Arnold Schwarzenegger
Governor

CLIMATE VARIABILITY OF THE SIERRA NEVADA OVER THE LAST MILLENNIUM: RECONSTRUCTIONS FROM ANNUALLY LAMINATED SEDIMENTS IN SWAMP LAKE, YOSEMITE NATIONAL PARK, CALIFORNIA

PIER INTERIM PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Scripps Institution of Oceanography

October 2007
CEC-500-2007-044

California Climate Change Center
Report Series Number 2007-013

Prepared By:
Lydia Roach and Dan Cayan
Scripps Institution of Oceanography
University of San Diego
8602 La Jolla Shores Drive
La Jolla, CA 92037

Commission Contract No. 500-02-004
Commission Work Authorization No. MR-025

Prepared For:
Public Interest Energy Research (PIER) Program
California Energy Commission

Beth Chambers
Contract Manager

Kelly Birkinshaw
Program Area Lead
Energy-Related Environmental Research

Laurie ten Hope
Office Manager
Energy Systems Research

Martha Krebs
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

B. B. Blevins
Executive Director

Acknowledgments

The work described here is an extension of the initial work by Dr. R. Scott Anderson of Northern Arizona University (NAU) and colleagues Drs. John Barron and Scott Starratt at the U.S. Geological Survey (USGS) in Menlo Park. The present work was organized by Lydia Roach, Dan Cayan, and Michael Dettinger at Scripps Institution of Oceanography, with support from Anderson and Barron (USGS Menlo Park), Jan van Wagtendonk (USGS, Yosemite Park) and Yosemite National Park Resources management (Jim Roche and Joe Meyers). Funding for this new effort to obtain and analyze freeze cores from Swamp Lake was provided by the California Energy Commission's Public Interest Energy Research (PIER) Program and by the National Science Foundation.

Please cite this report as follows:

Roach, Lydia, and Dan Cayan. 2007. *Climate Variability of the Sierra Nevada over the Last Millennium: Reconstructions from Annually Laminated Sediments in Swamp Lake, Yosemite National Park, California.* California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-044.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's Public Interest Energy Research (PIER) Program established the **California Climate Change Center** to document climate change research relevant to the states. This Center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

Climate Variability of the Sierra Nevada over the Last Millennium: Reconstructions from Annually Laminated Sediments in Swamp Lake, Yosemite National Park, California is the final report for the Swamp Lake portion of the Climatic Data Collection, Analyses, and Modeling project (contract 500-02-004, work authorization MR-025) conducted by Scripps Institution of Oceanography.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

Table of Contents

List of Figures

Abstract

Severe drought and other climate anomalies in the western United States have the potential for devastating and long-lasting environmental and socioeconomic impacts. This study aimed to reconstruct climatological and hydrological conditions of the Sierra Nevada Mountain range over the last millennium through physical and geochemical analyses of annually laminated lake sediments from Swamp Lake in Yosemite National Park. This lake's location in an isolated catchment on the western slope of the Sierra Nevada mountains makes it the ideal setting from which to study hydrological fluctuations in the range and their connection to established basin-scale modes of climate variability. Sediment cores were extracted from the lake using the freeze core method, a technique that preserves fine laminated structures, including the most recent and highly unconsolidated sedimentary layers. Quantifications of lamination thickness, which have been shown in previous studies to correlate with aspects of regional moisture budget, may demonstrate how these aspects have fluctuated in the region surrounding Swamp Lake over the last millennium, and geochemical analysis of the organic-rich sediments may reveal further insight into the area's changing climate. This is an interim status report. The final report will provide crucial information about how the hydrology of this region, which contains vital fresh water reserves for California's growing population, will respond to a changing climate over the twenty-first century.

Keywords: Paleoclimate, Sierra Nevada mountains, drought, lake sediments, varves, Yosemite, Swamp Lake

Executive Summary

Introduction

Potential climate change and a growing demand for fresh water in the western United States (henceforth "the West") in the twenty-first century leaves this region highly vulnerable to severe drought and the resulting widespread environmental damage and socioeconomic disruption. Analyses of instrumental climate data demonstrate a clear connection between documented modes of climate variability, such as the El Niño Southern Oscillation (ENSO), and arid conditions in the West. Paleoclimate reconstructions generated from geologic archives such as tree rings, lake sediments, and fossil corals suggest that these connections have been operating for at least the last 1000 years. Also, at certain periods over the last millennium, the West was witness to droughts of greater magnitude and duration than any in recorded history.

Purpose

This study sought to better understand paleoclimatic conditions in the West through the collection and analysis of sediment cores from Swamp Lake, which is located in an isolated catchment at the northwest corner of Yosemite National Park.

Project Objectives

This study had four objectives:

1. Create a time series of the hydrologic variability of Swamp Lake and the surrounding region through the analysis of morphology and thickness of sedimentary laminations.
2. Compare this time series to others throughout the West to assess the timing and coherency of major climate fluctuations throughout the last millennium.
3. Determine the quality with which climate information is recorded in the sedimentary archive through a comparison of the uppermost sedimentary layers with the instrumental record of the last several decades.
4. Use geochemical methods to further clarify the paleoclimate information stored in the Swamp Lake sediments.

Project Outcomes

For this project's first stage, which is reported here, the research team acquired a set of core samples from Swamp Lake's uppermost sediments, conducted a preliminary visual assessment, and developed plans for their analysis. First, researchers extracted six sediment freeze cores from Swamp Lake and transported them intact to a freezer facility at the Scripps Institution of Oceanography. The team then took high-resolution digital photographs of the cleaned frozen core surfaces to use in conducting lamination morphology analyses—specifically, quantifying the thickness of individual laminations. To further examine the structure and separate components of the fine laminations, subsamples were imbedded and cured with an epoxy resin.

Thin sections were then cut from the resulting inert blocks and examined by light or scanning electron microscopy. Photography and resin impregnation will be conducted at the Limnological Research Center at the University of Minnesota in Minneapolis, Minnesota.

An accurate age-versus-core-depth chronology must be established before a time series of climate variability can be assembled. Methods for creating this age model include counting of annual laminations from the digital images and making geochemical measurements of radiogenic sedimentary components, such as carbon 14 (^{14}C). The research team intends to employ both methods, with carbon-14 measurements made at the University of California, Irvine and/or the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory, with other radiogenic measurements made at the Scripps Institution of Oceanography. A comparison of the instrumental record of climate variability with the proxy record of the uppermost sedimentary layers can be made against an accurate chronology and will serve as a "Rosetta Stone" for understanding the paleoclimate information extracted from deeper in the cores.

Once these relatively non-invasive techniques have been carried out, the cores will be sampled and submitted for geochemical analyses. For example, the organic-rich sediments will lend themselves well to measurements of the stable isotopic variability within specific organic compounds, which has been shown to reflect fluctuations in surface air temperature and the partitioning of precipitation in rain and snow.

Benefits to California

This study's results will help researchers construct the climatologic framework within which the Sierra Nevada mountains—the major source of California's water supply—has operated over the last millennium. This framework can then be projected onto the coming decades, to evaluate how California's hydrology may vary in the future and to provide insight into how it will respond to climate change. Such information is crucial in the face of an already warming climate and a continually growing water demand.

1.0 Introduction and Purpose

Growing population and potential climate change pose major threats for water quality, quantity, and distribution in the western United States over the coming decades. Highlighting the need for water resources preparedness is evidence from paleoclimate reconstructions indicating that during the early part of the last millennium this region was witness to droughts of greater duration and severity than any occurring in recorded history. This aridity coincided with a period of anomalous warmth in much of the Northern Hemisphere often referred to as the *Medieval Warm Period* (MWP). Evidence for the MWP "mega-droughts" has been unearthed from a variety of geological archives, including tree rings, lake sediments, and drowned tree stumps. A clear connection of more recent droughts with the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) modes of climate variability has been established, and proxy records of these indices over the last 1000 years suggest that this connection was likely operating during the MWP as well.

While reconstructions provide a broad-scale picture of hydrological evolution of the western United States over the last 1000 years, many questions remain regarding the timing and regional distribution of climate variability throughout this time, and to what extent evidence of that variability is preserved in geological proxy records. Furthermore, a high-quality instrumental record of broad spatial coverage reaching back several decades can be compared to the most recent geological archives, to assess the quality and coherency with which preservation is achieved. This study's purpose was to tackle the issues mentioned through the collection and analysis of sediment freeze cores from Swamp Lake in Yosemite National Park.

Located at the northwest corner of Yosemite National Park (37º57'N, 119º46'W, 1554 meters [m] elevation), on the western side of the Sierra Nevada crest (Figure 1), Swamp Lake provides a rare setting from which to obtain high-quality sediment cores potentially documenting hydrological variability of the region over the last millennium. The lake is a flat, relatively deep (~ 20 m) basin surrounded by steep sides and has a surface area of about 0.64 hectares. The lake sits in an isolated catchment with a single seasonal inlet and no distinct outlet, but rather, a broad swampy overflow at the west end and, presumably, groundwater seepage. Protected within the confines of one of the country's oldest national parks, Swamp Lake has received negligible human impact, its sediment input undisturbed throughout the Holocene epoch. Although localized storms bring rain in the summer, the primary source of moisture to the Sierra Nevada region originates from snowpack at high elevations. Fluctuations in annual precipitation in the mountain range are linked to basin-scale climate anomalies over the Pacific Ocean, including the El Niño/Southern Oscillation and the Pacific Decadal Oscillation.

A project initially funded by the Yosemite Fund on expeditions to Swamp Lake, led by Dr. R. Scott Anderson of Northern Arizona University during the summer of 2001, revealed that the upper few meters of sediment from the deeper parts of the lake are annually laminated (varved). The formation of varves requires anoxic conditions at the bottom of the water column, which occurs when seasonal overturning does not penetrate to these depths (i.e., meromictic conditions). Numerous studies from high-latitude nival lacustrine settings have demonstrated a correlation between varve thickness and morphology with hydrological variables such as snowpack, spring snowmelt discharge, and annual runoff. The Swamp Lake cores therefore offer a unique opportunity to investigate fluctuations of these variables in the Sierra Nevada of over the last millennium through the analysis of the sedimentary varve structure.

An obstacle to recovering a usable sedimentary record is that the upper, most recent sediment in the lake is an uncompacted, soupy slurry at the lake bottom's water-sediment interface, and thus is difficult to extract without stirring these up and destroying the layered structure. Thus, most mechanical coring techniques are not able to preserve the upper sediment in its layered, undisturbed form. Fortunately however, by using a freeze corer (see Section 2), the most recent sedimentary layers can be captured undisturbed, allowing for the climatological information obtained from this geologic proxy to be directly compared with instrumental records compiled over the last few decades. The chronology and the biological, physical, and geochemical measures contained in these layers provide a Rosetta Stone for the translation of proxy records.

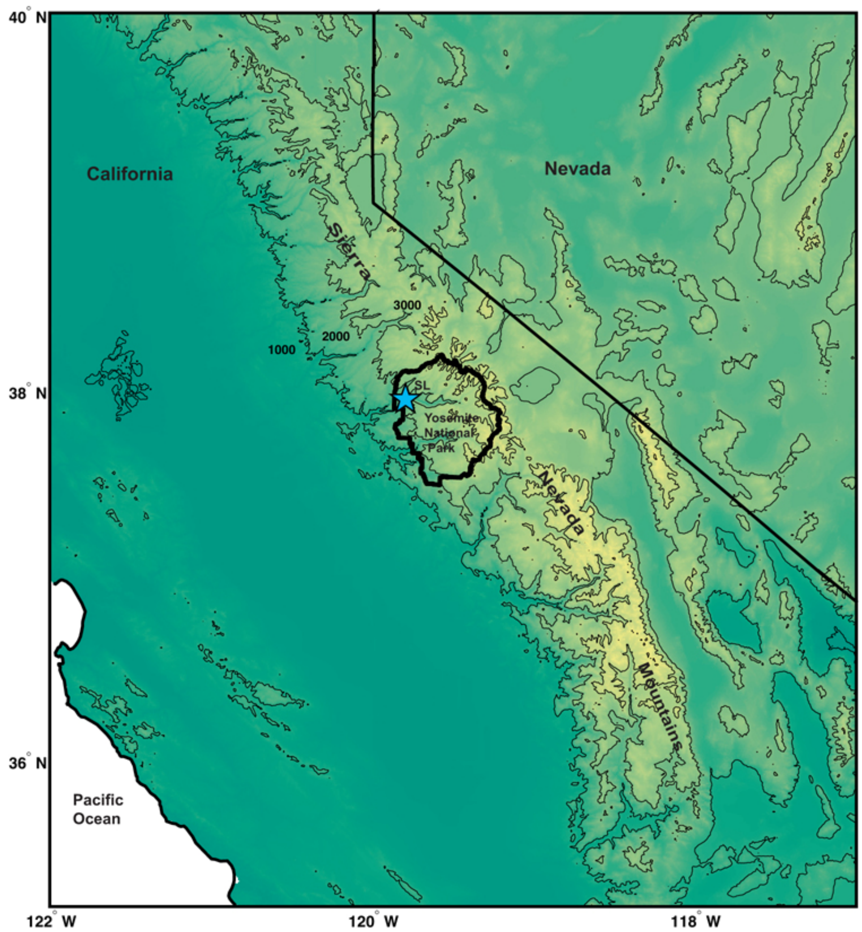

Figure 1. Location of Yosemite National Park along the crest of the Sierra Nevada Mountain Range. Swamp Lake is located in the northwest corner of the park (indicated by blue star). Contours in meters.

A component that is of interest here is the prospect of translating varve thickness into quantitative measurements of hydrological variability over the last millennium. The collection of these crucial upper several hundred years of sediment layers, while advantageous in its own right, should also provide an invaluable complement to the earlier coring expedition to this lake, at which time sediment deposited over the last few decades was not obtained.

2.0 Fieldwork and Initial Processing

Six sediment freeze cores were successfully collected from Swamp Lake during a field expedition carried out in October 2006. All six coring locations were distributed around the deepest section of the lake (Figure 2). The freeze coring technique entails lowering a hollow, weighted, aluminum wedge filled with a dry ice-ethanol slurry into the sediment, letting this sit for 10–15 minutes to freeze the upper sediment to the aluminum, and then pulling up the wedge and the crust of frozen sediment that surrounds it (Figure 3). This method is able to extract material without disturbing fine sedimentary structure, and is especially well-suited for capturing the upper, less-consolidated layers, including the sediment water interface. The frozen sedimentary wedge is then removed from the aluminum, wrapped in plastic, and placed in coolers. Using a portable raft (Figure 4) borrowed from S. Anderson and 400 hundred pounds of dry ice, six cores were obtained in one day's work on October 10, 2006. The sediment water interface and upper sedimentary layers were successfully obtained on five of the six cores extracted (Figure 5).

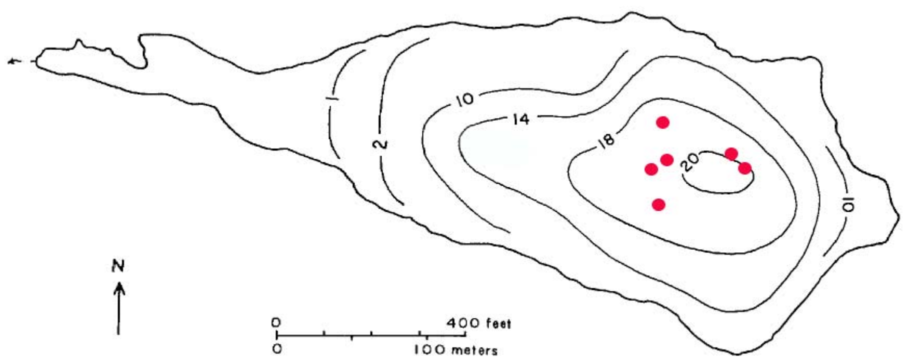

Figure 2. Map of Swamp Lake bathymetry with locations of six cores marked in red. The depth is in meters. (Modified from Smith and Anderson 1992).

Using pack stock and human porters (Figure 6), the cores and the coring gear were carried to and from Swamp Lake approximately seven miles from the road end point at Hetch Hetchy Reservoir. The pack stock ferried the gear and supplies from Hetch Hetchy to a base camp at Miguel Meadows Ranger Station, approximately one mile from Swamp Lake. The trail from Miguel Meadows to Swamp Lake had been overgrown and obscured by downed trees from a wildfire approximately 10 years before, but had been marked by U.S. Geological Survey (USGS) and Yosemite Park scientists Jan van Wagtendonk and Kent van Wagtendonk. Jan van Wagtendonk and a colleague Paul Gallez provided orientation to the lake during the first day of packing in gear. In addition to the coring work, two water level and water temperature loggers and a small air temperature logger were installed to record environmental conditions in and around Swamp Lake during the next year. The coring party consisted mainly of six members, shown in Figure 7.

(a)

(b)

Figure 3. (a) Aluminum wedge just pulled out of the water with sediment and lake water frozen along the outside; (b) The frozen sedimentary wedge just removed from the aluminum corer.

Figure 4. Raft used as coring platform, borrowed from R. Scott Anderson of Northern Arizona University

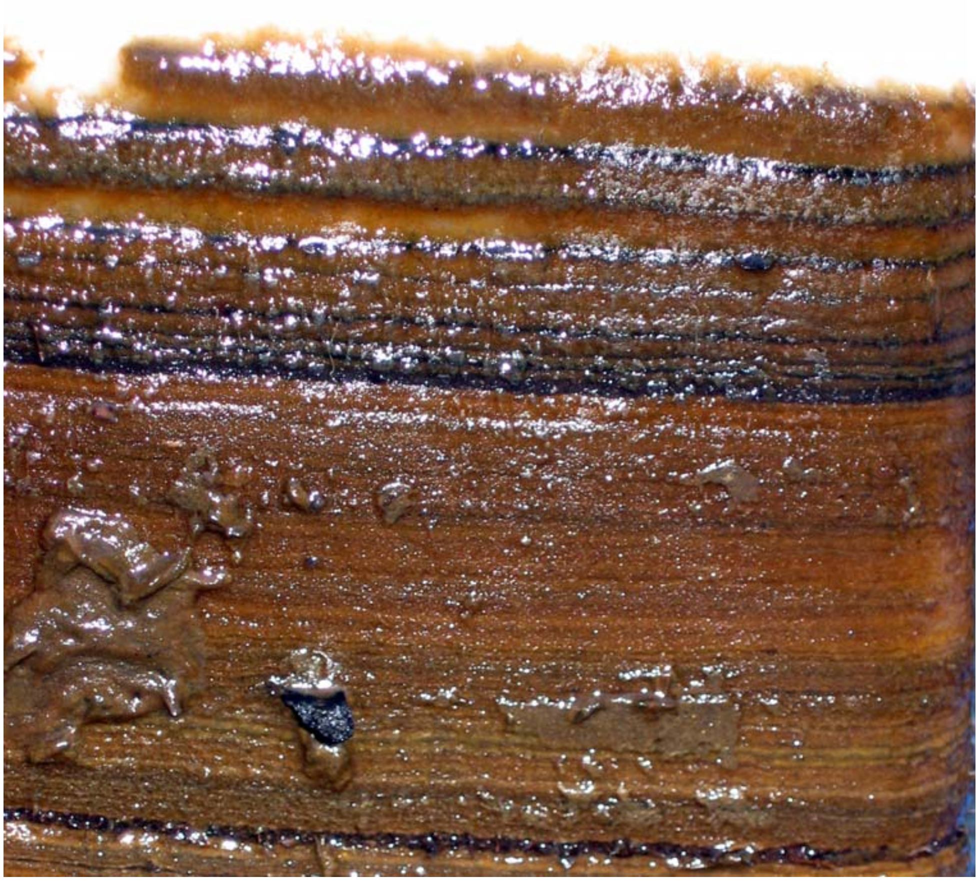

Figure 5. Photograph of upper sedimentary layers captured undisturbed, including the sediment water interface

Upon completion of fieldwork, the six cores were transported to a -25°C freezer at Scripps Institution of Oceanography. In the freezer, cores were slabbed, with two slabs created from each of the six frozen wedges. The slabs were divided into a set devoted to near-term analyses and a second set that is archived for later analyses. Some of the material will be distributed to collaborators S. Anderson at NAU and S. Starratt at USGS in Menlo Park. Core lengths range from 45 to 70 cm and they are all approximately 1–2 centimeter (cm) thick and 10 cm wide.

Figure 6. (top) Pack stock transporting coring equipment to Miguel Meadows Ranger Station. (above and left) Coring party members Josh Baccei and Sam Siemens (left) and Lydia Roach and Jane Teranes carrying equipment the final one mile from Miguel Meadows Ranger Station to Swamp Lake

Figure 7. Members of the coring party outside Miguel Meadow Ranger Station. From left to right: (back row) Sam Siemens, Josh Baccei, and Erik Ekdahl; (front row) Dan Cayan, Jane Teranes, Lydia Roach, and Patrick Rafter.

3.0 Outcomes

All six cores display two sections of clear laminations (Figure 8) separated by a massive unlayered section of varying thickness depending on core location (the section thins towards the north bank). Preliminary inspection of the sedimentary structure indicates that this section was laid down in two parts: an instantaneous deposition of larger, poorly sorted grains and a subsequent settling out of finer suspended grains. This structure suggests this deposit is most likely the result of a bank failure rather than an extended period of bioturbation.

Although varve thickness is quite thin, having millimeter to sub-millimeter thicknesses, light/dark couplets are visible to the naked eye. Scanning electron microscope (SEM) imaging carried out by Alan Kemp of University of Southampton on Livingston cores obtained from the earlier expedition (Figure 9) reveal that these couplets generally consist of a biogenic laminae, with diatomaceous ooze and organic-rich components, and a mineralogenic laminae composed of fine sand, silt, and clay. Preliminary x-radiographs of the core carried out at the University of California Medical Center (Figure 10) reveals that the density contrast between these coupled layers is too weak to resolve fine-scale varve structure using x-radiography. However, distinct layers of elevated density stand out in these images, suggestive of storm or fire events that lead to unusual sedimentary deposition. This initial probing of the Swamp Lake core obtained both in 2001 and on this most recent expedition demonstrates the need for a series of more thorough, detailed analyses in order to extract the wealth of information potentially stored therein.

4.0 Proposed Analyses

The first step in analyzing sediment structure will be to create a library of digital images from which varve characteristics can be quantified. These images will be especially useful because the frozen state of the original core material, although ideal for preserving fine laminations, makes this material difficult to work with directly. High-resolution digital photographs will be generated at the Scripps Institution of Oceanography from which to begin this process. In addition, however, because Scripps does not have a lab with equipment devoted to processing lake cores, further, more comprehensive analyses will be conducted at the Limnological Research Center at the University of Minnesota in Minneapolis, Minnesota. This facility is equipped to perform numerous processing techniques, including the impregnation of sediment with low-viscosity epoxy resin. This technique, which entails displacing the water within the core with a solvent that is subsequently displaced by a low-viscosity resin, produces solid, inert blocks, stable at room temperature that provide a stable, preserved substrate for certain forms of further processing such as digital scanning, photography, and electron microscopy. The epoxy resin technique has been employed for this purpose by numerous investigators with great success.

The research team also plans to combine radiometric dating and varve counting, to create as accurate an age-depth chronology as possible. Three to five carbon 14 (^{14}C) dates will first be made for each core at the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at University of California, Irvine, and/or the Center for Accelerated Mass Spectrometry at Lawrence Livermore National Laboratory followed by ^{210}Pb and ^{137}Cs measurements at Scripps Institution of Oceanography. The research team intends to quantify varve thickness through digital scanning and grayscale analysis. From the resulting time series, the research team hopes to reconstruct aspects of the hydrological history of Swamp Lake and the Sierra Nevada mountains, and compare this record to available instrumental records of precipitation and streamflow—as well as to previous reconstructions of climate history in the western United States over the last millennium.

Beyond these immediate analytical exercises, the research team intends to conduct geochemical analyses to extract other paleoclimatological information. For example, the deuterium isotope concentration in organic material has been shown in other limnological studies to correlate with surface air temperature. Because Swamp Lake sediments are organic-rich, they may be well-suited for this technique. A comparison of air temperature with hydrological conditions, especially during episodes of the MWP, when it is thought there were "mega-droughts," would shed light on the climate of southern California and the western United States during a very important period of the modern Holocene climate. Having a better description of the precipitation, temperature, and other environmental characteristics during these dry spells would be especially useful in scoping for potential changes in California's hydroclimate in the face of potential climate warming over the coming decades and centuries.

Figure 8. Photograph depicting massive section bounded above and below by laminated sediments

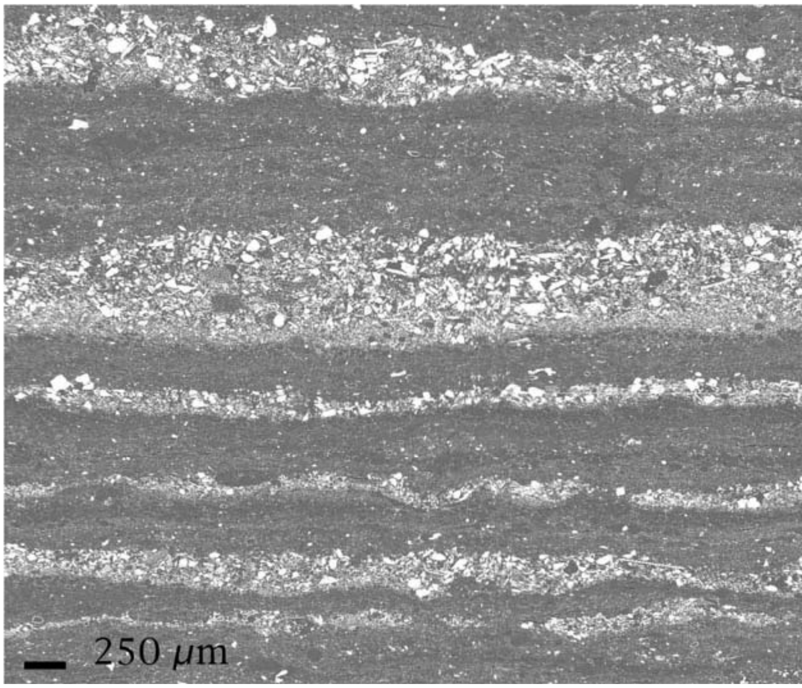

Figure 9. Scanning electron micrograph of a section (467–483 cm) from a Livingston core removed from Swamp Lake in 2001. Light/dark couplets are clearly visible with lighter bands consisting of mostly mineralogenic material and darker bands primarily organic material and diatomaceous ooze. Although sediment was not captured nearly this deep, this image is representative of the clear laminated structure. (Image provided by A. Kemp, 2004).

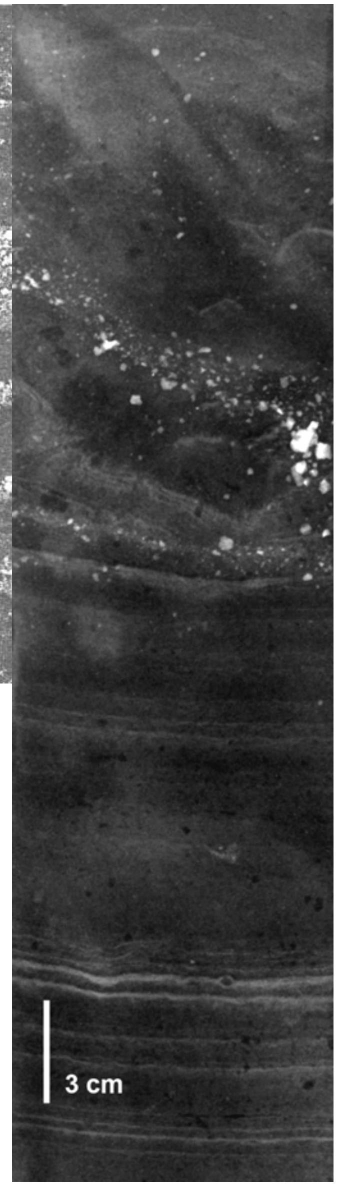

Figure 10. X-radiograph of the lower section of Core 3. The poorly sorted grains at the bottom of the massive section are visible, as well as a layer of disturbed laminations directly below this section. Numerous high-density varves are also visible.

5.0 References

Smith, S. J., and Anderson, R. S. 1991. "Late Wisconsin Paleoecologic Record from Swamp Lake, Yosemite National Park, California." *Quarternary Research* 38: 91–102.