DEPARTMENT OF INTERIOR

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REPORT OF A WORKSHOP ON THE CORRELATION OF MARINE AND TERRESTRIAL RECORDS OF CLIMATE CHANGES IN THE WESTERN U.S.

by

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INTRODUCTION AND OBJECTIVES (J.V. Gardner, and A. M. Sarna-Wojcicki)

A workshop was held at Pájaro Dunes, Watsonville, CA in January, 1991 as part of the USGS Climate Change Program to organize and coordinate a project to correlate marine and terrestrial paleoclimatic records from the western U.S. and eastern North Pacific Ocean. The focus of the project is to develop detailed, high-resolution paleoclimatic records of the last 130,000 years, with as many climate proxy variables as possible, and a time resolution of 1,000 years or less. The workshop convened a group of experts from the USGS and the academic community (participants are listed in Appendix I) to:

- prioritize potential sites to obtain long sediment cores in the western U.S. and the eastern North Pacific Ocean,
- identify the preferred methods and equipment for coring the proposed terrestrial and marine sites.
- discuss the logistics of sample treatment and archival and development of a database.
- review and discuss the best stratigraphic correlation and dating techniques to apply to these cores.

This report outlines the organization and objectives of the project and summarizes the consensus of the workshop on the above four topics.

Background

The western United States and eastern North Pacific Ocean were chosen for the focus of this project because the eastern North Pacific, dominated by the North Pacific High, the Aleutian Low, and the western U.S. Low, not only generates the dominant weather and climate of the western U.S., but effects the climate of the entire northern hemisphere (e.g., Namias and others, 1988). Changes in the positions and strengths of these atmospheric cells through time have had a profound influence on the environment of the western U.S. These cells control the position and strength of the California Current system, a large heat sink that extends along the western U.S. from about 50°N south to Baja California, a distance of ~3,000 km. This belt of cold, upwelling, nutrient-rich surface water modulates the coastal climate of western North America. The history of development and fluctuation of the California Current system is almost completely unknown but the system did respond to ENSO (El Niño-Southern Oscillation) events, based on historic records (Quinn and others, 1987) as well as varve-calibrated late Pleistocene and Holocene marine sedimentation events (Gardner and Hemphill-Haley, 1986; Gardner and others, 1988; Anderson and others, 1987; 1989; 1990).

Many studies over the past 25 years have shown that this region has been responsive to climate changes during the Pleistocene and Holocene. For example, marine plankton floras and faunas have shifted between polar and transitional assemblages; pollen spectra from coastal lakes have fluctuated between pine-dominated and oak-dominated assemblages; and, based on geochemical and micropalentological data, many of the lakes immediately east of the Sierra Nevada have undergone major swings in salinity. However, most of these records have not been accurately dated with modern methods, many have not been continuously cored, and virtually none of them have been unequivocally correlated to each other.

Project Objectives

The objectives of the project are to collect and correlate comprehensive, high-resolution, regional paleoceanographic, paleolimnologic, and paleoclimatic records from the western U.S. and eastern North Pacific Ocean. The high-resolution correlation of these records will allow us to map the paleoclimatic responses to changes in oceanic and atmospheric circulation of this sensitive region. The project is a relatively large, multidisciplinary attack on specific target areas that have a direct marine-continental tie, as demonstrated by the studies of Gardner and others (1988), Heusser (1988), and Sarna-Wojcicki and others (1985; 1987; 1988). We will concentrate on the past 130,000 years with a general temporal resolution of at least 1,000 years. Longer records, extending back 700,000 years or longer, may be obtained as time, equipment, and costs permit. The reconstructed sequences will include two major climatically warm intervals, the mid-Holocene and oxygen-isotope stage 5e, as well as the last glacial period and Termination I (oxygen isotope stage 2/1 boundary), a period when very rapid and extreme climatic changes occurred. This study will attempt to determine the climatic forcing and responses, reconstruct patterns of major air masses in the western U.S. and eastern North Pacific, and determine whether the California Current system responded in a quasi-periodic, linear manner to global climatic forcing, or if the response was nonlinear and unique. The longer records will be used to further assess synchroneity, leads, and lags between climatic forcing and responses between the marine and terrestrial records. The three foundations of the study are detailed *correlations* of the various marine and terrestrial records, *chronological ties* to an absolute time scale with the highest possible precision, and *paleoclimatic interpretations* of suitable proxy records..

Chronostratigraphy is an essential aspect of this project. Each record we collect and analyze must be very accurately dated with the highest precision and correlated with other records, and accuracy available. We anticipate that AMS ^{14}C dating will be our standard for shorter records, supplemented with U-series dating, stable-isotope and magnetic–susceptibility stratigraphy, tephrochronology, and laser–fusion $^{39}Ar/^{40}Ar$ dating. AMS ^{14}C dating will give us a resolution of

10^1 yrs and can reliably be used in sequences as old as about 40 ky. $^{18}O/^{16}O$ stratigraphy will be required from all marine sections to correlate with the SPECMAP global isotope curves. This isotope technique will allow us a dating precision of about 10^3 yr and extends throughout the Holocene and Pleistocene. Varves in some marine and lacustrine sequences will provide annual resolution, once carefully dated, but these are relatively rare in the marine record.

Several terrestrial paleoclimate records exist from the west coast. Various types of data are available from these sites to suggest that they contain high-resolution histories of the response to climatic changes that occurred during the last 1 My (Fig. 1). However, very few of these terrestrial sites contain an uninterrupted history of the Late Quaternary and Holocene and most have not been subjected to multidisiplinary high-resolution studies. Few paleoclimatic studies have been done on marine cores largely because they were collected for other purposes, such as sedimentological or geochemical studies. However, reconnaissance work has shown that several marine cores in hand at the USGS and Oregon State University probably contain records comparable to the terrestrial sections (Fig. 2). The existing marine cores are relatively short and none of them are calibrated by an independent, accurate chronology (e.g., magnetostratigraphy, tephrochronology, AMS ^{14}C dating). A few of the cores have been analyzed for oxygen isotopes (Fig. 2; Gardner and others, 1988; N.G. Pisias, personal communication, 1991) and the results showed the presence of the globally recognized pattern of $^{18}O/^{16}O$ fluctuations. Lastly, there has been little effort to make convincing physical or temporal ties between the Quaternary sections of the marine and terrestrial records in this region. We propose that climatically sensitive marine and terrestrial sites be identified, intensively studied and, where necessary, the sites be resampled and accurately dated so that the data from these paleoclimatic histories can be directly correlated. For example, continental sites near the Klamath River in south-central Oregon should be correlated with marine cores on the continental slope west of the mouth of the Klamath. Land sites such as Mono, Owens, and Tulare Lakes in central California should be correlated with marine records from the continental slope off south-central California; and

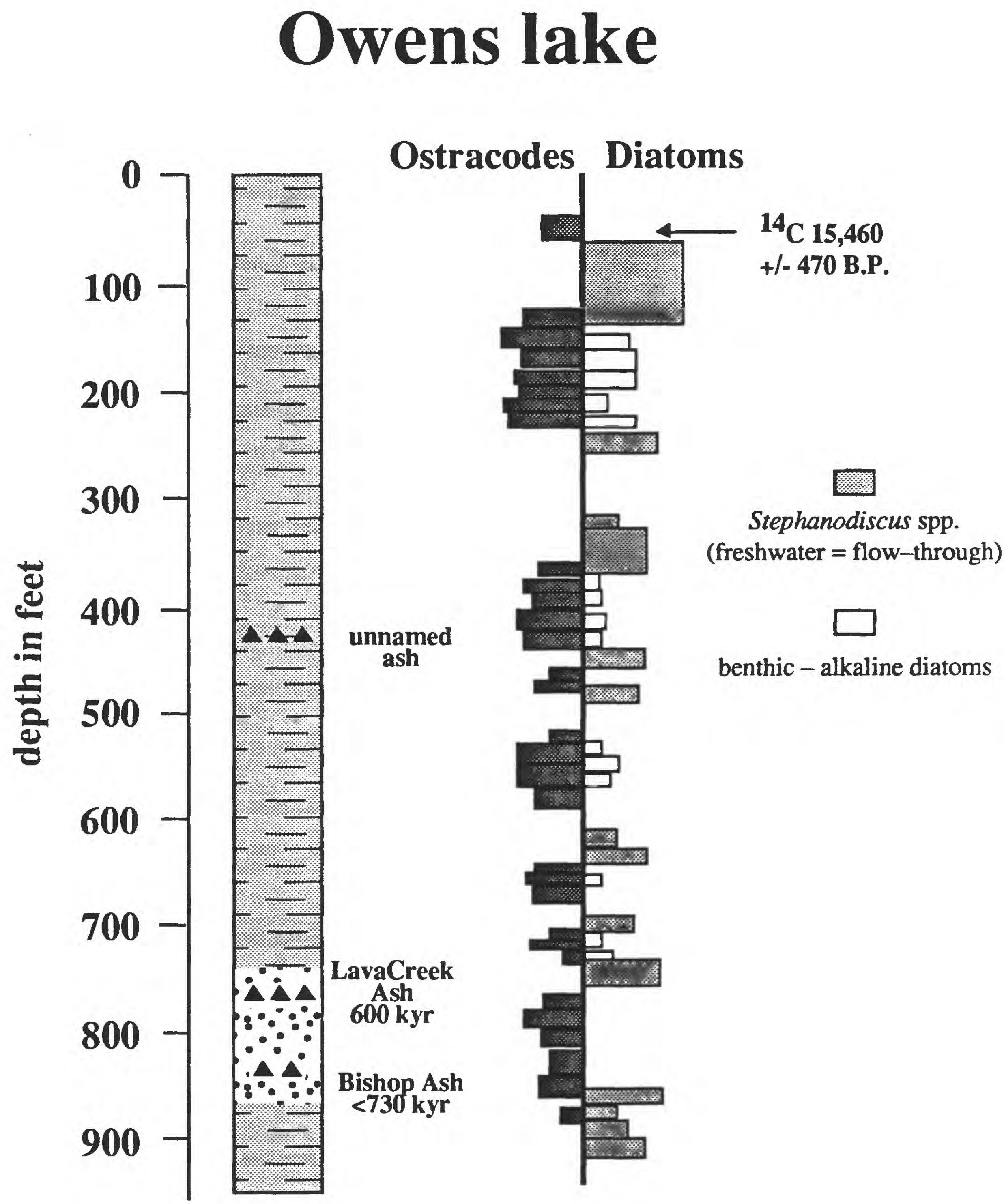

Figure 1. Semiquantitative evaluation of ostracode (dark histogram) and diatom abundance in core (Owens Drill Hole #1) from Smith and Pratt (1957). Gray diatom histogram represents dominance by *Stephanodiscus* species that indicate freshwater and probably flow–through conditions in Owens Lake. White diatom histogram indicates benthic diatoms of alkaline water suggesting non– or only intermittent drainage of Owens Lake.

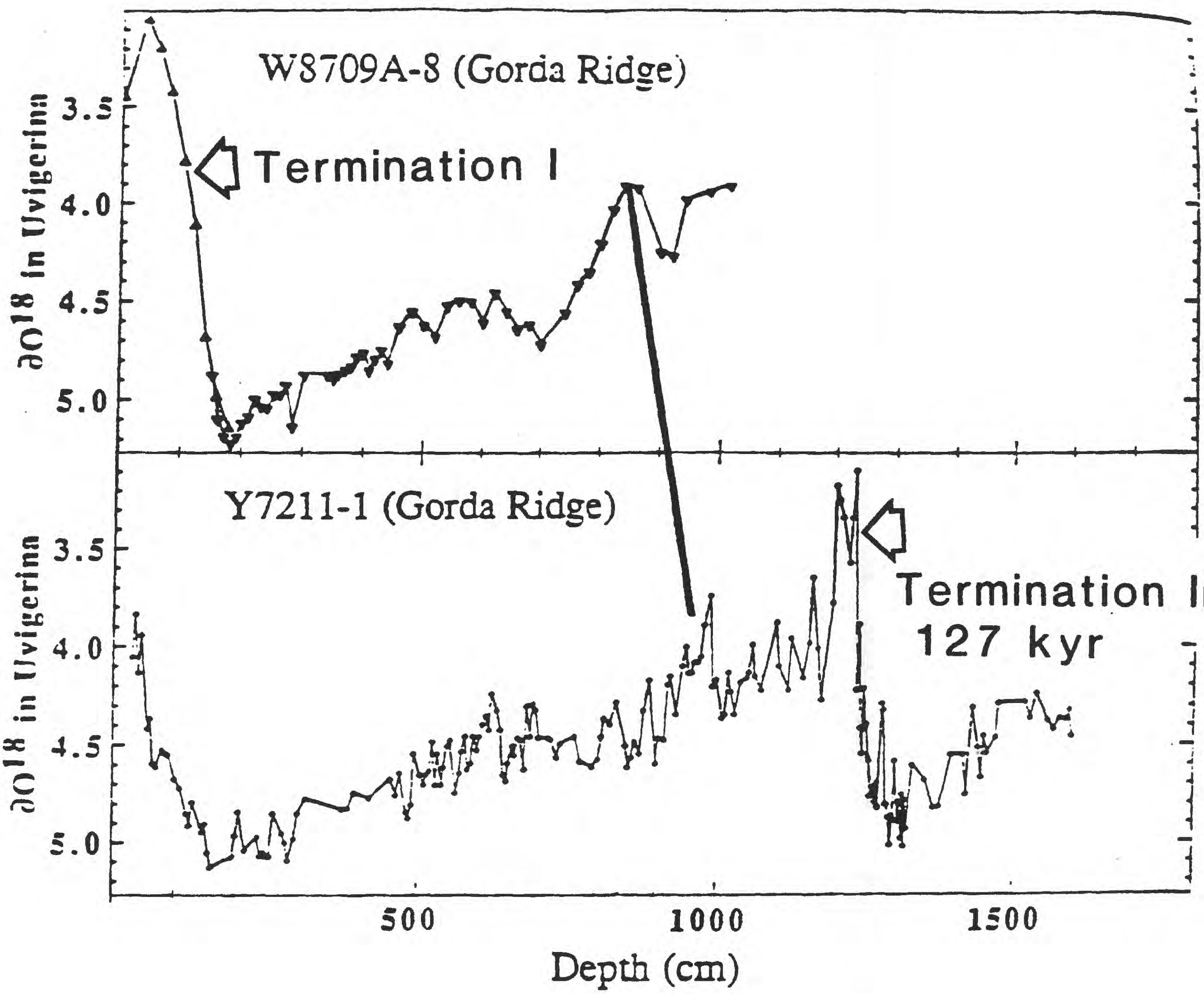

Figure 2. Oxygen-isotope curves from two cores from the eastern flank of Gorda Ridge (N.J. Pisias, unpublished data). The two cores can be correlated with confidence using the oxygen-isotope data and easily correlated to the globally recognized Quaternary oxygen-isotope curve. Terminiations I and II represent rapid deglaciation.

terrestrial sites in central Arizona should be correlated with marine sections cored in the northern Gulf of California or the eastern Pacific Ocean at comparable latitudes.

The reconstruction will provide the regional calibration needed by modelers to determine the specific relationships between climate-forcing factors and climate responses, which can then be used as a predictive tool. For example, we would like to be able to determine the nature and magnitude of sedimentological/ hydrological responses in terrestrial areas in relation to climate-proxy signals, such as variations in oxygen isotopes, in the marine record. Only with this type of spatial distribution of high-resolution temporal responses will we be able to map the effects of global climatic changes on the western U.S. and eastern North Pacific Ocean. Ultimately, we plan to construct a series of east-west marine-terrestrial transects between Washington and southern California or beyond. These will bracket the California Current system and provide the basis for a four-dimensional grid of sites across the western U.S. that describes the changes in climate-related factors through time and space.

ROLE OF THE PROPOSED PROJECT RELATIVE TO OTHER CLIMATE CHANGE STUDIES

Within the broader perspective of Climate Change Studies, the long-term strategy of our project, together with that of the companion Western Varved Lakes Project (a detailed study of climatic variations in mid- to late Holocene varved sequences), is to

• interpret high-resolution Holocene climate-proxy parameters by comparing them with historic records of climate and weather;

• interpret Holocene and pre-Holocene climate-proxy parameters (to 130,000 yrs or longer) by reference to the historic-Holocene record developed above,

• identify regional variations in the high-resolution records from site to site to explain the nature and timing of climatic changes in this region,

• provide numerical modelers with the baseline data necessary to determine: (a) whether the rates and magnitudes of historic changes in climate are significant relative to the longer-term prehistoric records that have been defined; (b) whether these historic changes are significantly different in intensity or rate from the spectrum of pre-historic natural climatic changes (i.e., is it likely that the changes can be attributed to human activity); and (c) what are the most probable specific prognoses for future climate change based on present and past observations. The baseline data we are able to provide to the numerical modelers for this study region will be critical to the solution of these broader societal questions (a-c).

CRITERIA FOR SELECTION OF SITES FOR CORING

A number of criteria were identified at the workshop as necessary or desirable attributes of candidate sites for the development of high-resolution climate records. Among the more general scientific requirements are that the preserved stratigraphic record exhibit:

- Sufficient duration (at least 10 ky for high-resolution records; at least 100 ky for long-term records)
- Continuity; i.e. have few or no hiatuses; and
- A sufficiently rapid depositional rate for the resolution required.

These requirements generally restrict candidate terrestrial sites to lakes or other closed basins and are problematical for most single marine sites. Corollary general comments applicable to such basins along the Pacific borderland and Great Basin are:

- Sites in northern Washington and farther north probably were covered by the Wisconsinan Cordilleran ice sheet, and records longer than about 10 ky are likely to be at least partly destroyed.
- Sites within the western Cordillera at higher altitudes probably suffered the same fate as the more northern sites from Wisconsinan Alpine glaciation.
- Sites in southern Washington are part of a well-integrated drainage system; rapid erosion and deposition in this area generally preclude the existence of long-lived lakes or closed basins

- Sites at the more southerly latitudes within the Pacific borderland (south of about 34-35° N latitude), and farther east within the Great Basin (east of about 117° W longitude) are likely to have been dry during warm/dry periods, and are thus more likely to have incomplete records due to non-deposition, deflation, and erosion.

- Candidate terrestrial sites should have a high potential for physical and/or temporal links with marine sites, although in many cases the existence of such links cannot be determined prior to sampling and analysis (see discussion on correlation and stratigraphy below).

These observations generally focus the search for site selection to the area south of Washington state, west of about 117° W longitude, and north of about 35° N latutude, although favorable sites also are found outside these boundaries.

Functional criteria such as accessibility, ease or cost of drilling, and prior knowledge of the stratigraphic record and hydrologic history of a basin through previous drilling or other studies are also important considerations. One consensus of the workshop participants was that sites selected for drilling would have to meet several of the scientific and functional criteria listed above, but that probably no single site would meet them all. Furthermore, it was appreciated that the specific history of a particular basin could have an effect on the quality of its preserved climate record. Factors such as tectonic or volcanic events, drainage changes such as stream capture or sporadic stream diversions, and variation in basin size, shape, and capacity relative to the rate and volume of sediment input can obscure or be confused with climatic signals in the sedimentary record. For this reason we have decided on a strategy that provides for drilling several subsidiary or satellite sites within the general area of an identified priority site, so that we have an opportunity to evaluate the quality of the climatic record, provide independent checks on age control, and eliminate factors that may obscure, or be confused with, the climatic signal. Such a strategy also would provide opportunities for comparing records of different resolutions. For example, a longer record (150+ ky) from a large dry lake basin with a time resolution of about 1 ky, might be supplemented by a shorted record (ca. 10 ky) from a smaller extant lake with much higher resolution, perhaps annual, of the young end of the record.

PRIORITY OF SITES TO BE STUDIED

Terrestrial Sites (A. Sarna-Wojcicki and D.P. Adam)[1]

The workshop participants reached a consensus for the most important terrestrial sites of the western U.S. to be studied by this project. Nearly 50 sites were discussed in detail, and of these 7 sites (Fig. 3 and Table 1) were considered high priority for the objectives outlined above. An additional 7 sites (Fig. 3) were considered to be exploratory in nature but potentially very valuable. The high-priority sites are discussed below in order of priority, followed by a brief summary of the exploratory sites.

Table 1. Priority Land Sites for Coring and Sedimentation Rates.

NAME	PRIORITY	AREA	SEDIMENT. RATES	EST. TIME SPAN (yr)
I.A. Klamath area	1	OR-CA	0.32 mm/yr	160,000 (Tulelake)
I.B. Mono Lake	2	CA	0.63 mm/yr	160,000
I.C. Owens Lake	3	CA	0.39 mm/yr	620,000
I.D. Tulare Lake	4	CA	0.41 mm/yr	620,000 (Tulare Lake)
			0.33-0.44 mm/yr	25,000 (Tulare Lake)
			0.12 mm/yr	620,000 (Wasco site)
I.E. Ruby Marshes	5	NV	0.19-0.39 mm/yr	37,000

IA ***Upper Klamath - South Cascades sites***: The Klamath Lake region offers several basins that provide contrasting depositional environments that have the potential to provide links between the 3-M.y. Tulelake record to the east (Adam and others, 1989) and the series of sediment cores from the

[1]The numbering system adopted for this report uses Roman numeral I for high-priority terrestrial sites, Roman numeral II for high-priority marine sites, and III for exploratory sites. The Roman numeral is followed by a capital letter that represent the priority ranking of each series.

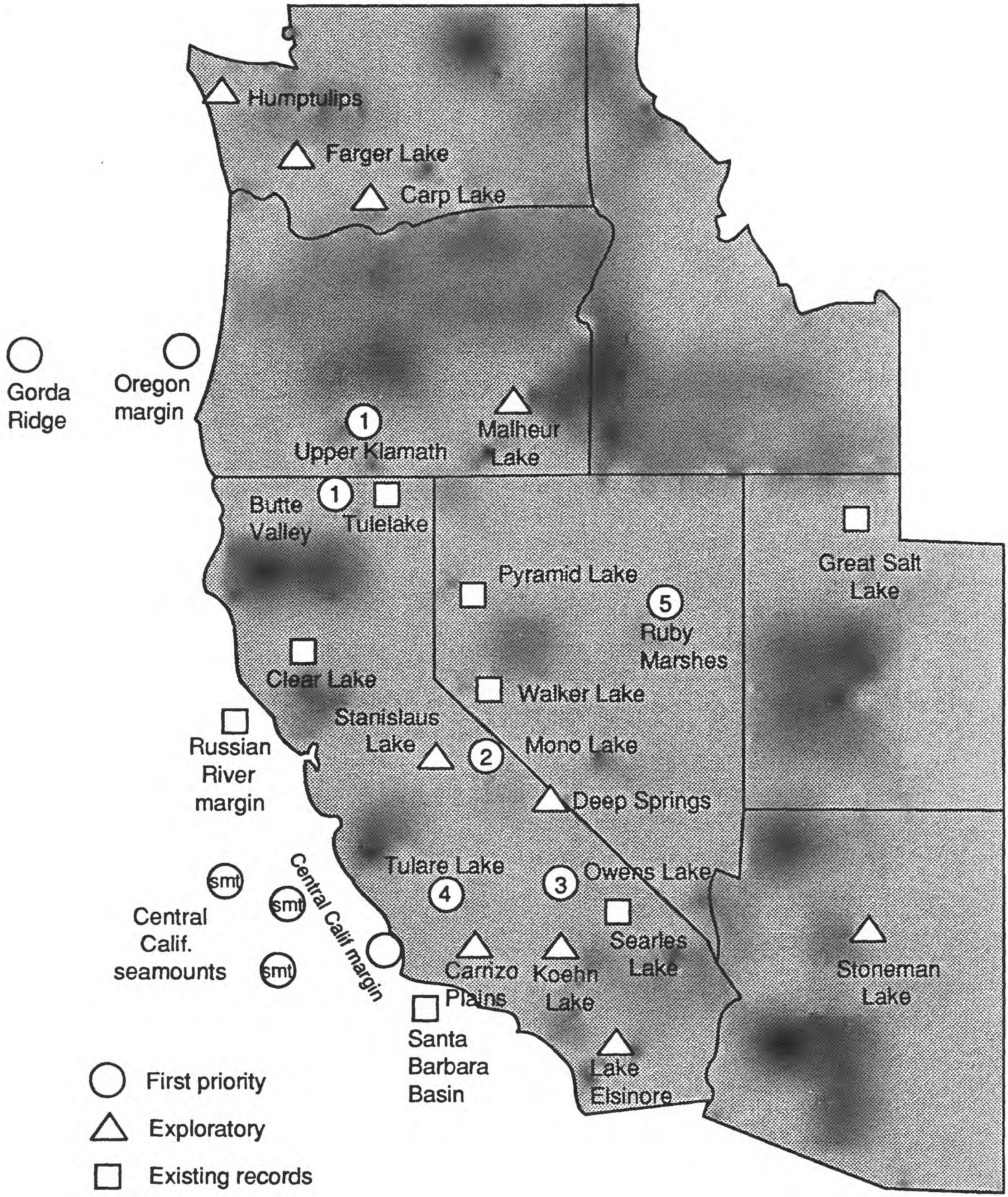

Figure 3. Location of First Priority and Exploratory sites for coring. Sites where several existing records occur are also shown.

Gorda Ridge (see below) and to cores that we plan to obtain from the continental slope near the mouth of the Klamath River in FY92. The initial drilling effort should focus on collecting relatively short (<100 m) cores from several of these basins during the summer of 1991. All of these sites are within the montane forests of the southern Cascades or at the eastern margin of the forest; consequently, the pollen records should be easier to interpret and to link to the pollen records from Gorda Ridge than are those from the more arid Tulelake region to the south. See Appendix I for a detailed description of individual Upper Klamath sites.

I.B. ***Mono Lake, California***: This is a large (16 x 22 km) lake situated within a closed, west-tilted structural basin in east-central California. The basin is downdropped and bounded on the west by the major frontal fault scarp of the high Sierra Nevada which rises to elevations of more than 3800 m a short distance to the west. Present lake level is at about 1950 m, making this one of the highest large lakes in North America, and thus sensitive to climate change. Young rhyolitic volcanoes, the Mono Craters, border the south shore of the lake. These, together with the Inyo Craters and Mammoth Mountain to the south in Long Valley, have produced explosive tephra over about the last 180 ka., many layers of which have been deposited in the lake and basin. Black Point, a late Pleistocene basaltic volcano, sits on the north shore of the lake, and is the source of a ca. 14 ka marker bed present throughout the basin. The lake contains the 2 km-long Paoha Island at its center, a result of uplift due to intrusion and eruption of volcanic rocks in late Holocene time. Two large streams drain into the lake from the high Sierra, with lateral moraines of at least three major glacial advances descending to near lake level, where incised outwash deltas are now exposed by Holocene and artificial lowering of the lake level. Drilling at Paoha Island in 1908 (Scholl and others, 1967, in Lajoie, 1968) indicates that the 738-ka Bishop Tuff is at a depth of 411 m below the lake. Rhythmically-bedded sets of lacustrine diatomite and fine-grained silts continue above the tuff to the top of the sediment section and suggest that sedimentation was climatically controlled, and that lake conditions have prevailed since at least the eruption of the Bishop tuff. No major lakes drain into Mono Lake, so the lake is not a hydraulically "buffered" system (like Owens, China, and Searles Lakes); Mono has spilled into Adobe and Owens Valleys in Quaternary time, but not during the late Wisconsin. The long-term (738 ka-present) sedimentation rate in the lake is 0.56 mm/yr; the shorter-term (170 ka-present) sedimentation rate is a minimum of 0.63 mm/yr, the highest rate for our high-priority sites. Ostracodes are present throughout the section of interest. Pollen is absent in the emergent upper part of the section, and diatoms are absent in the modern lake. Diatoms, however, are present in uplifted sequences on the island, and pollen and diatoms probably are present in unoxidized sediments.

A composite stratigraphic record for about the last 180 ka can be pieced together from uplifted exposures on Paoha Island, combined with emergent sections at the north and south shores of the lake; this record can be augmented by shallow drilling on the east shore of the lake. A single, continuous record for Brunhes time can be obtained by drilling from a barge between the lakeshore and island. Barge drilling would require more lead time for logistics, and could be deferred until FY1992 or later. Much of the above information is from Lajoie (1968), and K. R. Lajoie (personal commun., 1967- 1991), who will be able to participate in FY1992.

A number of satellite sites are available to complement a record from Mono Lake, including Crooked Meadow (Sarna-Wojcicki and Lajoie, in progress), Black Lake, and Fish Lake Valley (Reheis, Slate, and Sarna-Wojcicki, in progress). Mono Lake is probably one of the best single sites in the western U.S. for developing a multi-purpose, long-term, high-resolution record of climatic history. Climatic links using tephra can be established by correlation to small Sierran Lakes and to Tulare Lake in the Great Valley, to the west, which in turn can be correlated by physical links to the marine record off south-central California. Direct links to the marine record by tephra and magnetostratigraphy also are likely. Tephra correlations also have been made for ca. 150-180 ka between Mono and Lake Tecopa (CA), Long Valley (CA), Walker Lake (NV), Tulelake (CA), and Summer Lake (OR). The Mono (27 ka) and Paoha Island (=Jamaica?; ca.

175 ka) excursions have been identified in Mono lake beds, and the fresh glacial outwash silt beds in the basin preserve an excellent magnetic signal.

I.C. ***Owens Lake, California***. Owens Lake is now a dry playa, ca. 16 x 11 km, situated at an elevation of about 1080 m within Owens Valley, a 165-km-long, 25–km wide, south-trending structural graben bounded on the west by normal and right-slip faults and the high Sierra Nevada, with elevations to over 4,400 m (Mt. Whitney), and to the east by normal faults and the southern Inyo Mountains with elevations to over 3,300 m. To the southeast is the lower (to 2,300 m) Coso Range, composed of upper Pliocene volcanic rocks. The lake contained water during historic time, until tributary drainage was diverted to Los Angeles beginning in 1915. In addition to significant local runoff from the Sierra Nevada, the lake received major discharge in historic time from Long, Chalfant, and upper Owens Valleys via the Owens River, and in late Quaternary time, from Mono Lake as well. During wet periods in Quaternary time, Owens Lake drained into the daisy chain of pluvial lakes: China, Searles, Panamint, and Death Valley. This system may have spilled over into the Colorado River as well during stage 6 or earlier (Blackwelder, 1931).

Drilling in Owens Lake in 1952 (Smith and Pratt, 1957) encountered mostly lake clays to depths of 228 m, below which are interbedded sand, silt, and clay to a drilled depth of 280 m. Recovery was 66%. The Lava Creek (620 ka) and Bishop (738 ka) tephra layers were encountered at depths of 128 to 262 m, respectively. Based on the position of these tephra layers, the long-term sedimentation rate in the lake is about 0.35 to 0.38 mm/yr. Diatoms, ostracodes, and pollen are present throughout much of the 1952 core (Fig. 1). As with Mono Lake, there is no direct physical link with the Great Valley and the marine record except for the Lava Creek and the Bishop ash beds, but other tephra and magnetostratigraphy are good possibilities.

Access for a drill rig is easy via a causeway built across the playa. Owens Lake is a high priority site; it should probably be cored in the fall, (FY1991 or 1992) rather than in the summer, when it's very hot. Satellite sites recommended by panel participants are Deep Springs Valley to the east, and Fish Lake Valley, to the NE.

I.D. ***Tulare Lake, California***: Tulare Lake is a broad, drained, 54 x 44 km lake bed that was alternately a marsh or a shallow lake in historic time. It lies at an elevation of about 45 m, in the southern part of the 400-km-long, 100-km-wide San Joaquin Valley. The valley is bounded to the northeast by the westward-tilted block of the Sierra Nevada, with elevations up to 4400 m, and on the SW side by the southern Coast Ranges with elevations of up to 1200- to 1500-m high.

Main discharge into Tulare Lake comes from the Sierra Nevada during spring and summer snow pack melt; smaller intermittent discharge comes from the Coast Ranges during winter rains. In late Quaternary time, large fans of outwash were deposited during glacial periods by the Kings and San Joaquin Rivers from the Sierra Nevada. These fans have formed dams that periodically raised the level in Tulare Lake, interspersed with periods of downcutting of the fan dams and draining of the lake (Atwater and others, 1986).

The southern end of San Joaquin Valley, which includes Tulare, Buena Vista, and Goose Lakes, has been tectonically subsided during much of the Neogene , so that a thick section of alluvium and lake beds has accumulated. Much subsurface information is available from water and oil wells in the area. The top of the Corcoran Clay, dated at about 620 ka, is 250 m below the lake floor. It contains the Lava Creek ash bed and Friant Pumice, giving a long-term deposition rate of 0.41 mm/yr. Short-term deposition rates based on radiocarbon dates in the upper part of the section (Atwater and others, 1986) are similar: 0.33-0.44 mm/yr. The upper part of the section contains tephra layers erupted from the Mono Craters (O. Davis, written commun, 1990).

A promising satellite site is at Wasco, 20 km SE of Tulare Lake, well studied as a possible nuclear reactor site (Davis and others, 1977). It contains a considerably thinner section, with the Lava Creek ash bed at 73 m (620 ka), the Bishop ash bed (738 ka) at 84 m, and the Brunhes-Matuyama boundary (730 ka) at 89 m. The sedimentation rate based on these datums is only about 0.11 to 0.12 mm/yr. The section, however, contains a rhythmic sequence of silts and clays alternating with peaty deposits; there are about 22 sets of these rhythmites within the Bruhnes normal section, equivalent to the number of oxygen-isotope stages in the deep-sea record for the same period, thus a climatic control is strongly indicated.

The pollen record from the Tulare Lake area may be difficult to interpret because pollen are derived from a large and climatically diverse area with a large range in elevations, and thus a wide spectrum of ecotones. However, diatoms are abundant, and the rhythmic sediments suggest that this is at least indirect climatic control. Because the San Joaquin Valley drains into the Pacific via the Great Valley delta and San Francisco Bay, a physical link exists between Tulare Lake and marine sediments off central California. Tulare lake is situated strategically between the western Great Basin sites of Mono and Owens Lake, to the east, and the Pacific Ocean sites to the west, and may prove to be an important link within this east-west transect. Access to a suitable site and drilling logistics should be easy in this area; historically, it has been a driller's heaven.

I.E. ***Ruby Marshes, Nevada***: The Ruby Marshes are located in east-central Nevada at an elevation of about 1830 m. They consist of a perennial, spring-fed lake and marsh complex including Ruby Lake, an intervening marsh, and Franklin Lake, in all about 35 km long by 5 km wide. The marsh complex lies at the south end of Ruby Valley, a typical "Great Basin" valley 95 x 16 km, bounded on the west by the Ruby Range (to 3,360 m), and on the east by several lower (to about 2500 m) ranges. The complex was a single shallow lake in the 1930's.

A lake sediment record back to 37,000 years has been described and dated by Thompson and others (1990) using the AMS ^{14}C technique. Lake sediments probably extend over at least several glacial-interglacial cycles, and pollen, diatoms, and ostracodes are present throughout the examined section. Sedimentation rates for this site range from 0.19 to 0.39 mm/yr. The Mazama ash bed (~68 ka) has been identified in the section.

Ruby Lake was not part of the Lahontan or Bonneville systems, and thus it recorded conditions that uniquely reflect a central Great Basin environment. The site is also unique within this region because it is perennially wet, and it is likely that it remained wet in previous warm/dry periods. The site thus represents an important point in an east-west paleoclimatic transect, and in an overall paleoclimatic grid of sites.

II. Marine Sites (J.V. Gardner and W.E. Dean)

The workshop consensus for the most important marine sites to be studied can be subdivided into three distinctly different areas: Gorda Ridge and seamounts off California, the central California continental margin, and basins off southern California (Fig. 3) and possibly the basins of the Gulf of California . A few cores exist from Gorda Ridge and the central California margin, but for the most part new cores must be collected from all three areas to accomplish the objectives of the project.

II.A. *Gorda Ridge and Seamounts off California*

Pelagic sediments, containing siliceous and clacareous microfossils, blanket much of the ridges and seamounts west of the continental margin. These sediments are relatively undiluted by the terrigenous flux that floods the continental margin and basins closer to of the continent; consequently, sedimentation rates of pelagic sediment are generally low, on the order of a several centimeters to perhaps 10 cm per 1000 yrs, and the last glacial/interglacial cycle actually can be obtained with a relatively short (~10 m) piston corer. Pelagic sediment usually has a relatively undisturbed biostratigraphic record and thus contains an "uncontaminated" signal of oceanic response to climate changes. Because of the biogenic nature of pelagic sediment, usually there are ample foraminiferal tests for isotope analyses and AMS ^{14}C dating. Unfortunately, the seamounts are scattered throughout the margin, but most are off southern California. The ridge system is present only north of Cape Mendocino, California.

The seamounts and ridge system off the west coast rarely have been cored and are sparsely surveyed, with the exception of the USGS EEZ-SCAN GLORIA surveys (EEZ-SCAN 84, 1986; 1988) and the National Science Foundation MULTITRACERS study (Collier and others, 1989; Welling and others, 1989). The MULTITRACERS study collected a suite of about a dozen cores from the flanks of Gorda Ridge, most of which have not been opened for investigation because of lack of funding. Nick Pisias, a PI on the MULTITRACERS study from Oregon State University, is very interested in collaborating with this USGS project and he has proposed that together we examine the Gorda Ridge cores and choose three of them for detailed analyses. The location of the Gorda Ridge is ideal for receiving pelagic sediment that might document fluctuations in the strength and position of the California Current system at the latitude of about 43° N. The cores also could represent the western end of an east-west transect from southern Oregon to Gorda Ridge.

The seamounts off central and southern California with the best potential for containing a good stratigraphic record can be easily located using the USGS GLORIA data. However, one or more cruises will be needed to accurately survey and sample the summit regions of the candidate sites.

Because there is little chance of mounting a coring expedition this year (1991) and because no adequate coring gear is presently available, our highest priority for Year 1 for the marine sections is to sample and analyze three existing MULTITRACERS cores. We will first survey the MULTITRACERS cores with the USGS core logger to obtain down-core profiles of p-wave velocity, bulk density, and magnetic suceptibility. The second phase will be to quickly scan the three most promising cores for diatom stratigraphy and, once convinced there is a good chance of obtaining a long record, we will analyze the cores for oxygen and carbon isotopes. If a good record is found from the isotope analyses, then closely spaced AMS ^{14}C dating will be done on the upper sections of the cores.

II.B. *Central California Continental Margin*

The continental margin of the U.S. west coast is covered with hemipelagic sediment, a mixture of pelagic and terrigenous components. Hemipelagic sedimentation rates are generally several 10s of cm/1000 yr; consequently, very long cores (>25 m) are required to recover the last 100,000 yr of record. The terrigenous admixture renders continental-margin sediment very difficult to penetrate with traditional coring systems and a thin sand bed can stop a traditional coring system from penetrating any farther.

Continental-margin sediment is an important recorder of marine and terrestrial changes. Both planktonic and benthonic microörganisms of the margin environment have responded to changes in conditions within the California Current system (Pisias, 1978; 1979; Gardner and others, 1988). Terrestrial pollen has been studied in several margin cores and can be correlated to changes in vegetation in coastal regions (Heusser, 1975; 1978; 1982; 1988; Heusser and Balsam, 1977). Cores collected within the oxygen-minimum zone of the continental margin contain intervals of varved sediment that reflect changes in the strength of upwelling along the margin (Gardner and Hemphill-Haley, 1986; Anderson and others, 1987, 1989)

The continental margin north of San Francisco has been studied in some detail based on data from a few piston cores and numerous short gravity cords (see citations above) and a suite of 25 gravity cores was recently collected by the USGS immediately south of San Francisco. As a part of our highest priority for the marine record, we will examine the new USGS cores and chose three for analytical procedures described for the MULTITRACERS cores. However, the region of the offshore Santa Maria Basin, from Point Lobos to Point Conception, has never been sampled and this region should contain a detailed record of changes in Pacific climate and in the California Current. This region is the western end of another east-west transect, at about 34° N.

Year 2 of the project will require a 24-day coring cruise to core sites off central California. We have selected two regions for the highest priority coring during Year 2: the region of the oxygen-minimum zone along the Santa Maria basin margin, between 600- and 1200-m water depth, and the pelagic tops of seamounts off central California (Fig. 3). By Year 2 we should have acquired a Stacor coring system that will be able to collect long cores in hemipelagic continental-margin sediments.

II.C. *Laminated Sediment in Basins*

The third area of high priority for this project includes basins that have laminated (varved) sediment, such as Santa Barbara Basin (Fig. 3) and Guaymas Basin (Gulf of California). Varved sediments are accumulations of sediment laminae, typically alternating between more biogenic and more terrigenous components, that record the strong seasonal cycle of sedimentation in a continental margin setting. The seasonal sediment signal usually is lost by bioturbation even in dysrobic environments. An anoxic or nearly anoxic environment is required to eliminate all but microbial organisms and thus preserve the seasonal sediment components as varve laminae. Consequently, varved sediments rarely occur, but they are extremely important because they provide the highest resolution attainable in the marine record.

Studies of varved sediment from marine basins can be closely correlated with varved sediment from lakes in the western U.S. The upper parts of both marine and terrestrial varved sequences can be linked to historically documented climatic/oceanographic changes by virtue of the annual precision of varve-dating techniques. Thus, fine-scale analyses of climate changes will allow the interactions and effects of changes to be evaluated. Such interactions will serve as models for interpreting prehistoric climatic changes in older sections.

Some work has already been completed on the varve sediment record in Santa Barbara Basin (Pisias, 1978; 1979) but the available record only goes back to about 8000 yr. A sand bed halted all attempts of coring deeper in the section using traditional coring techniques. A high priority is to collect long (<25 m) from Santa Barbara Basin to investigate the annual, decadal, and centennial records of climatic changes at this locality.

Guaymus Basin is one of several basins in the Gulf of California that contain varved sediments. Long hydraulic piston cores were obtained from Guaymas Basin by DSDP Leg 64 (Schrader and others, 1980 Curray, Moore, et al., 1982; Keigwin and Jones, 1991). A recent NSF-funded expedition collected a suite of cores from the Gulf of California and we will initiate discussion with the principal investigators (L.D. Keigwin and R. Thunnell) to determine whether these cores could be made available to this project.

Although we do not anticipate coring basins that contain varved sediment during the cruise of Year 2, we will strive to core them as early as Year 3 or 4. However, we do anticipate that cores from within the oxygen-minimum zone off central California will contain intervals of varved sediments, as they do off northern California, recording changes in the strength of the California Current.

STRATIGRAPHIC CORRELATION TECHNIQUES AND AGE CONTROL

(A.M. Sarna-Wojcicki and H. J. Rieck)

The primary stratigraphic techniques for correlation of continental and marine sequences will be magnetostratigraphy and tephrochronology. Pollen profiles can be used for direct correlation of marine and terrestrial sites that are physically connected by a drainage system or that are geographically close. Because our major focus is to document the nature and timing of past climatic responses on land and in the ocean, we will generally attempt to avoid using physical stratigraphy or biostratigraphy for temporal correlation. Oxygen-isotope profiles will be used in marine sediments for refined site to site correlation. Correlated sequences will be dated by the AMS ^{14}C and U-series dating methods that are appropriate to each sequence or site.

Paleomagnetic Studies: In addition to providing high-resolution age control and correlation in cores of terrestrial and marine sediment, magntostratigraphy can provide information necessary for more meaningful interpretation of records of climate change. Potential problems in dating and detailed correlation of diverse and widely separated depositional records may be resolved by several approaches:

- Easily recognized polarity chronozone boundaries are present in records that extend back to at least 750 ka. These boundaries are easily recognized in both terrestrial and marine sediments..

- Smaller-scale features of brief subchrons and paleomagnetic excursions are present in the Tulelake and Mono Lake records and are associated with identified tephra layers. These magnetic markers, a few thousand years in duration, can be expected to be found in sediments from the Klamath area. These magnetostratigraphic events also have been found in marine cores.

- Exceptionally high-quality paleomagnetic records may show secular variations that allow correlations on the order of hundreds of years. The presence of such a record has been demonstrated in exposed sediments of Mono Lake and may well be found in the lake sediments from the Klamath area. At least two cores from the Klamath area, correlated on the basis of their tephrostratigraphy, will be analyzed in detail to determine their potential for valid secular variation records. Short stratigraphic intervals of at least two existing marine cores, correlated on the basis of their isotopic records, will be tested for possible detailed magnetic correlation.

- Changes in sediment magnetic properties reflect changes in depositional and diagenetic environments and provenance influenced by climatic, tectonic, and volcanic events. Although these properties do not provide direct age control, they may reflect events that could be used for local or perhaps regional lithostratigraphic correlation between the terrestrial sites, or between marine cores. Correlation between terrestrial and marine records based on rock magnetic properties will be tested.

Tephrostratigraphic Studies: Chronostratigraphic correlations from site to site and among sites, both marine and terrestrial, can be made by tephrostratigraphy at sites where macroscopic tephra are found. Many sites may require the identification of disseminated tephra.

Tephrostratigraphic work involves the identification of tephra in sediments, separation of particular tephra phases from the sediments, and then chemical and petrographic analyses of these phases to derive a characteristic chemical fingerprint. The fingerprint is compared by computer programs with an inventory of fingerprints of tephra layers of known age and distribution, and the best matches are identified. When a tephra with a new fingerprint is found, we attempt to date it by the most appropriate numerical method.

There are about 40 relatively widespread, dated tephra layers within the western conterminous U.S. within the age range of 0 to 750 ka. (Table 2) Several of these are very widespread. Favorable areas for development of tephrochronologic age control are in close proximity and downwind of explosive silicic volcanic source areas of late Quaternary age. For the purpose of this project, the best areas are near and downwind (and to a some extent, downstream) from:

- The Cascade Range in Washington, Oregon, and northern California. This is by far the best area for the development of a four-dimensional time- space reference framework for late Quaternary sediments, and the top priority sites are located in this region
- The Mono-Inyo Craters and Mammoth Mountain area of Mono Basin and Long Valley in east-central California.
- The Yellowstone National Park area and vicinity in northwestern Wyoming and east-central Idaho.

Critical sites situated upwind or at long distances from these source areas, such as Tulare Lake and marine sites off central California, also may be correlated to the more tephra-rich areas by

Table 2. List of tephra layers used for correlation and age control for the last 740 ka.

NAME OF LAYER OR SET	AGE (yr)	SOURCE
Layer T	180	Mount St. Helens, WA
Set W	400	Mount St. Helens, WA
Panum Crater	640	Mono Craters, CA
Tephra 1	~740	Inyo Craters, CA
Tephra 2	~1200	Mono Craters, CA
Unnamed	~1250	Newberry, OR
Unnamed	~2000	Mono Craters, CA
Set P	~2750	Mount St. Helens, WA
Set Y	~3400	Mount St. Helens, WA
Mazama, O	~6850	Crater Lake, OR
Tsoyowater	7015	Crater Lake, OR
Layers G, B	11,200	Glacier Peak, WA
Set S	12-13 ka	Mount St. Helens, WA
Layer K	19-20 ka	Mount St. Helens, WA
Layer M	19-20 ka	Mount St. Helens, WA
Trego Hot Springs	24.8 ka	Crater Lake, OR
Wono	24.8 ka	Crater Lake, OR
Ash Bed 15; Carson Sink Bed	27 ka	Mono Craters, CA
Set C	~34-38 ka	Mount St. Helens, WA
Olema	55-75 ka	unknown
Mt. Jefferson Pumice	~80 ka	Mt. Jefferson, OR
Pumice of Cloudcap Road	~120 ka	Crater Lake, OR
Tulelake 64	~120-130 ka	Crater Lake, OR
Summer Lake V	~135-145 ka	Crater Lake, OR
Summer Lake FF	~150 ka	unknown, Cascade Range
Summer Lake GG	~150 ka	unknown, Cascade Range
Summer Lake JJ	~160 ka	unknown, Cascade Range
Summer Lake KK	~160 ka	Medicine Lake, CA
Summer Lake NN	~180 ka	unknown, Cascade Range
Bend Pumice	~350 ka	Three Sisters area, OR
Rockland	~400 ka	Lassen Peak area, CA
Dibekulewe	~500-610 ka	unknown
Lava Creek B	620 ka	Yellowstone, WY
Rye Patch Dam	~630 ka	unknown, Cascade Range
Bishop	738 ka	Long Valley, CA

widespread, individual tephra layers. These widespread tephra layers include the Mazama (7 ka), Glacier Peak (11 ka), Mount St. Helens C (35 ka), Olema (75 ka), Loleta (350 ka), Rockland (400 ka), Lava Creek (620 ka), and Bishop (738 ka) ash beds.

Oxygen-isotope Studies: Oxygen isotopes ($^{18}O/^{16}O$) will be used to correlate marine sediments to one another (Fig. 2) and to assign ages to the sections older than about 35 ka, the limit of reliable AMS ^{14}C ages. The age assignments can be made from the isotope record by correlating the isotope record to the globally recognized, and orbitally tuned, oxygen-isotope record (Imbrie and others, 1983) These two dating techniques will allow us to assign a chronostratigraphy in the marine cores with a resolution of about 1000 yrs.

CORING METHODS

Terrestrial Coring Systems (D.P. Adam)

The thick sedimentary sections of the terrestrial sites can only be recovered using power-driven equipment. Although some sequences may be exposed in outcrops, such exposed deposits usually show at least some damage by oxidation or weathering to at least some of the proxies we wish to study, especially pollen. and many gochemical parameters Coring is thus essential in nearly all cases, even where outcrop studies are possible.

Several systems are available for the recovery of continuous sediment cores, including hollow-stem augering, conventional coring, and wire-line coring. Each of these has its own advantages and limitations, and the USGS Branch of Coal Geology has extensive experience with these methods. We plan to do most or all of our drilling using USGS equipment in order to take advantage of the flexibility that such an arrangement will permit. Outside contracting would divert a significant fraction of our efforts from the project itself into the contracting process. Because competent in-house drillers are available, a contracting effort would be counter-productive.

We plan to drill using a truck-mounted drill rig from the Branch of Coal Geology. Conventional drilling is the most efficient method for depths up to about 150 m (500 feet). Below 150 m, we will use wire-line drilling in order to avoid pulling the entire drill string each time a sample is taken.

With the possible exception of Mono Lake, our high-priority terrestrial sites will require no drilling over open water. Such drilling requires that the drill rig be mounted on a large barge. Both the logistical requirements and the expense of open-water drilling are greater than for similar work done on dry land. Because there are many excellent sites available that do not require open-water drilling, we have limited our FY91 efforts to land-based sites, but will seriously consider water drilling for the Mono Lake site.

Marine Coring Systems (J.V. Gardner)

Background

Most of the deep-sea sediment along the continental margin of the west coast is composed of hemipelagic sediment -- silty clays, sandy silts, clayey silts, etc. with varying amounts of siliceous and calcareous biogenic components. These sediment types are extremely difficult to penetrate to depths greater than a few meters using traditional coring systems and, because of extremely fast sedimentation rates, it is rare to collect a section representing the last 50,000 ys. Pelagic sediment, composed of biogenic silica and carbonate and little terrigenous material, blankets the numerous seamounts and the elevated ridge system of the East Pacific Rise. These sediments have relatively slow sedimentation rates, and we have a good prospect of recovering sediments from the last 100,000 yr or longer.

All available deep-sea cores from the Pacific margin of the U.S. have been collected by one of three systems; piston corers, gravity corers, and the Deep Sea Drilling Project. Piston corers have a piston inside the core barrel that is attached directly to the coring wire. In theory, when the corer completes its free fall of three to five meters (fixed prior to launch from the ship), the piston stops its travel at the sediment-water interface and the corer slides over it and penetrates the sediment. In practice, the piston is rarely stopped at the sediment-water interface. If the corer stops too early, then sediment is sucked into the core barrel and the entire section is sucked to the top of the core barrel. If the piston does not stop at the sediment-water interface, then the corer overpenetrates and the upper sediment is not collected and the section is disturbed. A gravity corer is basically a piston corer without a piston. Both systems typically employ a 1- to 2-ton weight to drive the corer into the sediment.

The Deep Sea Drilling Project (DSDP), and its successor the Ocean Drilling Project (ODP), use a number of advanced coring and drilling techniques to collect thousands of meters of sediment in virtually any water depth. To date, only 12 sites have been drilled along the western U.S. margin and none for paleoclimatic records; consequently, all have ignored collecting the Late Quaternary record. Therefore, existing DSDP cores are of minimal value for this project. The ODP is an internationally funded scientific drilling program that has an elaborate coordinating structure of panels and committees that plan drilling for several years in advance. Although several proposals for doing ODP advanced drilling along the California continental margin have been proposed by several researchers at the workshop, the ODP has no plans to drill any of these sites.

New Coring System

The USGS and the academic marine-geology community now have enough experience in attempting coring along the west-coast margin to identify the type of corer needed to obtain long complete cores. One of the most successful new techniques is the French-designed Stacor, constructed by Institut Francais du Petrole. The Stacor is a piston corer with a mechanically stabilized piston that stops at the sediment-water interface using a base plate that rests on the seafloor and is attached by cables to the piston. In a series of tests in the Atlantic, the Stacor was used at an abyssal-plain site (silty clays and clayey silts) along with several other new systems and outperformed them by collecting 34-m cores with no disturbance compared with the next-best penetration of 22 m by a Dutch piston corer (P. Schultheiss, personal communication, 1989).

The participants of the workshop recommend that the USGS acquire a Stacor-type coring system that can be used both on the USGS research vessel FARNELLA and on various UNOLS vessels of the academic fleet. The initial cost is substantial, but not prohibitive; the scientific benefits will be long ranging, not the least of which will be long, undisturbed, paleoclimatic records of the changes in the California Current System.

DATABASE AND CURATION OF MATERIALS (D.P. Adam)

Core sampling

Terrestrial sites will be cored with a system that collects 3-in diameter cores, similar to the marine-coring systems.. Terrestrial coring will be done in maximum increments of 1.5 m, again similar to the section lengths of marine cores. Each terrestrial core section will be described in the field, sampled as appropriate, wrapped in plastic wrap to retard moisture loss, and packaged in a shell made from split 3.5" PVC pipe for physical protection. Core sections will be placed in refrigerated storage in the field until they can be transported to Menlo Park for further laboratory work.

The Menlo Park core lab will be augmented by a refrigerated cargo container for core storage. A single 40-foot container should be able to hold all terrestrial cores collected this year with ample room to spare. We are also requesting that refrigerated storage be included in the new Rock Processing facility being constructed on the Menlo Park campus this year. Once that space is available, the cargo container will be moved to the Marine Facility (MARFAC) in Redwood City for long-term refrigerated storage of cores.

Marine cores will be first sectioned into 1.5-m lengths immediately after reaching the deck of the ship. Aboard ship, each section is passed through the Core Logger, a device that simultaneously measures p-wave velocity, bulk density, and magnetic suceptibility. The sections are then split, one half becoming the archive and the other the working half. The archive half is described visually described, and major lithologies are identified by smear slides. The archive half will be both photographed digitally imaged with a frame grabber for digital enhancement and inexpensive duplication to the various investigators involved.

The working half will be sampled at various intervals according to the established protocol for routine analyses of grain size, carbon-carbonate, biogenic silica, inorganic geochemistry, and biostratigraphy. Both halves are then placed in sealed D-tubes and stored under refrigeration aboard ship.

When unloaded at the dock, the cores are immediately transported to the Deer Creek Marine Sediment Lab refrigerated storage. Eventually, "inactive" cores are transported to the USGS Marine Facilities and stored in refrigerated cargo containers.

In order to permit systematic logging and description of terrestrial cores in the field and sampling before the cores are returned to Menlo Park, we plan to deploy a portable field core-logging laboratory. The lab will be constructed inside a 24-ft house trailer that will be transferred to the project from BSP/Denver. Facilities will include a long workbench, an electrical core logger, a camera, and a computerized frame-grabber for recording images of each core section before and after samples are removed.

Sampling of cores will be coordinated both in the field and in Menlo Park through a computerized database program already largely developed for the Tulelake cores. Both marine and terrestrial cores will be included in the database. A sample-tracking procedure will be developed and implemented as part of the database. We plan to visit and consult with the successful DSDP/ODP and the USGS Core Research Center core curation labs in order to benefit from their experience.

We will develop a detailed sampling protocol designed to allow efficient sampling of the cores for all planned investigations, minimal loss of core material, and consistent record maintenance throughout the investigations. A generalized version of such a protocol is shown in Table 3, but details of processing will depend on the nature of the cores.

ORGANIZATION OF THE PROJECT (D.P. Adam, J.P. Bradbury, W. E. Dean, J.V. Gardner, and A. Sarna-Wojcicki)

Steering Committee

During the planning for the workshop, a Steering Committee was organized to ensure that the appropriate specialists were invited to the workshop and that the workshop addressed the vital aspects

Table 3. Generalized Core-Sampling Protocol

I. Core recovery from hole
II. Removal of core from core barrel
III. Cleaning of outer surface
IV. Photography/Image capture
V. Logging
  A. Magnetic susceptibility
  B. Electrical logging
  C. Description
VI.. Core splitting
VI.I. Removal of samples
  A. Tephra
  B. Pollen
  C. Diatoms
  D. Mineralogy
  E. Paleomag
  F. Other (geochemistry, grain size, etc.)
VIII. Wrapping of core
  A. Saran Wrap to retard moisture loss
  B. PVC pipe shell for physical protection
IX. Refrigeration
X. Transfer from field to Menlo Park

of the project. The Steering Committee was chosen to represent the wide range of interests of the overall project. This concept worked so well it was decided that this group would continue to act as the coordination body to guide the required research and redirect, when necessary, the efforts of the project. Because the project has two distinct directions, the marine record and the terrestrial record, we decided that it would be most efficient if each direction was a separate subproject under the supervision of the Steering Committee.

Following the lead of large, multidisiplinary programs that have evolved over the last few decades both within and outside the USGS, we recommended and implemented an annual workshop for all investigators. This annual workshop will be the forum at which investigators will present and discuss their results with others in the project. Immediately after each annual workshop, the Steering Committee will meet to discuss possible changes in the direction or emphasis of the project. An annual progress report will be produced for the Program Coordinator.

The initial Steering Committee is composed of:

David P. Adam, Branch of Paleontology & Stratigraphy, Menlo Park
J. Platt Bradbury, Branch of Paleontology & Stratigraphy, Denver
Walter E. Dean, Branch of Sedimentary Processes, Denver
James V. Gardner, Branch of Pacific Marine Geology, Menlo Park
Andrei Sarna-Wojcicki, Branch of Western Regional Geology, Menlo Park
Milan Pavich, Program Coordinator, Reston.(*ex officio* member)

The program will be governed by the Steering Committee but the marine and terrestrial investigations will be treated as separate subprojects, each headed by a Project Chief. The Annual Workshop and Annual Report will be a product of the Steering Committee and will represent the work of the combined subprojects.

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APPENDIX I. SITE DETAILS AND EXPLORATORY SITES

Specific sites in the Upper Klamath - South Cascades region include:

I.A.1. Agency Lake (Oregon), at the northern end of the graben that contains Upper Klamath Lake; the valley is several miles across and should contain hundreds of meters of sediment and a good tephra record. Road access should be easy. Suitable sites are present both north of the lake and to the south, on the delta of the Williamson River.

I.A. Wocus Marsh (Oregon), reclaimed agricultural land at the southern end of Upper Klamath Lake; the reclamation of this area is quite recent, so the upper part of the section should still be in good condition. Access should not be difficult. This site should provide a record similar to the Agency Lake site(s).

I.A.3. Round Lake and Aspen Lake (Oregon), sediment-filled valleys west of Wocus Marsh. These valleys are internally drained, with water levels perched above the regional ground-water table. Because they lack through-flowing drainage, they should provide a more local climatic signal than the sites drained by the Klamath River.

I.A.4. Buck Lake (Oregon), a filled depression nearly 3 km in diameter on the west side of the structural ridge that separates Butte Valley from Lower Klamath Lake, but located north of the Klamath River. The site lies at an elevation of about 1500 m (versus 1260 m for Upper Klamath Lake), and is well within the mixed coniferous forest of the Cascades. The site is partly owned by USFS and is partly private land; access is as yet uncertain. This site appears to be the most promising one in the area for a long pollen record of the coniferous forest.

I.A.5. Lower Klamath Lake (California and Oregon), reclaimed land that before 1912 served as an overflow basin for the Klamath River; the upper Holocene part of the section was studied by Hansen (1947); the underlying section should resemble the Tulelake record, but with a stronger influence of the Klamath River. Access should be fairly easy.

I.A.6. **Grass Lake** (California), between Butte Valley and Mt. Shasta, is a basin perched above the regional groundwater table. The age of the basin is not well known, but there is a good possibility of recovering a record spanning at least the last full glacial cycle. Access may be a bit tricky because of spring flooding.

I.A.7. **Shasta Valley** (California), just north of the town of Weed, is blanketed by landslide deposits emplaced about 350 ka during the catastrophic collapse of an ancestral Mt. Shasta (Crandell, 1989). Valleys between the major landslide blocks are filled with sediment deposited since the landslide occurred. One attempt was made to core these deposits in 1983; core recovery was poor, but we know that the deposits are about 20 m thick, and that tephra layers are present. Careful site selection may permit us to recover a continuous core.

I.A.8. **Butte Valley** (California), is presently a dry valley that is hydrologically closed. According to residents, wells drilled in Butte Valley commonly encountered gastropod and mollusc shells, which are rare in the Tulelake record, but presumably also are rare in the other flushed deposits of the Klamath graben to the east. The subsurface deposits of Butte Valley are relatively well known (Wood, 1960) but have not been examined for a paleoclimate record.

EXPLORATORY SITES

The section is included here to mention sites considered to be exploratory. We did not include them in the Priority Sites section because we did not want to dilute our high-priority targets with long discussions of these secondary ones. Very little information is available from any of the exploratory sites, yet they are located in sensitive paleoclimatic positions and may well contain long and detailed records of paleoclimatic changes. Exploratory sites are those that will be drilled if an opportunity occurs where it would be time and cost effective. The coring of exploratory sites would consist of relatively short cores, possibly representing only one day of coring, to allow a reconnaissance of the potential paleoclimate record. If reconnaissance shows that the site contains a high-resolution record, then it may be studied later during the course of the project..

Humptulips, Washington: This site, a bog on the western coast of the Olympic Peninsula, has been studied by Calvin Heusser (NYU), who estimates that the 7.5-m section includes deposits that range in age from the present back to about 350 ka. It is the northernmost site we considered, and also is the closest to the Pacific Ocean. It would be desirable to get a new core and some AMS 1^4C dates from this section to refine our present knowledge of this site. The bog sediments should contain abundant pollen, but the site is probably poor for diatoms and ostracodes. Tephra layers are present, and the potential for a direct link into the marine record is good. The slow sedimentation rates at this site, however, suggests that a high-resolution record may not be possible; alternately, the slow sedimentation rate may reflect gaps in the record, which would also be undesirable. An exploratory look is worthwhile, however, to develop a link with tephra of the DSDP record.

Carp and Farger Lakes, Washington: These sites have been studied by Cathy Whitlock (U. of Oregon) and have a potential record extending back through at least one full glacial cycle.

Klamath Marsh (Oregon): Klamath Marsh lies directly east of Crater Lake, and the present valley is a wet marsh presumably underlain at shallow depth by a thick deposit of Mazama Ash (6.3 ka). What lies beneath the Mazama Ash is unknown to us, but there should be buried deposits of a former lake or marsh that should include tephra erupted by Mt. Mazama before its cataclysmic explosion.

Fort Rock Valley (Oregon): Fort Rock Valley includes several basins that held pluvial lakes at various times during the Quaternary. These include Paulina Marsh, Silver Lake, Christmas Lake, and Fossil Lake, all of which coalesced into a single large pluvial lake that overflowed through a now-concealed outlet channel into the Deschutes River and thence into the Pacific. Some of the basins (especially Christmas and Fossil Lakes) are presently dry and have undergone considerable deflation, whereas others (Paulina Marsh and Silver Lake) are presently wet or submerged and may have more continuous records. Fossil Lake is well known as a vertebrate fossil locality. Paulina Marsh and Silver Lake apparently now drain into the Summer Lake basin through underground channels that emerge at Ana Springs. However, during high stands of pluvial Lake Chewaucan (see below) that flow was reversed, and the underground drainage went from the Summer Lake basin into the Fort Rock Valley and then on to the Pacific.

Chewaucan Basin (Oregon): Several sites in the basin of pluvial Lake Chewaucan were cored in 1986, but no further work has been done. Our understanding of the fluvial and pluvial history of the Chewaucan Basin (e.g., Allison, 1982) will require significant revision as a result of the 1986 coring work. Cores presently in hand include the following:

Ana Springs, at the northern end of Summer Lake, is at present the main source of water for Summer Lake. The site has been described most recently by Davis (1985), who developed a chronology for numerous tephra layers deposited during the past 200 ka. Previously, we found many of these tephra in the Tulelake cores. The core we took in 1986 extended the stratigraphic record to a depth of 210 feet, which we estimate on the basis of tephra to correspond to an age of roughly 1 Ma. R. Negrini (Cal State, Bakersfield) and several coworkers have discovered a thicker section just east of Ana Springs, which they plan to core for paleomagnetic and paleoclimatic studies.

Upper Chewaucan Marsh occupies a relatively high valley bottom between Summer Lake and Lake Abert. Two cores taken in 1986 bottomed in sand at a depth of 55 m. The paleomagnetic record indicates that the age of the bases of the cores is about 900 ka. These cores and the Ana Springs core allow us to document that the Chewaucan River flowed into Summer Lake during much of the Quaternary, rather than into Lake Abert as it does today.

Lower Chewaucan Marsh lies between Upper Chewaucan Marsh and Lake Abert. A core taken in 1986 reached a depth of 115 feet and contained tephra, but no work has been done on the core to date.

Lake Abert is the present sump of the Chewaucan River. The hydrology, geochemistry, and clay mineralogy of Lake Abert have been extensively studied by Blair Jones (WRD) and his colleagues. The lake is shallow, but will be a challenge to core unless it dries up completely.

Other sites in the Chewaucan Basin offer the potential for even longer records. In particular, the sediment on the west side of present Summer Lake is at least 1200-feet deep, according to water-well records, and the core we took at Ana Springs indicates that the Summer Lake subbasin may have remained wet throughout the Quaternary, so the potential for a good pollen and ostracode record is excellent.

Northern Sierra Nevada to central Oregon transect: Many sediment-filled basins, well suited to our objectives, can be found along a north-south transect between the northern Sierra Nevada and east-central Oregon. The transect crosses some significant climatic and biogeographical boundaries, and the basins along the transect offer considerable physiographic variability, so there are many possibilities for studies of paired cores or suites of cores from closely spaced but paleoclimatically differing localities. Sites along this transect are presented below as groups, with individual sites listed under the groups.

Malheur Basin sites (Oregon): The Malheur Basin is presently occupied by Malheur and Harney Lakes, which coalesce during wet periods to form a single lake. During the late Pleistocene, the basin overflowed across a low sill into the Malheur River and thence into the Snake River. The major sources of inflow are the Silvies River from the north and the Donner und Blitzen (D&B) River from the south. The D&B drains the western slopes of the Steens Mountains, which were heavily glaciated. The channel of the D&B is strongly underfit between the Steens Mountains and Malheur Lake.

Malheur Lake and Harney Lake are the present low spots in a broad valley that receives drainage primarily from the Blue Mountains to the north and the Steens Mountains to the south. The basin was larger during pluvial intervals, and overflowed into the Snake River drainage. Lava flows deposited in stream channels in the southwestern part of the valley now form inverted topography, so significant erosion of older lake sediments has occurred.

Diamond Marshes lie at the upper end of the broad, marshy valley above Malheur Lake. Very detailed work has already been completed on Holocene sediments and packrat midden deposits from Diamond Crater maar by P.J. Mehringer of Washington State University. It is uncertain how far downvalley the glaciofluvial outwash deposits from the Steens Mountains glaciers extend, but a series of cores along the valley axis should provide a sensitive record of an isolated mountain glacier history.

Frenchglen is similar to the Diamond Marshes site, but farther upstream.

Catlow Valley is a broad valley that was occupied by a pluvial lake during late Pleistocene time. The basin probably overflowed into the Malheur basin near Frenchglen. Catlow Valley was probably fed purely by precipitation and springflow, because there are no glaciated mountains within the present drainage.

Warner Valley sites (Oregon): The Warner Valley was occupied during the late Pleistocene by a major pluvial lake system that was fed primarily by streamflow from the south, but that filled starting in the north. The present inflow is enough to maintain a string of lakes, but the lowest lake in the chain is presently dry. A set of cores taken along the present chain of basins and from peripheral basins that were only flooded when the pluvial lake overflowed into them would provide a sensitive record of hydrographic changes during the last pluvial, and perhaps of older pluvial cycles as well. Suitable coring sites include:

Upper Warner Valley, presently marshy valley bottom above the level of the highest modern lake.

Coleman Lake, a lateral valley that receives no water from the main stream system today, but was flooded during high lake stands.

Crump Lake, the highest of the modern lakes in the valley.

Hart Lake and Campbell Lake, two of the middle lakes in the present chain.

Bluejoint Lake, the lowest basin in the valley (largely dry in modern times).

Big Lake, a fault-bounded basin a few miles west of the pluvial lake on the eastern slope of the Warner Mountains. Big Lake should have a climatic record not complicated by the effects of a pluvial lake (see also Snake Lake below).

Cow Head Lake (California): a filled basin located between the southern end of the Warner Valley and the northern end of the Surprise Valley. Like Big Lake and Snake Lake, it should provide a record that is not affected by deep flooding. The reason for the closed basin is not clear, and the deposits may not be very deep. The valley has been drained and is presently used as farmland.

Surprise Valley sites (California and Nevada): Like the Warner Valley just to the north, the Surprise Valley held a major pluvial lake that extended north-south for many miles, and it presently includes both pluviated and non-pluviated subbasins, including:

Lake Mary (California), a small modern lake impounded behind a beach bar deposited by the last pluvial highstand at the north end of the valley.

Lower, Middle, and Upper Alkali Lakes (California), the remnants of the pluvial lake (unlike the Warner Lakes, these three basins are largely independent of each other, rather than forming a chain of successive evaporation ponds).

Snake Lake (California), an isolated fault basin that was not flooded during the last pluvial and is completely filled with sediment.

Duck Flat (Nevada), a broad marshy valley at the south end of the pluvial system that was only connected with the pluvial system during the highest lake stands.

Madeline Plain/Grasshopper Valley (California): A pluvial lake filled these two valleys in late Pleistocene time. Both valleys are completely dry at present. There is no external drainage, although Lake Madeline may have overflowed into Lake Lahontan during high stands. There was probably no glaciation within the drainage, so the response of the lake system to climate changes should be fairly easy to interpret.

Eagle Lake (California) consists of three large basins that are joined into one big lake with no outlet. Drilling over open water could present significant problems. The basin is unglaciated, and the record could be quite long.

Honey Lake (California and Nevada) was a part of the Lake Lahontan system during high stands. The subsurface stratigraphy is fairly well known as a result of WRD investigations, and mineralogical studies could provide a record of glaciation in cores from this valley. The record may be quite long.

Extinct Lakes of the Upper Feather River. The southern end of the northern Sierra Nevada to central Oregon transect includes all of the extinct lakes of the upper Feather River region, as described by Durrell (1987). Many of Durrell's sites seem quite promising, including:

Lake Almanor, a fault-bounded basin well west of the Sierran crest at an elevation of ca. 1365 m.

Grizzly Lake (1760 m), several miles long and 2-3 miles wide.

Indian Valley (1070 m), which Durrell estimates may contain about 425 m of sediment.

American Valley (1035 m), now occupied by the town of Quincy.

Lake Ramelli (ca. 1780 m).

Lake Beckwourth (1470 m), which left at least 390 m of sediments that now lie beneath Sierra Valley.

Upper Pit River (California): The Upper Pit River drains much of northeastern California, and the basin includes lacustrine and marsh deposits that range in age from Holocene back to several million years. The Upper Pit and Upper Klamath River drainages were once connected, and ground water still flows beneath the Medicine Lake highlands from the Tule Lake basin into the Upper Pit drainage. The breached basins of the Upper Pit drainage are in many ways analogous to the Feather River basins described by Durrell (1987), but they have not yet been so well described or interpreted. Promising deposits in the Upper Pit drainage include:

Goose Lake (Oregon and California): a shallow lake that straddles the Oregon/California border. Exposed old lake deposits in the northern part of the basin include tephra layers that correlate with those found in the Tulelake core. The modern lake occasionally overflows into the Upper Pit River, but the basin is usually hydrographically closed, and historically it has dried up at least once. Drilling would be fairly easy along the northern margin of the lake, but coring the middle of the basin might be difficult.

Dog Lake (Oregon) lies above the regional groundwater table in the Devils Garden volcanic field west of Goose Lake. Chrysophyte cysts collected at the site indicate that it may be a modern analog of the Clear Lake, California area during the late Quaternary. The area is well forested, and should provide a good record of arboreal pollen from a site between the Cascades and the pluvial basins of the northern Great Basin.

Alturas (California): Water-well logs indicate at least 180 feet of gray clay underlies parts of Alturas, and this record should provide a good paleoclimatic record.

Jess Valley (California) occupies a faulted basin on the western side of the Warner Mountains. The Warner Mountains were glaciated during the late Pleistocene, and the outwash from some of those glaciers passed through Jess Valley, so the site offers a chance to recover a long pollen record that can be linked to the glacial record. The Jess Valley site would be a good site for comparison with a record from Snake Lake, which lies just to the east on the other side of the Warner Mountains.

Big Valley (California) lies at an elevation of 1260 m along the Pit River, and includes such localities as Big Swamp and Muck Valley. The Pit River is presently downcutting through a bedrock sill that ponded the drainage when faulting created the basin. There is a good possibility of recovering a section spanning at least a couple of million years.

Fall River Valley (California) lies downstream from Big Valley at an elevation of about 1000 m. Huge freshwater springs, in large part fed by underground seepage from the Tule Lake basin to the north, emerge from the Medicine Lake lava fields at the north end of the valley and keep the valley wet throughout the year. The sediments in the valley have been ponded in much the same way as those of Big Valley; a waterfall at the lower end of the valley forms the biogeographic boundary between the lower and upper Pit River regions. Prospects for a long climatic record are good, and the site is wetter than the Tulelake basin and on the upwind side of the Sierra Nevada, so the oak pollen record should provide a much stronger signal than at Tulelake.

Round Valley lies in the North Coast Ranges of California along the Eel River at an elevation of 412 m. The valley, although large, is considerably smaller than the Clear Lake basin, and it is also closer to the high mountains of the Yolla Bolly region, so a pollen record from Round Valley might provide a different view than the Clear Lake record. The continuity of the deposits near the top of the section is problematic because of the present through-flowing drainage, but the possibility of lacustrine deposits at depth should be explored. The valley is presently within an Indian reservation, so access might be difficult.

Rohnert Park lies at the southern end of the Santa Rosa Valley, just north of San Francisco Bay, at an elevation of 35 m. Subsurface studies indicate that up to 75 m of reduced, fine-grained basin deposits of Holocene and Pleistocene age underlie the southern end of the valley (Herbst, 1979). This site offers a good opportunity to recover a low-elevation climatic record not directly coupled to sea-level changes. The area is densely settled, so access might be a problem.

Tolay Creek Bog is a fault-formed basin just north of San Francisco Bay that has been drained and is currently used as farmland. The potential of the site is about the same as that for Rohnert Park, but the subsurface stratigraphy is not known. Access may be difficult.

Lake Tahoe offers great possibilities but tremendous logistical problems. The basin is probably about two million years old in its present form, and glaciers of the various Sierran glaciations discharged directly into the lake, so the chances of linking a lake-bottom climatic record to the glacial record are pretty good. However, the bottom deposits are known to contain numerous turbidity-current layers related to downstream johkuhlaups. The lake is over 350-m deep in most parts, and the drilling capabilities required to recover long cores from such great water depths are far beyond those required elsewhere in this program.

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