Title
Lake Sediments as Evidence of Natural and Human-Induced Environmental Change from California and Nevada

Author
Reidy, Liam Michael

Publication Date
2013

Lake Sediments as Evidence of Natural and Human-Induced Environmental Change from California and Nevada

By

Liam Michael Reidy

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Geography

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Roger Byrne, Chair
Professor Lynn Ingram
Professor Kent Lightfoot
Dr. Michael Rosen

Fall 2013

Lake Sediments as Evidence of Natural and Human-Induced
Environmental Change from California and Nevada

By

Liam Michael Reidy

Abstract

Lake Sediments as Evidence of Natural and Human-Induced
Environmental Change from California and Nevada

By
Liam Michael Reidy
Doctor of Philosophy in Geography
University of California at Berkeley
Professor Roger A. Byrne, Chair

This study focuses on the history of natural and human-induced environmental change as recorded in the sediments of two lakes: Mountain Lake in the Presidio National Park, San Francisco, California and Big Soda Lake, near Fallon, Churchill County, Nevada. The records of these lakes examined in this study cover approximately the last 2,000 years. Sediment cores from the lakes were dated with radiocarbon, lead-210, plutonium 240/239, tephrachronology, and the first appearance of non-native pollen types. The cores were analyzed to determine changes in stable isotopes (carbon and oxygen), sediment chemistry, fossil pollen, magnetic susceptibility, organic content, and brine shrimp cyst concentrations.

Big Soda Lake has been the subject of scientific investigation since the 19th Century and two famous scientists have previously worked at the site. First, the geologist, Israel Russell explored the lake in 1882 as part of his work on Pleistocene Lake Lahontan and provided the first scientific report on the lake. Later in 1933, Evelyn Hutchinson, the famous Yale limnologist, provided the first detailed limnological report for the lake. More recently in the 1980's, the lake has been studied by scientists from the United States Geological Survey. However, prior to the research reported on here, very little was known of the history of the lake or to what extent its sediments contained a useful record of environmental change.

The sediments of Big Soda Lake provide clear evidence for both natural and human-induced environmental change during the past 1600 years. The climate record developed from the analyses of stable isotopes of oxygen and carbon, sediment chemistry, and the concentrations of brine shrimp cysts show several significant shifts in climate. The early part of the record from A.D. 400-850 is period marked by a fluctuating climate, with alternating wet/dry phases each lasting several decades each (40-60 years). During the period known as the Medieval Climate Anomaly (MCA)(A.D. 850-1400), we observe at least two relatively dry periods from A.D. 850-1150 and A.D. 1260-1400. Between the two dry phases, there is a pronounced wet period from A.D. 1150-1260. This wet period matches fairly well with evidence presented in other

paleoenvironmental studies in the western Great Basin. During the Little Ice Age (LIA), the evidence indicates that the Big Soda Lake area was not always colder and/or wetter, but that it was in fact drier and perhaps warmer from A.D. 1400-1700 than it had been in the previous millennium. Pronounced dry phases were observed around A.D. 1400, A.D. 1500 and A.D. 1650. The wettest period during the LIA came between A.D. 1750-1800.

The human impact record at Big Soda Lake developed from the analyses of stable isotopes of oxygen and carbon, sediment chemistry, and the concentrations of brine shrimp cysts show several dramatic changes in and around the lake since Anglo American settlement of the area began, in the 1850's. Several human impacts have been identified, including regional mining activity, soda salt extraction from the lake, and irrigation induced rising groundwater levels in the last century. Two of these events have dramatically impacted the lake in that time. Firstly, the development of a commercial soda manufacturing and processing facility at the lake beginning in 1875 until the early 20th century; and secondly, the development of irrigation agriculture which led to an 18 m rise in lake level in the first few decades of the twentieth century.

The sediments at Mountain Lake provide evidence of unprecedented heavy metal contamination at the San Francisco Presidio during the past 60 years. The lake evidence is consistent with local land-use changes initiated by the arrival of Europeans in the area after 1776 and the construction of California State Highway 1 adjacent to the lake in the late 1930's. The study shows how small water bodies alongside roads can concentrate heavy metals and demonstrates the need for careful scientific investigation of sediments earmarked for dredging to determine what if any contaminants are present.

A key outcome of the Mountain Lake research carried out as part of this dissertation was that in the Fall of 2011 a Federal judge ordered the California Department of Transportation (Caltrans) to pay 13.5 million dollars to the Presidio Trust so that the contaminated sediments could be removed and further run-off from the road be prevented from entering the lake.

To my parents who always encouraged me to stay in school
(although not this long!)
and to Stephanie who has seen me through from start to finish.

Table of Contents

Introduction

A Sedimentary Record of Heavy Metal Contamination in the Presidio National Park, San Francisco, California, USA

A History of Human Impacts on Big Soda Lake, Nevada, USA (1850-2010)

A 1600 Year Record of Climate Change from Big Soda Lake, Nevada, USA

Summary

Figures

Tables

Appendices

Acknowledgments

I am sincerely grateful to all those who have helped me with this research and take full responsibility for any mistakes and omissions.

I would like to thank my committee chair, and advisor during my graduate studies, Roger Byrne. This body of work, as well as several earlier projects, has benefited greatly from his careful review. I have been very fortunate to have had undertaken extensive field and laboratory work with Roger over the years, since my first trip south of the border to Mexico in 1998 and more recently our efforts at Big Soda Lake. There is no doubt that I have had a fantastic graduate school experience and during that time we have developed a close working relationship, which I truly appreciate.

A special thank you to Michael Rosen and Kip Allander (USGS-Carson City, NV) and Larry Miller (USGS-Menlo Park, CA) for help in recovering the initial short cores from Big Soda Lake. Marith Reheis (USGS-Denver, CO) was most supportive of the Big Soda Lake study by helping to secure the funds required for the long core recovery. Thank you also to the LacCore team at the University of Minnesota, Minnealopolis (Anders Noren, Amy Mybro and Kristina Brady). Sarah Edwards and Forood Azari-Dehkordi provided help in the lab. I am also grateful to the three members of my committee, Lynn Ingram, Kent Lightfoot, and Michael Rosen for thoughtful and timely reviews of this dissertation, and for support all along the way.

Susan Zimmerman, Tom Guilderson and Paula Zermeño at CAMS at Lawrence Livermore National Laboratory were tremendously supportive of the radiocarbon dating effort. Dave Wahl has been a friend and colleague from the beginning. Many others have provided help at key times through discussion of ideas, or assistance in the field. For help coring Marc Parisien, Elizabeth Watson, Jim Wanket, Francis Smith, and Maria-Teresa Ramirez. Donna Cossette at the Churchill County Museum was very helpful in locating many of the early historical photographs of the Big Soda Lake area. Christiane Hassel at the University of Indiana, Bloomington was very helpful with sorting the brine shrimp cysts and pollen. Tim Teague provided assistance with XRF and XRD preparation and analysis. Marie Champagne provided invaluable help and assistance in the final days before the filing date.

I am also very grateful for several sources of funding that made this work possible. Carl O. Sauer Fellowship in the Department of Geography, UC Berkeley and a LacCore student travel grant. Additional funding for analyses was provided by the Stahl Foundation at the Archaeology Research Facility, UC Berkeley, National Science Foundation Doctoral Dissertation Improvement Grant Award # 1130462, and the Jonathan O. Davis Scholarship in Quaternary Sciences.

Many thanks to all my family for their encouragement and support to enter graduate school and accomplish this goal. I am grateful to my father and mother for encouraging education from a young age. I am forever grateful to Jim and Peggy O'Sullivan for all their help and for treating me like a son, long before I was their son-in-law. I am grateful to my three children Shane, Aoibhínn, and Fintan for constantly reminding me that there is an entire life outside of the "lab".

And saving the best for last, I am deeply grateful to my wife Stephanie for her gracious support and care of myself and the whole family. Her patience and love have always been there to carry us through. Her efforts, despite her own busy schedule, for the last several years have made it an overall joyous experience.

CHAPTER 1

Introduction

This dissertation focuses on evidence of natural and human environmental change preserved in the sediments of two lakes, Mountain Lake in the Presidio National Park, San Francisco, California and Big Soda Lake, near Fallon, Nevada.

I use a variety of techniques to reconstruct environmental change including; pollen analysis, measurement of stable isotopes of oxygen and carbon, measurement of brine shrimp cyst concentrations, magnetic susceptibility, X-ray fluorescence, X-ray diffraction, digital photography, loss on ignition, lead-210, plutonium 240/239, radiocarbon, and tephra dating. The combined analyses provide a perspective on what happened in both areas prior to and since the arrival of Spanish and American settlers.

Sediment cores upon which this dissertation is based were taken between 1999 and 2010. The cores at Mountain Lake were recovered between 1999 and 2000 by myself and other graduate students from the University of California, Berkeley. Cores from Big Soda Lake were taken at various times between 2008-2010, by groups of students from UC Berkeley, scientists from the USGS in Carson City and Menlo Park, and also with the help of personnel from LacCore, at the University of Minneapolis, Minnesota.

Chapter 2 presents the results of the Mountain Lake research. Mountain Lake is a potentially important site for several reasons. First, undisturbed, permanent natural lakes in coastal California are rare. Second, sedimentation rates are high, allowing for sampling at short intervals. Third, there is a well documented historical record which can be compared to recent changes in the paleolimnological record. The cores were analyzed for pollen, organic content, magnetic susceptibility, and changes in sediment chemistry. The results show the environmental impact of human activities consistent with local land-use changes initiated by the arrival of Europeans in the area after 1776 and the construction of California State Highway 1 adjacent to the lake in the late 1930's. The study shows how small water bodies alongside roads can concentrate heavy metals and demonstrates the need for careful scientific investigation of sediments earmarked for dredging to determine what if any contaminants are present.

Chapter 3 presents evidence of environmental change in and around Big Soda Lake from 1850 to 2010. The evidence was recovered from cores taken between 2008 and 2010. The bottom waters of Big Soda Lake are anoxic, and the sediments are therefore seasonally laminated. In addition, the lake has risen by 18 m during the 20th Century due to irrigation inputs and so it allows an opportunity to examine how the lake responded to changes in hydrology.

The cores were analyzed to determine changes in stable isotopes (carbon and oxygen), organic content, brine shrimp cyst concentrations and sediment geochemistry which shows the impact of human activities during the late pre-historic (pre-1850) and historic time period (1850 to 2010). Several human impacts have been identified, including regional mining impacts, soda salt extraction from the lake, and artificially rising groundwater levels in the last century. Two major developments have dramatically impacted the lake in that time; the development of a commercial soda manufacturing and processing facility at the lake beginning in 1875 until the early 20th century, and the development of irrigation agriculture which led to an 18 m rise in lake level in the first few decades of the twentieth century.

Chapter 4 deals with a record of climate change from Big Soda Lake that covers the last 1600 years developed from the analyses of stable isotopes of oxygen and carbon, sediment chemistry, and the concentrations of brine shrimp cysts. The results are compared to those of similar paleoclimate studies in the Great Basin.

Chapter 5 provides a summary of the findings of the dissertation research, and its important contributions to the scientific and wider community.

CHAPTER 2

A Sedimentary Record of Heavy Metal Contamination in the Presidio National Park, San Francisco, California, USA

Abstract

Sediment cores from a natural lake (Mountain Lake) in the Presidio National Park, San Francisco, California, USA provide a stratigraphic record of unusually high heavy metal contamination, with lead concentrations peaking at 4128 ppm and zinc levels at 1330 ppm. The cores were independently dated by radiocarbon and exotic pollen, which, together with sharp changes in core stratigraphy, indicate the high concentrations postdate the construction of a nearby roadway (California State Highway 1) completed in 1940. Anthropogenic lead increases sharply after road construction, peaks around 1975, and declines towards the surface, reflecting the history of leaded gasoline use in California. Zinc levels follow a similar trend but continue to increase after 1975. The contaminated sediments are a major cause for concern for National Park Service (NPS) staff at the Presidio as dredging of the lake is proposed as part of a lake improvement plan. The results of this study highlight the severity of environmental lead contamination that still exists in some areas of the U.S., four decades after leaded gasoline was phased out.

Introduction

Since the beginning of the Industrial Revolution, heavy metal inputs to the environment have increased significantly, resulting in widespread contamination (Nriagu and Pacyna, 1988). Lead in particular has been a major contaminant. Industrial and municipal wastewater effluent, stack emissions from smelting operations, and fossil fuel combustion have all contributed lead to the environment. Another important source of contamination has been leaded gasoline (tetraethyl lead), which accounts for 80–90% of all the existing environmental lead pollution in the US (Nriagu, 1990). Lead additives in gasoline were first made available in the US in 1923 and were used extensively until the early 1970's. After the Clean Air Act was enacted by the United States Congress in 1970, U.S. oil companies complied with the new environmental regulations and began to phase out leaded gasoline beginning in December 1973. On Jan 1, 1996 Lead additives in motor vehicle gasoline were finally prohibited (Eisenriech et al., 1996; Thomas, 1995). The ban reflected the fact that, even in small amounts, lead is hazardous to human health (Needleman and Bellinger, 1991; Tong et al., 2000).

Several studies have provided evidence for the direct relationship between environmental lead contamination and automobile use (Culbard et al., 1988; Leharne et al., 1992; Wong and Mak, 1997). In some special cases with heavy vehicular traffic and restricted atmospheric conditions (e.g. Mexico City), lead has accumulated in the atmosphere to levels that posed risks to human health (Romieu et al., 1994). Numerous studies provide historical records of automobile lead contamination in forest soils (Steinnes et al., 2005), coastal sediments (Chow et al., 1973; Crescelius and Piper, 1973; Valette-Silver, 1993), and reservoir and lake sediments (Von Gunten et al., 1997; Callendar and Van Metre, 1997; Heyvaert et al., 2000; Siver and Wozinciak, 2001; Yang et al., 2002; Arnason et al., 2003; Mahler et al., 2006; Rosen and Van Metre, 2010). The isotopic composition of lead in sediments indicates that it is derived mainly from the combustion of leaded gasoline (Chow et al., 1973; Gobeil et al., 1995; Farmer et al., 1996). Typically these studies report levels of contamination that are relatively low, i.e. 1-2 orders of magnitude above background levels (Siver and Wozinciak, 2001). In this paper we present a record of unusually high lead and zinc levels in sediments from Mountain Lake, a natural lake in San Francisco (Figure 2.1). The goal of the initial study at Mountain Lake was to reconstruct the history of the lake since its formation around 2,000 years ago. However, the unexpectedly high levels of metals identified in the near surface sediments forced us to look more closely at the source of contamination, especially as the upper sediments were earmarked for dredging as part of a lake deepening project with the goal of improving water quality.

Environmental Setting

Mountain Lake (37 m asl; 37° 47' 16"N, 122° 28' 16"W) is a small (1.7 ha) freshwater lake located within the Golden Gate National Recreation Area at Presidio National Park in San Francisco (Figure 2.1). The lake formed during the late Holocene in a depression behind an extensive area of sand dunes on the northern San Francisco Peninsula (Cooper, 1967). Currently, the lake has a maximum water depth of 3.30 m. Historical evidence indicates that in the past the lake overflowed its basin and drained via Lobos Creek to the Pacific Ocean, only 1.5 km to the west (Reidy, 2001). At present there is no surface outlet and water loss is by evaporation and seepage. The local bedrock consists of radiolarian chert, greenstone, and sandstones of the Franciscan Complex (Yates et al., 1990; Schlocker, 1974). Overlying the Franciscan rocks are the surficial sandy Colma Formation deposits laid down 120,000- 80,000 years ago, which are found throughout the northern San Francisco Peninsula (Schlocker, 1974; Sloan and Karachewski, 2006).

Cultural History

The San Francisco Presidio was established by Spain in 1776 on what was then the northern frontier of Alta California. Its purpose was to protect Spanish interests from Russian expansion southward along the California coast. After Mexico gained its independence from Spain in 1821, the Mexican Army occupied the Presidio (Langellier and Rosen, 1996). This occupation was short lived, however, because in 1848 (following the Mexican-American war) the US army took over the property (Thompson, 1997). The Presidio remained under the control of the US army until 1994 when the base was closed and transferred to the National Park Service (NPS). It is now known as the Presidio National Park (Figure 2.1b). Since 1996 an executive agency called the Presidio Trust has partnered with the NPS and developed a plan to preserve and enhance the natural, cultural, and recreational resources in the park. One component of this plan is the restoration of Mountain Lake to a more natural pre-European condition. Our investigation of the environmental history of the Mountain Lake area was undertaken as part of this effort.

Methods

In April 1999, we took a 595 cm long master core (ML1) from the deepest part of the lake using a modified Livingstone piston corer. An additional 80 cm short core (ML2) and surface sediment samples were recovered in 2000 (Figure 2.1c). Cores were split, described, and sampled in the Quaternary Paleoecology Laboratory in the Department of Geography at UC Berkeley. Whole core magnetic susceptibility measurements were determined for each 1 cm interval with a Bartington magnetic MS2 susceptibility sensor. The magnetic susceptibility data provides an index of environmental change based on the changing magnetic properties of the lake sediments. The organic content of the sediments was determined by loss on ignition (LOI) (Dean, 1974). Weighed samples were dried at 100˚C for twenty-four hours to determine water content, and combusted at 550˚C for two hours to determine organic content.

Heavy metal concentrations on 80 samples were analyzed using X-ray fluorescence (XRF). Standard reference sediment and blanks were submitted randomly among samples for quality control. All samples were analyzed with a Phillips PW 2400 X-Ray Fluorescence scanner to determine bulk elemental composition in the Dept. of Earth and Planetary Sciences, UC Berkeley. Samples were prepared by combustion at 550˚C for one hour to remove water and organic material. Three grams of sediment per sample were ground to a powder, treated with a bonding agent, and compressed into pellets.

Pollen analysis was carried out using standard extraction and preparation techniques (Faegri and Iversen, 1985). Fifty-four pollen counts were undertaken at regular intervals (5 or 10 cm) on a Zeiss transmitted light microscope at the 400x magnification. CAPALYN software was used to enter the pollen data, calculate percentages, and plot the pollen diagram (Bauer et al., 1990). The pollen data provide information about the history of vegetation change including the first appearance of exotic species. Plant species not indigenous to the San Francisco area were introduced during the historic period and in some cases their pollen can be readily identified. The first appearance of these exotic pollen types provides chronological markers in the stratigraphic record, as their history of local introduction is relatively well documented in the botanical record. The identification of exotic pollen types in paleoecological studies from California has proven to be a very useful dating tool (Mudie and Byrne, 1980; Cole and Liu, 1994; Mensing and Byrne, 1998; Cole and Wahl, 1999; Watson, 2004). Pollen from *Erodium cicutarium* (Redstem filaree), *Rumex acetosella* (sheep sorrel), *Plantago lanceolata* (English plantain), and *Eucalyptus* spp. (blue gum) all provide age constraints for the upper 195 cm of the record.

Three bulk organic samples (595-585 cm; 450-460 cm; 298-306 cm) were submitted to Beta Analytic, Florida for radiocarbon analysis.

Results and Interpretation

Core Chronology

Figure 2.2 includes key chronological, pollen, and sedimentological data. The chronology for core ML1 was established using radiocarbon, the first appearance of exotic pollen grains, and changes in the type of sediment accumulating in the lake. Results indicate the arrival of Europeans in the area and the onset of heavy metal contamination which facilitate the calculation of changing sedimentation rates through time. Table 2.1 shows the results of three radiocarbon determinations used to provide a chronological framework for the lower section of core ML1 (Reidy, 2001). Table 2.2 displays the pollen and stratigraphic indicators to date the historical sections of the core. The basal sediments indicate that the sediment spans the last 1800 years. The uppermost radiocarbon date from 306-298 cm yielded an uncalibrated date of 510±70 B.P. When calibrated and converted to calendar years (cal yr A.D.) using the CALIB v4 program (Stuiver et al., 1998a; 1998b), the sample yielded a date of A.D. 1340. This date provides a basis for discussing the last 650 years of the record.

Several non-native pollen types are present in the upper 195 cm of the core which are correlated with historical developments near the lake. The European weed *Erodium cicutarium* appears first at 195 cm, likely connected to the Spanish introduction of cattle to the area after 1776. *Rumex acetosella* appears at 185 cm and its presence locally can be dated to 1840±5 years (Frenkel, 1970). The first appearance of *Plantago lanceolata* in San Francisco is dated to 1860-1864 (Brewer et al., 1876). Based on the history of *Eucalpytus* and *Cupressus* (cypress) plantings in the Presidio by the army in the late nineteenth century (Hall, 1902), we date the first appearance of *Eucalpytus* pollen and the rise in *Cupressus* pollen to 1870±10 years.

Sediment Characteristics

Whole core magnetic susceptibility (K) values for the core indicate two sections with elevated values: between 195-160 cm and between 120-25 cm (with a distinct peak between 75-65 cm) (Figure 2.2). These sections coincide stratigraphically with changes in sediment color, texture, and inorganic content. Between 325 cm and 191 cm, the sediment is mostly clay, dark brown (10 YR 2/2). Above 190 cm, the sediment texture is fairly homogenous with an increase in clay and a shift to lighter brown (7.5 YR 5/2). Above 160 cm the sediment is silt clay and the color varies from black (7.5YR 2/0) to very dark brown (7.5YR 2/4) with distinct banding (7.5YR 6/0) between 75 and 65 cm. Inorganic dry bulk density is low between 310 cm and 191 cm, ranging between 0.1 and 0.2 g/cm^3. Inorganics rise sharply above 190 cm to about 0.6 g/cm^3 and are coincident with increases in the magnetic susceptibility profile and stratigraphic color changes. Inorganic content remains high throughout the upper section of the core, with a second peak between 75-65 cm. Above 65 cm the inorganic content declines gradually towards the top of the core to about 0.3 g/cm^3.

Geochemistry

Metal concentration profiles are shown in Figure 2.3. A total of 34 elements were measured in the XRF analysis (Reidy, 2001). Here we present the twelve that showed the most variation (Fe, Si, Al, Ba, Sr, Co, V, Cr, Ni, Cu, Pb, and Zn). In most cases, all major metal concentrations increase above 190 cm. The largest increases (especially lead and zinc) occur above 55 cm. Metal data from the undated ML2 core on the western edge of the lake yielded the highest recorded lead levels in the lake (4128 ppm) (Figure 2.4). The highest zinc values (1327 ppm) were recorded in the surface sample of ML1. Elemental analyses on several surface and downcore samples from the around the lake (north, east, and southern edges) provide information on the spatial distribution of metals at the lake and indicate the lowest concentrations of all metals investigated (Table 2.3). A sample of soil collected from the shoulder of California State Highway 1 yielded a lead content of 836 ppm and a zinc level of 958 ppm.

Discussion

Pre-European Period (A.D. 1350-1775)

The low magnetic susceptibility values, low inorganic content, and low sedimentation rate (0.23 cm yr^{-1}) reflect a fairly stable environment in the area around the lake from A.D. 1350-1775 (Figures 2.2 and 2.3). Concentrations of the major elements (e.g. Pb, Zn, Cu, Cr, V, and Ni) are all consistently low, and represent the natural background component of these metals in the Franciscan bedrock and overlying Colma Formation. Elemental measurements reported for the local Franciscan bedrock indicate low amounts of heavy metals e.g. lead <100 ppm (Bradford et al., 1996). The low stable background levels of heavy metals are consistent with results for other US lakes during pre-European times (Eisenreich et al., 1996; Callendar and Van Metre, 1997; Siver and Wozinciak, 2001; Hilfinger et al., 2001; Vermillion et al., 2005).

Post-European Period (A.D. 1775-1940)

Permanent settlement of the San Francisco area by the Spanish in A.D. 1776 marks the beginning of a series of dramatic local environmental changes, which are reflected-in the stratigraphic, pollen, geochemical, and historical records. Sharp increases in magnetic susceptibility and dry bulk density, the first appearance of *Erodium*, and a near doubling of metal concentrations mark the beginning of this period. Although sediment accumulation rates in this early Spanish period remain similar to those in the pre-European period, the types of sediment accumulating in the lake changed. Increases in clay content and in the magnetic properties reflect disturbance and erosion in the watershed, which likely resulted from the introduction of cattle by Spanish settlers. Spanish soldiers maintained a cattle ranch in the vicinity of the Presidio called Rancho del Rey (King's Ranch) whose herd numbered between 115 and 1200 cattle from A.D. 1777-1791 (Bancroft, 1886).

In the decades after the Spanish-Mexican war (A.D. 1823 onwards), the Presidio fell into ruin. Following the Mexican-American war in A.D. 1848, the US army took control of the property and established an army post. The large-scale tree plantings in the Presidio, which began as a US army beautification project in the 1880's (Jones, 1883; Hall, 1902), are reflected in the pollen record, with the expansion of cypress and first appearance of *Eucalyptus* (Figure 2.2). Development and expansion residential housing adjacent to the post between A.D. 1880 and A.D. 1940 was probably also partly responsible for the increase in sedimentation rates from 0.50 to 0.71 cm yr $^{-1}$ during this period (Figure 2.5).

A second major disturbance observed in the core is dated to the late 1930's. The sharp peak in magnetic susceptibility and higher inorganic clay content can be related to road construction adjacent to the lake between A.D. 1938 and 1940. Construction of California State Highway 1 alongside the lake greatly altered the morphology of the water body by infilling the western side of the lake, and reducing its overall size by 25%. During road construction, sedimentation rates (3.75 cm yr $^{-1}$) rose dramatically to rates not seen before or since (Figure 2.5).

Post Road Construction (A.D. 1940-Present)

Sediment geochemistry changed dramatically after A.D. 1940. Lead and zinc in particular increase sharply. Possible sources for lead in the Presidio include dumping by the army, lead-shot, lead paint, regional fossil fuel combustion, and leaded gasoline. Although several contaminated dumping sites are located in the Presidio, none are located in the Mountain Lake watershed (Dames and Moore, 1997). Analysis of heavy metals in soils on the Presidio indicate high lead levels in areas adjacent to old army buildings but not beyond a few feet of these structures (Dames and Moore, 1997). While regional fossil fuel combustion as atmospheric fallout is no doubt a contributing factor to heavy metal fall-out in the park, results from this study indicate that run-off from Highway 1 is the main source of contamination.

The short cores and surface samples analyzed from around the lake indicate heavy metal levels close to background concentrations (Table 2.3). One exception is the core recovered from the western edge of the lake (ML2), which recorded the highest concentration of lead in the lake (a value of 4128 ppm at the 45 cm interval) (Figure 2.6). Thus, the core and surface metal data clearly point to Highway 1 as the source of the pollution. While the lead profiles for ML display trends that are consistent with results from previous studies in the US (Callendar and Van Metre, 1997; Siver and Wozinciak, 2001; Hilfinger et al., 2001), the extremely high concentrations of lead are unprecedented.

Maximum lead deposition occurs between A.D. 1950 and A.D. 1975 and tracks the history of leaded gasoline use. Lower lead concentrations after A.D. 1975 reflect the removal of tetraethyl lead from gasoline. One explanation for the difference in lead levels between ML1 and ML2 is the location of the core sites. Automobile lead is closely tied to traffic density and distance from the highway with maximum concentrations usually found within 10-150 feet of roadways (Daines et al., 1970). ML2 was recovered close to a storm water culvert that delivers roadway runoff to the lake (<15 feet from side of Highway 1) while ML1 is located in the center of the lake (about 400 feet from the road). Zinc, derived mainly from automobile tires, follows a similar pattern to lead but continues to increase in the near surface sediments. Several discarded old tires were observed in the shallow waters of the western edge of the lake during the coring operation.

Local Traffic and Lead Concentrations

Daily totals for traffic across the Golden Gate Bridge (GGB) into San Francisco are available since A.D. 1938. Traffic totals from A.D. 1961 are also available for a location near the lake (junction of Lake Street and Park Presidio Boulevard)(Figure 2.1b). There is a strong positive correlation between the increase in vehicular traffic across the bridge between A.D. 1940 to A.D. 1975 and the increase in heavy metal accumulation in the lake, especially for lead. Southbound average daily traffic (ADT) on the GGB increased from 17,594 in A.D. 1940 to 92,000 in A.D. 1975. This represents an increase of about 400% during the period A.D. 1940-1975. Lead concentrations which peak at 1344 ppm in ML1 around A.D. 1975 also increase ~ 400% for the same time period when compared to the background levels (Figure 2.7).

Contaminated Sediments

Due to the extremely high levels of metals, the ML sediments are considered eco-toxic and efforts are underway to remove the contaminants. The lake and the surrounding lands are heavily used as a recreational destination for the neighborhood, with trails, tennis courts and a playground at the lake edge. Keeping the public safe from coming in contact with any lake bottom sediments is paramount. Although there is currently no threat to public safety as the sediments are buried 2-3 feet below the sediment water interface, there is concern for aquatic organisms that come in contact with the lake floor sediments. Presently, the biological impacts of high lead on the wildlife in and around the lake is unclear. However, at least one incident of lead toxicosis involving waterfowl at the lake has been documented. In A.D. 1996 a distressed mute swan (*Cygnus olor*) was removed from the lake in poor physical condition and transferred to the San Francisco Zoological Hospital, where it died a few days later (Dunker, 1996). Geochemical analysis of liver tissue from the swan as part of a necropsy report indicated a lead concentration of 47 ppm. A concentration of 8 ppm is considered toxic. Lead toxicosis is one of the more commonly diagnosed ailments in birds (Benson et al., 1976; Samour et al., 2002).

Conclusion

The history of metal accumulation at Mountain Lake shows dramatic changes during the last two centuries, especially for the last 60 years. The lake evidence is consistent with local land-use changes initiated by the arrival of the Spanish in the area after A.D. 1776 and the construction of California State Highway 1 adjacent to the lake in the late 1930's. This study outlines how small water bodies alongside roads can concentrate heavy metals. This study also demonstrates the need for careful scientific investigation of sediments earmarked for dredging to determine what if any contaminants are present. Furthermore, if the sediments are contaminated, they should be properly handled during the dredging process to limit cross contamination and properly disposed of at a certified landfill.

The initial purpose of the study was not to provide specific proposals for future management of Mountain Lake but rather to determine what has happened in the past. However, the evidence that has been uncovered provided useful baseline data in the development of an environmentally sound management plan.

Acknowledgements

I would like to thank Clare Polansky, Dave Wahl, Jungjae Park, Madeline Solomon, James Coil, Nelia White, and Francis Smith for assistance in the field. Thanks also to Scott Starratt, Robert Dull, Marc Parisien, Dave Wahl, David Edwards, Kent Lightfoot, Maria-Teresa Ramirez, Michael Rosen and Marie Champagne who read earlier drafts of this paper. The project was funded with a Graduate Opportunity Student Fellowship at UC Berkeley and a research grant from the Golden Gate National Parks Association.

Addendum

In 2000, as part of the Mountain Lake Improvement Plan, the Presidio Trust proposed to dredge upwards of 2 m of sediment from the lake to improve water quality. The sediment removal plan called for mechanical dredging of the lake and temporary storage of the spoils on the lakeshore. This was to allow the wet sediments to dry for later used in landscaping projects throughout the Presidio.

However, the results of the paleoenvironmental reconstruction reported above forced the postponement of the dredging project until the high levels of lead could be investigated further. In 2003, a subsequent investigation by an environmental consulting company (URS Corporation) re-examined the lake sediments for the presence of heavy metals and confirmed that there was indeed a serious environmental contamination problem. Following this investigation, all planned improvement projects in and around the lake were put on hold as the Presidio Trust worked towards addressing the problem.

Presidio Clean-up Funds

When the U.S. Army departed the Presidio in 1995, it contributed 100 million dollars to a special remediation fund specifically for environmental clean-up and restoration. In 1999, the Presidio Trust negotiated with the Zurich-American Insurance Company to issue insurance policies amounting to 100 million dollars underwriting the risks of environmental remediation cost-over runs and the costs of unknown contamination not covered by the U.S. Army fund.

When the Mountain Lake lead contamination issue surfaced in the early 2000’s the Presidio Trust filed a claim with Zurich-American to cover $807,000 spent on addressing the issues related to lake contaminants. However, the company denied liability and refused to pay. Zurich claimed that it had issued an environmental liability policy to pay for the clean-up of pollution discovered after the date of the policies' inception in May 1999, and not before.

Legal Cases Brought by the Presidio Trust

In response, the U.S. Government launched a suit on behalf of the Presidio Trust and the U.S. Army against Zurich in November 2008 in the U.S. District Court for the Northern District of California. Zurich staunchly opposed the Government's claims, contending it had no duty to pay for the clean-up because the contamination had been identified well in advance. Earlier stratigraphic and geochemical analyses by private environmental consulting firms working on behalf of the U.S. Army (Dames and Moore, 1997) and the Presidio Trust (Erler and Kalinowksi, 1998) had identified the presence of elevated lead and the possibility of contamination in certain areas of the lake.

However, Zurich was not the only entity targeted by the government for remediation efforts at Mountain Lake. In January 2009, the Presidio Trust sued the California Department of Transportation (Caltrans) for allegedly reneging on a 1938 agreement signed before California State Highway 1 was constructed. The United States claimed a breach of a 1938 permit that authorized Caltrans to build Highway 1 through the Presidio and required Caltrans to repair any damage caused by construction and operation of the highway. The government claimed that Caltrans' construction of Park Presidio Boulevard caused the lake to become contaminated with lead and other substances and that the agency is required to fund the clean-up. As part of this two pronged approach to resolve the lead problem at Mountain Lake, the Presidio Trust made efforts to consolidate both Zurich and Caltrans lawsuits into one, but the judge overseeing the case stated “while the actions both concern payment for the Mountain Lake clean-up, they are not sufficiently similar to be related” (Chesney, 2009).

In September 2010, as part of the legal battle between Zurich and Presidio Trust, my advisor (Roger Byrne) and I received a subpoena from the U.S. District Court for the Northern District of California through the UC Berkeley Office of Legal Affairs to produce all documents (including electronically stored information) relating to our research at Mountain Lake. All files, results, documents, and e-mails pertaining to our paleoenvironmental work at Mountain Lake were presented to the UC Berkeley legal team.

In addition, Professor Byrne also provided an oral deposition to both the Zurich and Presidio Trust legal teams in Berkeley in December, 2010. The following month Zurich and the government negotiated a settlement over the remediation at the lake, and in February 2011 the U.S. Government dropped its case against Zurich. (The case is U.S. v. Zurich Insurance Co. et al., case number 08-cv-5005, in the U.S. District Court for the Northern District of California).

Court Victory for the Presidio Trust against Caltrans

Throughout the rest of 2011, the Presidio Trust versus Caltrans legal battle worked its way through the court system, and on November 10th, federal officials announced a civil settlement with Caltrans (Department of Justice, 2011). Under the terms of the settlement, Caltrans was required to pay $5.5 million to the United States for remediation of Mountain Lake, $4 million for re-configuring the Mountain Lake overflow pipeline, and $500,000 for the Presidio's legal costs. Caltrans was also required to fund and construct a run-off diversion project, at an estimated cost of $3.5 million, so that contaminants from Highway 1 will no longer enter Mountain Lake. The total settlement was set at $13.5 million.

Preservation of the Mountain Lake Sediment Cores

Over the years, I attended many public and community meetings at the Presidio relating to Mountain Lake. During 2012, as plans to remediate the contaminated sediments in the lake were unveiled, I attended several more State mandated public outreach meetings hosted by California Department of Toxic Substances Control (DTSC), the Presidio Trust, and Caltrans. At one of the meetings, I had an opportunity to address community members from the Mountain Lake neighborhood. I used my oral commentary time to highlight the scientific importance of the paleoenvironmental record in Mountain Lake. I urged that every effort should be made to preserve an archive of the lake bottom sediments prior to dredging and so that they can be made available for future research and analyses. Otherwise the record will be destroyed and lost forever. At the same meeting I proposed that $20,000 be made available from the allocated remediation funds to core, and archive the lake's stratigraphic record at LacCore (the National Lacustrine Core Facility) at the University of Minnesota, Minnealopolis. The request was met with enthusiasm among the people present, and the Presidio Trust agreed to fund this effort. I also submitted a written statement of the request to the DTSC during the period of public commentary on the Mountain Lake remediation project. A few months later, the request was successful and in October 2012, with the help of personnel from LacCore, we recovered four long cores up to 7 m in length, and twelve short cores up to 2 m in length from Mountain Lake. The cores are currently archived at the University of Minnealopolis and available to the wider scientific community for research. Initial core description, magnetic susceptibility, and photo imagery of one long core is displayed in Appendix 1.

Remediation Action Plan

As part of the proposed dredging at Mountain Lake, a Draft Feasibility Study/Remedial Action Plan (FS/RAP) was prepared by consultants Kennedy and Jenkins (2012) to comply with the applicable requirements of the U.S. Environmental Protection Agency (USEPA), National Oil and Hazardous Substances Pollution Contingency Plan (NCP), 40 Code of Federal Regulations (CFR), Part 300.400 (USEPA 1990), and the California Health and Safety Code (HSC), Chapter 6.8, Section 25356.1. The Draft FS/RAP also facilitates community review and public participation in selection of a remedial alternative to address the chemically-impacted sediment on the floor of Mountain Lake. Pre-dredging risk assessment undertaken by the Presidio Trust demonstrated that contaminants in Mountain Lake do not pose a risk to human health because humans are not exposed to the sediment. However, the contaminants in the lake do pose an unacceptable risk to ecological and aquatic receptors in the lake. The chemicals of concern (COCs) are lead and total petroleum hydrocarbons as motor oil

(TPHmo).

As part of the remedial process, the following alternatives were evaluated in the Draft FS/RAP to address sediment with chemicals of concern (COC) exceeding ecological clean-up levels:

- **Alternative 1** – No Action

Under this alternative, site conditions at Mountain Lake would remain unchanged, as no action would be taken to remediate sediment.

- **Alternative 2** – Capping

Clean sand would be imported and placed over sediment contaminated with COCs. Long-term monitoring and maintenance of the cap would be required.

- **Alternative 3** – Dredging and Offsite Disposal with Limited Capping

The remedial action chosen for Mountain Lake was Alternative 3: Dredging with Offsite Disposal and Limited Capping. The primary elements of the proposed remedy are as follows:

- Dredging of 15,600 cubic yards of sediment from the lake to achieve COC concentrations that are protective of ecological resources.
- Placement of a sand cap in areas that cannot be dredged.
- Dewatering of sediment and discharge of water back into the lake.
- Transportation and offsite disposal of dewatered sediment at a permitted landfill.
- Restoration of areas impacted by operations.

Highway 1 Improvements

Geotechnical stability of the Highway 1 (Park Presidio Boulevard) roadway embankment was a prerequisite to performing the dredging operation. As a result, Caltrans installed 400 stone columns into the roadway adjacent the lake to stabilize and protect the highway from failure during dredging operations. This work was completed in early 2013. Caltrans is currently developing and implementing a sediment remediation project associated with run off from the road. Under the proposed remedy, Caltrans will treat runoff from Highway 1 to prevent future buildup of contaminants in the lake.

Lake Dredging Plan

The remedial action area at Mountain Lake covers nearly the entire footprint of the lake to a depth of 0.75 m below sediment surface (bss), and in some areas to 1.5 m to 2 m bss. The dredging is currently being performed by a private contractor hired by the environmental consulting firm CH2M on behalf of the Presidio Trust. All project activities are under the regulatory oversight of the California Environmental Protection Agency (CEPA) and DTSC. Hydraulic dredging was chosen as the best option for wet sediment removal because it minimizes site impacts and the potential for cross contamination. Hydraulically dredged material is being pumped through a temporary pipeline to a staging area north of the lake, for pretreatment to remove water prior to loading, off-site hauling and disposal (Figure 2.8a). The anticipated volume of sediment to be removed is 15,600 cubic yards, total solids at 4573 cubic yards or 4,417 tons. This volume takes into account the removal of the COCs and actual implementation of a sediment removal process. Hydraulic dredging of the lake began in June 2013 and will be completed by the end of 2013 (Figure 2.8b).

References

Arnason, J. G., and Fletcher, B. A. (2003). A 40+ year record of Cd, Hg, Pb, and U deposition in sediments of Patroon Reservoir, Albany County, NY, USA. *Environmental Pollution*, *123*(3), 383-391.

Bancroft, H. H. (1886). *History of California.* San Francisco.

Bauer, R.L., Orvis, K.H., and Edlund, E.G. (1990). Calpalyn Pollen Diagram Computer Program. Pollen Laboratory, University of California Museum of Paleontology, Berkeley.

Benson, W. W., Brock, D. W., Gabica, J., and Loomis, M. (1976). Swan mortality due to certain heavy metals in the Mission Lake area, Idaho. *Bulletin of Environmental Contamination and Toxicology*, *15*(2), 171-174.

Beutel, M. (1997). Mountain Lake Water Quality Report 1996/1997 submitted to the National Parks Service. Department of Environmental Engineering, University of California, Berkeley.

Boutron, C. F., Görlach, U., Candelone, J. P., Bolshov, M. A., and Delmas, R. J. (1991). Decrease in anthropogenic lead, cadmium and zinc in Greenland snows since the late 1960's. *Nature*, *353*(6340), 153-156.

Bradford, G.R., Chang, A.C., Page, A.L., Bakhtar, D., Frampton, J.A., and Wright, H. (1996). Background Concentrations of Trace and Major Elements in California Soils, March 1996. Kearney Foundation of Soil Science, Division of Agriculture and Natural Resources, University of California, Riverside

Brewer, W. H., Watson, S., and Gray, A. (1876). *California Geological Survey*. Botany. Harvard University, Cambridge.

Callender, E., and VanMetre, P. C. V. (1997). Reservoir sediment cores show US lead declines. *Environmental Science and Technology*, *31*(9), 424A-428A.

Chesney, M. (2009). http://www.law360.com/articles/227555/us-drops-presidio-coverage-suit-against-zurich

Chow, T. J. (1970). Lead accumulation in roadside soil and grass. *Nature*, *225*, 295-296.

Chow, T. J., Bruland, K. W., Bertine, K., Soutar, A., Koide, M., and Goldberg, E. D. (1973). Lead pollution: records in southern California coastal sediments. *Science*, *181*(4099), 551-552.

Cooper, W. S. (1967). *Coastal Dunes of California* (Vol. 104, No. 1-4). Geological Society of America.

Cole, K. L., and Liu, G. W. (1994). Holocene Paleoecology of an Estuary on Santa Rosa Island, California. *Quaternary Research*, *41*(3), 326-335.

Cole, K. L., and Wahl, E. (2000). A late Holocene Paleoecological record from Torrey Pines State Reserve, California. *Quaternary Research*, *53*(3), 341-351.

Crecelius, E. A., and Piper, D. Z. (1973). Particulate lead contamination recorded in sedimentary cores from Lake Washington, Seattle. *Environmental Science and Technology*, *7*(11), 1053-1055.

Culbard, E. B., Thornton, I., Watt, J., Wheatley, M., Moorcroft, S., and Thompson, M. (1988). Metal contamination in British urban dusts and soils. *Journal of Environmental Quality*, *17*(2), 226-234.

Daines, R. H., Motto, H. L., and Chilko, D. M. (1970). Atmospheric lead: its relation to traffic volume and proximity to highways. *Environmental Science and Technology*, *4*(4), 318-322.

Dames and Moore. (1997). Final Feasibility Study Report, Presidio Main Installation.

Dean, W.E. (1974). Determination and carbonate and organic matter in calcareous sedimentary rocks by loss on ignition: Comparison with other methods. *Journal of Sediment Petrology,* 44, 242-248.

Degernes, L. A., Frank, R. K., Freeman, M. L., and Redig, P. T. (1989). Lead poisoning in trumpeter swans. In *Proceedings of the Annual Conference of the Association Avian Veterinarians* (pp. 144-155).

Dunker, F. (1996). Necropsy Report # 96-34. 5/14/1996, San Francisco Zoological Hospital.

Eisenreich, S. J., Metzer, N. A., Urban, N. R., and Robbins, J. A. (1986). Response of atmospheric lead to decreased use of lead in gasoline. *Environmental Science and Technology*, *20*(2), 171-174.

Erler and Kalinowski. (1998). Report on sediment sampling at Mountain Lake, The Presidio. Report submitted to the Presidio Trust.

Faegri, J. and Iversen, K. (1985). *Textbook of Pollen Analysis*. (fourth ed.). Hafner Press, New York.

Farmer, J. G., Eades, L. J., Mackenzie, A. B., Kirika, A., and Bailey-Watts, T. E. (1996). Stable lead isotope record of lead pollution in Loch Lomond sediments since 1630 AD. *Environmental Science and Technology*, *30*(10), 3080-3083.

Frenkel, R.E. (1970). *Ruderal Vegetation along some California Roadsides*. University of California Publications in Geography, Vol. 20, Berkeley.

Gobeil, C., Johnson, W. K., Macdonald, R. W., and Wong, C. S. (1995). Sources and burden of lead in St. Lawrence estuary sediments: isotopic evidence. *Environmental Science and Technology*, *29*(1), 193-201.

Hall, W.L. (1902). Plan for the Improvement and Extension of the Forest on the Military Reservation of the Presidio of San Francisco, California. U.S. Department of Agriculture, Bureau of Forestry. Washington, D.C.

Heyvaert, A. C., Reuter, J. E., Slotton, D. G., and Goldman, C. R. (2000). Paleolimnological reconstruction of historical atmospheric lead and mercury deposition at Lake Tahoe, California-Nevada. *Environmental Science and Technology*, *34*(17), 3588-3597.

Hilfinger IV, M. F., Mullins, H. T., Burnett, A., and Kirby, M. E. (2001). A 2500 year sediment record from Fayetteville Green Lake, New York: evidence for anthropogenic impacts and historic isotope shift. *Journal of Paleolimnology*, *26*(3), 293-305.

Hornberger, M. I., Luoma, S. N., van Geen, A., Fuller, C., and Anima, R. (1999). Historical trends of metals in the sediments of San Francisco Bay, California. *Marine Chemistry*, *64*(1), 39-55.

Jones, W.A. (1883). *Plan For The Cultivation Of Trees Upon The Presidio Reservation.* Report submitted to the Assistant General at the Department of California, Presidio, San Francisco.

Kennedy, S., Crisler, J. P., Smith, E., and Bush, M. (1977). Lead poisoning in sandhill cranes. *Journal of the American Veterinary Medical Association*, *171*(9), 955-958.

Kennedy and Jenkins (2012). Draft Feasibility Study/Remedial Action Plan, Mountain Lake, Presidio of San Francisco, California. http://www.presidio.gov/about/Documents/Mountain%20Lake%20FSRAP_Public%20Review%20Draft.pdf

Langellier, J. P., and Rosen, D. B. (1996). *El Presidio de San Francisco: A History Under Spain and Mexico 1776-1846*. D. B. Nunis (Ed.). Arthur H. Clark Company.

Leharne, S., Charlesworth, D., and Chowdhry, B. (1992). A survey of metal levels in street dusts in an inner London neighbourhood. *Environment International*, *18*(3), 263-270.

Mahler, B. J., Van Metre, P. C., and Callender, E. (2006). Trends in metals in urban and reference lake sediments across the United States, 1970 to 2001. *Environmental Toxicology and Chemistry*, *25*(7), 1698-1709.

Mensing, S. and Byrne, R. (1998). Pre-mission invasion of *Erodium cicutarium* in California. *Journal of Biogeography,* 25, 757-762.

Mudie, P.J. and Byrne, R. (1980). Pollen evidence for historic sedimentation rates in California Coastal Marshes. *Estuarine and Coastal Marine Science*, 10, 305-316.

Needleman, H. L., and Bellinger, D. (1991). The health effects of low level exposure to lead. *Annual Review of Public Health*, *12*(1), 111-140.

Nightingale, H.I. (1975). Lead, zinc and copper in Soils of Urban Storm-Runoff Retention Basins. *Journal of American Water Works Association*, 67, 443-446.

Nriagu, J. O., and Pacyna, J. M. (1988). Quantitative assessment of worldwide contamination of air, water and soils by trace metals. *Nature*, *333*(6169), 134-139.

Nriagu, J. O. (1990). The rise and fall of leaded gasoline. *Science of the Total Environment*, *92*, 13-28.

Reidy, L.M. (2001). *Evidence of Environmental Change Over the last 2000 years at Mountain Lake in the northern San Francisco Peninsula, California.* Unpublished MA Thesis, Geography Department, University of California, Berkeley.

Romieu, I., Palazuelos, E., Avila, M. H., Rios, C., Muñoz, I., Jimenez, C., and Cahero, G. (1994). Sources of lead exposure in Mexico City. *Environmental Health Perspectives*, *102*(4), 384.

Rosen, M. R., and Van Metre, P. C. (2010). Assessment of multiple sources of anthropogenic and natural chemical inputs to a morphologically complex basin, Lake Mead, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *294*(1), 30-43.

Samour, J. H., and Naldo, J. (2002). Diagnosis and therapeutic management of lead toxicosis in falcons in Saudi Arabia. *Journal of Avian Medicine and Surgery*, *16*(1), 16-20.

Schlocker, J. (1974). *Geology of the San Francisco North Quadrangle, California*. U.S. Geological Survey Professional Paper 782. 109 p. US Government Printing Office.

Siver, P. A., and Wizinciak, J. A. (2001). Lead analysis of sediment cores from seven Connecticut lakes. *Journal of Paleolimnology*, *26*(1), 1-10.

Sloan, D., and Karachewski, J. (2006). *Geology of the San Francisco Bay Region*. University of California Press.

Steinnes, E., Sjøbakk, T. E., Donisa, C., and Brännvall, M. L. (2005). Quantification of pollutant lead in forest soils. *Soil Science Society of America Journal*, *69*(5), 1399-1404.

Stockmarr, J. (1971). Tablets with spores used in absolute pollen analysis. *Pollen et Spores*, 13, 615-621.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v.d. Plicht, J., and Spurk, M. (1998a). INTCAL98 Radiocarbon Age Calibration, 24,000-0 cal BP. *Radiocarbon*, 40, 1041-1083.

Stuiver, M., Reimer, P.J., and Braziunas, T.F. (1998b). High-Precision Radiocarbon Age Calibration for Terrestrial and Marine Samples. *Radiocarbon*, 40, 1127 1151.

Thomas, V. M. (1995). The elimination of lead in gasoline. *Annual Review of Energy and the Environment*, *20*(1), 301-324.

Thompson, E.N. (1997). *Defender of the Gate: The Presidio Of San Francisco: A History From 1846-1995.* U.S. Department of the Interior, National Parks Service, Denver.

Tong, S., Schirnding, Y. E. V., and Prapamontol, T. (2000). Environmental lead exposure: a public health problem of global dimensions. *Bulletin of the World Health Organization*, *78*(9), 1068-1077.

URS (2003). Report on the sediments at Mountain Lake. 133 pp.

U.S. Department of Justice (2011).
http://www.justice.gov/opa/pr/2011/November/11-enrd-1484.html

U.S. Department of Transportation. (1938-1999). California Division of Highway Traffic Counts, Census, and Volumes. Sacramento, California.

Valette-Silver, N. J. (1993). The use of sediment cores to reconstruct historical trends in contamination of estuarine and coastal sediments. *Estuaries*, *16*(3), 577-588.

Von Gunten, H. R., Sturm, M., and Moser, R. N. (1997). 200-year record of metals in lake sediments and natural background concentrations. *Environmental Science and Technology*, *31*(8), 2193-2197.

Vermillion, B., Brugam, R., Retzlaff, W., and Bala, I. (2005). The sedimentary record of environmental lead contamination at St. Louis, Missouri (USA) area smelters. *Journal of Paleolimnology*, *33*(2), 189-203.

Watson, E. B. (2004). Changing elevation, accretion, and tidal marsh plant assemblages in a South San Francisco Bay tidal marsh. *Estuaries*, *27*(4), 684-698.

Wong, J. W. C., and Mak, N. K. (1997). Heavy metal pollution in children playgrounds in Hong Kong and its health implications. *Environmental Technology*, *18*(1), 109-115.

Yang, H., Rose, N. L., Battarbee, R. W., and Boyle, J. F. (2002). Mercury and lead budgets for Lochnagar, a Scottish mountain lake and its catchment. *Environmental Science and Technology*, *36* (7), 1383-1388.

Yates, E. B., Hamlin, S. N., and McCann, L. H. (1990). Geohydrology, water quality, and water budgets of Golden Gate Park and the Lake Merced area in the western part of San Francisco, California. *U.S.G.S. Water-Resources Investigations Report*.

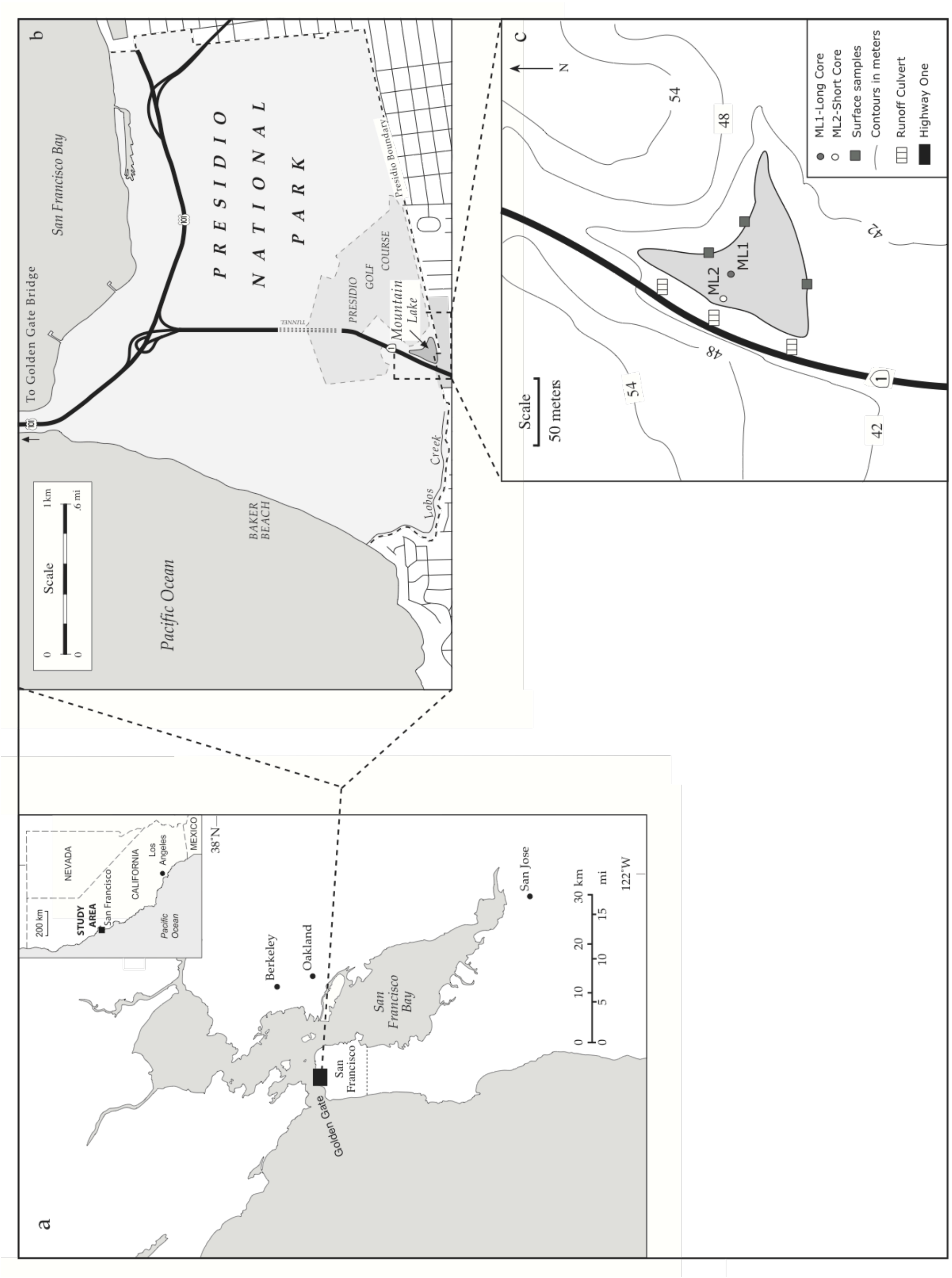


Figure 2.1 Map of study site and core recovery locations at Mountain Lake in the Presidio National Park, San Francisco, California.

Mountain Lake, San Francisco, California

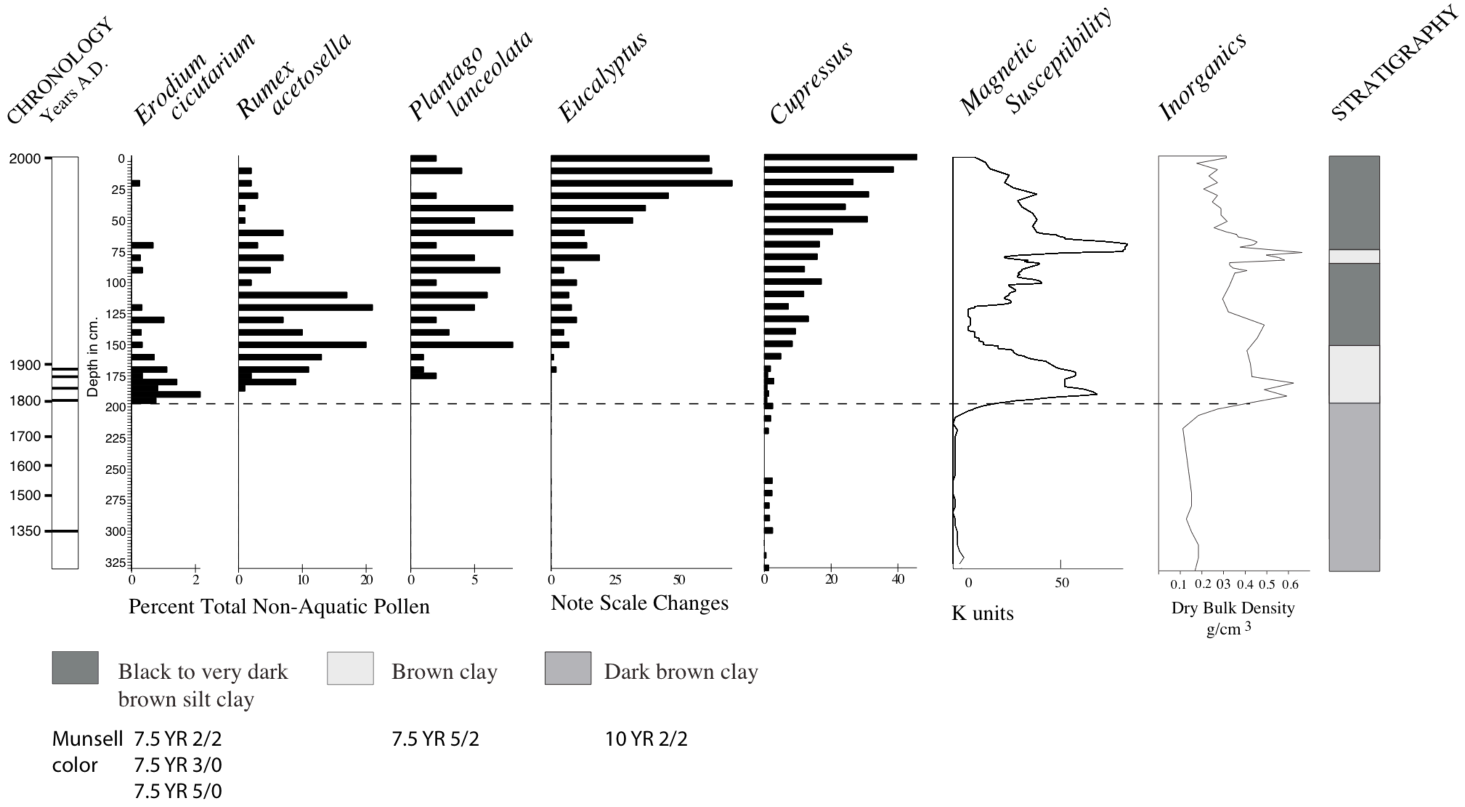


Figure 2.2 Stratigraphy, chronology, exotic pollen, inorganic content, and magnetic susceptibility data for ML1.

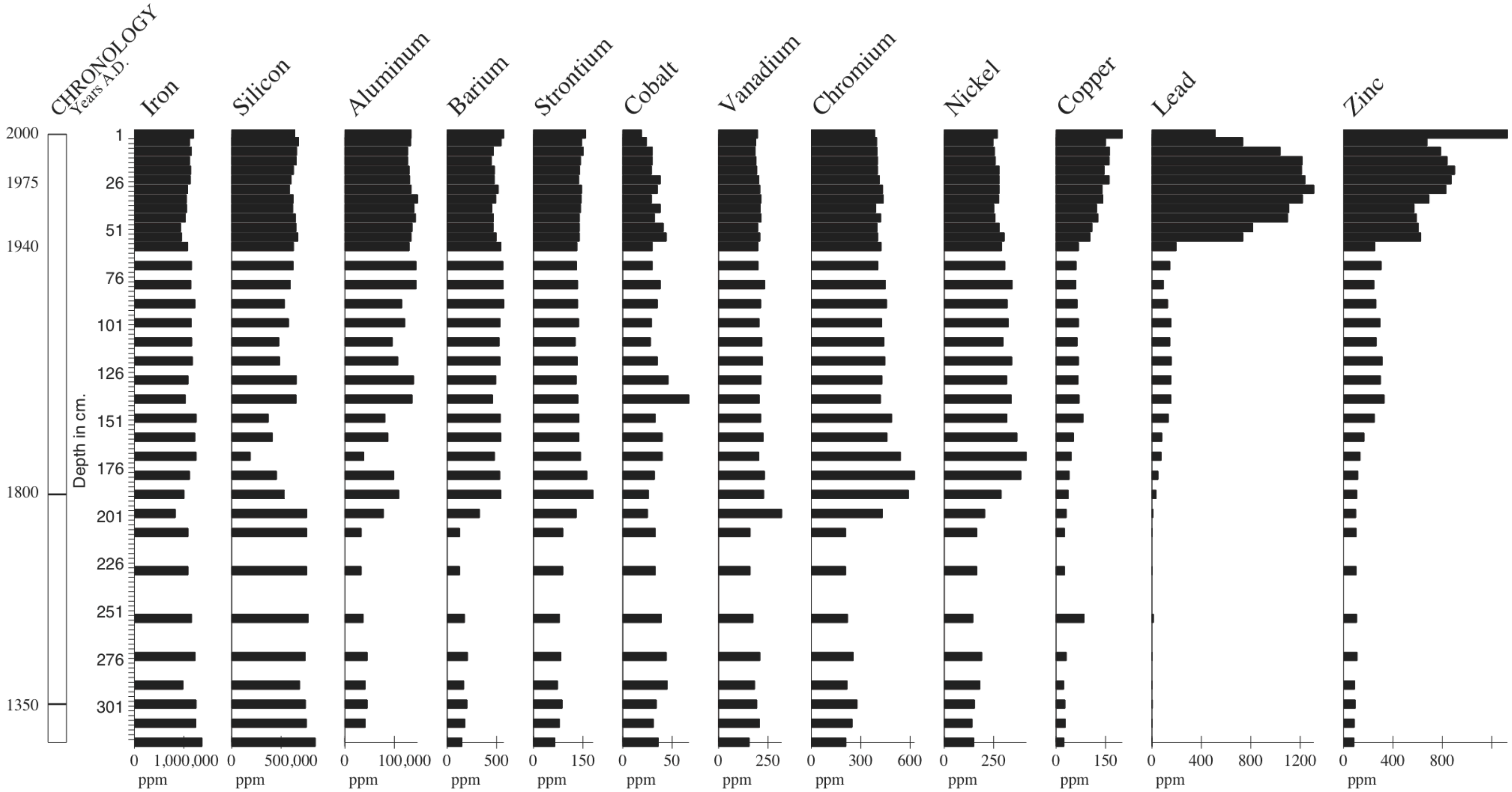


Figure 2.3 Selected geochemical data (ppm) from Mountain Lake, San Francisco.

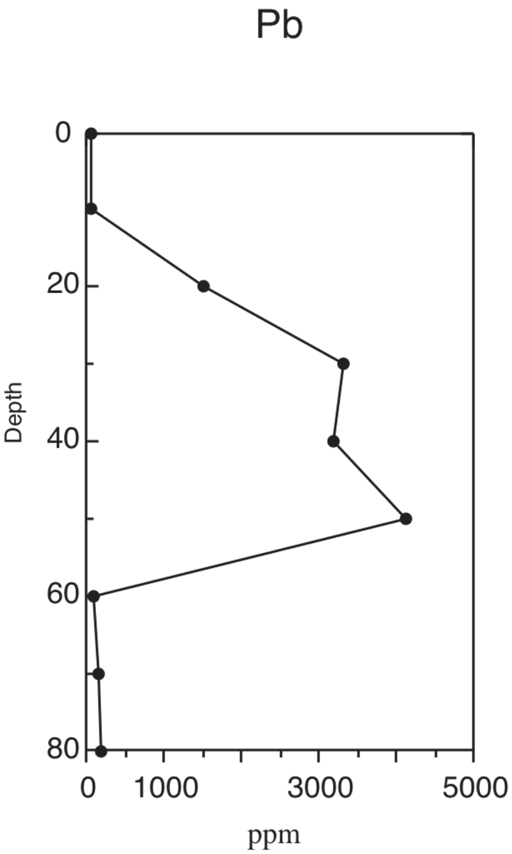


Figure 2.4 Pb and Zn data for ML2 (undated), recovered very close to the western edge of the lake adjacent to California State Highway 1.

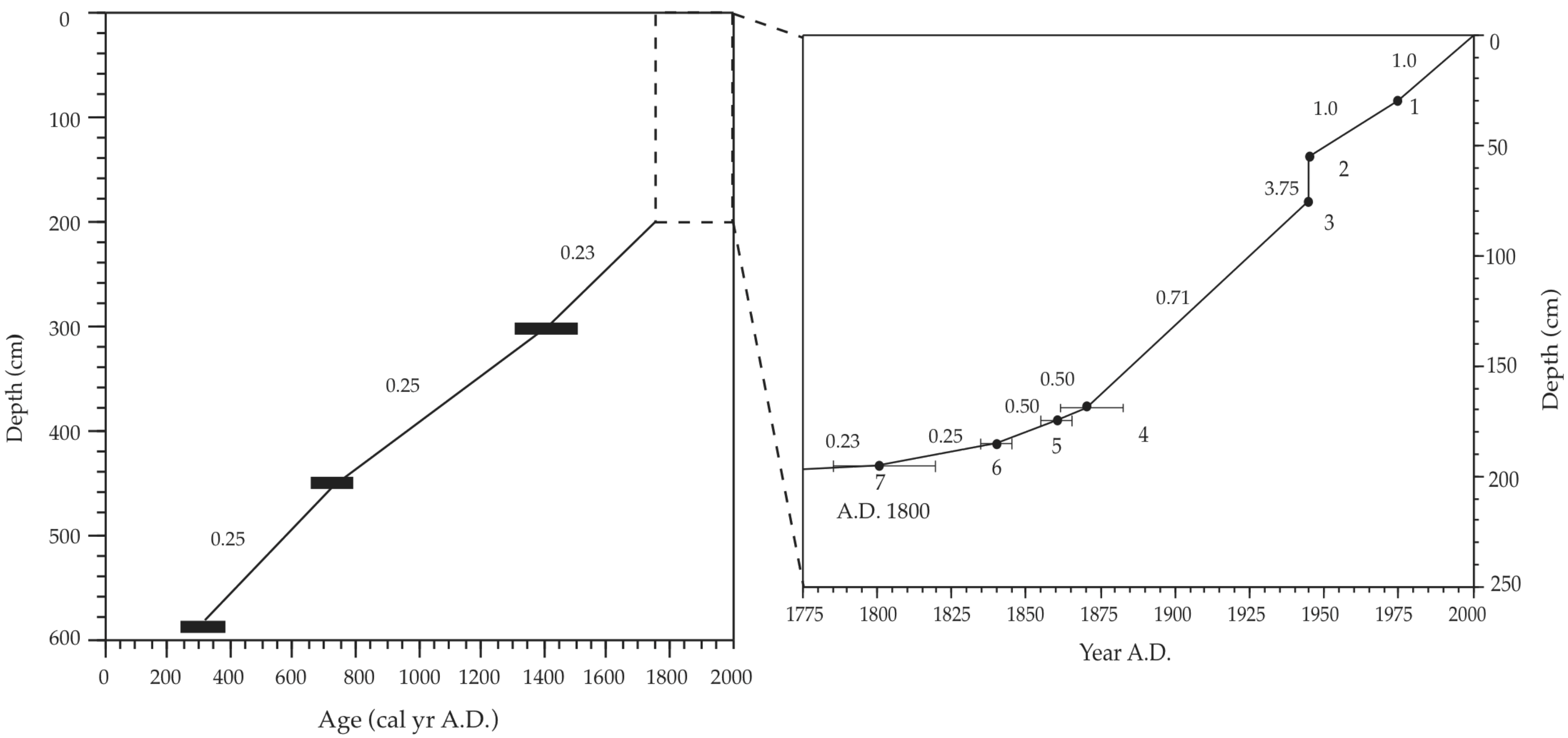


Figure 2.5 Mountain Lake Age-Depth curve. Radiocarbon ages are shown as solid lines representing the 95% confidence limits in cal yr (Stuvier et al., 1998b). Numbered solid dots indicate recent ages listed and described in Table 2.2. Sedimentation rates are shown above each trend line (cm cal yr^{-1}).

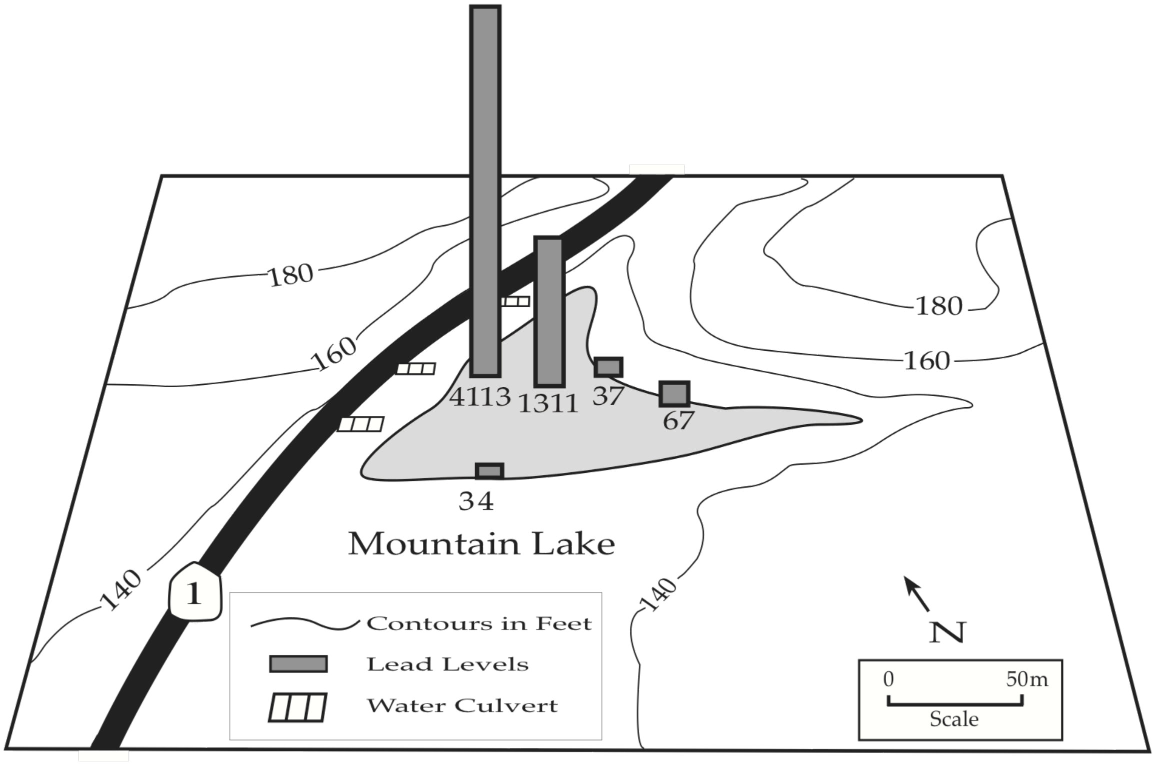


Figure 2.6 Highest lead concentrations (in ppm inorganic fraction) for each sampled location. The number indicates the maximum value at the sampling site.

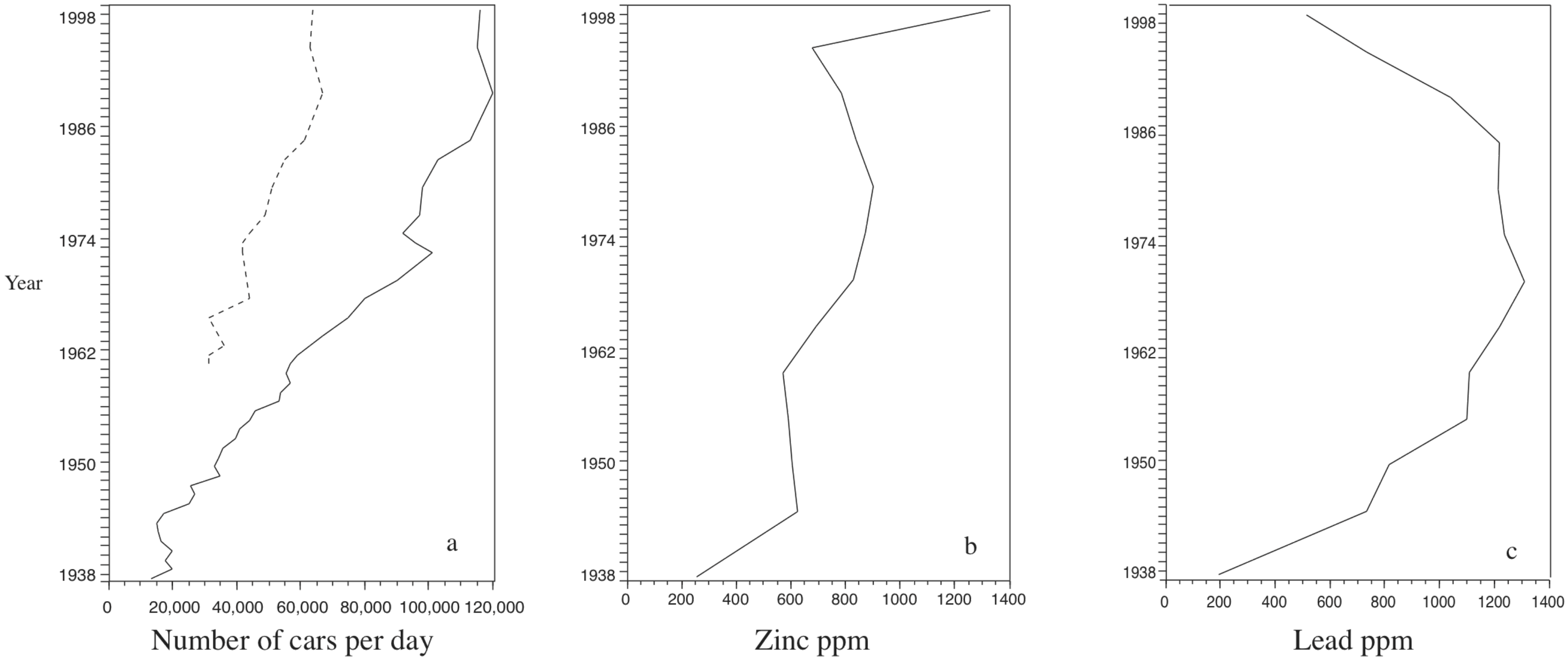


Figure 2.7 (a) Average daily traffic totals. The solid line represnts the traffic across the Golden Gate Bridge from 1938-1999; the dashed line represents traffic passing the junction of Lake Street and Park Presidio Boulevard between 1961 and 1999. (b and c) Zinc and lead concentrations in ML1. (California Division of Highway Traffic Counts, Census, and Volumes 1938-1999).

Figure 2.8

(a) The staging area north of the lake where the dredged sediment will be dewatered prior to being hauled off-site.
(b) Hydraulic dredging in operation at Mountain Lake in June, 2013.
(Photos: Liam Reidy)

Radiocarbon Dates for Mountain Lake Core ML1.

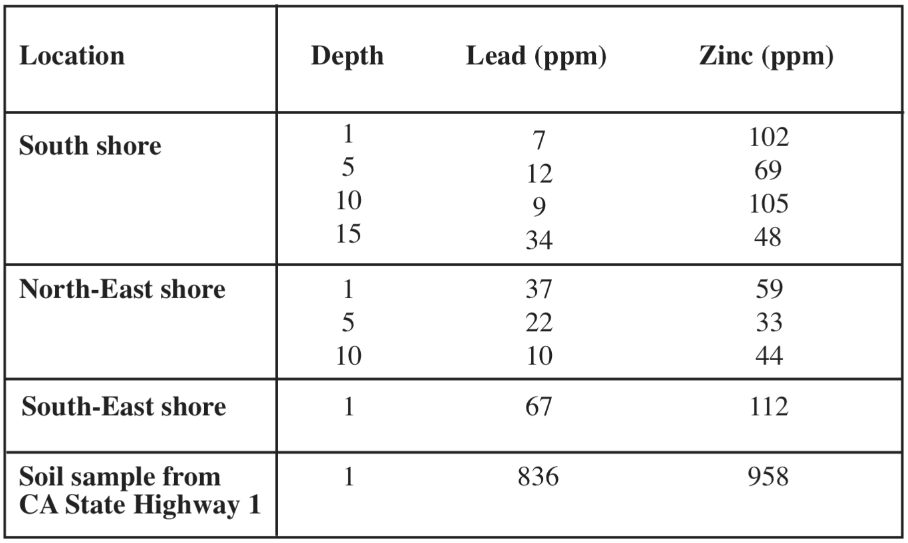
Depth below surface (cm)	Lab Number	Uncalibrated ^{14}C	Probability	Calibrated Age Range (1 Sigma)	Material dated
298-306	BA-151637	510 ± 70 B.P.	0.252	A.D. 1319-1352	bulk sediment
			0.748	A.D. 1389-1454	
450-460	BA-151638	1310 ± 60 B.P.	0.661	A.D. 661-728	bulk sediment
			0.339	A.D. 737-773	
585-595	BA-140195	1750 ± 70 B.P.	1.000	A.D. 219-392	bulk sediment

Table 2.1

Pollen and Stratigraphic Indicators Used to Date Historical Sections of the Core

	Depth (cm)	Proposed date (A.D.)	Pollen or sediment data	Probable cause
1.	30	1975	-peak in Pb values	-rise in automobile traffic using leaded gasoline
2.	60	1940	-Pb and Zn levels remain low	-construction of Highway 1 completed
3.	80	1938	-magnetic susceptibility increases -base of clay layer	-construction of Highway 1 alongside the lake causes increased erosion
4.	170	1880± 10yr	-first *Eucalyptus* pollen	-trees planted in gardens near the Presidio
5.	175	1860± 5 yr	-first *Plantago* pollen	-period of American settlement after 1849
6.	185	1840± 5yr	-first *Rumex* pollen	-period of Mexican settlement in the Presidio
7.	195	1800± 20yr	-first *Erodium* pollen -magnetic susceptibility increases -decrease in organic content	-Spanish present in the watershed -increased erosion associated with cattle grazing in the hills around the lake

Table 2.2



Location	Depth	Lead (ppm)	Zinc (ppm)
South shore	1	7	102
	5	12	69
	10	9	105
	15	34	48
North-East shore	1	37	59
	5	22	33
	10	10	44
South-East shore	1	67	112
Soil sample from CA State Highway 1	1	836	958

Table 2.3

Elemental XRF data for surface sediment and soil samples collected around Mountain Lake (See **Figure 2.1** for collection locations).

CHAPTER 3
A History of Human Impacts on Big Soda Lake, Nevada, USA (1850-2010)

Abstract

Big Soda Lake, a maar lake on the western margin of the Great Basin, has been the subject of scientific enquiry since the late 19th Century (King, 1877; Russell, 1885; Hutchinson, 1937; Breeze, 1968; Kharaka et al., 1984; Oremland et al., 1988; Rosen el al., 2004). However, prior to the research reported here, very little was known about the history of the lake or to what extent its sediments contained a useful record of environmental change. United States Geological Survey (USGS) scientists recovered several short cores from the lake in the 1980's as part of a project focusing on the biogeochemistry of the lake's sediments (Oremland et al., 1988), but dating problems limited their usefulness for paleoenvironmental research. Here we present stratigraphic evidence of human impacts on Big Soda Lake during the period of Anglo American settlement. Sedimentological and geochemical analyses performed on two short cores document the impact and chronology of anthropogenic impacts on the lake during the past 160 years. Core chronologies are based on atom ratios of $^{240}Pu/^{239}Pu$, ^{210}Pb dating, and peaks in heavy metal concentrations (Pb, Cu, and Zn). Abrupt changes in sediment geochemistry, color, sedimentation rates, and brine shrimp cyst concentrations clearly reflect the establishment of a commercial soda production facility at the lake in 1875 and the subsequent increase in lake depth following the development of irrigation agriculture in the area during the last century. The distribution of irrigation water from the Carson river to the Lahontan Valley caused the lake level to rise by 18 meters during the period 1907-1930. The salinity decline is shown clearly in the sediments as a dramatic reduction in brine shrimp cyst concentrations and in the amounts of Na and Cl in the sediments.

Introduction

Previous paleolimnological research in the Great Basin region of the western United States has produced several long-term records of environmental change. Much of this research has focused on lake level changes and their implications for our understanding of climate change (Benson, 1978; Benson and Thompson, 1987; Bradbury et al., 1989). In addition, there are now several pollen and stable isotope records of Great Basin lakes that extend back to the late Pleistocene (Benson et al., 1996; Davis, 1999; Li et al., 2000; Benson et al., 2002; Yuan et al., 2004; 2006; Mensing, 2001; Mensing et al., 2004). However, few lake studies in this area focus on the recent past (last 150 years) and the impacts of Anglo American settlement (Heyvaert et al., 2000; Beutel et al., 2001).

Big Soda Lake (Figures 3.1 and 3.2) was first discovered in the 1840's by Anglo Americans crossing the nearby 40-mile desert. The first scientific description of the lake was provided by a United States government geological expedition in the late 1870's (King, 1877). Several years later in 1882, Israel Russell explored the lake and its environs as part of his research on Pleistocene Lake Lahontan. He provided the first scientific report on the lake's origin, limnology, and mineral content of the alkaline waters (Russell, 1885). He also produced a detailed bathymetric map (Figure 3.3) and concluded based on local geomorphic evidence and the stratigraphic deposits in the walls encircling the lake that the lake formed as the result of at least two volcanic eruptions. Russell rejected the theory presented by King (1877) that the lake formed as the result of powerful sub-lacustrine springs. Russell examined the lake bottom sediments, tested and provided mineral content details of the lake water and trona (bicarbonate of soda) deposits exposed on the shore. He noted that sediment accumulating on the bottom of the lake was fine-grained mud, black in color with a strong odor of hydrogen sulfide, which once exposed to the air was quite similar to the deposits that form a large part of the crater walls. Russell also suggested that much of the organic matter in the sediments must be derived from the millions of brine shrimp (*Artemia franciscana*) present in the near surface water of the lake. Finally, he described the process by which bicarbonate of soda was being mined from the lake (Figure 3.4). During the winter, natural lake water was pumped into large evaporating ponds and the soda allowed to precipitate out; when the weather was hot, lake water was pumped from the lake into ponds and allowed to evaporate in the heat.

Beginning around 1907, farmers in the Fallon area began irrigating their farms with water diverted out of the Truckee River and stored in Lahontan Reservoir with Carson River water as part of the Newlands Reclamation Project. This caused a rise in the groundwater table, and the lake level rose by 18 m between 1907 and 1930 (Figure 3.5). In 1937 Evelyn Hutchinson, the famous Yale limnologist reported on the limnology of the lake and documented the changes in the lake morphology and volume up to the 1930's (Hutchinson, 1937). He paid particular attention to the effects of the recent rise in the local water table which he hypothesized resulted in the permanent stratification of the lake water column (meromixis). Hutchinson also suggested that the commercial exploitation of the lake for soda during the late 19th and the beginning of the 20th centuries may have initiated the meromictic condition. Comparisons made between Russell's calculations of the dissolved mineral content of the water in 1882 and those at the time of Hutchinson's measurements in 1933 indicated that there was at least a 23 percent reduction of chloride and carbonates in the lake water.

In the 1980's, a team of USGS scientists focused on the biogeochemistry of the lake as a model of how lacustrine petroleum reservoirs are generated (Oremland et al., 1982; Oremland, 1983; Oremland and Des Marais, 1983; Kharaka et al., 1984; Oremland et al., 1988). More recently, Rosen et al., (2004) showed that the tufa mounds growing alongside the lake were formed from subaerial groundwater springs that were inundated after the rise in the water table in the early 1900's and are less than 100 years old. In addition, they highlighted the need for caution when developing paleoclimatic or paleohydrological reconstructions from tufa deposits because of the unequal mixing of groundwater and lake water during the formation of the tufa.

A few short cores were taken from Big Soda Lake as part of the USGS investigations in the 1980's. A brief discussion of core stratigraphy, sediment composition, carbon stable isotope data, and radiocarbon dating of the upper ~50 cm is provided by Oremland et al. (1988). The difficulty in recovering sediment cores from this deep lake (maximum water depth is currently 63 m) has more than likely precluded earlier efforts at reconstructing the lake's history. Here we present a high-resolution stratigraphic record of human impacts and hydrological change spanning the last 160 years from laminated sediment cores recovered during 2009 and 2010. Dramatic changes in sedimentology, stable isotopes, brine shrimp cyst concentrations, geochemistry, and hydrology reflect the major changes in land use around the lake since Anglo American settlement of the area began in 1850's.

Site Setting

Big Soda Lake (39° 31′N, 118° 52′) is a maar (surface area 1.6 km^2) located in northwestern Nevada along the western margin of the Great Basin of the western United States. The lake is situated near the town of Fallon at the southwestern margin of the Carson Sink (Figure 3.2). The lake is fed by groundwater and the small amount of precipitation that falls directly on the lake. Mean annual rainfall is 12.7 cm/yr at Fallon, Nevada with a maximum annual precipitation of about 23 cm. Evaporation rates range from about 125 to 135 cm/yr and tend to be less variable than the mean annual precipitation (Mifflin and Wheat, 1979; Milne, 1987).

It has typical maar crater morphology with steep walls and a small catchment area with a relatively flat bottom. The lake currently has a surface elevation of 1216 m amsl, a mean depth of 26 m and a maximum depth of 63 m. Its waters are alkaline (9.7 pH) and saline, 26 g/L in the hypolimnion and 87.6 g/L in the monimolimnion (Kharaka et al., 1984). Big Soda like many other lakes in the western Great Basin is located in the area formerly occupied by Pleistocene Lake Lahontan (Russell, 1885; Hutchinson, 1937; Morrison, 1964). The lake is rimmed by a mixture of basalt flows, volcanic tuffs, and Lahontan sediments blown out by repeated eruptions (Russell, 1885; Olmsted et al., 1975). Russell (1885) postulated that the first eruption took place prior to the dendritic stage of Lake Lahontan while the second blast occurred sometime well after the Pleistocene lake had disappeared. The basal section of a recently recovered long core (9.3 m) has produced a radiocarbon date that may indicate a minimum age of 14,740 cal yrs B.P. for the lake (Reidy et al., unpublished data). As the scope of this chapter is to reconstruct the recent history of the lake, only the upper 40 cm of the record is presented here.

Methods

In 2009 researchers from UC Berkeley and the USGS recovered four 5 cm diameter cores measuring 60 cm (SODA-2009-1), 200 cm (SODA-2009-2), 220 cm (SODA-2009-3), and 60 cm (SODA-2009-4) from a water depth of ~63 m. Cores were obtained using a modified gravity coring system equipped with a one-way valve and a 100 lb weight deployed over the side of a Carolina Skiff. A battery-powered winch aided the recovery of the cores from the lake bottom. In May of 2010, we recovered an additional core measuring 150 cm (SODA-2010-1). Here we report on the upper 15 cm of SODA-2009-4 and the upper 40 cm of core SODA-2010-1. Cores were returned to the UC Berkeley Quaternary Paleoecology Laboratory for analyses in plastic polycarbonate liners, split lengthwise, photographed, and sampled. Core SODA-2009-4 was dated by ^{210}Pb at Flett Research, Canada. The ^{210}Pb activity was detected via its granddaughter isotope ^{210}Po. Disintegrations per minute per gram (dpm/g) were obtained with a multichannel alpha-counter. Unsupported levels of ^{210}Pb activity were determined by subtracting the supported or background level.

Plutonium isotopic composition ($^{240}Pu/^{239}Pu$) in the SODA-2010-1 core was determined by multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) at Lawrence Livermore National Laboratory. A total of 10 samples were analyzed. Samples were prepared for analysis by combustion at ~600 degrees to remove organic material. Once ashed, the samples were leached in 8M HNO_3 + trace HF, and Pu isotope ratio and concentration measurements were completed on the leachates. Sample leachates were spiked with ^{244}Pu tracer for Pu concentration measurements by isotope dilution mass spectrometry (IDMS). Pu was purified from sample matrix using a three-step ion exchange procedure. First, Pu was separated using an anion exchange column with 8M HNO_3 followed by 0.1M HCl + 0.005M HF and then 0.1M HCl + HI. Pu was further purified using an anion exchange column in 9 M HCl and then 9M HCl + HI. Final Pu purification was completed using a TEVA resin bed (Eichrom Technologies) in 3 M HNO_3 followed by 0.1M HCl + 0.005M HF and then 0.1 M HCl + HI. Pu isotope ratio measurements were made using the Nu Plasma HR MC-ICP-MS in static ion counting mode for $^{240}Pu/^{239}Pu$, and using peak-jumping ion counting for the IDMS measurement.

Plutonium activity in the environment is an important anthropogenic radionuclide and is primarily a reflection of nuclear power industries and atomic weapons testing. Two isotopes, ^{239}Pu (half-life: 24110 y) and ^{240}Pu (6564 y), are the most abundant plutonium isotopes in the environment. The ability to determine the isotopic ratio of ^{240}Pu and ^{239}Pu provides a powerful post-1950 dating tool in environmental studies (Hardy et al., 1973; Kelley et al., 1999).

Carbon and oxygen isotopic analyses on bulk carbonate was performed on 40 dried salt-free samples taken at 1 cm intervals from SODA-2010-1. Samples were reacted with phosphoric acid at 90°C to release CO_2 using an autoprep device attached to a Micromass Optima mass spectrometer in the Dept. of Earth and Planetary Science (EPS), UC Berkeley. Analytical precisions were ±0.25% for $\delta^{18}O$ and ±0.15% for $\delta^{13}C$ based on replicate analyses of a calcite standard performed during runs. Replicate analyses of core samples were also performed. Isotopic results were reported relative to the Vienna Pee Dee Belemnite (VPDB) standard.

Bulk sediment geochemistry data was developed for 40 samples from SODA10-1 on a Phillips PW 2400 X-Ray Fluorescence (XRF) scanner in the EPS Dept., UC Berkeley. Samples were prepared by combustion at 550˚C for one hour to remove water and organic material. Three grams of inorganic sediment per sample were ground to a powder, treated with a bonding agent, and compressed into pellets. One sample from the 15 cm interval in SODA-2010-1 was submitted for X-Ray Diffraction (XRD) analysis, to the EPS Dept., UC Berkeley.

The organic and carbonate content of the sediments was determined by loss on ignition (Dean, 1974). Weighed samples of 1.25 cm^3 were dried at 100˚C for twenty-four hours to determine water content (% wet weight) and combusted at 550˚C for two hours to determine organic content (% dry weight).

For brine shrimp (*Artemia franciscana)* cyst analysis, 3 cm^3 of wet sediment was washed and sieved using fine meshes (150μm and 300μm) and later concentrated using a COPAS Select large particle flow-cytometry machine in the Dept. of Biology at the University of Indiana. Brine shrimp are the dominant macrozooplankton in many hypersaline environments. Although physiologically able to adapt to salinities near seawater, they are seldom abundant when salinities fall below 45 g/L (Persoone and

Sorgeloos, 1980). At salinities below 100 g/L, predators and competitors can establish and depress populations (Persoone and Sorgeloos, 1980; Wurtsbaugh, 1992) and shifts in phytoplankton assemblage structure and pathogens may also influence survival. Here at Big Soda Lake, changing brine shrimp concentrations reflect unavoidable harvesting during soda salt mining and changing salinity conditions within the lake.

Results and Discussion

Core Chronology

The chronology of the upper section of the Big Soda Lake cores was developed with three lines of evidence: the first appearance of man made radioactive isotopes of ^{239}Pu and ^{240}Pu generated by atomic weapons testing in the 1950's, the vertical distribution of ^{210}Pb, and peaks in heavy metal concentration attributed to local ore smelting in the Virginia City area and also the Sierra Nevada.

The atomic ratios of ^{240}Pu and ^{239}Pu detected in SODA-2010-1 are shown in Figure 3.6. The ^{240}Pu/^{239}Pu ratios observed in the Big Soda Lake area are similar to the global fallout ratio of 0.18 (±0.014) due to weapons tests, as reported in Kelley et al., (1999). Here we attribute the date of 1954 to the first appearance of Pu in the record based on the history of atomic weapons testing at Nevada Test Site (NTS)(Beck et al., 1990).

^{210}Pb activity was determined by measuring the activity of its grand-daughter product ^{210}Po by alpha spectrometry and age calculated using the constant rate of supply (CRS) model (Appleby and Oldfield, 1978). The ^{210}Pb profile exhibits the classic exponential decrease from the surface to background activities at a depth of 8 cm. ^{210}Pb activity declined significantly between the section 0-8 cm (from 4.25 dpm/g to 0.49 dpm/g)(Figure 3.7).

The presence of peaks in heavy metal concentrations (Pb, Cu, and Zn) (Figure 3.8) which we assume to have resulted from the operation of silver/lead-smelting plants in the Virginia City area (ca. 70 km to the south-west of the lake), provide an age estimate of ~1865 for this section of the core (Smith, 1998). The chronological data and age-depth curves developed for SODA-2009-4 and SODA-2010-1 are displayed in Figure 3.9.

For the purposes of discussion we divide the short core records into three time periods:

a) The Pre-Anglo American settlement period (Pre-1850), the period that spans the time before western settlers moved into the area.
b) The early Anglo American period (1850-1906), which chronicles the period of time when the area around the lake was first settled and until lake levels began to increase.
c) The third period (20th Century Changes) reports on changes at the lake from 1906 to the present.

Pre-Anglo American Settlement Period (Pre-1850)

Sediments in the pre-settlement period are comprised of finely laminated sequences composed mostly of yellow, olive, light green, and grey laminae (Figure 3.10). Organic content averages 10 percent and is predominantly made up of abundant amorphous organic material, pollen, spores, diatoms, woody fragments, charcoal, phytoplankton, and the chitinous remains of zooplankton and crustaceans (Oremland et al., 1988). The laminations are a reflection of the seasonal climate of the area and their preservation is evidence of the lack of bioturbation.

Hutchinson (1937) assumed that the meromictic condition at Big Soda Lake was a result of a recent rise in groundwater levels and perhaps even earlier when soda salts were mined from the lake water in the late 19th Century and earlier 20th Century. However, it is clear from the core photo presented in Figure 3.10 that the lake was anoxic and the lake water stratified prior to the 20th Century, for the laminations to form. The XRF (Figure 3.8) and stable isotope data ($\delta^{18}O$ and $\delta^{13}C$)(Figure 3.11) show some synchronous changes in the period before 1850. The $\delta^{18}O$ and $\delta^{13}C$ data reveal wide shifts in values ranging from –3.0 ‰ to 3.0 ‰, and 2.5 ‰to 1.0 ‰ respectively. There are declines in Na_2O and Cl, and increases in SiO_2, Al2O_3, and K_2O, which we interpret these changes to be the result of climatic change during the Little Ice Age and are discussed elsewhere in Chapter 4. Abundant brine shrimp cysts provide evidence of a healthy population in the lake prior to Anglo American settlement. Cyst concentrations range from 1500-2500 cysts/cm^3 in this period (Figure 3.11).

Prior to Anglo American settlement of the area, the land around the lake was occupied by the Northern Paiute of northwest Nevada. The small fresh water springs on the shores of Big Soda Lake were probably utilized by Paiute as a source of water but it is unlikely their impact changed the lake substantially from its natural state. The stratigraphic record reflects a fairly stable environment in the decades prior to Anglo American settlement.

Early Anglo American Period (1850-1906)

The first major perturbation clearly visible in the core stratigraphy is the abrupt change in the color of the sediments accumulating in the lake ca. 1850. These sedimentological changes are unprecedented and are not previously seen in the earlier period. Finely laminated sequences are replaced by sediments with varying thickness and colors of green, gold, brown, orange, white, and black to grey (Figure 3.10). The XRF results do not reveal much change in this early part of this period (ca. 1850-1865) apart from increases in heavy metal concentrations (Pb, Cu, and Zn), which reach peak values around 1865. The Na_2O and Cl concentrations remain unchanged. However, after 1875, there are several changes in the record, especially in the brine shrimp cyst data. Cyst concentrations decrease sharply from ~3,500/cm^3 in 1870 to less than 100/cm^3 cysts in 1904. Na_2O and Cl both begin to decline slightly and there is a small shift in the $\delta^{18}O$ and $\delta^{13}C$ records to lighter isotope values (Figure 3.11), reflecting slightly fresher conditions and reduced biological productivity in the lake respectively.

It is clear from initial changes in the sediments that the transformation of the environment in and around Big Soda Lake began not long after the area was settled. The historical record supports the changes in this section of the core. Ragtown, a small trading post two miles east of Big Soda Lake, was established in 1854 (Figure 3.5) and in the following year, 1855, the discovery of soda salt resources at Little Soda Lake was the first recorded mineral discovery in Churchill County (Angel, 1973). The discovery of other mineral deposits (silver) in 1859 southwest of Big Soda Lake at Virginia City, and associated smelting activities provide the first evidence of human impact in the record. Heavy metals increase and peak around 1865.

Commercial mining of the soda deposits exposed on the dry floor of Little Soda Lake began in 1868. In 1875, soda salt mining expanded to Big Soda when a processing facility consisting of evaporating ponds was established on the lake-shore. Russell (1885) described the processing techniques employed to produce the soda salts using vats and evaporating ponds. Natural lake water was pumped into evaporating ponds and the liquid was allowed to evaporate. As the sun heated the solution, he noted that the brine shrimp died and settled, becoming part of the cake of bicarbonate of soda. The cyst data show a precipitous decline in this period and according to Russell's historical account "millions of brine shrimp" from the lake water were unavoidably incorporated into the cake of soda. This likely accounts for the sharp reduction in cysts in the stratigraphic record during this time.

It is interesting to note that there is no significant decline in Na_2O and Cl in the sediments during the time when soda salts were being extracted from the lake. The historical account provides information that may account for this unexpected result. Based on Russell's (1885) measurements of the salt properties of the lake water, the lake water contained 428,000 tons of sodium carbonate. When he visited the lake in 1882, he noted that the soda mining operation was still in the experimental stage and only two or three hundred tons of soda had been processed since it began in 1875. It seems that the volume of soda produced was very small compared to the potential volume, and so the impact of the soda mining was negligible. The soda mining operation ceased operation in 1906 due to rising lake water levels brought about by the development of irrigation farming locally.

20th Century Changes (1906-Present)

From 1906 onwards, there are a number of dramatic changes in color, lamination thickness, and geochemistry of the sediments. The most dramatic change is the abrupt increase in calcium (CaO)(Figure 3.8). After ca. 1906, CaO rises sharply from background levels of <2 percent to over 37 percent. This increase is clearly visible in the cores as ~1 cm thick white layer (Figure 3.10). XRD analysis confirmed that this white layer is calcite. Above 1915, calcium drops gradually and returns to background levels around 1975. Cl and Na_2O values drop sharply between 1906 and 1915, with Na_2O declining from 70 to 25 percent and Cl dropping from 45 to 20 percent. There are marked increases in SiO_2, $Al2O_3$, and K_2O after 1910 to the present.

While brine shrimp cyst numbers remain low from 1906 to the present (Figure 3.11), the stable isotope data begins a gradual shift to more negative $\delta^{18}O$ values above 1970 while the $\delta^{13}C$ values become lighter after 1950. The color of the sediments between 15 and 8 cm (1906-1930) ranges from dark brown, brown, beige, black, grey, white to peach and orange while the laminae are of varying thickness of (0.25-2.00 mm). It seems possible that the sediments associated with the earlier soda mining activity were re-mobilized as the lake water rose, and that some of the "mother liquid" deposits observed by Russell were re-deposited in the central part of the basin. A transect of cores from the central part of the lake to the south shore could shed light on this possibility. The dramatic changes in sediment characteristics during the last 100 years reflect major changes in local hydrology. Unlike many of the lakes in the Great Basin whose levels dropped during the last Century due to freshwater diversion for domestic and agricultural use (Melack et al., 1985; Jellison et al., 1998, Benson et al., 2002), the lake level at Big Soda Lake increased by ~18 m. Beginning in 1903, the U.S. Reclamation Service (USRS) as part of the Newlands Irrigation Project began bringing irrigation water to the Lahontan Valley via the Truckee Canal, which resulted in the dramatic rise in the regional water table (Townley and James, 1998). Between 1907 and 1930, when the lake stabilized, the lake level had risen by 18 m (Figure 3.5).

The changes in lake level are clearly reflected in the visual stratigraphy and sediment chemistry, indicating an increase in freshwater inputs via groundwater flow and reduction in lake salinity during the 20th Century. The abrupt increase in calcium and gradual increases in SiO_2, $Al2O_3$, and K_2O from around 1905 onwards is likely due to the initial freshwater irrigation inputs from groundwater flow. The groundwater would have initially been unsaturated with calcium carbonate ($CaCO_3$) but when it entered the lake, saturation levels were eventually reached (due to photosynthesis by phytoplankton) and calcium carbonate would have been precipitated. Rosen et al. (2004) clearly demonstrated that the growth of tufa deposits on the edge of Big Soda Lake is linked to the groundwater inputs after 1905. An additional source of calcium carbonate within the lake basin may have been the basal deposits of the evaporating ponds which had been previously used for soda salt mining. As brine evaporates one of the first compounds to precipitate is calcium carbonate. Therefore, it is possible that as lake levels rose and flooded the evaporating ponds, calcium carbonate present in the base of those ponds may have dissolved back into the lake. The increases in $Al2O_3$, $SiO_2$and K_2O also reflect the increasing freshwater inputs, partly due to erosion in and around the lake due to rising water levels, and perhaps diatom blooms.

In the past 80 years the sediments become finely laminated once again (~0.25 mm to 0.5 mm) and are unusual in that they have a distinctively green color (from preserved chlorophylls and their degradation products). Usually, sediments in highly sulfidic environments are black due to the presence of amorphous iron sulfides. However, because of the low iron content of the lake, iron sulfides are not present in sufficient abundance to mask the organic coloration (Hutchinson, 1937; Oremland et al., 1988).

Deepening of the lake due to the irrigation and subsequent stratification of the water column hypothesized by Hutchinson (1937) was probably responsible for the return to more regular laminations in this period. Additional geochemical evidence points to a freshening of the lake during the last century. Reduced salinity is revealed by declining Na and Cl concentrations towards the upper part of the cores. Hutchinson (1937) calculated that vast quantities of chlorine had left the lake basin through groundwater flow since the time of Russell's visit in 1882. When Hutchinson compared his calculations with Russell's he estimated that some 4.4 metric tons of salts per day were being lost to groundwater flow. We do see a large decline in Cl from 45 to 20 percent from 1906 to the present day, along with a decline from 70 to 20 percent in Na_2O.

One important note with regards to the oxygen and carbon isotope data is that the shifts to negative values do not synchronously match the rising lake levels. The carbon isotope values begin to shift to more negative values after 1950, while the oxygen values shift after 1970, even though the lake level stabilized in 1930, 18 m higher than the level recorded in 1907. This is likely due to the time it takes for regional groundwater with much more negative oxygen isotopic signatures (Rosen et al., 2004) to flow to the lake in enough volume to alter the isotopic values of the carbonate precipitated. A shallow well just to the west of Big Soda Lake sampled by Lico and Seiler (1994) had a tritium concentration near the detection limit of 0.3 pCi/L, indicating that the water was likely recharged near the beginning of nuclear testing and was about 45 years old at the time.

Another important indicator of the dramatic reduction in salinity during the 20th century is provided by the brine shrimp cyst concentrations. Although the initial decline in brine cysts was caused by soda production in the late 19th Century, brine shrimp have not returned to previous levels in the lake due to their intolerance of low salinity levels. Also, a predator may be benefiting from the recent reduction in lake salinity and depressing the brine shrimp population.

Conclusion

This study documents analyses of sediment geochemistry, brine shrimp cysts, radiogenic and stable isotopes from two short cores from Big Soda Lake, near Fallon, Nevada. The cores represent the period of time since Anglo Americans first entered the Big Soda Lake area i.e. the past 160 years. There have been dramatic changes within the lake and its watershed during this time period of time. Several human impacts have been identified, including regional mining impacts, soda salt extraction from the lake, and artificially rising groundwater levels in the last century. Two major developments have dramatically impacted the lake in that time. Firstly, the development of a commercial soda manufacturing and processing facility at the lake beginning in 1875 until the early 20th century. Secondly the development of irrigation agriculture which led to an 18 m rise in lake level in the first few decades of the twentieth century. This study shows the importance of human influences on changes to the hydrology of a modern lake system.

Acknowledgements

I would like to acknowledge lab assistance provided by Sarah Edwards and Forood Azari-Dehkordi. Field assistance from Larry Miller, Michael Rosen, Kip Allander, Francis Smith, Maria-Teresa Ramirez, Marc Parisien, Jim Wanket, Elizabeth Watson, Kristina Brady, Anders Noren, and Amy Mybro. Amy Gaffney at Lawrence Livermore National Laboratory undertook the Plutonium analysis. Partial funding for this project was provided by the USGS Earth Surface Processes program; LacCore-National Lacustrine Core Repository; University of Minnesota, Minneapolis; USGS Nevada Water Science Center. Additional funding for analyses provided by the Stahl Foundation, Carl Sauer Scholarship, and the Larsen Foundation (all at UC Berkeley), LacCore Graduate Student grant, National Science Foundation Doctoral Dissertation Improvement Grant Award # 1130462, and the Jonathan O. Davis Scholarship in Quaternary Sciences from the Desert Research Institute, Reno, Nevada.

References

Appleby, P. G., and Oldfield, F. (1978). The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena*, *5*(1), 1-8.

Beck, H. L., Helfer, I. K., Bouville, A., and Dreicer, M. (1990). Estimates of fallout in the continental US from Nevada weapons testing based on gummed-film monitoring data. *Health Physics*, *59*(5), 565-576.

Benson, L. V. (1978). Fluctuation in the level of pluvial Lake Lahontan during the last 40,000 years. *Quaternary Research*, *9*(3), 300-318.

Benson, L., Kashgarian, M., Rye, R., Lund, S., Paillet, F., Smoot, J., Kester, C., Mensing, S., Meko, D., and Lindstrom, S. (2002). Holocene multidecadal and multicentennial droughts affecting Northern California and Nevada. *Quaternary Science Reviews*, 21, 659 – 682.

Benson, L.V., Burdett, J.W., Kashgarian, M., Lund, S. P., Phillips, F. M., and Rye, R.O. (1996). Climatic and Hydrologic Oscillations in the Owens Lake Basin and Adjacent Sierra Nevada, California. *Science*, 274. (5288) 746 – 749.

Benson, L. V., and Thompson, R. S. (1987). Lake-level variation in the Lahontan basin for the past 50, 000 years: *Quaternary Research*, 28, 69-85.

Benson, L., White, L. D., and Rye, R. (1996). Carbonate Deposition, Pyramid Lake Subbasin, Nevada: 4. Comparison of the stable isotope values of carbonate deposits (tufas) and the Lahontan lake-level record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *122*(1), 45-76.

Bradbury, J.P., Forester, R. M. and Thompson R.S. (1989). Late Quaternary paleolimnology of Walker Lake, Nevada. *Journal of Paleolimnology*, 1, 249-267.

Breeze, C. R., Jr., (1968). *A general limnological study of Big Soda Lake*. Unpublished M.S. Thesis. University of Nevada, Reno.

Beutel, M. W., Horne, A. J., Roth, J. C., and Barratt, N. J. (2001). Limnological effects of anthropogenic desiccation of a large, saline lake, Walker Lake, Nevada. In *Saline Lakes* (pp. 91-105). Springer Netherlands.

Cloern, J.E., Cole, B.E., and Oremland, R.E. (1983). Seasonal changes in the chemistry and biology of a meromictic lake (Big Soda Lake, Nevada, U.S.A.). *Hydrobiologia*, (105), 195–206.

Davis, O.K. (1999). Pollen Analysis of a Late-Glacial and Holocene Sediment Core from Mono Lake, Mono County, California. *Quaternary Research*, 52(2), 243-249

Hardy E. P., Krey P. W., and Volchok, H. L. (1973). Global inventory and distribution of fallout plutonium. *Nature*, 241, 444-445.

Heyvaert, A.C., Reuter, J.E., Slotton, D.G. and Goldman, C.R. (2000). Paleolimnological reconstruction of historical atmospheric lead and mercury deposition at Lake Tahoe, California-Nevada, *Environmental Science and Technology*, 34 (17), 3588–3597.

Hutchinson, G.E. (1937). A contribution to the limnology of arid regions, primarily founded on observations made in the Lahontan Basin. *Connecticut Academy of Arts and Sciences Transactions*, 33, 47–132.

Jellison, R., Romero, J. and Melack, J.M. (1998). The onset of meromixis during restoration of Mono Lake, California: Unintended consequences of reducing water diversions. *Limnology and Oceanography*. 43, 706-711.

Kharaka, Y.K., Robinson, S.W., Law, L. M., and Carothers, W.W. (1984). Hydrogeochemistry of Big Soda Lake, Nevada: An alkaline meromictic desert lake. *Geochimica et Cosmochimica Acta*, v. 48, 823–835.

Kelley, J. M., Bond, L. A., and Beasley, T. M. (1999). Global distribution of Pu isotopes and ^{237}Np. *Science of the Total Environment*, 237, 483-500.

King, C. (1877). *United States Geological Exploration of the 40th parallel.* U.S. Army Engineer Department Professional Paper 18, 7 volumes.

Li, H. C., Bischoff, J. L., Ku, T. L., Lund, S. P., and Stott, L. D. (2000). Climate variability in East-Central California during the past 1000 years reflected by high-resolution geochemical and isotopic records from Owens Lake sediments. *Quaternary Research*, *54*(2), 189-197.

Lico, M.S., and Seiler, R.L., (1994). *Groundwater quality and geochemistry, Carson Desert, Western Nevada*. U.S. Geological Survey Open-File Rep. 94-31.

Mifflin, M.D. and Wheat, M.M. (1979). *Pluvial lakes and estimated pluvial climates of Nevada*, Bulletin 94. Nevada Bureau of Mines and Geology, Reno, NV.

Milne, W. (1987). *A Comparison of Reconstructed Lake-Level Records since the mid-1880's of some Great Basin Lakes*. Unpublished M.S. Thesis, Colorado School of Mines.

Melack, J.M., Cooper, S., and Henz, P.H. (1985). *The ecology of Mono Lake, California* National Geographic Society Res. Report 1979 Projects, 461-470.

Mensing, S. A. (2001). Late-glacial and early Holocene vegetation and climate change near Owens Lake, eastern California. *Quaternary Research*, *55*(1), 57-65.

Mensing, S. A., Benson, L. V., Kashgarian, M., and Lund, S. (2004). A Holocene pollen record of persistent droughts from Pyramid Lake, Nevada, USA. *Quaternary Research*, *62*(1), 29-38.

Mensing, S., Smith, J., Burkle Norman, K., and Allan, M. (2008). Extended drought in the Great Basin of western North America in the last two millennia reconstructed from pollen records. *Quaternary International*, *188*(1), 79-89.

Morrison, R. B. (1964). *Lake Lahontan: Geology of the Southern Carson Desert.* Professional Paper 401. United States Geological Survey

Angel, M. (1973). *History of Nevada*. Ayer Company Pub.

Olmsted, F.H., Glancy, P.A., Harrill, J.R., Rush, F.E. and A.S. VanDenburgh (1975). Preliminary Hydrogeologic appraisal of selected Hydrothermal systems in northern and central Nevada. U.S. Geological Survey, Open-File Report 75-56.

Oremland, R.S., Cloern, J.E., Sofer, Z., Smith, R.L., Culbertson, C.W., Zehr, J., Miller, L., Cole, B., Harvey, R., Iversen, N., Klug, M., Des Marais, D.J., and Rau, G. (1988). Microbial and biogeochemical processes in Big Soda Lake, Nevada. In Fleet, A.J., et al., Eds., Lacustrine petroleum source rocks. Geological Society [London] Special Publication, 40, 59–75.

Oremland, R. S. (1983). Hydrogen metabolism by decomposing cyanobacterial aggregates in Big Soda Lake, Nevada. *Applied and Environmental Microbiology*, *45*(5), 1519-1525.

Oremland, R. S., and Des Marais, D. J. (1983). Distribution, abundance and carbon isotopic composition of gaseous hydrocarbons in Big Soda Lake, Nevada: an alkaline, meromictic lake. *Geochimica et Cosmochimica Acta*, *47*(12), 2107-2114.

Oremland, R. S., Marsh, L., and DesMarais, D. J. (1982). Methanogenesis in Big Soda Lake, Nevada: an alkaline, moderately hypersaline desert lake. *Applied and Environmental Microbiology*, *43*(2), 462-468.

Persoone, G. and Sorgeloos, P. (1980). *General aspects of the ecology and biogeography of Artemia*. In Persoone, G.P. Sorgeloos, O. Roels and E. Jaspers (eds). *The Brine Shrimp Artemia,* 3. Ecology, Culturing. Use in Aquaculture., 3-23. Wetteren Universa Press.

Rosen, M.R., Arehart, G.B., and Lic, M.S. (2004). Exceptionally fast growth rate of <100-yr-old tufa, Big Soda Lake, Nevada: Implications for using tufa as a paleoclimate proxy. *Geology* 32, 5, 409-412.

Rush, F.E. (1972). *Hydrologic Reconnaissance of Big and Little Soda Lakes, Churchill County, Nevada* Carson City, Nevada Department of Conservation and Natural Resources, Division of Water Resources.

Russell, I.C. (1885). *Geological History of Lake Lahontan, A Quaternary Lake of Northwestern Nevada*. Washington, D.C., U.S. Geological Survey.

Smith, G. H. (1998). *The History of the Comstock Lode: 1850-1997* (Vol. 24). University of Nevada Press.

Stark, M., Wilt, M., Haught, J.R., and Goldstein, N., (1980). *Controlled-source electromagnetic survey at Soda Lakes Geothermal Area, Nevada* Lawrence Berkeley Laboratory Report LBL11221.

Townley, J. M., and James, S. A. (1998). *Turn This Water Into Gold: The Story of the Newlands Project*. Nevada Historical Society.

Wurtsbaugh, W.A. (1992). Food web modification by an invertebrate predator in the Great Salt Lake (U.S.A.). *Oecologia* (89), 168-175.

Yuan, F., Linsley, B. K., Howe, S. S., Lund, S. P., and McGeehin, J. P. (2006). Late Holocene lake-level fluctuations in Walker Lake, Nevada, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *240*(3), 497-507.

Yuan, F., Linsley, B. K., Lund, S. P., and McGeehin, J. P. (2004). A 1200 year record of hydrologic variability in the Sierra Nevada from sediments in Walker Lake, Nevada. *Geochemistry, Geophysics, Geosystems*, *5*(3).

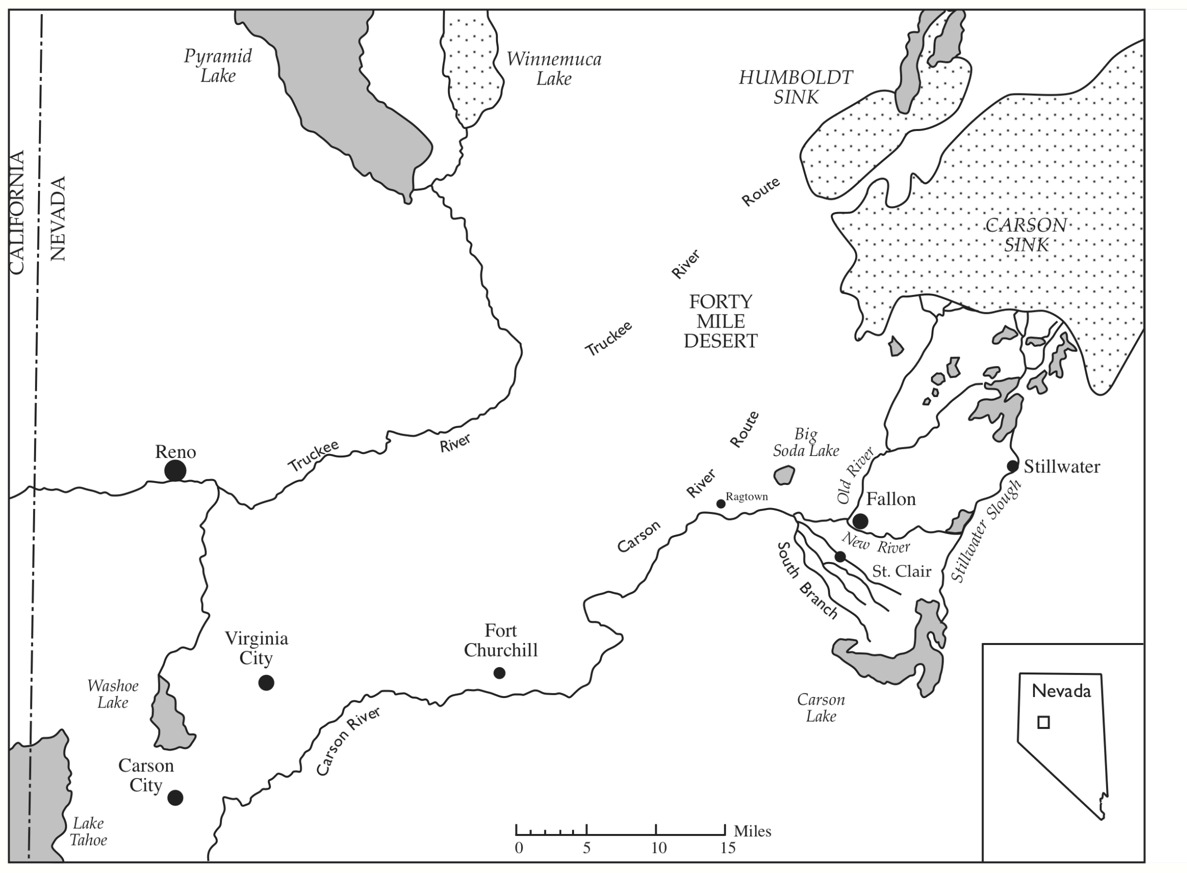


Figure 3.1 Big Soda Lake and surrounding area, including Ragtown, Fallon, Virginia City, Carson City, and the Carson Sink.

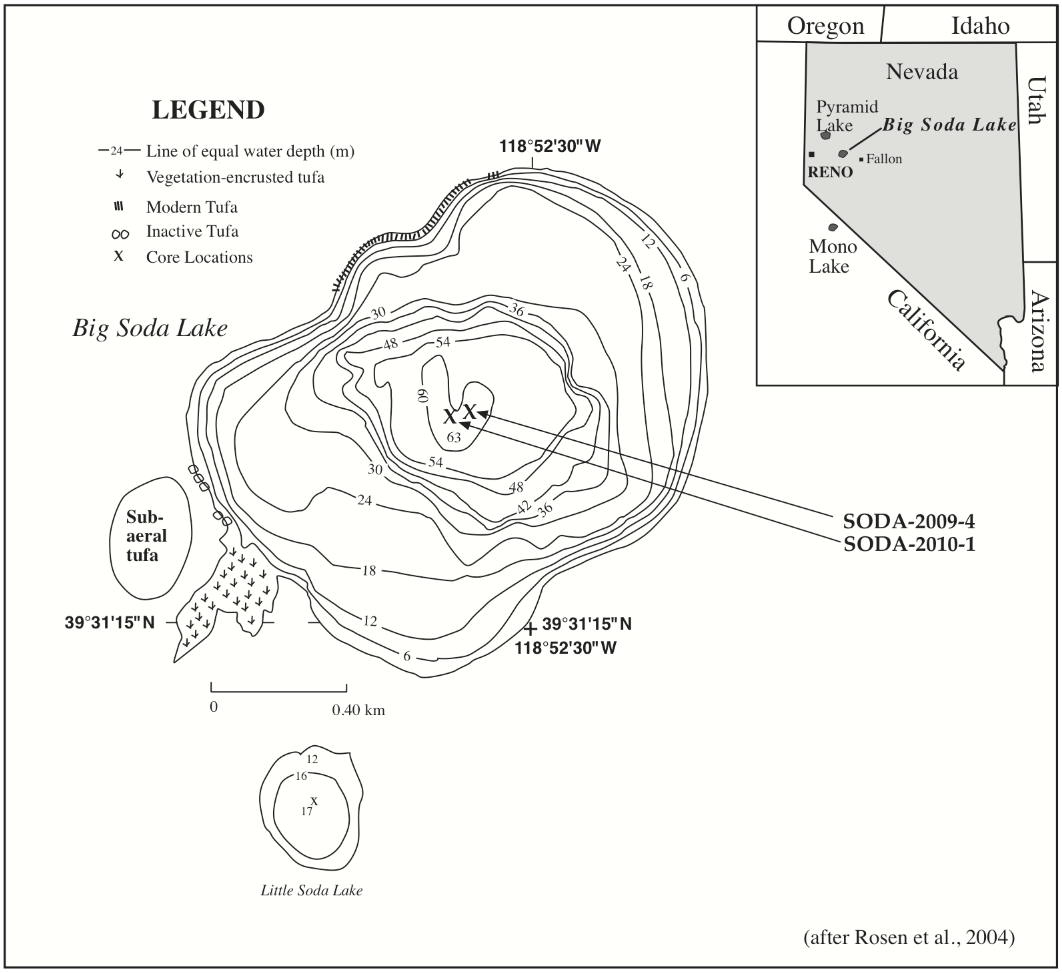


Figure 3.2 Big Soda Lake, Churchill County, Nevada. Core recovery locations for SODA-2010-1 and SODA-2009-4 are also indicated.

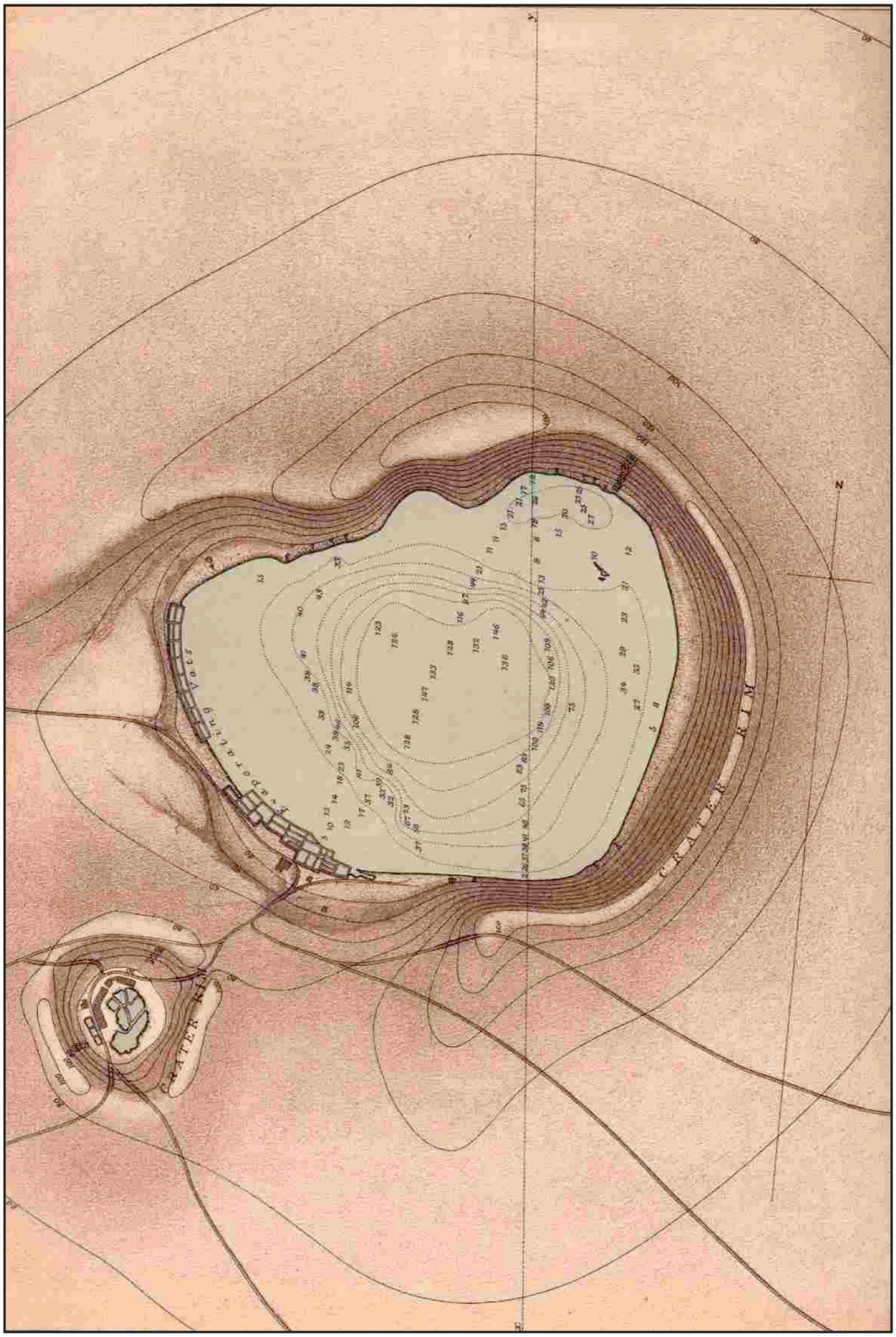


Figure 3.3 Israel Russell's map of the bathymetry of Big Soda Lake and Little Soda Lake (Russell, 1885).

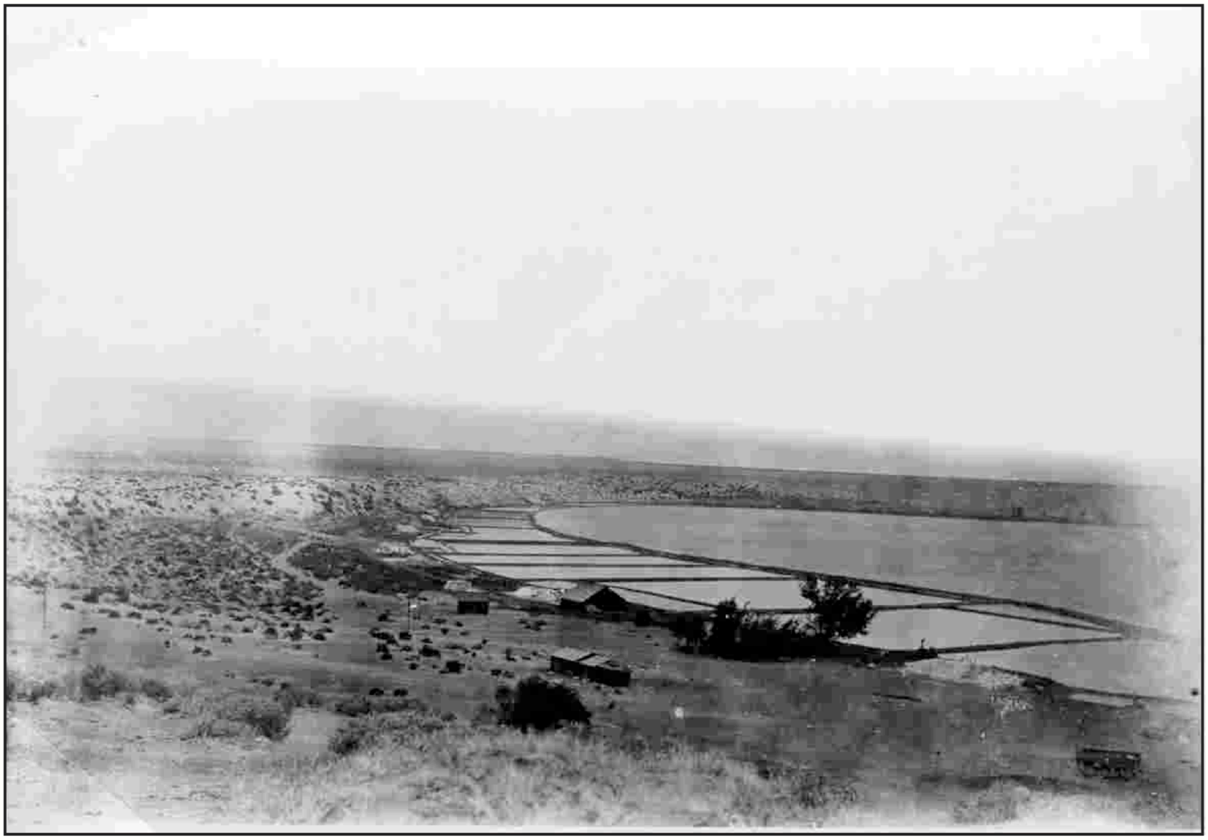


Figure 3.4 Big Soda Lake and associated soda salt mining facility with evaporating ponds along the south shore of the lake in 1902. *Photo courtesy: Churchill County Museum.*

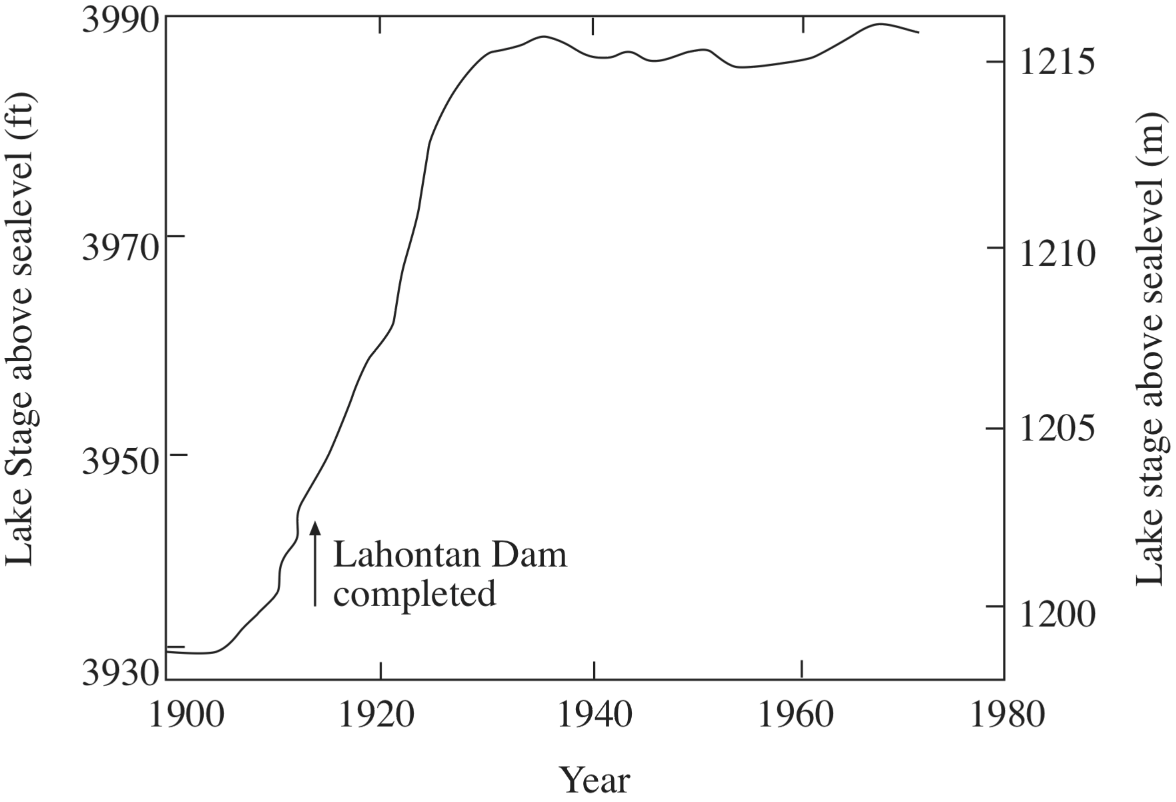


Figure 3.5 Big Soda lake surface water level, 1900-1970 (adapted from Kharaka et al., 1984).

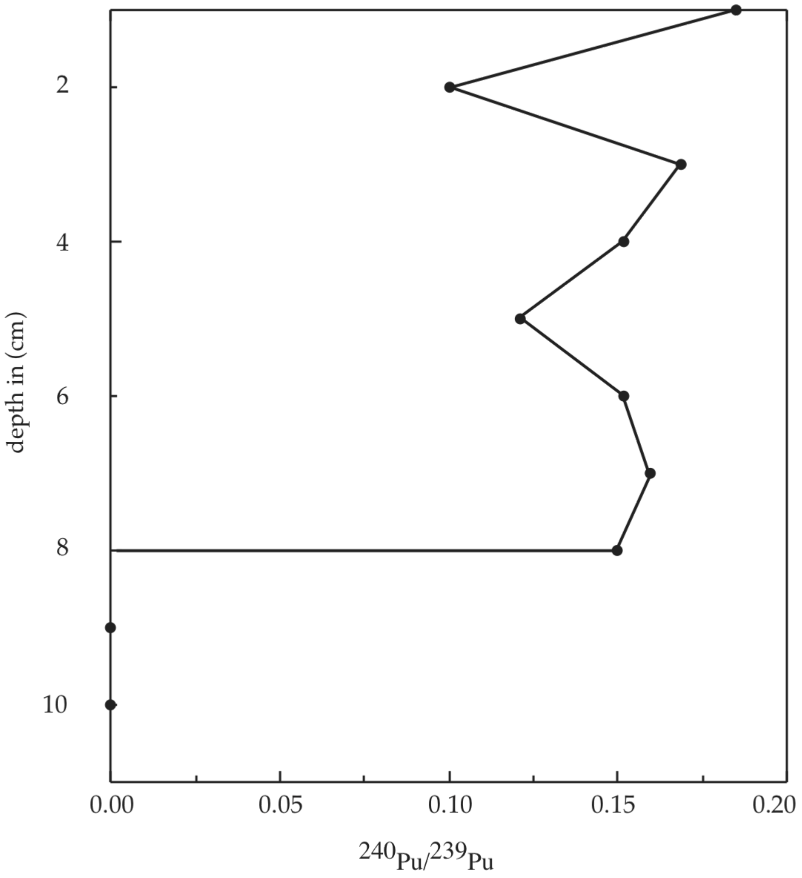


Figure 3.6 Ratios of ^{240}Pu and ^{239}Pu in SODA-2010-1.

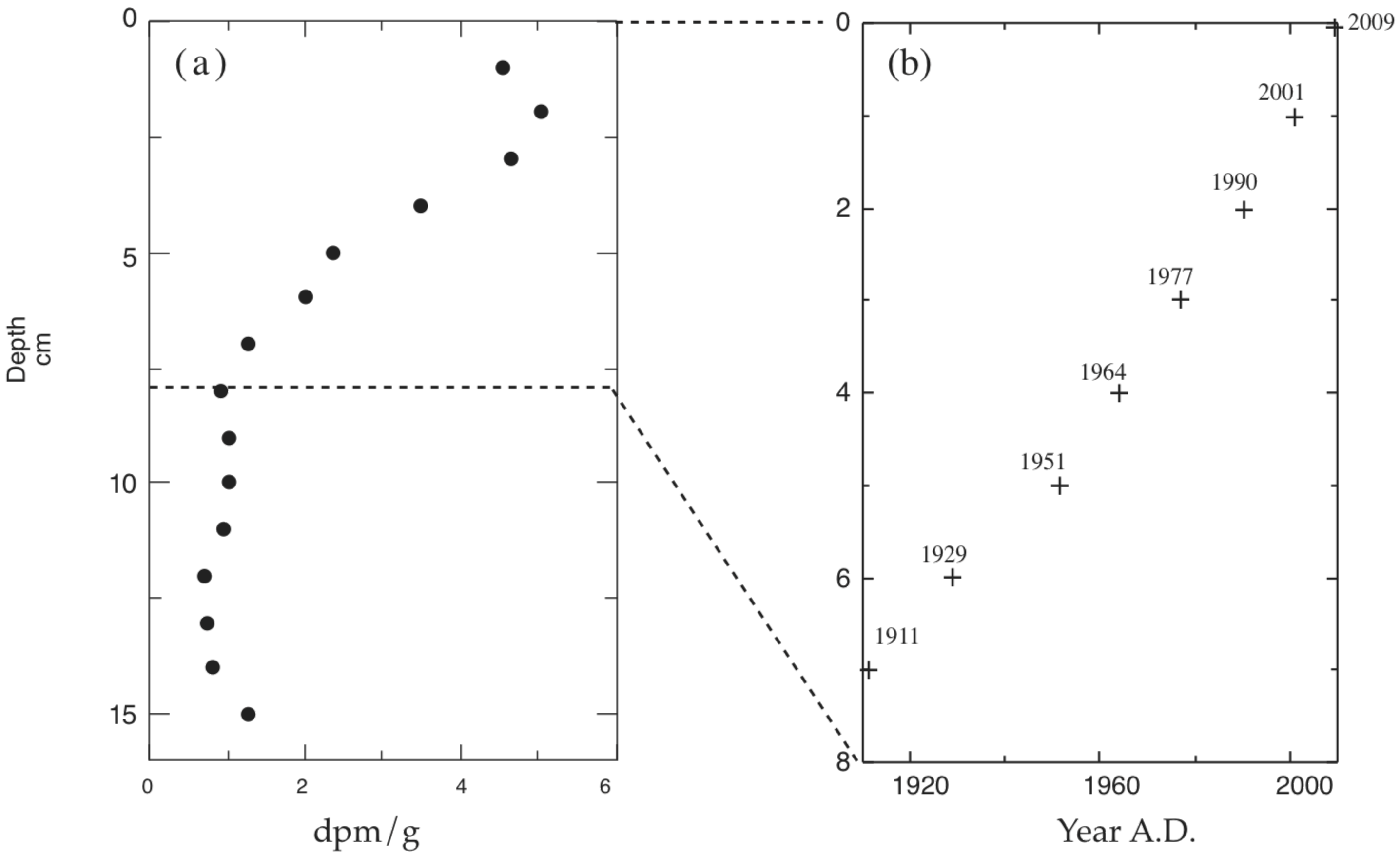


Figure 3.7 (a) Total ^{210}Pb Activity (dpm/g) V Depth from SODA-2009-4 and (b) ^{210}Pb chronology based on the constant rate supply (CRS) model.

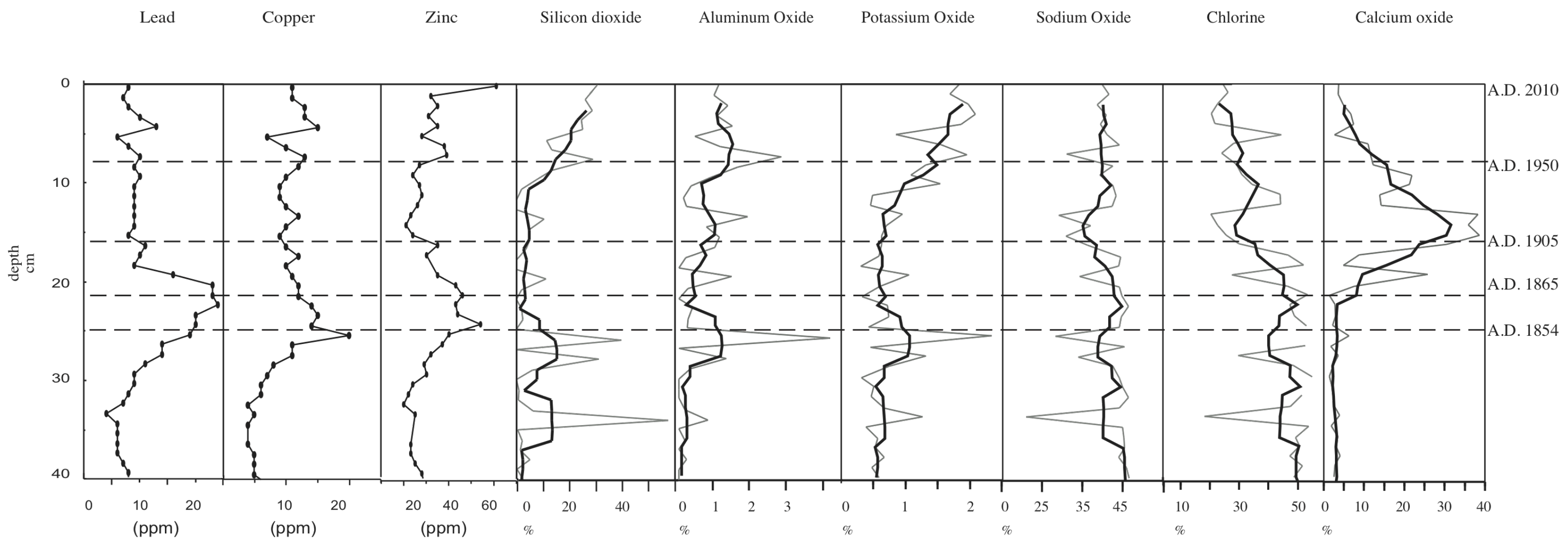


Figure 3.8 Selected XRF data for SODA 2010-1. The black solid lines are 3 point running means.

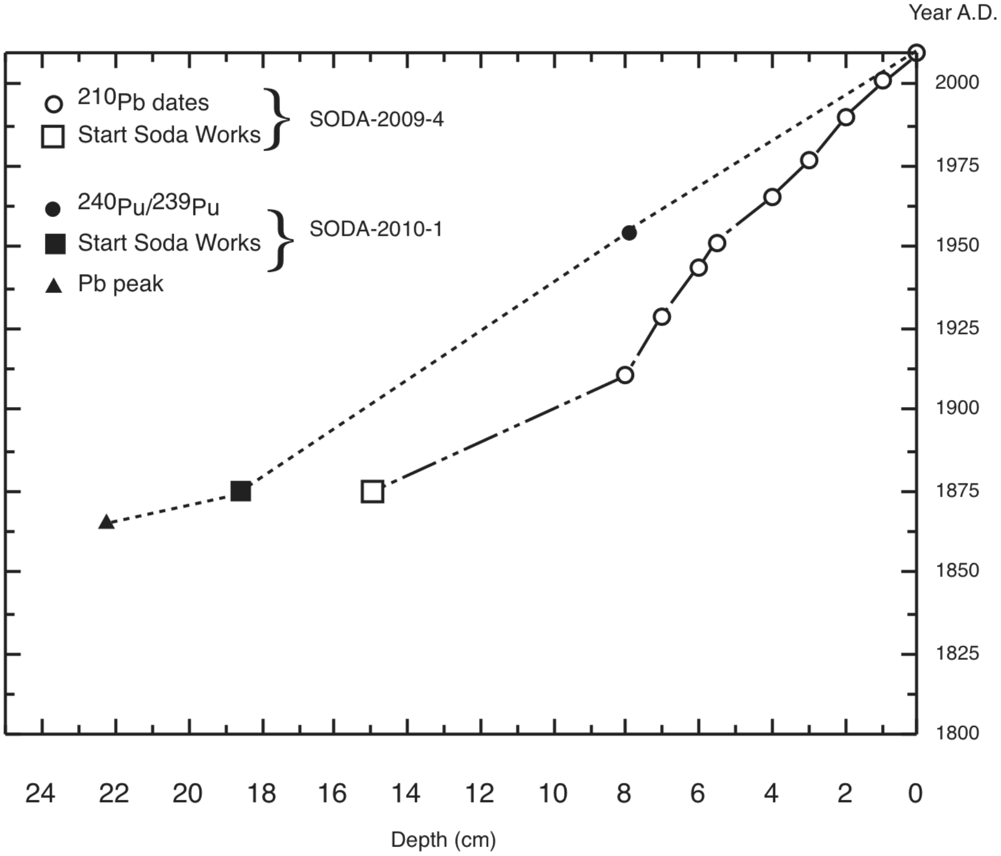


Figure 3.9 Age-Depth curves for SODA-2009-4 and SODA-2010-1.

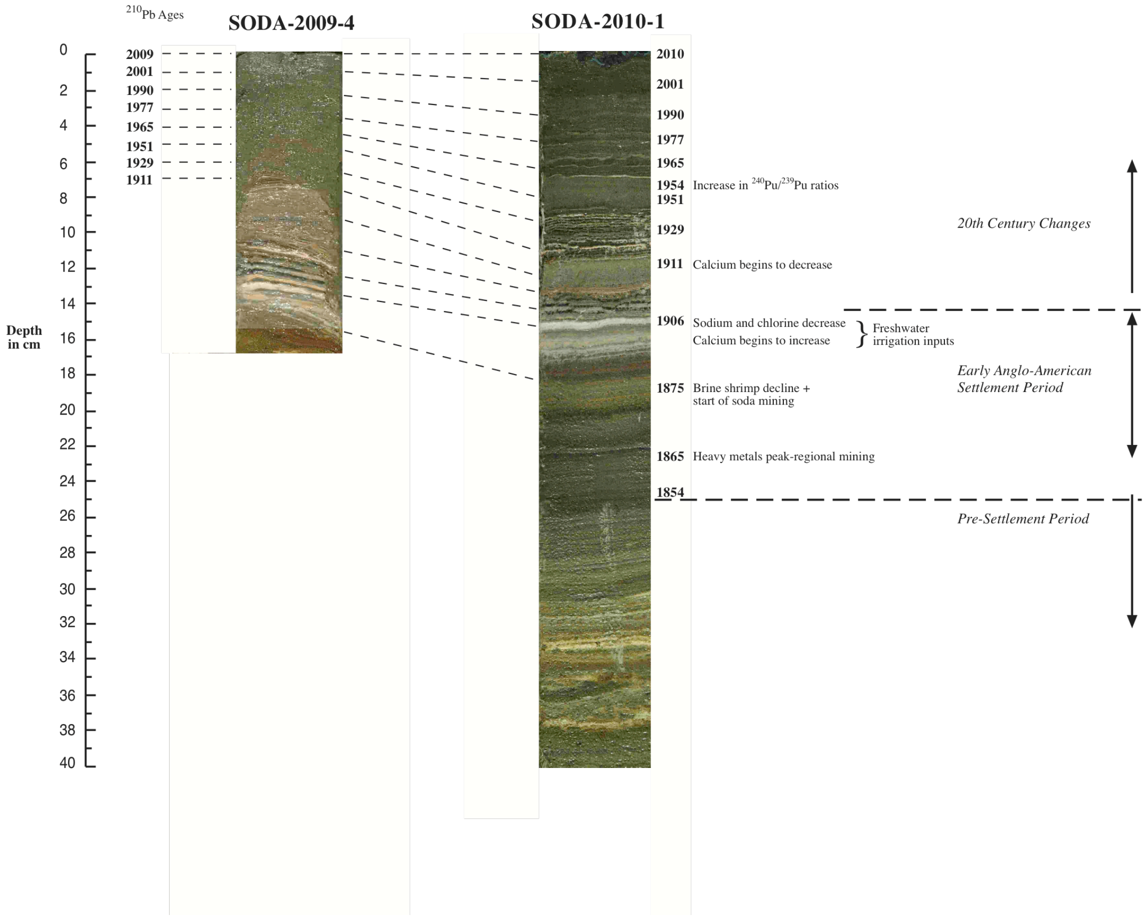


Figure 3.10 Correlations between SODA-2009-4 and SODA-2010-1 based on ^{210}Pb dates and stratigraphic markers between the two cores.

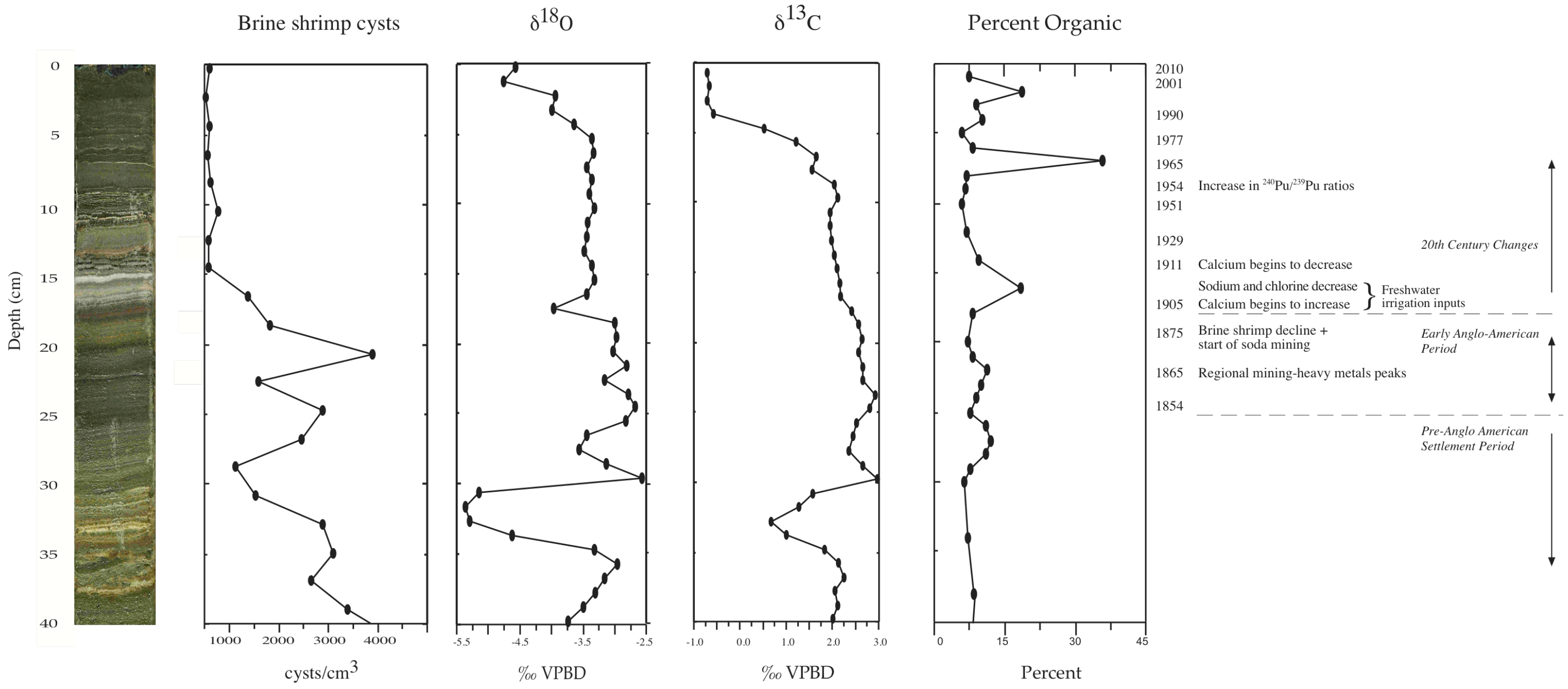


Figure 3.11 Brine shrimp cyst concentrations, stable isotope ratios, and loss on ignition for SODA-2010-1.

CHAPTER 4

A 1600 Year Record of Climate Change from Big Soda Lake, Nevada, USA

Abstract

In this chapter I report on the results of several analyses carried out on a 150 cm core recovered from Big Soda Lake in May of 2010. The analyses include: measurement of the stable isotope of oxygen and carbon inorganic carbonates; quantification of changes in brine shrimp cyst abundance; and measurement of changes in the elemental composition of the sediments with x-ray fluorescence. The core has an estimated basal date of A.D. 400.

The stable isotope, geochemistry, and brine shrimp cyst results all indicate significant shifts in climate during the time period covered. From A.D. 400-850 the climate alternated between wet and dry conditions; from A.D. 850-1060 it was relatively dry; wet conditions prevailed between A.D. 1050-1260; drier conditions returned between A.D. 1260-1400. From A.D. 1400 to A.D. 1700 the climate was relatively drier overall, but after A.D. 1700 the climate became relatively wet again. The period since A.D. 1850 has been complicated by human activity in and around the lake. However, it is worth pointing out that the recent artificial increase in lake level, by 18 m during the early decades of the twentieth century, due to irrigation inputs, resulted in a major shift in the isotopic, geochemical and brine shrimp cysts in the lake record.

Introduction

Climate change during the last two millenia has recently received considerable attention because of the concern surrounding global warming (Crowley, 2000; Jones et al., 2001; Jones and Mann, 2004; Benson et al., 2002; Cobb et al., 2003). During this time period global climate has been characterized by century-scale changes in mean temperature and precipitation. Temperatures appear, for example, to have been slightly warmer (a couple of tenths of a degree Centigrade) during the period A.D. 850-1400 often referred to as the Medieval Warm Period (MWP) or the Medieval Climatic Anomaly (MCA) relative to the earlier period A.D. 200-850 and the later cooler period known as the Little Ice Age (LIA) from A.D. 1400-1850. Since A.D. 1850 most areas of the globe have experience increasing temperatures (Bradley, 2000; Jones and Mann, 2008).

Previous paleoclimatological research in the Great Basin region of the western United States has produced several records of long-term climate change. This research has focused on the evidence of lake level changes and the implications of other paleoclimate proxies such as pollen, diatoms, geochemistry and stable isotopes (Benson, 1978; Benson and Thompson, 1987; Bradbury et al., 1989; Stine, 1990; 1994; Davis, 1999; Li et al., 2000; Benson et al., 2003; Mensing, 2001). Several late Holocene records of multi-decadal to multi-centennial droughts and effectively wetter episodes in the Sierra Nevada and western Great Basin are becoming increasing well established (Leavitt, 1994; Benson et al., 2002, Mensing et al. 2004; Yuan et al., 2004; 2006). Evidence for extended periods of drought far more severe than we have experienced during the historical period is derived from lowered lake and river levels (Stine, 1994), submerged tree stumps (Lindström, 1990; Kleppe et al., 2011), tree rings (Graumlich, 1993) and oxygen stable isotope studies (Benson et al., 2002; Yuan et al., 2004; 2006). In the recent past there were also multiple periods when climate in this region was effectively wetter than the historic average (Grayson, 2011; Stine, 1990; Leavitt, 1994; Hughes and Funkhouser, 1998; 2003; Strachan et al., 2011).

In spite of advances in understanding the response of the Great Basin and Sierra Nevada region to century-scale climatic "events" (Stine, 1990; 1994; Hughes and Graumlich, 1993; Benson et al., 2002; Meko et al., 2001; Kleppe, 2005) the climatic dynamics and hydrologic fluctuations in the region are not well understood. The causes for these changes are not exactly known, but may have to do with large-scale changes in atmospheric circulation patterns and their effects on the hydrologic cycle (Cayan et al., 1999; Enzel et al., 1989; Redmond and Koch, 1991).

Here, we examine the geochemistry, stable isotope, and brine shrimp record from a laminated core recovered from Big Soda Lake, a maar lake in north-west Nevada. The purpose of the research was to develop a high-resolution paleolimnological record to examine the lake's response to known anthropogenic changes in hydrology during the twentieth century, with changes that may have occurred in the past.

Maar Lakes as Archives of Environmental Change

One of the challenges in reconstructing past climate change from lake records is the wide variation in the climate sensitivity of the various sites, climate indicators that are used and the development of reliable lake chronologies. Lake sediments may provide the most continuous high-resolution records available, but lakes vary in their sensitivity to climate, making it difficult to quantify paleoclimate data and compare records between sites. Maar lakes have the potential to provide some of the best stratigraphic records of environmental change (Brauer et al., 1999; Zolitschka, 1996; Park et al., 2010). These lakes typically have small well-defined catchment basins, are steep sided with flat bottoms, and rapid sediment accumulation rates. In addition, deep water (>40 m) maars with stratified water columns that result in anoxic lake bottom conditions ensure the preservation of accumulating sediments as laminations or varves, which can allow the construction of annual to sub-decadal lake histories.

Site Setting

Big Soda Lake (39° 31′N, 118° 52′) is a small meromictic maar lake (surface area 1.6 km^2) located in northwestern Nevada about 90 km east of Reno. The lake is situated near the town of Fallon at the southwestern margin of the Carson Sink (Figure 4.1). The lake is predominantly fed by groundwater and precipitation, has a typical maar crater morphology with steep walls and a relatively flat bottom (Figure 4.2). The lake currently has a surface elevation of 1216 m amsl, a mean depth of 26 m and a maximum depth of 63 m. Its waters are alkaline (9.7 pH) and saline, 26 g/L in the hypolimnion and 87.6 g/L in the monimolimnion (Kharaka et al., 1984). Mean annual rainfall is limited in this region to 12.7 cm/yr at Fallon, Nevada and a maximum annual precipitation of about 23 cm. Evaporation rates range from about 125 to 135 cm/yr and tend to be less variable than mean annual precipitation rates (Mifflin and Wheat, 1979; Milne, 1987).

Big Soda like many other lakes in the western Great Basin is located in the area formerly occupied by Pleistocene Lake Lahontan (Russell, 1885; Hutchinson, 1937; Morrison, 1964). The lake is rimmed by a mixture of basalt flows, volcanic tuffs and Lahontan sediments blown out by repeated eruptions (Russell, 1885; Olmsted et al., 1975). Russell (1885) postulated that the first eruption took place prior to the dendritic stage of Lake Lahontan, while the second blast occurred sometime well after the Pleistocene lake had disappeared. The basal section of a recently recovered long core (9.3 m) has produced radiocarbon dates that may indicate a minimum age of 14,740 cal yrs B.P. for the lake (Reidy et al. unpublished data). As the scope of this chapter is to reconstruct the late Holocene history of the lake, only the upper 150 cm of the record is presented here.

Methods

In 2010 researchers from UC Berkeley and the U.S. Geological Survey recovered a 5 cm diameter core measuring 150 cm (SODA-2010-1) from the deepest part of Big Soda Lake (water depth ~62 m). A micro-Kullenberg gravity coring device equipped with a one-way valve and a 100 lb weight was deployed over the side of a Carolina Skiff. A battery-powered winch retrieved the cores from the lake bottom. The core was returned to the UC Berkeley Quaternary Paleoecology Laboratory for analyses in plastic polycarbonate liners, split lengthwise, photographed, and sampled for the various analyses.

Carbon and oxygen isotopic analyses on bulk carbonate was performed on 150 dried salt-free samples taken at 1 cm intervals. Samples were reacted with phosphoric acid at 90°C to release CO_2, using an autoprep device attached to a Micromass Optima mass spectrometer in the Earth and Planetary Science (EPS) Department, UC Berkeley. Analytical precisions were ±0.25 percent for $\delta^{18}O$ and ±0.15 percent for $\delta^{13}C$ based on replicate analyses of a calcite standard performed during runs. Replicate analyses of core samples was also performed. Isotopic results were reported relative to the PeeDee Belemite (PDB) standard.

Bulk sediment geochemistry data was developed for 150 samples from SODA-2010-1 on a Phillips PW 2400 X-Ray Fluorescence (XRF) scanner in the EPS Dept., UC Berkeley. Samples were prepared by combustion at 550˚C for one hour to remove water and organic material. Three grams of inorganic sediment per sample were ground to a powder, treated with a bonding agent, and compressed into pellets.

For brine shrimp (*Artemia franciscana)* cyst analysis, 3 cm^3 of wet sediment was washed and sieved using fine meshes (150μm and 300μm) and later concentrated using a COPAS Select large particle flow-cytometry machine in the Department of Biology at the University of Indiana.

Results and Discussion

Core Chronology

The chronology for the upper section (0 cm to 22 cm) of SODA-2010-1, which covers the last 150 years, was discussed in Chapter 2, and is not repeated here. The chronology for the lower section (23 cm-150 cm) was established with three radiocarbon dates on pine pollen concentrates (minimum of 10,000 grains) and two independently dated tephras. The radiocarbon dates were obtained by accelerator mass spectrometry at Lawrence Livermore National Laboratory and converted to calendar ages using the computer program CALIB 4.4 (Stuiver and Reimer, 1993). The median calibrated ages are the most probable values constrained by a 2-σ error range (Table 4.1). The age model was developed using linear interpolations between dates and an extrapolation to the base of the core. The age model indicates a change to higher sedimentation rates beginning around A.D. 1350.

The volcanic ashes were analyzed by David Wahl and Elmira Yan at the U.S. Geological Survey Tephrachronology Laboratory, Menlo Park. The uppermost tephra at 89 cm was identified as the most recent Mono 1 tephra, and the lower tephra at 117 cm as Mono 2 (Wood, 1977; Sieh and Bursik, 1986). The age model for Big Soda Lake 2010-1 core is shown in Figure 4.3.

Stable Isotopes, Sediment Chemistry and Brine Shrimp Cysts

As outlined in Chapter 3, I interpret the XRF results showing increases in SiO_2 (silicon), Al_2O_3 (aluminum), and K_2O (potassium) and reductions in Cl (chlorine) and Na_2O (sodium) to characterize rising water levels due to increased groundwater flow from ca. A.D. 1910 onwards. I therefore interpret the analogous increases in SiO_2, Al_2O_3 and K_2O, and decreases in Cl and Na_2O in the past as indicators of increased groundwater flow and therefore wetter conditions. Conversely, the decreases in SiO_2, Al_2O_3 and K_2O and increases in Cl and Na_2O to are assumed to represent periods of reduced groundwater flow and/or precipitation reflecting drier conditions.

The stable isotope ratios of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) of lake water are influenced by watershed hydrology and closely linked to local climatic conditions. The oxygen isotopic composition of the lake water is determined by the isotopic composition of the input waters from catchment runoff, precipitation falling directly into the lake, and groundwater flow and evaporative enrichment caused by preferential evaporation of the lighter $\delta^{16}O$ in water molecules. Water isotope ratios in saline lakes, especially in arid and semi-arid regions, where evaporation has a strong influence on the isotopic composition of lake water primarily reflect the water balance precipitation/evaporation (P/E) of the lake system (Gasse and Fontes, 1992; Gibson and Edwards, 2002). Variations in the $\delta^{13}C$ isotope ratios reflect mainly variations in biological productivity, nutrient supply, and dissolved carbonate within a lake basin, and can also provide valuable paleoclimatological information. Here at Big Soda Lake we infer lighter i.e. more negative values to represent wet periods and heavier isotopic values to reflect drier conditions.

The changing concentrations of brine shrimp cysts in the record provide evidence for changing salinity conditions in the lake, which are likely related to changes in groundwater flow and therefore climate. Brine shrimp are the dominant macrozooplankton in many hypersaline environments. Although physiologically able to adapt to salinities below seawater, they are seldom abundant when salinities fall below 45 g/L (Persoone and Sorgeloos, 1980). At salinities below 100 g/L, predators and competitors can establish and depress populations of brine shrimp (Persoone and Sorgeloos, 1980; Wurtsbaugh, 1992). In the Big Soda Lake record brine shrimp cysts only appear in record after A.D. 1650 and changing brine shrimp cyst concentrations reflect changing salinity conditions within the lake.

The results of stable isotope, XRF, and brine shrimp analyses are shown in Figures 4.4, 4.5 and 4.6**.** In order to facilitate discussion and comparison with other reported records the graphics are zoned using four time periods of paleoclimatic interest.

1. A Pre-Medieval Climatic Anomaly Period (A.D. 400-850)
2. The Medieval Climatic Anomaly (MCA) (A.D. 850-1400)
3. The Little Ice Age (LIA) (A.D. 1400-1850)
4. Modern Period (A.D. 1850-2010)

The use of the terms Medieval Climatic Anomaly and the Little Ice Age for what are assumed to be climatically distinctive time periods is widespread in the paleoclimatic literature. However, it should be emphasized that there is no consensus as to the timing of these "events", nor is there any indication that they involved the same kinds of climate change over large areas of the globe. In this chapter they are simply used as a chronological framework for discussion of results

Pre-Medieval Climatic Anomaly (A.D. 400-850)

The variation in the $\delta^{18}O$ and $\delta^{13}C$ values is shown in Figure 4.4. In the period A.D. 400-850, $\delta^{18}O$ ratios range from -7‰ to –3‰, while the $\delta^{13}C$ range exhibits a narrow range (~1.5 ‰). There are several short-term minor fluctuations towards more negative $\delta^{18}O$ isotopes at between A.D. 400-440, ca. A.D. 480-520, ca. A.D. 600-660, ca. A.D. 700-740, and between A.D. 820-850. The $\delta^{13}C$ values also exhibit minor fluctuations towards more negative values in this period and ranges from 1‰ to 2.5‰. There are minor peaks at A.D. 400, A.D. 600, and A.D. 700-740 with a larger peak from A.D. 780-820. Covariance is characteristic of closed lake basins (Talbot, 1990; Li and Ku, 1997), but may also occur in open lakes where stable water residence times allow co-evolution of $\delta^{18}O$ and $\delta^{13}C$ (McKenzie, 1993). Enrichment and covariance thus point to a more stable water residence time than before, with a lower flushing rate.

The variations of selected geochemical elements are shown in Figure 4.5. In this lowest section of the core there is significant short-term variation in SiO_2 with values ranging from 5 percent to 30 percent. There are prominent peaks at A.D. 500, A.D. 640, A.D. 760, and A.D. 840. Al_2O_3 (0.25 percent to 1.25 percent) and K_2O (0.25 percent to 1.25 percent) have similar patterns to SiO_2 but are the opposite to Na_2O (35 percent to 45 percent) and Cl (25 percent to 50 percent). There is a prominent peak in Cl from A.D. 660-720 and concomitant minima in SiO_2, Al_2O_3 and K_2O. Iron (Fe_2O_3) also exhibits minor variations (2.0 percent to 3.5 percent) in this period while calcium (CaO) remains unchanged at values around 2 percent.

The more or less regular variation in elemental concentrations and the minor fluctuations in the stable isotope ratios in this section of the core is evidence that climate changes during this time period were relatively minor and involved alternating wet/dry phases each lasting 20-60 years.

Medieval Climatic Anomaly (A.D. 850-1400)

During the MCA there are several broad shifts in elemental composition and stable isotope ratios, indicating significantly wet and dry conditions during this period. Beginning around A.D. 850, $\delta^{18}O$ ratios become less negative (-3.75‰ to -2.5‰) and the trend is maintained through to A.D. 1080. At A.D. 1080 the $\delta^{18}O$ ratios change dramatically towards more negative values, reaching as low as -7‰ at A.D. 1200. The $\delta^{18}O$ ratios remain negative until A.D. 1250, when they become less negative. From A.D. 1250-1400 $\delta^{18}O$ ratios remain around -2.5‰. The $\delta^{13}C$ record is relatively complacent between A.D 850-1060 but begins a shift to less positive values from ca. A.D. 1100. The $\delta^{13}C$ ratios remain less negative between A.D. 1100-1400 and reach a peak low of -0.5 ‰ at A.D. 1200.

Between A.D. 850-1140, SiO_2, Al_2O_3, and K_2O exhibit minor fluctuations but the overall trend shows an increase. Between A.D. 1140-1260, SiO_2, Al_2O_3, and K_2O all reach peak values before declining again between A.D. 1260-1400. Similarly, Cl and Na_2O display short-term fluctuations between A.D. 850-1140. From A.D. 1160-1260 Cl decreases from 45 to 30 percent while Na_2O decreases from 35 percent to 20 percent. After A.D. 1260, Cl and Na_2O increase again towards A.D. 1400. During this period we see a noticeable increase in CaO for the first time. CaO increases from background concentrations of around 3 percent to 11.25 percent from A.D. 1140-1260.

Based on the changes in elemental concentrations and isotopic ratios during the period A.D. 850-1400 I sub-divide the period into three sections. The period A.D. 850-1150 we interpret to represent a period of drier conditions. Then there is a prolonged wet period from A.D. 1150-1260, based on the large negative excursion in the oxygen and carbon isotope ratios and the increase in CaO. The CaO peak is likely the result of increased groundwater flow into the lake at this time, similar to the effect that the 20th century freshwater water inputs had on lake sediment chemistry outlined in Chapter 3 and displayed again in Figure 4.6. Thirdly, there is a return to drier conditions again from A.D. 1260-1400.

Little Ice Age (A.D. 1400-1850)

The earlier part of the Little Ice Age (A.D. 1400-1850) is marked by minor fluctuations in the both $\delta^{18}O$ and $\delta^{13}C$ values. The early part of the LIA from A.D. 1400-1700 is relatively dry although there is evidence for two fairly wet phases at A.D. 1400-1440 and from A.D. 1540-1600. There are at least two relatively dry phases in this section of the core based on less negative $\delta^{18}O$ values between A.D. 1440-1540 and A.D. 1580-1680. After A.D. 1700, the $\delta^{18}O$ shifts to more negative values (-5 ‰), and we see a return to wetter conditions especially for the period A.D. 1750-1800.

Brine shrimp cysts first appear in the core around A.D. 1650. And provide additional evidence for changing salinity conditions in the lake, more likely related to changes in groundwater flow. Initially the brine shrimp maintained a relatively steady population. However, between A.D. 1725 and A.D. 1800 they decline. The drop in brine shrimp cyst concentrations parallel shifts towards more negative lighter isotopic values of both carbon and oxygen, declines in Cl and Na_2O, and increases in SiO_2, Al_2O_3 and K_2O (Figure 4.6), providing further evidence for a freshening of the lake due to wetter conditions during the latter part of the LIA.

Modern Period (A.D. 1850-2010)

As outlined in Chapter 3, Big Soda Lake was affected by human activities through the development of a commercial soda processing enterprise on the lake shore in A.D. 1875 and the increase in lake level resulting from the development of irrigation farming in the area beginning in A.D. 1905. These anthropogenically-induced changes are clearly recorded in sediments by a sharp reduction in brine shrimp cyst concentrations, shifts to more negative isotopic values for both $\delta^{13}C$ and $\delta^{18}O$, increases in SiO_2, Al_2O_3, and K_2O, and concomitant reductions in Cl and Na_2O (Figure 4.6)

What is noteworthy to point out is that although lake level stabilized around A.D 1930 following irrigation inputs, we do not see a synchronous change in the stable isotope ratios reflecting this change in the lake's hydrology. The $\delta^{13}C$ values shift around A.D. 1950, while the $\delta^{18}O$ values in the core only begin to shift to more negative values beginning around A.D. 1970.

Comparison to Other Paleoclimate Records in the Great Basin

There are several late Holocene paleoclimatic records now available for the Great Basin and comparing the Big Soda Lake record, especially the $\delta^{18}O$ curve, to these yields interesting results. Although researchers employ different proxy records from different parts of the Great Basin, it allows us to examine the synchronicity of the inferred climate changes observed.

Reconstructed Late Holocene Lake Levels at Mono Lake

Stine (1990) developed a detailed late Holocene lake level curve for Mono Lake based on geomorphic, stratigraphic, and historical evidence. The results of his study indicate that lake has fluctuated over a vertical range of 40 m in response to changes in inflow and evaporation during past 3,800 years. During the past 1200 years there has been a sequence of centennial scale large-scale fluctuations, with as many as five transgressions (high stands), and five regressions (low lake levels).

The names and timing of the five transgressions are: the Post Office (ca. A.D. 1100), Rush Delta (A.D. 1270-1345), Danberg Beach (A.D. 1400-1485), Clover Ranch (A.D. 1575-1650), and the historic high stand between A.D. 1857-1910. The five regressions are: Lee Vining Delta (A.D. 700-1100), Simis Ranch (A.D. 1100-1270), 10-Mile Road (A.D. 1345-1400), Navy Beach (A.D. 1485-1570) and the Pre-Historic low-stand (A.D. 1650-1857).

The Big Soda Lake δ^{18}O record and the Mono Lake reconstructed lake level curve are very similar although the former lags the latter by 50 or more years (Figure 4.7). The reconstructed high stands at Mono Lake match fairly well with more negative δ^{18}O values at Big Soda Lake. The period A.D. 400-850 at Big Soda Lake is marked by a narrow range of fluctuating negative δ^{18}O values, while the lake levels at Mono Lake are stable, low and fluctuate in a narrow range (ca. 1945-1952 m).

It should be pointed out that some of the differences between Mono Lake and Big Soda Lake records could be due to uncertainties in dating or to lag affects between hydrological changes and the δ^{18}O values of the lake sediment. For example, measured δ^{18}O values at Big Soda during the twentieth century, (a time when the lake level rose by 18 m) indicate that although isotopically lighter freshwater inputs began entering the lake via groundwater flow from A.D. 1905 onwards, a shift to more negative δ^{18}O values is not indicated in the sediments until about A.D. 1970.

The Lee Vining Delta recession between A.D. 700-1100 matches fairly well with the less negative δ^{18}O values at Big Soda Lake. During the MCA, the lake evidence indicates two extended dry periods (or "mega-droughts" according to Stine (1994) occurring between A.D. 950-1100 and A.D. 1200-A.D. 1350. While, we do see a shift to less negative δ^{18}O values at Big Soda Lake during these periods, it is certainly not a pronounced shift indicative of century long droughts. Between these MCA two dry periods, the Post Office transgression provides strong evidence of a wet period ca. A.D. 1100-1200 in the Mono Basin. The Big Soda δ^{18}O also provides evidence for a wet period, however the lag in response time is centered around A.D. 1150-1260.

Both the Mono Lake and Big Soda Lake records show the same alternating sequence of wet and dry periods during the last 500 years. Evidence for three high-stands in the LIA period: the Rush Delta (A.D. 1270-1345); Danberg Beach (A.D. 1400-1485), and the Clover Ranch (A.D. 1575-1650) are all very similar to peaks in the Big Soda lake δ^{18}O values. Similarly, Mono Lake regressions: 10-Mile Road (A.D. 1345-1400), Navy Beach (A.D. 1485-1570), and the Pre-Historic low stand (A.D. 1650-1857) correspond remarkably well with less negative δ^{18}O values in the Big Soda Lake record.

Walker Lake

Yuan et al. (2006) in their analyses of stable isotopes in cores from Walker Lake found evidence for persistent wet conditions between 450 B.C.-A.D. 950 and drier climate during the MCA (A.D. 950-1350). The Big Soda Lake δ^{18}O record and the Walker Lake δ^{18}O record are generally similar (Figure 4.8). Several wet periods at Big Soda Lake match relatively closely with wet intervals at Walker Lake ca. A.D. 620, A.D. 740, A.D. 920, A.D. 1150-1200, and A.D. 1420-1500 and A.D. 1175. Dry periods match relatively closely between A.D. 680-720, A.D. 1100-1150, and A.D. 1650-1750.

However not all of the lake-level fluctuations at Walker Lake are interpreted to be climatic. Diversion of the Walker River to the Carson Sink, has long been suspected as a complicating factor (Benson and Thompson, 1987; King, 1993; Adams 2003; 2007), and recent studies suggest that at least part of the flow into the Walker River was diverted into the Carson Sink during the periods A.D. 450-950, and A.D. 1450-1650 (Adams, 2007). The close match with the Walker Lake hydrological record is not surprising, because water flowing into the Carson Sink will raise the water table around Big Soda Lake and would provide fresh water to the lake.

Pyramid Lake

The Pyramid Lake $\delta^{18}O$ curve developed by Benson et al., (2002) for the latter part of the late Holocene is also very similar to Big Soda Lake record (Figure 4.8). Several of the peaks and troughs both the wet and periods are slightly offset but there is strong overall agreement between the records. During the period, A.D. 400-950, several wet phases can be matched between the sites. Close correlations are evident between A.D. 500-540, A.D. 700-740, A.D. 840-880. During the MCA, both sites broadly display similar $\delta^{18}O$ curves, with less negative values between A.D. 900-1000, and from 1250-1300, corresponding to dry phases. The pronounced wet phase between these dry periods at Pyramid Lake is estimated to be A.D. 1075-1225, again overlapping closely in time with the Big Soda wet phase (A.D. 1150-1250). During the LIA several features of the curves can be matched with wet phases positively matched at ca. A.D. 1450, A.D 1550, and between A.D. 1650-1800.

The chronological differences between the two records maybe partly explained by uncertainties in dating both records, and the differences in the $\delta^{18}O$ curves maybe explained by the difficulties in interpreting exactly how fluctuations in $\delta^{18}O$ content correspond to changes in lake volume. The salinity, size and volume of Pyramid Lake compared to Big Soda Lake are much different. Pyramid Lake has a current depth of 109 m, and has a much larger watershed with more freshwater surface inflow than Big Soda Lake, which is predominantly fed by groundwater.

Late Holocene Lakes in the Carson Sink

Morrison (1964) postulated on the basis of a series of concentric shorelines that shallow lakes formed in the Carson Desert during the late Holocene. The lakes reached elevations between 1198 m and 1204 m. Adams (2003) confirmed the presence of at least two of these late Holocene lakes at Wildcat scarp (1198 m) and Salt Wells beach barrier (1204 m) by radiocarbon dating of the associated shoreline features outlined by Morrison (1964). The dates for the high stands spanned the periods ca. A.D. 450-650 at Wildcat scarp and A.D. 1050-1400 at the Salt Wells beach barrier site. The Big Soda Lake $\delta^{18}O$ curve provides additional evidence to support these findings, as both periods correspond to relatively wet phases, especially the period at A.D. 1150-1260.

Conclusion

This paper presents the results of analyses of sediment geochemistry, brine shrimp cysts concentrations, and stable isotopes from a 150 cm sediment core recovered from Big Soda Lake, near Fallon, Nevada. The core represents approximately the past 1600 years. The results indicate several changes in climate during the period of time investigated. During the pre-MCA (A.D. 400-850) period there were several alternating wet and dry phases each lasting 20-60 years. Later in the MCA period (A.D. 850-A.D. 1400) we observe two relatively dry phases between A.D. 900-1150 and A.D. 1260-1400. These dry phases are separated by a pronounced wet phase that lasted for at least a century (A.D. 1150-1260). The transition to the LIA (A.D. 1400-1850) and the early part of the period (A.D. 1400-1700) is relatively dry, although there is evidence for two fairly wet phases at A.D. 1400-1440 and from A.D. 1540-1600. There are at least two dry periods between A.D. 1440-1540 and A.D. 1580-1680. After A.D. 1700 we see return to wetter conditions especially for the period A.D. 1750-1800. During the LIA we first identify the presence of brine shrimp cysts in the sediments. The changing concentrations of their abundance provides supportive evidence of wetter conditions during the latter half of the LIA when the brine shrimp cyst concentrations were reduced in response to freshening of the lake.

The Big Soda Lake record indicates that climate oscillations on both the decadal and centennial scales have occurred during the past 1600 years and that these changes are in broad agreement with several other paleoclimatic records that have been developed in the western Great Basin, suggesting that these fluctuations in climate were at least regional in scale.

References

Adams, K.D. (2007). Late Holocene sedimentary environments and lake-level fluctuations at Walker Lake, Nevada, USA. *Geological Society of America Bulletin*, 119(1-2), 126-139.

Adams, K.D. (2003). Age and paleoclimatic significance of late Holocene lakes in the Carson Sink, NV, USA. *Quaternary Research*, *60*(3), 294-306.

Benson, L.V. (1978). Fluctuation in the level of pluvial Lake Lahontan during the last 40,000 years. *Quaternary Research*, *9*(3), 300-318.

Benson, L.V., Berry, M.S., Jolie, E.A., Spangler, J.D., Stahle, D.W. and Hattori, E.M. (2007). Possible impacts of early-llth-, middle-12th-, and late-13th-century droughts on western Native Americans and the Mississippian Cahokians. *Quaternary Science Reviews,* 26, 336-350.

Benson, L., Kashgarian, M., Rye, R., Lund, S., Paillet, F., Smoot, J., Kester, C., Mensing, S., Meko, D. and Lindstrom, S. (2002). Holocene multidecadal and multicentennial droughts affecting Northern California and Nevada. *Quaternary Science Reviews,* 21, 659-682.

Benson, L.V., and Thompson, R. S. (1987). Lake-level variation in the Lahontan Basin for the past 50,000 years. *Quaternary Research,* 28, 69-85.

Bradbury, J.P., Forester, R. M. and Thompson R.S. (1989). Late Quaternary paleolimnology of Walker Lake, Nevada. *Journal of Paleolimnology,* 1, 249-267.

Bradley, R. (2000). 1000 years of climate change. *Science*, *288*(5470), 1353-1355.

Brauer, A., Endres, C., Günter, C., Litt, T., Stebich, M., and Negendank, J. F. (1999). High resolution sediment and vegetation responses to Younger Dryas climate change in varved lake sediments from Meerfelder Maar, Germany. *Quaternary Science Reviews*, *18*(3), 321-329.

Cayan, D.R., Redmond, K. T., and Riddle, L. G. (1999). ENSO and Hydrologic Extremes in the Western United States. *Journal of Climate*, *12*(9), 2881-2893.

Cobb, K.M., Charles, C. D., Cheng, H., and Edwards, R. L. (2003). El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature*, *424*(6946), 271-276.

Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M. and Stahle, D.W. (2004). Long-term aridity changes in the western United States. *Science*, 306, 1015-1018.

Park, J., Byrne, R., Böhnel, H., Garza, R. M., and Conserva, M. (2010). Holocene climate change and human impact, central Mexico: a record based on maar lake pollen and sediment chemistry. *Quaternary Science Reviews*, *29*(5), 618-632.

Crowley, T. J. (2000). Causes of climate change over the past 1000 years. *Science*, *289*(5477), 270-277.

Davis, O.K. (1999). Pollen Analysis of a Late-Glacial and Holocene Sediment Core from Mono Lake, Mono County, California. *Quaternary Research*, 52, (2), 243-249

Enzel, Y., Cayan, D. R., Anderson, R. Y., and Wells, S. G. (1989). Atmospheric circulation during Holocene lake stands in the Mojave Desert: evidence of regional climate change. *Nature*, *341*(6237), 44-47.

Gasse, F., and Fontes, J-C. 1(989). Palaeoenvironments and palaeohydrology of a tropical closed lake (Lake Asal, Djibouti) since 10,000 yr BP. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 9, 67-102.

Gibson, J. J., and Edwards, T. W. D. (2002). Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lakes in northern Canada. *Global Biogeochemical Cycles*, *16*(2), 10-1.

Graumlich, L. J. (1993). A 1000-year record of temperature and precipitation in the Sierra Nevada. *Quaternary Research*, *39*(2), 249-255.

Grayson, D. K. (2011). *The Great Basin: a Natural Prehistory*. University of California Press.

Hughes, M. K., and Funkhouser, G. (1998). Extremes of moisture availability reconstructed from tree rings for recent millennia in the Great Basin of western North America. In *The Impacts of Climate Variability on Forests* (pp. 99-107). Springer Berlin Heidelberg.

Hughes, M. K., and Funkhouser, G. (2003). Frequency-dependent climate signal in upper and lower forest border tree rings in the mountains of the Great Basin. In *Climate Variability and Change in High Elevation Regions: Past, Present and Future* (pp. 233-244). Springer Netherlands.

Jones, P. D., and Mann, M. E. (2004). Climate over past millennia. *Reviews of Geophysics*, 42(2), RG2002.

Jones, P. D., Osborn, T. J., and Briffa, K. R. (2001). The evolution of climate over the last millennium. *Science*, *292*(5517), 662-667.

King, G. Q. (1993). Late Quaternary history of the lower Walker River and its implications for the Lahontan paleolake system. *Physical Geography*, *14*(1), 81-96.

Kleppe, J. A., Brothers, D. S., Kent, G. M., Biondi, F., Jensen, S., and Driscoll, N. W. (2011). Duration and severity of Medieval drought in the Lake Tahoe Basin. *Quaternary Science Reviews*, *30*(23), 3269-3279.

Kleppe, J. A. (2005). A study of ancient trees rooted 36.5 m (120') below the surface level of Fallen Leaf Lake, California. *Journal of the Nevada Water Resources Association*, 29.

Leavitt, S. W. (1994). Major wet interval in white mountains medieval warm period evidenced in δ^{13}C of bristlecone pine tree rings. *Climatic Change*, *26*(2-3), 299-307.

Li, H. C., Bischoff, J. L., Ku, T. L., Lund, S. P., and Stott, L. D. (2000). Climate variability in East-Central California during the past 1000 years reflected by high-resolution geochemical and isotopic records from Owens Lake sediments. *Quaternary Research*, *54*(2), 189-197.

Li, H.-C. and Ku, T.-L. (1997). δ^{13}C-δ^{18}O covariance as a paleohydrological indicator for closed-basin lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 133, 69-80.

Lindström, S. (1990). Submerged tree stumps as indicators of mid-Holocene aridity in the Lake Tahoe Basin. *Journal of California and Great Basin Anthropology*, *12*(2), 146-157.

Mann, M. E., and Jones, P. D. (2003). Global surface temperatures over the past two millennia. *Geophysical Research Letters*, *30*(15).

Mann, M.E., Bradley, R.S. and Hughes, M.K. (1999). Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters*, 26, 759-762.

Meko, D. M., Therrell, M. D., Baisan, C. H., and Hughes, M. K. (2001). Sacramento river flow reconstructed to A.D. 869 from tree rings. *JAWRA Journal of the American Water Resources Association*, 37(4), 1029-1039.

Mensing, S.A. (2001). Late-glacial and early Holocene vegetation and climate change near Owens Lake, eastern California. *Quaternary Research*, *55*(1), 57-65.

Mensing, S.A., Benson, L.V., Kashgarian, M. and Lund, S. (2004). A Holocene pollen record of persistent droughts from Pyramid Lake, Nevada, USA. *Quaternary Research*, 62, 29-38.

Mifflin, M.D., and Wheat, M.M. (1979). *Pluvial lakes and estimated pluvial climates of Nevada,* Bulletin 94. Nevada Bureau of Mines and Geology, Reno, NV.

Milne, W. (1987). A *Comparison of Reconstructed Lake-Level Records since the mid-1880's of Some Great Basin Lakes.* Unpublished M.S. thesis, Colorado School of Mines.

Morrison, R. B. (1964). *Lake Lahontan: Geology of the Southern Carson Desert. Professional Paper 401*. United States Geological Survey.

McKenzie, J.A. (1993). Pluvial conditions in the eastern Sahara following the penultimatedeglaciation: implications for changes in atmospheric circulation patterns with global warming. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 103, 95-105.

Olmsted, F.H., Glancy, P.A., Harrill, J.R., Rush, F.E, and VanDenburgh, A.S. (1975). *Preliminary Hydrogeologic appraisal of selected Hydrothermal systems in northern and central Nevada*. U.S. Geol. Surv. Open-file Report, 75-56.

Park, J., Byrne, R., Böhnel, H., Garza, R. M., and Conserva, M. (2010). Holocene climate change and human impact, central Mexico: a record based on maar lake pollen and sediment chemistry. *Quaternary Science Reviews*, *29*(5), 618-632.

Persoone, G. and Sorgeloos, P. (1980). General aspects of the ecology and biogeography of *Artemia*. In Persoone, G.P. Sorgeloos, O. Roels and E. Jaspers (eds). *The Brine Shrimp Artemia,* 3. Ecology, Culturing. Use in Aquaculture. 3-23. Wetteren: Universa Press.

Redmond, K. T., and Koch, R. W. (1991). Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. *Water Resources Research*, *27*(9), 2381-2399.

Russell, I. C. (1885). *Geological history of Lake Lahontan: a Quaternary lake of northwestern Nevada* (Vol. 11). U.S. Geological Survey, 288pp.

Sieh, K., and Bursik, M. (1986). Most recent eruption of the Mono Craters, eastern central California. *Journal of Geophysical Research*, *91*(B12), 12539-12.

Stine, S. (1990). Late holocene fluctuations of Mono Lake, eastern California. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *78*(3), 333-381.

Stine, S. (1994). Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature*, 369, 546-549.

Strachan, S., Biondi, F., and Leising, J. (2011). 550-Year Reconstruction of Streamflow Variability in Spring Valley, Nevada. *Journal of Water Resources Planning and Management*, *138*(4), 326-333.

Stuiver, M. and Reimer, P. J. (1993). Extended ^{14}C data base and revised CALIB 3.0 '4C age calibration program. In Stuiver, M., Long, A. and Kra, R. S. (eds.) *Radiocarbon*, 35(1), 215-230.

Talbot, M.R (1990). A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. *Chemical Geology (Isvotope Geoscience Section)* 80, 261-79.

Wood, S.H. (1977). Distribution, correlation, and radiocarbon dating of late Holocene tephra, Mono and Inyo craters, eastern California. *Geological Society American Bulletin*, 88, 89–95.

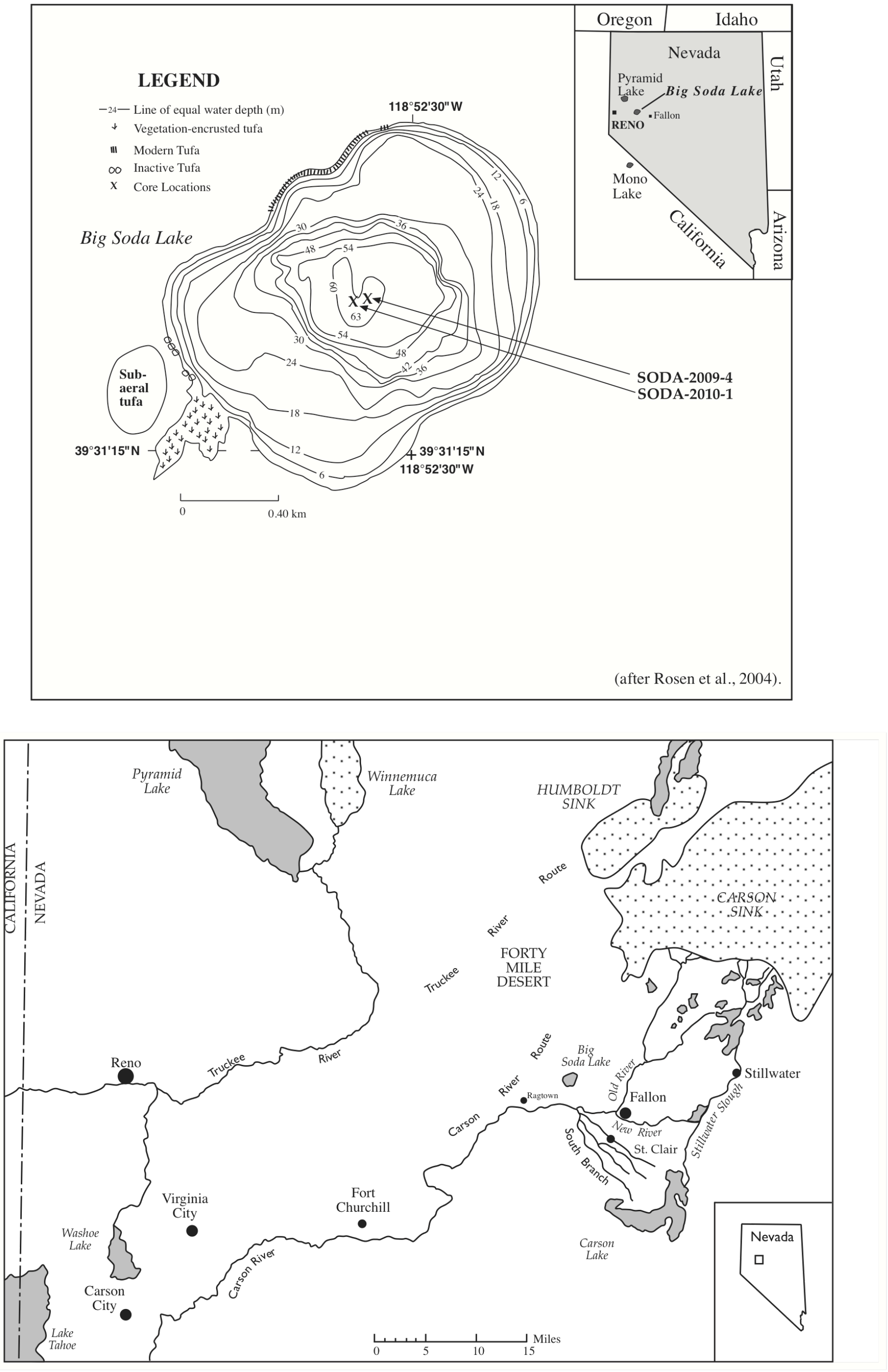
Woodhouse, C.A. (2004). A paleo perspective on hydroclimatic variability in the western United States. Aquatic Sciences, 66, 346-356.

Wurtsbaugh, W.A. (1992). Food web modification by an invertebrate predator in the Great Salt Lake (U.S.A.). *Oecologia* (89), 168-175.

Yuan, F., Linsley, B. K., Howe, S. S., Lund, S. P., and McGeehin, J. P. (2006). Late Holocene lake-level fluctuations in Walker Lake, Nevada, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *240*(3), 497-507.

Yuan, F., Linsley, B. K., Lund, S. P., and McGeehin, J. P. (2004). A 1200 year record of hydrologic variability in the Sierra Nevada from sediments in Walker Lake, Nevada. *Geochemistry, Geophysics, Geosystems*, *5*(3).

Zolitschka, B. (1996). Image analysis and microscopic investigation of annually laminated lake sediments from Fayetteville Green Lake (NY, USA) Lake C2 (NWT, Canada) and Holzmaar (Germany): a comparison. Geological Society, London, Special Publications, 116(1), 49-55.



(after Rosen et al., 2004).

Figure 4.1. Location of Big Soda Lake, Churchill County, Nevada. Core recovery locations for SODA-2009-4 and SODA-2010-1 are also indicated.

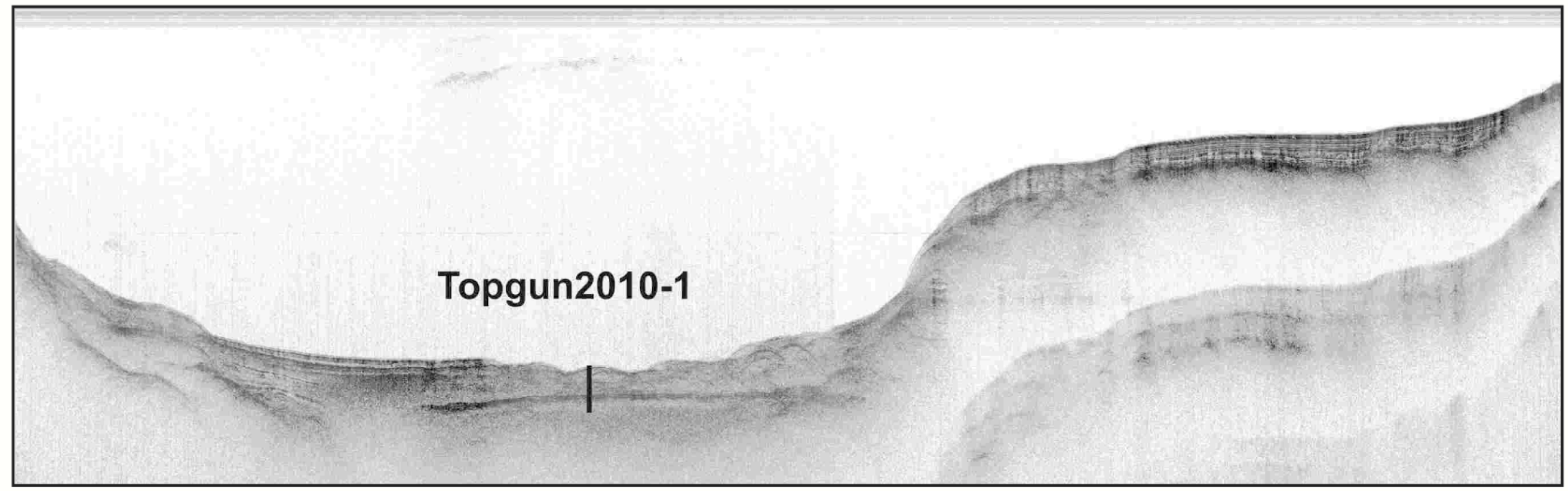


Figure 4.2 Seismic profile (Line 5) of Big Soda Lake, showing the relatively flat bottom.

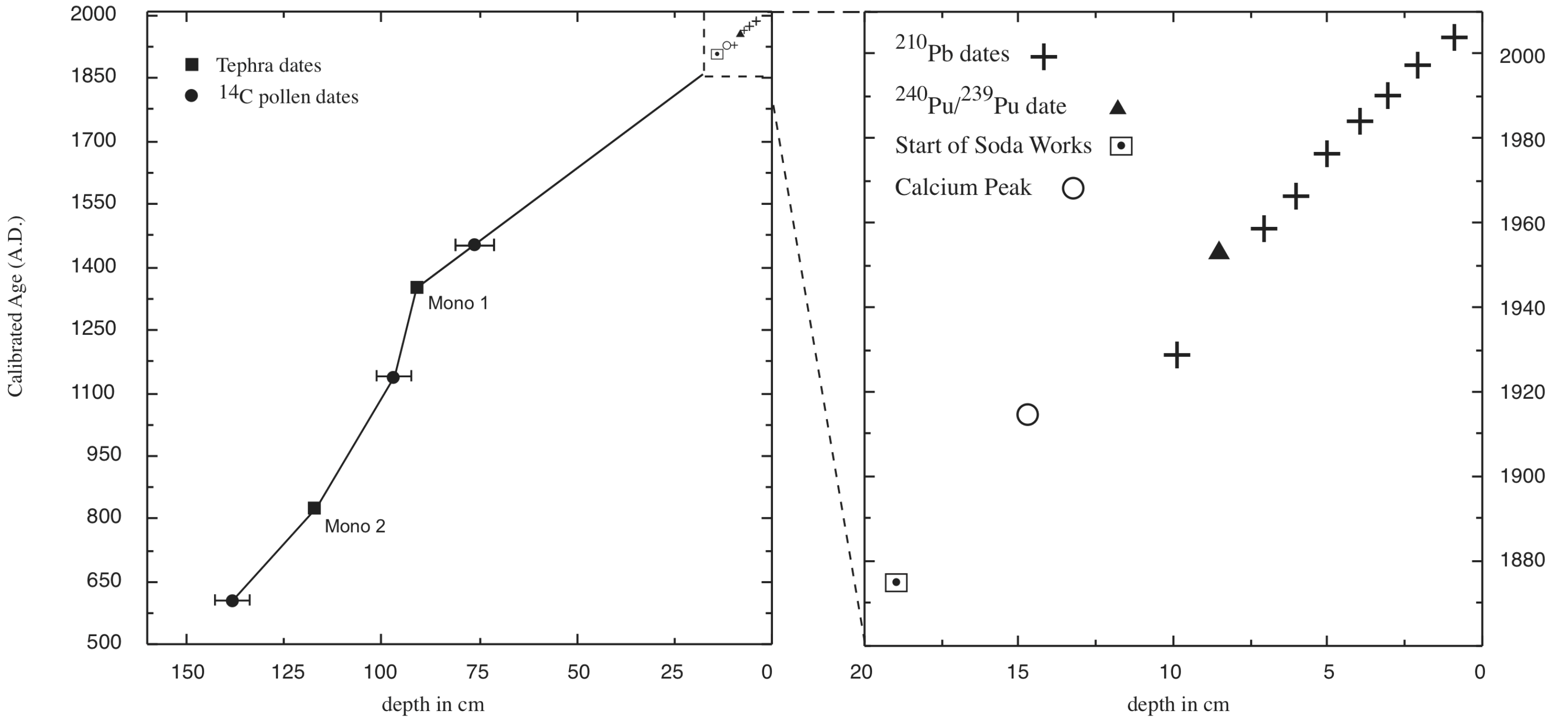


Figure 4.3 Big Soda Lake age-depth profile. Radiocarbon ages, tephras, and ^{240}Pu /^{239}Pu age estimates are all from SODA-2010-1. Lead-210 age estimates are from SODA-2009-4.

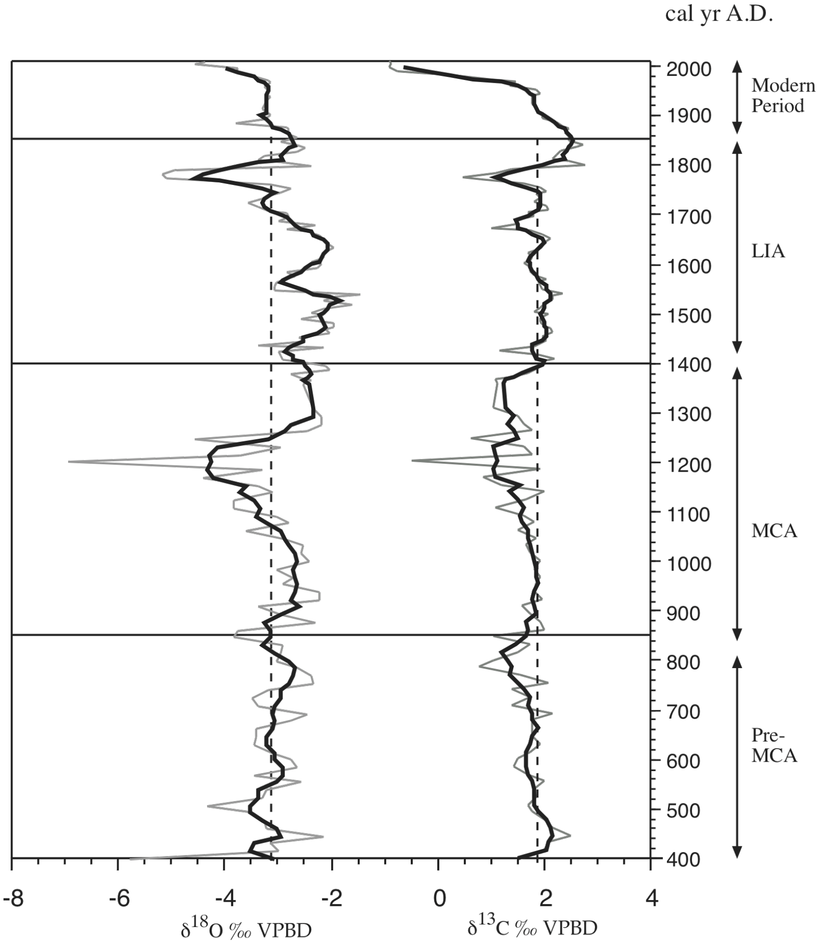


Figure 4.4 δ^{18}O and δ^{13}C results from SODA-2010-1 for the last 1600 yrs. Black soli lines are 5 point running means. Dashed lines through the isotope curves is the mean for each data set. MCA=Medieval Climatic Anomaly, LIA=Little Ice Age.

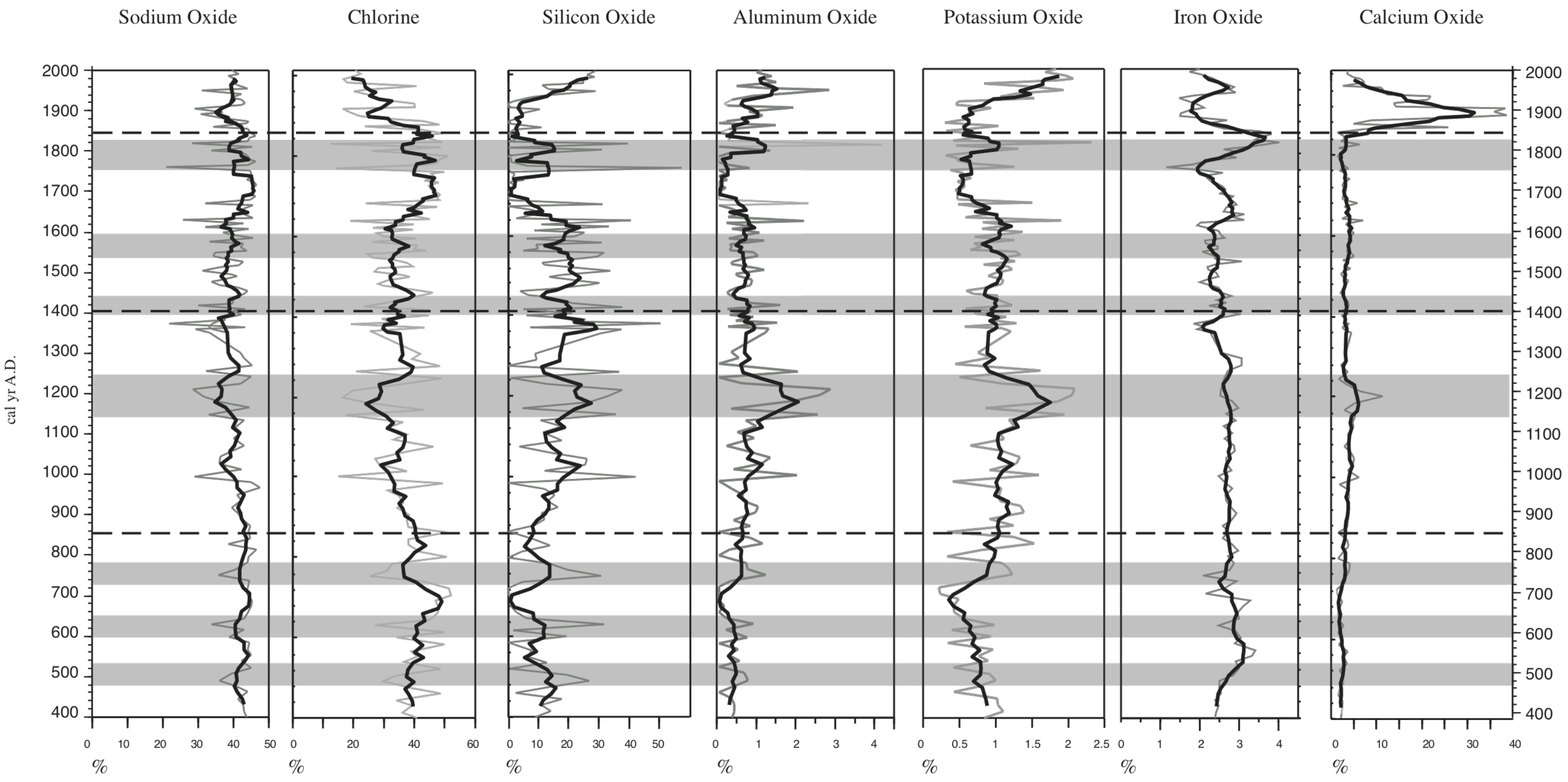


Figure 4.5. Selected XRF data from SODA 2010-1 (solid black line is 5 point running mean). The grey shading indicates assumed wetter phases.

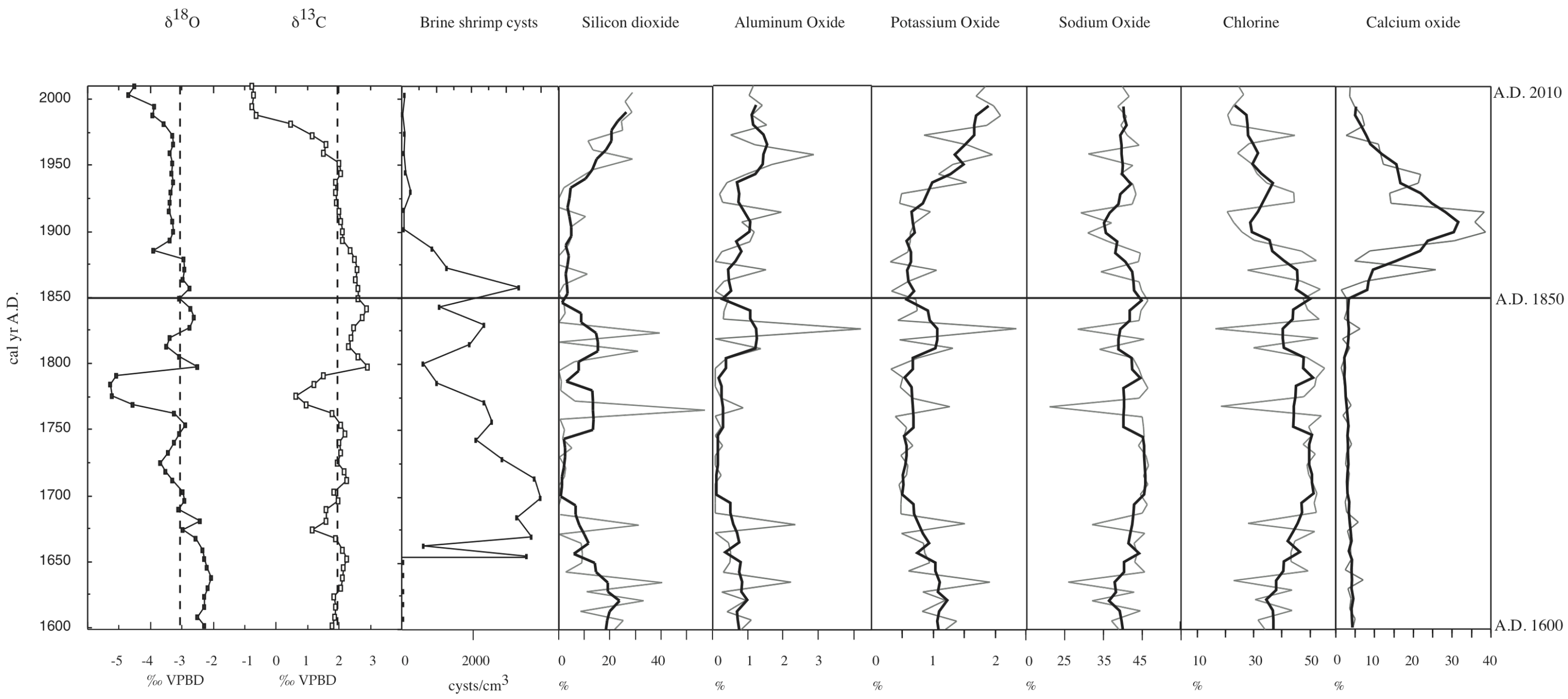


Figure 4.6 Stable isotope, brine shrimp cyst, and selected XRF data for the period A.D. 1600-2010.

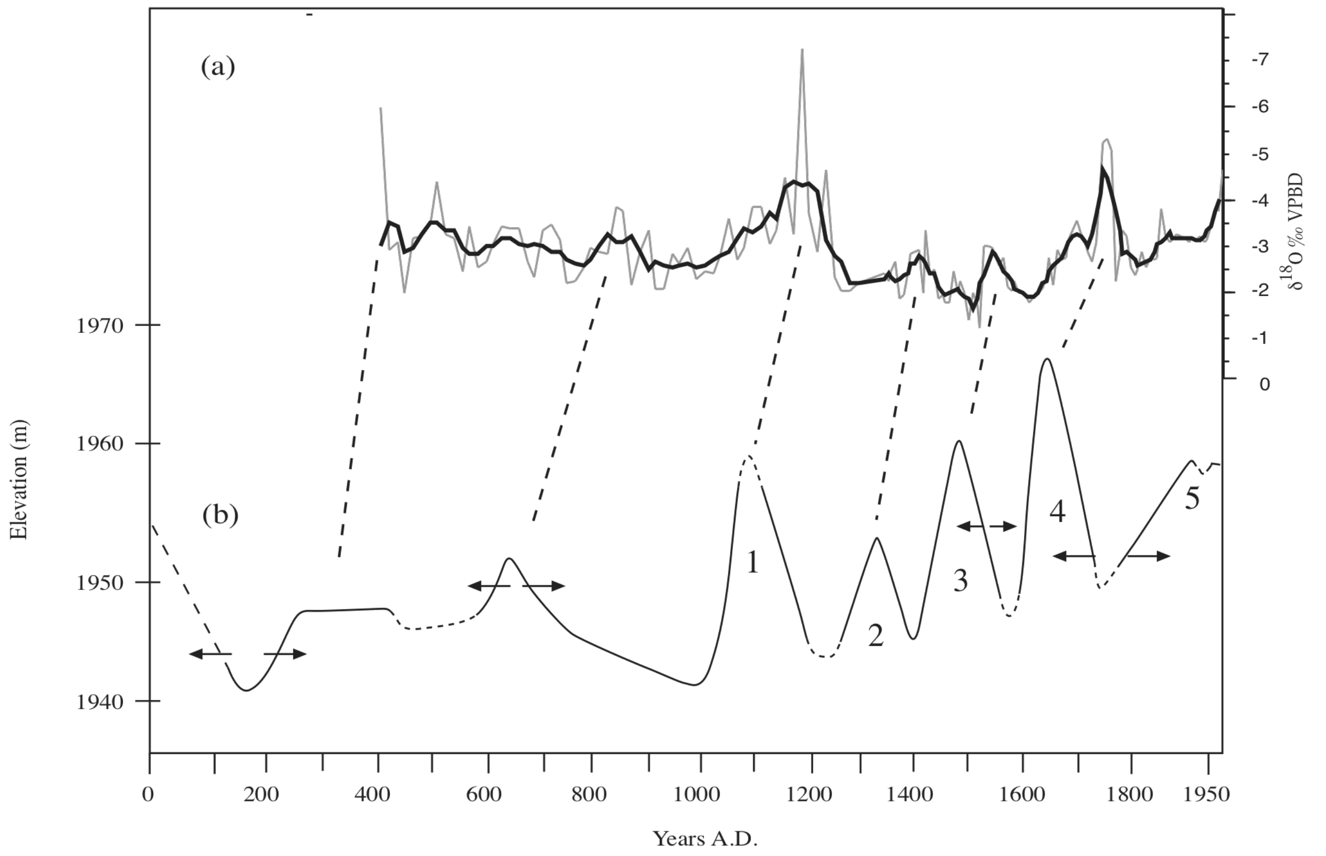


Figure 4.7 Comparison between (a) the Big Soda Lake δ^{18}O record and (b) the fluctuations of Mono Lake indentified by Stine (1990). Dashed lines denote possible connections between more negative δ^{18}O and Mono Lake highstands (Stine, 1990).

Mono Lake Highstands: 1. Post Office (ca. A.D. 1100), 2. Rush Delta (A.D.1270-1345), 3. Danberg Beach (A.D. 1400-1485), 4. Clover Ranch (A.D. 1575-1650). 5. Historic Highstand (A.D. 1857-1910).

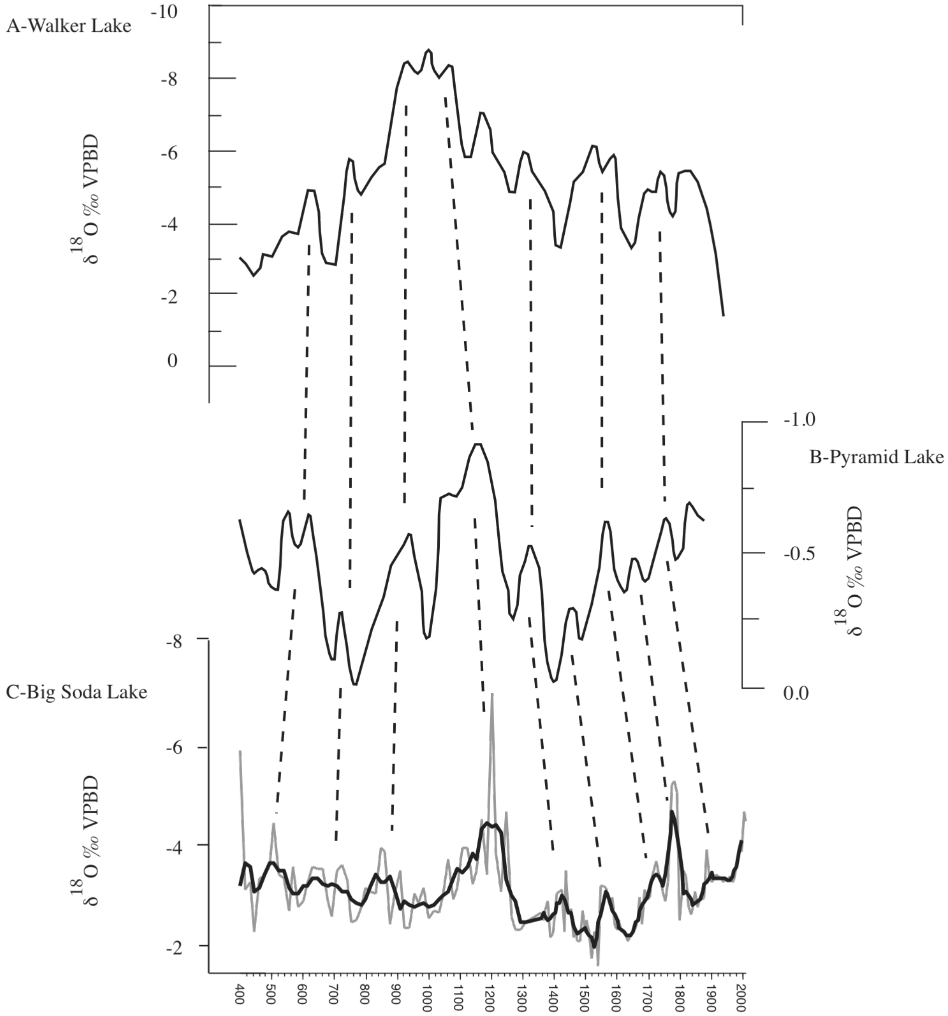


Figure 4.8 (A) Walker Lake δ^{18}O (Yuan et al., 2006). (B) Pyramid Lake δ^{18}O (Benson et al., 2002). (C) Big Soda Lake δ^{18}O (this study). Note that the vertical scales for the three records are not the same. Dashed lines indicate the probable connections between the three records.

Radiocarbon Dates and Volcanic Ashes from Big Soda Lake (SODA-2010-1).

Sediment Depth (cm)	Material Dated	Lab Number	Radiocarbon age (^{14}C years BP)	Error (± year)	Median calibrated age (cal years A.D.)	Calibrated age (cal years B.P.)
77	pollen	Cams-152524	440	40	1450	n/a
89	tephra	n/a	n/a	n/a	1345[1]	560 ± 20
94	pollen	Cams-152525	880	60	1145	n/a
117	tephra	n/a	n/a	n/a	830[2]	1200 ± 40
138	pollen	Cams-152526	1435	50	605	n/a

[1] Sieh and Bursik, (1986).

[2] Wood, (1977).

Table 4.1

CHAPTER 5

Summary

This dissertation has focused on the evidence of natural and human-induced environmental change preserved in lake sediments from California and Nevada. The results of the paleoenvironmental work performed here provides a perspective on what happened in both areas prior to and after the arrival of the Spanish to the San Francisco area and Anglo American settlers to north-western Nevada.

In Chapter 1, I outline the tools used to reconstruct the history of environmental change at both Mountain Lake and Big Soda Lake. A multi-proxy approach was used to develop the data including: pollen analysis, measurement of stable isotopes of carbon and oxygen, measurement of brine shrimp cyst concentrations, X-ray fluorescence, X-ray diffraction, digital photography, magnetic susceptibility, loss on ignition, lead-210 dating, plutonium 240/239 ratios, radiocarbon and tephra dating.

In Chapter 2, paleolimnological evidence is presented from Mountain Lake on the history of local land use changes since the arrival of the Spanish to the area in 1776. The results reconstruct the history of local land use changes during the early European period and also track the history of lead and zinc contamination during the past 60 years. The contamination problem arose when State Highway 1 was constructed by Caltrans adjacent the lake in 1938. Runoff from the roadway was allowed to drain into Mountain Lake via several culverts. As a result, contaminants including lead and zinc became concentrated in the lake causing environmental contamination of the lake sediments.

In Chapter 3, the results are presented of a high resolution XRF, stable isotope and brine shrimp cyst analyses on two short cores from Big Soda Lake. The combined evidence details a clear contrast between pre-Anglo American and post-Anglo American settlement of the area.

Chapter 4 presents a climate change record developed from the analyses of stable isotopes of oxygen and carbon, sediment chemistry, and the changing concentrations of brine shrimp cysts. The early part of the record from A.D. 400-850 is period marked by a fluctuating climate, with alternating wet/dry phases each lasting several decades each (40-60 years). During the period known as Medieval Climate Anomaly (MCA)(A.D. 850-1400), we observe at least two relatively dry periods from A.D. 850-1150 and A.D. 1260-1400. Between the two dry phases, there is a pronounced wet period from A.D. 1150-1260. This wet period matches fairly well with evidence presented in other paleoenvironmental studies in the western Great Basin. During the Little Ice Age (LIA), the evidence indicates that is was not always colder and/or wetter, but that it was in fact drier and perhaps warmer from A.D. 1400-1700 than it had been in the previous millennium. Pronounced dry phases were observed around A.D. 1400, A.D. 1500 and A.D. 1650. The wettest period during the LIA came between A.D. 1750-1800.

Around A.D. 1650, we first identify the presence of brine shrimp cysts in the sediments. The changing concentrations of their abundance provides supportive evidence of wetter conditions during the latter half of the LIA when brine shrimp cyst concentrations declined between A.D. 1750-1800

In brief, the combined analyses of the Mountain Lake and Big Soda Lake records have provided a multifaceted perspective on the history of late Holocene environmental change in both areas. Although, the sites are geographically almost 300 miles apart, the records are complementary in many ways, especially with respect to human impacts since the period of time that Spanish and Anglo American settlers moved into these areas.

The results of this dissertation have made a number of important contributions to the public and the wider scientific community. The work performed as part of the paleoenvironmental reconstruction at Mountain Lake encouraged the Presidio Trust to take a closer look at the near surface sediments of the lake, and to examine them more carefully for contaminants prior to the proposed dredging. When it was confirmed that was indeed a major environmental problem at the lake, all planned work to improve and enhance the area around the lake was postponed indefinitely. While this upset some residents in the neighborhood, it allowed the Presidio Trust time to address the environmental clean-up of the lake as an integral part of overall improvement project. It also allowed time for the Presidio Trust to secure the necessary funds for the expensive clean-up of the lake, which is now underway.

The preservation of the rich natural archive of environmental change on the lake bottom was also achieved as part of this dissertation. Multiple lake cores were recovered prior to the start of the dredging, and the cores are stored at LacCore-the National Lacustrine Depository at the University of Minneapolis, Minnesota. They are now available to paleoenvironmentalists and the scientific community for future research and analyses.

The initial purpose of the study was not to provide specific proposals for future management of Mountain Lake but rather to determine what has happened in the past. However, the evidence that has been uncovered provided useful baseline data in the development of an environmentally sound management plan.

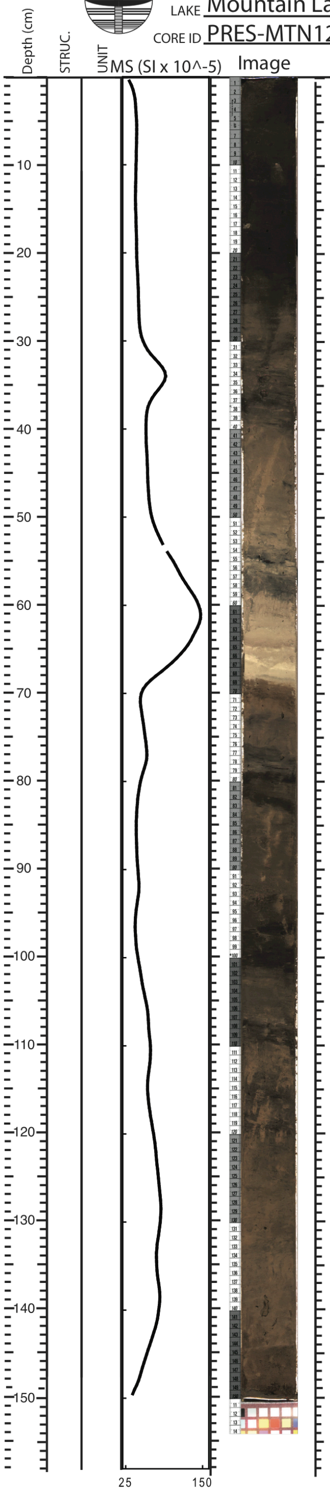
The work at Big Soda Lake provides a valuable historical paleolimnological perspective on what happens when a saline lake which is influenced by increasing freshwater inputs. The changes during the period 1910 to the present are in effect analogous to what potentially happens to the lake during a period of wetter climate conditions in the past. It is clear from the Big Soda Lake isotope data that the changes are not immediate, and that it takes a period of time (~40 years or so) before you see changes in the isotope ratios. This phenomenon should be incorporated into any lake history interpretation that involves major changes in hydrology and climate change in the past, especially in small saline lakes.

Appendix 1

INITIAL CORE DESCRIPTION

LAKE Mountain Lake
CORE ID PRES-MTN12-4B-1B-1
SECTION LENGTH (cm) 150
SED. LENGTH (cm) 150
mblf top 0
mblf bot
Describer ACM
Date 3/26/13

LITHOLOGIC DESCRIPTION



0-53 cm Correlation with 4A-1P; Unevenly bedded (5-30 cm) alternating black-brown and dark tan organic rich clayey silt with diatoms (ex. *Cymbella, Anomoeneis, Cyclotella, Surirella,* and *Stephanodiscus*) and some pyrite. Evidence of bioturbation or other vertical disturbance.

53-69 cm Faintly bedded or streaked pale brown with black clayey silt.

High MS; higher sand content

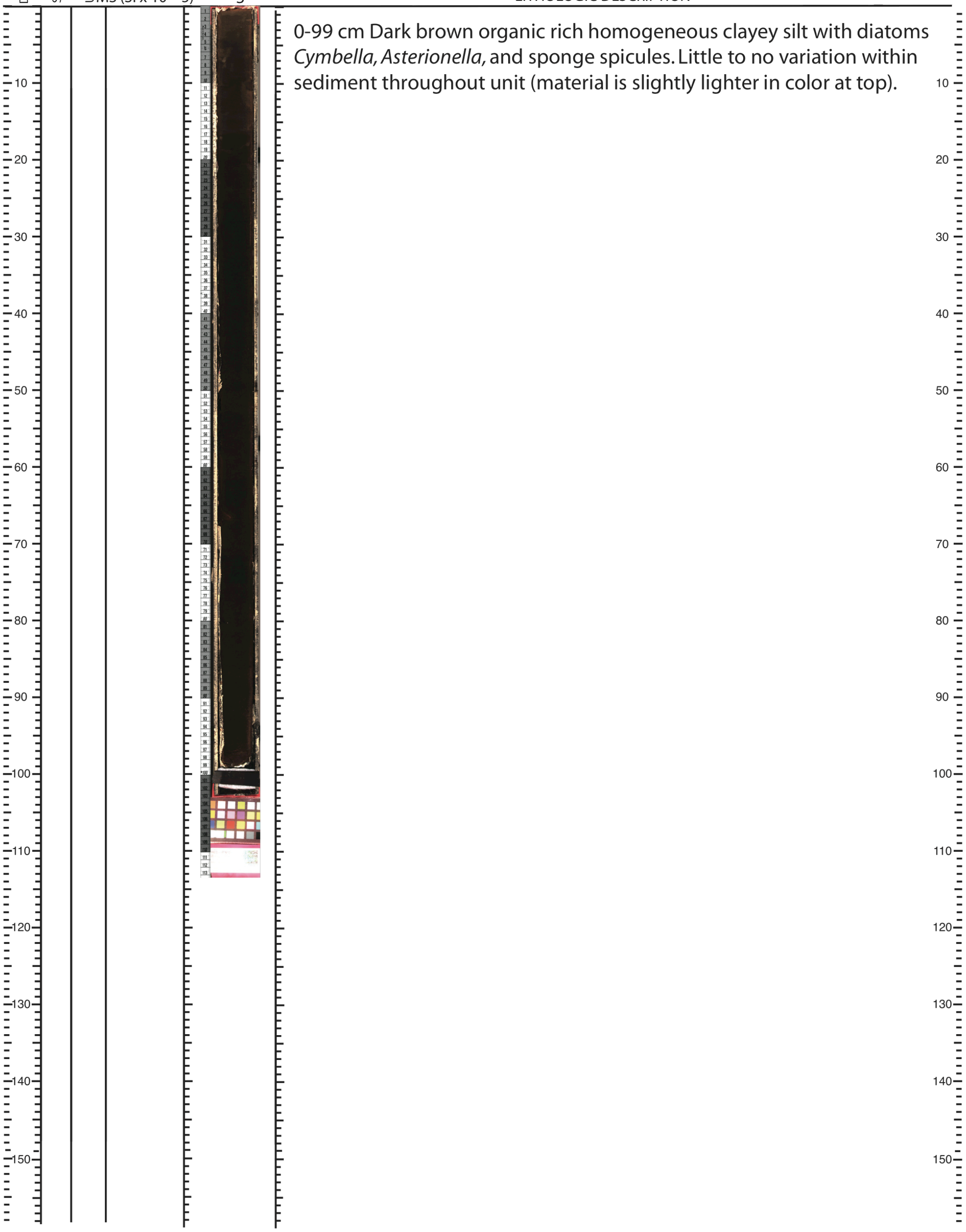
69-150 cm Large beds of alternating brown to dark brown clayey silt. Evidence of bioturbation or other vertical disturbance. Especially dark material between 79-80, 81-83, 96.5-101.5, 107.5-110 cm.

Initial core description and magnetic susceptibility for Mountain Lake (PRES-MTN12-4B-1B-1).

INITIAL CORE DESCRIPTION

LAKE Mountain Lake
CORE ID PRES-MTN12-4B-2L-1
SECTION LENGTH (cm) 99
SED. LENGTH (cm) 99
mblf top 0
mblf bot
Describer ACM
Date 3/28/2013

Depth (cm) | STRUC. | UNIT | MS (SI x 10^-5) | Image | LITHOLOGIC DESCRIPTION



0-99 cm Dark brown organic rich homogeneous clayey silt with diatoms *Cymbella, Asterionella,* and sponge spicules. Little to no variation within sediment throughout unit (material is slightly lighter in color at top).

Initial core description for Mountain Lake (PRES-MTN12-4B-2L-1).

INITIAL CORE DESCRIPTION

LAKE Mountain Lake
CORE ID PRES-MTN12-4B-3L-1
SECTION LENGTH (cm) 99
SED. LENGTH (cm) 99
mblf top 0
mblf bot
Describer ACM
Date 3/26/2013

Depth (cm)	STRUC.	UNIT	MS (SI x 10^-5)	Image	LITHOLOGIC DESCRIPTION
					0-99 cm Dark brown organic rich massive clayey silt with diatoms *Cymbella, Asterionella,* and sponge spicules (same material as overlying unit, 2L). Very faintly laminated. Little to no variation within sediment throughout unit.

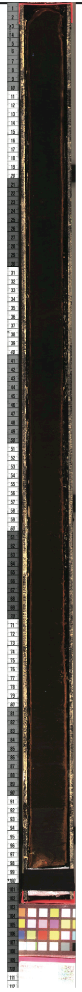
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Initial core description for Mountain Lake (PRES-MTN12-4B-3L-1).

INITIAL CORE DESCRIPTION

LAKE Mountain Lake
CORE ID PRES-MTN12-4B-4L
SECTION LENGTH (cm) 98
SED. LENGTH (cm) 98
mblf top
mblf bot
Describer ACM
Date 3/28/2013

Depth (cm) | STRUC. | UNIT | MS (SI x 10^-5) | Image | LITHOLOGIC DESCRIPTION



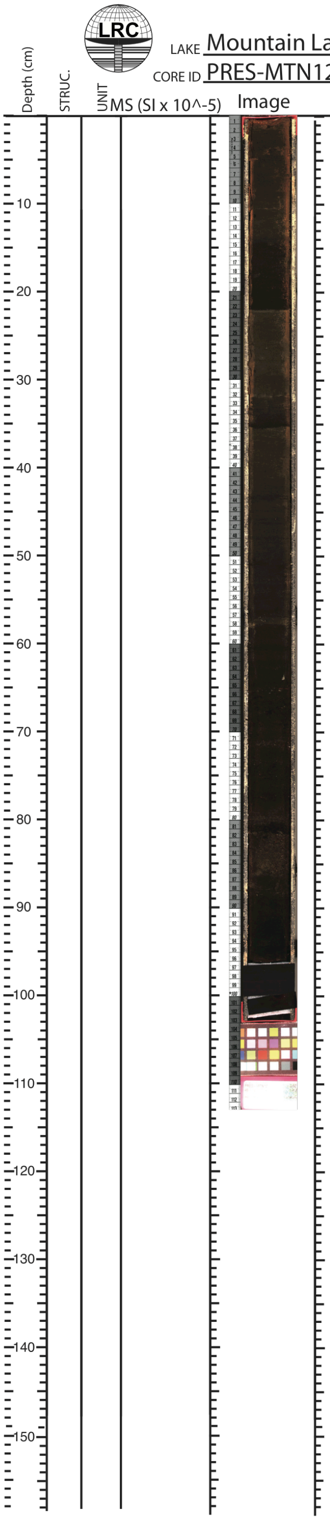
0-91 cm Dark brown organic rich homogeneous clayey silt with diatoms *Cymbella, Asterionella,* and sponge spicules (same material as overlying units, 2L and 3L). Very faintly laminated. Little to no variation within sediment throughout unit.

91-98 cm Brown quartz/feldspar rich homogeneous clay with organic matter. Slightly lighter than material above (0-91 cm).

Initial core description for Mountain Lake (PRES-MTN12-4B-4L).

INITIAL CORE DESCRIPTION

LAKE Mountain Lake
CORE ID PRES-MTN12-4B-5L-1
SECTION LENGTH (cm) 96
SED. LENGTH (cm) 96
mblf top 0
mblf bot
Describer ACM
Date 3/28/2013



LITHOLOGIC DESCRIPTION

0-96 cm Brown to dark brown massive organic rich clayey silt with quartz/feldspar. Material has a smooth texture and is similar to that in overlying layers (2L, 3L, and 4L). Darker material between 15-22 cm, 35 cm, 61-79 cm, 89-96 cm).

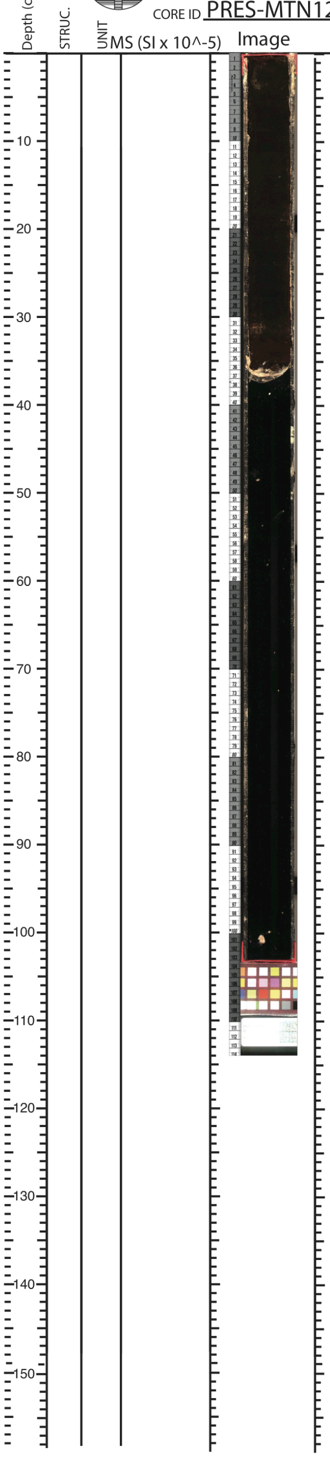
~65-96 cm Textured material.

~81 cm Woody material (resembling that in 4B-5L at 21.5 cm) was observed.

Initial core description for Mountain Lake (PRES-MTN12-4B-5L-1).

INITIAL CORE DESCRIPTION

LAKE Mountain Lake
CORE ID PRES-MTN12-4B-6L-1
SECTION LENGTH (cm) 36
SED. LENGTH (cm) 36
mblf top 0
mblf bot
Describer ACM
Date 4/1/2013



LITHOLOGIC DESCRIPTION

0-31 cm Dark brown massive organic rich clayey silt (same material as 0-21 and 65-96 cm in 4B-5L).

31-31.5 cm Light brown faintly laminated diatom rich clayey silt (diatoms include *Cymbella* and *Asterionella*).

31.5-36 cm Brown massive organic rich clayey silt (same material as 0-31 cm, but slightly lighter in color).

Initial core description for Mountain Lake (PRES-MTN12-4B-6L-1).

Appendix 2

Big Soda Lake XRF Results (First Set 0.5-51.5 cm), SODA-2010-1

Depth (cm)	Na_2O (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	P_2O_5 (%)	SO_3 (%)	Cl (ppm)
0.5	n	0.8	1.3	25.7	0.27	5.95	114169
1.5	47.2	0.8	1.1	23.2	0.19	7.54	118722
2.5	42	1	1.6	26.6	0.17	8.28	93431
3.5	43.1	0.8	1.3	22.4	0.13	11.52	73660
4.5	44.2	1	1.6	21.9	0.13	10.21	89411
5.5	55.3	0.4	0.6	10.9	0.02	0.58	218910
7.5	32.8	2.7	3.2	28.9	0.21	4.67	99368
8.5	53.7	0.9	1.4	10.3	0.08	6.4	158273
9.5	59.5	0.7	0.7	5.2	0.08	2.85	189805
10.5	60.9	0.7	0.6	3.4	0.06	2.64	191945
11.5	64.4	0.4	0.4	1	0.04	0.42	247964
12.5	63.3	0.4	0.4	0.6	0.03	0.81	248947
13.5	48.9	1.4	1.4	7.2	0.12	1.81	138990
14.5	51.6	1.1	1	5.2	0.12	3.9	129200
15.5	50.8	1	0.9	4.2	0.12	1.01	149402
16.5	23	2	2	8.7	0.27	2.15	72570
17.5	63.1	0.4	0.4	1.1	0.03	0.89	255253
18.5	61.9	0.3	0.3	0	0.01	0.48	274594
19.5	59.1	0.4	0.6	9.1	0.03	1.1	231786
20.5	61.4	0.4	0.5	3	0.03	1.51	246240
21.5	61.9	0.3	0.3	0.1	0.01	0.65	279483
22.5	60.1	0.4	0.5	2.9	0.02	2.02	246266
23.5	61.5	0.4	0.4	3.1	0.02	0.75	258166
24.5	61.7	0.3	0.3	0.5	0.01	0.56	277348
25.5	25.6	3.2	4.5	38.5	0.3	5.15	59975
26.5	61.5	0.3	0.3	1.1	0.01	0.26	273583
27.5	45.2	1.1	1.7	32.1	0.08	1.81	158052
28.5	58.6	0.4	0.4	5.6	0.02	0.4	248725
29.5	60.3	0.3	0.3	0.3	0.01	0.29	279753
30.5	61	0.3	0.3	1.9	0.01	0.34	269574
31.5	60.1	0.3	0.3	2	0.01	1.74	260435
32.5	60.2	0.4	0.3	5.6	0.02	0.72	253515
33.5	30	0.9	1.2	56	0.07	2.38	101894
34.5	58.9	0.3	0.3	1.4	0.01	1.74	263394
35.5	54.3	0.6	0.7	19.5	0.03	0.81	205282
36.5	62.2	0.3	0.3	2.2	0.02	0.51	267186
37.5	61.2	0.4	0.4	5.5	0.02	0.52	252312
38.5	60.9	0.3	0.3	1.6	0.02	0.33	268300
39.5	59.1	0.4	0.4	3.2	0.02	2.59	246720
40.5	61.4	0.3	0.3	3.1	0.02	0.71	260203
41.5	59.9	0.3	0.3	1.2	0.01	2.5	254335
42.5	60.6	0.3	0.3	1.7	0.02	0.62	267425
43.5	61.7	0.3	0.3	1.3	0.02	0.28	268187
44.5	61.6	0.3	0.3	1.5	0.01	0.35	271166
45.5	43.5	1.3	2.7	33.5	0.09	1.33	148105
46.5	62	0.3	0.3	1.1	0.01	0.39	272344
47.5	59.1	0.4	0.5	8.7	0.03	0.87	233845
48.5	59	0.4	0.6	9.7	0.03	1.68	225622
49.5	59.5	0.5	0.7	9.2	0.03	1.56	228297
50.5	59.8	0.4	0.4	4.2	0.02	1.63	247447
51.5	28.9	1.6	2	33.2	0.13	1.62	78503

Big Soda Lake XRF Results (First Set 0.5-51.5 cm), SODA-2010-1

Depth (cm)	K_2O (%)	CaO (%)	TiO_2 (%)	V (ppm)	Cr (ppm)	MnO (%)
0.5	1.16	2.25	0.15	246	12	0.04
1.5	1.06	2.3	0.14	301	6	0.04
2.5	1.26	3.25	0.17	244	14	0.04
3.5	1.1	3.69	0.15	177	12	0.04
4.5	1.11	4.82	0.19	183	5	0.04
5.5	0.43	1.35	0.13	63	5	0.04
7.5	1.35	8.45	0.23	201	14	0.04
8.5	0.81	8.67	0.22	110	11	0.05
9.5	0.58	13.61	0.13	80	10	0.03
10.5	0.54	16.32	0.11	87	9	0.03
11.5	0.25	9.36	0.1	72	1	0.03
12.5	0.21	8.99	0.1	51	6	0.03
13.5	0.59	26.19	0.16	92	5	0.04
14.5	0.48	27.99	0.14	67	5	0.03
15.5	0.42	28.57	0.12	52	0	0.03
16.5	0.85	38.58	0.18	43	15	0.04
17.5	0.27	5.29	0.13	88	10	0.04
18.5	0.11	2.68	0.09	83	0	0.03
19.5	0.49	1.89	0.16	74	7	0.05
20.5	0.3	4.64	0.13	51	5	0.04
21.5	0.11	0.47	0.11	51	15	0.04
22.5	0.35	1.38	0.17	56	5	0.05
23.5	0.32	1.33	0.15	71	9	0.05
24.5	0.14	0.82	0.11	45	7	0.04
25.5	1.65	4.43	0.33	123	14	0.07
26.5	0.16	0.6	0.12	49	9	0.04
27.5	0.97	2.7	0.21	76	3	0.05
28.5	0.3	0.99	0.12	48	13	0.04
29.5	0.08	0.41	0.08	25	5	0.03
30.5	0.19	0.73	0.11	44	4	0.04
31.5	0.18	0.97	0.09	32	0	0.03
32.5	0.28	1.21	0.08	54	13	0.03
33.5	1.05	3.35	0.12	43	1	0.03
34.5	0.13	0.67	0.07	34	11	0.03
35.5	0.55	1.82	0.14	80	5	0.04
36.5	0.2	1.48	0.09	49	6	0.03
37.5	0.31	2.25	0.11	52	0	0.04
38.5	0.19	1.24	0.09	45	9	0.03
39.5	0.25	1.14	0.1	63	1	0.04
40.5	0.26	1.79	0.11	49	7	0.04
41.5	0.17	1.54	0.1	49	12	0.04
42.5	0.18	1.3	0.1	48	3	0.03
43.5	0.19	1.1	0.11	61	7	0.04
44.5	0.18	1.26	0.11	47	4	0.04
45.5	1.19	4.86	0.26	84	6	0.06
46.5	0.18	1.39	0.11	54	1	0.04
47.5	0.45	2.12	0.14	67	5	0.05
48.5	0.49	2.38	0.14	64	8	0.04
49.5	0.51	2.25	0.16	67	4	0.05
50.5	0.31	1.27	0.13	42	12	0.04
51.5	1.19	4.59	0.21	88	6	0.06

Big Soda Lake XRF Results (First Set 0.5-51.5 cm), SODA-2010-1

Depth (cm)	Fe_2O_3 (%)	Co (ppm)	Ni (ppm)	Cu (ppm)	Zn (ppm)	Ga (ppm)	Ge (ppm)
0.5	1.38	10	11	16	61	5	3
1.5	1.27	9	8	16	32	5	2
2.5	1.45	9	8	18	35	5	1
3.5	1.33	9	8	18	31	4	1
4.5	1.62	7	11	20	35	6	1
5.5	1.59	10	4	12	28	6	5
7.5	1.86	12	12	18	38	6	2
8.5	2.05	10	12	17	39	7	1
9.5	1.25	9	9	15	27	5	1
10.5	1.08	8	9	14	24	3	1
11.5	1.19	7	9	14	27	3	1
12.5	1.27	8	9	15	28	5	1
13.5	1.43	8	10	17	26	4	1
14.5	1.28	10	9	15	23	3	1
15.5	1.08	8	8	14	21	3	1
16.5	1.44	11	8	15	24	4	1
17.5	1.64	9	9	17	35	6	4
18.5	1.36	9	8	15	30	6	9
19.5	1.89	12	10	16	35	7	4
20.5	1.62	10	8	17	35	6	3
21.5	1.99	10	8	17	43	8	5
22.5	2.28	12	11	19	46	10	4
23.5	2	11	11	20	43	8	5
24.5	1.91	11	9	19	44	8	4
25.5	2.76	11	13	25	54	9	5
26.5	1.88	10	6	16	40	7	6
27.5	2.03	12	9	16	37	7	7
28.5	1.66	22	6	13	32	6	7
29.5	1.4	9	4	12	29	6	5
30.5	1.62	9	5	11	30	7	5
31.5	1.27	8	5	11	24	5	3
32.5	1.09	12	4	9	22	4	5
33.5	1.09	9	5	10	20	3	2
34.5	1.14	8	3	9	25	4	3
35.5	1.56	10	7	13	29	6	4
36.5	1.25	9	5	10	23	5	4
37.5	1.34	9	5	10	23	5	2
38.5	1.28	8	5	10	25	5	3
39.5	1.43	9	7	12	28	6	5
40.5	1.51	10	6	12	29	6	3
41.5	1.49	9	7	14	31	6	3
42.5	1.4	10	8	12	27	6	4
43.5	1.62	10	7	13	31	6	4
44.5	1.59	10	6	15	32	6	4
45.5	2.32	12	10	17	39	9	3
46.5	1.66	9	6	13	33	8	4
47.5	1.66	10	8	14	30	5	4
48.5	1.67	11	7	13	31	7	3
49.5	1.86	11	7	15	34	8	5
50.5	1.68	12	7	15	33	7	6
51.5	1.91	9	8	14	30	7	4

Big Soda Lake XRF Results (First Set 0.5-51.5 cm), SODA-2010-1

Depth (cm)	As (ppm)	Rb (ppm)	Sr (ppm)	Y (ppm)	Zr (ppm)	Nb (ppm)	Mo (ppm)	Ba (ppm)
0.5	31	60	295	2	53	3	79	152
1.5	38	61	449	4	49	2	115	136
2.5	34	61	560	4	43	3	93	171
3.5	29	58	619	4	41	3	87	171
4.5	23	57	1030	8	43	4	71	190
5.5	10	57	324	3	65	5	20	129
7.5	28	55	1301	10	46	4	70	258
8.5	29	58	1452	14	58	6	43	238
9.5	24	31	2341	14	13	3	45	176
10.5	25	20	3052	18	0	3	45	187
11.5	18	24	2067	12	16	3	28	135
12.5	16	32	1585	14	40	4	17	134
13.5	15	26	1424	13	32	4	29	166
14.5	15	17	1641	13	21	3	22	179
15.5	14	11	2031	16	13	3	10	213
16.5	16	6	3020	18	0	3	27	562
17.5	14	53	901	12	60	5	24	140
18.5	18	48	708	8	56	5	19	75
19.5	14	71	395	8	80	6	24	163
20.5	16	55	733	10	69	5	41	144
21.5	13	71	444	7	91	6	43	108
22.5	16	81	508	13	118	7	43	183
23.5	18	74	462	9	91	6	54	163
24.5	17	73	533	10	92	6	42	115
25.5	22	77	508	9	97	7	60	386
26.5	14	69	400	6	86	6	37	119
27.5	17	66	411	6	80	5	34	268
28.5	14	62	400	4	72	5	32	139
29.5	11	61	406	5	75	5	24	79
30.5	10	61	402	5	75	5	24	133
31.5	18	55	406	4	61	4	17	88
32.5	17	50	345	2	49	3	24	109
33.5	12	47	331	1	44	3	16	165
34.5	8	50	368	2	57	4	17	86
35.5	11	59	373	5	69	4	18	154
36.5	15	51	449	3	55	4	23	123
37.5	13	51	478	4	60	4	20	135
38.5	12	54	454	4	60	4	22	123
39.5	15	60	447	6	68	4	34	110
40.5	9	61	467	7	75	5	22	131
41.5	11	61	527	9	70	5	30	113
42.5	11	56	469	5	72	5	31	112
43.5	15	61	443	6	71	5	44	130
44.5	14	61	463	7	72	4	37	101
45.5	15	73	503	10	97	6	28	351
46.5	12	66	538	9	86	5	32	146
47.5	17	60	393	6	71	4	32	168
48.5	18	63	401	7	77	4	30	170
49.5	11	68	410	8	81	5	36	178
50.5	17	67	394	8	80	5	39	137
51.5	15	59	384	4	68	5	37	281

Big Soda Lake XRF Results (First Set 0.5-51.5 cm), SODA-2010-1

Depth (cm)	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Pb (ppm)	Th (ppm)	U (ppm)
0.5	28	24	3	0	4	8	4	3
1.5	15	17	2	0	3	7	5	6
2.5	7	17	2	0	3	8	4	5
3.5	7	16	0	0	3	10	6	5
4.5	13	18	0	0	4	13	7	3
5.5	4	20	0	0	3	6	3	5
7.5	18	17	4	2	3	10	8	4
8.5	13	26	0	0	5	9	8	4
9.5	17	15	2	0	2	10	11	4
10.5	16	21	2	0	3	9	12	1
11.5	15	19	1	0	3	9	11	6
12.5	13	10	0	0	3	9	11	4
13.5	19	14	5	0	3	9	9	6
14.5	10	19	1	0	3	9	10	3
15.5	30	17	4	0	3	8	11	4
16.5	8	21	0	0	3	11	13	2
17.5	13	16	2	0	3	10	8	3
18.5	14	13	2	0	3	9	7	7
19.5	19	12	4	0	3	8	5	2
20.5	8	19	3	0	3	23	10	4
21.5	20	17	2	0	3	23	6	3
22.5	10	29	2	3	4	24	9	8
23.5	20	12	3	0	3	20	6	3
24.5	10	22	2	0	3	20	8	4
25.5	16	26	4	8	4	19	6	7
26.5	6	22	0	3	4	14	4	5
27.5	14	12	2	0	3	14	3	4
28.5	21	9	3	0	2	11	4	5
29.5	8	10	0	0	3	9	5	5
30.5	17	2	1	0	2	9	4	5
31.5	10	17	2	0	3	8	4	7
32.5	9	18	1	0	3	7	4	6
33.5	0	13	0	0	2	4	1	6
34.5	16	12	1	1	3	6	5	5
35.5	17	17	1	0	2	7	4	7
36.5	1	14	1	0	3	6	3	6
37.5	2	15	1	0	2	6	4	4
38.5	15	16	2	0	3	7	6	7
39.5	10	8	0	0	3	8	6	5
40.5	7	18	2	1	3	8	6	9
41.5	4	15	0	0	3	8	6	8
42.5	12	17	0	0	3	9	8	7
43.5	16	15	3	2	3	7	6	6
44.5	21	19	4	3	3	8	6	6
45.5	18	20	1	4	2	11	8	6
46.5	14	19	2	6	3	10	7	4
47.5	9	26	2	1	3	6	5	6
48.5	8	17	1	0	3	9	6	5
49.5	24	16	5	0	3	9	6	5
50.5	27	14	4	0	3	9	7	6
51.5	17	22	2	0	3	7	5	6

Appendix 3

Big Soda Lake XRF Results (Second Set 0.5-149.5 cm), SODA-2010-1

Depth (cm)	NaO (%)	AlO$_3$ (%)	SiO$_3$ (%)	Cl (%)	KO$_2$ (%)	CaO (%)	MnO (%)	FeO$_3$ (%)
0.5	39.69	1.14	28.59	20.59	1.83	3.64	0.052	2.014
1.5	41.53	1.01	25.76	22.38	1.68	3.52	0.050	1.746
2.5	38.56	1.39	28.52	18.97	1.96	4.86	0.057	2.038
3.5	40.94	1.09	24.26	16.84	2.07	6.63	0.068	2.342
4.5	39.45	1.52	24.82	17.98	1.85	7.39	0.064	2.473
5.5	41.11	0.50	11.21	40.65	0.84	2.60	0.061	2.666
6.5	44.13	1.19	13.22	24.44	1.54	10.96	0.071	2.867
7.5	31.08	2.84	28.57	20.25	1.94	11.55	0.062	2.751
8.5	42.43	1.65	13.29	25.34	1.31	12.21	0.062	2.915
9.5	39.31	0.93	7.50	27.03	1.07	21.86	0.054	1.900
10.5	42.44	0.38	1.89	30.68	1.53	21.20	0.046	1.489
11.5	43.24	0.19	0.00	40.10	0.48	13.82	0.049	1.785
12.5	42.35	0.27	0.00	40.31	0.45	14.25	0.047	1.991
13.5	29.08	1.94	10.31	16.64	0.94	38.22	0.057	2.121
14.5	37.09	0.81	4.48	18.94	0.69	35.87	0.042	1.730
15.5	30.88	1.16	4.88	21.90	0.62	38.65	0.044	1.535
16.5	36.26	1.04	3.62	26.04	0.62	30.54	0.044	1.508
17.5	44.41	0.25	0.00	42.93	0.58	8.73	0.068	2.691
18.5	43.89	0.05	0.00	48.27	0.30	4.81	0.061	2.274
19.5	34.21	1.49	10.93	23.81	1.04	25.74	0.080	2.338
20.5	44.06	0.31	1.86	42.69	0.59	7.45	0.068	2.619
21.5	44.80	0.05	0.00	49.49	0.32	1.40	0.078	3.512
22.5	46.38	0.42	1.95	43.54	0.71	2.73	0.084	3.833
23.5	44.59	0.31	2.32	45.15	0.73	2.88	0.090	3.552
24.5	44.15	0.28	0.00	49.14	0.42	2.17	0.080	3.405
25.5	28.34	4.18	39.24	12.46	2.32	6.19	0.094	4.014
26.5	45.35	0.05	0.00	48.75	0.45	1.66	0.077	3.306
27.5	33.91	1.35	30.86	26.02	1.31	3.54	0.061	2.616
28.5	42.55	0.36	6.02	44.63	0.74	2.29	0.073	2.954
29.5	44.11	0.05	0.00	51.08	0.31	1.40	0.060	2.615
30.5	44.95	0.05	0.94	48.28	0.50	1.93	0.068	2.926
31.5	46.31	0.05	0.70	47.52	0.46	2.30	0.055	2.239
32.5	44.12	0.22	6.27	43.80	0.66	2.67	0.056	1.831
33.5	21.12	0.84	57.09	14.43	1.26	3.88	0.036	1.150
34.5	44.94	0.05	0.49	49.88	0.38	1.81	0.054	2.018
35.5	45.17	0.23	2.08	45.54	0.56	3.41	0.062	2.585
36.5	45.47	0.05	1.37	46.87	0.52	3.12	0.061	2.160
37.5	43.88	0.27	5.03	43.45	0.66	4.08	0.064	2.207
38.5	45.90	0.05	0.26	47.88	0.47	2.72	0.060	2.282
39.5	46.59	0.05	2.50	44.91	0.58	2.48	0.063	2.466

Big Soda Lake XRF Results (Second Set 0.5-149.5 cm), SODA-2010-1

Depth (cm)	NaO (%)	AlO_3 (%)	SiO_3 (%)	Cl (%)	KO_2 (%)	CaO (%)	MnO (%)	FeO_3 (%)
40.5	45.17	0.23	2.08	45.54	0.56	3.41	0.062	2.585
41.5	46.30	0.05	0.00	46.90	0.44	3.23	0.068	2.646
42.5	44.38	0.05	0.78	48.40	0.48	2.95	0.061	2.523
43.5	46.26	0.05	0.00	47.47	0.47	2.45	0.071	2.850
44.5	44.92	0.05	0.42	48.15	0.47	2.80	0.072	2.751
45.5	31.98	2.32	31.05	24.08	1.50	5.80	0.070	2.871
46.5	45.59	0.05	0.00	47.59	0.48	2.93	0.074	2.927
47.5	42.90	0.43	8.50	40.59	0.83	3.63	0.077	2.681
48.5	43.57	0.50	9.03	39.17	0.85	3.85	0.070	2.611
49.5	43.04	0.48	8.83	39.24	0.93	3.91	0.080	3.119
50.5	45.62	0.29	2.59	45.19	0.59	2.46	0.075	2.825
51.5	25.83	2.21	40.40	18.99	1.90	7.05	0.092	3.125
52.5	42.84	0.25	10.79	39.70	0.82	3.14	0.060	2.027
53.5	32.11	0.93	32.99	26.54	1.19	3.90	0.055	1.940
54.5	44.45	0.39	8.43	39.64	0.81	3.62	0.063	2.224
55.5	37.02	1.08	25.05	27.57	1.37	5.00	0.070	2.484
56.5	39.01	0.78	21.59	30.11	1.19	4.36	0.075	2.543
57.5	45.56	0.30	5.88	40.82	0.71	3.68	0.064	2.626
58.5	33.38	1.20	30.78	26.24	1.26	4.62	0.056	2.124
59.5	42.94	0.32	9.01	40.87	0.70	3.59	0.056	2.151
60.5	42.00	0.38	9.85	39.96	0.80	4.13	0.064	2.467
61.5	43.94	0.32	4.88	43.94	0.65	3.38	0.065	2.458
62.5	34.87	0.92	31.59	24.46	1.28	4.42	0.055	2.061
63.5	34.35	1.04	29.13	26.29	1.34	5.06	0.060	2.377
64.5	37.14	0.72	22.82	32.81	1.07	2.64	0.060	2.396
65.5	42.84	0.38	11.02	37.55	1.27	3.33	0.081	3.057
66.5	41.67	0.37	11.77	39.57	0.83	2.93	0.059	2.439
67.5	36.33	0.96	26.46	28.27	1.16	4.23	0.055	2.190
68.5	31.34	1.21	33.70	26.84	1.23	3.08	0.051	2.223
69.5	39.51	0.48	17.59	36.43	1.00	2.16	0.057	2.408
70.5	41.13	0.52	13.31	38.47	0.90	2.77	0.060	2.470
71.5	36.56	0.90	23.86	31.26	1.10	3.74	0.052	2.200
72.5	33.80	0.89	30.02	28.24	1.10	3.56	0.052	2.010
73.5	36.35	0.86	26.13	29.75	1.08	3.19	0.061	2.239
74.5	41.13	0.52	13.31	38.47	0.90	2.77	0.060	2.470
75.5	44.06	0.28	3.93	46.15	0.60	2.02	0.063	2.513
76.5	42.92	0.27	6.44	44.13	0.70	2.52	0.066	2.588
77.5	40.92	0.43	13.06	38.22	1.03	3.07	0.066	2.804
78.5	40.19	0.66	18.81	32.89	1.00	3.60	0.058	2.446
79.5	39.94	0.88	20.86	30.33	1.12	3.78	0.063	2.665

Big Soda Lake XRF Results (Second Set 0.5-149.5 cm), SODA-2010-1

Depth (cm)	NaO (%)	AlO_3 (%)	SiO_3 (%)	Cl (%)	KO_2 (%)	CaO (%)	MnO (%)	FeO_3 (%)
80.5	30.00	1.61	37.49	23.24	1.23	3.81	0.054	2.234
81.5	43.38	0.27	4.82	45.13	0.59	2.71	0.067	2.661
82.5	39.94	0.88	20.86	30.33	1.12	3.78	0.063	2.665
83.5	42.31	0.33	5.93	44.90	0.70	2.33	0.067	3.047
84.5	37.27	0.93	25.26	29.45	1.14	3.07	0.060	2.479
85.5	37.86	0.49	20.99	34.05	0.94	3.01	0.058	2.251
86.5	21.78	1.54	50.04	19.24	1.29	4.00	0.051	1.848
87.5	43.39	0.29	7.22	43.47	0.58	2.50	0.061	2.119
88.5	29.36	1.32	37.33	25.41	1.09	3.16	0.049	1.939
89.5	33.33	1.23	30.13	26.98	1.21	4.47	0.059	2.264
90.5	42.01	0.37	8.85	41.83	0.76	3.20	0.063	2.548
91.5	43.08	0.56	9.36	39.19	0.93	3.38	0.077	3.057
92.5	45.39	0.05	0.00	48.56	0.44	2.06	0.068	3.061
93.5	32.19	2.05	36.43	20.88	1.62	3.69	0.069	2.716
94.5	45.05	0.05	0.64	48.95	0.50	1.73	0.069	2.628
95.5	41.96	0.64	12.64	37.22	1.10	3.39	0.069	2.595
96.5	28.55	2.88	37.54	19.69	2.09	6.24	0.071	2.553
97.5	31.66	2.62	32.84	16.57	2.05	11.25	0.072	2.524
98.5	36.20	1.95	26.68	24.87	1.85	5.16	0.080	2.827
99.5	44.64	0.37	4.62	43.19	0.86	2.89	0.074	2.984
100.5	32.95	2.56	35.36	17.61	1.95	5.34	0.073	2.674
101.5	43.04	0.74	10.54	36.43	1.18	4.71	0.079	2.922
102.5	40.64	1.01	17.56	31.59	1.26	4.89	0.070	2.620
103.5	42.41	0.53	11.42	37.60	1.05	3.72	0.071	2.825
104.5	39.98	0.94	17.58	33.34	1.12	4.00	0.063	2.628
105.5	43.04	0.25	3.59	46.30	0.65	2.86	0.069	2.863
106.5	39.48	0.84	13.73	37.17	1.07	4.36	0.072	2.898
107.5	36.28	1.35	25.76	27.19	1.33	5.01	0.065	2.664
108.5	36.13	1.15	25.28	28.35	1.29	4.71	0.062	2.683
109.5	42.22	0.42	11.81	37.71	0.92	3.67	0.067	2.796
110.5	29.13	2.03	41.74	15.09	1.60	6.10	0.062	2.482
111.5	45.15	0.05	0.00	49.47	0.41	1.83	0.064	2.646
112.5	47.69	0.38	11.92	31.37	1.08	3.59	0.070	2.829
113.5	41.16	0.65	15.28	34.87	1.05	3.94	0.065	2.647
114.5	42.20	0.66	12.89	36.47	1.06	3.63	0.070	2.665
115.5	39.53	1.05	16.36	34.52	1.34	3.97	0.074	2.799
116.5	41.35	0.99	10.78	38.35	1.39	3.75	0.078	2.939
117.5	42.22	0.42	11.81	37.71	0.92	3.67	0.067	2.796
118.5	44.81	0.86	8.62	37.99	1.25	3.47	0.072	2.579
119.5	44.24	0.05	0.00	50.64	0.33	1.58	0.071	2.724

Big Soda Lake XRF Results (Second Set 0.5-149.5 cm), SODA-2010-1

Depth (cm)	NaO (%)	AlO_3 (%)	SiO_3 (%)	Cl (%)	KO_2 (%)	CaO (%)	MnO (%)	FeO_3 (%)
119.5	44.81	0.86	8.62	37.99	1.25	3.47	0.072	2.579
120.5	38.61	1.17	13.56	38.10	1.53	3.78	0.081	2.802
121.5	46.60	0.32	4.45	41.67	0.80	2.74	0.082	2.987
122.5	44.24	0.05	0.00	50.64	0.33	1.58	0.071	2.724
123.5	44.11	0.75	13.79	32.78	1.09	4.19	0.074	2.863
124.5	40.55	0.78	19.30	31.12	1.17	3.89	0.071	2.763
125.5	35.89	1.24	30.50	25.51	1.23	3.14	0.055	2.093
126.5	44.69	0.37	4.67	43.11	0.71	3.06	0.074	2.944
127.5	44.12	0.05	0.00	51.38	0.22	1.20	0.059	2.623
128.5	43.79	0.05	0.00	52.01	0.24	1.35	0.055	2.149
129.5	45.29	0.05	1.00	47.03	0.49	2.42	0.069	3.283
130.5	45.13	0.20	0.77	48.11	0.43	1.81	0.069	3.105
131.5	44.36	0.05	2.57	47.66	0.43	1.54	0.072	2.963
132.5	43.07	0.24	5.86	45.05	0.56	1.80	0.072	2.990
133.5	33.74	0.93	31.56	27.18	0.98	2.76	0.060	2.477
134.5	43.15	0.23	1.43	49.98	0.40	1.47	0.066	2.907
135.5	38.81	0.77	19.19	34.26	0.94	2.55	0.073	3.044
136.5	44.58	0.05	0.00	49.99	0.34	1.73	0.069	2.881
137.5	44.15	0.55	7.78	39.06	0.96	3.63	0.084	3.420
138.5	45.09	0.31	6.27	41.04	0.77	2.74	0.078	3.327
139.5	42.43	0.59	12.63	36.66	0.90	3.45	0.068	2.921
140.5	45.07	0.05	0.55	48.60	0.42	1.86	0.075	3.006
141.5	39.51	0.70	19.15	33.70	0.92	2.77	0.065	2.845
142.5	36.12	0.79	26.50	29.97	1.00	2.72	0.059	2.506
143.5	40.81	0.42	13.73	39.40	0.74	2.00	0.059	2.494
144.5	44.09	0.05	2.21	48.69	0.43	1.55	0.061	2.539
145.5	41.38	0.36	17.56	34.21	1.02	2.64	0.065	2.386
146.5	42.94	0.44	10.81	39.34	1.03	2.50	0.065	2.478
147.5	43.18	0.44	13.99	36.18	1.11	2.23	0.062	2.418
148.5	43.92	0.38	8.90	40.98	0.84	2.14	0.064	2.385
149.5	63.74	0.10	0.00	11.51	0.70	2.34	0.073	2.864

Appendix 4

Big Soda Lake Oxygen and Carbon Stable Isotopes, SODA-2010-1

Depth (cm)	δ18O (‰ VPBD)	δ13C (‰ VPBD)	Depth (cm)	δ18O (‰ VPBD)	δ13C (‰ VPBD)
0	-4.56	-0.75	49	-2.33	2.28
1	-4.75	-0.70	50	-2.25	2.17
2	-3.93	-0.75	51	-2.12	2.13
3	-3.99	-0.61	52	-2.23	2.09
4	-3.64	0.49	53	-2.33	1.87
5	-3.35	1.18	54	-2.34	1.92
6	-3.33	1.62	55	-2.57	1.89
7	-3.44	1.52	56	-2.35	1.79
8	-3.36	2.01	57	-2.46	1.90
9	-3.39	2.08	58	-3.03	1.90
10	-3.32	1.92	59	-2.86	1.96
11	-3.42	1.92	60	-3.08	2.19
12	-3.44	1.95	61	-3.22	2.07
13	-3.47	2.01	62	-3.23	2.08
14	-3.36	2.07	63	-3.24	2.12
15	-3.32	2.13	64	-1.65	2.52
16	-3.44	2.14	65	-2.09	2.33
17	-3.96	2.39	66	-2.31	2.31
18	-3.00	2.53	67	-1.77	2.18
19	-2.97	2.61	68	-2.31	2.11
20	-3.02	2.54	69	-2.55	1.99
21	-2.81	2.63	70	-2.33	2.25
22	-3.15	2.62	71	-2.75	2.09
23	-2.78	2.90	72	-2.13	2.08
24	-2.68	2.77	73	-2.15	2.15
25	-2.82	2.49	74	-2.27	2.27
26	-3.43	2.41	75	-2.23	2.33
27	-3.56	2.33	76	-2.79	2.12
28	-3.13	2.63	77	-2.68	2.19
29	-2.57	2.94	78	-3.56	2.06
30	-5.14	1.54	79	-2.34	1.97
31	-5.35	1.24	80	-3.18	1.31
32	-5.28	0.64	81	-3.15	2.07
33	-4.61	0.97	82	-3.10	2.35
34	-3.31	1.80	83	-2.74	2.17
35	-2.96	2.09	84	-2.30	2.15
36	-3.15	2.22	85	-2.20	2.02
37	-3.30	2.02	86	-2.96	1.87
38	-3.49	2.08	87	-2.74	1.54
39	-3.73	1.97	88	-2.56	1.23
40	-3.57	2.20	89	-2.71	1.29
41	-3.37	2.26	90	-2.52	1.21
42	-3.03	1.85	91	-2.36	1.67
43	-2.98	1.99	92	-2.37	1.80
44	-3.17	1.62	93	-2.64	1.94
45	-2.49	1.62	94	-4.73	0.78
46	-3.02	1.16	95	-3.15	1.80
47	-2.62	1.90	96	-3.91	1.95
48	-2.39	2.13	97	-7.14	-0.34

Big Soda Lake Oxygen and Carbon Stable Isotopes, SODA-2010-1

Depth (cm)	δ18O (‰ VPBD)	δ13C (‰ VPBD)	Depth (cm)	δ18O (‰ VPBD)	δ13C (‰ VPBD)
98	-3.48	2.09	147	-3.32	2.26
99	-4.59	1.01	148	-3.17	2.17
100	-3.54	1.37	149	-5.98	1.75
101	-3.28	2.16	150	-3.77	2.22
102	-4.02	1.83			
103	-4.01	1.24			
104	-3.22	1.79			
105	-2.97	1.99			
106	-3.77	1.68			
107	-3.06	2.00			
108	-2.71	1.82			
109	-2.75	1.90			
110	-2.61	2.10			
111	-3.22	1.96			
112	-2.91	2.10			
113	-3.09	2.02			
114	-2.40	1.97			
115	-2.42	2.12			
116	-3.56	1.73			
117	-3.15	1.91			
118	-2.49	2.10			
119	-3.95	2.18			
120	-4.00	1.19			
121	-3.11	1.91			
122	-3.14	1.67			
123	-3.20	1.19			
124	-2.82	0.93			
125	-2.57	1.69			
126	-2.50	2.25			
127	-3.36	1.56			
128	-3.67	1.88			
129	-3.54	1.56			
130	-2.65	2.31			
131	-2.95	1.92			
132	-3.60	1.93			
133	-3.59	1.94			
134	-3.62	2.10			
135	-3.27	1.89			
136	-2.94	1.65			
137	-2.83	1.59			
138	-3.63	1.86			
139	-2.74	2.17			
140	-3.39	1.98			
141	-3.48	2.01			
142	-4.51	1.85			
143	-3.67	1.94			
144	-3.43	2.17			
145	-3.39	2.32			
146	-2.31	2.67			

Appendix 5

Big Soda Lake Brine Shrimp, SODA-2010-1

Depth (cm)	#sorted	Comments	Depth (cm)	#sorted	notes
1 cm	99	few cysts	138 cm	101	no cysts
3 cm	33	few cysts	151 cm	0	no cysts
5 cm	98	few cysts	155 cm	6	no cysts
7 cm	71	few cysts	161 cm	280	no cysts
9 cm	127	few cysts	170 cm	484	no cysts
11 cm	270	few cysts	171 cm	304	no cysts
13 cm	77	few cysts	172 cm	806	no cysts
15 cm	79	mostly cysts, but too few	181 cm	60	no cysts
17 cm	886	cysts	185 cm	75	no cysts
19 cm	1317	cysts	186 cm	152	no cysts
21 cm	3394	cysts	191 cm	88	no cysts
23 cm	1099	cysts	200 cm	33	no cysts
25 cm	2389	cysts	201 cm	18	no cysts
27 cm	1963	cysts	231 cm	76	no cysts
29 cm	634	cysts	241 cm	361	no cysts
31 cm	1025	cysts	261 cm	70	no cysts
33 cm	2390	cysts	271 cm	188	no cysts
35 cm	2607	cysts	281 cm	288	no cysts
37 cm	2158	cysts			12 cysts by visual,
39 cm	2903	cysts	291 cm	318	no cysts
41 cm	3834	cysts	315 cm	215	no cysts
43 cm	4003	cysts			no cyst-like material seen;
45 cm	3329	cysts	335 cm	1060	kept this sample to send as
47 cm	3746	cysts			a visual
48 cm	650	cysts	375 cm	54	no cysts
49 cm	3611	cysts	400 cm	83	no cysts
51 cm	113	no cysts	434 cm	169	no cysts
78 cm	124	no cysts	470 cm	83	no cysts
94 cm	117	no cysts	500 cm	125	no cysts
111 cm	97	no cysts			

Appendix 6

Radio Carbon Dates from Big Soda Lake

CAMS #	Core Label	Material Dated	Core Depth	$d^{13}C$	14 C age	+/-	cal yr B.P. median probability	-error	+error	Two Sigma age range cal yr BP
152524	SODA-2010-1	pollen	77	-25	440	40	500	170	40	331-540
152525	SODA-2010-1	pollen	94	-25	880	60	800	110	115	694-918
152526	SODA-2010-1	pollen	138	-25	1435	50	1335	60	75	1276-1413
155638	SODA10-LacCore	pollen	140	-25	1065	35	975	50	80	927-1056
155639	SODA10-LacCore	pollen	160	-25	1445	40	1340	45	60	1294-1400
155640	SODA10-LacCore	pollen	180	-25	1375	45	1300	120	65	1182-1367
155641	SODA10-LacCore	pollen	200	-25	1390	45	1310	125	75	1186-1385
152527	SODA10-LacCore	pollen	210	-25	1570	70	1465	145	145	1316-1607
152528	SODA10-LacCore	pollen	250	-25	3720	70	4070	200	220	3869-4289
155642	SODA10-LacCore	pollen	299	-25	3860	90	4275	285	245	3989-4519
152529	SODA10-LacCore	pollen	315	-25	4590	110	5265	370	315	4962-5584
152530	SODA10-LacCore	pollen	335	-25	5500	110	6295	300	210	5994-6502
155643	SODA10-LacCore	pollen	375	-25	4115	40	4645	125	175	4523-4821
152531	SODA10-LacCore	pollen	400	-25	5560	130	6360	350	295	6008-6653
152532	SODA10-LacCore	pollen	434	-25	4990	130	5740	410	260	5332-6000
155644	SODA10-LacCore	pollen	438	-25	4750	80	5480	170	160	5312-5640
155645	SODA10-LacCore	pollen	450	-25	6120	110	7000	260	260	6739-7260
155646	SODA10-LacCore	pollen	475	-25	5470	130	6250	320	250	5932-6503
155647	SODA10-LacCore	pollen	485	-25	4930	100	5680	210	320	5470-5909
155648	SODA10-LacCore	pollen	500	-25	5330	90	6110	180	175	5930-6285
155649	SODA10-LacCore	pollen	520	-25	4725	50	5465	145	120	5323-5584
155650	SODA10-LacCore	pollen	540	-25	4740	120	5460	405	270	5054-5727
155651	SODA10-LacCore	pollen	560	-25	4640	80	5380	325	205	5054-5584
155652	SODA10-LacCore	pollen	575	-25	4790	45	5520	190	80	5331-5603
155653	SODA10-LacCore	pollen	700	-25	4670	100	5400	350	200	5052-5596
155654	SODA10-LacCore	pollen	730	-25	6430	120	7345	315	225	7028-7571
155655	SODA10-LacCore	pollen	840	-25	12570	230	14740	825	1120	13915-15860

Appendix 7

Core ID and Recovery Locations

Core ID	Water Depth	Latitude	Longitude	Sediment Recovered
SODA08-1	63	39.6447	118.5691	50-100 cm
SODA-SODA09-1	62.0	39.5253	118.8786	200 cm
SODA-SODA09-2	55.0	39.5253	118.8786	60 cm
SODA-SODA09-3	55.0	39.5254	118.8786	220 cm
SODA-SODA09-4	60.8	39.8767	118.8767	60 cm
SODA-2010-1	62	39.5254	118.8786	150 cm
SODA-2010-2	62	39.5238	118.8803	200 cm
TOPGUN-SODA10-1B	62.2	39.5247	118.8786	100 cm
TOPGUN-SODA10-2A	62.6	39.5244	118.8784	880 cm
TOPGUN-SODA10-2B	62.6	39.5244	118.8784	68 cm
TOPGUN-SODA10-3A	60.5	39.5257	118.8791	930 cm
TOPGUN-SODA10-3B	60.5	39.5257	118.8791	102 cm