U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

REPORT OF 1994 WORKSHOP ON THE CORRELATION OF MARINE AND TERRESTRIAL RECORDS OF CLIMATE CHANGES IN THE WESTERN UNITED STATES

by

David P. Adam[1]
J. Platt Bradbury[2]
Walter E. Dean[2]
James V. Gardner[1]
Andrei M. Sarna-Wojcicki[1]

U.S. GEOLOGICAL SURVEY OPEN-FILE REPORT 95-34

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[1]Menlo Park, CA 94025
[2]Denver, CO 80225

TABLE OF CONTENTS

Overview of the Marine-Terrestrial Correlations Project:

David P. Adam, J. Platt Bradbury, Walter E. Dean,
James V. Gardner, and Andrei M. Sarna-Wojcicki

INTRODUCTION

The third workshop of the Correlation of Marine and Terrestrial Records (CMTR) Project met at the Pajaro Dunes Conference Center in Watsonville, California, in March of 1994. The meeting was attended by thirty investigators from the U.S.G.S. and several other institutions (Table 1); in addition, part of the meeting overlapped with a similar workshop for the U.S.G.S. LITE Project (Last Interglacial -- Timing and Environments).

The objective of the 1994 workshop was to present summaries of what has been accomplished by the various investigations up to the time of the meeting; locations of most of the sites studied are shown in Figure 1-1. Major aspects of the work included summaries of work done on sediment cores from the upper Klamath Basin (California and Oregon), Owens Lake, California,and the eastern Pacific, with additional reports on related work from Carp Lake, Washington, and Lake Estancia, New Mexico. Extended abstracts describing the work presented at the workshop comprise the bulk of this report.

OBJECTIVES

The initial objective of the Correlation of Marine and Terrestrial Records (CMTR) project was to collect both marine and continental records of paleoclimatic proxies for the past 130,000 years along the west coast of North America with the goal of correlating these records between the marine and terrestrial environments. The western United States and eastern North Pacific Ocean were chosen as the focus for the 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 affects the climate of the entire northern hemisphere (for example, 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 flows south for ~3000 km along the western coast of the U.S., from the Gulf of Alaska to Baja California. This belt of cold, upwelling, nutrient-rich surface water modulates the coastal climate of western North America.

Marine and terrestrial paleoenvironments have commonly been studied by different groups of researchers, with relatively few workers being expert in both realms. The CMTR project reflects this history: the initial data-generation phases of the project have been done by two largely independent groups, one working on the marine aspects and the other on terrestrial cores. The goal of the project is to integrate results from both realms into correlations of major climatic episodes.

TERRESTRIAL STUDIES

The terrestrial component of the CMTR project includes three focused investigations: Carp Lake, a crater lake in the Columbia Basin that has yielded a high-resolution record of the last 33,000 years and may extend back to the beginning of Oxygen Isotope Stage 5; the upper

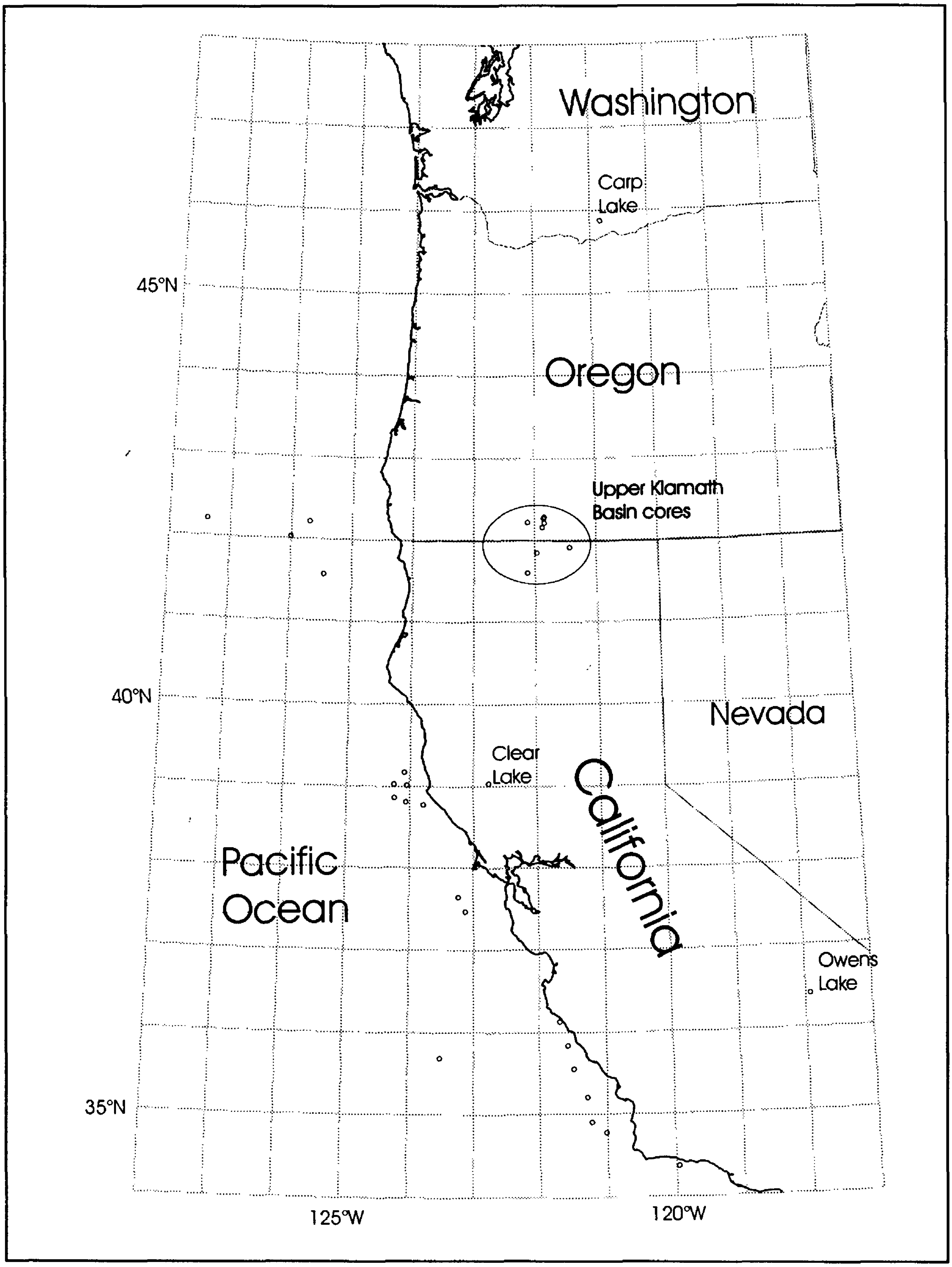

Figure 1-1.--Index map showing locations of most of the cores studied for this report. Marine cores are labeled in Figure 10-1 of Gardner and Dartnell (this volume).

Klamath Basin of south-central Oregon and northern California; and Owens Lake, in southeastern California. The strategies used have been somewhat different for the Klamath Basin and Owens Lake subprojects.

Klamath Basin

The approach taken in the Klamath Basin study was to recover multiple cores from basins of varying size, elevation, vegetation, and hydrography in order to maximize the probability of obtaining cores that could be reliably correlated with the proxy records being developed by the marine group. In addition, we hoped to generate relatively long records that would overlap the interval spanned by the 3.1-Ma Tulelake core (Adam and others, 1989) but provide a better record of the history of the forests of the Cascade Range. Six sites in the upper Klamath Basin were cored in the fall of 1991, with one additional core taken a year later (Chapter 3).

Because of the position of the upper Klamath Basin downwind from many Cascade Range volcanoes and the availability of the tephra record from the Tulelake core (Rieck and others, 1992), the tephra in the various Klamath Basin cores have provided the primary means of dating the cores, which span intervals ranging from ~30-40 kyr (Caledonia Marsh, core 2) to over 1 Myr (Butte Valley, and perhaps Wocus Marsh and Round Lake).

Much of the initial evaluation of the Klamath Basin cores has involved work on deposits older than those studied by the marine group. Although those older deposits have their own importance, they were not the primary objective of the CMTR project. An important conclusion of the workshop was that the best opportunity for detailed correlation with the presently available marine record lies in more detailed study and dating of core 2 from Caledonia Marsh, Oregon.

Because numerous cores were taken in the upper Klamath Basin, and because the cores vary significantly in length, time interval spanned, and lithological character, not all cores are equally suitable for study by any given technique. Each core has been studied by a different combination of techniques that reflect the nature of the core and the availability of researchers. At a minimum, tephra and magnetic susceptibility have been studied from all cores.

Owens Lake

The Owens Lake core, drilled in 1992, was intended to provide a climate record spanning the Brunhes Normal-Polarity Chron. Because the subproject was part of the CMTR project, initial emphasis for some of the detailed climatic work was targeted at the past 130,000 years. The position of the Owens Lake drainage immediately downwind from the Sierra Nevada offers an opportunity to relate climate proxy records from a continuous depositional sequence to upstream glacial record.

The sampling strategy pursued for the Owens Lake core was tailored to the needs of the various investigators. The varying suitability of different parts of the core for particular analyses and the differences in time required per sample led to an irregular sampling pattern by which each investigator tried to attain fairly even coverage within the constraints of time and materials. More details are given by the Owens Lake Core Study Team (Chapters 8 and 9).

MARINE STUDIES

Heusser (Chapter 7) and Wan and others (Chapter 8) present evidence for marine-terrestrial correlations of pollen profiles and tephra layers. These results indicate that the major CMTR objective is feasible, although more data from long, continuous records are needed to provide a better synopsis.

The marine group has collected a suite of cores from a transect through and along the California current (Figure 1-1 and Table 2). The goal was to collect an internally consistent multivariate dataset of paleoceanic and paleoclimatic proxies for the past 130,000 years. Initial AMS ^{14}C dating results for piston cores taken along the transect indicate that the cores contain a continuous record of only the past 50,000 years or less. This shorter-than-expected stratigraphic record is the result of faster-than-expected sedimentation rates along the continental margin. However, these high sedimentation rates have produced very high-resolution records, sometimes exceeding 50 cm kyr^{-1}, for oxygen-isotope stages 1 through 3. The marine group has taken advantage of this opportunity to shift their studies from millenial to centennial resolution, but for a shorter interval than originally proposed (Gardner and others, 1991, 1992).

The subsampling and analytical strategy followed by the marine group has contributed significantly to the success of their approach. Cores were routinely sampled at 10-cm intervals, and each investigator received a sample from each interval. The data points on their various primary proxy curves ($CaCO_3$, organic carbon, inorganic geochemistry, planktonic and benthonic forams, diatoms, radiolaria, pollen, oxygen and carbon isotopes, etc.) thus all represent the same set of levels in each core (Chapter 10). The time interval per sample for the marine cores ranges from ~200 to ~500 years, depending on sedimentation rates. Each primary proxy can be used, either by itself or in combination with other proxies, to generate derivative paleoceanic and/or paleoclimatic variables. These derivative values include paleoproductivity, the location and intensity of paleo-upwelling, the flux of pollen to the sediments, sea-surface temperature estimates, etc., as is shown by the variety of variables discussed in the various abstracts included in this volume.

In addition to analyzing multivariate data, an age model based on AMS ^{14}C dates has been developed for each core. Enough cores have now been analysed to allow display of various primary and derivative proxies in a common space-time framework (Chapter 10). Examples are shown by Sabin and Pisias (Chapter 12), who show trends of paleoenvironmental tracers that can be followed along the margin of California through time, clearly demonstrating changes that have occurred in the California Current.

Primary data for the marine group are in two databases: 1) a HyperCard 2.0 database for internal project use, continually kept up-to-date and made available to all CMTR researchers at the workshop, and 2) the larger USGS Climate and Global Change database that will eventually store all USGS paleoclimate data. Reformatting of the internal database for inclusion in the USGS database is in progress.

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TABLE 1
List of attendees

Name	Institution
David P. Adam	USGS - Menlo Park
Roger Y. Anderson	Univ. of New Mexico
Lisa Ramirez Bader	USGS - Denver
Art Bettis	Iowa Geological Survey
James L. Bischoff	USGS - Menlo Park
J. Platt Bradbury	USGS - Denver
Jonathan Glen	UC Santa Cruz
Julie Brigham-Grette	University of Massachusetts
Peter Dartnell	USGS - Menlo Park
Walter E. Dean	USGS - Denver
James V. Gardner	USGS - Menlo Park
Thomas D. Hamilton	USGS - Anchorage
Eileen Hemphill-Haley	USGS - Eugene, OR
Linda Heusser	Lamont-Doherty
Michaele Kashgarian	Lawrence Livermore Laboratory
Kenneth R. Ludwig	USGS - Denver
Mary McGann	USGS - Menlo Park
Kirsten Menking	UC Santa Cruz
Daniel R. Muhs	USGS - Denver
Nicholas G. Pisias	Oregon State University
Milan J. Pavich	USGS - Reston
Paula Quinterno	USGS - Menlo Park
Richard Reynolds	USGS - Denver
Joseph Rosenbaum	USGS - Denver
Ann Sabin	Oregon State University
Andrei M. Sarna-Wojcicki	USGS - Menlo Park
George I. Smith	USGS - Menlo Park
Alexander van Geen	Lamont-Doherty
Cathy Whitlock	University of Oregon
Isaac J. Winograd	USGS - Reston
Wally Woolfenden	University of Arizona/USFS

TABLE 2 -- Status of analyses for marine cores studied for this report

Core	Water Depth (m)	AMS # of dates	Age at Bottom	CaCO3	Corg	Opal	Diatoms	Rads	Forams	Pollen	Inorg. Geoch.	C & O Isotopes	Cd/Ca	del 13Corg	Rock Eval
END77-29	3695			Y	Y							Y			
PAR85-01		6		Y	Y										
PAR85-34	2445	1		Y	Y										
PAR87A-01	3480							Y							
TT39-PC12	2369							Y							
TT39-PC17	2795							Y							
W8709A-13PC	2712	25	60	Y	Y		QR'92	Y		Y	Y	Y			
W8709A-8PC	3111	4	58	Y	Y		?	Y		Y		Y			
Y7211-1	2913							Y		Y		Y			
Y70-5-64	2944			Y	Y							Y			
Y6910-2	2743							Y		Y		Y			
V1-80-G22	1508		11.5	Y	Y		Y				Y				
TT197-G330	700					Y	Y				Y			Y	Y
L13-81-G117	695		47	Y	Y	Y	Y				Y			Y	Y
L13-81-G138	2531		34	Y	Y		Y	Y	Y	Y	Y	Y		Y	Y
L13-81-G145	698					Y	Y				Y			Y	Y
V1-80-P3	1600		18	Y	Y		Y	Y	Y	Y		Y	P	Y	
V1-80-G1	2045		33	Y	Y				Y	Y					
F8-90-G21	1605	16	16	Y	Y	Y		Y	----------		Y	----------	B		
F8-90-G25	1720	9	12	Y	Y		Y	Y			Y				
F2-92-P51	775			Y	Y						Y			Y	Y
F2-92-P3	803	28	33	Y	Y	Y	Y	Y	Y	Y	Y	----------	P/B		
F2-92-P54	3305	20	120	Y	Y		----------		Y	Y	Y	----------			
F2-92-P40	760	18	24	Y	Y	Y			----------	Y	Y				
F2-92-P33	570			Y	Y						Y			Y	Y
F2-92-P34	610	9	60	Y	Y	Y	----------			Y	Y				
F2-92-P18	584			Y	Y						Y			Y	Y
ODP 893A	576	23	160	Y	Y		Y			Y		Y			
AHF-10614												Y			
V1-81-G15	1430	9	49	Y	Y		Y	Y		Y	Y	Y		Y	Y
			Y =	completed						P =	planktonic				
			-	in progress						B =	benthic				

TABLE 2 -- Status of analyses for marine cores studied for this report

Carp Lake: A long record from the Columbia Basin:

Cathy Whitlock
Department of Geography, University of Oregon, Eugene, OR

INTRODUCTION

Carp Lake lies in the southwestern Columbia Plateau within a volcanic crater of early Pleistocene age (Klickitat County, Washington, latitude 45°55'N, longitude 120°53'W, elevation 714 m). The lake covers an area of 11 ha, and has a maximum water depth of 2 m and a drainage area of less than 50 ha. The study area lies in *Pinus ponderosa* forest within 5 km of the steppe/forest ecotone. Changes in the position of this ecotone through time are easily recognized in pollen data and provide a sensitive record of past climatic fluctuations.

1982 Core (0-33 ka)

In 1982, I retrieved a 7.8-m core from Carp Lake and described the vegetational history of the last 33,000 years (Barnosky, 1985; Figure 2-1). Pollen assemblages in sediments dating from 33 to 23.5 ka suggested a period of temperate climate and steppe coinciding with the end of the Olympia Interglaciation. The Fraser Glaciation (25-10 ka) was a period of periglacial steppe or tundra vegetation and conditions too cold and dry to support trees. Aridity was also inferred from sedimentologic evidence of low lake levels between 21 to 8.5 ka and especially after 13.5 ka. At 10 ka Chenopodiineae and other temperate taxa

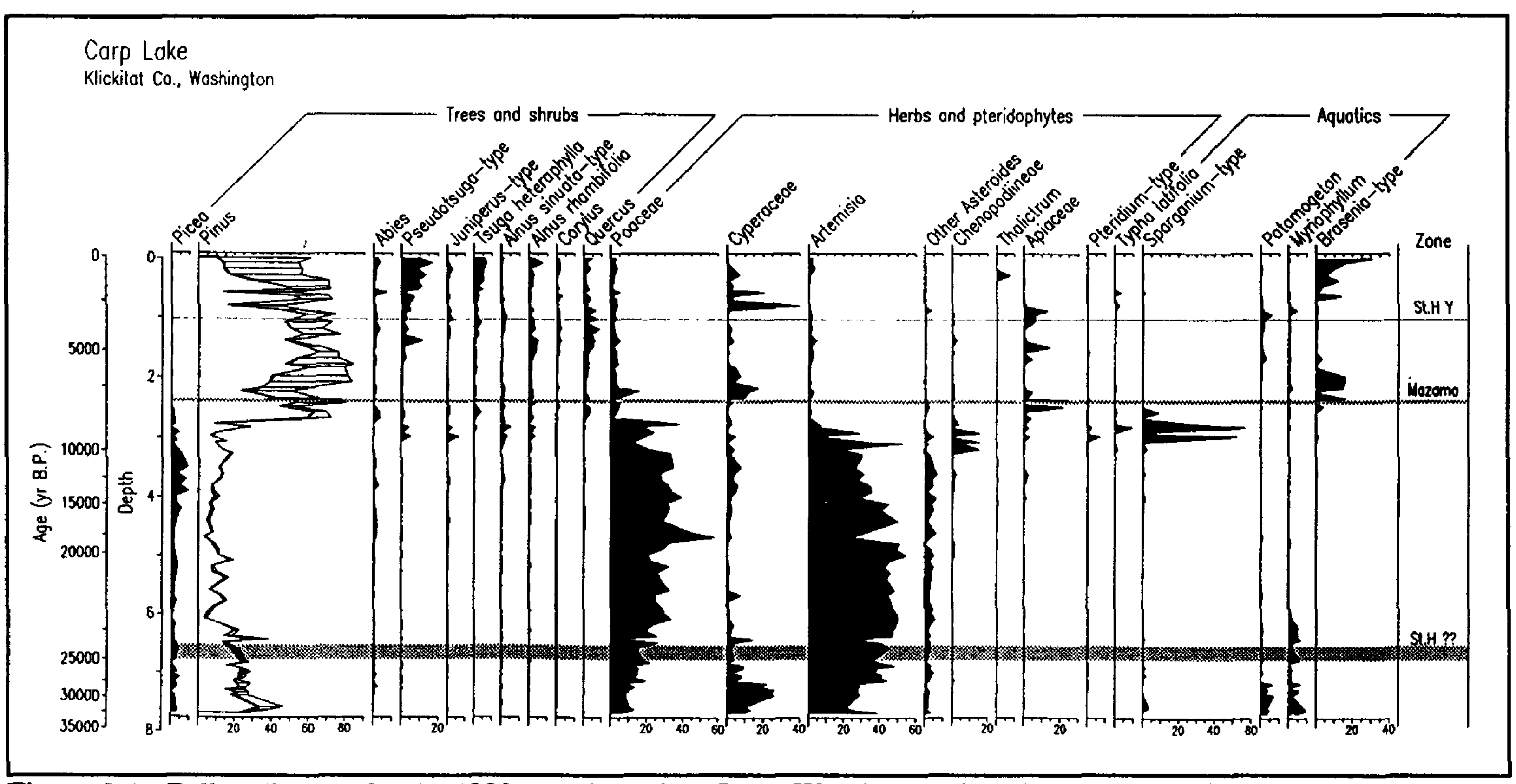

Figure 2-1.--Pollen diagram for the 1982 core from Carp Lake, Washington (from Barnosky, 1985).

spread locally during a shift from cold dry to warm dry conditions. Pine woodland developed at the site with the onset of humid conditions at 8.5 ka. Further cooling was suggest at 4 ka when *Pseudotsuga* and *Abies* were established locally.

1990 Core (0 - ~85 ka?)

In September, 1990, we returned to Carp Lake with a sturdier platform and coring equipment. This investigation was funded by Westinghouse Hanford Operations as part of their paleoclimatic assessment of the Hanford Reservation. We recovered a 20-m core -- 12 m longer than the original core -- before our equipment failed in the stiff sediment.

The new core contains ten tephra layers (Figure 2-3). The organic and diatom content of the sediment increases between 19 and 20 m depth (Figure 2-2), suggesting that the lowest sediments represent a time of greater lake productivity and warmer conditions. The sediment below 19 m may represent the top of Stage 5.

Carp Lake is an excellent candidate for a long terrestrial record from the Pacific Northwest. The paleoclimatic history of the last 33,000 years at Carp Lake contrasts with climatic history inferred from the southwestern U.S. For example, periods of low lake levels and dry conditions in the Northwest generally correspond in time with pluvial conditions in the Southwest. This contrast probably results from shifts in the position of the jet stream and westerly storm tracks, as well as the differential response to the changes in the seasonal cycle of insolation (Thompson *et al.*, 1993).

Pollen analysis of the new core is underway. With proper drilling equipment a longer record can be obtained.

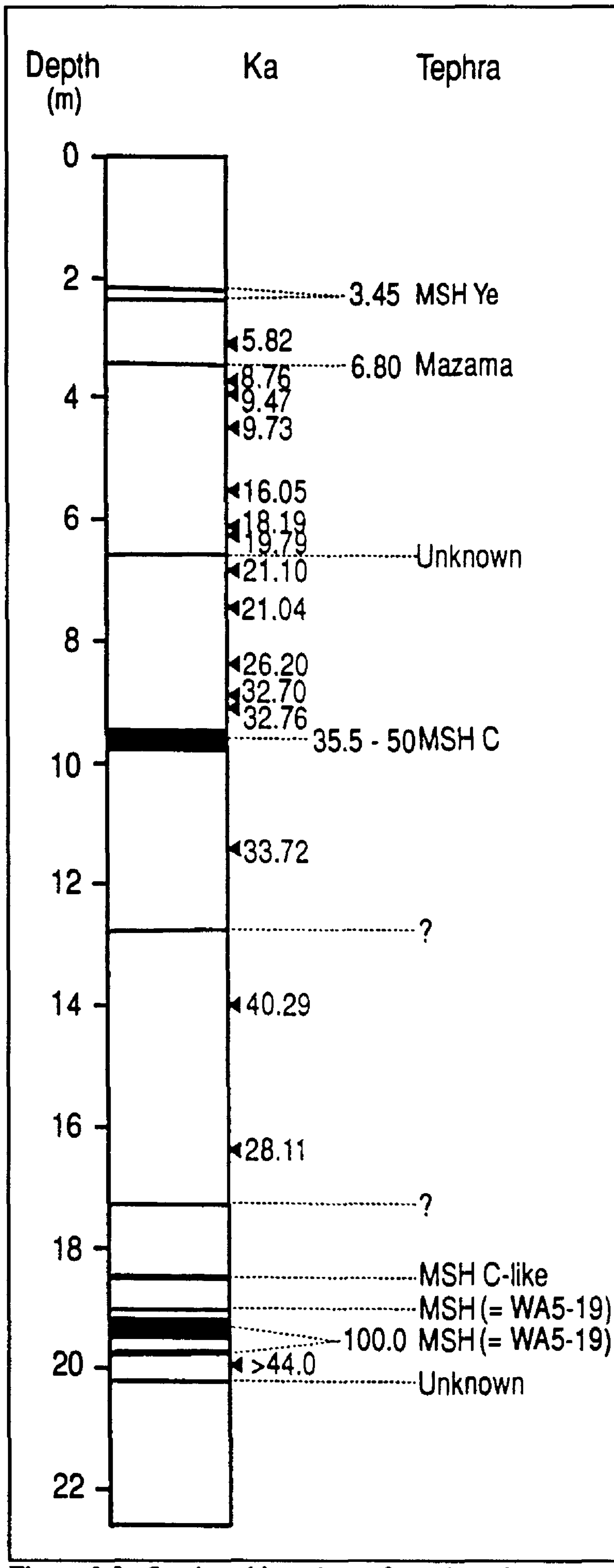

Figure 2-2.--Stratigraphic plot of tephra layers and radiocarbon ages for the Carp Lake 1990 core.

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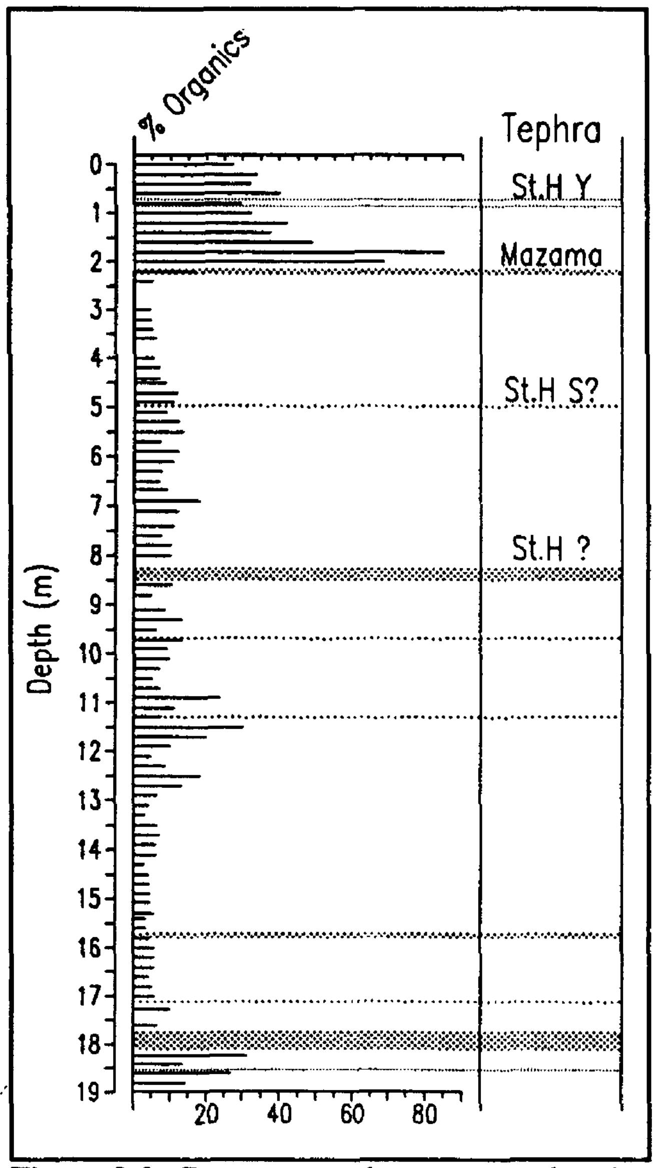

Figure 2-3.--Percent organic content and tephra layers in 1990 core from Carp Lake, Washington.

Status Report on cores taken in 1991-1992 in the Upper Klamath Basin and vicinity, Oregon and California:

Klamath Core Study Team*

*Team members: David P. Adam[1], J. Platt Bradbury[2], Claire Carter[1], Walter E. Dean[2], Kathryn Hakala[3], Mary McGann[1], Richard J. Reynolds[2], Hugh J. Rieck[4], Andrew Roberts[5], Joseph G. Rosenbaum[2], Andrei M. Sarna-Wojcicki[1], Karen Schiller[1], and Cathy Whitlock[6]

Addresses: [1]Menlo Park, CA; [2]Denver, CO; [3]Pittsburgh, PA; [4]Flagstaff, AZ; [5]Davis, CA; [6]Eugene, OR

INTRODUCTION

This report describes work on cores collected by the Marine-Terrestrial Correlations Project in the Klamath Falls, Oregon/California region in 1991 and 1992. The results summarized here represent the work of numerous investigators both within and outside the USGS. The cores are summarized in Table 3-1; a summary chart showing tephra correlations and relative fluctuations in magnetic susceptibility with depth for all of the cores is shown as Figure 3-1.

Butte Valley

Rock Magnetics The core has been logged for magnetic susceptibility throughout (Figure 3-1). Paleomagnetic studies by Roberts identify the Brunhes/Matuyama reversal at 65 m depth; assuming a roughly linear sedimentation rate, the base of the core lies within the Jaramillo normal event, and is about 1 million years old (Figure 3-2).

Lithology A summary of the lithology of the Butte Valley core is shown in Figure 3-3. Lacustrine facies are more common at depth in the core than near the surface, and core recovery was also somewhat better at depth.

Tephra At least twenty-one tephra layers have been identified in the core, and nine of these provide correlations to other localities (Figure 3-1).

Palynology Eighty-six pollen samples have been counted; a preliminary pollen diagram is shown in Figure 3-4. Major variations in the percentages of pollen types through time are evident.

Diatoms Selected samples have been scanned for diatoms by Bradbury, but other cores have taken priority.

Figure 3-1 (in pocket).--Tephra and magnetic susceptibility correlations among the various cores. The curve within the box for each core shows relative fluctuations in magnetic susceptibility, with higher values to the right. Numbers next to each column are sample numbers for tephra samples. Solid correlation lines represent tephra correlations; lighter-colored, thicker lines indicate correlations suggested by susceptibility fluctuations. Tephra work is by A. Sarna-Wojcicki and colleagues; susceptibility curves are by D.P. Adam.

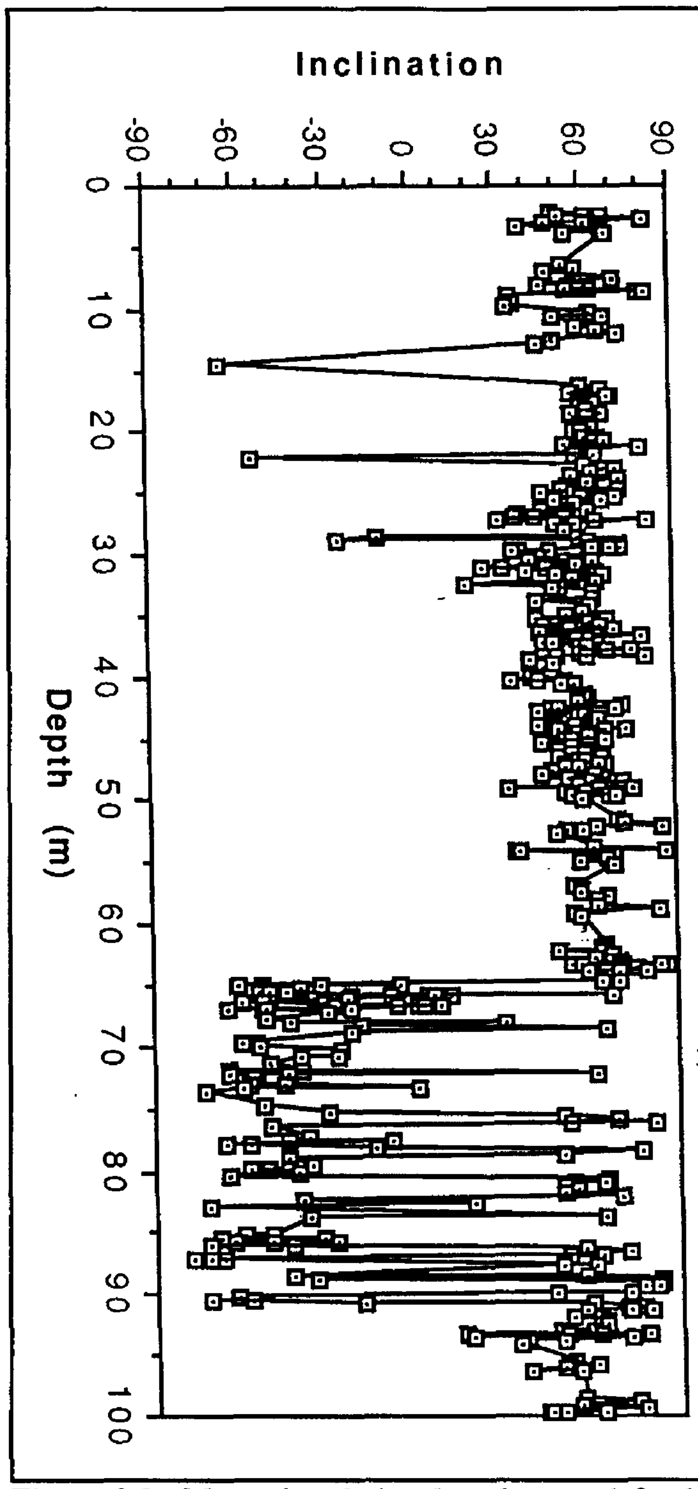

Figure 3-2.--Magnetic polarity plotted *vs.* depth for the Butte Valley core (A. Roberts).

Ostracodes One hundred and eleven ostracode samples have been processed by Carter; two ostracode-rich zones were found, one from 28-39 meters depth and the other from 83.5 meters to the base of the core (Figure 3-5). Several thinner zones or single ostracode-bearing samples were found as well.

Grass Lake

Tephra Two tephra layers have been identified in the Grass Lake core (Figure 3-1). The Olema tephra, with an age of about 60 ka, occurs at a depth of 14.1 meters. At 16.6 meters, Sarna-Wojcicki and his colleagues have identified a tephra that correlates with a layer found in DSDP-173-1, where its age is estimated at about 120 ka. Pollen work on the Grass Lake core leads us to doubt that age for the tephra; it is probably younger.

Rock Magnetics The magnetic susceptibility data for core 2 is complete (Figure 3-1); core 1 was too short to be worth processing. Susceptibility shows wide and systematic fluctuations with depth that probably relate to climate. A graduate student at the University of Colorado, Patti Best, is doing a Master's thesis on the rock magnetic properties and sedimentology of the core under the supervision of Reynolds and Rosenbaum.

Palynology The palynology of the Grass Lake section is being done as a dissertation project by Hakala at the University of Pittsburgh under the supervision of Whitlock. Fifty pollen samples have been counted under a contract with the USGS, and a pollen diagram is complete (Figure 3-6). Additional samples at a 10-cm sampling interval have been provided, but no further support from the USGS is planned. Pollen is present through most of the section, but intervals of poor pollen preservation and/or recovery were noted at the bottom of the core and at a few other horizons.

Radiocarbon The identification of the Olema tephra at 14 meters indicates that deeper layers are beyond the range of radiocarbon dating. Two radiocarbon age estimates are available: 12,810 ± 110 BP at 4.95 meters depth, and 16,160 ± 170 BP at 5.71 meters. Six additional samples have been submitted.

Diatoms No diatom work is planned for the Grass Lake cores unless specific questions arise, but samples are available.

Ostracodes No ostracodes are likely in the Grass Lake cores.

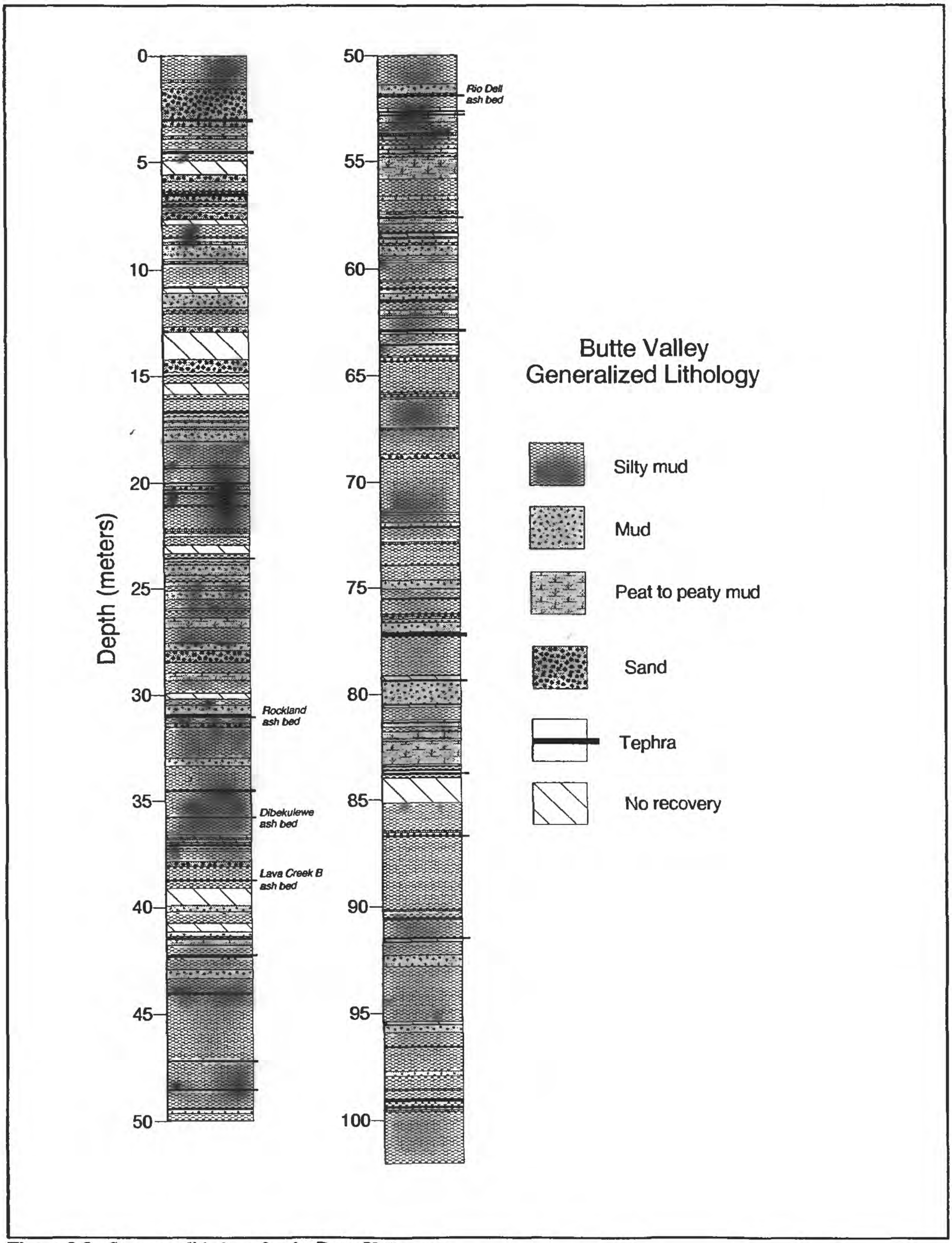

Figure 3-3.--Summary lithology for the Butte Valley core.

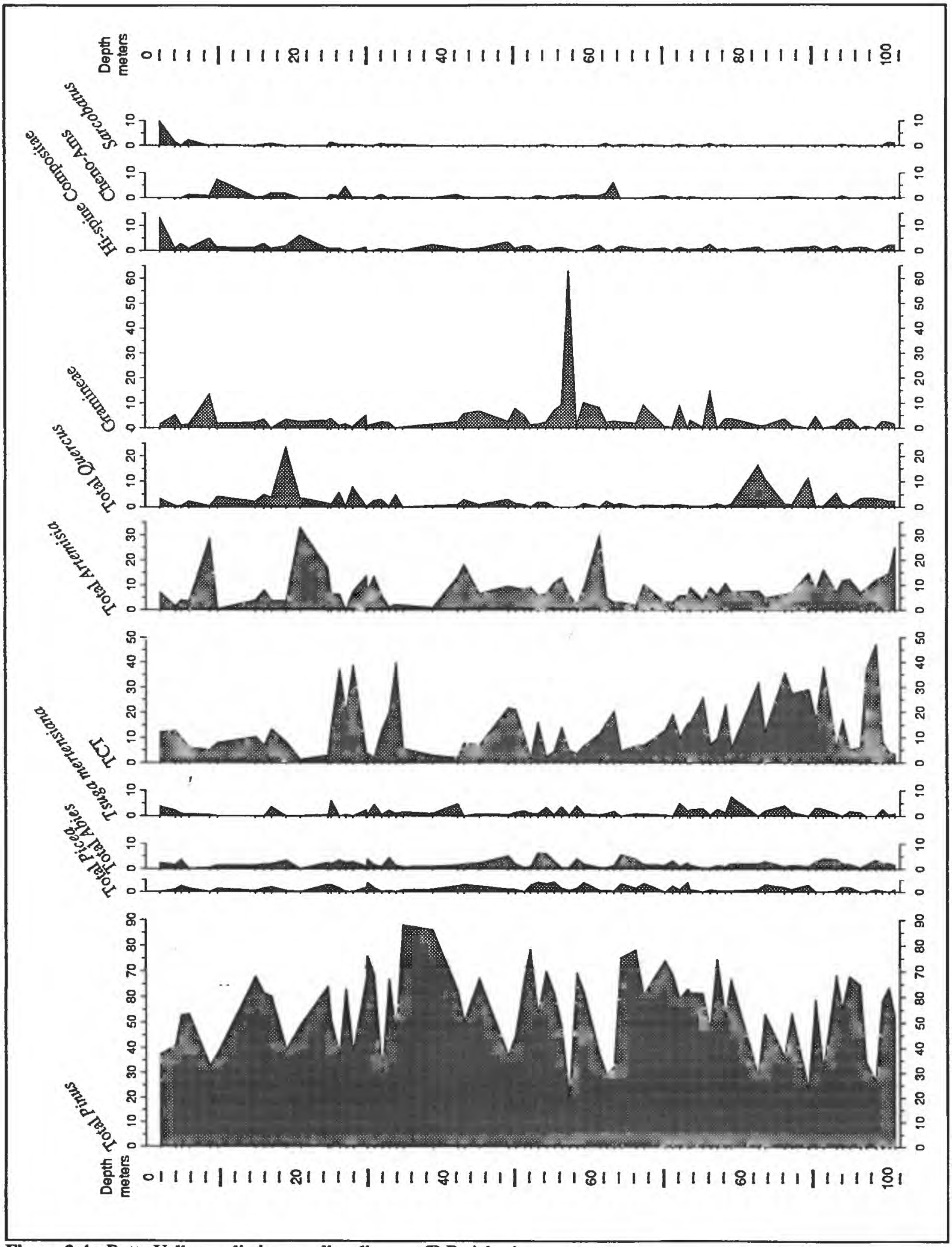

Figure 3-4.--Butte Valley preliminary pollen diagram (D.P. Adam).

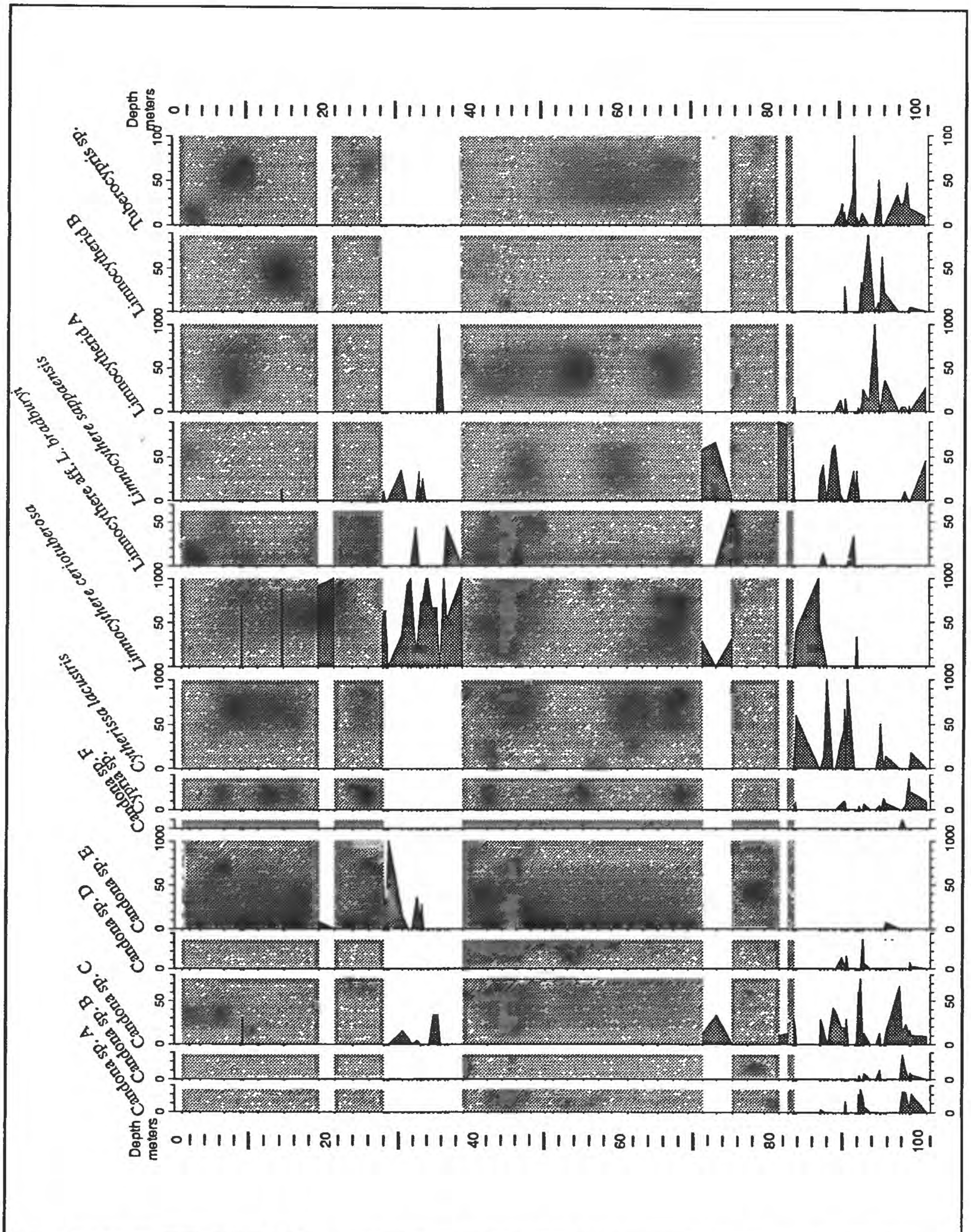

Figure 3-5.--Butte Valley ostracode diagram (C. Carter). Horizontal shaded bars represent zones barren of ostracodes; single ostracode-bearing samples within these zones are shown as horizontal bars.

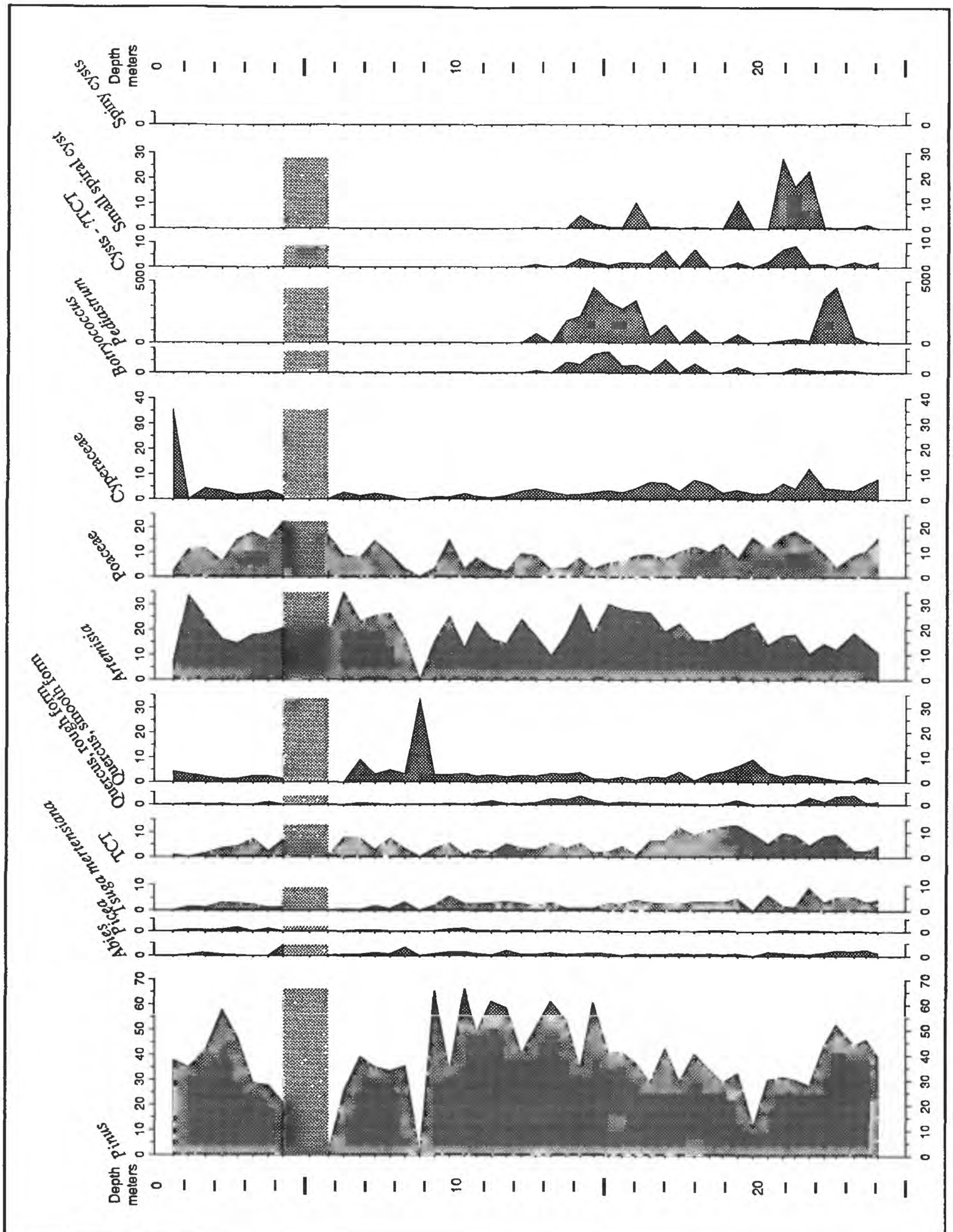

Figure 3-6.--Grass Lake pollen diagram (K. Hakala)

Geochemistry No work is planned, but the samples are available (geochemistry work is done on splits of the diatom samples).

Buck Lake

Lithology An open-file report describing the lithology of the Buck Lake cores is complete (Adam and others, 1993). A summary lithologic section is shown in Figure 3-7.

Tephra Eighteen tephra samples have been analysed from the Buck Lake cores (Figure 3-1), and these have produced eight correlations to other areas. The tephra establish that the main lacustrine phase represented in the core lasted from about 300 to 400 thousand years ago.

Rock Magnetics Work on the rock magnetic properties of the Buck Lake section by Rich Reynolds and Joe Rosenbaum has established that certain easily-measurable properties appear to be related to climate (Rosenbaum and others, this volume). Their detailed studies have confirmed the validity of the susceptibility measurements made by palynologists. Comparison of susceptibility and pollen curves indicates that rock-magnetic changes at the transitions from cool to warm periods occur prior to changes in pollen percentages.

Palynology Sixty-eight samples from Buck Lake have yielded satisfactory pollen counts (Figure 3-8). These are concentrated in the interval between 5 and 20 meters depth that represents the main lacustrine phase of the lake. Two warm and two cold phases are represented; the Loleta ash bed/Bend Pumice, with an estimated age of 300-400 ka, is found near the base of the upper warm phase, and the Rockland ash bed, with an estimated age of ~400 ka, lies just below the base of the lower cool phase at the base of the lacustrine deposits. The upper warm phase represents a vegetation for which there may be no modern analog, with high frequencies of oak, fir, and TCT (probably incense cedar) pollen occurring together.

Diatoms No intensive diatom work is planned for the Buck Lake cores, but samples are available.

Ostracodes No ostracodes have been found in the Buck Lake cores.

Geochemistry Some geochemical work is being done in conjunction with the rock magnetic properties work of Reynolds and Rosenbaum.

Wocus Marsh

Lithology The Wocus Marsh lithology open-file report is complete (Adam and others, 1994). A summary lithologic section is shown in Figure 3-9. The Wocus Marsh section is the only instance in our cores of repeated alternations between peats and clastic sediments through time.

Tephra Seventeen tephra layers have been identified in the Wocus Marsh section (Figure 3-1). A key unit is the Rockland Ash, which is found at a depth of 26.6-28.0 meters and has an age of ~400 ka. This unit provides direct correlations with the Buck Lake and Butte Valley cores of this study, as well as with the Tulelake cores and the Mohawk "lake beds" to the south and east.

Radiocarbon Several samples were submitted to the Menlo Park radiocarbon laboratory for conventional radiocarbon analysis. Two ages of >48,000 and >49,000 were obtained at a depth of 20 meters, as well as two inverted ages of 31720 ± 860 at 11.23 meters and 27,550 ± 780 at 14.5 meters (Figure 3-9). The remaining samples from >20 meters will not be

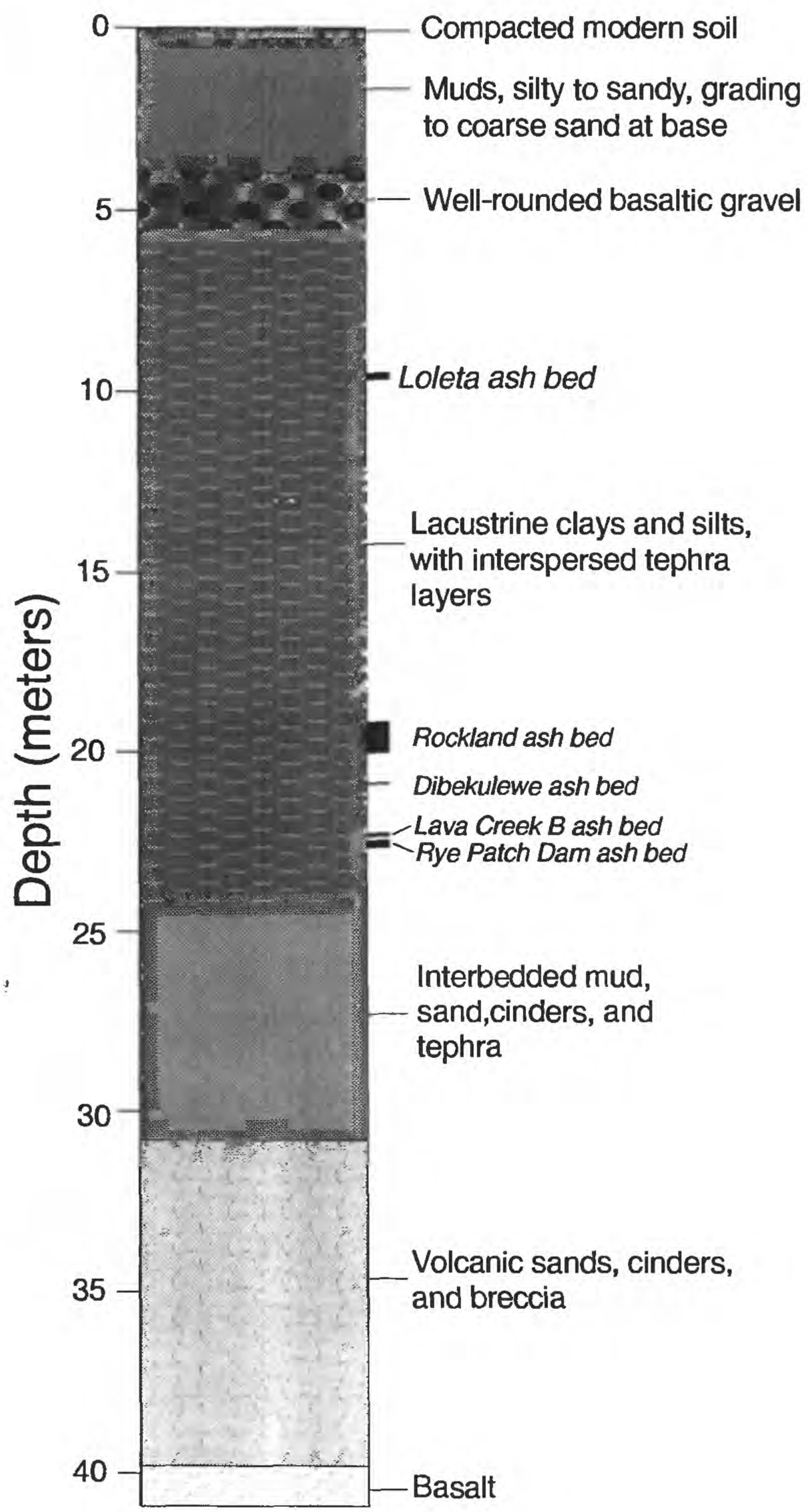

Figure 3-7.--Summary of the Lithology of the Buck Lake, Oregon, section (from Adam *et al.*, 1993)

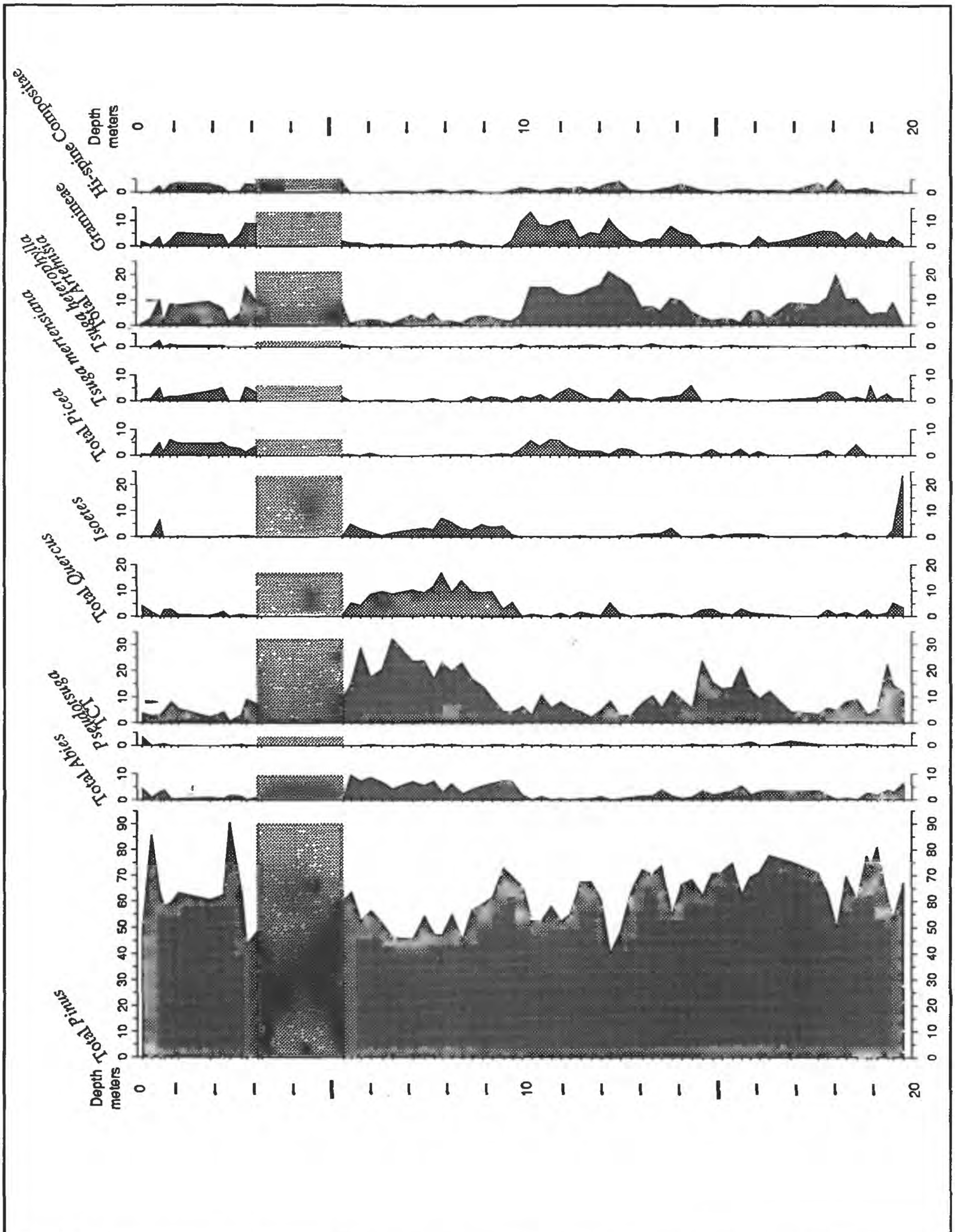

Figure 3-8.--Buck Lake pollen diagram (D.P. Adam). Horizontal shaded bars represent a zone barren of pollen.

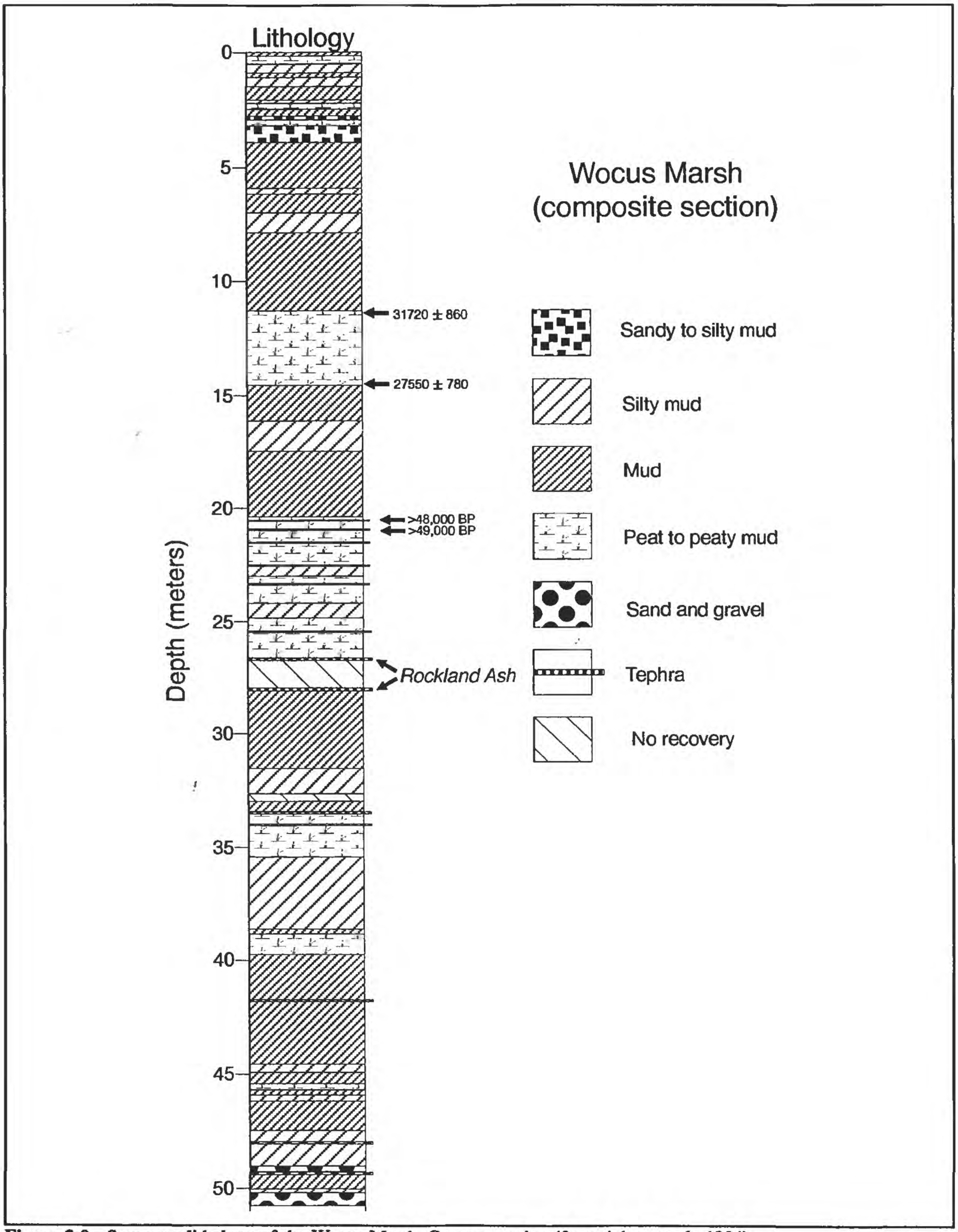

Figure 3-9.--Summary lithology of the Wocus Marsh, Oregon, section (from Adam *et al.*, 1994)

dated.
Rock Magnetics The magnetic susceptibility logs for cores 1 and 2 are complete (Figure 3-1). Susceptibility shows broad systematic fluctuations with depth that probably relate to climate. Palynology The palynology of the Wocus Marsh section is being handled by Prof. Cathy Whitlock of the Geography Department of the University of Oregon. Forty-six pollen samples have been processed to date, and a preliminary pollen diagram is available (Figure 3-10). The identification of the Rockland ash bed near the middle of the section has shown that the record spans a much longer interval than we initially supposed. More detailed analyses at a 10-cm sampling interval are being undertaken by Prof. Whitlock with support from an NSF grant.
Diatoms Diatom work on the Wocus Marsh section is proceeding in conjunction with similar work on the Caledonia Marsh core. Initial observations suggested that the base of the Wocus Marsh section could be over one million years old, which is in general agreement with the identification of the Rockland ash near the middle of the section.
Ostracodes No ostracodes have been found in the Wocus Marsh cores.

Caledonia Marsh
Tephra Seven visible tephra layers are known from Core 2, and two from Core 1 (Figure 3-1). The Olema ash bed was found at the base of core 2, and provides a maximum estimated age of 60 ka for the bottom of the record. Stratigraphically higher tephra in Core 2 include Mt. St. Helens C_W, the Trego Hot Springs ash (21.8 ka), and the Mazama Ash (7 ka). An apparent problem with the Olema tephra appearing at different depths in cores 1 and 2 we now attribute to poor core recovery in core 1, which created large uncertainties in sample depths in that core.
Rock Magnetics Magnetic susceptibility measurements are complete for both Core 1 and Core 2 (Figure 3-1). The poor recovery just noted for Core 1 is apparent in Figure 3-1. Work by Rosenbaum and Reynolds on the rock magnetic properties of Core 2 has shown that the relationship between susceptibility and climate observed at Buck Lake also holds in the sediments of Upper Klamath Lake (Rosenbaum and others, this volume).
Palynology Thirty-seven pollen samples have been counted for Caledonia Marsh Core 2, and a preliminary pollen diagram is complete (Figure 3-11). The record appears to be continuous for at least the past 40 ka.
Diatoms Diatom analyses of the Core 2 record are underway, and are a top priority.
Radiocarbon Most of the initial samples submitted for conventional radiocarbon analyses were judged too small and low in carbon content for dating, and have been returned. Ten samples have been submitted for AMS dates on parts of the core where changes in pollen frequencies take place.
Geochemistry Geochemical samples to match the diatom samples have been submitted. A profile of organic carbon is complete (Figure 3-12), and elemental analyses are in progress.

Round Lake
Lithology A summary lithologic section for the Round Lake core is shown in Figure 3-13. The top 25 meters of the section consists of very sticky clays, and only one visible tephra layer was found (Figure 3-1). This part of the section may represent a time when the lake

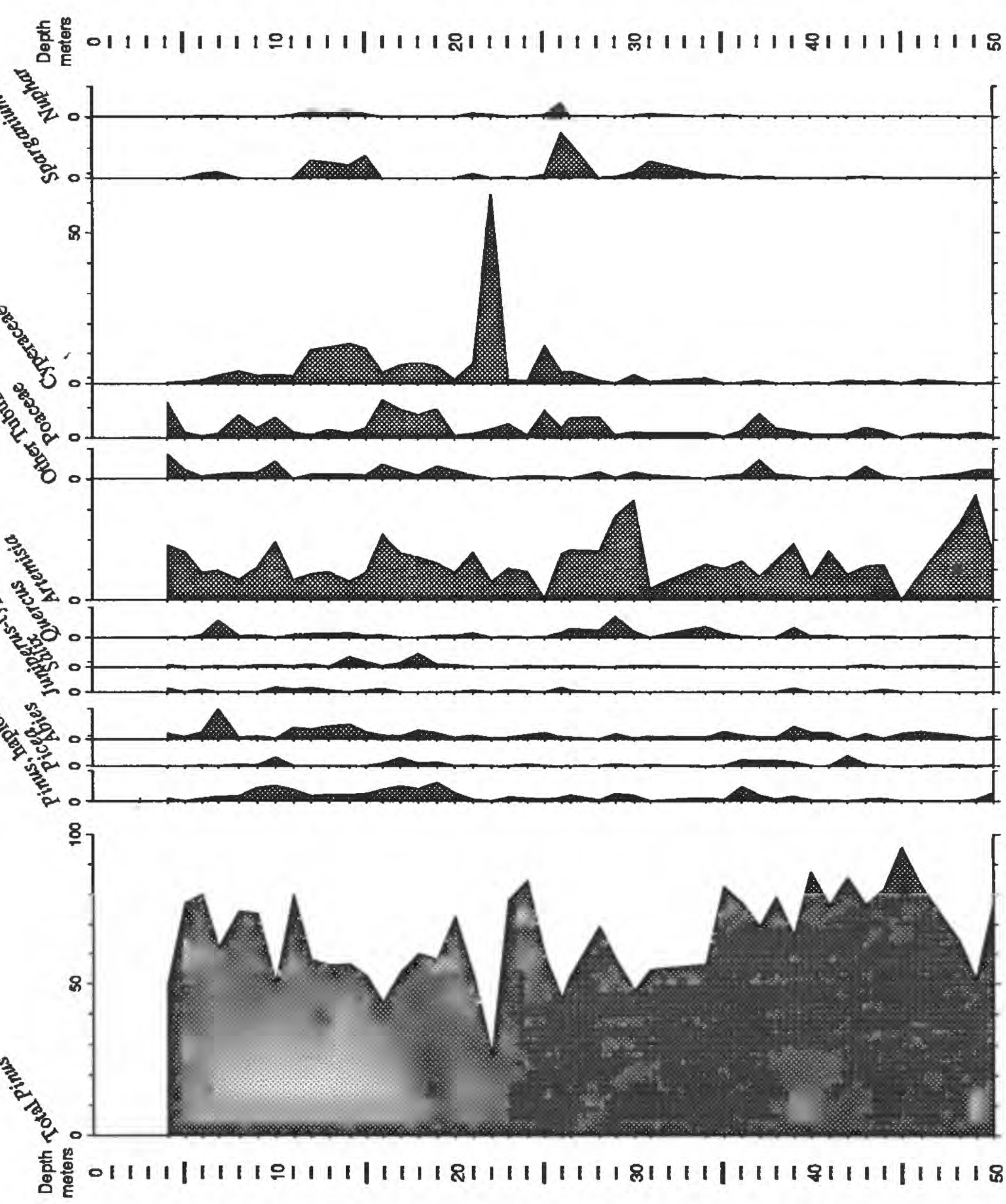

Figure 3-10.--Preliminary pollen diagram for Wocus Marsh, Oregon (C. Whitlock)

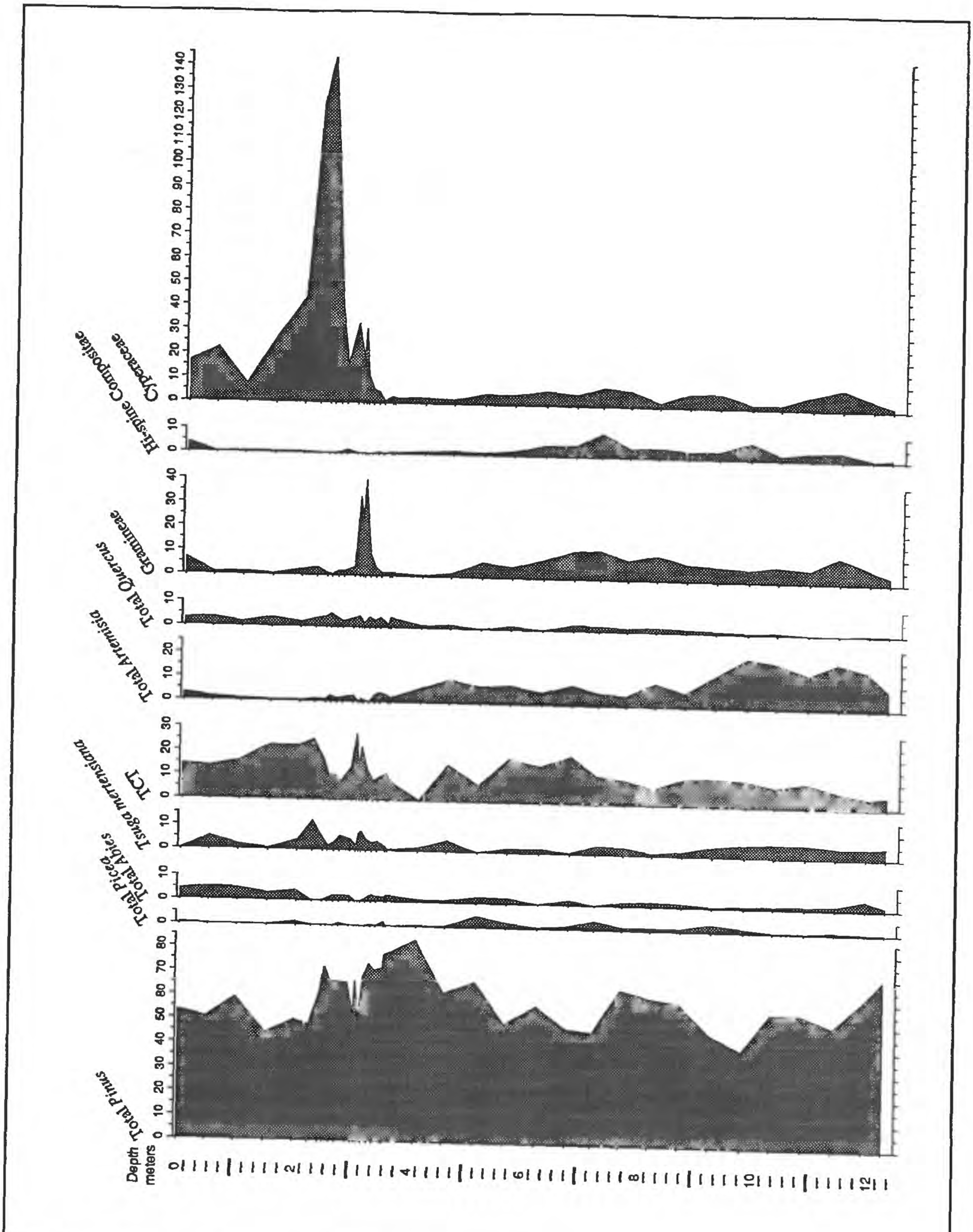

Figure 3-11.--Preliminary pollen diagram for Caledonia Marsh, Oregon, Core 2 (D.P. Adam)

dried out frequently, and swelling and shrinking of the surface sediment through wetting and drying cycles mixed the surface layers and destroyed any visible stratigraphy. The bottom 25 meters, by contrast, consists of organic lake muds with several interbedded tephra layers (Figure 3-1), and apparently represents an open-water lake environment. This sequence offers a good opportunity to examine the long-term dynamics of a middle- to early-Pleistocene lacustrine sequence from a moderate-sized lake in a closed basin.

<ins>Tephra</ins> Seven visible tephra layers have been sampled in the Round Lake core, all but one from the bottom half of the section. A series of samples near the base of the Round Lake core matches a similar series at the base of the Wocus Marsh section, but the exact correlations are not yet clear. The tephra layer from the upper half of the core, at 6.8 meters, correlates with a tephra found at Paoha Island in Mono Lake, and has an estimated age of 160-180 ka.

<ins>Rock Magnetics</ins> A susceptibility log for the Round Lake core is complete (Figure 3-1), and reflects the lithology noted above. The upper half of the core is rather homogeneous, but below about 20 meters the susceptibility curve shows broad systematic fluctuations that suggest several cyclical climatic events. The pronounced susceptibility changes are in marked contrast to the lithologic uniformity in this part of the core.

<ins>Palynology</ins> Very little pollen work has been done, but the Round Lake core appears to contain pollen throughout. The bottom half of the core appears to be well worthy of study, but preservation in the top half may be less than optimum.

<ins>Diatoms</ins> Status is the same as for pollen.

<ins>Ostracodes</ins> No ostracodes have been found in the Round Lake core.

<ins>Geochemistry</ins> No geochemical work has been done.

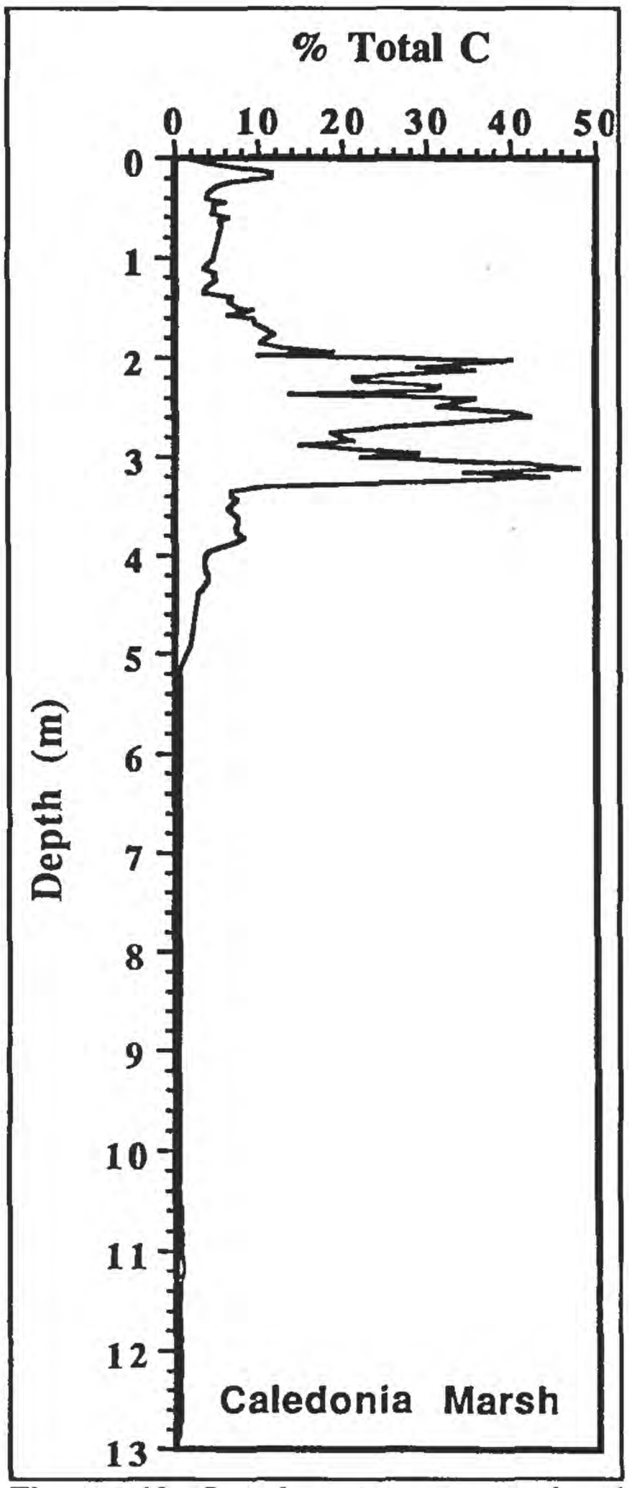

Figure 3-12.--Organic carbon percent plotted vs. depth for Caledonia Marsh, Oregon, Core 2 (W. Dean)

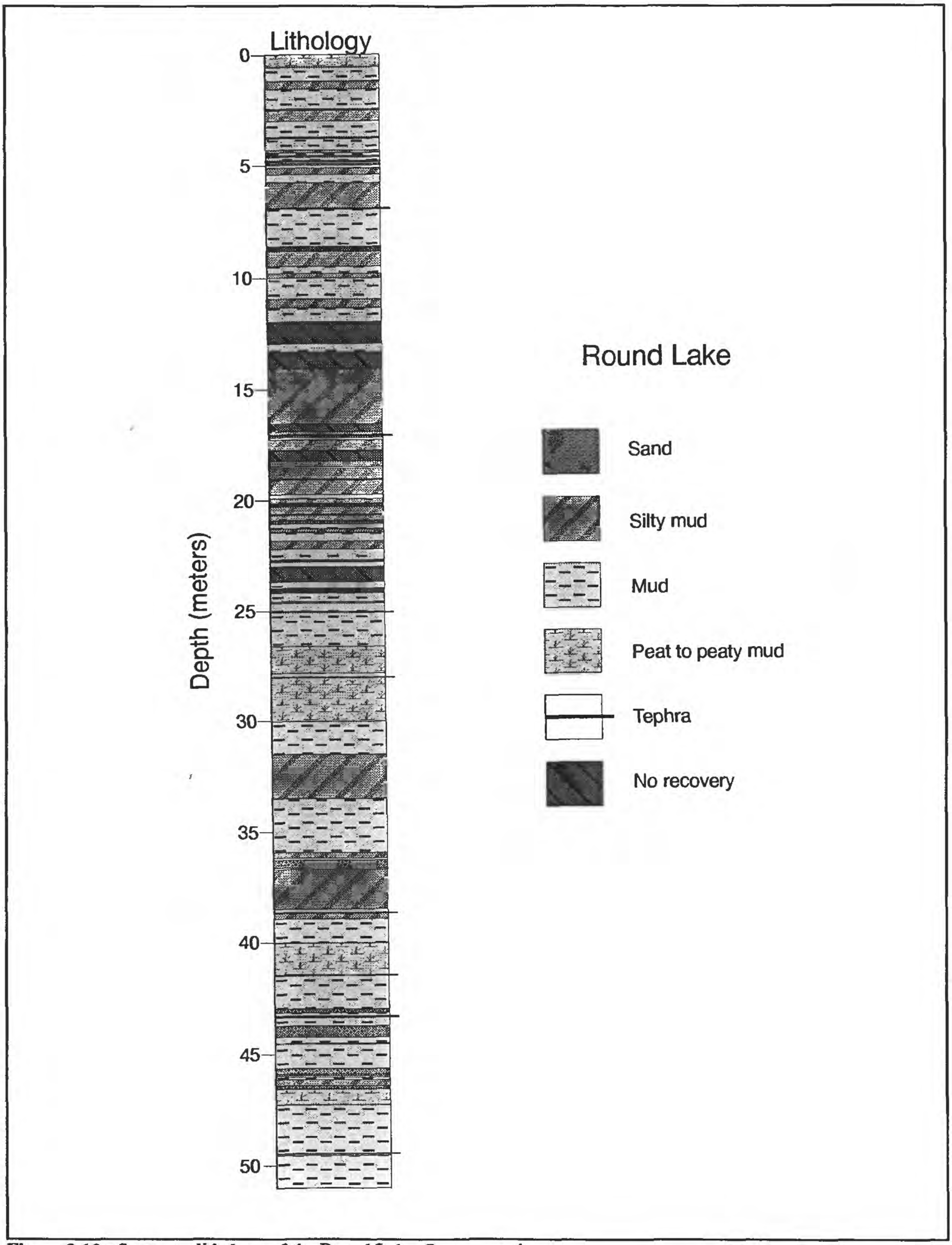

Figure 3-13.--Summary lithology of the Round Lake, Oregon, section.

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Table 3-1.--USGS Klamath Falls Cores

Site name	Core length (meters)	Recovery	Description
Butte Valley, CA	102	excellent	Both perennial and ephemeral lake deposits; numerous tephra; carbonate often preserved.
Grass Lake, CA	29	excellent	Basin dammed by lava flow; lake and marsh deposits at top of core, changing to volcanic debris flow at base; numerous tephra.
Buck Lake, OR	41.3	excellent	Top 30 m lacustrine clay with numerous tephra; bottom 11 m is volcanic debris flow underlain by basalt.
Round Lake, OR	50	good	Top 25 m very tight clays with no visible tephra, probably representing intermittent lake;
		excellent	bottom 25 m open-water lake muds with several tephra.
Wocus Marsh, OR	52	excellent	Interbedded peats, organic muds, inorganic muds (basaltic rock flour?), and tephra. Probably includes glacial sediment from Mt. Mazama.
Caledonia Marsh, OR	15.3	good	Very soupy lacustrine muds with several tephra. Drilling stopped by artesian water. Upper 12 meters sampled with good recovery using manual equipment in 1992.

Climate Records from Quaternary Sediment, Buck Lake and Caledonia Marsh, Southern Oregon: Comparison of Magnetic and Pollen Data:

J.G. Rosenbaum[1]; R.L. Reynolds[1], D.P. Adam[2], A.M. Sarna-Wojcicki[2]; C.G. Whitney[1]; M.W. Kerwin[3], and P. Fitzmaurice[1]

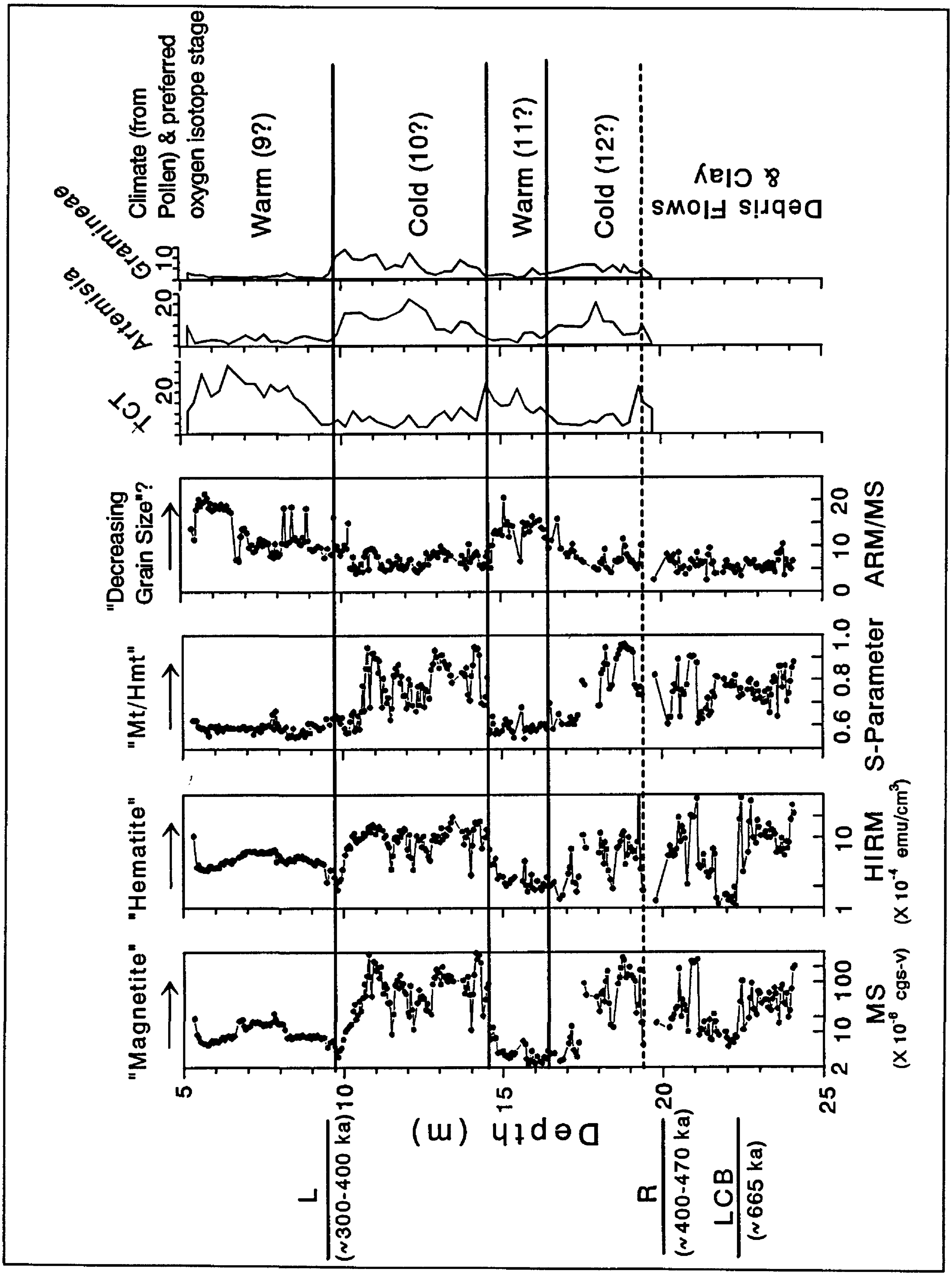
[1]U.S. Geological Survey, Denver, CO
[2]U.S..Geological Survey, Menlo Park, CA
[3]INSTAAR, Univ. of Colorado, Boulder, CO

INTRODUCTION

Magnetic properties of lake sediments that indicate the amount, type, and grain size of magnetic minerals can provide proxy records of climate change (Thompson and Oldfield, 1986; King and Channell, 1991). Evidence for the connection between sediment magnetic properties and climate is provided by comparing such properties with biological indicators of paleoclimate, such as pollen, diatoms, or ostracodes. Magnetic properties can play a powerful complementary role to the more direct paleoclimate indicators, because large numbers of samples can be analyzed rapidly and with high sensitivity, thus yielding high-resolution records. In lacustrine settings, paleoclimate interpretations of sediment magnetic data usually require that variations in the magnetic mineralogy reflect changes in detrital magnetic-mineral flux that is controlled by (l) physical and chemical weathering in the catchment, (2) the mode and energy of sediment transport, and (3) the energy of deposition. Therefore, post depositional modification of magnetization caused by the alteration or authigenesis of magnetic minerals must be evaluated. Similarly, one must recognize changes in environmental conditions of the lake or source area, or shifts to different source areas, that are not related to climate change but that could affect magnetic-mineral flux at a given site, such as might be caused by tectonism and volcanism.

Sediment magnetic and palynological records from two sites of Middle Pleistocene and latest Pleistocene - Holocene lacustrine sediments (Buck Lake and Caledonia Marsh) in southern Oregon (Chapter 3, this volume) show systematic variations. In both basins X-ray diffraction analysis confirms the presence of magnetite and hematite, and thermomagnetic analysis demonstrates that the magnetite contains titanium. Both methods indicate an absence of magnetic sulfide minerals and nonmagnetic sulfides associated with the magnetite. In addition, well-preserved pollen indicates a lack of post-depositional oxidation. Changes in the magnetic

Figure 4-1 (next page). Plots of magnetic properties with depth for Middle Pleistocene sediments from Buck Lake, Oregon. Magnetic susceptibility (MS) is primarily a measure of magnetite content. "Hard" isothermal remanent magnetization (HIRM) is a measure of the concentration of high coercivity magnetic minerals (*e.g.*, hematite), whereas the S parameter reflects the amount of magnetite relative to amounts of high coercivity magnetic minerals (for definitions of HIRM and S see King and Channell, [1991]). Higher values of S indicate relatively more magnetite. For magnetite bearing sediments ARM/MS (ARM=anhysteretic remanent magnetization) is used as a measure of magnetic grain size. Higher values of this ratio are commonly interpreted to indicate smaller magnetic grain size, but high values may also arise from low ratios of magnetite to hematite. L, R and LCB indicate positions of tephra correlative with the Loleta ash bed/Bend pumice, the Rockland ash bed, and the Lava Creek B ash bed. Warm and cold intervals are inferred from the pollen record, from which TCT, *Artemisia*, and Gramineae are shown (see Chapter 3, this volume).


"Magnetite"
"Hematite"
"Mt/Hmt"
"Decreasing Grain Size"?
TCT
Artemisia
Gramineae
Climate (from Pollen) & preferred oxygen isotope stage
Warm (9?)
Cold (10?)
Warm (11?)
Cold (12?)
Debris Flows & Clay
MS (X 10^-6 cgs-v)
HIRM (X 10^-4 emu/cm^3)
S-Parameter
ARM/MS
Depth (m)
L (~300-400 ka)
R (~400-470 ka)
LCB (~665 ka)

properties thus reflect changes in the quantity and type of detrital Fe-oxide minerals, and they apparently reflect changes in physical and chemical weathering in the catchment in response to climate change.

BUCK LAKE

A 42-m core was obtained by rotary-core drilling at Buck Lake, an open meadow just east of the crest of the Cascade Range at an elevation of 1500 m. Middle Pleistocene lacustrine clays, which extend from 5 to 20 m below the surface, are unconformably overlain by sand and gravel, and are underlain by interbedded clays and volcanic debris-flow deposits (Adam and others, 1994). The age of the sediment is indicated by several tephra layers correlative with the Loleta ash bed/Bend pumice (≈300-400 ka, 9.5-9.6 m), the Rockland ash bed (≈400-470 ka, 19.9 m), and the Lava Creek B ash bed (≈665 ka, Izett and others (1992), 22.3 m). Normal polarity inclinations are measured in clay to 24.1 m indicating deposition of the sediment during the Brunhes chron (<780 ka).The lacustrine section may be divided into four zones on the basis of pollen percentages (Figure 4-1). Two zones are dominated by high percentages of *Artemisia* and grass pollen, indicating cold environments of sagebrush steppe. The other zones are characterized by abundant *Calocedrus* and(or) *Juniperus* pollen, indicating warm climate. Assuming that each pollen zone correlates to a deep-sea oxygen-isotope stage and assuming the absence of major hiatuses, three possible matches can be made given the uncertainties in ages of the tephra. Correlation of the pollen zones with oxygen isotope stages 9 (warm) through 12 (cold) provides the most comfortable match with the tephrochronology.

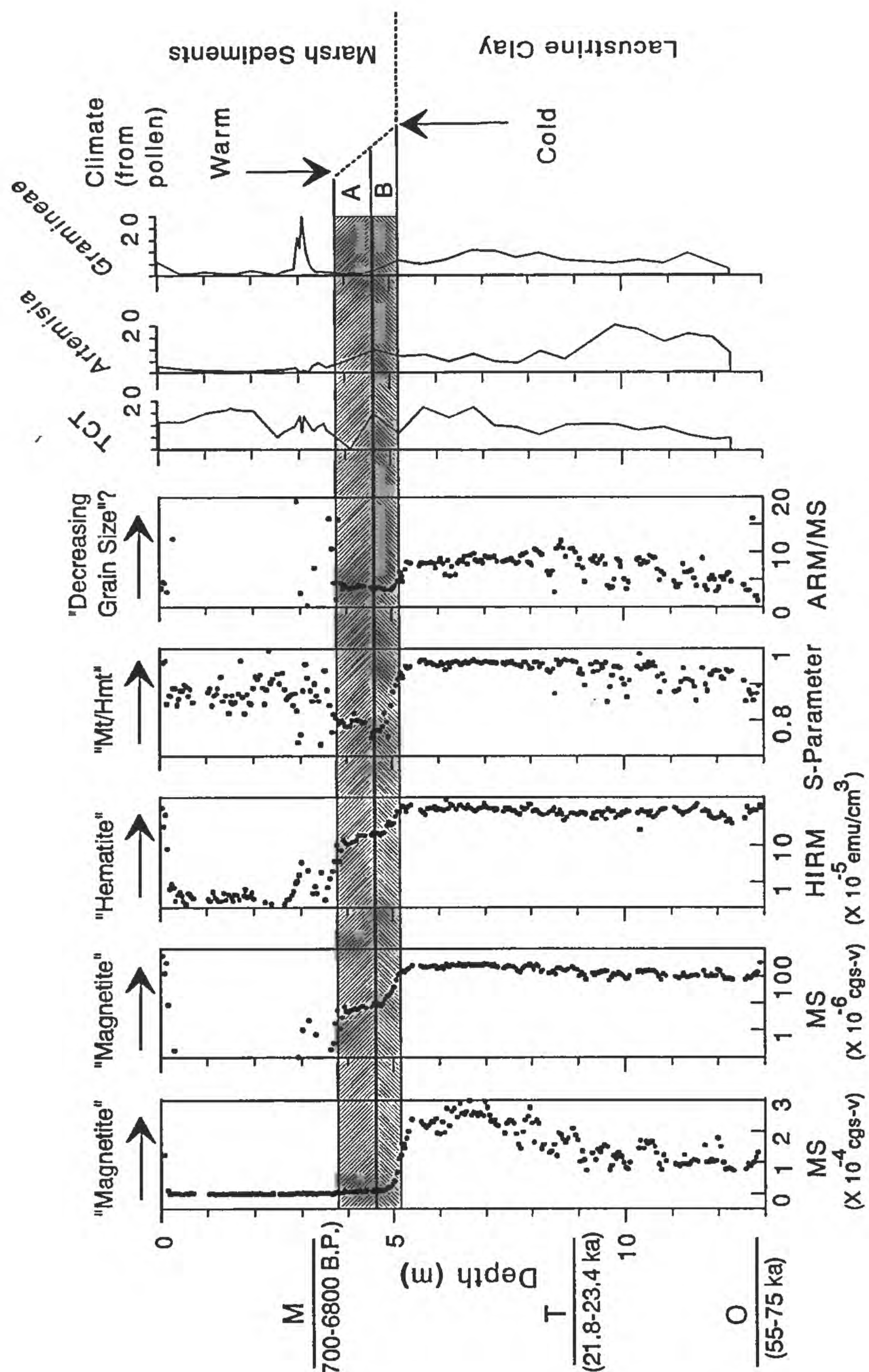
Magnetic susceptibility (MS), which is largely a measure of magnetite content, ranges over two orders of magnitude in the lacustrine beds (Figure 4-1). Two zones of high MS (10.3-14.5 and 17.4-20 m) generally coincide with the cold intervals inferred from the pollen zonation. Similarly, two zones of low MS (5.3-10.3 m and 14.5-17.4 m) generally coincide with the warm intervals. Both transitions from high to low MS precede changes from cold to warm pollen zones, whereas the transition from low to high MS at 14.5 m coincides with the change in pollen assemblages. Other striking features in the MS data are the well defined high frequency variations ("spikes") in the high MS zones and the three-part division in the upper low-MS zone. There are no readily apparent changes in lithology that correspond with either the MS variations or the pollen zonation.There is a strong positive correlation between MS and "hard" isothermal remanent magnetization (HIRM), which is largely a measure of ferric oxide mineral content (*e.g.*, hematite) (Figure 4-1). A negative correlation should exist between these parameters if magnetite and hematite were related by post-depositional alteration. Changes in total content of these Fe-oxides probably reflect differences in the amount of detrital heavy minerals and therefore may reflect the energy of sediment transport and(or) deposition. Moreover, the S parameter, which indicates the ratio of magnetite to ferric oxide minerals, does not remain constant (Figure 4-1). Greater amounts of total Fe-oxide minerals correspond to greater relative amounts of magnetite (high S values). This relation suggests that high Fe-oxide content is associated with source rocks that have undergone little chemical weathering involving alteration of magnetite to ferric oxide. Conversely, low Fe-oxide content may be associated with relatively more chemical weathering (low S values), possibly during soil formation in the catchment. ARM/MS, a parameter commonly used to infer magnetic grain size of magnetite, shows strong variations with the MS zones (Figure 4-1). High ARM/MS values correspond to low MS zones, and low ARM/MS values correspond to high MS zones. The close correspondences result from changes in magnetic mineralogy between the zones rather than from grain-size differences. Hematite dominates the low MS zones (indicated by low S values) and causes elevated values of ARM/MS. Magnetic grain-size information, nevertheless, is contained in the high-MS zones. Within both high MS zones the magnetic grain size typically increases (lower ARM/MS) as magnetite content and S values decrease. These magnetic grain-size variations may be due to the preferential alteration of finer-grained magnetite to hematite (thereby increasing magnetic grain size of the remaining magnetite) during warmer periods with diminished mechanical weathering and enhanced chemical weathering.

CALEDONIA MARSH

The section recovered in a 12.8-m-long core from Caledonia Marsh, at upper Klamath Lake, represents roughly the past 55-75 ka, on the basis of identification of the Olema ash bed at the bottom of the core (Figure 4-2). The Mazama ash bed (6700-6800 B.P., Sarna-Wojcicki and others, (1991)) occurs at ≈3.2 m and the Trego Hot Springs ash bed (23.4 ka, Sarna-Wojcicki and others, (1991); 21.8 ka, Negrini and Davis, (1992)) occurs at ≈8.8 m. Lacustrine clays, which comprise the section below 5.15 m, are in sharp contact with overlying organic-rich clay deposited in a marsh. If a constant sedimentation rate throughout the marsh deposits is assumed (controlled by the present day surface and the Mazama ash bed) then the 5.15 m level corresponds to a loosely constrained age of 10.8 ka, close to 11 ka estimates of the boundary between oxygen isotope stages 1 and 2 (*e.g.*, Morley and Hays, (1981)). Amelioration of the climate is indicated by changes in pollen percentages within the marsh sediments (Figure 4-2). *Artemisia* and grass pollen are plentiful throughout the lacustrine sediments; grass pollen declines upward between 5.2 and 4.6 m, and *Artemisia* declines between 4.6 and 3.8 m.

MS varies from mostly negative values in the upper 3.6 m to high values (most $>10^{-4}$ emu/cm^3) in the lacustrine clay (Figure 4-2). The negative values probably reflect the diamagnetism of abundant diatoms and extremely small quantities of Fe-oxides. MS begins to decline sharply at about 5.5 m, approximately 30 cm below the lithologic break and the start of the decrease in grass pollen. Values of MS continue to fall as grass pollen concentration declines and then less steeply as *Artemisia* pollen declines. As in the sediments from Buck Lake, there are strong positive correlations (1) between HIRM (quantity of hematite) and MS (quantity of magnetite), and (2) in the sediments below the negative MS zone, between total Fe-oxide content (MS and HIRM) and the S-parameter (amount of magnetite relative to hematite). In the upper 3.6 m, however, high relative magnetite content (high values of S) corresponds to sediment with the lowest Fe-oxide content. This change in the upper marsh sediments may reflect one or more factors including a different source for the Fe-oxides, a different mode of deposition, and different post-depositional conditions. ARM/MS values probably reflect magnetic grain size in

Figure 4-2 (next page). Plots of magnetic properties with depth for latest Pleistocene - Holocene sediments from Caledonia Marsh, Oregon. Variables are described in Figure 4-1. Note that MS is plotted on both a linear scale (on the left) and a log scale (on the right). M, T, and O indicate positions of tephra correlative with the Mazama, Trego Hot Springs, and Olema ash beds. Zones in which *Artemisia* pollen and grass pollen (Gramineae) decline upwards are denoted by A and B, respectively; TCT percentages are also shown (see Chapter 3, this volume).


"Magnetite"
"Magnetite"
"Hematite"
"Mt/Hmt"
"Decreasing Grain Size"?
TCT
Artemisia
Gramineae
Climate (from pollen)
Warm
Cold
A
B
Marsh Sediments
Lacustrine Clay
Depth (m)
M (6700-6800 B.P.)
T (21.8-23.4 ka)
O (55-75 ka)
MS (X 10^{-4} cgs-v)
MS (X 10^{-6} cgs-v)
HIRM (X 10^{-5} emu/cm^3)
S-Parameter
ARM/MS

both the high- and low- MS zones, because hematite is not as dominant in the low-MS sediments (S mostly >0.75) as it is in those from Buck Lake (S mostly <0.6). As in the high-MS sediments from Buck Lake, fine magnetic grain size generally corresponds to high magnetite content.

CONCLUSIONS

Magnetic-petrologic and palynologic studies of cores from Buck Lake and Caledonia Marsh demonstrate a correlation of sediment magnetic properties with climatic changes. The amount of heavy Fe-oxide minerals probably reflects the energy of transport and(or) deposition, whereas the proportion of magnetite to hematite may reflect the relative importance of mechanical and chemical weathering. Mechanical weathering and high energy apparently dominate cold climatic intervals. Magnetic properties, particularly those indicating magnetite content, both absolute and relative to hematite, vary closely with changes in climatic conditions indicated by pollen. In both basins the transitions from cold to warm climate based on pollen are preceded by sharp changes in the magnetic properties. This relation suggests that shifts in climate have been recorded more rapidly by changes in erosional and weathering processes than by changes in plant cover. High-frequency variations in magnetic properties, such as those within the high MS zones in the Buck Lake core, apparently arise from the same types of mineralogical variations as the longer wavelength features and may thus provide information about climate fluctuations within individual oxygen isotope stages.

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An 800,000-yr paleoclimatic record from Core OL-92, Owens Lake, southeast California:

Owens Lake core-study team*

*Team members: D.P. Adam[1], I. Altschul[2], V.A.S. Andrle[3], R.L. Anderson[4], L. Benson[5], J.L. Bischoff[1], S.S. Boughn[4], J.P. Bradbury[3], C. Carter[1], R.S. Coe[4], J.R. Firby[6], J.P. Fitts[1], J.A. Fitzpatrick[1], N.O. Frederiksen[7], I. Friedman[3], J.M. Glen[4], M.M. Hannah[4], C.A. Johnson[3], R.J. Litwin[7], K.M. Menking[4], C.E. Meyer[1], A. Sarna-Wojcicki[1], T.P. Sheehan[7], G.I. Smith[1], G.R. Smith[8], S. Soles[1], W.G. Spaulding[9], T.W. Stafford, Jr.[10], M.L. Tuttle[3], E. Wan[1], and W.B. Woolfenden[11].

Affiliations and locations: [1]USGS, Menlo Park, CA; [2]University of Southern California, Los Angeles, CA; [3]USGS, Denver, CO; [4]University of California, Santa Cruz, CA; [5]USGS, Boulder, CO; [6]University of Nevada, Reno, NV; [7]USGS, Reston, VA; [8]University of Michigan, Ann Arbor, MI; [9]Dames & Moore, Las Vegas, NV; [10]University of Colorado, Boulder, CO; [11]University of Arizona, Tucson, AZ.

INTRODUCTION

An important element of paleoclimatic investigations is the record of past changes in precipitation in now-arid parts of the United States. More than a century of geologic investigations produced several lines of evidence indicating that major changes in precipitation and runoff occurred throughout much of this region during the Quaternary period. Among the most convincing evidence were large changes in the sizes of lakes in the Great Basin. These basins are sometimes termed "nature's rain gages" because their water levels primarily record precipitation amounts within their drainage areas, and their lake-level histories thus document past major changes in this element of climate. There is, however, an inadequate consensus about the sequences and ages of these ancient lakes as well as the quantitative meteorological significance of their fluctuations. Because changes in precipitation amounts were--and in the future, would be--among the most critical to various forms of life, the timing and intensities of these climatic changes pose important questions to earth and paleoclimate scientists.

Evidence indicating lake histories extending from the present to periods much older than about 100 ka are relatively rare because the sediments and geomorphic evidence of their existence have been destroyed by erosion or buried by younger deposits. Records of earlier Pleistocene-age lakes can be found, however, in deposits beneath the surfaces of many modern lakes or playas, and a core drilling program with this goal, lasting several years and targeting a number of basins, was envisioned by members of a group attending a paleoclimate workshop in the Spring of 1990. Owens Lake, a closed basin in southeast California, was determined to be one of the promising sites because:

- Paleoclimatologically, Owens Lake and the succession of downstream basins that were hydrologically connected during wet ("pluvial") periods of the Pleistocene represent a setting capable of recording a wide range of precipitation extremes. This results from the geometry of the chain of lakes that starts with Owens, because each climate-caused increase in runoff, upon reaching certain threshold levels, created new lakes in one or more of the formerly-dry downstream basins which had cumulative surface areas that could evaporate up to tenfold increases in regional runoff (Gale, 1914; Smith and Street-Perrott, 1983).

- Hydrologically, Owens Valley today presents an uncommonly well-known setting as a result of more than a century of measurements by scientists and engineers concerned with the water supply for the City of Los Angeles.

- Geophysical studies show that the deepest and widest part of the bedrock surface beneath southern Owens Valley lies under Owens Lake, and that this area is underlain by more than 1.8 km of low-density sediments that were probably dominated by late Cenozoic lacustrine deposits.

- Geological studies suggest that the central Sierra Nevada has been within about 500 m of its present elevation during the Quaternary Period (Huber, 1981), and meteorological considerations suggest that even during an arid period like the present, a mountain range having its elevation would have orographically produced enough precipitation to support a perennial water body in Owens Lake. During this time, therefore, the basin probably always contained a perennial lake, minimizing climatic-record losses due to erosion or hiatuses caused by periods of non-deposition.

Although Owens Lake had an area of about 290 sq km and held about 15 m of slightly saline water during the mid-1800's, increased evaporation caused by irrigation in Owens Valley shrank the lake area to about 75 percent of its earlier size by 1905, and diversion of the remaining Owens River water to Los Angeles in 1913 caused it to evaporate to near-dryness between then and 1920. The drill site was in the south-central part of the now-dry lake (Figure 5-1). Core drilling commenced in April and finished in June, 1991. Data collected during the first year and a half of study following completion of the core-drilling phase are given by Smith and Bischoff (1993). This paper summarizes our paleoclimate interpretations of those data.

PROGRESS TO DATE

The drilling project at Owens Lake commenced in April, 1991. The recently-released USGS Open-File Report 93-683, "Core OL-92 from Owens Lake, southeast California," makes available the data collected during the first year of study following our completion of the core-drilling phase. In it, nineteen data collections and preliminary interpretations are presented, the work of fifteen first-authors and a number of co-authors. Besides an introduction and a set of supplemental data, studies of the recovered core include: a lithologic log (1 contribution), sedimentological analyses (1), clay-mineral identifications (1), compositional and isotopic analyses of the sediments and pore waters (5), paleomagnetic, tephrochronologic, and ^{14}C dating

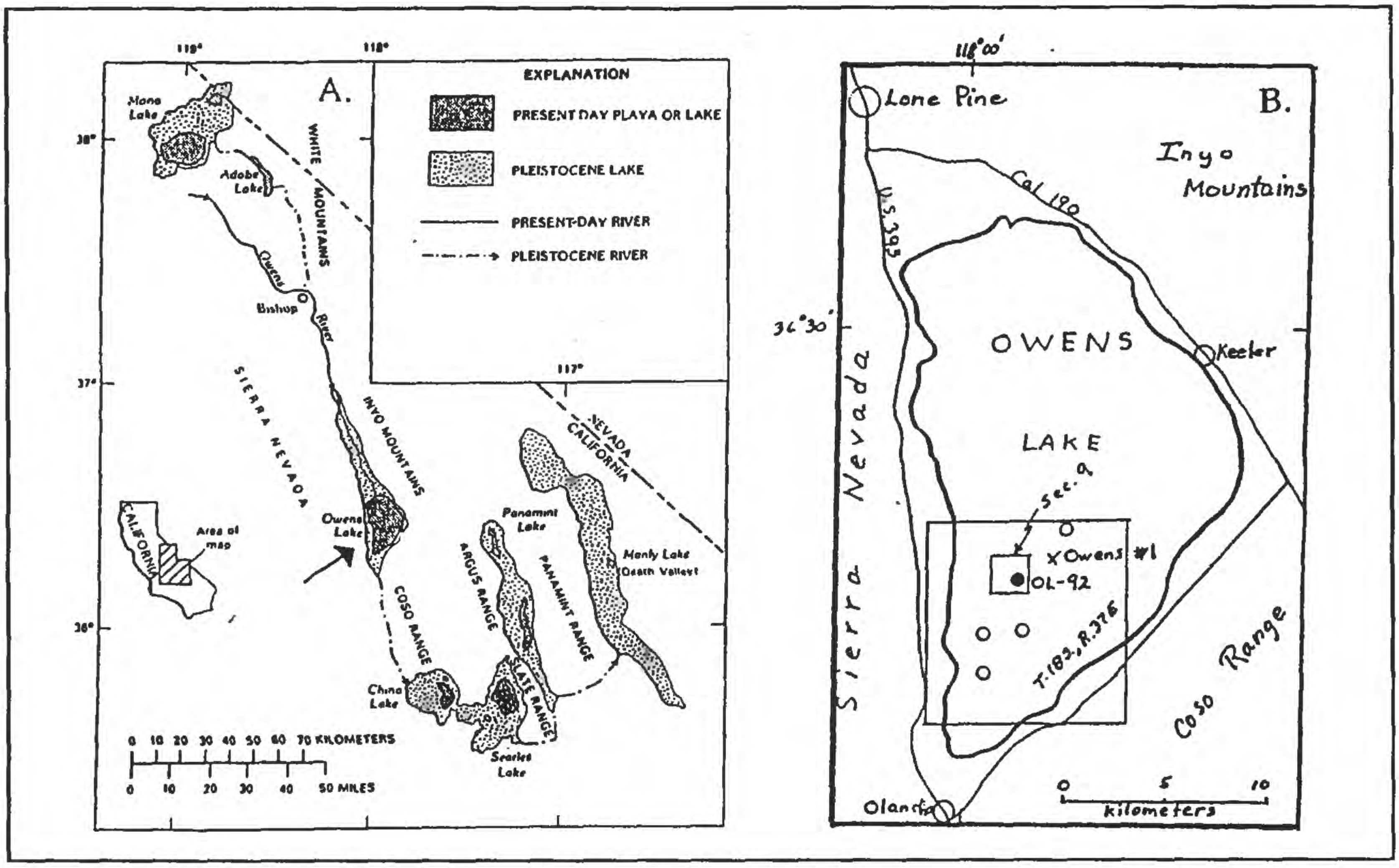

Figure 5-1.--Maps showing location of core OL-92. **A**, Location of Owens Lake (arrow) and other lakes hydrologically connected with it during pluvial periods of the Pleistocene. **B**, Solid circle shows location of OL-92 on the surface of Owens Lake (Sec. 9, T 18 S., R. 37 E.); open circles show locations of cores described by Newton (1991, fig. 1-2); X shows location of Owens Drill Hole 1.

studies (3), laboratory-based reconstruction of sedimentation rates (1), and identifications of fossil materials--diatoms, ostracodes, molluscs, fish, pollen, and plant fragments (7).

Plans are to next prepare a short manuscript summarizing the data and outlining our paleoclimatic conclusions for a widely-read journal. This will be followed by a volume publication dedicated to individually authored or co-authored articles that present each element of the study in suitable detail and the authors' "final" conclusions.

DESCRIPTION OF SEDIMENTS AND INFERRED ENVIRONMENTS OF DEPOSITION

Core OL-92 is 323 m long (Figure 5-2), and the presence near its base of the Bishop ash (760 ka) and the Brunhes-Matuyama magnetic-reversal boundary (780 ka) indicate that the core record extends back to about 800 ka. Core recovery was 80 percent.

The top 5 m of the core consists of 20th-century salts and late Holocene oolites. The underlying sediments can be divided into two thick units. The upper unit, 199 m thick, is dominated by silt and clay that is mostly dark colored and either faintly bedded or mottled (bioturbated?), although two thin beds of medium to coarse sand occur in the upper half of this interval. Virtually all sediments in this unit are deep-water lacustrine deposits.

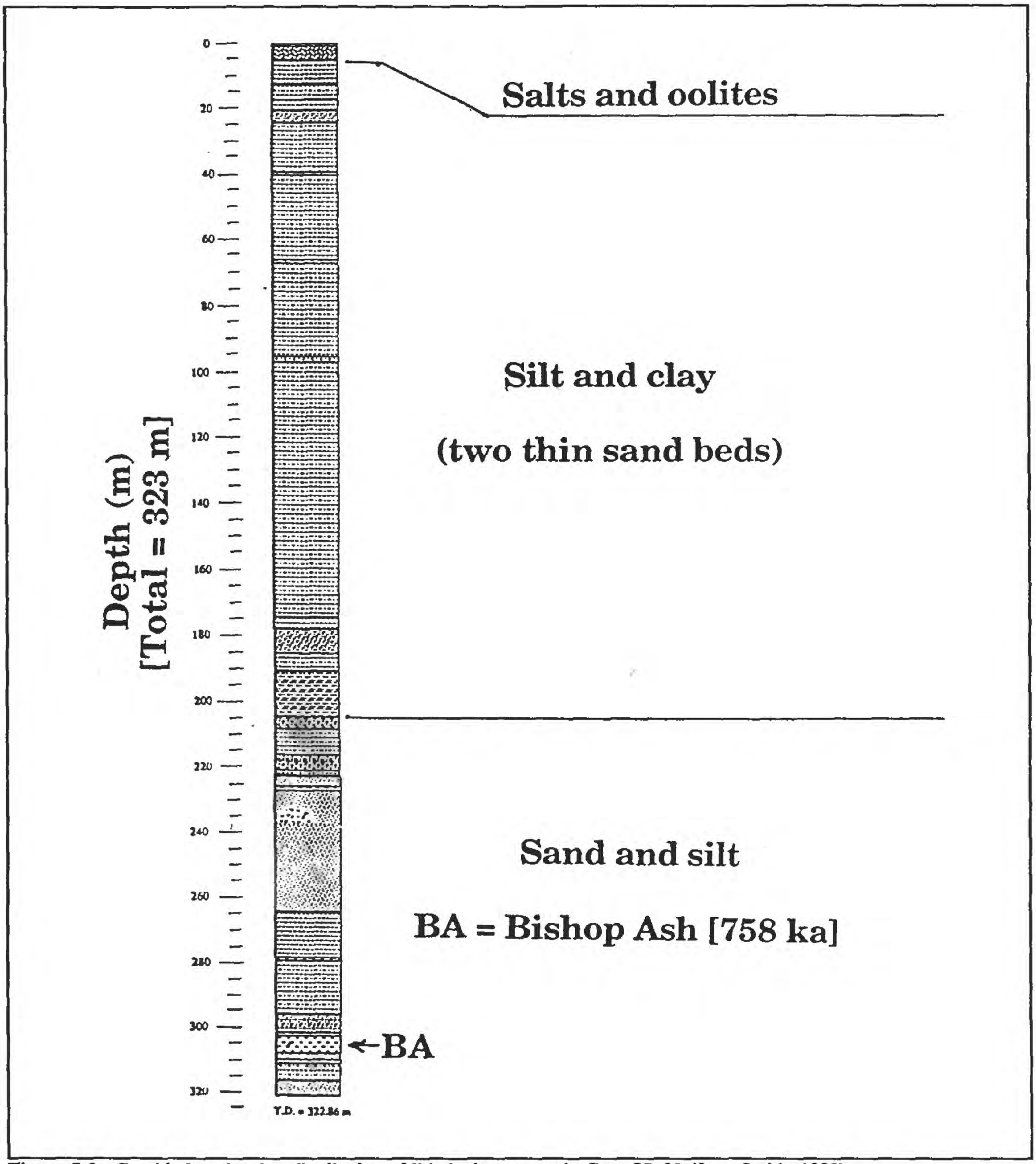

Figure 5-2.--Graphic log showing distribution of lithologies present in Core OL-92 (from Smith, 1993).

The lower unit, 119 m thick, is composed of sediments that also include silt and clay, but coarse- to medium-grained sand is more abundant. Bedding and sorting characteristics make it likely that even the coarsest sandy sections are shallow-water lacustrine deposits, but some could be fluvial. Diatom assemblages in parts of this section, especially *Fragilaria*, indicate very shallow (*e.g.*, 2 m) fresh water (Bradbury, 1993). Near 200 m, concentrations of fish (G.R.

Smith, 1993) and mollusk remains (Firby, 1993) indicate fresh shallow water. Similar concentrations of fossils near 300 m also include salmonid remains, even more strongly implying cool fresh water. Detailed descriptions of these deposits are given by G.I. Smith (1993).

SAMPLING AND LABORATORY PROCEDURES

Core OL-92 was sampled in two ways: (1) "spot" samples were collected from 2x2-cm areas on the face of the split core, an interval that represents about 0.05 kyrs or less of deposition; (2) "channel samples" were collected as approximately 3-m-long continuous strips carved from the split-core face, an interval that represent about 7.5 kyrs. Sediment samples collected as channel samples were analyzed for sediment composition, isotope chemistry, grain-size, and clay mineralogy (Bischoff *et al.*, 1993c; Benson and Bischoff, 1993; Menking *et al.*, 1993a, b); spot samples were used for radiocarbon analyses, sulfur-isotope studies, and pore water study (volume, salinity, and deuterium-hydrogen ratios) (Bischoff *et al.*, 1993a, b; Friedman *et al.*, 1993; Tuttle, 1993).

Prior to chemical analysis, laboratory processing of all core samples substituted Cs for exchangeable Na in their clay fractions. When Cs percentages were later plotted, as the ratios of "weight-percent Cs" (Cs) to "weight-percent clay-*sized* material" ("clay"), high ratios differentiated samples that contained abundant clay minerals having large exchange capacities (*e.g.*, smectite) from samples that contained mostly clays with low exchange capacities (*e.g.*, illite) or clay-sized minerals that have none (*e.g.*, glacial flour).

PALEOCLIMATIC INTERPRETATIONS

An underlying assumption in the following correlations with glacial stages in both the Sierra Nevada area and globally is that evidence of increases in precipitation in the Owens Lake watershed--the phenomenon our paleoclimatic criteria actually reflect--coincided with major increases in glacier sizes in the Sierras and elsewhere. This is reasonable inasmuch as the budgets of expanding or established glaciers depend on large snow volumes as well as on sufficiently cold temperatures, and the large volumes of ice required to fill the Sierra Nevada canyons to the high levels where moraines are now preserved support the premise that glacial periods were strongly dependent on major contributions from regional precipitation.

Criteria and rationales

The Pleistocene part of Core OL-92 appears to represent relatively- to very-fresh water lacustrine deposition. The nearly 199-m-section of mostly silt and clay immediately below the oolites has many small variations in lithology, but there are few variations that can be translated into a history of changing lake level or water chemistry. Fortunately, the chemical, sediment size, and clay-species analyses of the core material provides a very readable record of change during that period. The underlying 119 m of the core has more lithologic variability and thus allows fluctuations in lake depth to be identified. The fossil content shows that the shallow waters were mostly fresh, rather than saline waters caused by a period of aridity that led to decreased inflow or increased evaporation.

In the finer facies, climatic cycles were reflected in OL-92 by several parameters, but most markedly in the percentages of Ca- and Mg-carbonates (CO_3), organic carbon (C_{org}), and in the mineralogy and cation-exchange capacity of the clay fraction (Cs/"clay"), the proxy for clay-exchange capacity. All reach minimal values in the same segments of the core, though they vary more randomly in the zones between those segments. These minima are interpreted as indicators of sedimentation in a very fresh, low-nutrient lake whose waters had such a low residence time in the basin that evaporation and nutrient accumulation was very low--becoming, in essence, a wide part of the Owens River. This would be best explained as the result of increased regional precipitation caused in part by decreased temperature, that combined to generate or expand glaciers in the adjoining mountains. Climate changes of these types and glacier activity would have both accelerated mechanical erosion, thus decreasing the time available for exposed rock surfaces to undergo chemical weathering and clay production, and introducing increased volumes of clay- and silt-sized glacial flour which would contain virtually no exchangeable Na.

This interpretation led to the testing of three approaches aimed at developing a chronology for past climate fluctuations. Our first approach was to plot the CO_3 percentages against the other two components, after multiplying the absolute values of the "organic C" percentages by 20 and the "Cs/'clay'" ratios by 200 to bring their plotted magnitudes closer to each other (Figure 5-3A, Figure 5-4A, and Figure 5-5A). (For brevity, we refer hereafter to the weighted values of these *three chemical criteria* as "TCC.") In Figure 5-3, Figure 5-4, and Figure 5-5, the base is plotted in terms of estimated age (ka) using the sedimentation-rate relation developed by Bischoff (1993).

The second method was to plot the TCC data as a *sum* of the three components (Sum-TCC) against time (ka). The percentage of "sand" is also shown in these plots (Figure 5-3B, Figure 5-4B, and Figure 5-5B) because the three chemical criteria used to identify the younger glacial stages are concentrated in the clay- and silt-sized fractions, so significant percentages of sand in a given segment of the core create easily-misinterpreted troughs in each of the other curves.

To avoid the uncertainties caused by extreme magnification of analytical data, our third method of reconstructing paleoclimates was to use plots showing only the weight-percentages of CO_3 (plus that of "sand"; Figure 5-3C, Figure 5-4C, and Figure 5-5C). This method does depend on the premise that those percentages reflect lake chemistry accurately, but its clear advantage is that the plotted values are unaltered analytical data.

In Figure 5-3, the base is plotted in terms of estimated age (ka) using the sedimentation-rate relation developed earlier. Only the relatively short period between 0 ka and 200 ka is shown in Figure 5-3 so that the details of component variations, plotted using the three methods described above, are more easily compared. In Figure 5-3A, for example, very low values for each of the three individual TCC components are found between 15 ka and 20 ka and again between about 125 ka and 150 ka, but major differences between their values are found between these minima. Figure 5-3B and Figure 5-3C present the same data in a more easily-followed form, but the high sand percentages at about 165 ka cause "synthetic" troughs in Figure 5-3B and at both 50 ka and 165 ka in Figure 5-3C. Notable in all three diagrams, however, is that the minima occupy about the same time periods, and that between these minima, the three variables are much less coherent. We suspect that study of the core data as presented by any one of these three methods would lead most investigators to nearly identical conclusions about which periods represent wet (glacial?) conditions, but the climatic or other causes of the remaining variations in the TCC components would be more difficult to explain. Some of the fluctuations in organic

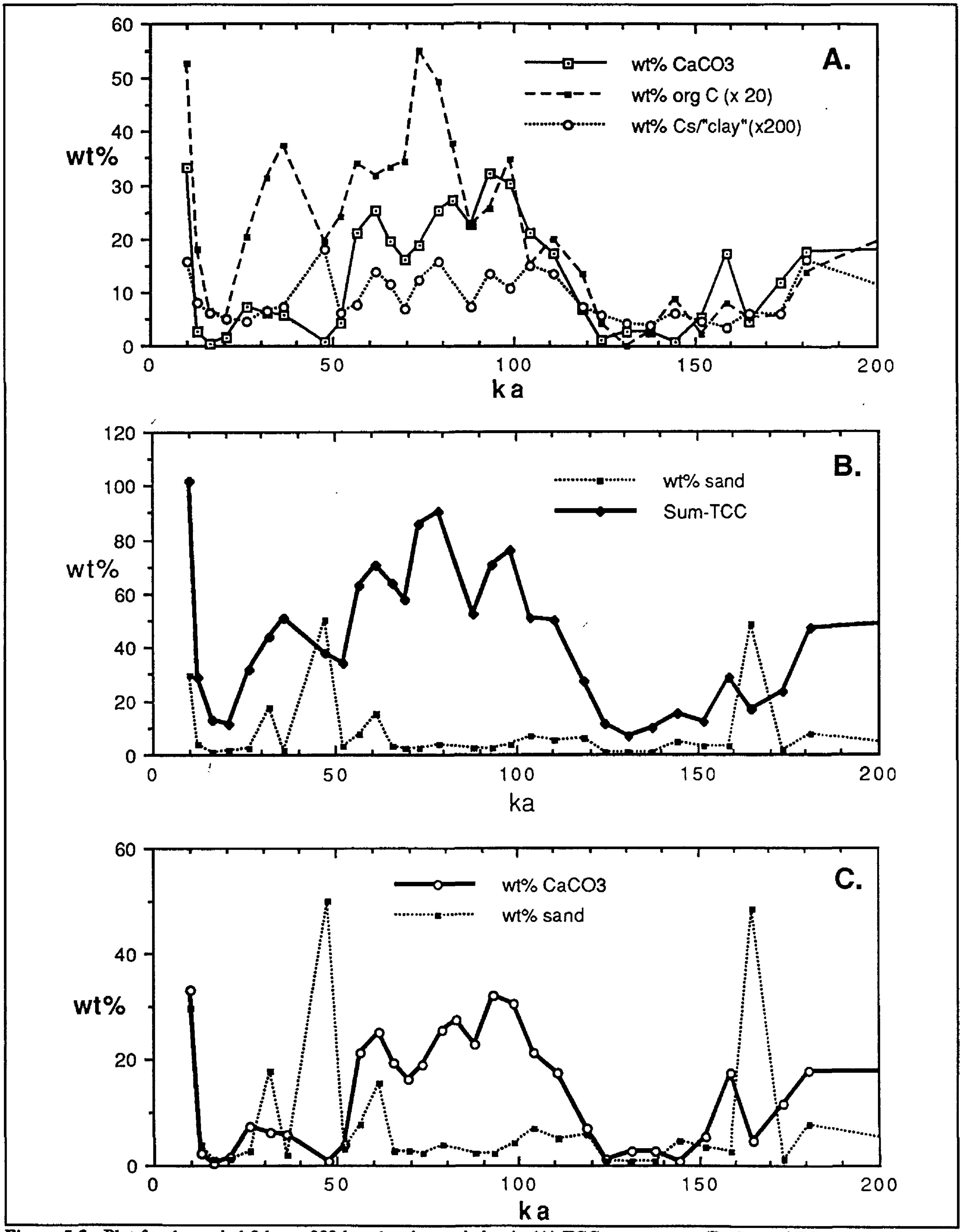

Figure 5-3.--Plot for the period 0 ka to 200 ka, showing variation in (A) TCC components, (B) Sum of TCC components and "sand", and (C) CO_3.

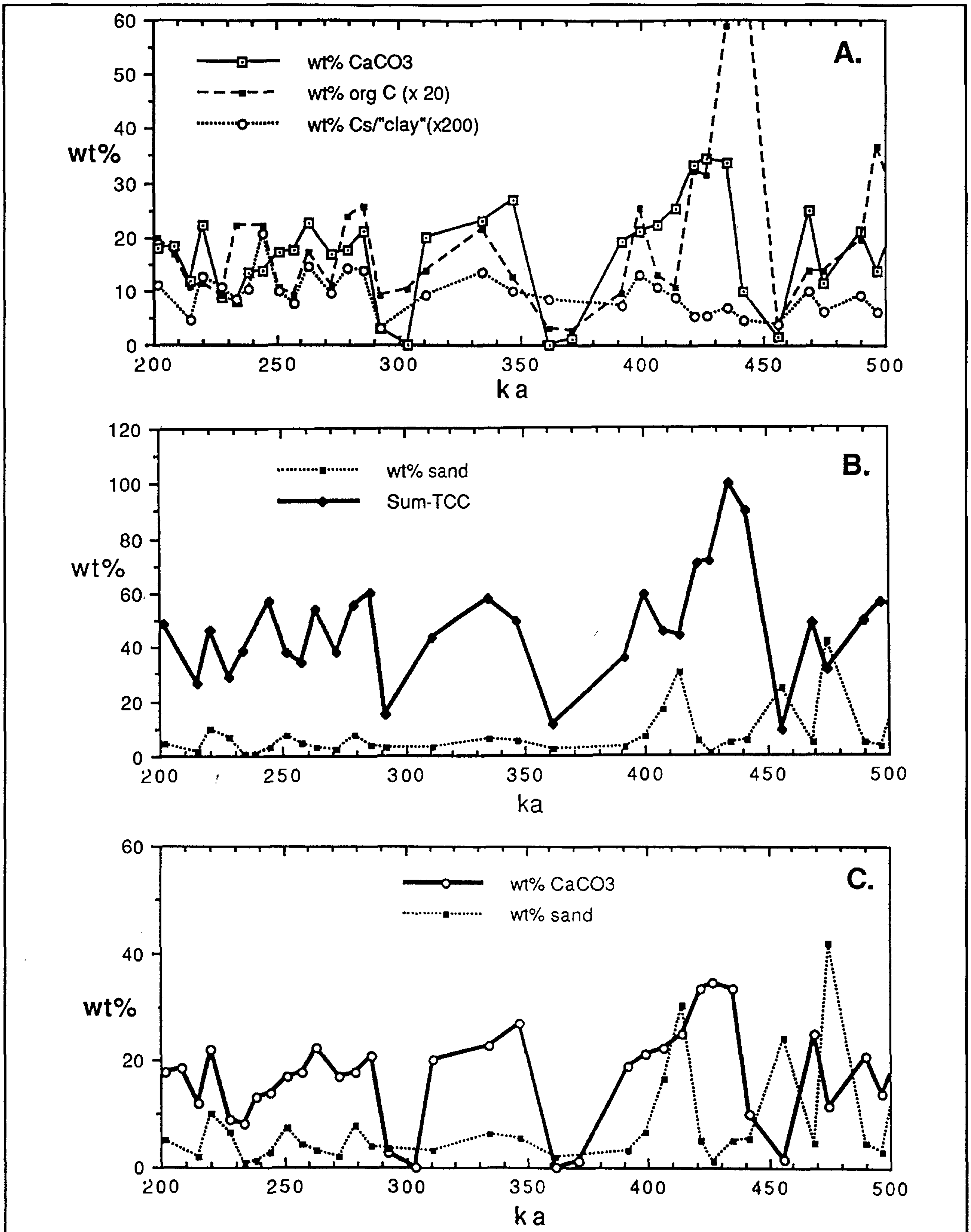

Figure 5-4.--Plot for period 200 ka to 500 ka, showing variation in (A) TCC components, (B) Sum of TCC components (also "sand"), and (C) CO^3.

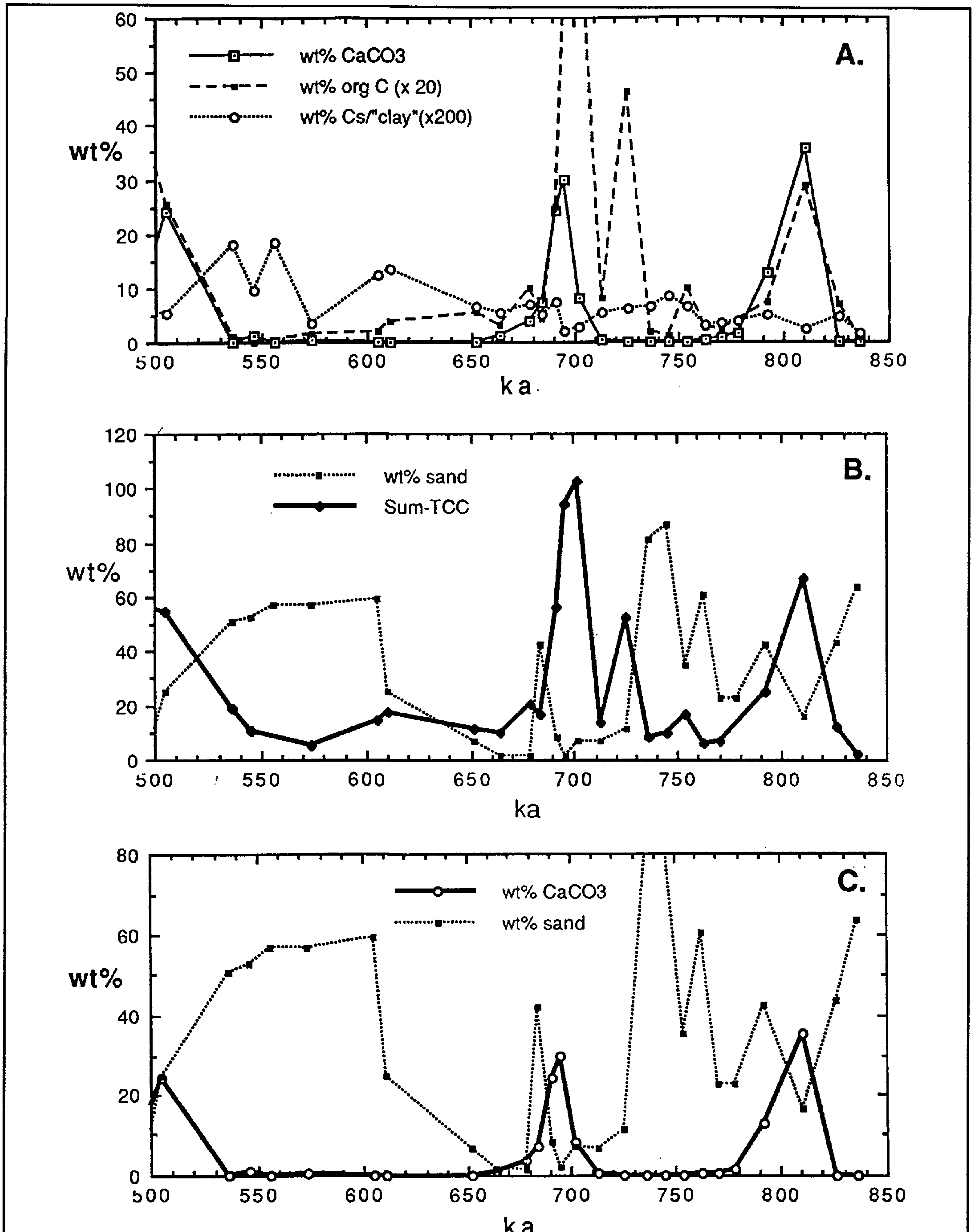

Figure 5-5.--Plot for period 500 ka to 850 ka, showing variation in (A) TCC components, (B) Sum of TCC components (also "sand"), and (C) CO³.

C may be expressions of post-burial reactions involving sulfate-reducing bacteria rather than climate-related changes (Tuttle, 1993).

Similar plots for the periods 200 ka to 500 ka, and for 500 ka to 850 ka are presented in Figure 5-4 and Figure 5-5. These are discussed in more detail when the climatic record provided by Core OL-92 is related to glaciation in the Sierra Nevada and in polar regions.

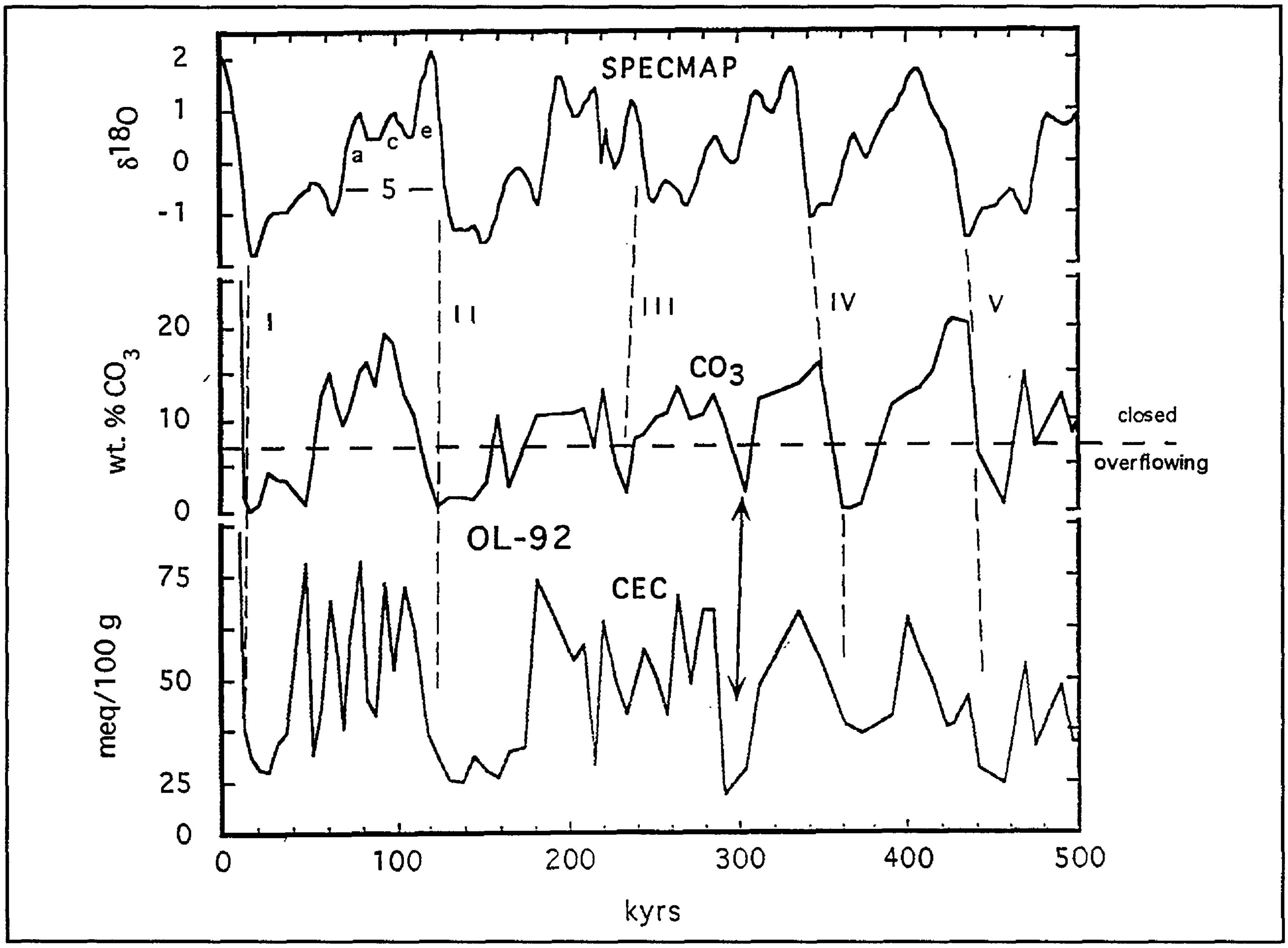

Figure 5-6.--Carbonate ($CaCO_3$) and organic-carbon content (C_{org}) of sediments of Owens Lake drill hole OL-92 versus age for the past 500 ka. Shown for comparison is the COMPOSITE normalized marine $\delta^{18}O$ record from Williams et al. (1988) showing the positions of major glacial terminations I through V. Closed lake conditions (local interglacials) are characterized by high carbonate and organic-carbon contents while overflowing lake conditions (local glacials) are characterized by low contents of the same components. The positions of terminations I, II, IV and V are clearly shown in the Owens Lake core by abrupt increases in the carbonate content of the sediments, reflecting change from strongly-overflowing to relatively-closed lake conditions. The position of termination III is not clearly reflected in the Owens Lake section.

Figure 5-6 is a plot of weight percent CO_3 against age over the range 0 ka to 500 ka, approximately at the top of the sand-rich section. A horizontal line at about 7 percent CO_3 represents the calculated carbonate content of the sediment that should differentiate between periods when Owens was a closed lake, retaining and depositing all CO_3 entering the basin, and periods when it was an overflowing lake, exporting much or almost all of its CO_3 to downstream basins. On the assumption that the flux is independent of flow volume, the percentage is calculated using the CO_3 flux from the modern Owens River (Los Angeles Department of Water and Power, written commun., 1993), the mass accumulation rate of the lake sediments (Bischoff, 1993), and the area of the Owens Lake basin at sill level (Smith and Street-Perrott, 1983). This calculated value, as plotted in Figure 5-6, suggests that Owens Lake did not overflow for about 75 percent of the time between 0 ka and 500 ka.

The amount of time proposed for a non-overflowing Owens Lake conflicts with several lines of evidence. Whenever Owens Lake stopped overflowing, evaporation would have caused it to develop a significant salinity within a few thousand years. For example, the 6 to 9 percent salinity observed in Owens during the late 1800's had to develop in a period less than 10 kyrs long, as overflow from it was supplying water to a downstream lake in Searles Valley up to about 10.5 ka (Stuiver and Smith, 1979). Other calculations conclude that Owens Lake's salinity developed in 2 kyrs (Smith, 1976) to 4 kyrs (Gale, 1914). Also, the closed period plotted between about 50 ka and 115 ka (Figure 5-6) conflicts with many of the data obtained from the ostracode fauna and diatom flora extracted from OL-92 (Carter, 1993; Bradbury, 1993) which indicate mostly fresh and sometimes cold water in Owens Lake during these periods. It also conflicts with studies of exposed and subsurface sediments from downstream Searles Lake (Smith, 1979, 1984; Bischoff *et al.*, 1985; Jannik *et al.*, 1991) which conclude that a large lake, fed by overflow from Owens Lake, existed in Searles basin during much of the time when Figure 5-6 indicates that Owens Lake was closed. We have not been able to reconcile these data. It is possible that the annual carbonate flux in the Pleistocene Owens River was at times much greater than at present, or that Owens Lake was stratified during the spring-summer runoff so that large volumes of very fresh water flowed out of the basin without depleting the carbonate stored in the deeper part of the lake.

Relation between Holocene lake history and climate

In the mid-1800's, before settlers in Owens Valley began to divert a significant part of the Owens River for crop irrigation and domestic needs, its flow was enough to stabilize Owens Lake at depths near 15 m and maintain its salinity between about 6 and 9 percent (Gale, 1914). Stratigraphic criteria indicate that the lake floor prior to desiccation consisted mostly of oolites, products of a lake that was alkaline enough to precipitate most of the dissolved carbonate that entered and sufficiently shallow for wind energy to create currents strong enough to agitate the carbonate granules on the lake bottom. A ^{14}C date on carbonate from the lowest part of the oolite bed is 5090±80 yrs (uncorrected), and a sample of organic-rich mud from a layer immediately below the nearly-homogenous oolite layer provided an age of 8930±70 yrs (uncorrected). These dates, and the pattern of dates from both the oolite and mud layers (Figure 5-7), indicate an erosional event that removed the youngest part of the pre-oolite depositional record.

We conclude from this that during early or middle Holocene time, evaporation began to exceed lake inflow and lowered the lake surface to a level where sublacustrine erosion could occur at the site of the OL-92 core. The dated oolites show that erosion ceased by middle Holocene. During the second half of Holocene time, deposition of a virtually uniform bed of oolites suggests that the lake remained similar to its mid-1800's state--shallow, quite alkaline, and slightly saline, but neither dry nor substantially deeper.

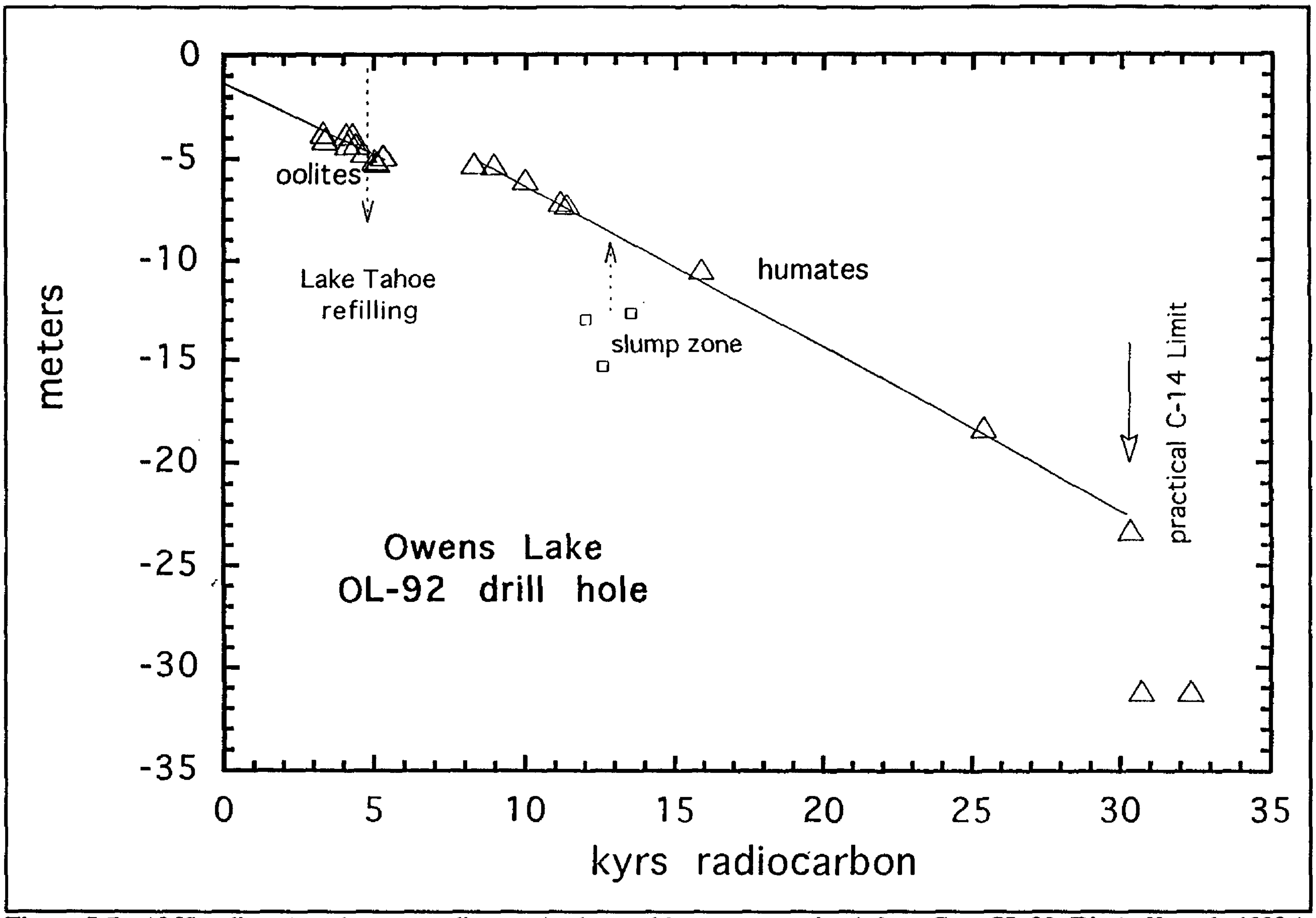

Figure 5-7.--AMS radiocarbon dates on sediments (oolites and humate extractions) from Core OL-92 (Bischoff *et al.*, 1993a). Symbol size is about twice the counting error for each sample.

It is notable that in the remainder of Core OL-92, we recovered no earlier evidence of oolites, salts, desiccation, or erosion, apparently meaning that the latter part of the Holocene in this region has been more arid than during any period back to at least 800 ka.

Relation between Pleistocene lake history and Sierra Nevada glaciation

The existence of Pleistocene-age glaciers in the Sierra Nevada has been known for more than a century (McGee, 1885; Russell, 1889). More modern studies (Blackwelder, 1931; Putnam, 1950; Sharp and Birman, 1963; Sharp, 1968, 1972; Burke and Birkeland, 1979; Clark, 1994) subdivided some of the Pleistocene stages, but the basic sequence may be generalized as follows:

<u>Recess Peak, Tioga, and Tenaya stages</u> : Youngest late Pleistocene deposits; moraines have sharp crests, their deposits are less extensive than older moraines, and exposed boulders are nearly unweathered.

<u>Tahoe and Mono Basin stages</u> : Older late Pleistocene deposits; moraines have subdued crests, their deposits are more extensive than those of younger ages, and their boulders are distinctly weathered.

<u>Sherwin stage</u> : Oldest(?) Pleistocene deposits; tills are very widespread but the moraine morphology is destroyed, and their large plutonic fragments are mostly decomposed; tills are

covered by the 760-ka Bishop ash.

We interpret the minima between 10 ka and 20 ka in plots A, B, and C of Figure 5-3 to be undifferentiated expressions of the Recess Peak, Tioga, and Tenaya glacial stages, and the minima between about 125 ka and 150 ka in those figures to be expressions of the Tahoe and Mono Basin glacial stages.

On the basis of the moraine record in the Sierras, the period between the Sherwin and the Tahoe-Mono Basin glaciations is commonly reported to have been free of glaciers. Several workers have suggested the possibility that glacial advances occurred but that their moraines were destroyed by subsequent glacial advances during the extensive Tahoe and Mono Basin stages, but the evidence is inconclusive. However, evidence indicating three (or four?) wet periods that might have been glaciations during this interval is found in Core OL-92. Figure 5-4 and Figure 5-5, which together cover the period 200 ka to 850 ka, plot three combinations of TCC components, as well as the percentages of sand to allow differentiation between troughs possibly caused by high percentages of sand rather than by high runoff (glaciation?). Troughs at about 300 ka, 360 ka, and 670 ka do not coincide with high percentages of sand, and thus appear to have the characteristics of wet, possibly glacial, episodes. Another trough at about 455 ka approaches the baseline of the diagram but is associated with a 25 weight-percent peak in the "sand" plot, making it a questionable though possible indication of wet and possibly glacial conditions.

The Sherwin glacial stage, which preceded deposition of the Bishop ash at 760 ka, may be equivalent to sediments near the base of OL-92, but the evidence is inconclusive. Plots of the components against age, covering the interval between 500 ka and 850 ka (which is beyond the projected age of the core base), are shown in Figure 5-5. Other than the above-mentioned feature near 670 ka, the troughs in these curves are close to being mirror images of the "sand" curves (Figure 5-5B and C), and we place little reliance on them as indications of a wet (glacial?) environment.

The evidence indicating Owens Lake to be a shallow, freshwater lake during the earliest 300± kyrs represented by OL-92, however, may be a consequence of the Sherwin glacial episode. On the basis of subsurface evidence from Searles Lake that indicates a persistent and probably intense pluvial period, Smith *et al.* (1983) consider the Sherwin stage to have reached its maximum intensity between about 1,300 ka and 1,000 ka. For Owens to have been a mostly shallow-but-freshwater lake during the period represented by the lower part of OL-92, its spillway and its floor at the site of Core OL-92 must have been close to the same elevations. What might this indicate? Erosion could have lowered the spillway, tectonic changes in the basin could have have either slowed its rate of depression or laterally shifted its center of depression, or lake-sedimentation rates during the much-earlier Sherwin glacial period could have outstripped tectonic depression rates--our interpretation. A long and intense glacial period, as suggested by both the thickness and the areal extent of Sherwin moraines near its type area to the north (Sharp, 1972) and the 300-ka-long pluvial interval inferred from the Searles Lake record, might have caused such a marked increase in the amount of clastic debris carried into Owens Lake each year that it filled the basin with sediment nearly to its spillway level. While the other possibilities that would cause the lake to be shallow can not be excluded, we consider this explanation to be more probable.

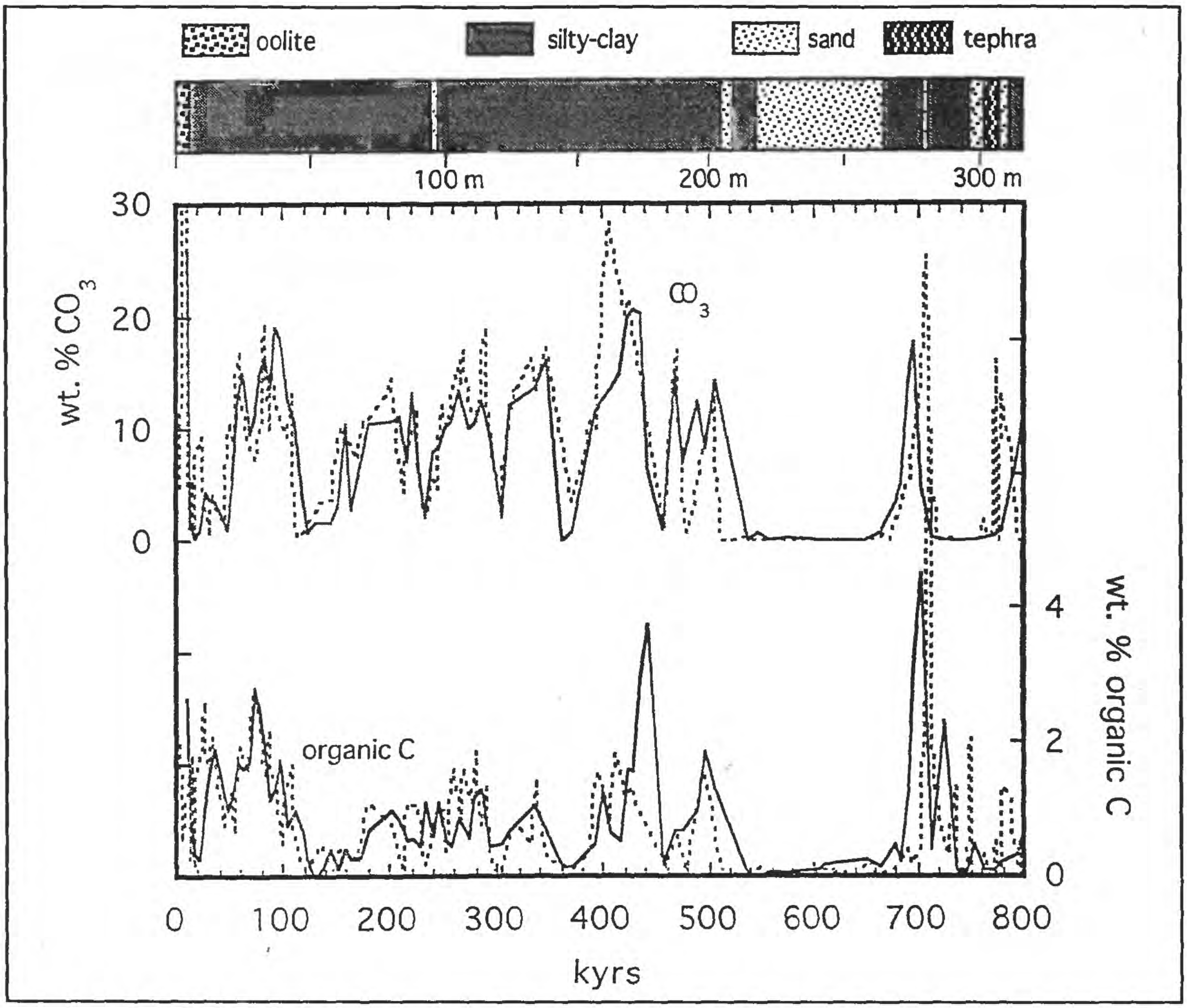

Figure 5-8.--Variation of carbonate (CO_3) and total organic-carbon (TOC) with depth and age of sediments from Owens Lake drill hole OL-92. Solid lines are from channel samples, dotted lines from point samples. Lithology generalized from core log presented in Smith (1993). Lacustrine conditions prevailed back to 500 ka (220 m) below which fluvial and lacustrine conditions may have alternated. Point and channel samples show almost coincident patterns. CO_3 and TOC display values very close to zero during the most recent glacial maximum at 17 to 25 ka, suggesting that the lake overflowed during glacial maxima.

Relation between Owens Lake history and global ice ages

Most of the individual TCC values, the Sum-TCC values, and the CO_3 oscillations found in OL-92 correlate fairly closely with those of the marine $\delta^{18}O$ cycles back to about 500 ka, the approximate point where increasing sand percentages in OL-92 interfere with pattern matching (Figure 5-8). For example, four of the last five terminations which characterize the abrupt warming events at the end of each glacial period, Terminations I, II, IV and V, correspond approximately with the times of abrupt increases in the carbonate content of the OL-92 sediments, reflecting change from rapidly-overflowing to more-closed lake conditions. Termination III at about 250 kyrs in the marine record, however, may not be reflected in the Owens Lake record where its age corresponds most closely to a maxima in carbonate. Carbonate minima at 230 ka or at 300 ka could be correlative with termination III, but the age discrepancies make this questionable. Resolution of this discrepancy may come from further study of fluctuations in the abundances certain pollen types extracted from Core OL-92. Parts of their variation patterns with age resemble those of the TCC components in Figure 5-3, Figure 5-4, and Figure 5-5, but as pollen reflect atmospheric conditions, not lake-water chemistries, comparisons must be made cautiously (Litwin *et al.*, 1993; Woolfenden, 1993).

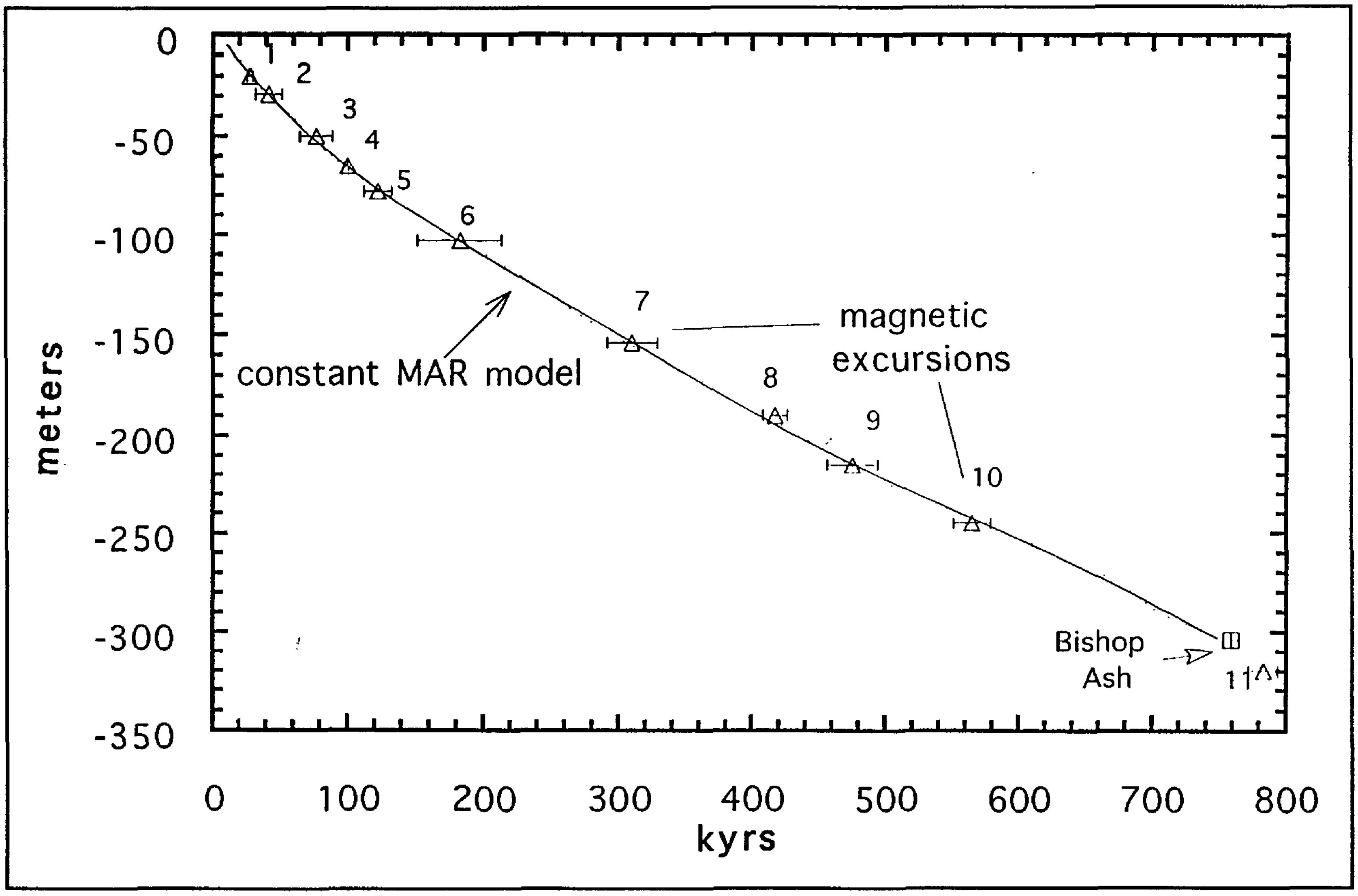

Figure 5-9.--Age-depth plot for Owens Lake drill hole OL-92 based on constant mass-accumulation rate (MAR) model (Bischoff, 1993). Also shown are 10 paleomagnetic excursions between the Bishop Ash and the surface reported by Glen et al. (1993) as follows: 1. Mono Lake, 2. Laschamp, 3. NGS, 4. Fram Strass, 5. Blake, 6. Jamaica/Biwa 1, 7. Levantine/Biwa 2, 8. Biwa 3, 9. Emperor, 10. Big Lost; 11. is the Brunhes/Matuyama magnetic reversal. Position of Bishop Ash from Sarna-Wojcicki *et al.* (1993).

If the patterns for global Terminations I, II, IV and V are so clearly shown, it is difficult to understand why Termination III is an exception. An outside possibility is that some of the stratigraphic section is lost in the core due to faulting or core losses. Surface expression of a northwest-trending 20th-century(?) fault (Carver, 1970) lies within about 0.3 km of the OL-92 drill site, but fault displacements in this area are predominantly horizontal which would cause minimal disruption of a flat-lying stratigraphic section. No visual evidence for faulting was found in the core, although it would be difficult to recognize, and core loss was minimal during that part of the drilling process. A fault-caused irregularity of this magnitude also would probably be evident in the age-depth curve (Figure 5-9). Faulting is a possibility, however, that cannot be excluded.

It is important to remember, though, that the marine record of glaciation primarily reflects ice-volume changes in high-latitude areas, and that the Owens Lake record reflects precipitation in a middle-latitude area. As studies of the Searles Lake record have shown, climatic changes in the high- and middle-latitude regions have not always had the same relation. The best example of reversed climatic responses in the Owens Lake-Searles Lake area is that at about the time of Termination II, there was a major increase in the depth of Searles Lake (Smith, 1979, 1984; Bischoff *et al.*, 1985) whereas at the time of Termination I, that lake fluctuated rapidly but ultimately desiccated (Stuiver and Smith, 1979; Smith, 1984).

The Owens Lake age-percent carbonate curve (Figure 5-8) has the abrupt increase which corresponds to termination II occurring at 117 ka (Figure 5-3) (the three TCC curves begin to increase at 125 ka but reach the half-way point in the transition at about 117 ka). The marine isotope records estimate the age of this event to be 128 ka (Williams *et al.*, 1988, and references therein). This ≈11-kyr difference reflects either a ≈10 percent error in our age-depth model, a comparable error in the time-scale used for the marine record, or a significant time-lag between changes in the high-latitude ice-volumes and the mid-latitude manifestation of the climate change that influenced the geochemistry and sedimentology of Owens Lake.

Comparison of the climatic changes inferred from the OL-92 core record with the $\delta^{18}O$ record from calcite in Devils Hole, Nevada (Winograd *et al.*, 1988, 1992) shows several similarities in shape, but the ages of the extreme–and theoretically correlative–climate reversals differ by 10 ky to 30 ky in many instances. The Owens Lake and Devils Hole records, however, measure very different elements of climate–earth-surface precipitation amounts in the Owens Lake record and upper-atmosphere condensation temperatures in the Devils Hole record. One must remember that the relation between precipitation changes and temperature changes may not be as closely linked as simple climate models predict. Condensation temperatures are mainly determined by the absolute humidity of the incoming moist-air masses which, in turn, determine the temperature at which condensation can occur. To be sure, if the absolute humidity is lower because nearby sea-surface temperatures are lower, then earth-surface temperature are also likely to be lower. If, however, there is a change in air-mass trajectories, bringing incoming storm masses via paths that traverse more land or higher terrain prior to reaching the sampling point, more of the original moisture would have already precipitated, shifting the isotopic ratios toward the "colder" direction and lowering absolute humidity. Under such conditions, upper-atmosphere condensation temperatures and isotopic ratios would probably have little relation to earth-surface temperatures and precipitation amounts.

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Fine Resolution Pollen Analysis of Core OL-92,Owens Lake, California:

Wallace B. Woolfenden
University of Arizona, Tucson, AZ 85721

Ongoing analysis of the palynomorphs present in the upper 90 m section of core OL-92 is revealing a continuous record of relatively well-preserved pollen, spore, and algae assemblages. The depth interval was chosen to cover the last 150 kyr of lake sediments, based on the radiocarbon- and Bishop Ash-constrained age-depth curve. This interval was chosen because it spans two full glacial cycles, beginning with $\delta^{18}0$ isotope Stage 6. The research objectives are to reconstruct the terrestrial and aquatic vegetation history of the southern Owens Valley region--including the Sierra Nevada and Inyo Mountains--over the sampled core interval, to correlate climatically sensitive pollen taxa with marine $\delta^{18}0$ isotope chronostratigraphies, and to model the response of vegetation to climate change. Comparisons between such critical periods as Terminations I and II will be closely studied. The core was sampled at 20 cm (~340 yr) intervals although most of the analysis will be done at 40 cm (~670 yr) or greater intervals, depending on the significance of various time periods to research issues. The core interval 0-62.72 m was initially surveyed to evaluate pollen concentration and quality of preservation. Pollen concentration in the 3.80 m of oolite sand at the top of the core is too low for a significant sum. The pollen record begins at 5.52 m (~9 ka). Counting is now proceeding on a fine resolution scale.

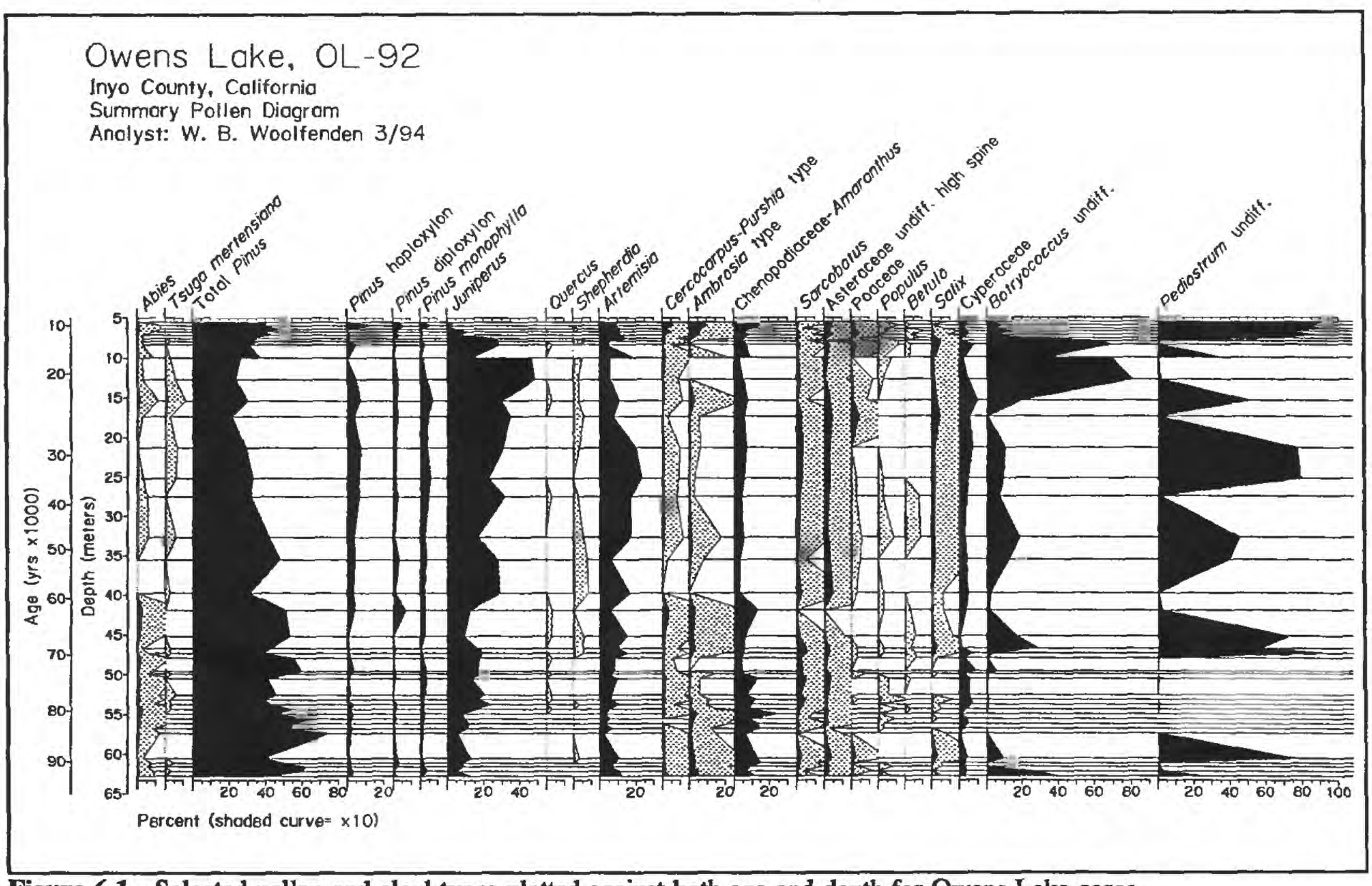

Figure 6-1.--Selected pollen and algal types plotted against both age and depth for Owens Lake cores.

A preliminary proportional diagram of selected taxa is given in Figure 6-1. The high variance in the pollen frequencies implies sensitivity of the record to climate change. The most obvious trend is the inverse relationship between *Pinus* and *Juniperus*. A general increase in *Juniperus* from ~60 ka to a peak frequency at ~20 ka probably indicates the expansion of *Juniperus osteosperma* (Utah juniper) and perhaps *J. scopulorum* (Rocky Mountain juniper) woodland on the bajadas and alluvial fans of the Sierra Nevada and Inyo Mountains and around the lake margins throughout isotope Stage 3 to a maximum in isotope Stage 2, during the full-glacial. White pine (haploxylon) and *Pinus monophylla* (pinyon pine) pollen have frequencies proportionally higher relative to yellow pine (diploxylon) pollen during this interval. Most of the white pine pollen curve may represent the expansion of *Pinus longaeva* (bristlecone pine) and *P. flexilis* (limber pine) forests in the Inyo Mountains. The increase in *Pinus monophylla* indicates a lowering of the elevational limits of this species on the bajadas as an associate of *Juniperus*, and possibly an increase in its range further to the south. These trends, along with the concomitant increase in *Artemisia* (sagebrush) pollen, and higher percentages of Poaceae (grass), *Tsuga mertensiana* (mountain hemlock) and *Salix* (willow), suggest a transition to a colder climate relative to today. Lower frequencies of *Artemisia* between ~25 and 20 ka are problematic and may be a result of using percentage data. Termination I is represented by a decrease in *Juniperus* relative to *Pinus* and an increase in *Cercocarpus-Purshia* type (probably mountain mahogany, bitterbrush, and *Coleogyne ramosissima* (blackbrush)), *Ambrosia* type, and Chenopodiaceae-*Amaranthus* (mostly saltbush). This trend indicates an expansion of xerophytic shrub species into the Owens Lake basin. The interval between ~90 to 60 ka has relatively high proportions of *Abies* (fir), *Pinus*, Chenopodiaceae-*Amaranthus*, *Cercocarpus-Purshia* type, and *Ambrosia* type. The warm, subhumid nature of this assemblage may represent the latter substages of isotope Stage 5. Stage 4 is unresolved, perhaps due to the broad intervals between tabulated samples. *Botryococcus* and *Pediastrum* algal assemblages have the potential for a lake environment record. The very low numbers of algal colonies within the ~85-70 ka interval may be evidence for shallow lake levels. This is weakly supported by concurrent higher pollen percentages of the hydrohalophyte *Sarcobatus* (greasewood).

Direct Marine-Terrestrial Paleoclimatic Correlation of the Last 160,000 Years: Evidence from High-Resolution Pollen Data in Marine Cores from the Northeast Pacific Ocean:

Linda E. Heusser
Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York

Pollen data from the seventeen marine cores listed below (Table 7-1) provide detailed (as high as ~200 yr-sampling intervals) continuous records of terrestrial vegetation and inferred climatic variations of coastal California, Oregon, and Washington. Chronostratigraphic control for these cores is based on radiocarbon and oxygen isotope analyses of foraminifera from subsets of the same samples from which pollen was analyzed. Basic patterns of change in the pollen stratigraphy of all the cores are consistent. Glacial intervals are generally typified by increased representation of *Pinus*, herbs (including Gramineae, Compositae, Chenopodiaceae/*Amaranthus*), and decreased representation of broad-leafed elements (*e.g., Quercus*) and temperate conifers, such as *Sequoia sempervirens* and *Tsuga heterophylla*. Interglacials *sensu stricto* (oxygen isotope substage 5e and stage 1) are characterized by an abrupt rise in successional assemblages with *Alnus*, which are rapidly followed by development of coastal lowland coniferous forest, mixed evergreen forest, and/or oak woodland assemblages.

Coastal vegetation from ~34°N to 47°N (inferred from these pollen assemblages) appears to have retained its regional identity over the past ~160 k.y. Throughout the last glacial cycle, the composition of Oregon and Washington lowland forests is distinguished from that of northern and southern California forests and woodlands by the presence of indigenous conifers such as mountain hemlock (*Tsuga mertensiana*). Sediments deposited off southern California are characterized by an abundance of Cupressaceae along with components of chaparral and coastal sage communities. There is no evidence in any of these regional records of large-scale latitudinal migration of diagnostic elements of coastal vegetation, *e.g.*, southward migration of *T. heterophylla* or *S. sempervirens* well beyond its present southern limit.

Regional variations in late Quaternary maritime climates of northern California, Oregon, and Washington inferred from these marine pollen data appear to vary in frequency and intensity with regional marine and global paleoclimatic fluctuations derived from the analyses of marine microfossils in samples from the same cores.

Table 7-1 -- Cores studied for this report			
CORE	Latitude (°N)	Longitude (°W)	WATER DEPTH (m)
ODP893	34°17.25'	120°02.20'	576
Y71-10-117P	34°16.00'	120°04.00'	576
F2-92-P34	35°01.85'	121°13.54'	610
V1-81-G15	35°20.8'	122°25.77'	1430
F2-92-P40	35°25.09'	121°24.95'	760
F2-92-P54	35°34.66'	122°42.95'	3305
F2-92-P3	35°37.39'	121°36.28'	803
L13-81-G145	38°16.28'	123°25.77'	698
V1-80-G1	38°24.95'	123°53.40'	2045
V1-80-P3	38°25.51'	123°47.77'	1600
L13-81-G138	38°45.0'	123°25.77'	2531
Y6910-2	41°16.0'	126°24.0'	2743
W8709A-8PC	42°15.74'	127°40.68'	3111
W8709A-13PC	42°07.01'	125°45.00'	2712
Y7211-1	43°15.0'	126°22.0'	2913
Y6705-7	46°04.0'	126°38.0'	2638
TT63-13	47°08.5'	125°16.8'	1502

Correlations of Latest Pleistocene and Holocene Tephra Layers in Sediments of the Pacific Margin and Adjacent Land Areas, Western Conterminous U.S.:

Elmira Wan, Charles E. Meyer, and Andrei M. Sarna-Wojcicki
U.S. Geological Survey, Menlo Park, CA 94025

Three piston cores, TT063-13 (47°08.5'N, 125°16.8'W), Y72-11-1P (43°15.0'N, 126°22.0'W) and F8-90-G21 (37°13.4'N, 123°14.6'W), recovered from the northeastern Pacific Ocean off the western continental margin of the conterminous U.S. yielded 20 intervals that contained volcanic glass shards. One of these intervals was a discrete tephra layer. Further examination of these intervals revealed the presence of four cryptic or disseminated tephra layers with ages ranging from 125,000 to 6850 yr B.P. The tephra layers were identified by electron-microprobe analysis as well as by the petrographic characteristics of individual glass shards. The ages were determined by correlating the geochemical and morphologic characteristics of the tephra-bearing intervals to previously dated tephra layers. The tephra ages agree well with oxygen isotope and radiocarbon chronologies available for core TT063-13 and Y72-11-1P and thus further refine the stratigraphy of the region. However, the most important result of this study is that these tephra layers provide the only direct means of correlation between the marine record and currently studied terrestrial sections in the western U.S., fulfilling a major objective of a larger study, the Correlation of Marine and Terrestrial Record Project of the U.S. Geological Survey Global Change Program.

The three tephra units found in the cores that are also widespread in the western U.S. are:

(1) The Mazama ash bed, ca. 6850 yr B.P., which was identified as a discrete layer in TT063-13, 209-211 cm, within $\delta^{18}O$ Stage 1. A previous ^{14}C age (corrected) of ca. 6565 yr B.P. has been determined for the 200-220 cm interval by others.

(2) The Glacier Peak ash bed, ca. 11,200 yr B.P., which was recognized in this core at 401-405 cm, near the top of $\delta^{18}O$ Stage 2.

(3) The Wono ash bed, ca. 27,500 yr B.P.; identifed in Core Y72-11-1P, at 460-470 cm, near the top of $\delta^{18}O$ Stage 3.

An unnamed ash in Y72-11-1P, at a depth of 1223-1225 cm, is present just above the boundary of oxygen isotope stages 5 and 6, at 125,000 yr B.P. Volcanic glass shards from three more intervals in this core (≈640 cm, ≈950 cm, and ≈1160 cm) are currently being analyzed to test for additional correlations.

Lastly, we found an interval of heterogeneous shard populations in Core F8-90-G21, at a depth of 37-41 cm. The shards, >3% of the sediment sample, comprise at least four major chemical modes. The most abundant mode matches late Pleistocene tephra erupted from the Mono Craters in east-central California. The age range of the Mono Craters tephra layers is

≈35,000 to 12,000 yr B.P. These shards are as much as 150 mm in diameter and highly pumiceous, with unconnected, spindle-shaped vesicles. Because of their low effective density, these shards may have been carried by stream and ocean currents to their depositional site. Two shards matching the Wono ash bed are also present in this assemblage. All of the shards in this interval may have been reworked and define only a maximum age for the enclosing sediments. These shards are considerably older than the interpolated age of ca. 6090 yr B.P. obtained from AMS radiocarbon ages on sediments further down the core.

Inorganic and Organic Geochemical Analyses of California Margin Marine Cores:

Walter E. Dean and Lisa R. Bader

Splits of samples used for carbon analyses from about 16 of the marine cores used to define the offshore transect from southern Oregon to southern California were analyzed for major, minor, and trace elements by induction-coupled, argon-plasma emission spectrometry (ICP), and for major-element oxides by wavelength-dispersive X-ray fluorescence spectrometry (XRF). The methods used are discussed in Baedecker and others (1987). We typically obtain values above the detection limits on about 30 elements. Many of the elements analyzed provide valuable information on sources of detrital aluminosilicate and other clastic material (*e.g.*, Si, Al, Fe, Mg, Na, K, Ti, Li, La, Ce, Y, Sc, and Ga). For example, values of Al, Fe, Mg, and Li from cores F2-92-P34 and F2-92-P40 from the central California margin (Figure 9-1) show that all four elements in P34 apparently were derived from the the same detrital clastic material because variations in element concentration are all similar. However, variations in concentration of Fe and Mg in P40 are similar to each other, but are different from that of Al. This suggests that they were derived, at least in part, from different sources. Variations in the concentration of Li suggest yet another source. Sometimes, relations between and among elements can be clarified by using various element ratios, but usually more advanced multivariate statistical methods such as R-mode and Q-mode factor analysis are required to detail inter-element relationships and changes in these relationships in time and space.

Variations in Si shown in Figure 9-1 differ from those of other elements mainly because of the addition of biogenic silica. Concentrations of Ca and Sr are determined almost entirely by the biogenic carbonate fraction. Several trace elements (*e.g.*, Zn, Cd, Cu, and Ni) commonly are associated with the organic fraction, and several other trace elements (*e.g.*, Cr, Mo, and V) have been suggested as possible indicators of intense sulfate reduction in the water column. We have focused on molybdenum (Mo) as an indicator of bottom-water anoxia because this element has the highest concentration of any heavy metal in seawater, and has a uniform concentration with depth in the water column. Figure 9-2 shows that in core F2-92-P33 on the central California margin the elevated concentrations of Mo only occur in laminated sediments. The laminated sediments alone tell us that bottom-water oxygen levels were sufficiently low to eliminate burrowing bottom organisms. However, the elevated Mo concentrations tell us that not only were bottom-waters low in dissolved oxygen, but in fact, they were anoxic.

The laminated sediments in core P33 (Figure 9-2) also have elevated concentrations of organic carbon (OC) relative to the overlying and underlying bioturbated sediments, suggesting that the flux of OC was greater during deposition of the laminated sediment and/or that the preservation of organic matter was enhanced in the laminated sediments. We have used Rock-Eval pyrolysis to determine the type and degree of preservation of organic matter in samples from many of the California margin transect cores. The Rock-Eval method provides a rapid determination of the hydrogen richness and degree of preservation of sedimentary organic matter (see Tissot and Welte, 1984, and Peters, 1986 for details of this method). During pyrolysis, free and adsorbed hydrocarbons (HC) are released by programmed heating of the sample in a stream of helium at a relatively low temperature (250°C) for five minutes and are recorded as the area

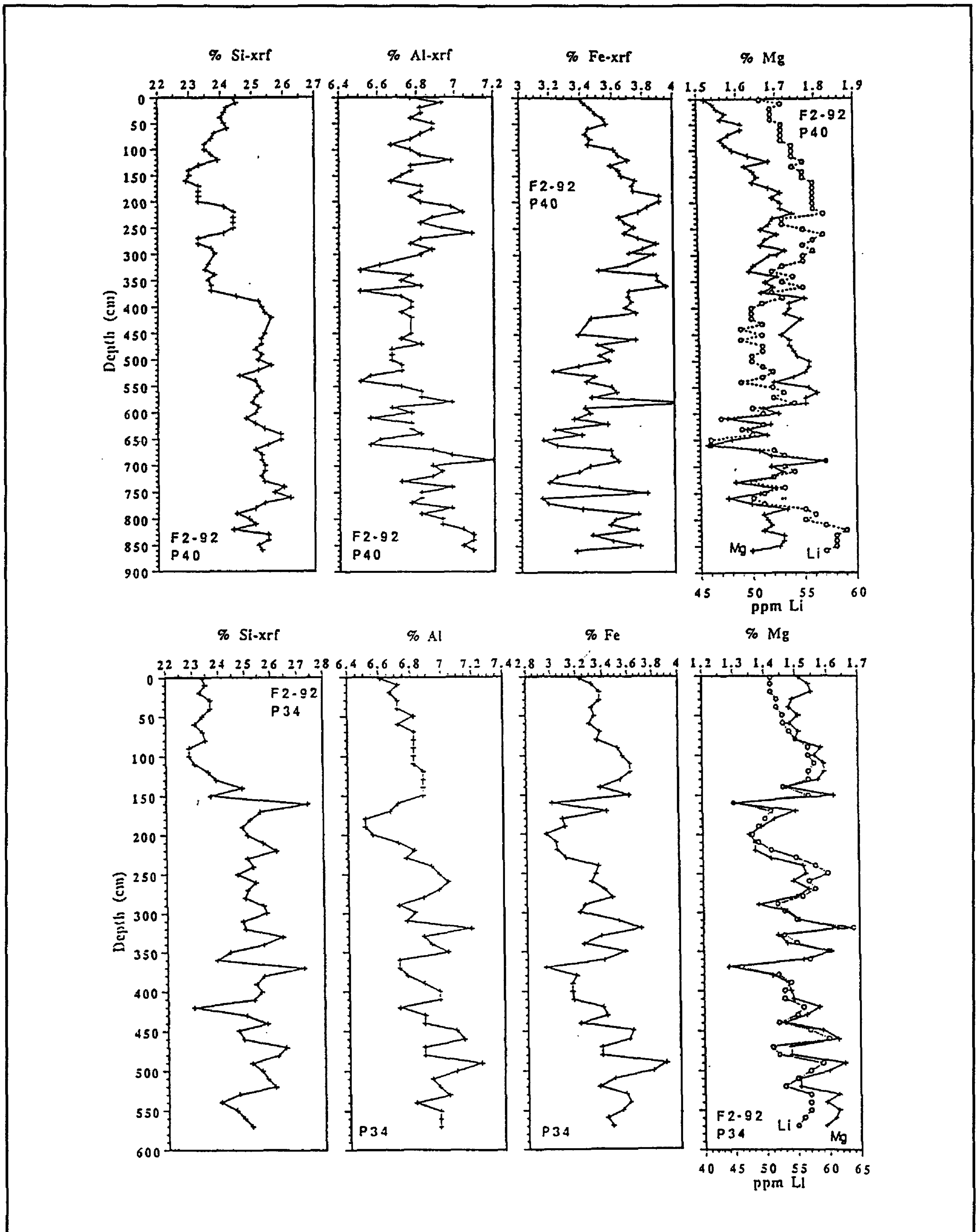

Figure 9-1.--Profiles of percent Si, Al, Fe, and Mg, and parts per million (ppm) Li in sediments from cores F2-92-P40 (top) and F2-92-P34 (bottom) from the continental margin off central California.

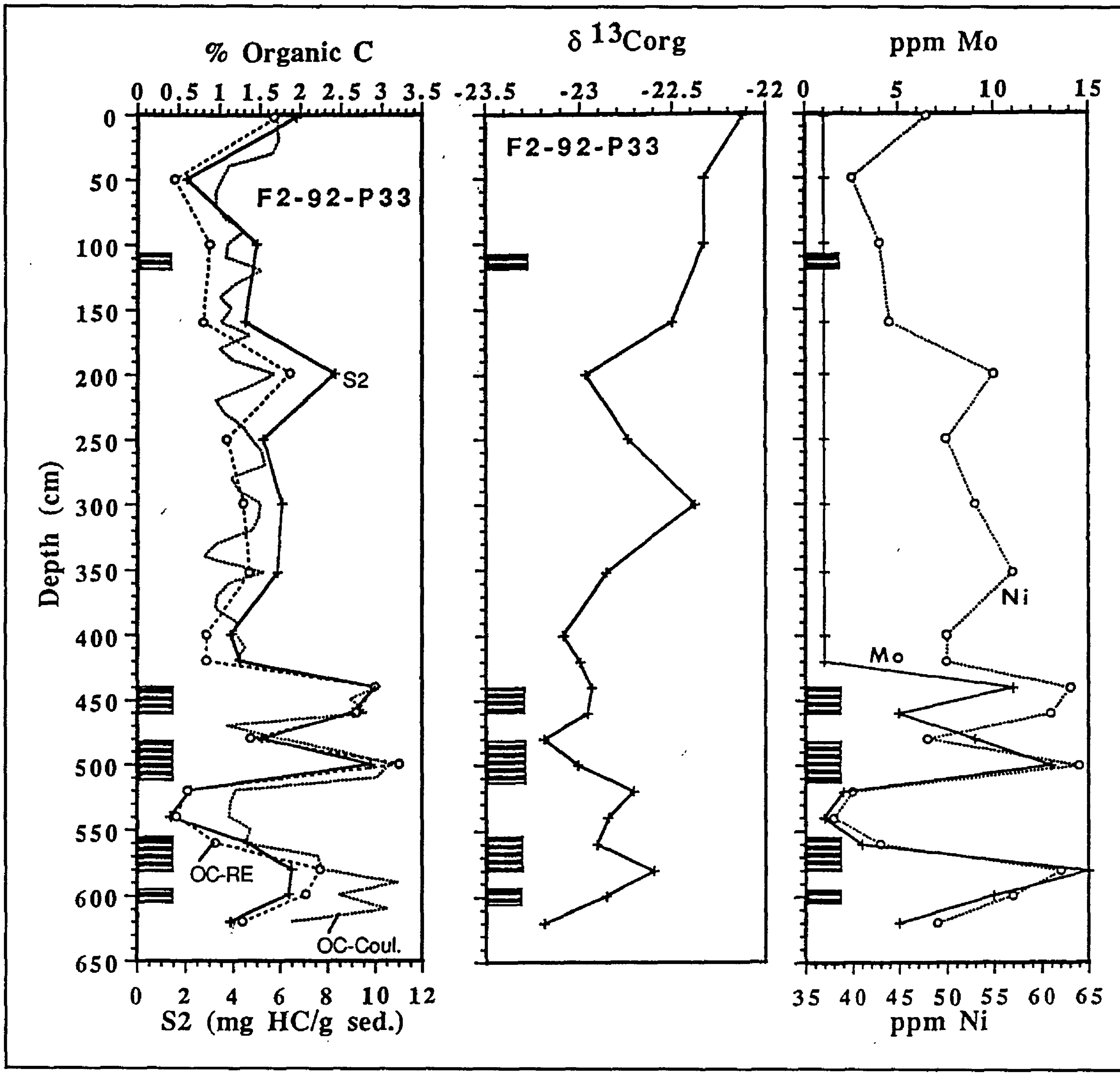

Figure 9-2.--Profiles of percent organic carbon determined by coulometer and by Rock-Eval pyrolysis (RE; left panel); Rock-Eval pyrolysis S2 peak (in milligrams of hydrocarbons per gram of sediment); values of $\delta^{13}C$ of organic matter (in parts per mil, ‰, relative to PDB, the marine carbonate standard; center panel); and parts per million (ppm) Mo and Ni (right panel) in sediments from core F2-92-P33 off central California. Locations of laminated sediment are indicated by the boxes with black and white bars next to the depth scale in each panel.

under the first peak on a pyrogram (S1) (milligrams of HC per gram of sample). The S1 peak is roughly proportional to the content of organic matter that can be extracted from the rock or sediment with organic solvents. The second peak on a pyrogram is composed of pyrolytic hydrocarbons generated by thermal breakdown of kerogen as the sample is heated from 250° to 550°C (S2; milligrams of HC per gram of sample). The S2 peak area, when calibrated and normalized to percent organic carbon (OC), yields a hydrogen index (HI) expressed as milligrams

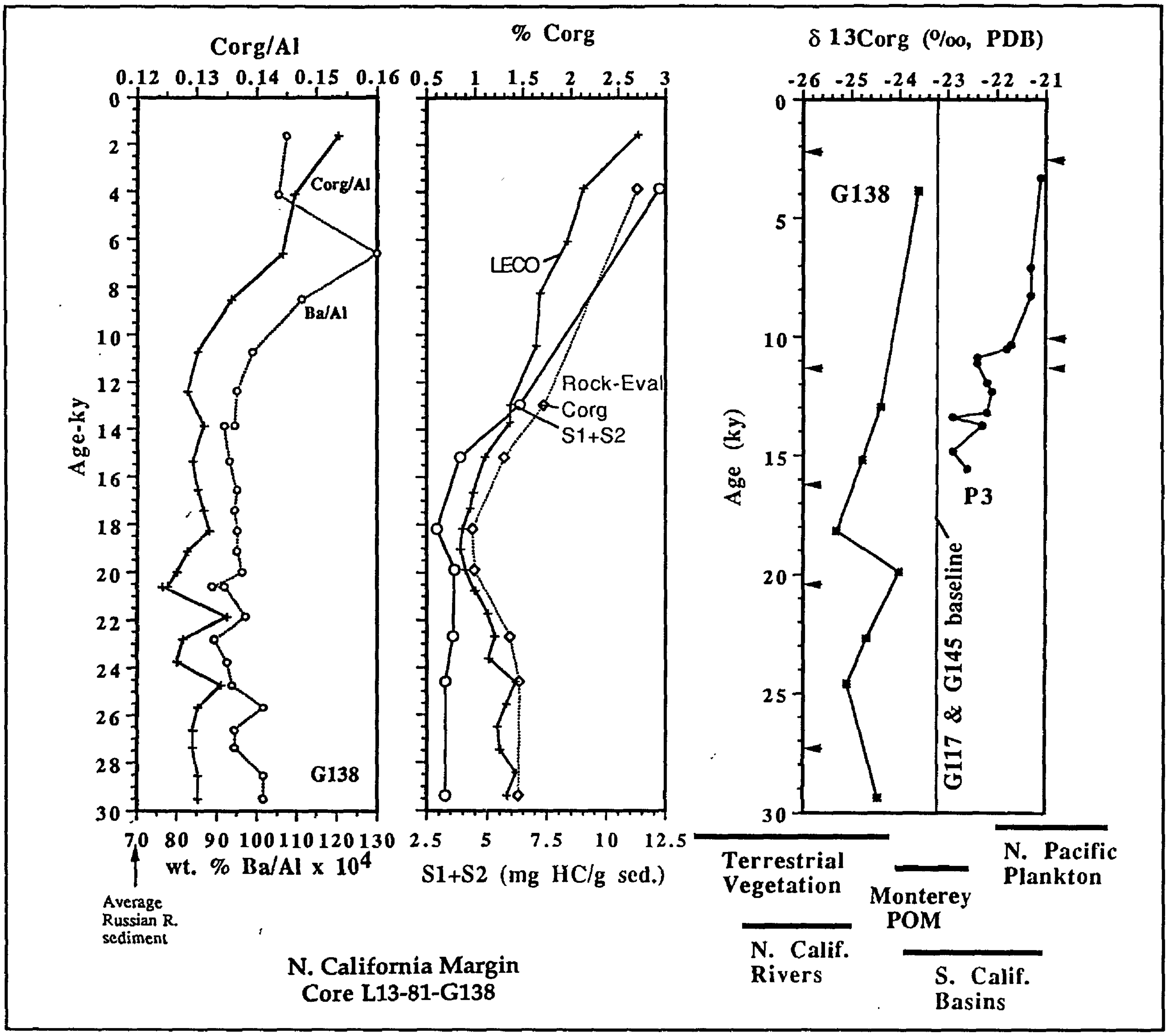

Figure 9-3.--Profiles of ratios of organic carbon to aluminum and barium to aluminum (left panel); percent organic carbon determined by LECO and Rock-Eval, and Rock-Eval S1+S2 (in milligrams of hydrocarbons per gram of sediment; center panel) in sediments from core L13-81-G138; values of $\delta^{13}C$ in organic matter (in parts per mil, ‰, relative to PDB, the marine carbonate standard; right panel) in sediments from cores L13-81-G138 and V1-80-P3. Arrows on left and right margins of the isotope (right) panel mark locations of ^{14}C dates. Vertical line at 23.2‰ $\delta^{13}C$ in the right panel represents an assumed average baseline mixture of terrestrial and marine, but dominantly marine, organic matter reaching the slope off northern California. Bars at the bottom of the right panel show the ranges of values of $\delta^{13}C$ in various sources of organic matter. Modified from Dean and others (1994).

of HC per gram of OC. In HC source rock nomenclature, S1+S2 is called the genetic potential (Tissot and Welte, 1984), because it represents the sum of H-rich organic matter that has already been transformed into HC (S1) and that which has not yet been transformed into HC (S2). We usually use S1+S2 as a measure of the total lipid-rich, sapropelic (type II) organic matter present in the sediment (Tissot and Welte, 1984). In most Quaternary marine sediments, S1 is a minor part of the genetic potential and can be ignored. Because this H-rich organic matter also is the most labile, it will be the first to be consumed by aerobic and anaerobic decomposition. Therefore, the rate of change in S1+S2 , or simply S2, with depth can be taken as a measure of the rate of decomposition of reactive, metabolizable organic matter. Figure 9-2 shows that the laminated sediments in core P33 contain higher values of S2 than the bioturbated sediments indicating that the organic matter in the laminated sediment not only is more abundant (higher values of OC), but also is better preserved (*i.e.*, richer in more labile H-rich components).

The isotopic composition of organic carbon in sediments, as measured by values of $\delta^{13}C$, often is used as an indicator of the relative abundances of terrestrial and marine sources of organic matter (*e.g.*, Deines, 1980). Values of $\delta^{13}C$ in terrestrial organic matter typically are in the high negative 20s (-26 to -28‰), and those of marine organic matter typically are in the low negative 20s (-20 to -22‰). The bars in the lower right side of Figure 9-3 show ranges of values of $\delta^{13}C$ for terrestrial vegetation, organic matter in northern California rivers, particulate organic matter (POM) from sediment traps off Monterey, organic matter in southern California borderland basins, and north Pacific plankton. Values of $\delta^{13}C$ in organic matter in cores from the California margin typically show that the organic matter is a mixture of terrestrial and marine sources, but that the relative abundance of marine organic matter (heavier, or less negative values of $\delta^{13}C$) has increased over the last 18,000 years as sea level rose. This is shown for cores G138 and P3 from off northern California in Figure 9-3 (Dean and others, 1994) and for core G33 off the central California margin in Figure 9-2. For core G138, the increase in marine organic matter also is shown by increases in the percentage of organic carbon, in the Rock-Eval pyrolysis values of S1+S2, and in the Ba/Al ratio that has been identified as a proxy for organic productivity (*e.g.*, Dymond, 1992).

These are just some of the types of information that can be obtained from inorganic and organic geochemical analyses of sediments from the west coast marine transect. The next year will be spent documenting these proxy variables and verifying their significance using various statistical techniques.

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Centennial-scale changes in the fluxes of carbonate, organic carbon, and biogenic opal within the California Current and their relationships to paleoproductivity over the past 50,000 yrs:

James V. Gardner and Peter Dartnell
U.S. Geological Survey, Menlo Park, CA 94025

We have concentrated our studies on a series of 17 cores that span the region from 32° to 44°N along the California and Oregon margin (Figure 10-1). Our objectives are to understand the changes in fluxes of biogenic material and determine if these changes were in phase along the N-S extent of the California as well as with global climate changes. The fluxes of $CaCO_3$, organic carbon (C_{org}), and biogenic opal can be empirically related to productivity, which can in

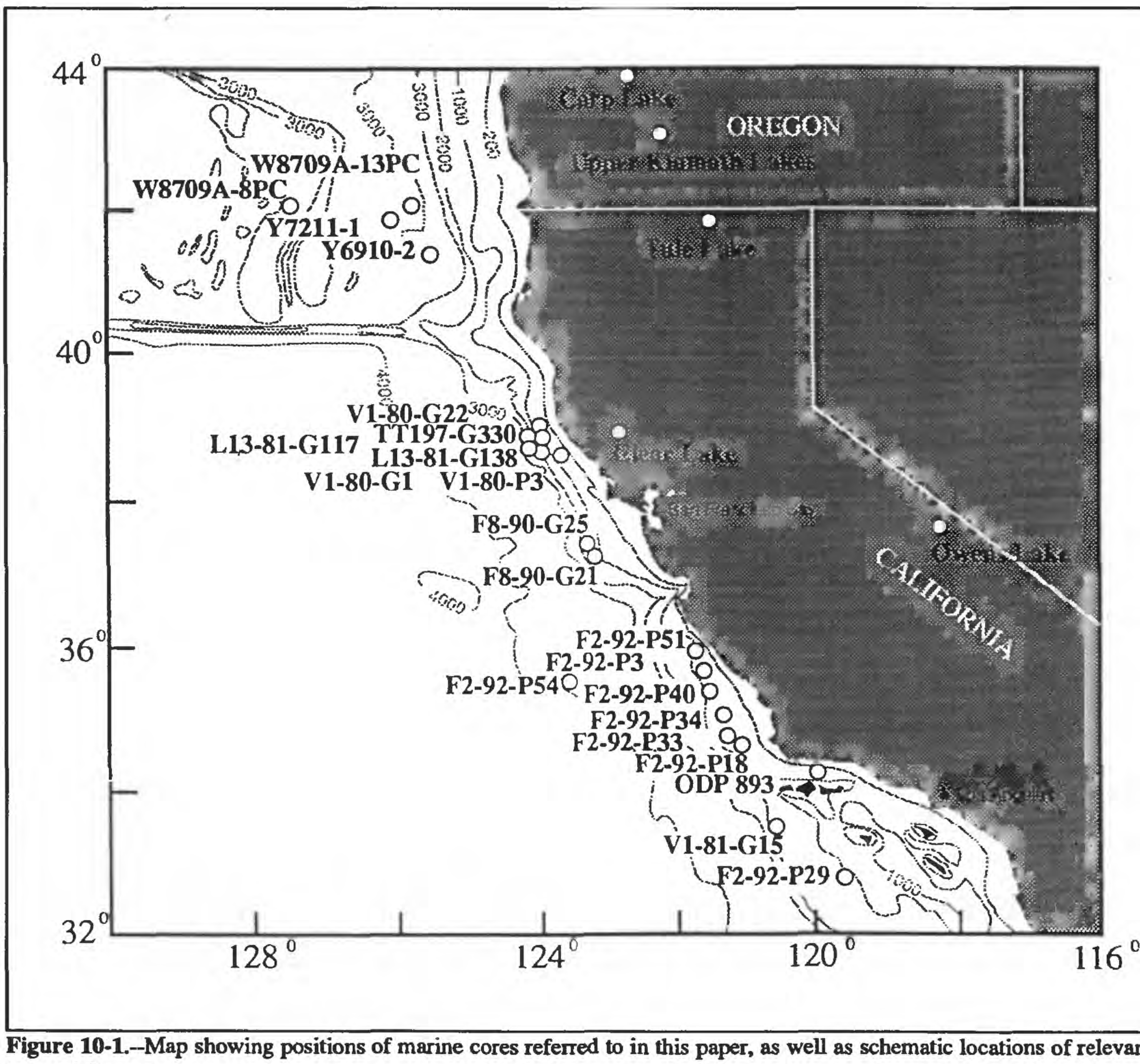


Figure 10-1.--Map showing positions of marine cores referred to in this paper, as well as schematic locations of relevant terrestrial cores.

turn be related to the intensity and location of upwelling along the California Current. We analyzed cores at 10-cm intervals for $CaCO_3$, C_{org}, and biogenic opal. All of these cores have either been sufficiently dated with AMS ^{14}C for a reliable age model, or are presently submitted for analysis. Because we have age models for each core, we are able to plot our data versus age rather than depth. Our interest is in the flux of $CaCO_3$, C_{org}, and opal because these fluxes are the direct result of new productivity (the flux of C_{org} that rained from the oxygen-minimum zone). The low $CaCO_3$ concentrations found in cores from the California margin are not empirically correlated to measured dry bulk density (DBD), a measurement required to calculate fluxes. However, we have found an empirical relationship between biogenic opal and DBD of the sediment (DBD = (0.129 * opal) + 0.315; r = 0.844) so that we can now estimate a reliable value of DBD on those cores collected prior to our ability to directly measure DBD. The relationship allows us to calculate fluxes in all of our cores.

We had to develop a model to account for the biological consumption of recently deposited C_{org} so that sediment that has been through this "burndown" of C_{org} can be directly compared with sediment that is undergoing burndown. The model we developed assumes all labile C_{org} is consumed before the sediment is buried below the level of biological consumption, *i.e.*, the burndown has reached the background level of refractory C_{org}. This assumption requires further testing by using an independent proxy for biogenic degradation, possibly $\delta^{13}C$ of the organic fraction. The results of our burndown model can be seen in Figure 10-2. Instead of a steady increase of C_{org} during the Holocene (which could be interpreted as an increase in productivity), the C_{org} actually was deposited at a constant flux, a flux somewhat lower than that which occurred during the last glacial maximum and the last interstadial (OIS-3). This result has important ramifications for estimating paleoproductivity, not just within the California Current but

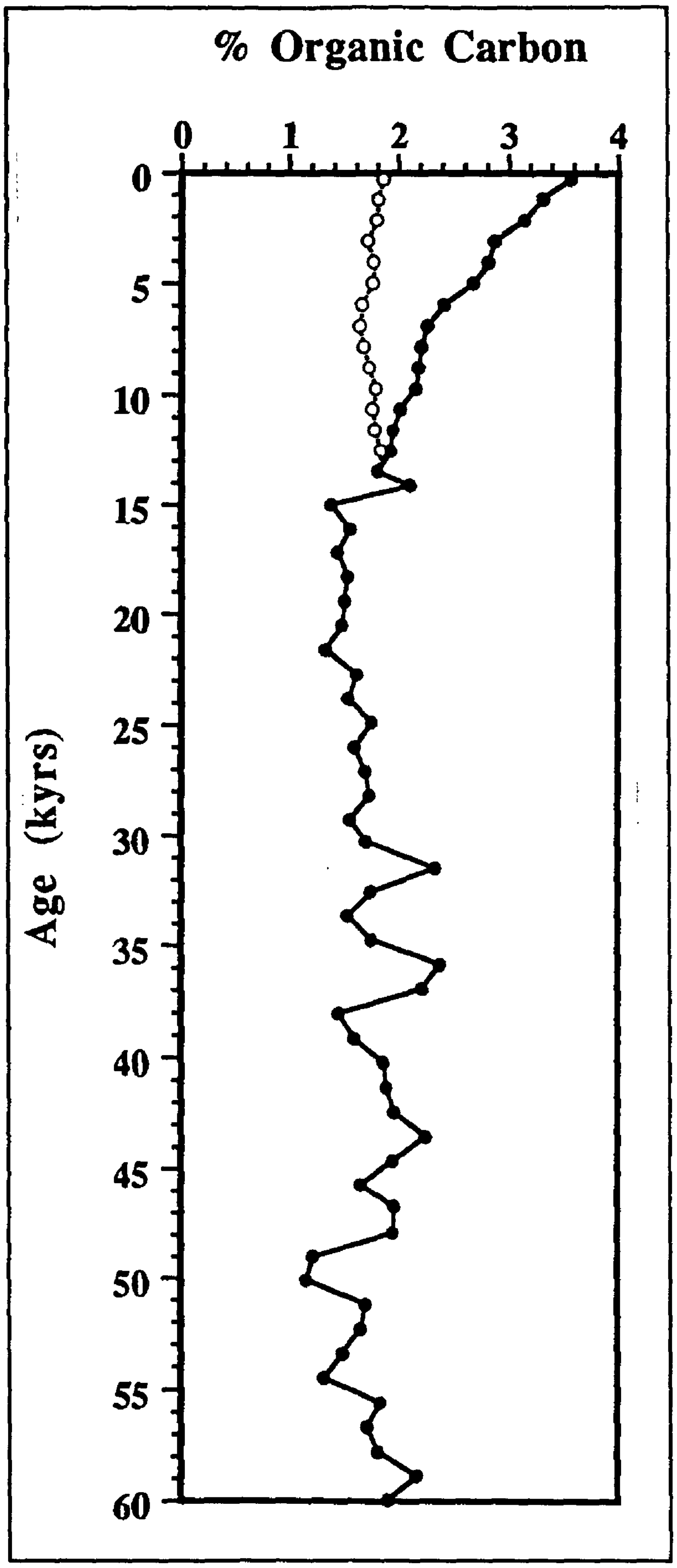


Figure 10-2.--Percent organic carbon plotted *vs.* depth for core F2-92-P34. Solid circles = observed C_{org}; open circles = C_{org} after correction using "burndown" model (see text for discussion).

throughout the world oceans.

We have also found that the flux of C_{org} is highly correlated with the flux of biogenic opal (diatoms and radiolaria) in cores north of Pt. Conception but C_{org} is correlated with $CaCO_3$ (planktonic forams and coccoliths) in the one core we have analyzed south of Pt. Conception (Figure 10-3). This result has prompted us to analyze another core from south of Pt. Conception, but the samples are still being processed at this writing. If the second core confirms our earlier findings, then we will have identified an oceanic front that separated the very-high productivity, upwelling waters from the much lower productivity, non-upwelled waters that can be spatially traced through the past 50 kyr.

The $CaCO_3$ Mean Accumulation Rate (MAR) records all show a ~3 kyr interval centered at 10 kyr when $CaCO_3$ MAR preservation was enhanced over any other period in the records. Preservation of $CaCO_3$ is suggested by a large decrease in foram fragmentation at the time when $CaCO_3$ MAR values are highest.

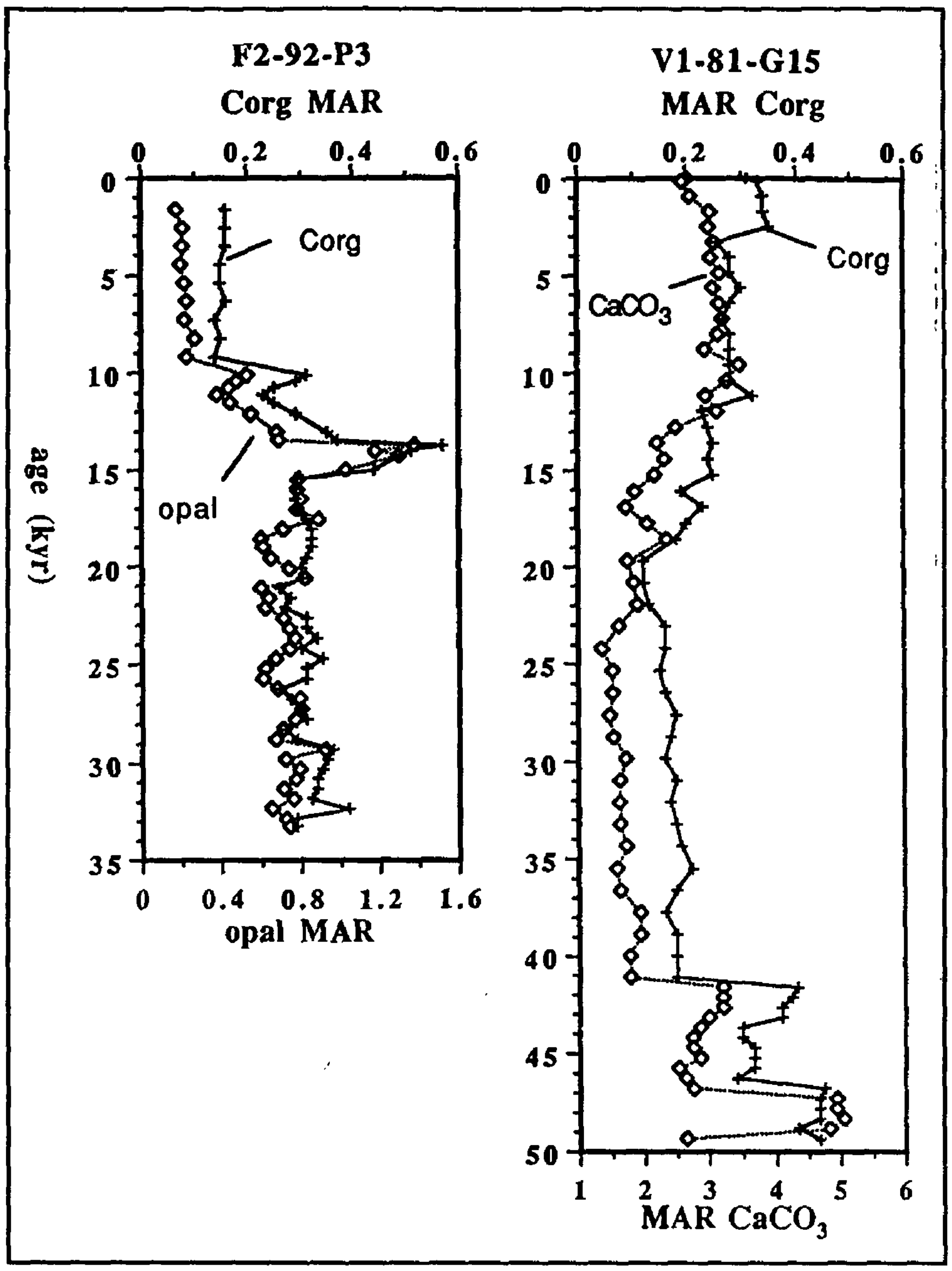


Figure 10-2.--C_{org} *vs.* depth parallels biogenic opal north of Pt. Conception (Core F2-92-P3, left), but parallels $CaCO_3$ south of Pt. Conception (Core V1-81-G15, right). See Figure 10-1 for core positions.

Preliminary Biostratigraphic Results of Planktonic and Benthic Foraminifers from Cores Collected off Central California:

Paula J. Quintemo and Bradley A. Carkin
U.S. Geological Survey, Menlo Park, CA 94025

INTRODUCTION

Two cores collected during the U.S. Geological Survey Cruise F2-92 of the R.V. FARNELLA (see Figure 10-1 of Gardner and Dartnell, this volume) were quantitatively analyzed for benthic and planktonic foraminifers. The preliminary results of those analyses are presented here and are compared with three previously-collected cores. All five cores show an abrupt and pronounced decrease in the abundance of *Neogloboquadrina pachyderma* (dextral) between approximately 14 and 15 ka which, for the most part, continued downcore. This suggests a general trend of warmer surface waters from about 14 ka to the present. The benthic foraminifer, *Cassidulina translucens*, is present in 4 of the 5 cores but is absent or rare in intervals younger than 14 ka, indicating a change in bottom water conditions. Benthic assemblages typical of low oxygen conditions are present throughout core F2-92-P3 with an abundance peak (96%) at about 14.5 ka.

METHODS

Because the samples collected during the F2-92 cruise are being analyzed for ^{14}C and oxygen isotopes as well as foraminiferal fauna, the following procedures were necessary. The samples were weighed wet and then oven dried at 30° to 40°C; after recording the dry weights to the nearest 0.1 gram, the samples were put in a weak solution of Alconox and distilled deionized water and agitated on an unheated oscillating plate for up to 1/2 hour to disaggregate the sediment. The sediment was washed with distilled deionized water on a 63 micrometer screen and dried at 30° to 40°C. The above procedure was repeated up to three times, if necessary, to break down the sediment. The dry weight (>63 micrometers) was recorded to the nearest 0.1 gram. If more than approximately 300 specimens each of planktonic and benthic foraminifers were present in the >150 micrometer fraction, a microsplitter was used to obtain approximately 300 specimens of planktonic and 300 specimens of benthic foraminifers. All specimens in the splits were picked, identified and counted.(Note: Subsamples were obtained from the archive half of V1-81-G15 and processed as above; however, due to time constraints, the samples have not yet been picked; but a rough count was made, so the core could be compared with the more northern cores).

DISCUSSION OF CORES

F2-92-P3 (35°37.39'N, 121°36.28'W; 799 m water depth).

The warmer water planktonic foraminifer, *Neogloboquadrina pachyderma* (dextrally coiling form), predominates over polar to subpolar *N. pachyderma* (sinistrally coiling form) from the top of the core to 214 cm. The dominance is reversed below this level (Figure 11-1A, B). Based on the AMS ^{14}C age model generated for this study, the reversal takes place at approximately 14,500 y.b.p.

Globigerina bulloides, a transitional to polar planktonic species characteristic of upwelling

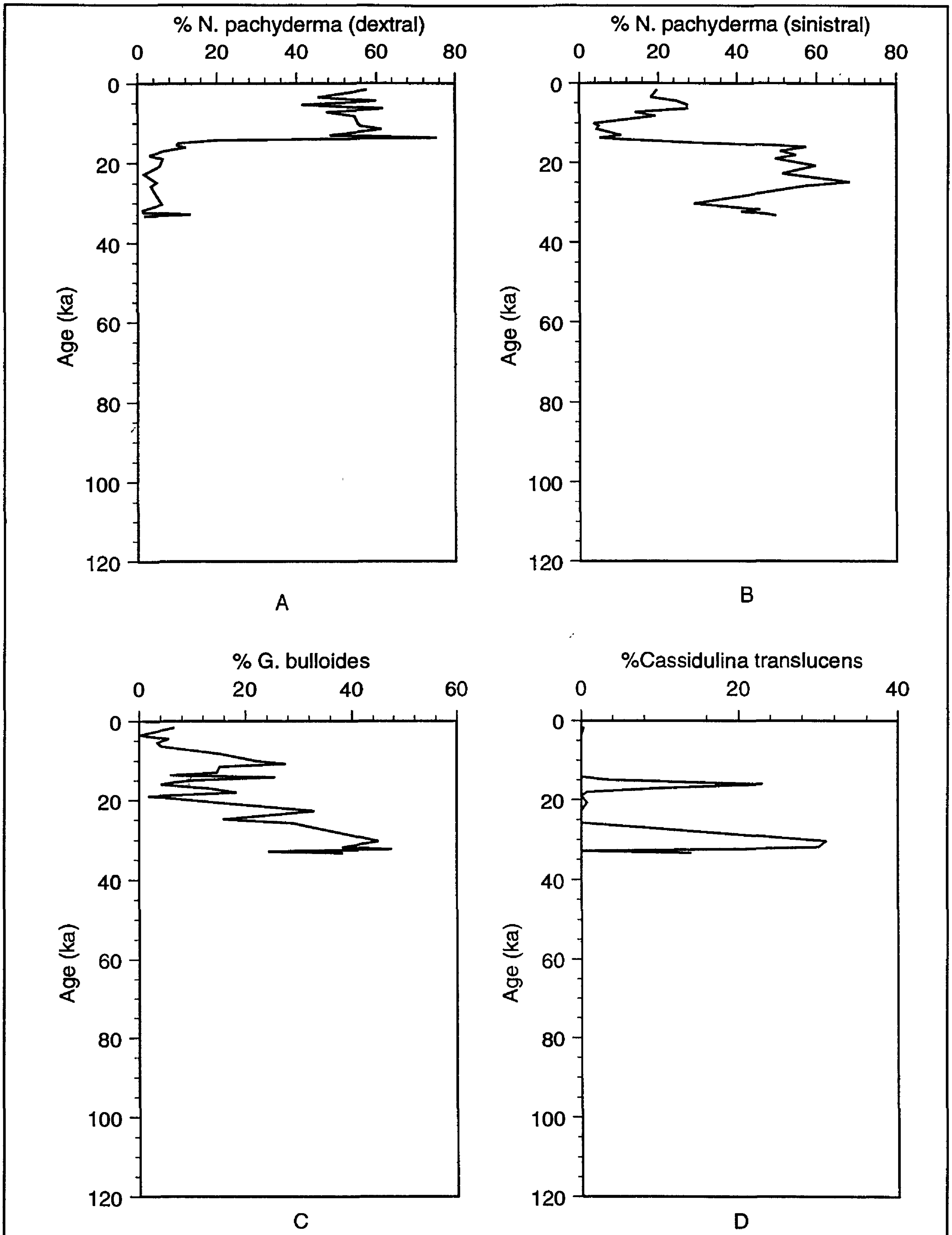
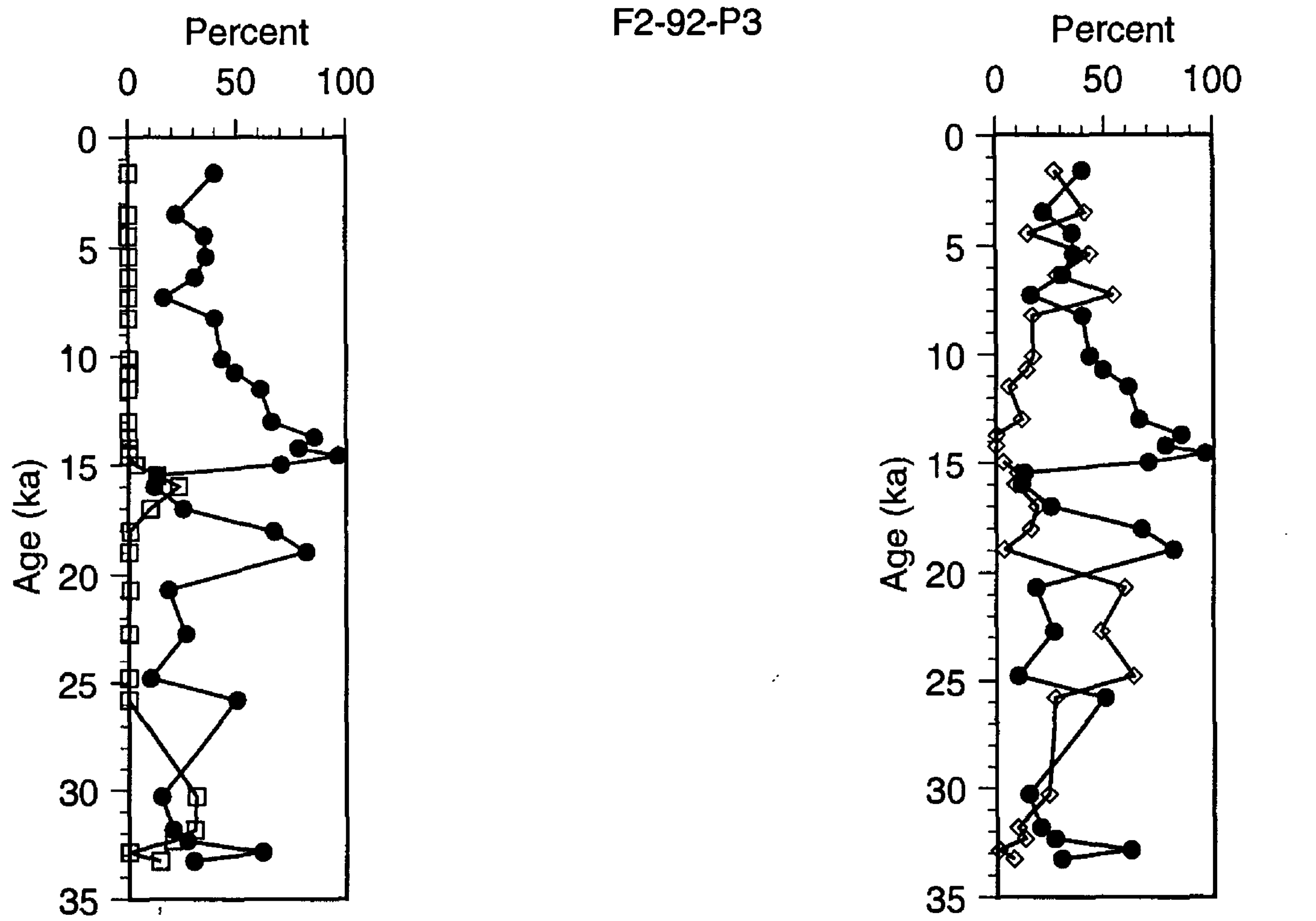


Figure 11-1.--Percentages of species plotted against ^{14}C ages for core F2-92-P3.

regions, oscillates is abundance, but shows a general increase downcore (Figure 11-1C).

Less abundant planktonic species, *Globigerinita glutinata* and *Orbulina universa*, also exhibit changes in abundance at 214 cm--*G. glutinata* generally has higher abundances below 214 cm and *O. universa*, above.

The following benthic species are known to be abundant under very low oxygen



A. Percent of low oxygen species (●) and *Cassidulina translucens* (□).

B. Percentages of low oxygen species (●) and *Uvigerina peregrina* (◇).

Figure 11-2.

conditions and are plotted on Figure 11-2 as "low oxygen species": ***Bolivina argentea*** (includes ***B. interjuncta bicostata***), ***B. pseudobeyrichi***, ***B. spissa***, ***B. seminuda***, ***B. subadvena***, ***Buliminella tenuata***, and *Cassidulina delicata*. Although *U. peregrina* may occur in abundance in low oxygen environments, it probably does not typically occur in the core (<0.3 ml per liter) of the oxygen minimum zone. Figure 11-2B shows the inverse relationship of *U. peregrina* with the "low oxygen species" in core F2-92-P3. Note the 4 major peaks(>50%) of the low oxygen species. The largest peak occurs at 214 cm (about 14.5 ka) at the base of a series of laminated sediments.

Except for one specimen at 10 cm, the benthic foraminifer *Cassidulina translucens* is absent from the top of the core through 214 cm (Figure 11-1D); it is present in 10 of the 15 samples below and varies inversely with the low oxygen fauna (Figure 11-2A).

F2-92-P54 (35°34.66'N, 122°42.95'W; 3305 m water depth).

N. pachyderma (dextral) dominates the plankonic fauna from 10 cm to 40 cm (8.2-14.09 ka AMS ^{14}C) (Figure 11-3A); *N. pachyderma* (sinistral) dominates from 50 cm to 780 cm (14.99-93.53 ka) (Figure 11-3B). The interval from 820 cm to 940 cm (97.85-110.80 ka) is barren or nearly barren of planktonic foraminifers. Near the bottom of the core, *N. pachyderma* (dextral) dominates briefly (113.0-114.1 ka), and in the lowest sample at 990 cm (116.20 ka) *N. pachyderma* (sinistral) again predominates (Figure 11-3). In general, the abundance of *G. bulloides* varies inversely with abundances of *N. pachyderma* (dextral), but 970 cm is an exception (Figure 11-3C).

The deep water species *Uvigerina senticosa* dominates the benthic fauna throughout most of this core.

V1-81-G15 (33°35.8'N, 120°25.3'W; 1430 m water depth)

Although only 11 intervals have been counted for foraminifers to date, the change from *N. pachyderma* (dextral) to *N. pachyderma* (sinistral) takes place between 100-105 cm (15.26-16.10 ka), and *Cassidulina translucens* occurs only from 105 cm to 300 cm (Figure 11-4).

V1-80-G1 (38°26.7'N, 123°52.2'W; 2045 m water depth)

Faunal trends are not clear in the upper 120 cm of this core, but from 145 cm (14.33 ka) to the bottom, *N. pachyderma* (sinistral) predominates over *N. pachyderma* (dextral) and *G. bulloides* becomes abundant. *C. translucens* also increases below 145 cm (Figure 11-5).

V1-80-P3 (38°25.5', 123°47.4'W; 1600 m water depth)

As in V1-80-G1, the relationship between sinistral and dextral *N. pachyderma* is not clear in the upper part of the core; however, below 240 cm (>14.58 ka) the sinistral form is dominant, and the benthic species, *C. translucens* becomes abundant (Figure 11-6).

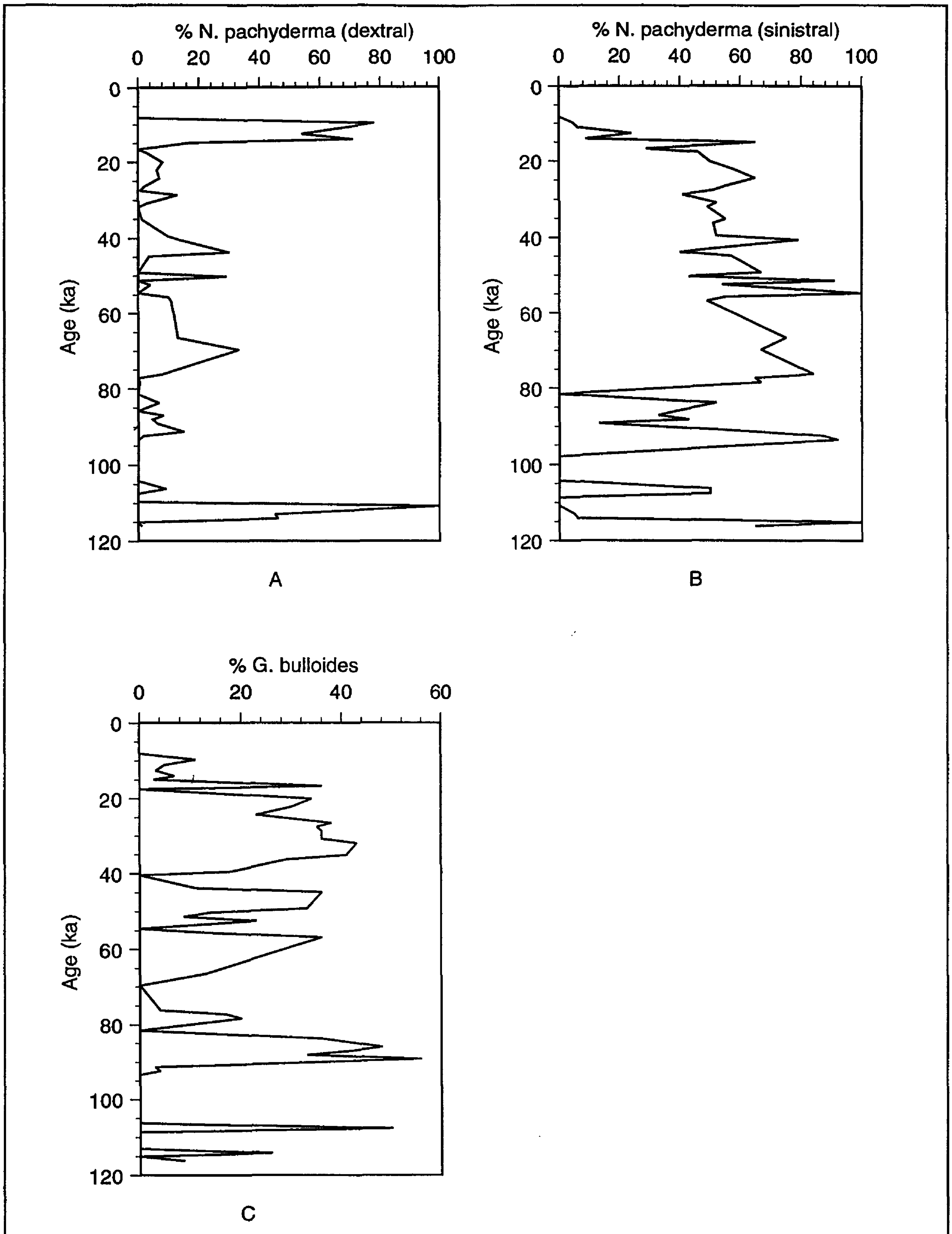


Figure 11-3.--Percentages of species plotted against ^{14}C ages for Core F2-92-P54.

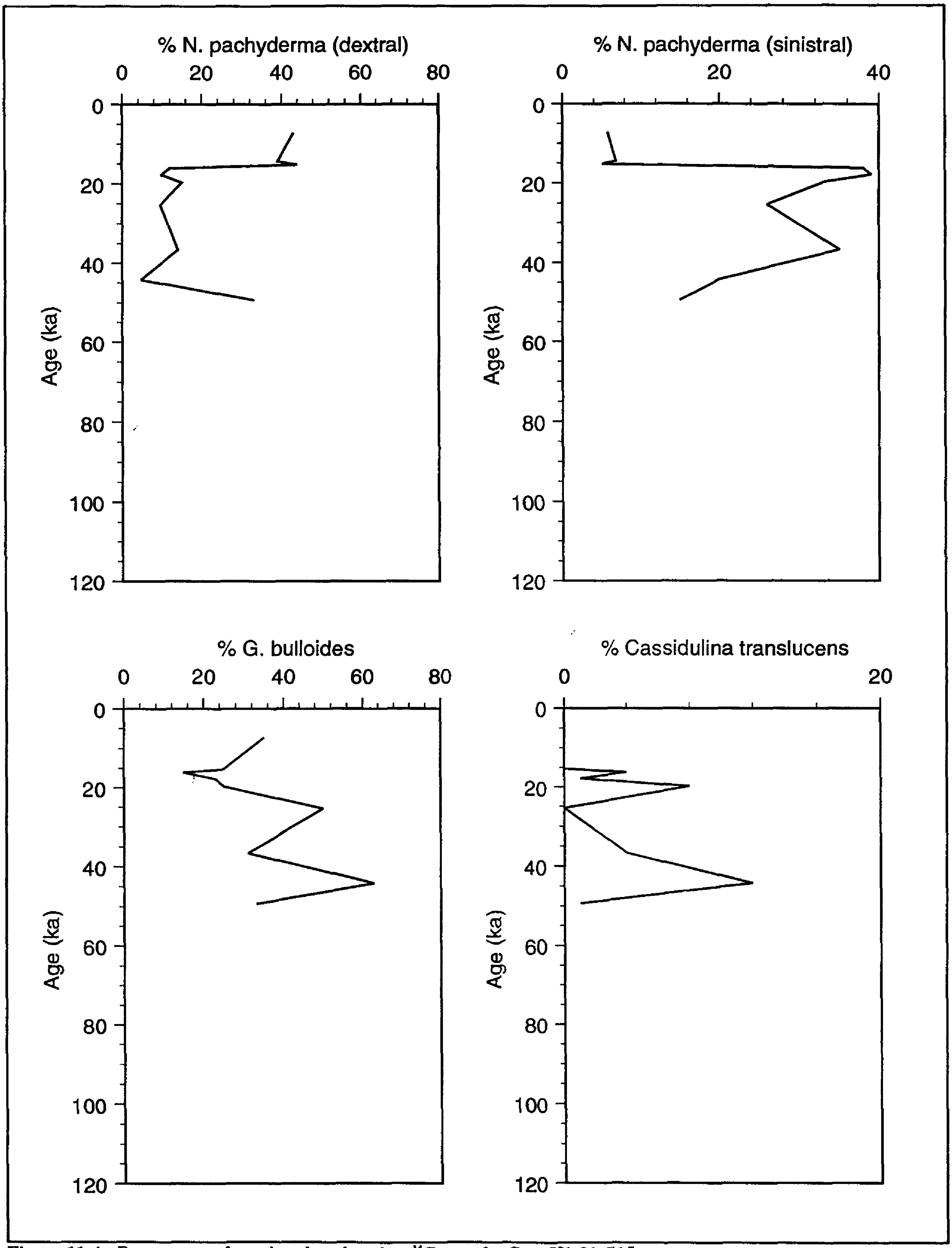


Figure 11-4.--Percentages of species plotted against ^{14}C ages for Core V1-81-G15.

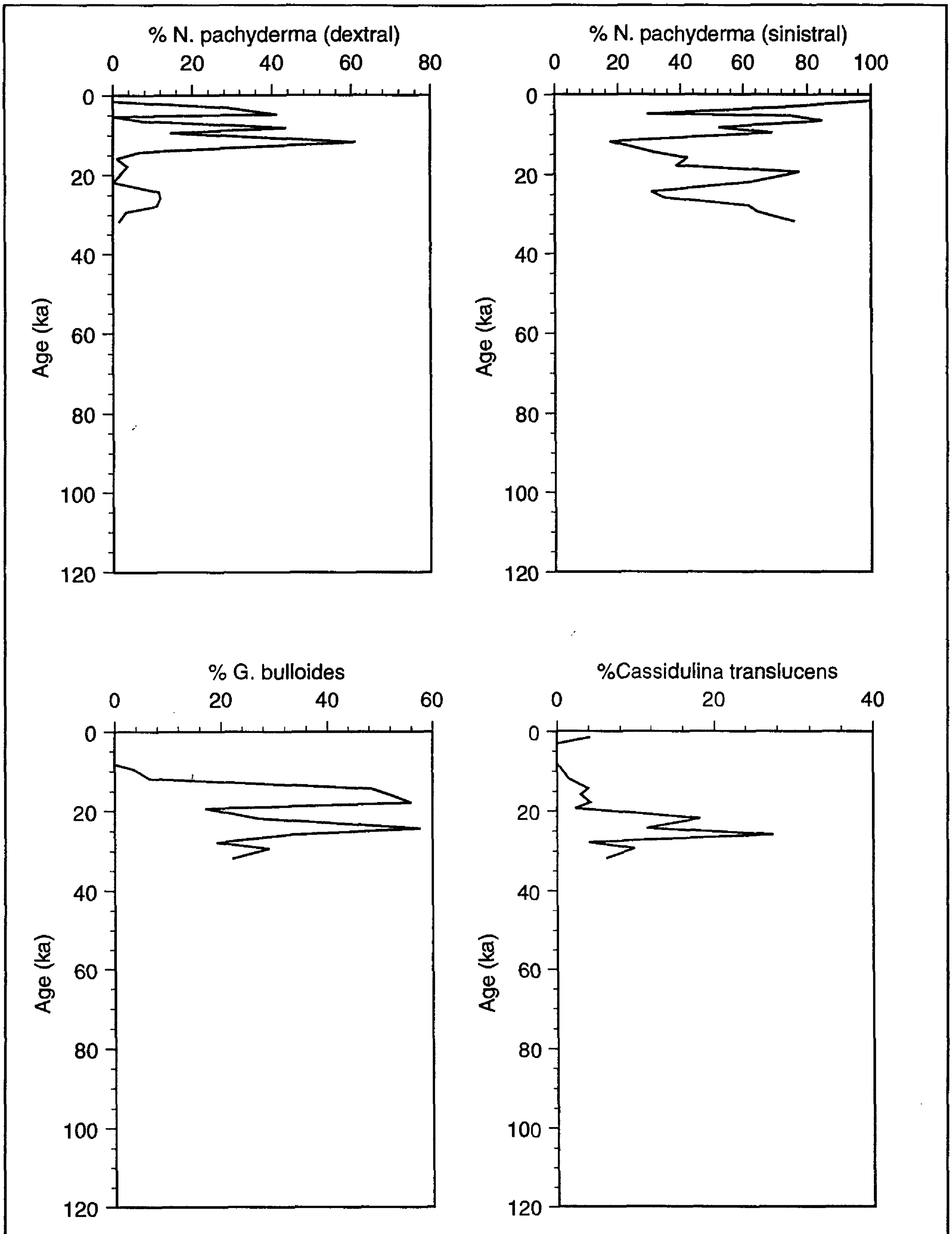


Figure 11-5.--Percentages of species plotted against ^{14}C ages for Core V1-80-G1.

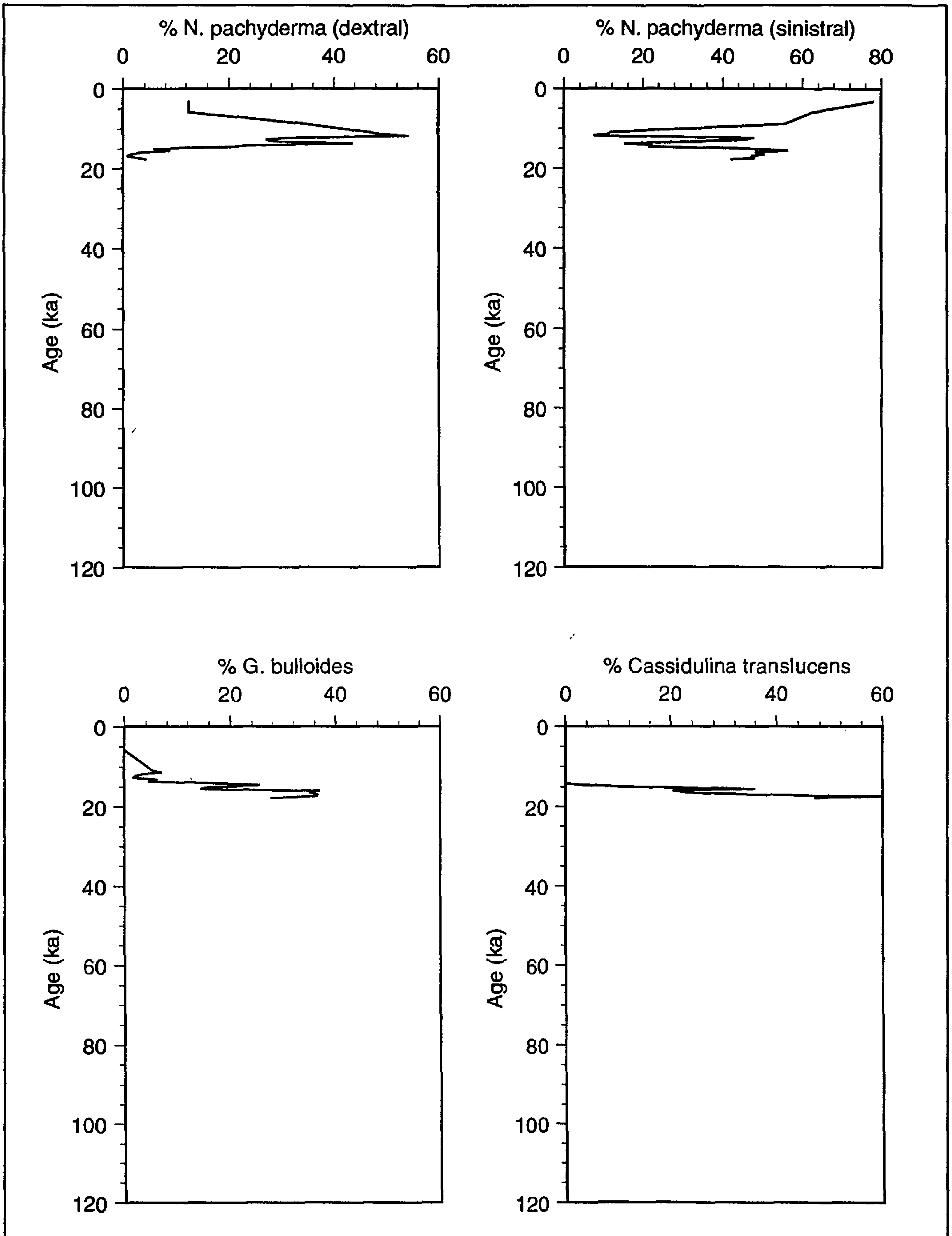


Figure 11-6.--Percentages of species plotted against ^{14}C ages for Core V1-80-P3.

Sea Surface Conditions in the Northeastern Pacific during the last 20,000 years:

A.L. Sabin, N.G. Pisias
College of Oceanic and Atmospheric Sciences
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis OR 97331-5503

The primary objective of this research is to reconstruct sea surface conditions of the northeastern Pacific during the last glacial cycle. It is hypothesized that sea surface temperatures and changes in ocean circulation play an important role in controlling climatic conditions of western North America. In this research we utilize the distribution of marine microfossil in modern ocean sediments to estimate past sea surface conditions based on the analysis of microfossils found in marine sediment cores. In this study we have constructed a transect of eleven cores which span eleven degrees of latitude along the west coast of North America (Figure 12-1). Using radio-carbon age dates from these sediment cores we have sampled each core over the past 20,000 years with an average sample interval of 1000 years. With this transect we are able to document how sea surface conditions changed in the eastern Pacific during the latest Pleistocene and Holocene.

To reconstruct sea surface conditions we utilized the relative abundance of radiolarian microfossils. Relative abundances were transformed to estimates of past sea surface temperatures using the strategy of Imbrie and Kipp (1971). A factor analysis of 41 radiolaria species from core top data across the Pacific ocean showed that the radiolarian population can be described by 7 factors. These factors were then used to describe the radiolarian population in the eleven sediment cores in the Northeast Pacific Ocean (Sabin, 1994). One of the factors, called the Eastern Boundary Current factor, corresponds to regions of upwelling along the west coast of the Americas. Its highest factor loading at present in the northeast Pacific occur at the coastline between 30°N and 45°N latitude.

Over the past 20 ka, the Eastern Boundary Current factor has experienced a significant expansion. At 20 ka, the factor was insignificant in the northeast Pacific (Figure 12-2), suggesting that upwelling was at a minimum. A northward expansion of the factor began at 17 ka, which continued through the Holocene. A significant increase occurred from 15 to 13 ka, during which the Eastern Boundary Current Factor reached its northernmost expansion. After a slight southward retreat to 5 ka and a northward excursion at 4 ka, the factor maintained its strength for the rest of the Holocene, with values similar to today's factor loadings. The northward expansion of the Eastern Boundary Current factor points to an increase in upwelling intensity from 20 ka to the present.

The factors were also used in generating a sea surface temperature equation (s.e. = ±1.5°C) (N. Pisias and A. Mix, personal communication), which was applied to the sediment cores. The sea surface temperature record from the cores illustrates the general warming trend which has occurred since the last glacial retreat (Figure 12-3). The warming, which began at 20 ka, is relatively steady in the northeast Pacific Ocean and persists until the present, with temperature increases on the order of 4°C.

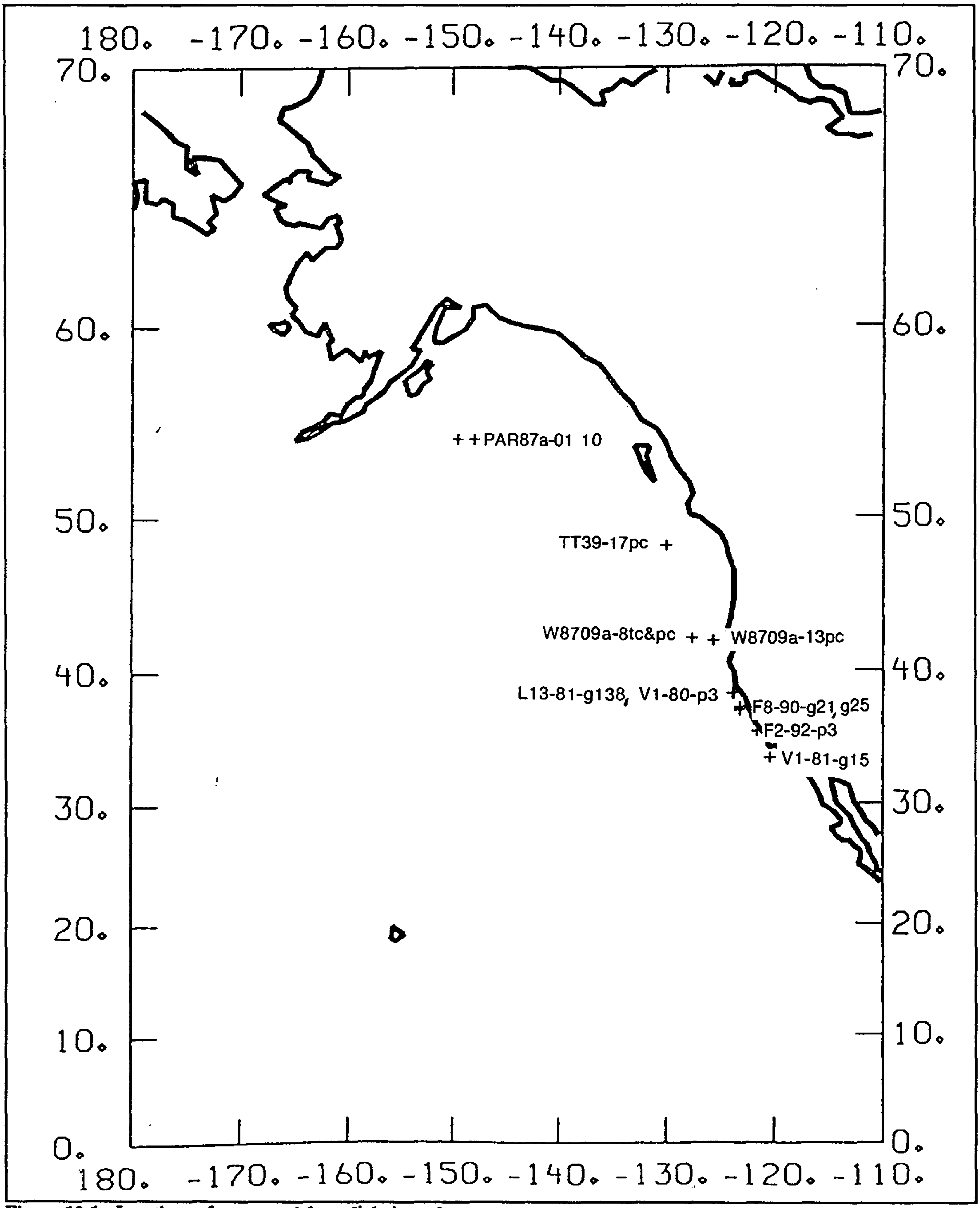


Figure 12-1.--Locations of cores used for radiolaria analyses.

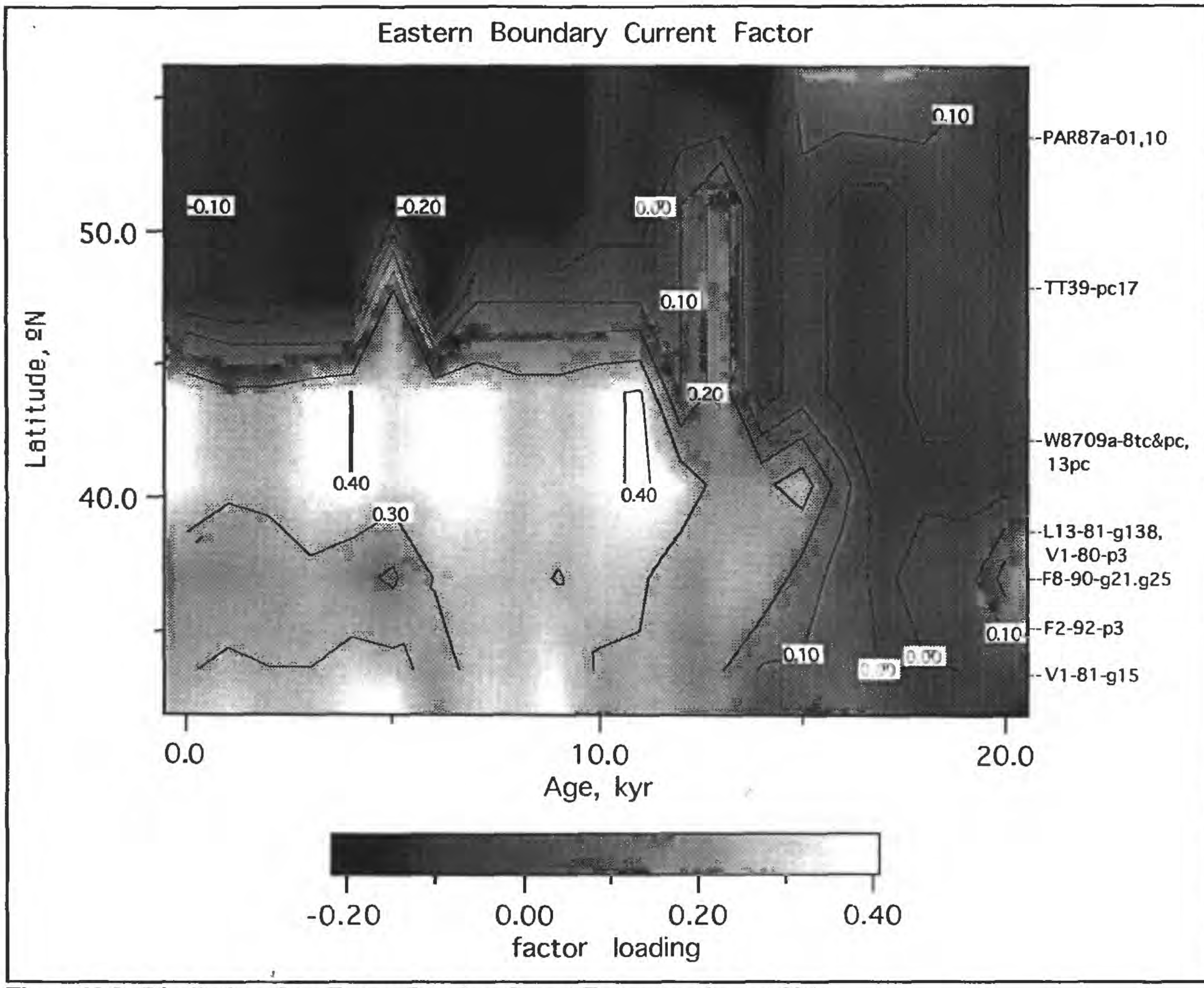


Figure 12-2.--Distribution of the Eastern Boundary Current Factor over the past 20 ka.

Superimposed on this general trend are some localized temperature variations. At sites south of 36°N, there has been little temperature change. An absolute maximum of 15°C occurred at 10 ka, with a temperature increase of 2.5°C since 18 ka. Temperatures then decreased at a relatively stable rate to final temperatures between 12° and 13°C. The sites at latitudes between 36° and 45°N experience three maxima: at 18, 11 and 3 ka, with temperature increases of 4°, 2° and 1.5°C, respectively, from their previous minima. The 18 ka maximum, which is not seen north of 42°N, is followed by a slight minimum at 14 ka. Temperatures increased to 12°C at the 11 ka maximum and then decreased slightly, except at 42°N, where temperatures dropped 4°C. After reaching the thermal maximum at 3 ka, temperatures remained around 11°C to the present. North of 45°N latitude, temperatures increased gradually from 7°C at 20 ka to 10°C at 13 ka. The area experienced a 2°C decrease at 11 ka, after which temperatures increased by 2°C and remained constant for the rest of the Holocene.

Sea surface temperature and the radiolaria factor may not be sensitive to short period climatic variations (<5 kyr), but are good indicators of atmospheric conditions in the NE Pacific. The temperature and factor variation is clearly significant on time scales of 5 kyr. Figure 2

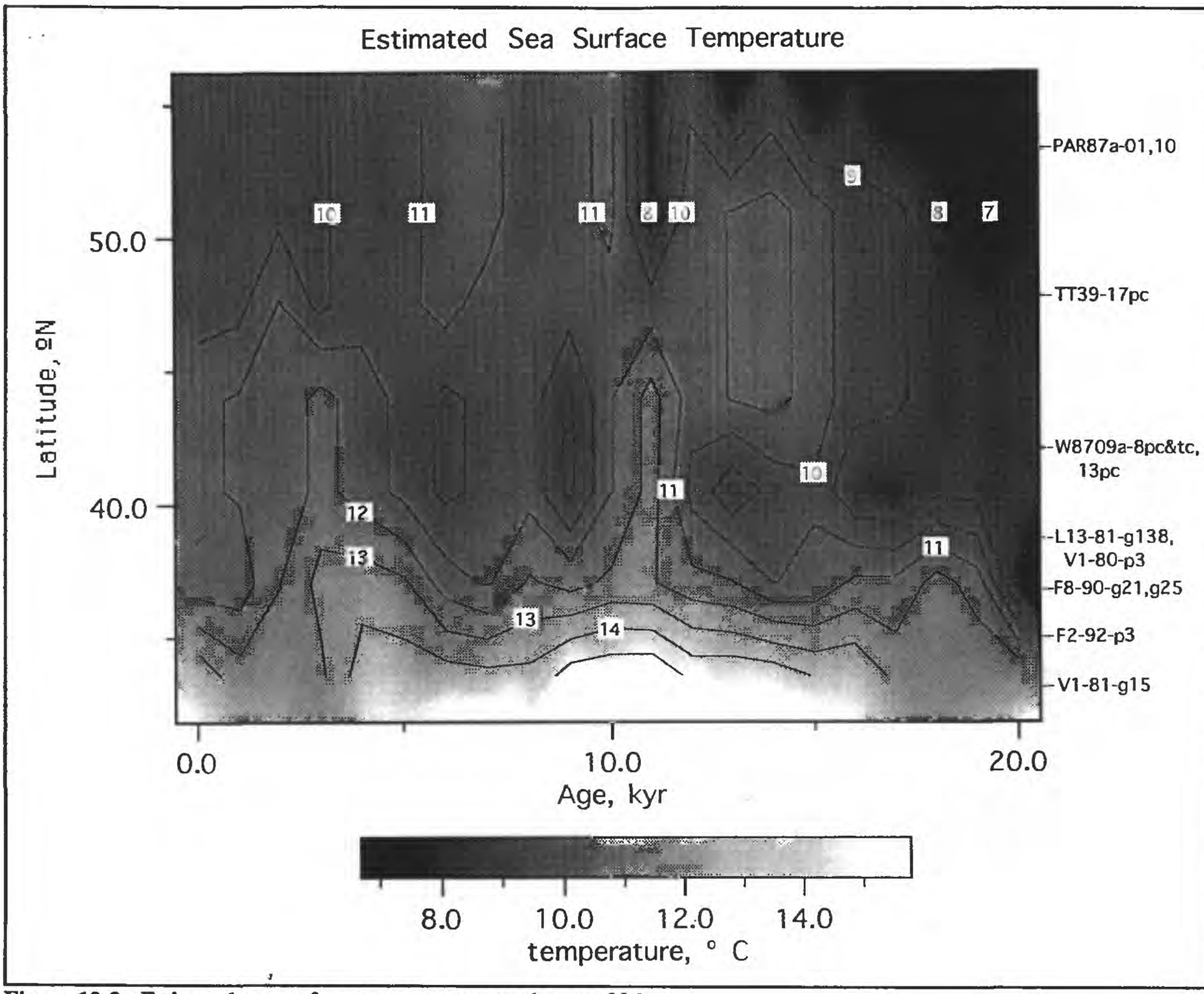


Figure 12-3.--Estimated sea surface temperature over the past 20 ka.

shows many minor temperature variations which are less than 1.5°C. While these are smaller than the standard error of the temperature equation, the geographic patterns and smoothing used in fitting the data suggest that the patterns may be real.

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Foraminiferal Evidence of Paleoceanographic Changes Off Central California During the Last 16,000 Years, Farallones Core F8-90-G21:

Mary McGann
U.S. Geological Survey, Menlo Park, California 94025

Foraminiferal data from a 1.6 m core (F8-90-G21) obtained off the Farallon Islands in the vicinity of Pioneer Seamount and Pioneer Canyon (37°13.4'N lat.; 123°14.6'W long.) indicates significant paleoceanographic changes over the last 16,000 years. The core was obtained at a depth of 1605 m and yielded thirteen species of planktic foraminifers and forty-four species of benthic foraminifers.

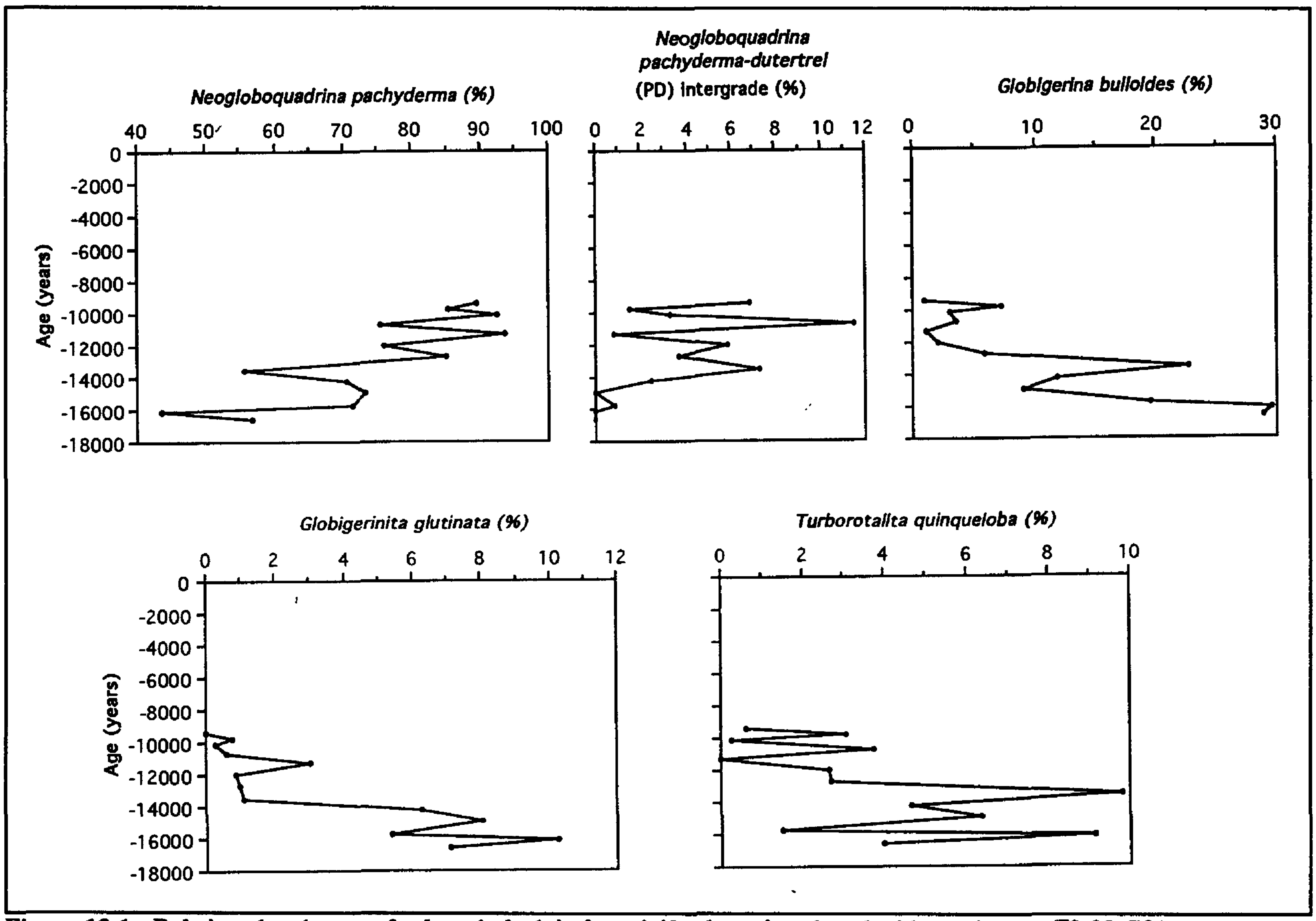

Figure 13-1.--Relative abundances of selected planktic foraminiferal species plotted with age in core F8-90-G21.

The planktic foraminiferal assemblage from 160-125 cm (AMS ^{14}C dates of ≈16-14,000 years B.P.) is dominated by *Neogloboquadrina pachyderma* (Figure 13-1), particularly the dissolution resistant left-coiling morphotype (Parker and Berger, 1971; Malmgren, 1983; Reynolds and Thunell, 1986; Figure 13-2) which prefers colder water (<8°C) of the subpolar to polar regions (Keller, 1978; Sautter and Thunell, 1989). Recovered with *N. pachyderma* were *Globigerinita glutinata* and *Turborotalita quinqueloba*, a common colder-climate association which has been documented elsewhere in the Eastern Pacific (Reynolds and Thunell, 1985;

Sautter and Thunell, 1989, 1991). The other dominant species obtained in this study is *Globigerina bulloides*. It is another highly solution-resistant taxon (Berger, 1968; Thunell and Honjo, 1981) which prefers, but is not restricted to, cool waters that are associated with upwelling (Thunell and Reynolds, 1984; Reynolds and Thunell, 1985; Sautter and Thunell, 1989, 1991).

From 125-60 cm (≈14-9,000 years B.P.), the planktic foraminiferal assemblage changes substantially. The cool-water thriving forms *G. bulloides*, *G. glutinata* and *T. quinqueloba* decrease significantly in abundance and are replaced by a greater proportion of *N. pachyderma* and taxa assignable to the *N. pachyderma-N. dutertrei* intergrade. Among the *N. pachyderma* population, a shift occurs at 125 cm from 77% left- to 75% right-coiling morphotypes (Figure 13-2). The latter then steadily increase in abundance from 125-70 cm, where they peak at 94%. Right-coiling forms reside in subpolar to tropical regions but prefer conditions where the water temperature is a relatively warm 8-12°C (Reynolds and Thunell, 1986; Sautter and Thunell, 1991). This upcore warming trend appears to have been interrupted by a brief return to colder conditions, as indicated by a sudden increase in left-coiling *N. pachyderma* at 90 cm (≈11,000 years B.P.). This shift in the coiling ratio may be due to one of two factors: increased dissolution of the planktic foraminiferal assemblage (Figure 13-3 and Figure 13-4) which tends to favor the solution-resistant left-coiling *N. pachyderma* morphotype, or a tentative correlation with the Younger Dryas event of the North

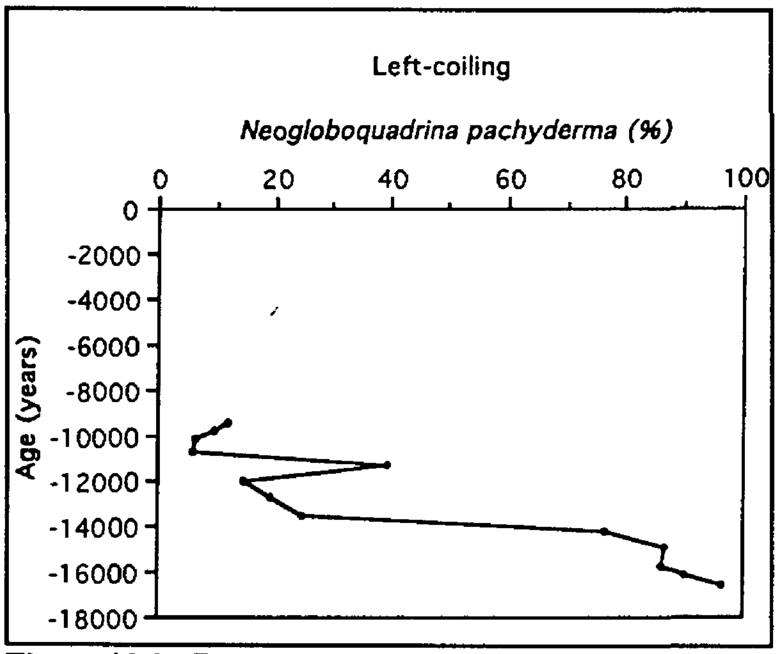

Figure 13-2.--Relative abundance of left-coiling *N. pachyderma* to total *N. pachyderma* plotted with age.

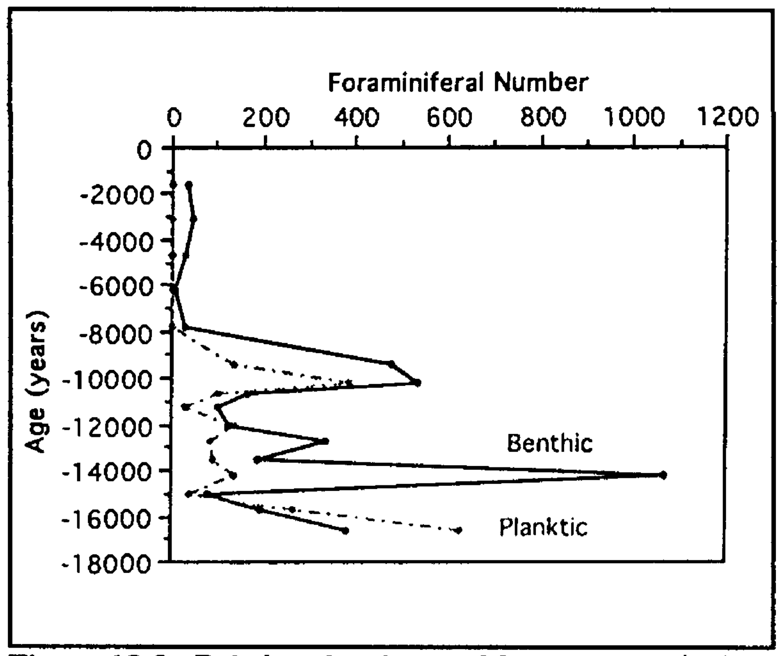

Figure 13-3.--Relative abundance of fragments, and whole benthic and planktic foraminifers plotted with age.

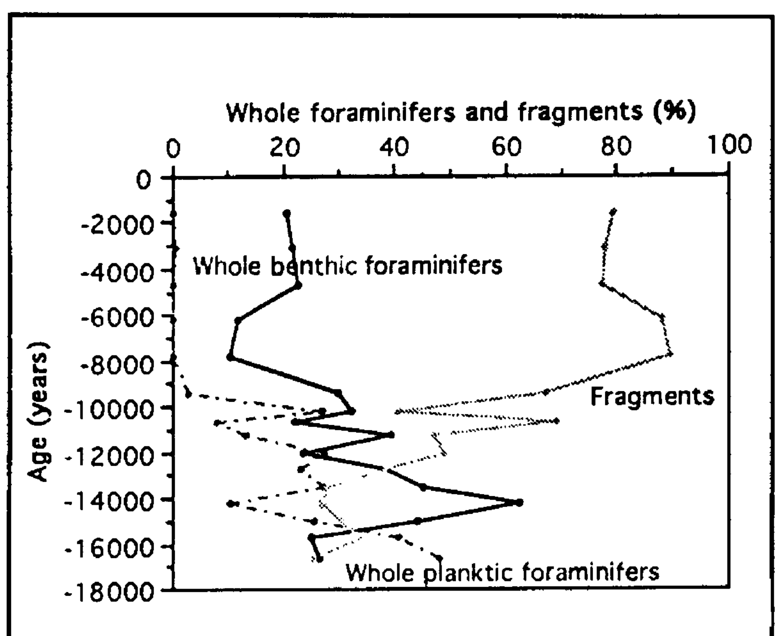

Figure 13-4.--Modified benthic and planktic foraminiferal numbers (foraminifers/gram wet weight) plotted with age.

Atlantic region (Wright, 1989). A pollen study from the British Columbia coast (Mathewes and others, 1993) and several foraminiferal studies in the Pacific (Chinzei and others, 1987; Gardner and others, 1987; Brunner and Ledbetter, 1989) have also recorded this cooling event. The warming trend established again from 63-60 cm is replaced by sediments nearly devoid of planktic foraminifers from 60 cm to the top of the core (≈9,000-0 years B.P.; Figure 13-3 and Figure 13-4).

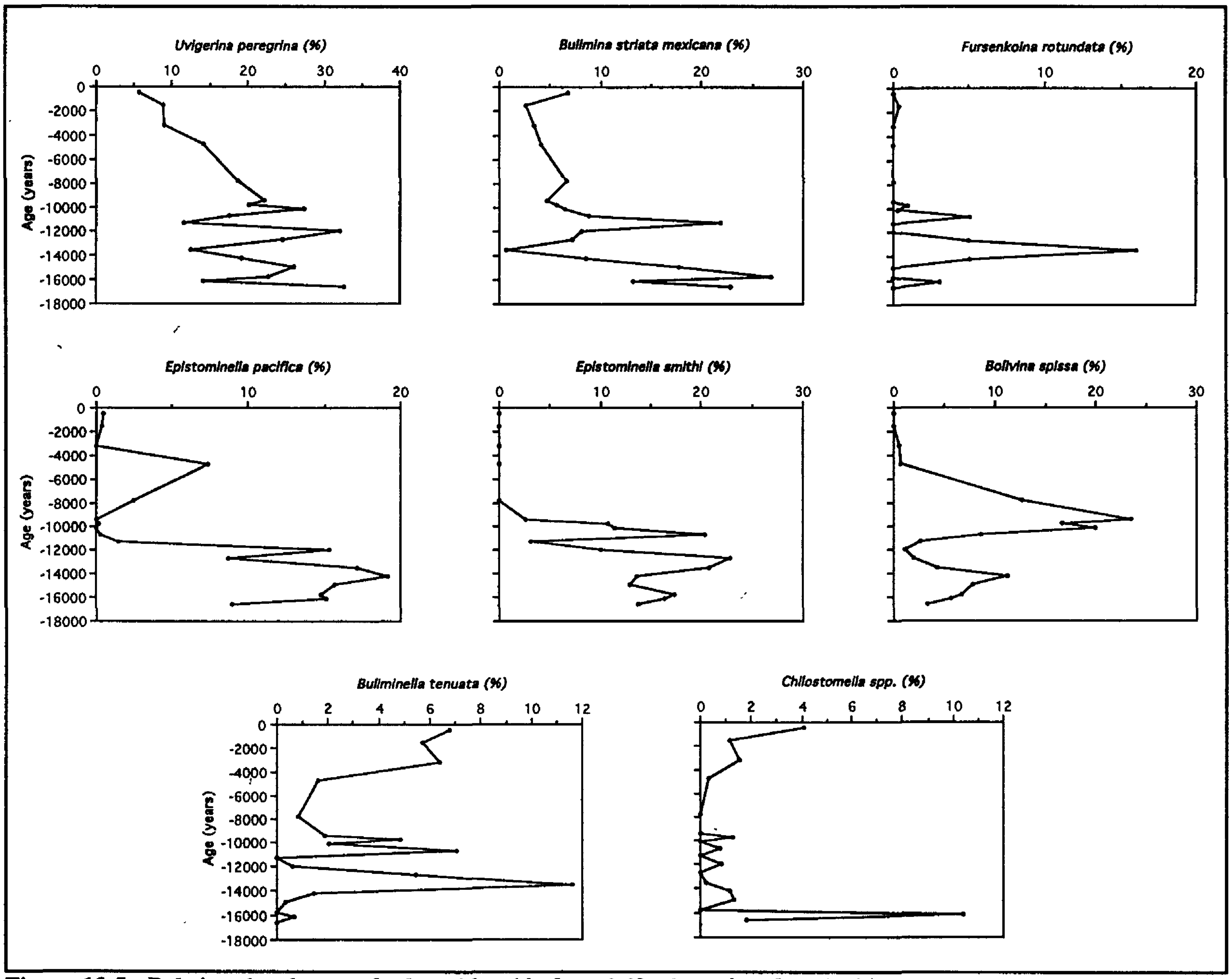

Figure 13-5.--Relative abundances of selected benthic foraminiferal species plotted with age.

The benthic fauna in the lower half of the core (Figure 13-5) is dominated by infaunal-dwelling low-oxygen taxa (Douglas, 1979; Corliss, 1985, 1991; Corliss and Chen, 1988; Corliss and Emerson, 1990; Gooday, 1994), such as *Uvigerina peregrina*, *Bulimina striata mexicana/B. spicata*, *Fursenkoina rotundata*, *Epistominella smithi*, *E. pacifica*, *Bolivina spissa*, *Buliminella tenuata*, and *Chilostomella* spp. This association has been previously reported in low-oxygen (<0.5 ml/L) regions nearby off Big Sur (Mullins and others, 1985; Vercoutere and others, 1987), Cordell Bank (Bandy, 1953), and the Russian River (Quinterno and Gardner, 1987). The fauna then slowly changes character from approximately 80-60 cm (≈10,500-9,000 years B.P.; the nature of this boundary may become more apparent in a Q-mode cluster analysis to be run later). In the upper part of the core, the dominance in the benthic foraminiferal population switches to infaunal and epifaunal taxa that require more oxic conditions (>0.5-2.2 ml/L): *Uvigerina hispida*, *U. proboscidea*, and *Cibicides mckannai* (Bandy, 1953; Mullins and others, 1985; Quinterno and Gardner, 1987; Gooday, 1994; Figure 13-6) while some low-oxygen tolerant forms (*Buliminella tenuata*, *Globobulimina* spp. and *Chilostomella* spp.) continue to appear in abundance. And as with the planktic foraminifers, preservation of benthic tests drops substantially in the upper 60 cm of the core (Figure 13-3 and Figure 13-4).

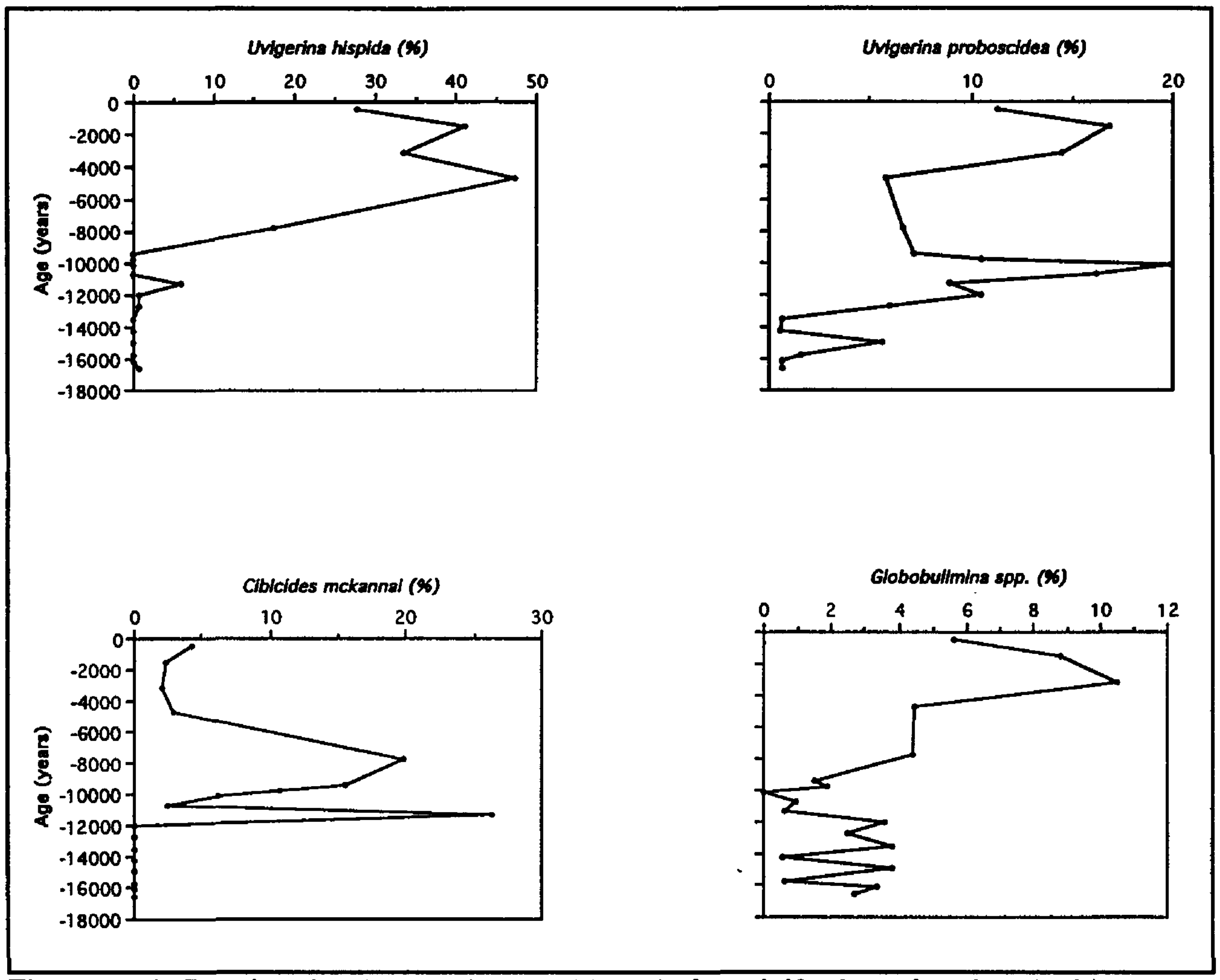

Figure 13-6.--Relative abundances of selected benthic foraminiferal species plotted with age.

Interestingly, while low-oxygen conditions are usually associated with high total organic carbon (TOC) content in the sediments (Bernhard, 1986; Gooday, 1994), the trend does not appear to be true in this core (Gardner, unpublished data; Figure 13-7). The benthic foraminiferal fauna suggests a switch from oxygen-minimum conditions in the lower half of the core to more oxic conditions above, while the TOC content shows a steady increase upcore. The TOC content of the surface sediments were similarly found to "mimic" the oxygen concentration in the oxygen-minimum zone off Big Sur (Vercoutere and others, 1987). In core F8-90-G21, this

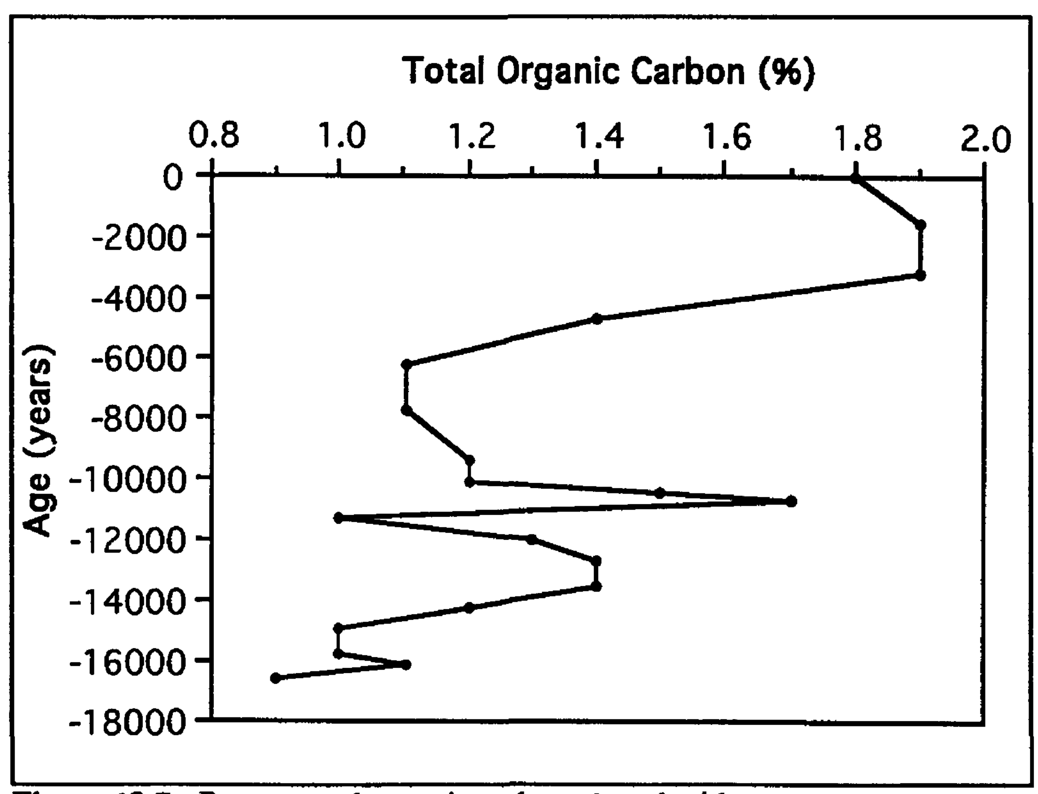

Figure 13-7.--Percent total organic carbon plotted with age.

negative association is particularly evident in the abundance curves of *Uvigerina peregrina* and the TOC content in the sediments (Figure 13-5 and Figure 13-7), in contrast to the trend found by Quinterno and Gardner (1987) off the Russian River. However, as with that study, the abundance of *U. proboscidea* in this core correlates extremely well with the TOC content (Figure 13-6 and Figure 13-7). Such variable results suggests that the oxygen content in the water column and within the pore waters at the core site, not the organic carbon, is the limiting factor in the distribution of benthic foraminifers in this core.

In conclusion, it would appear that paleoceanographic conditions changed dramatically off central California in the vicinity of this core over the last 16,000 years. During the last glacial, an oxygen-minimum existed at depth, overlain by cool (<0.8°C) subpolar to polar waters. At approximately 14,000 years B.P., deglacial warming began, eventually warming the surface waters to a relatively warm 8-12°C. Although considerably delayed (≈10,500-9,000 years B.P.), the bottom waters followed by becoming more oxic. The apparent presence of a Younger Dryas-like event in core F8-90-G21 may be simply a result of the substantial increase in the fragmentation of foraminiferal tests during the last 12,000 years, rather than a direct result of climate.

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Marine Diatom Studies for the Correlation of the Marine and Terrestrial Records of Climate (CMTR) Project:

Eileen Hemphill-Haley

To date, marine diatoms have been analyzed in a series of cores forming a north-south transect in the California Current. Pertinent cores include TT197-G330 (~39°N, Point Arena); L13-81-G138, V1-80-P3, L13-81-G145, L13-81-G117 (~38.5°N, Russian River slope); F8-90-G25 (~37°N, Farallon slope); F2-92-P3, F2-92-P34, F2-92-P11 (~35°N, Santa Lucia margin); and ODP Site 893A (~34°, Santa Barbara Basin). The diatom data indicate (1) broad paleoecological changes between interglacial, glacial, and interstadial periods spanning approximately the last 45,000 yr, (2) more vigorous coastal upwelling during latter part of Oxygen-Isotope Stage 3 relative to Stage 2 or the Holocene, and (3) at least seasonal incursions of subtropical diatoms along the length of the California Current beginning about 12,000 yr B.P.

Diatoms were analyzed in detail in core F2-92-P3, but preservation was found to be poor throughout most of core. Comparison with other cores from the south-central California margin showed that preservation is poor due to severe dissolution in bioturbated sediment in all cores south of about 35°N. However, laminated intervals, and isolated sections of bioturbated sediment, contain abundant diatoms. Several of the F2-92 cores (*e.g.*, P40, P51, P18) include extensive laminated sections in which diatom preservation is excellent, and for which analyses will likely be informative. Diatom concentrations, dominated by the upwelling group *Chaetoceros* spp., exceed 1×10^6 diatoms/g dry sediment between 180-210 cm in core F2-92-P3 (Figure 14-1). This suggests an episode of intense coastal upwelling approximately 13-14,000 yr B.P., and correlates to occurrences of laminated sediment and high diatom fluxes in F2-92-P40 and Site 893A, and possibly to several other cores for which ^{14}C data are not yet available. A narrow zone of laminations between 204-214 cm in F2-92-P3 is about 20 cm below the interval of highest diatoms concentrations, suggesting the possibility that an originally thicker zone of laminated sediment could have been disrupted by post-depositional bioturbation.

Evidence for stronger wind stress and coastal upwelling during late Stage 3 off northern California is suggested by comparing diatoms in core TT197-G330 off Point Arena (~39°N) and L13-81-G117 off the Russian River (~38.5°N). Laminated sediments in both cores were deposited approximately 40,000 yr B.P., based on conventional and AMS ^{14}C dates, and whereas laminated sediment in the Russian River core contains abundant planktonic marine diatoms, laminated sediment deposited beneath the upwelling center at Point Arena is diatom-poor. This difference can be explained by relatively fast surface-water flow generated by strong wind stress at Point Arena that restricted the growth and deposition of diatoms in the area of strongest upwelling, but resulted in high productivity and deposition of diatoms south of the upwelling center. This theory is supported by studies of modern upwelling centers in which linear correlations between areas of most intense upwelling and lowest phytoplankton biomass have been documented, with the greatest accumulation of biomass "downstream" of upwelling centers. Therefore, the diatom data from L13-81-G117 and TT197-G330 suggest more vigorous upwelling and primary productivity in the California Current preceding the transition to Oxygen-Isotope Stage 2 and global glaciation.

Documentation of diatoms from the CMTR cores distributed from Oregon to southern

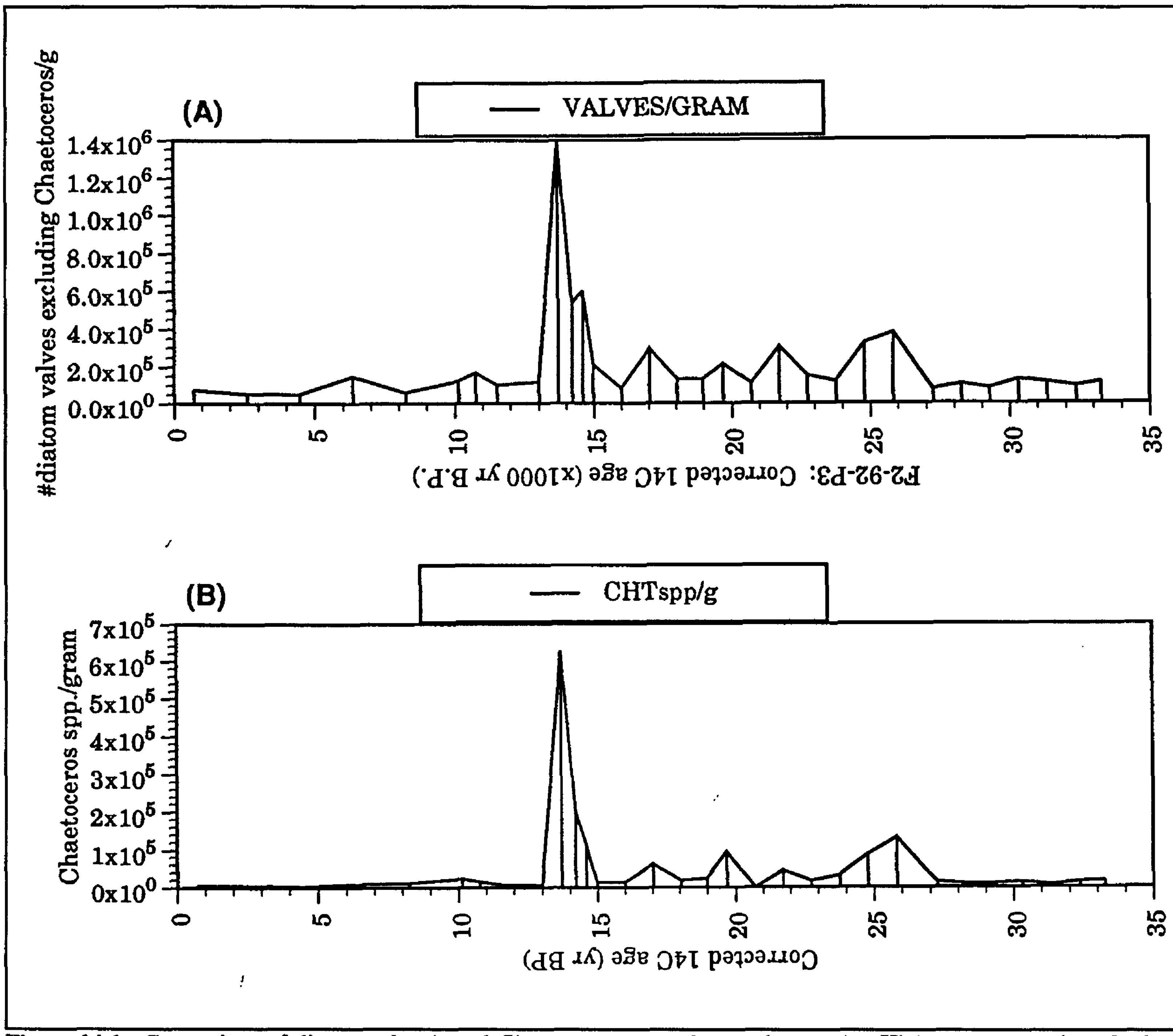

Figure 14-1.--Comparison of diatom valves/g and *Chaetoceros* spp. valves and spores/g. Highest concentrations for both groups are in the interval from 180 to 210 cm (~13-15 ka).

California indicates that the Pleistocene-Holocene transition involved the incursion of subtropical diatoms in the California Current, particularly *Fragilariopsis doliolus* (?). The first appearance of *F. doliolus* occurs about 12,000 yr B.P. in most cores, and relative abundance curves show peaks at about 9,000 yr B.P. and 4,000 yr B.P. The disappearance of *F. doliolus* at 6,000-7,000 yr B.P. may indicate a temporary return to cool, glacial-like conditions during the mid-Holocene, and correlates with terrestrial climatic records as well as a strong carbonate dissolution event in the northeastern Pacific (Karlin *et al.*, 1992). *F. doliolus* is found in all CMTR cores with moderate to good preservation, and serves as an important chronostratigraphic marker for the Quaternary in the California Current region.

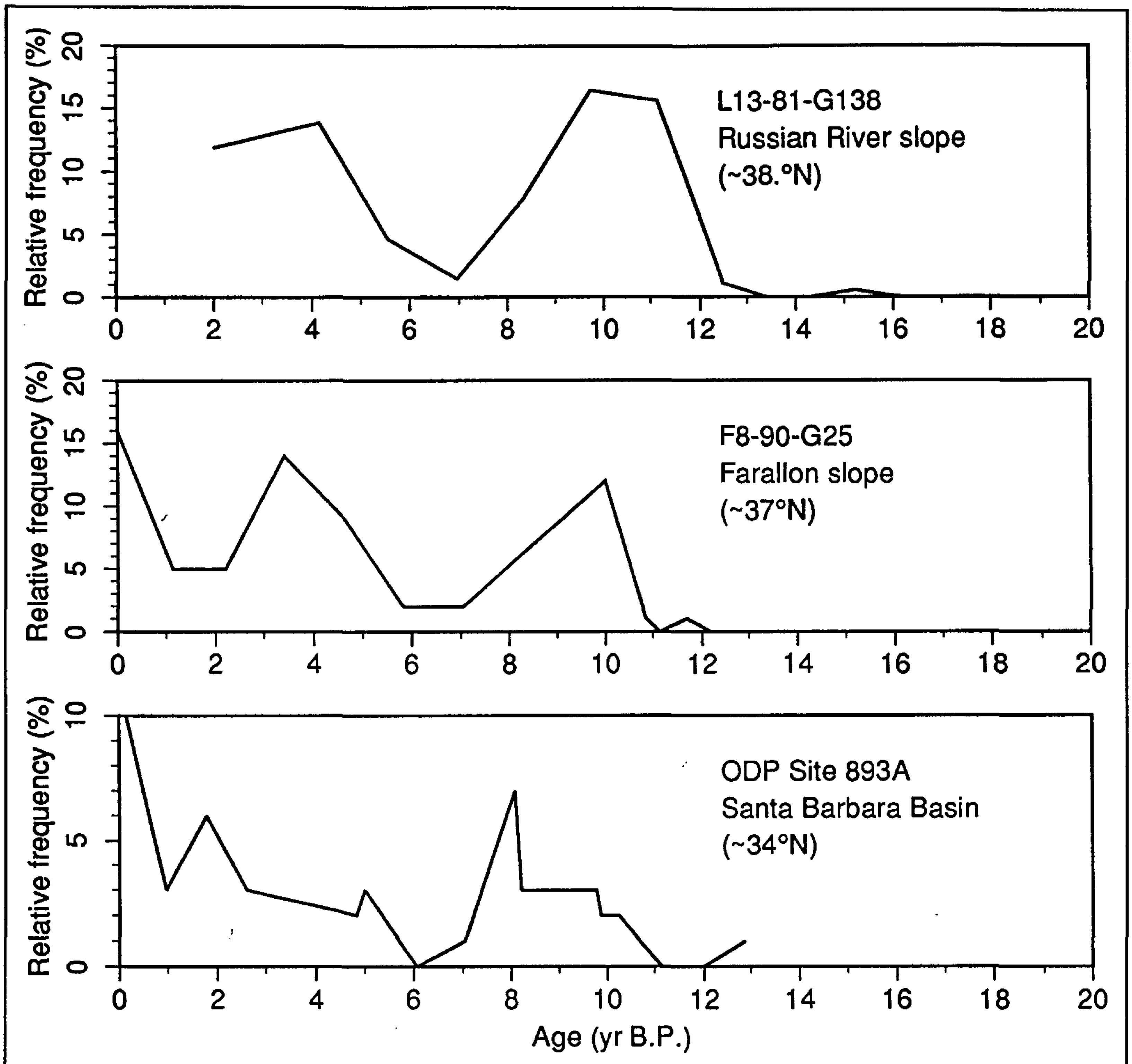

Figure 14-2.--Comparison of the subtropical diatom *Fragilariopsis doliolus* in cores L13-81-G138, F8-90-G25, and ODP Site 893A.

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