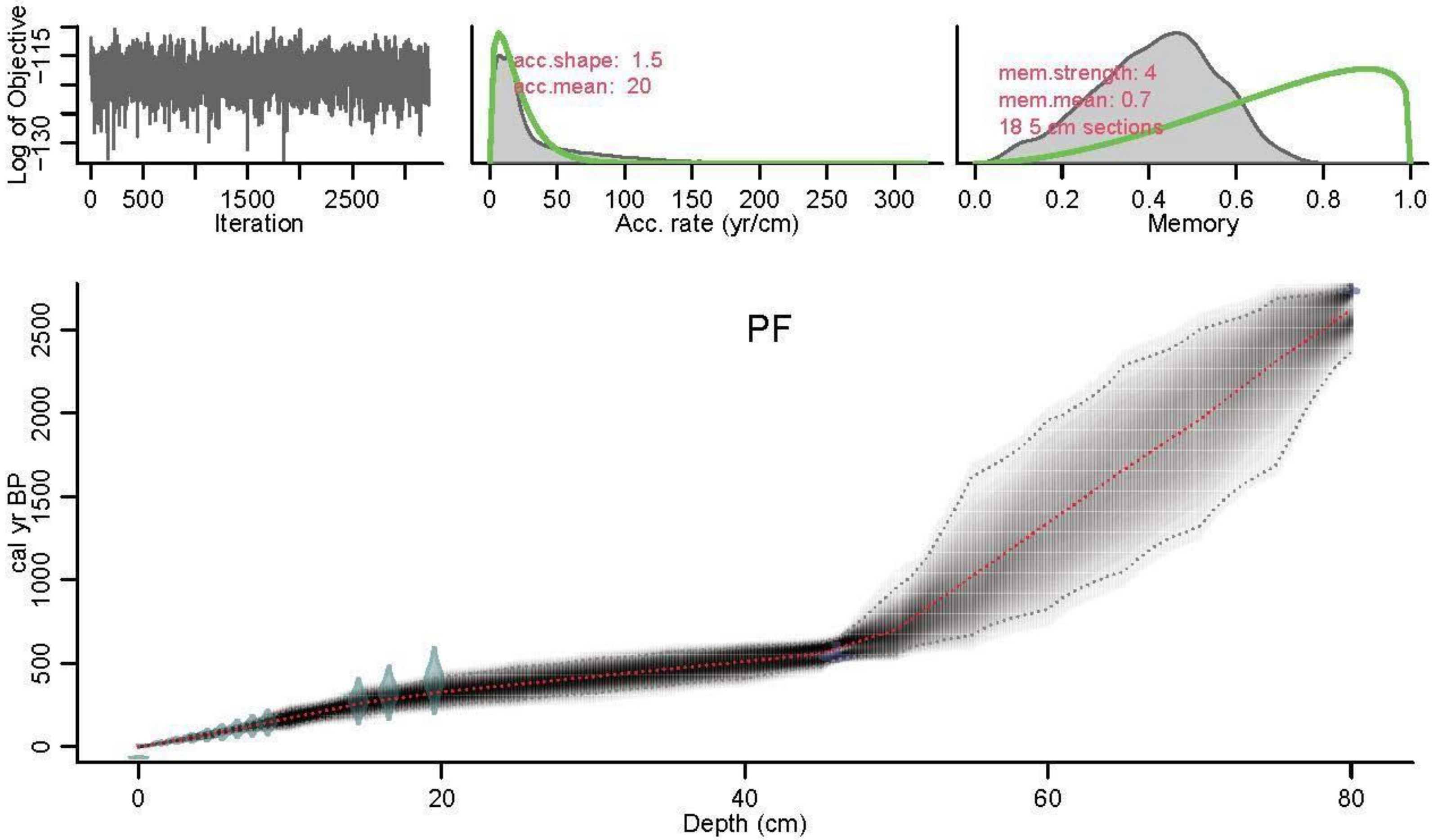

Figure 3.3. Age-depth model for the Porcupine Flat (YNP) core.

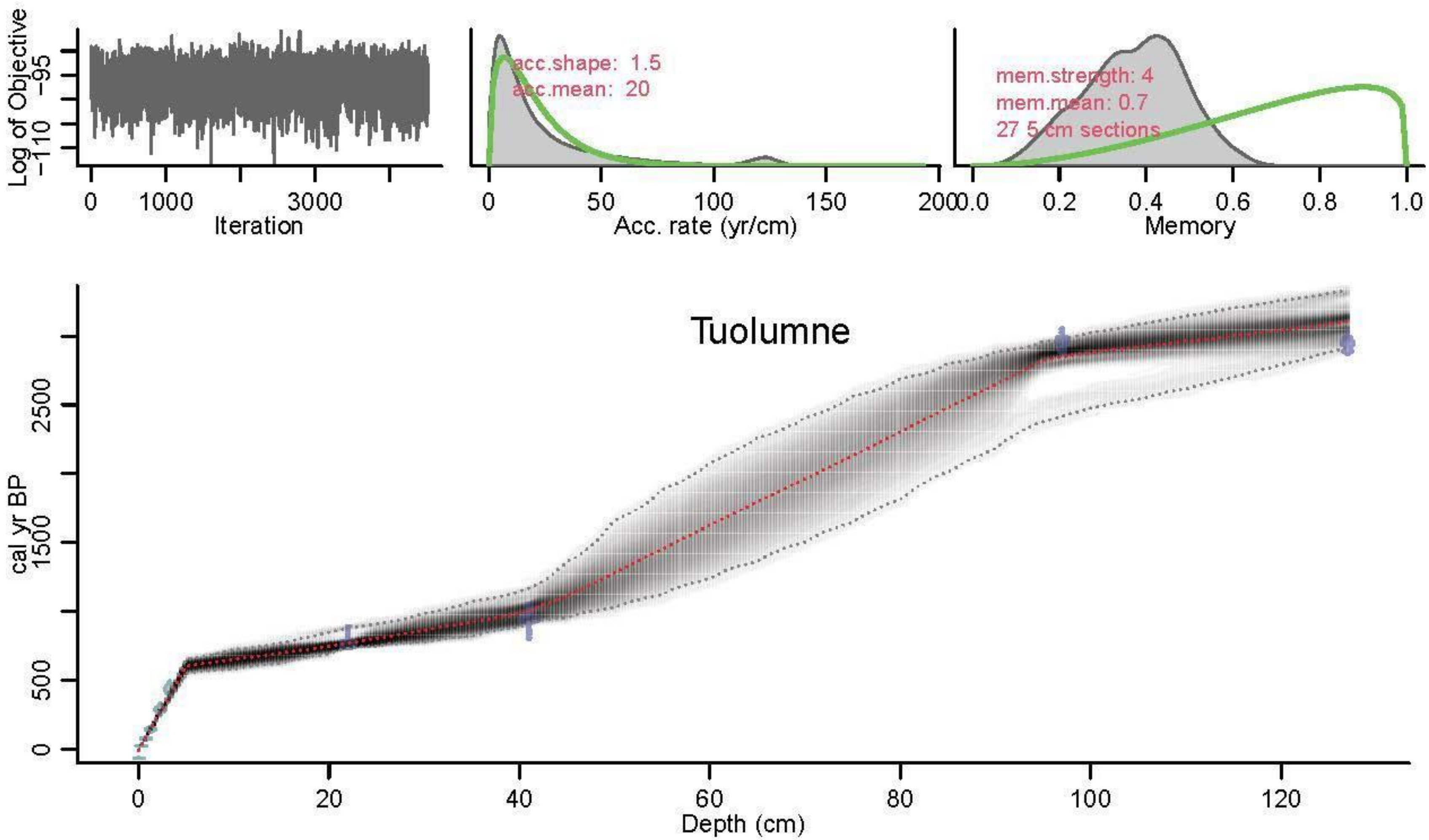

Figure 3.4. Age-depth model for the Tuolumne Meadows (YNP) core.

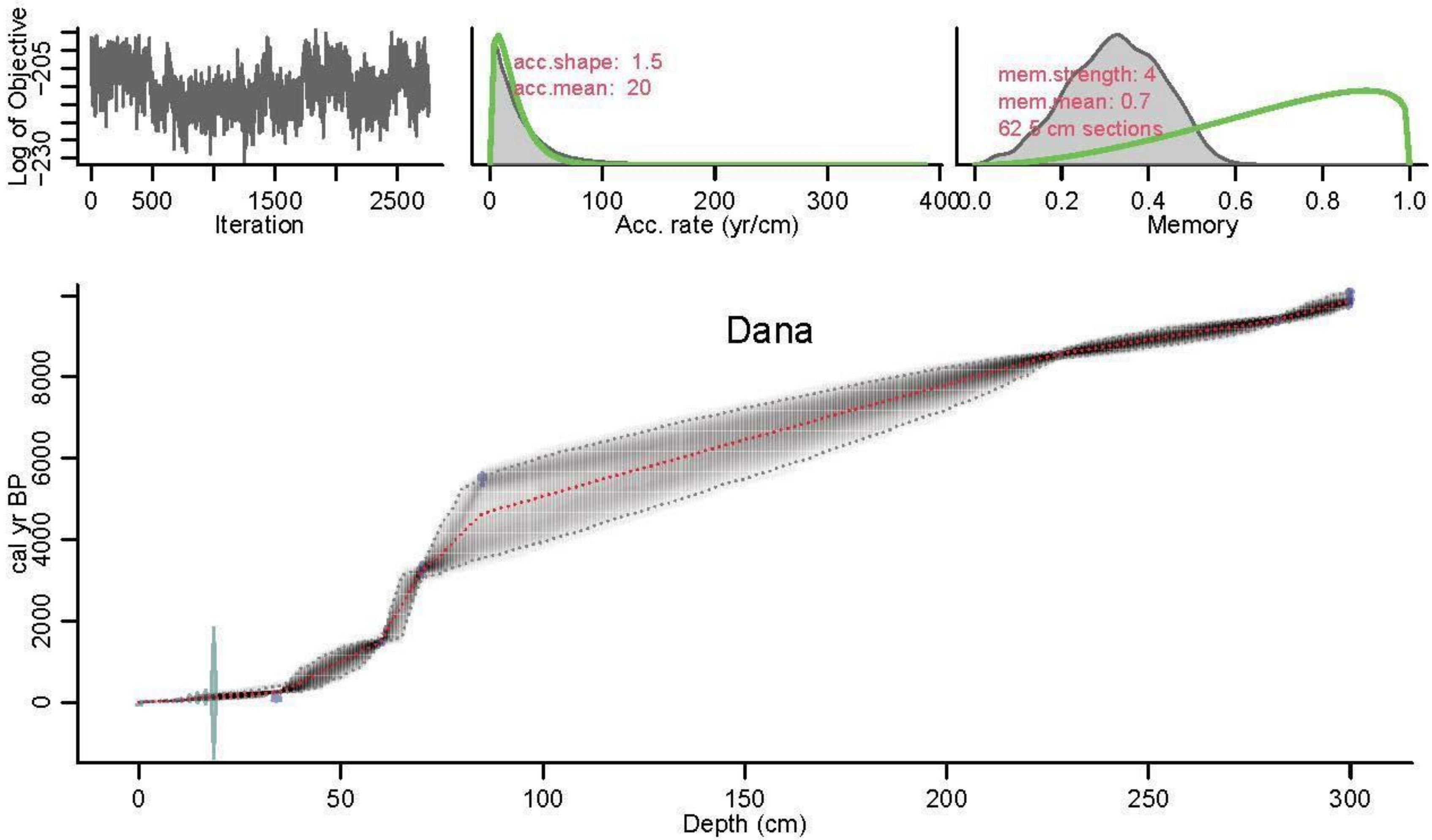

Figure 3.5. Age-depth model for the Dana Meadows (YNP) core.

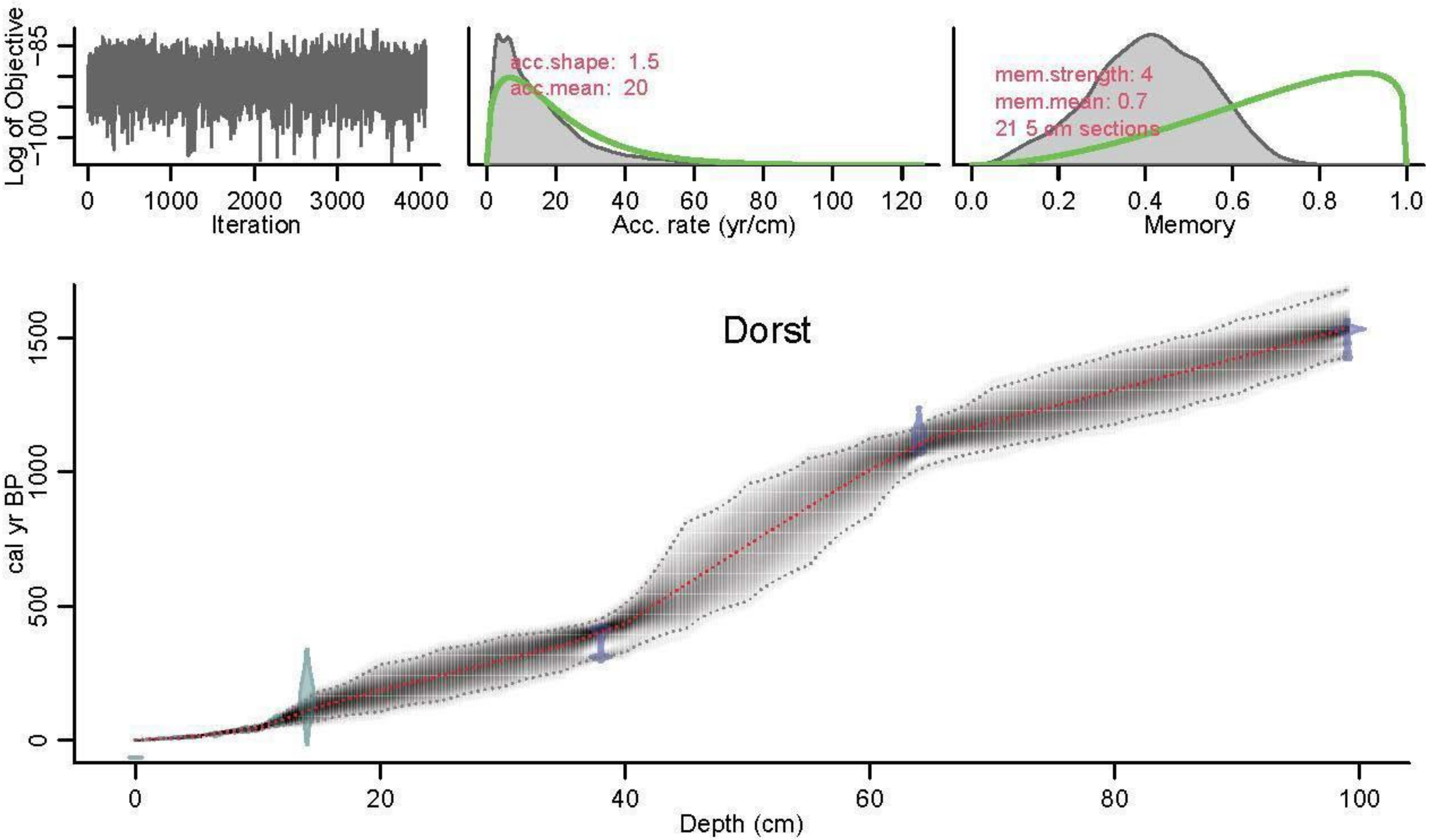

Figure 3.6. Age-depth model for the Dorst Meadow (SKCNP) core.

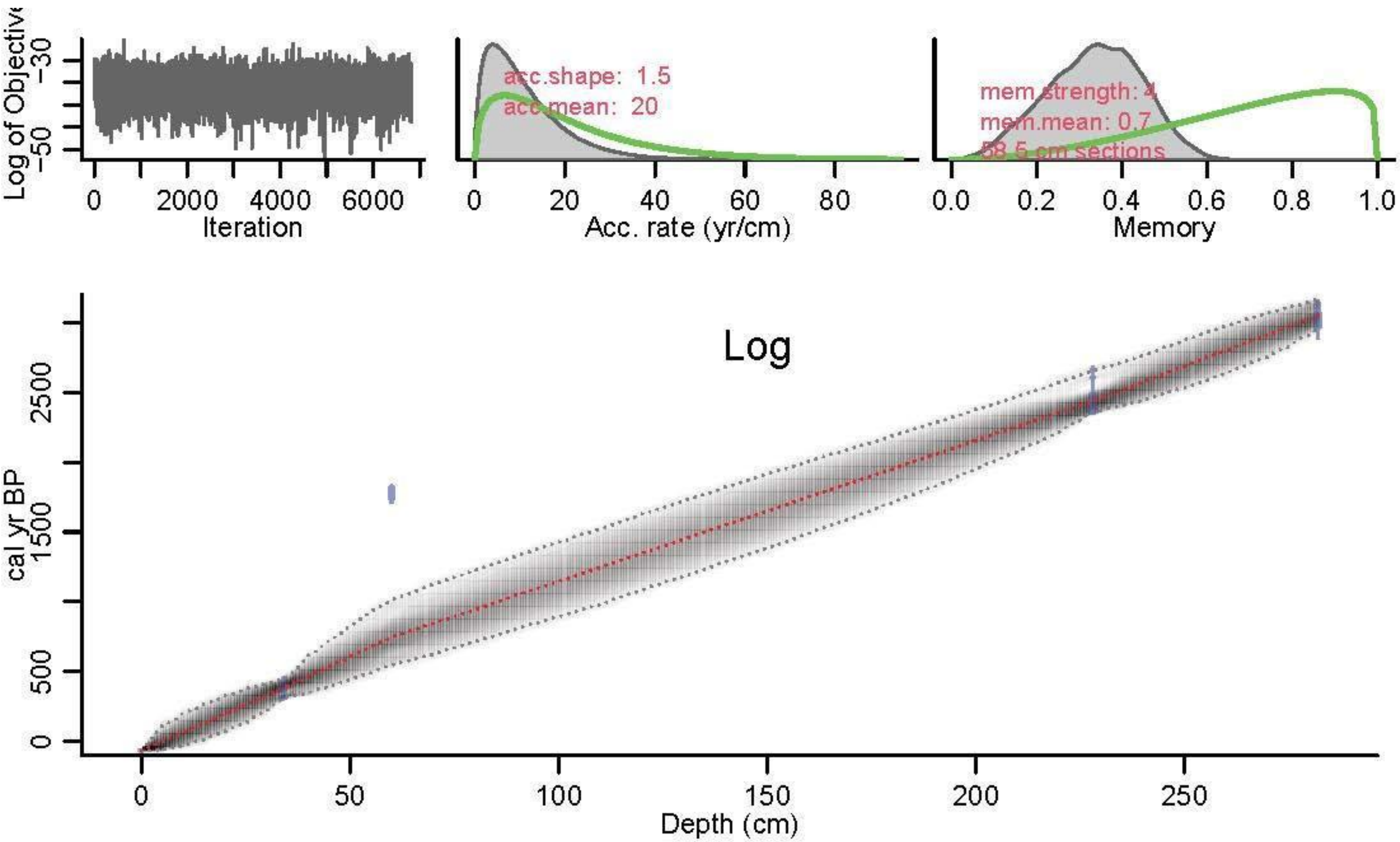

Figure 3.7. Age-depth model for the Log Meadow (SKCNP) core.

3.5.2 Loss-On -Ignition, Charcoal and Elemental Geochemistry

3.5.3 Porcupine Flat (PF)

The PF record began around at ~2700 call yr BP, showing %LOI values below 15% from that time until 500 cal yr BP when organic content rose to ~90% (see Figures 3.8, 3.9). Sediment accretion at PF generally was stable and slightly increasing from 0.2 cm yr^{-1} to 0.4 cm yr^{-1}, then elevated at 500 cal yr BP to 0.8 cm yr^{-1}. The overall sediment accretion rate was 0.46 cm yr^{-1}. Both the %LOI and accretion increase at 600 to 500 cal yr BP and there is a decrease in bulk density at the time to 0.2 g cm^3. Subsequently %LOI, sediment accretion, and bulk density varied, but LOI and OC remain high. The increase in accretion, OC and increased variability at ~500 cal yr BP coincides with the LIA but extends into the recent warm period also.

3.5.4 Tuolumne Meadow (TUO)

The TUO record began around at ~2000 cal yr BP, with %LOI above 24% that then decreased to 0% around ~700 cal yr BP and the MCA (Figures 3.10, 3.11). Sediment accretion at TUO was below 0.1 cm yr^{-1} until 1300 cal yr BP when it gradually increased to 0.4 cm yr^{-1}, where it has remained for roughly the last 1,000 years. The overall sediment accretion rate was 0.32 cm yr^{-1}. There is no clear relationship between any of the measured parameters and the MCA or LIA.

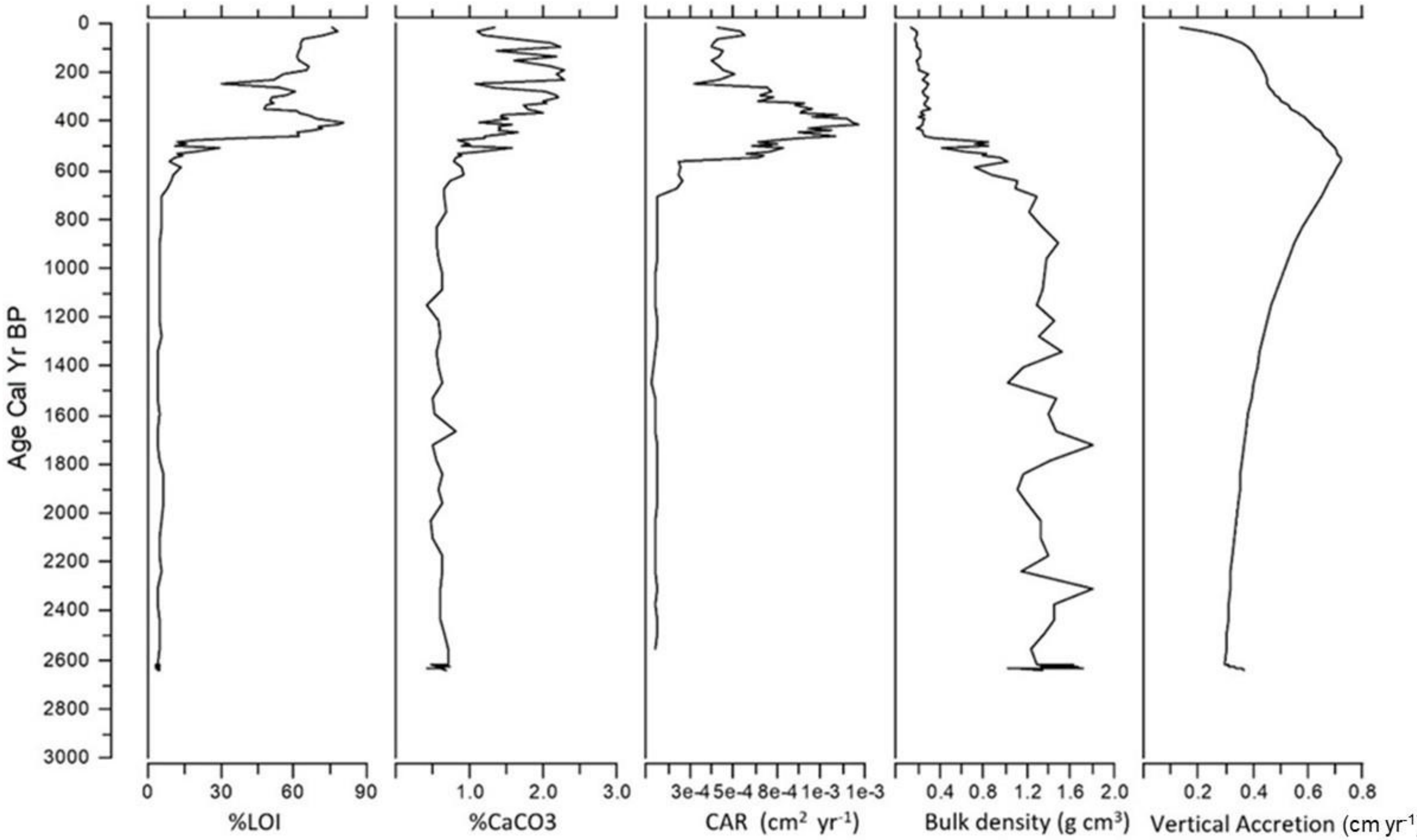

Figure 3.8. Sedimentology diagram for Porcupine Flat (YNP) core. During the Little Ice Age (after 500 cal yr BP), C accumulation increased in variability in comparison to the previous portions of the core.

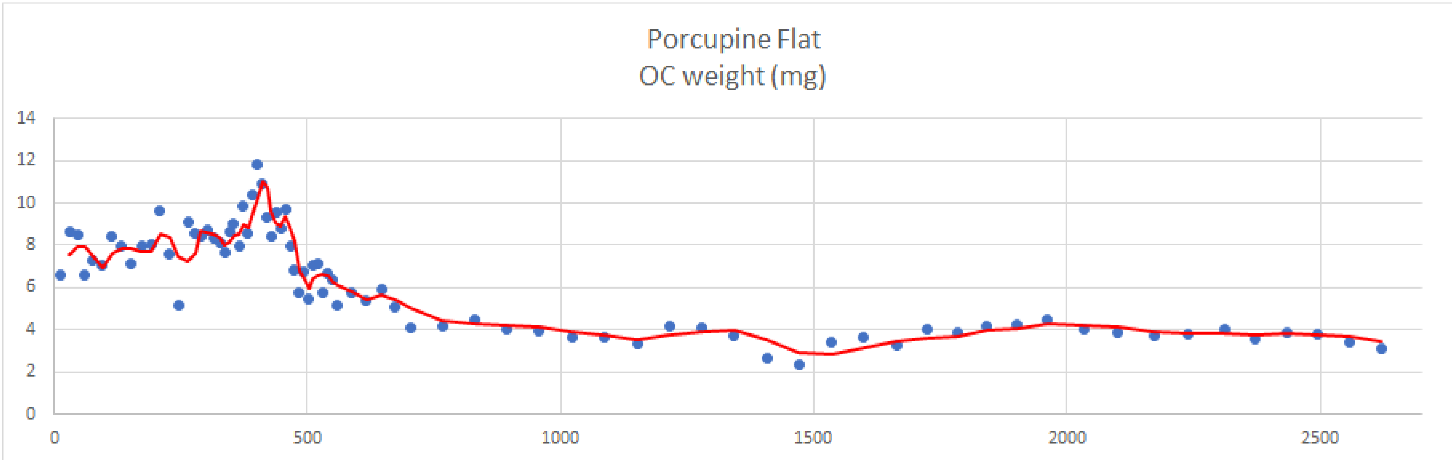

Figure 3.9. An x-y scatter plot showing organic content weight (mg) on the y-axis against age cal. Radiocarbon cal years BP are on the x-axis for the Porcupine Flat (YNP) core. A 3-part moving average is shown by the red line.

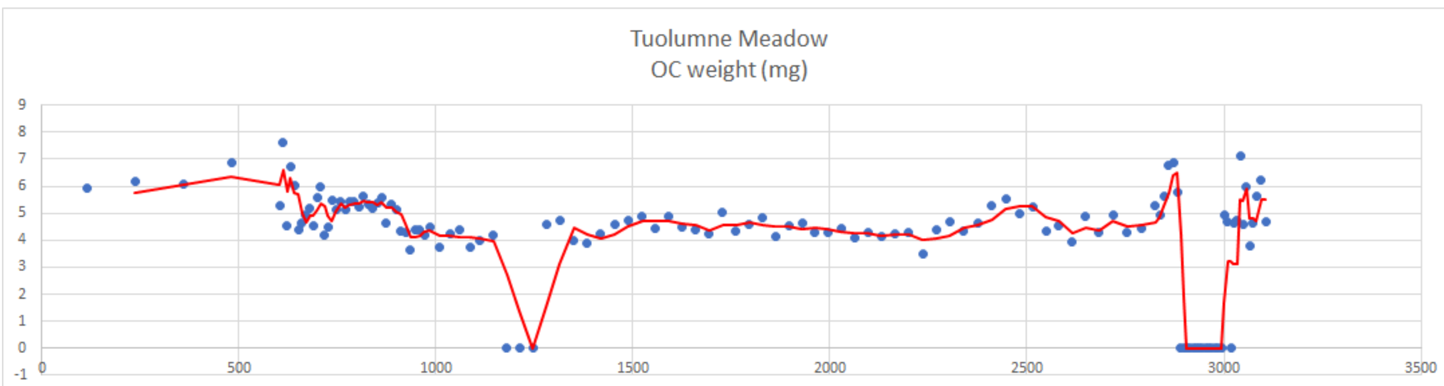

Figure 3.10. An x-y scatter plot showing organic content weight (mg) on the y-axis against age cal. Radiocarbon cal years BP are on the x-axis for the Tuolumne Meadow (YNP) core. A 3-part moving average is shown by the red line. After the Medieval Climate Anomaly (after 1200 cal yr BP), organic content increased both in weight and variability.

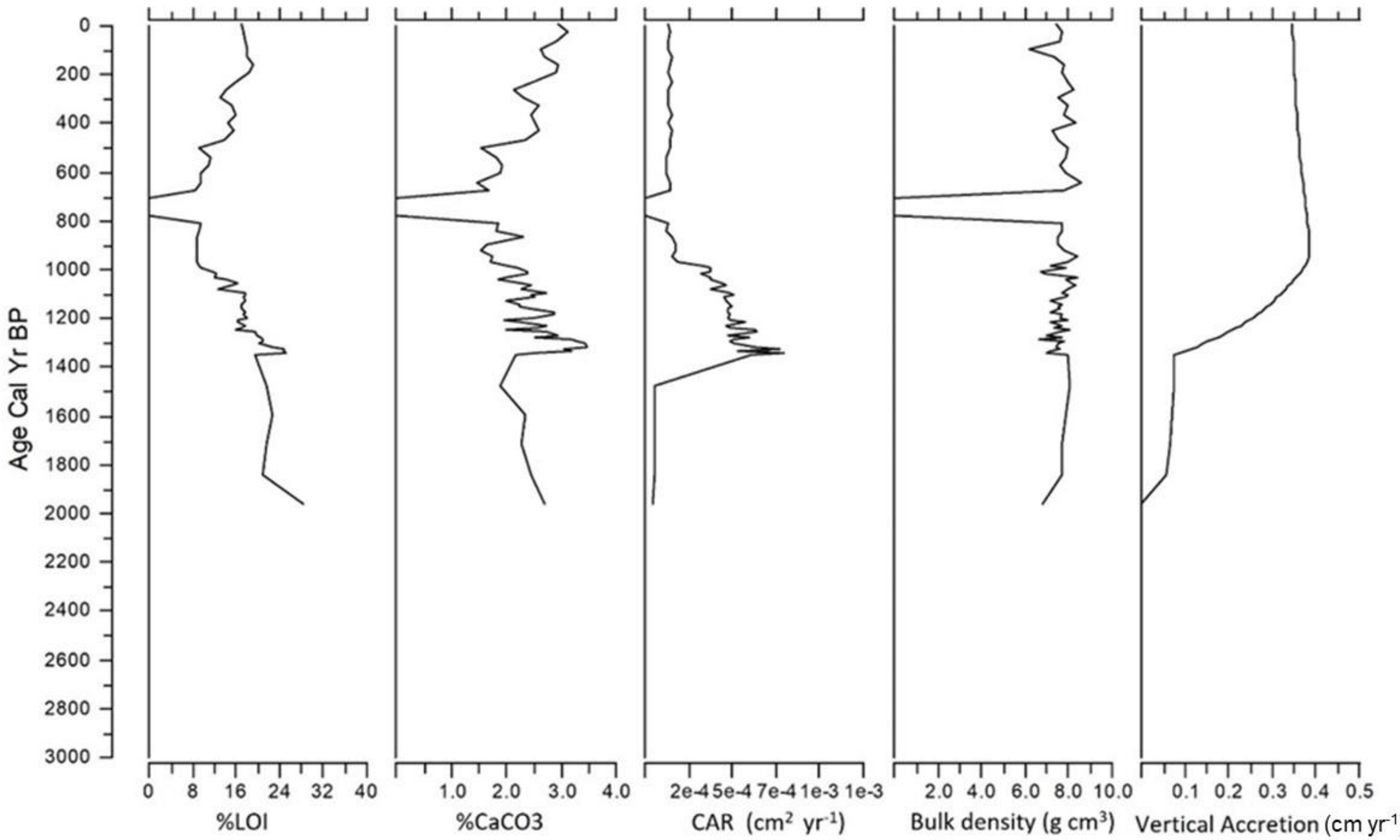

Figure 3.11. Sedimentology diagram for Tuolumne Meadows (YNP) core.

3.5.5 Dana Meadow (DM)

The DM core has a basal depth age of 8850 cal yr BP and was subject to more analysis (charcoal and elemental geochemistry) than the other sites; however, to simplify comparisons across all the sampled wet meadows, only the last 3000 years from the DM record are shown in Figures 3.12 and 3.13 and discussed. Starting ~3000 cal yr BP, %LOI was ~12% and stable until ~1200 cal yr BP and the MCA. Then at that time %LOI decreased to 8% and crustal metal concentrations of Rb, Ti, and Rb/Sr show elevated variability that continued into the LIA (Figures 3.12, 3.13). Sediment accretion at DM at 3000 cal yr BP was 0.2 cm yr^{-1} and increasing until peaking at 1.0 cm yr^{-1} during the LIA (Figure 3.12). The overall sediment accretion rate was 0.34 cm yr^{-1}. With respect to fire history, CHAR concentration stayed below 2.4 particles cm^3yr^- from 3000 cal yr BP until ~300 cal yr BP and the LIA. This indicates an increase in macroscopic charcoal accumulation resulting from elevated fire activity during the last 300 years. Similarly to PF, these there is an increase in OC, carbon accumulation and variability coincident with the onset of the LIA that also extends into the recent period.

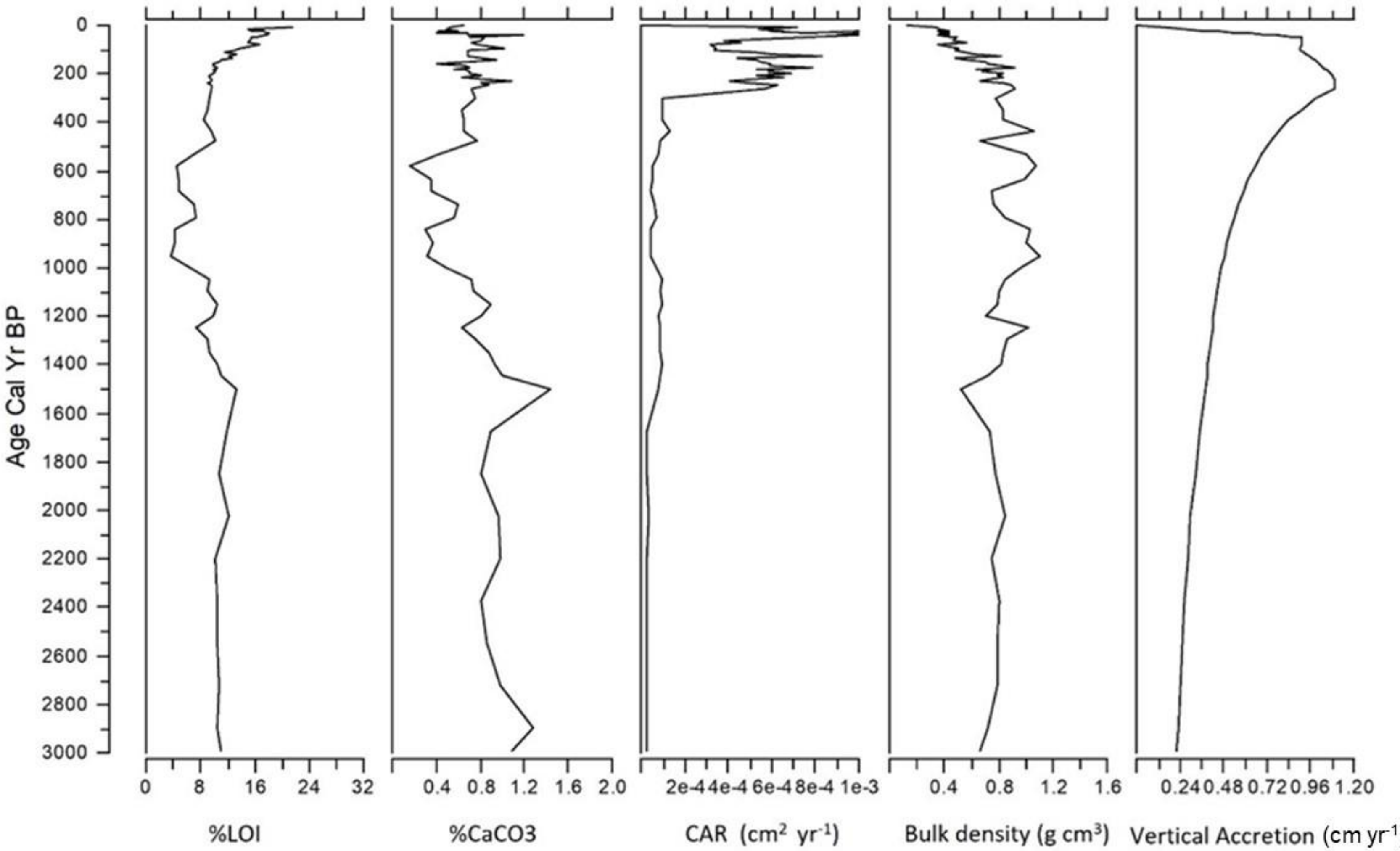

Figure 3.12. Sedimentology diagram for Dana Meadow (YNP) core.

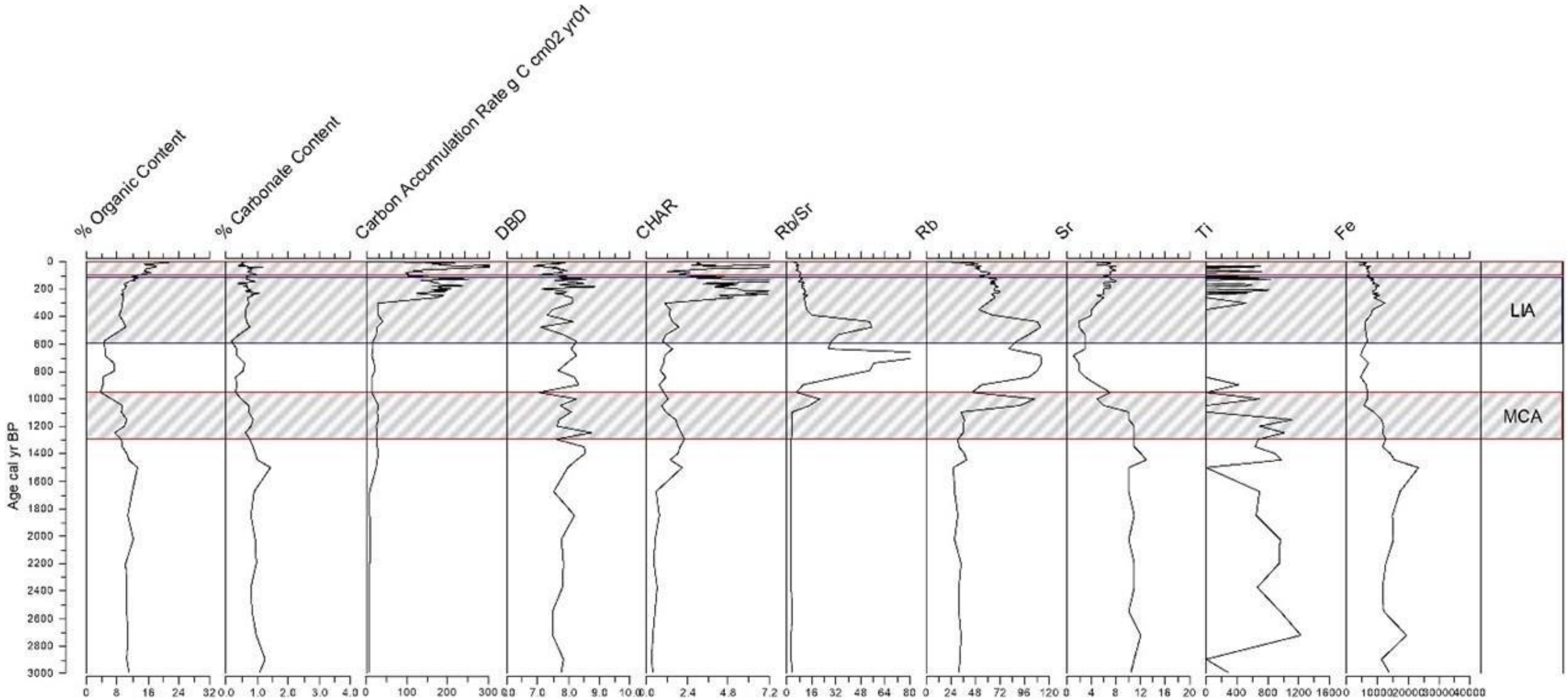

Figure 3.13. Sedimentology, CHAR, and Geochemical diagram for Dana Meadows (YNP) core. The Rb/Sr ratio represents increased precipitation during the LIA which likely led to more fire activity (see CHAR) as elevated vegetation growth and subsequent drying resulted in fuel loading. Such conditions resulted in higher C accumulation in the LIA in comparison to the MCA.

3.5.6 Dorst Meadow (DOM)

The core from DOM has a basal depth age of ~1500 cal yr BP. The %LOI was 10% in these basal sediments. At 1400 cal yr BP organic content spiked to 40%, then suddenly decreased at 1300 cal yr BP to around 5% (Figures 3.14 and 3.15). This pattern shows significant variability and suggests system sensitivity to local hydrogeomorphology conditions. This pattern of variability continued into the MCA, but organic content at that time never exceeded 10%. Sediment accretion also decreased from 0.65 cm yr^{-1} at 1500 cal yr BP to ~0.4 cm yr^{-1} around 1100 cal yr BP during the MCA. The overall accretion rate was 0.67 cm yr^{-1} . This record shows relatively high variability in all the paleo indices measured, suggesting the importance of local hydrogeomorphology as the primary driver of C accumulation and ecosystem functioning throughout the core. At the top of the core, %LOI is 50% and accretion is ~0.75 cm yr^{-1}.

3.5.7 Log Meadow (LOG)

The record from LOG has a basal depth age of 3000 cal yr BP, when %LOI varied between 35% and 72% (Figures 3.16, 3.17). Starting at the base, sediment accretion was below 0.5 cm yr^{-1} until 200 cal yr BP when it reached 1.0 cm yr^{-1}. The overall rate was 0.51 cm yr^{-1}. The LOG meadow core shows no significant relationship between the paleo indices measured and climate, and local hydrogeomorphology likely was the primary driver of C sequestration and wet meadow functioning. During the last 100 years (top of the core), %LOI spiked to 50% with accretion is 1.5 cm yr^{-1} because of minimal time for decomposition (Young et al., 2019).

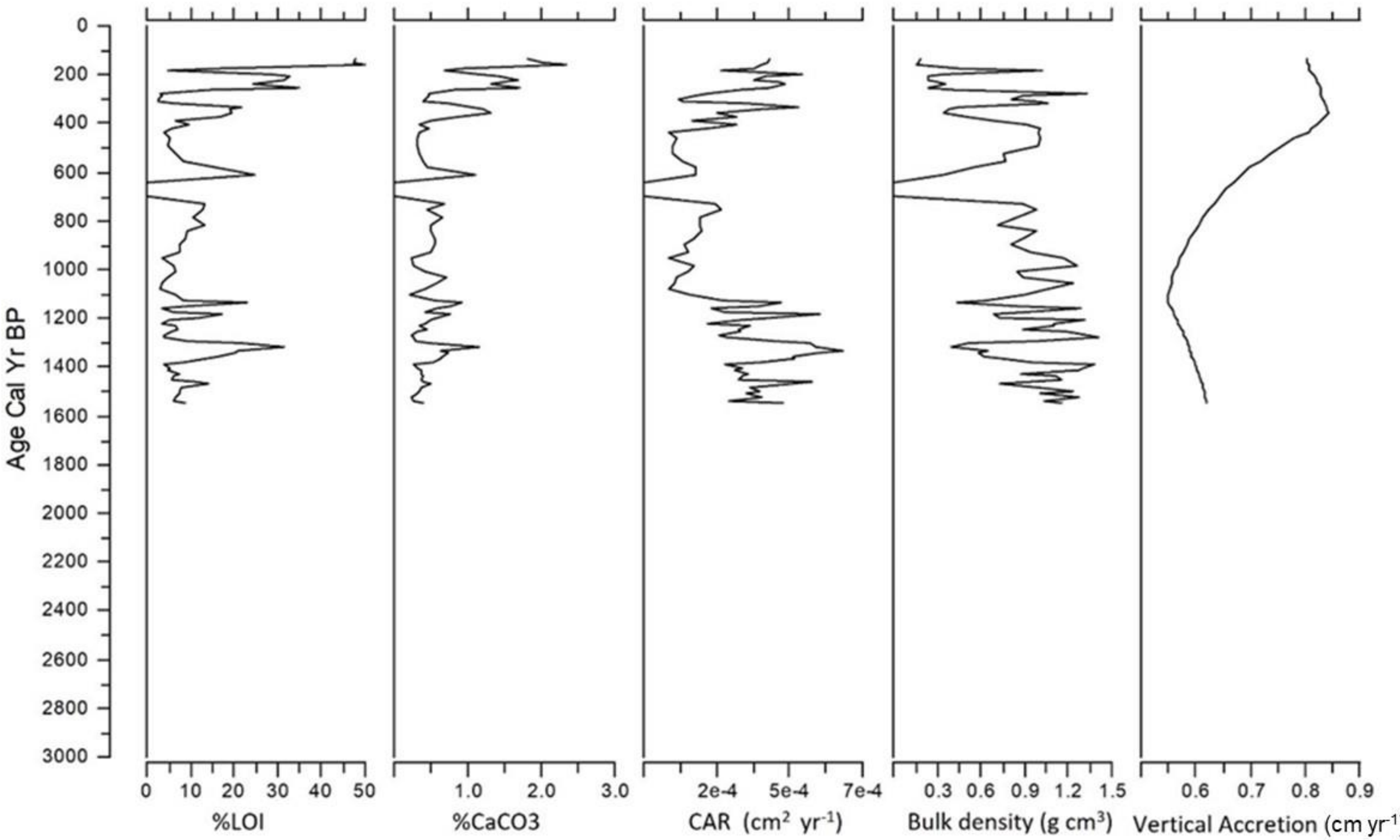

Figure 3.14. Sedimentology diagram for Dorst Meadow (SKCNP) core.

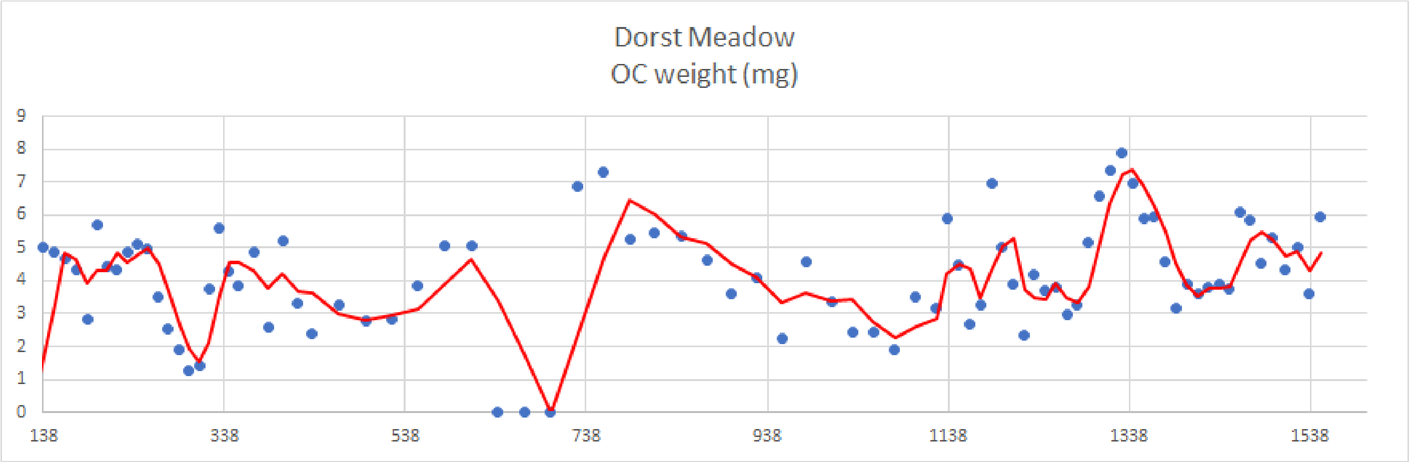

Figure 3.15. An x-y scatter plot showing organic content weight (mg) on the y-axis against age cal. Radiocarbon cal years BP are on the x-axis for the Dorst Meadow (SKCNP) core. A 3-part moving average is shown by the red line.

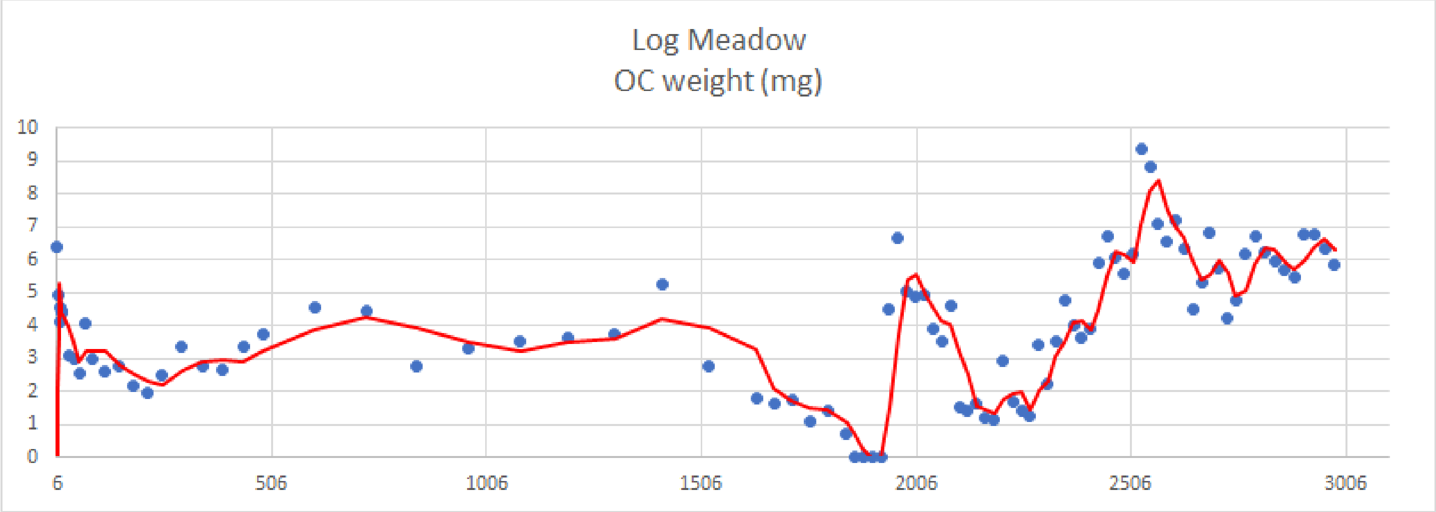

Figure 3.16. An x-y scatter plot showing organic content weight (mg) on the y-axis against age cal. Radiocarbon cal years BP are on the x-axis for the Log Meadow (SKCNP) core. A 3-part moving average is shown by the red line.

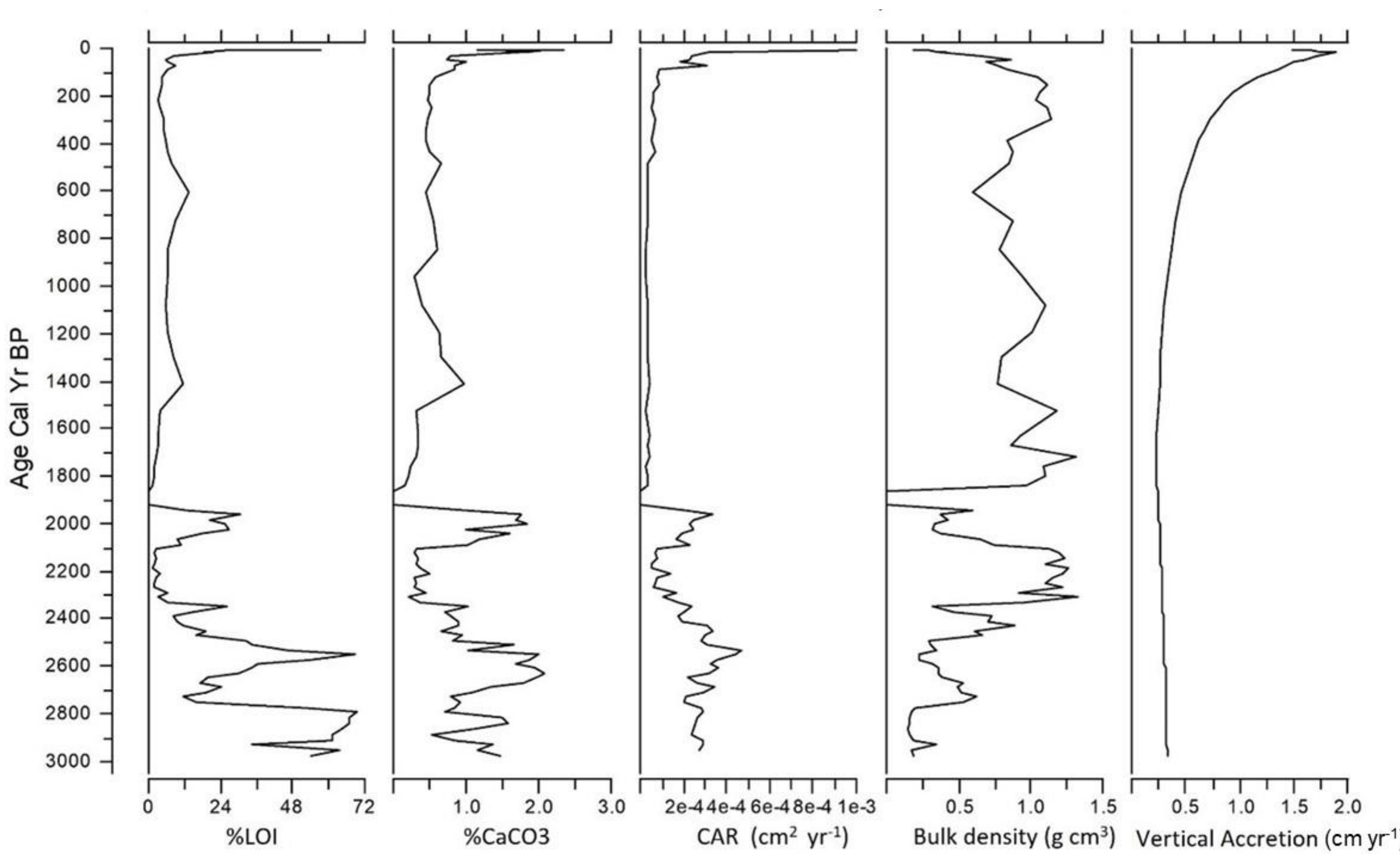

Figure 3.17. Sedimentology diagram for Log Meadow (SKCNP) core.

3.5.8 Multi-Site Comparison

The organic matter (%LOI) and C accumulation rates (CAR) recorded at the tops (present-day conditions) at the five sites ranged from approximately 20% to over 80% (LOI) and 25 g C m^2y^{-1} to 100 g C m^2y^{-1} (CAR) respectively (Figure 3.18). This indicates that even under present day conditions these wet meadows display appreciable variability in organic matter and C sequestration rates. This site-to-site variability is likely driven by local climatic, ecological and hydrogeomorphological factors. Comparing the downcore %LOI and C accumulation rates for the 5 wet meadows are presented each in Figure 3.18, and it show a high degree of temporal variability across these Sierra Nevada wet meadow systems. Two of the wet meadows, PF and DM, show no change in %LOI from ~3000 cal yr BP until roughly the MCA and LIA. The LOG record shows elevated %LOI at the bottom of the core, and no change in C accumulation until and increase in the last 100 years. That could likely result from a lack of decomposition time for recently accumulated organic material. It is not possible to compare the TUO and DOM cores with the other 3 wet meadows until around 1900 cal yr BP and 1500 cal yr BP, when the records for those two systems start. From about 1400 cal yr BP towards the top of the core, each sediment core record shows different %LOI and C accumulation signals during the MCA, LIA, and during recent anthropogenic warming. Such variation across the wet meadows suggests the importance of elevation, latitude, and local ecology and particularly local hydrogeomorphology as the principal drivers of variations in ecosystem functioning and C sequestration. There certainly is no universal correspondence with climatic variations such as the MCA, LIA or recent warming that is apparent in the records.

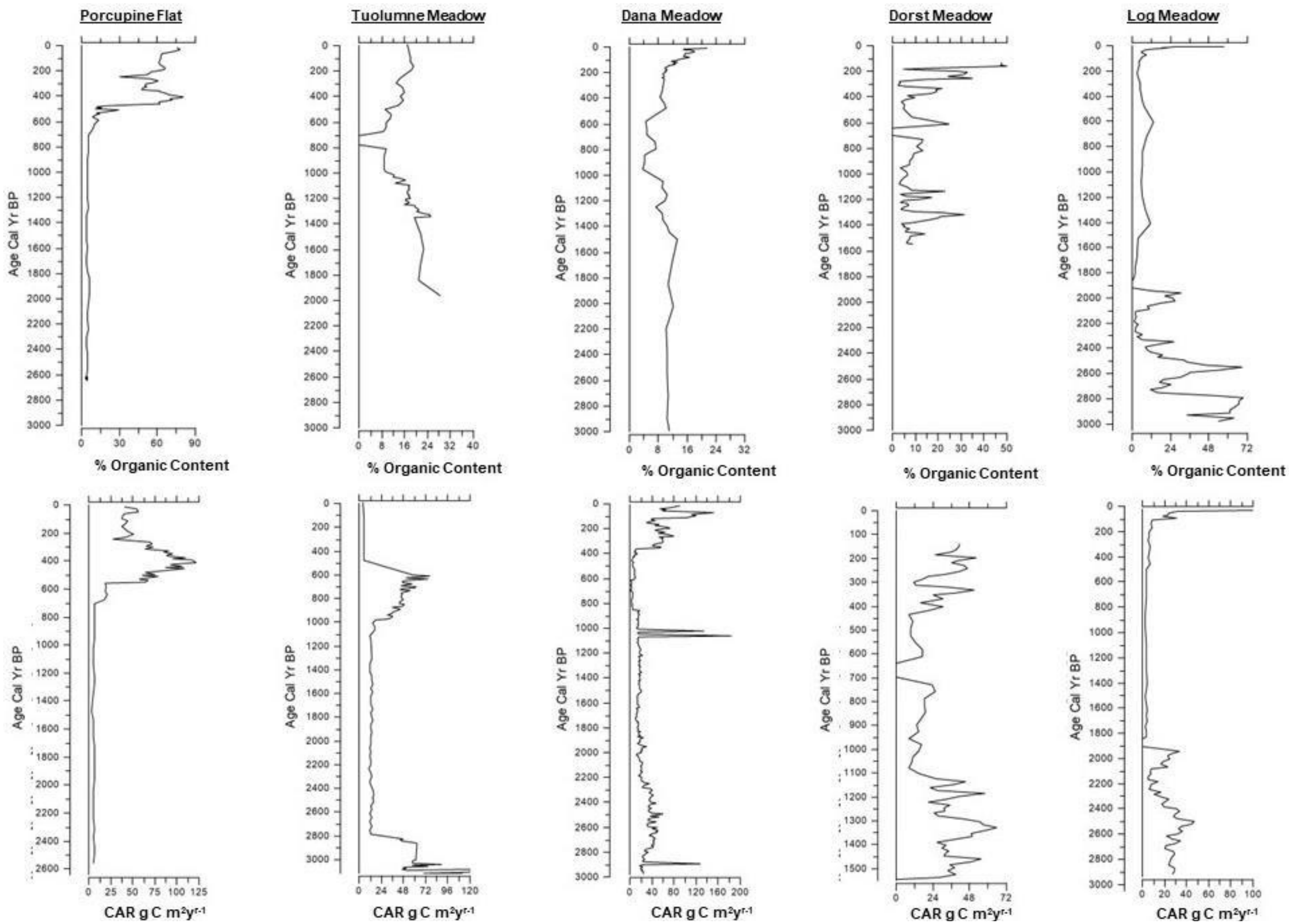

Figure 3.18. Comparison of Organic Content and CAR at all the wet meadow sites reported here.

Despite the site-to-site variability in current conditions and long-term patterns of LOI% and CAR, the long-term overall sediment accretion rates for the sites over the past 3000 years is somewhat similar. These values range from 0.46 (PF) to 0.32 (TUO), 0.34 (DM), 0.67 (DOM) and 0.51 (LOG) cm yr^{-1}.

3.6 Discussion

1. What are the long-term patterns and changes in sediment C sequestration rate at the sampled sites in YNP and SKCNP during the late Holocene?

The data generated by this study show that the wet meadows have had highly variable rates pf C sequestration (and organic matter content) over time. These rates have varied over time at the same site and such variations do not occur at the same times at the different sites. This variability likely resulted from sensitivity to local hydrogeomorphic factors (e.g. changing patterns of surface water flow and drainage, ; local cloud cover and shading causing variations in insolation reaching the surface to drive photosynthesis), site specific changes in meadow vegetation acting as the primary drivers of variations in local meadow ecosystems, sediment organic matter and C sequestration (Anderson & Smith, 1997; Drexler et al., 2015; Huang et al., 2018; Koehler & Scott Anderson, 1994; Wolf & Cooper, 2015). In addition to natural variations in such ecologic and hydrogeomorphic factors, the 5 wet meadows sampled likely do not all have the same local land-use histories, though all the sites likely were impacted by indigenous fire burning, Euro-American introduction of livestock grazing, and placer mining towards the latter half of the 19^{th} century (Anderson & Stillick, 2013; J. G. Holmquist et al., 2010, 2013a, 2013b; Koehler & Scott Anderson, 1994; Yang et al., 2017). The local scale impacts of such practices are unknown. Such land-use practices may have influenced different C accumulation rates near the surface of each core, though this is speculative at this point to say (Young et al., 2021).

The most striking finding from this study is that local hydrogeomorphic factors are the primary drivers of long-term C accumulation at each of the wet meadow sites. In reviewing the long-term patterns, there is no universal trend towards greater of less organic matter and C sequestration, nor temporally correlated changes in these variables over time.

2. How did sediment C content/sequestration rates change at YNP and SKCNP during past periods of prolonged higher temperatures, e.g. during the Holocene Thermal Maximum (3000 cal yr BP to 3800 cal yr BP) and Medieval Climate Anomaly (950 cal yr BP to 1350 cal yr BP)?

Changes in C sequestration were not uniform across all the wet meadows during the MCA. For example, at PF (2472 m MSL) on the west slope of the Sierra, %LOI was less than 15% throughout the MCA. Further upslope, however, at TUO (2611 m MSL) %LOI ranged from 8-16% between 800 to 900 cal yr BP, and then reached 0% at ~700 cal yr BP. C sequestration was relatively low at DM, LOG, and DOM meadows during the MCA. Periods of increased variability occurred at different times at each site due because of local hydrogeomorphic conditions.

The geochemical and CHAR records from DM perhaps provide some evidence that the MCA resulted in reduced C accumulation, an increase in crustal elements, and subsequent fire erraticism at this specific locality during the LIA that corresponds with some findings from previous studies (Brunelle & Anderson, 2003; Chang et al., 2013; Jin et al., 2006; Loisel et al., 2017). Specifically, %LOI at DM befor the MCA never rose above 10%, and %LOI fell below 8% at ~900 cal yr BP. This decrease in organic content coincides with the prolonged and persistent aridity prevalent during the MCA that impacted other systems found elsewhere in the Sierra Nevada (Bloom et al., 2003; MacDonald et al., 2016; Potito et al., 2006; Stine, 1994; Williams et al., 2020; Woodhouse et al., 2010). The two-pronged spike in Rb/Sr geochemistry suggests a potential delayed response to MCA drought conditions at DM that reduced ecosystem productivity and led to reduced water runoff into the system that exposed crustal and alkali elements (Chang et al., 2013; Jin et al., 2006). One can speculate that this reduced productivity influenced the variable and erratic CHAR record shown during the LIA, and points to the DM location being a climatically sensitive system (Macdonald et al., 2016; Stine, 1994b; Williams et al., 2020).

3. What is the relationship between sediment C content/sequestration rates at YNP and SKCNP during the prolonged cooling of the Little Ice Age (100 cal yr BP to 600 cal yr BP)?

During the LIA, C content increased at some wet meadows. Such increases in C sequestration appears to have coincided with elevated variability. This likely reflects changes in moisture availability at each site and surface runoff/groundwater recharge into the meadow (Cooper et al., 2015; Drexler et al., 2013, 2015; Huang et al., 2018; Lindquist et al., 2019). DOM shows high variability in C accumulation during the LIA, and MCA, suggesting that hydrogeomorphic conditions are particularly important for this wet meadow (Drexler et al., 2009, 2013, 2015). During the same period PF and DM show relatively high and variable rates of sequestration, whereas TUO and LOG reflect little change at all. These findings suggest that the LIA was not the primary driver of C sequestration at these wet meadows, but rather the dominant factor was local hydrogeomorphic conditions.

4. Do western mountain regions show similar C content and sediment accretion rates to the wet meadows sampled at YNP and SKCNP?

Although not exactly similar, mountain fens have been the subject of similar studies in the mountains of western North America and will be considered here. The data from the present study is similar to C content findings from Drexler et al., (2015) stating Yosemite fens have an

%LOI range from 33% to 43% during the last 50-100 years. Depending on the year examined, the 3 Yosemite cores here show that %LOI was as low as 16% at TUO and as high as 76% at DM during the 20th century, a broader range reported by Cooper and Wolf (2006) of ~25% to 45%. Data here also correspond with previous studies stating that boreal rich fens in western North America as far north as central and southern Alberta, Canada, report similar vertical accretion rates to those found in Yosemite from this study (see Table 3.2 below). Furthermore, the rates of accumulation/accretion from the SKCNP cores are greater than those from this study's Yosemite cores, again indicating that the elevation, hydrogeomorphic conditions, and latitude were primary drivers of C accumulation/accretion for the SKCNP wet meadows reported on here. Broadly speaking, the data presented here shows broadly similar values to the peatlands of Alberta, Canada (Bauer et al., 2009; Vitt et al., 2009; Yu, 2006).

Location	Mean Vertical Accretion (cm yr^{-1})	Time Period (cal yr BP)	Elevation (m MSL)	Latitude/Longitude	Reference
Porcupine Flat	0.46	3000 years	2472	37°48'21.64"N 119°33'55.35"W	This study
Tuolumne Meadow	0.32	3000 years	2611	37°52'39.02"N 119°23'18.82"W	This study
Dana Meadow	0.34	3000 years	2964	37°52'48.21"N 119°15'0.20"W	This study
Dorst Meadow	0.67	3000 years	2113	36°36'57.72"N 118°47'5.41"W	This study
Log Meadow	0.51	3000 years	2039	36°33'22.23"N 118°44'52.31"W	This study
Yosemite	0.18 to 0.28	50 to 100 years		37°48'21.64"N 119°33'55.35"W	Drexler (2015)
Southern Alberta	0.068 to 0.176		1246	49°13'7.25"N 113° 5'24.05"W	Yu (2006)
North/ Central Alberta	0.46	Last 67 to 156 years	700	54° 7'8.89"N 113°58'7.04"W	Bauer et al. (2009), & Vitt et al.(2009)

Table 3.2. Comparison of vertical accretion data from previous studies focused on meadow and fen C accumulation in Yosemite and Alberta, Canada.

3.7 Conclusions

The wet meadows of California's Sierra Nevada are a potentially important C pool for California today because of 21st century climate change. This study showed high-resolution paleoecological data from 5 sediment cores gathered from YNP and SKCNP. C accumulation and ecosystem functioning were primarily driven by local hydrogeomorphology with past climate change serving as a secondary driver apparent in some sites only during the last 3,000 years. Some examples of local hydrogeomorphic factors are: 1) natural changes in surface water runoff; 2) local changes in the supply of inorganic sediment or soil moisture; 3) flooding events; 4) slope instability and erosion could change the supply of inorganic sediment to the system. No regionally coherent climatic response was shown in the paleo indices measured for the YNP and SKCNP sediment cores. Mean rates of accretion and organic content percentages are similar to findings from previous studies that focused on the last 100 to 150 years t from wet meadow/fen sites as far north as Alberta, Canada. Although carbon content and overall sediment accretion rates are similar, the high degree of spatial and temporal variability in C sequestration rates and ambiguous relationship to past climatic variations over the past 3000 years, suggests that it will be hard to anticipate the exact nature of changes in C sequestration in these wet meadow systems as climate change progresses over the 21st century.

4. Mid-Holocene Carbon Sequestration and Ecosystems at Dana Meadow, Yosemite

4.1 Abstract

This study presents paleoecological data of the impacts of past climatic changes on wetland systems and forests in the Sierra Nevada, California. The paper addresses important questions about long-term rates of carbon storage in these ecosystems. A keen emphasis was placed on carbon storage and wetland system functioning during the Holocene Thermal Maximum (HTM; 8000-3000 cal yr BP). A 300 m sediment core retrieved from Dana Meadow, Yosemite National Park, indicates carbon storage was ≥ 24 g m^2 yr^{-1} during the HTM. By the mid-Holocene, upland vegetation pollen types like *Quercus* and *Tsuga mertensiana* expanded upslope amid prolonged warming. Changes in upland forest cover and density correspond with reduced quantities of CHAR until ~6500 cal yr BP. Such findings provide baseline carbon storage data and insights on how these ecosystems may respond to 21st century warming.

4.2 Introduction

Ecosystems that naturally capture and store atmospheric carbon are being examined as one means to combat anthropogenic climate change (Bonan, 2008; Seddon, 2022; Seddon et al., 2020; Thorslund et al., 2017). In California, two such systems include forests and wetlands (Gonzalez et al., 2015; Nahlik & Fennessy, 2016). Wet meadows and the surrounding forests of the Sierra Nevada are one area where significant natural carbon capture and sequestration could occur (Norton et al., 2013; Lalonde et al., 2018) However, important questions remain regarding the long-term rates of carbon storage in these systems and the response of the ecosystems to climate change, particularly prolonged warming (Blackburn et al., 2021; Norton et al., 2011). Desiccation and decay of organic matter might decrease carbon content in wet meadows and forest fires and vegetation change might decrease carbon stored in forests

(Gonzalez et al., 2015; Moomaw et al., 2018) as climate warms in the future. Paleoecological studies of the impacts of past climatic changes on wetland systems and forests can provide insights into the long-term carbon sequestration of these systems and the responses to climatic warming.

4.2.1 Research Questions

For this study a long sediment core that spans the past 10,000 years was taken from Dana Meadows, Yosemite National Park, and a number of physical and biological analyses were conducted to address the following questions: 1. What is the total depth of organic meadow sediment and average % carbon content stored in this meadow system based on the core?; 2. How has the rate of carbon sequestration and storage varied over time?; 3. How have large-scale climatic events such as the Holocene Thermal Maximum (HTM), Medieval Climate Anomaly (MCA) and Little Ice Age Impacted the meadow ecosystem, surrounding forest and rate of carbon sequestration and storage?

4.3 Study Area

The Sierra Nevada covers an area of roughly 78,000 ha, with Yosemite (YNP) considered a treasure for wilderness conservation in California (Viers et al., 2013a, 2013b). YNP has several wet meadow areas, mostly in designated wilderness areas. Elevations in the park range from roughly 500 to 4000 m, with montane conifer forest starting at ~1800 m MSL and subalpine conifer forest at 2400 m MSL. A Mediterranean climate with warm and dry summers and moist winters characterizes the parks. Average maximum and minimum January temperatures at the Dana Meadows site are 5^{o} C and -11^{o} C, while average maximum and minimum July temperatures are 22^{o} C and 4^{o} C. Average annual precipitation is 758 mm, most of which occurs as winter snowfall (https://www.nps.gov/yose/planyourvisit/weather.htm).

The YNP wet meadows represent a sample of similar systems found throughout the Sierra Nevada. The site sampled for this study is: Dana Meadow (DM, 350.7 ha, 2964 m MSL, 37°52'48.21"N 119°15'0.20"W). The site was likely deglaciated by 15000-14000 cal yr BP (Wahrhaftig et al., 2019). According to the National Park Service (2014), vegetation at the wet meadow is a diverse assemblage of herbs (e.g. Drosera rotundifolia), graminoids (e.g. Carex vesicaria), and bryophytes (e.g. Sphagnum subsecundum). Shrubs including *Artemisia tridentata*, *Vaccinium caespitosum* and *Salix* species occur in the area dependent upon site moisture. Dense forest composed primarily of Pinus in YNP dominate the landscape near the edges of the meadows. This meadow was selected because of its representative nature, relatively undisturbed condition, and ease of equipment access. Sediment cores were collected from the sites in 2016 using a Russian peat auger.

4.4 Materials and Methods

4.4.1 Field Work

During the summer of 2016, sediment cores from Dana Meadows were gathered using a 5-cm diameter Russian peat auger. The auger penetrated through the upper peats until compacted mineral material at the basal depth impeded further drives. The core drives were extruded in the field, then wrapped longitudinally in cellophane and aluminum foil and placed in core boxes. Subsequently, the cores were transported and placed in cold storage (~5°C) at the UCLA laboratory.

Figure 4.1. Topographic map of Dana Meadow site sampled in Yosemite National Park (YNP) plotted on Google Earth satellite image. Dana Meadows is near the crest of the Sierra, roughly 16 km west of Mono Lake.

4.4.2 Laboratory Analysis

Plant macrofossil material for radiocarbon dating was selected from macrofossil rich portions of each core. Roots were avoided. The plant macrofossils were radiocarbon dated at the University of California Irvine (UCI) Keck Radiocarbon lab, where a 500 kV accelerator mass spectrometer (AMS) device from National Electrostatics Corporation was used for the analysis. All samples were pretreated following the UCI hydrogen reduction method (Santos et al., 2007). Subsequently, the organic samples were calibrated using the IntCal20 calibration curve (Reimer et al., 2020).

Standard loss on ignition (LOI) procedures were followed to determine sediment organic matter/C (Goodsite et al., 2004; Heiri et al., 2001). LOI was analyzed at intervals of 1-cm. Bulk density was obtained by obtaining wet weight of the sample, drying overnight at 110°C, then weighing again to obtain dry weight (Goodsite et al., 2004). Sediment organic C content was assessed by weight loss after combusting sediment samples in a muffle furnace at 550 ^{o} C, and $CaCO_3$ by combusting the same samples at 1000^{o} C. LOI organic matter estimates were converted to C estimates using a traditional 0.58 correction factor, although it is recognized that dependent upon sediment type this may misestimate actual C content (Westman et al. 2006; Pribyl, 2010). Elemental geochemistry was also analyzed for Dana Meadow using a portable x-ray fluorescence (pXRF) handheld device at 5-cm intervals. The elements presented and discussed here include Rb, Ti, Sr and Fe.

Pollen extraction and analysis was conducted using standard techniques (Faegri et al., 1989) with use of a collection of reference samples and taxonomic books at the UCLA lab and online taxonomic resources. Macroscopic charcoal (i.e. > 250 and > 150 μm) was analyzed following the procedures of Chipman et al., (2015) and Higuera et al., (2009) at continuous 1-cm intervals. Charcoal accumulation rates (CHAR) were modeled in R using the software program CHAR (Higuera et al., 2010, 2011; Vachula et al., 2018; Whitlock & Larsen, 2002).

4.4.3 Statistical Analysis

Data analysis and visualization was done using C2, Microsoft Excel, and R. Statistical modeling was conducted using R and paleocological modeling software C2 (Juggins 2007). The R package Bacon was used to develop the core chronologies and sediment accumulations rates used to reconstruct C sequestration and other paleo proxies (Blaauw & Christen, 2011). Bacon relies on Bayesian statistics to reconstruct accumulation rates by incorporating radiocarbon dates into an age-depth model (Blaauw & Christen, 2011).

4.5 Results

4.5.1 Chronology

The DM core was 300 cm (3.0 m) in length. A total of 21 plant terrestrial plant macrofossil samples were collected from the sediment to develop chronologies spanning the Holocene (Table 1). The radiocarbon dates indicate that the DM core dates to approximately 10,000 cal yr BP (see Table 4.1 below).

Sample Name	UCIAMS Lab #	Depth (cm)	Material	D14C (‰)	±	^{14}C age (BP)	±	Cal yr BP
DM34	191918	34	Plant	-225.12	1.5	35	15	Modern
DM60	191940	60	Plant	-227.2	3.6	1630	15	413
DM70	168457	70	Plant	-453.5	5.5	3065	45	1397
DM85	193511	85	Plant	-418	2.1	4810	45	3642
DM228	168456	228	Plant	-376.2	3.1	7800	20	6647
DM282	185590	282	Plant	-41.6	1.4	8480	20	7578
DM299.5	185591	299.5	Plant	-110.2	1.4	8830	20	7572
DM300	191941	300	Plant	-213.5	1.4	8850	20	8171

Table 4.1. Dana Meadow AMS radiocarbon dates from UC Irvine Keck Radiocarbon lab

An age-depth model developed using the BACON software is presented in Figure 4.2. Despite the uniformity of the peat sediments at the surfaces, there have been appreciable variations in sediment type and/or accumulation rates over time. Most decreased sedimentation in the latter Holocene, followed by an increase in the past 1000 years

4.5.2 Carbon Storage and Accumulation Rates

The core has bulk density (DBD) and high carbon content (>10%) similar to the modern surface for the entire depth, consistent with the site being a wet meadow for all of the past 10,000 years (Fig. 3). The site was likely deglaciated by 15000-14000 cal yr BP (Wahrhaftig et al., 2019), but the core did not yield sediment older than approximately 10,000 cal yr BP, so earlier conditions are unknown. Highest sustained carbon content is approximately 20% during the period 10,000 to 8000 cal yr BP after which there is a long-term decline to values of less than 10% during the period around 1000 cal yr BP (Fig. 4.3). Average value for the core is 12.787%. Highest sustained rates of C accumulation rates of around 48 gm m^2 yr^{-1} occur during the period approximately 9500 – 8700 cal yr BP and declines thereafter. The lowest rates of around 20 gm m^2 yr^{-1} occur during the period of about 3000 - 2000 cal yr BP (Fig. 4.3). Apparent carbon accumulation rate is very high at the top of the core, but this may represent the fact that decomposition processes have not reduced the carbon content of very recent organic sediment (Young et al., 2019)

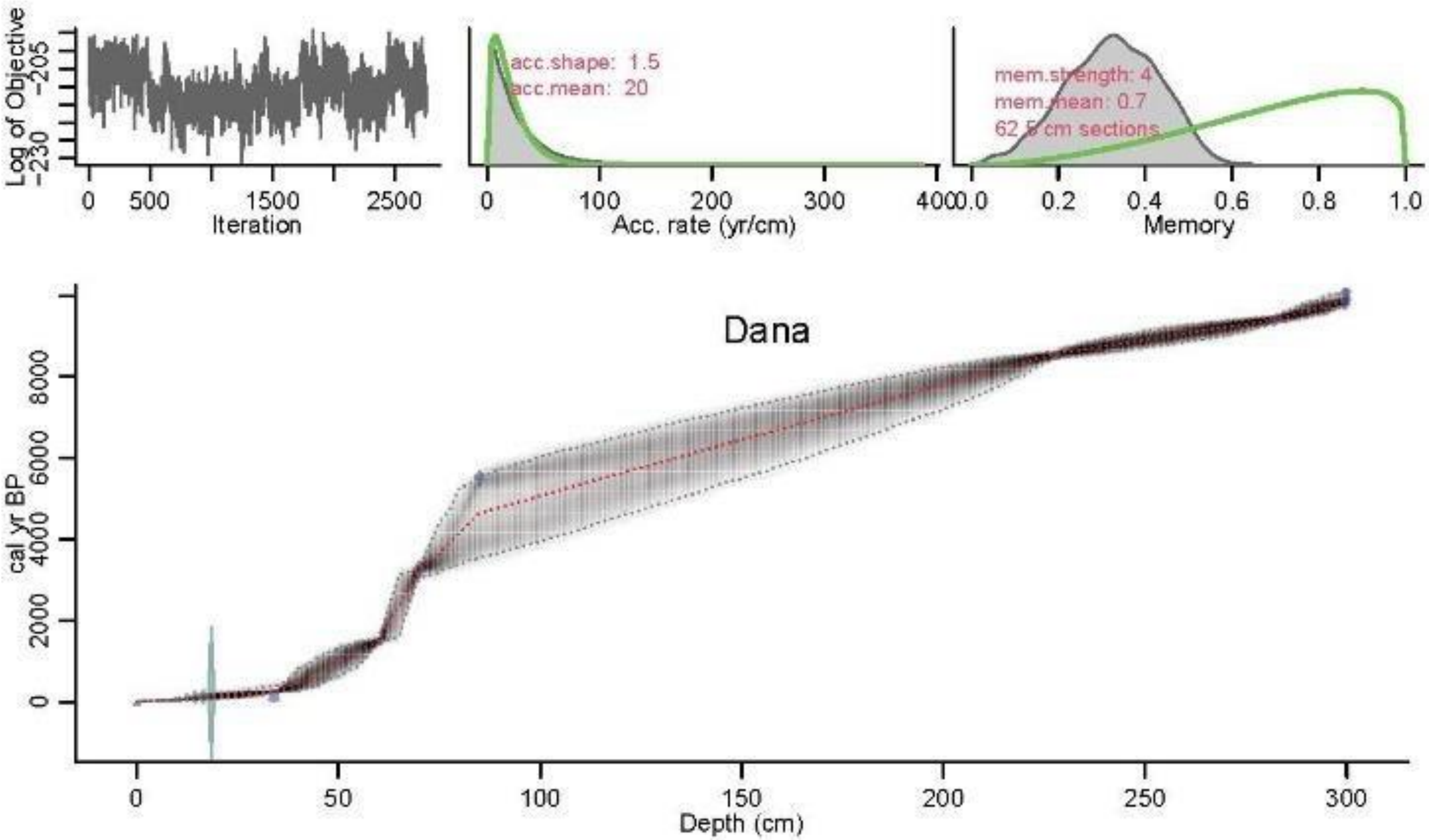

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Figure 4.2. Age-depth model for the Dana Meadow (YNP) core.

4.5.3 Elemental Geochemistry, Charcoal and Pollen

Elemental geochemical data (Fig. 4.3) indicates that the period of highest C content and accumulation corresponds to a period of low inputs of crustal elements (Rb, Sr, Ti, Fe), suggesting a more organic-dominated depositional system than the subsequent history of the meadow, including the recent past. A strong peak the Rb/Sr ratio between 1000 and 500 cal yr BP. High values of the ratio of Rb/Sr can be associated with strong chemical weathering in the watershed of lakes and wetlands, or increased inputs of terrigenous material (An et al., 2018; Xu et al., 2010). The fact that the Rb/Sr peak is associated with declines in the concentrations of other crustal elements such as Ti and Fe may indicate factors favoring increased weathering in the watershed and erosion into the site during the start of the Little Ice Age (LIA ~600 - 200 cal yr BP).

The fossil pollen record (Fig. 4.3) shows that the high carbon percentages and accumulation rates between approximately 10000 to 8000 cal yr BP are associated with maximum percentages of *Artemisia* and Cyperaceae pollen. There are also relatively high percentages of *Pinus* pollen. The high Cyperaceae at this time is consistent with a productive sedge-dominated wet meadow. The high *Artemesia* and *Pinus* suggest a relatively open upland vegetation with pine woodlands and sagebrush understory. Perhaps reflecting proximal post-deglaciation conditions of the early Holocene. High amounts of *Quecus* and *Tsuga* pollen from approximately 7000 – 3000 cal yr BP, coupled with the decrease in *Artemisia*, suggests an upward movement of these mid-elevation taxa and the establishment of a more closed forest cover near the site during the Holocene Thermal Maximum (HTM ~8000 – 3000 cal yr BP) (Fig. 4.3). High percentages of *Pinus* pollen indicate the continued dominance of this genus in the local area. The declines in *Quercus* and *Tsuga* in the latter Holocene, following the close of the

HTM is likely a response to climatic cooling experienced in the Sierra Nevada (Koehler and Anderson, 1994; Konrad et al., 1998; Scudari and Fawcett, 2013).

The CHAR record indicates the presence of local fires starting around 7500 cal yr BP as forest cover increased during the HTM. Local fires have continued through the remainder of the Holocene. High values of CHAR in the very recent period may reflect Indigenous and European influences on fire regime.

4.6 Discussion

This research set-out to address three specific questions**.** The insights provided to these questions will be discussed in turn below.

1. What is the total depth of organic meadow sediment and average % carbon content stored in this meadow system based on the core?

The total depth of organic meadow sediment in this meadow system based on the core is 300 cm. The average % carbon content stored in the meadow is 12.79%. In comparison to 79 fens in the Sierra Nevada reported on by Wolf & Cooper (2015), the % carbon content for the Dana Meadow core is similar. Carbon content differs greatly from system-to-system based on local hydrogeomorphology, elevation, slope, climate, soil, etc. This core's % carbon content is similar to other systems at a similar elevation (roughly 20% to 80%), although the total depth of organic material at Dana Meadow exceeds similar systems by about 1.0 to 1.5 m (e.g. Abbot View Fen, Inyo National Forest; Mosquito Meadow, Sequoia National Park; Wolf & Cooper, 2015). Because the Dana Meadow core's organic material is deeper than other cores collected from other systems in the Sierra Nevada, it is both representative of long-term C sequestration variability and unique in that it provides a deeper deposit and encompasses most of the Holocene

Thermal Maximum. In contrast, a core from Sequoia National Park from a current wet meadow spans at least the past 14,000 year but suggests that modern wet meadow conditions at that site only developed in the past 3000 years and the upper sediment contains appreciable layers of silts and sands (Koehler and Anderson, 1994). Taken together, this indicates that to make accurate estimates of total carbon in Sierra Nevada wet meadow systems, cores have to be taken to ascertain depth and C content, rather than extrapolating average values.

2. How has the rate of carbon sequestration and storage varied over time?

The rate of C sequestration in the wet meadow generally decreased from 45 g m^2 yr^{-1} at 9287 cal yr BP to 2 g m^2 yr^{-1} by the end of the HTM. Such changes in C sequestration and storage correspond with increased temperatures and prolonged aridity that occurred during the HTM after deglaciation (MacDonald et al., 2016). After the HTM, C storage in the wet meadow remained low until 1448 cal yr BP when it suddenly increased to 20 g m^2 yr^{-1}. From 1350 - 1000 cal yr BP, during the MCA, average C sequestration was below 10 g m^2 yr^{-1} [1], and average C storage was 8 g m^2 yr^{-1} until 950 cal yr BP when it dropped to 4 g m^2 yr^{-1}. Near the top of the core C storage leaps above 60 g m^2 yr^{-1} during the LIA and the 20th century possibly because of reduced decomposition time of organic content near the surface (Young et al., 2021).

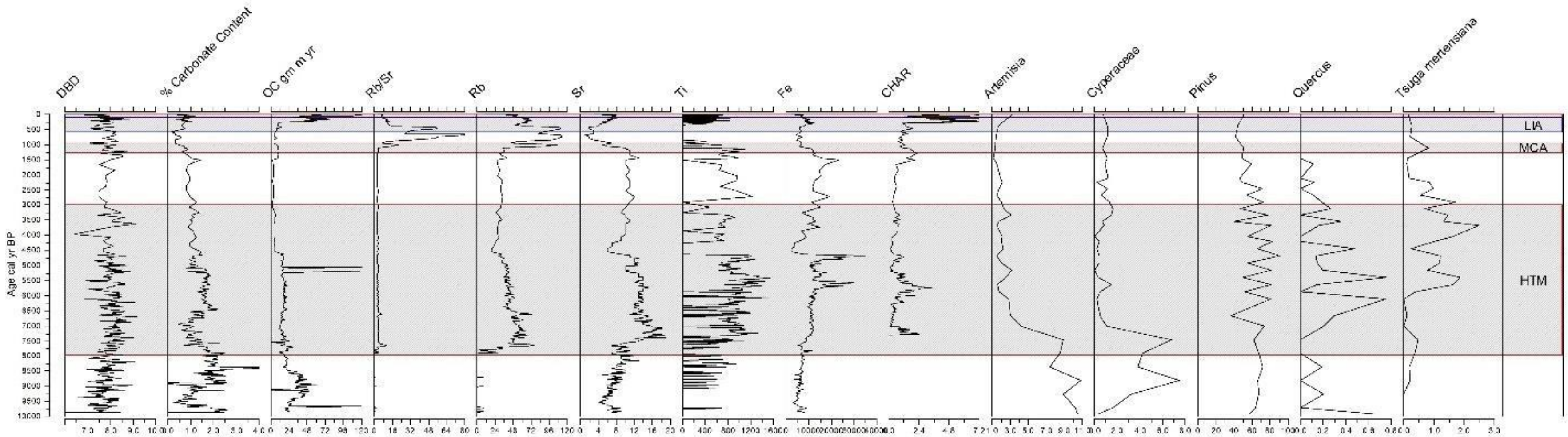

Figure 4.3. Dana Meadow (YNP) core bulk density, organic content, C accumulation rate estimate, elemental geochemistry. Important pollen types. The Holocene Thermal Maximum (HTM ~8000-3000 cal yr BP), Medieval Climate Anomaly (MCA ~1400-1000 cal yr BP) and Little Ice Age (LIA; ~600 to 200 cal yr BP cal yr BP) are indicated.

The data for the Dana Meadow long-core show that the wet meadow system was highly variable in terms of C sequestration and storage during the Holocene. Such changes in C accumulation occurred at different points in time. Changes in wetland C storage likely resulted from sensitivity to local hydrogeomorphic factors like changing patterns of surface water flow and drainage, local cloud cover and shading causing variations in insolation reaching the surface to drive photosynthesis, and site specific changes in meadow vegetation acting as the primary drivers of variations in local meadow ecosystems, sediment organic matter and C sequestration (Anderson & Smith, 1997; Drexler et al., 2015; Huang et al., 2018; Koehler & Scott Anderson, 1994; Wolf & Cooper, 2015). In addition to natural variations in these ecologic and hydrogeomorphic factors, the wet meadow likely was impacted by indigenous fire burning, Euro-American introduction of livestock grazing, and placer mining towards the latter half of the 19th century (Anderson & Stillick, 2013; Holmquist et al., 2010, 2013a, 2013b; Koehler & Scott Anderson, 1994; Yang et al., 2017). The magnitude of these localized impacts is unknown, but they did potentially lead to changes in C storage near the surface of each core, although this is speculation currently (Young et al., 2021).

The lack of CHAR during the early Holocene, and increased levels of *Artemisia*, Cyperaceae, *Quercus*, and *Pinus* until roughly 7000 cal yr BP, indicates upland vegetation, due to a lack of fire, may have been a more efficient and longer-term C sink than in later periods. However, the lower forest cover/density during the pre-7500 cal yr BP period may have helped mitigate wildfire, but also suggests less standing biomass in which C would be stored. High CHAR in the early HTM and increases to maximum levels over the past 2000 years suggests periods during which fires have more actively released biomass carbon from the upland vegetation to the atmosphere. The highest CAR values occur over the past 1000-500 years and suggest the recent past has experienced the highest rates of fire generated releases of biomass carbon. California' indigenous people's used fire in several ways and it has been estimated that California forest fire regimes may have released as must as much 23196 to 62611 g of CO_2 annually during the immediate pre-European period (Stephens et al., 2007).

3. How have large-scale climatic events such as the Holocene Thermal Maximum (HTM), Medieval Climate Anomaly (MCA) and Little Ice Age Impacted the meadow ecosystem, surrounding forest and rate of carbon sequestration and storage?

Prior to the HTM the wet meadow C sequestration rates at DM were high, reaching values of 30-40 20 g m2 yr-1. There was a decline into the start of the HTM. However, during the early HTM, C sequestration remained relatively high, ≥ 24 g m^2 yr^{-1}, until declining to prolonged minimum values between 5500 and about 1500 cal yr BP. The decrease in C sequestration during the HTM may reflect increasing aridity impacting meadow plant productivity and increased rates of decomposition of organic matter in the meadow. However, the variable nature of the relationship between the HTM and C sequestration, and the prolonged low rates of sequestration after the close of the HTM until 1500 cal yr BP, suggest local factors of hydrogeomorphology, hydrology and microclimate likely also played roles.

. The lack of CHAR during the early Holocene possibly suggests that upland forest cover C storage was not as impacted by fires as during later periods. The increase in CHAR after 7500 cal yr BP, and relatively high values at this point, is consistent with a more robust fire regime. Climate was warmer and drier and the vegetation denser and containing more low- to mid-elevation components such as *Quercus* and *Tsuga*. After 3000 cal yr BP lower elevation elements of the vegetation retreated from the wetland area to downslope sites in the Sierra Nevada. This general pattern of upslope expansion of upland forest during the HTM followed by downslope retreat during the early Holocene is like findings from other locations in the Sierra (Anderson, 1990; Hallett & Anderson, 2010; LaMarche, 1973; Lloyd & Graumlich, 1997; Scuderi, 1994). In general, the HTM is strongly represented by the Dana Meadow core. However, CHAR decreased from the early HTM peak and relatively consistent lower values remained for most of the HTM until about 1500 cal yr BP. The fact that CHAR remained similar to the late HTM until 1500 cal yr BP suggests that fire remained a factor in the C balance of the system after the HTM, and indeed reached very high values relative to the HTM in the recent past. Why there was a peak in CHAR in the early HTM and then lower values persisted through the remainder of the HTM and into the post-HTM period remains uncertain from the DM record.

The LIA and MCA do show variability in wetland C storage, vegetation, and CHAR. The geochemical and CHAR records from DM perhaps provide some evidence that the MCA resulted in reduced C accumulation in the wet meadow, an increase in crustal elements, and subsequent fire variability at this specific meadow during the LIA that corresponds with some findings from previous studies at other Sierra sites (Brunelle & Anderson, 2003; Chang et al., 2013; Jin et al., 2006; Loisel et al., 2017). Specifically, C sequestration at DM before the MCA increased to roughly 20 g m^2 yr-1, then decreased below 10 g m^2 yr^{-1} at 900 cal yr BP. This decrease in C storage coincides with the prolonged and persistent aridity during the MCA that impacted other systems found elsewhere in the Sierra Nevada (Bloom et al., 2003; MacDonald et al., 2016; Potito et al., 2006; Stine, 1994; Williams et al., 2020; Woodhouse et al., 2010). The two-pronged spike in Rb/Sr geochemistry suggests a potential delayed response to MCA drought conditions at DM that reduced ecosystem productivity and led to reduced water runoff into the system that exposed crustal and alkali elements (Chang et al., 2013; Jin et al., 2006). One can speculate that this reduced productivity influenced the variable and erratic CHAR record shown during the LIA, and points to the DM location being a climatically sensitive system (Macdonald et al., 2016; Stine, 1994b; Williams et al., 2020). Despite these climatic impacts to the meadow system, wetland changes during the LIA and MCA were not as persistent or strong as those that took place during the HTM.

4.7 Conclusions

The Dana Meadow wetland system naturally captures and stores atmospheric C and this ecosystem was examined as a means to combat anthropogenic climate change (Bonan, 2008; Seddon, 2022; Seddon et al., 2020; Thorslund et al., 2017). This research was conducted as a way of assessing variability and climatic sensitivity of C storage in wetlands and adjacent forest in California to add to knowledge on this topic (Gonzalez et al., 2015; Nahlik & Fennessy, 2016).(Blackburn et al., 2021; Norton et al., 2011). The DM records indicates a highly variable C sequestration and storage system, apparently sensitive to both climatic changes and more local influences. The paleorecord remains preliminary in its ability to disentangle the factors that promoted the range of variability apparent on the record. As climate warms in the future, desiccation and decay of organic matter might decrease C content in wet meadows, and forest fires and vegetation change will impact C stored wetlands and in forests (Gonzalez et al., 2015; Moomaw et al., 2018). The DM record suggests the response of specific sites may be complex and potentially not generalizable.

5. Dissertation Conclusions

The research presented in this dissertation has sought to provide a long-term perspective on environmental change and carbon sequestration in both low elevation and high elevation wetlands in the San Joaquin River watershed area of California. As anthropogenic climate change progresses towards 2100, scientists and policy makers have taken a keen interest in the natural C sequestration and storage of freshwater wetlands globally, and in California (Bonan, 2008; Seddon, 2022; Seddon et al., 2020; Thorslund et al., 2017). Temperatures could increase 2.0˚ to 4.0˚C, which could lead to prolonged aridity (Cayan et al., 2007; Cloern et al., 2011; Dettinger et al., 2016a; Kumar et al., 2013; Taylor et al., 2007; Bedsworth et al., 2018). The freshwater wetlands in the Sacramento-San Joaquin Delta and Sierra Nevada wet meadows are important stores of C amid the pressing risk of desiccation and fire during 21st century climate warming (Gonzalez et al., 2015; Nahlik & Fennessy, 2016).

The San Joaquin Watershed connects the Sierra wet meadows to the freshwater wetlands of the Delta by hydrology. Hydroclimatic conditions in the Sierra near the river's headwaters drive C storage in the adjacent wet meadows and forests, and C sequestration in the freshwater wetlands found downstream in the Delta. By gathering sediment cores from the 7 wetlands for this dissertation, analytical chemistry methods estimated organic content and C sequestration at high resolution (1 cm) for the length of each core (Heiri et al., 2001). Paleoecological studies such as this illuminate impacts of past climate and other environmental changes on wetland systems and the responses to past warming and aridity during the Holocene (Brunelle & Anderson, 2003; Fard et al., 2021; J. R. Holmquist et al., 2016; MacDonald et al., 1991; MacDonald et al., 2016; Whitlock & Larsen, 2002; Yu et al., 2011).

Although each of the substantive chapters (Chapters 2,3,4) addressed particular questions related to climatic and environmental changes and the response of wetlands and C sequestration, some overarching questions common to all can be summarized as:

1. What are the long-term conditions and patterns and changes in the wetlands and their sediment C content/sequestration rates over the Holocene?

2. How did the wetlands change in nature and in terms sediment C content/sequestration rates during past periods of widespread climate change such as the prolonged higher temperatures during the Holocene Thermal Maximum (~3000 cal yr BP to 8000 cal yr BP: calendar years before 1950 CE)) and Medieval Climate Anomaly (950 cal yr BP to 1350 cal yr BP), or the prolonged cooling of the Little Ice Age (100 cal yr BP to 600 cal yr BP)? In particular, do these suites of wetlands examined display similar contemporaneous responses to these past climatic variations?

3. What other changes related to local vegetation cover, local fire or local hydrological or geomorphological conditions appear to have occurred and impacted each wetland and their C content/sequestration rates and what is their relative importance?

A clear message from the analyses and records presented here is that there is much local variability in the histories of these wetlands and their C sequestration records. Although the long-term C sequestration rates at the delta sites may be somewhat similar to each other, and the same when the overall average C sequestration rates at the Sierra sites are compared to one another and to other studies from the region, no regionally coherent response to past climatic changes was shown in the paleo indices measured for the 7 sediment cores from the Delta and Sierra. There is much variability between systems in terms of depth of high C sediment – and thus the total amount of C stored at any site. Local variations in hydrogeomorphology appears to be a primary driver of natural C sequestration and storage for each site. Because of these factors, it is not possible to generalize the amount of C stored at a specific wetland to other wetlands. There has been much variability in the rates of C sequestration during the Holocene. Such variability reflects impacts of known past climatic change as well as local hydrogeomorphology. Each wetland system formed at different times as a response to changing climatic and environmental conditions (e.g. deglaciation) and hydrogeomorphology (e.g. brackish marsh; freshwater marsh; low elevation meadow; high elevation).

As climate change progresses over the 21st century, these wetland systems and similar ones in California will likely show much variability regarding C storage and sequestration. The variability between each system over the Holocene could be enhanced this century because of significantly different conditions near each site and adjacent areas, such as land-use and population, that could impact local hydrogeomorphology. At this juncture, however, the cause of this variability aside from local conditions is speculative.

Although this study detected no widespread coherent response of the San Joaquin wetlands C dynamics to past Holocene climatic changes, documenting and helping to understand the potential variability of such environmental systems is arguably just as important in anticipating California's climate change future and its potential variability of responses. Accordingly, future research should continue building long-records of total C storage and sequestration rates. Such studies will provide greater resolution of the degree of variability displayed by these systems. Moreover, the forces that control the variability between wetland systems requires further investigation, both through paleo studies and examinations of modern systems. Identifying the causes that drive C variability across systems over the Holocene, and how such variability may be expressed over the 21st century, remains a priority for scientists and useful information for policy makers in California.

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