9.00
+9

Palynology of Two Upper Quaternary Cores from Clear Lake, Lake County, California

---

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1363

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" are no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Books and Open-File Reports
Federal Center, Box 25425
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Federal Center, Box 25286
Denver, CO 80225

Residents of Alaska may order maps from

Alaska Distribution Section, U.S. Geological Survey,
New Federal Building - Box 12
101 Twelfth Ave., Fairbanks, AK 99701

OVER THE COUNTER

Books

Books of the U.S. Geological Survey are available over the counter at the following Geological Survey Public Inquiries Offices, all of which are authorized agents of the Superintendent of Documents:

- **WASHINGTON, D.C.**--Main Interior Bldg., 2600 corridor, 18th and C Sts., NW.
- **DENVER, Colorado**--Federal Bldg., Rm. 169, 1961 Stout St.
- **LOS ANGELES, California**--Federal Bldg., Rm. 7638, 300 N. Los Angeles St.
- **MENLO PARK, California**--Bldg. 3 (Stop 533), Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**--503 National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**--Federal Bldg., Rm. 8105, 125 South State St.
- **SAN FRANCISCO, California**--Customhouse, Rm. 504, 555 Battery St.
- **SPOKANE, Washington**--U.S. Courthouse, Rm. 678, West 920 Riverside Ave..
- **ANCHORAGE, Alaska**--Rm. 101, 4230 University Dr.
- **ANCHORAGE, Alaska**--Federal Bldg, Rm. E-146, 701 C St.

Maps

Maps may be purchased over the counter at the U.S. Geological Survey offices where books are sold (all addresses in above list) and at the following Geological Survey offices:

- **ROLLA, Missouri**--1400 Independence Rd.
- **DENVER, Colorado**--Map Distribution, Bldg. 810, Federal Center
- **FAIRBANKS, Alaska**--New Federal Bldg., 101 Twelfth Ave.

Palynology of Two Upper Quaternary Cores from Clear Lake, Lake County, California

By DAVID P. ADAM

With a section on DATING

By STEPHEN W. ROBINSON

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1363

The climatic sequence derived from a continuous pollen record spanning the last full glacial cycle indicates several large and sudden shifts in climate during the early part of the last glacial cycle between 125,000 and 75,000 years ago.

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1988

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*

Library of Congress Catalog card No. 88-600599

For sale by the Books and Open-File Reports Section,
U.S. Geological Survey, Federal Center, Box 25425, Denver, CO 80225

CONTENTS

ILLUSTRATIONS

[Plates are folded in pocket]

TABLES

PALYNOLOGY OF TWO UPPER QUATERNARY CORES FROM CLEAR LAKE, LAKE COUNTY, CALIFORNIA

By David P. Adam

ABSTRACT

Clear Lake occupies a structural depression near the south end of the northern California Coast Ranges at an elevation of 404 m. Eight sediment cores were taken from the lake in 1973; the palynology of cores 4 and 7 is reported here. Core 4 is 115.21 m long and is interpreted to cover the entire last glacial cycle. Core 7 is 27.43 m long and covers at least the last 40,000 radiocarbon years.

The pollen records of cores 4 and 7 are dominated by oak, pine, and TCT (Taxodiaceae, Cupressaceae, and Taxaceae) pollen types, which together account for between 75 and 99 percent of the pollen in each sample. Aquatic and riparian pollen types are also numerous in parts of core 7.

The present vegetation around Clear Lake consists of oak woodland; mixed coniferous forest is found at higher elevations in the mountains. The present pollen rain into Clear Lake is dominated by oak. During the cooler parts of the last glacial cycle, oak pollen in the sediments of Clear Lake was largely and at some times entirely replaced by coniferous pollen (mostly pine and TCT) in response to climatically caused vertical displacements of vegetation belts.

Eucalyptus tracer pollen was added to each sample before processing and counting. For the core 4 samples a technique using two exotic tracer grains (*Eucalyptus* and *Lycopodium*) was used to calculate two independent estimates of the concentrations of the three major pollen types. A Q-mode factor analysis was used to separate variations caused by changes in pollen concentrations from variations produced by errors in the amount of tracer pollen added to the samples. Comparison of pollen percentage data and pollen concentration data for the core 4 record shows that the percentage data are in most cases equivalent to the concentration data, but a few differences are noted.

Pollen counts consisted of at least 200 grains of all fossil pollen; 10 algal types were also counted outside the pollen sum. One hundred twenty-one variables (including tracers) were counted; these were reduced to 51 composite variables prior to analysis by lumping together selected types. The pollen data were further reduced in dimensionality by a Q-mode factor analysis. Five factors were defined that account for over 98 percent of the variance: three summarize aspects of the behavior of the regional forest vegetation around Clear Lake, and two summarize the behavior of the aquatic and swamp vegetation of the lake itself.

Zoning of the pollen diagrams was done using an iterative algorithm that minimizes the total sums of squares of the factor loadings within zones. Twenty-one pollen zones are defined for core 4, and 4 are defined for core 7. The zones were compared to each other using mean-linkage cluster analysis.

The pollen zones of core 4 are used to propose a series of informal climatic units that include the time interval from the end of the penultimate (= Illinoian) glaciation to the present. The major units proposed are (1) the Tsabal cryomer, equivalent to marine oxygen-isotope stage 6 and the Illinoian glaciation of the midcontinent; (2) the Konocti thermomer, equivalent to oxygen-isotope substage 5e; (3) the Pomo cryomer, equivalent to the oxygen-isotope stage 2 through substage 5d interval; and (4) the Tuleyome thermomer, which corresponds to stage 1 or the Holocene.

The Pomo cryomer is divided into three phases. The early Pomo consists of a series of five cool-to-warm oscillations that are designated the Tsiwi cryomers and the Boomli thermomers, numbered from Tsiwi 1 (oldest) to Boomli 5 (youngest). These units are correlated with deep-sea oxygen-isotope substages 5a through 5d. Middle Pomo time consists of the Cigom 1 cryomer, correlated with oxygen-isotope stage 4, and the Halika thermomers, a series of three minor warm intervals that are correlated with part of oxygen-isotope stage 3. Late Pomo time consists of the Cigom 2 cryomer and a transitional interval following it and preceding the Holocene. All of late Pomo time is correlated with oxygen-isotope stage 2.

The climatic changes of the Tsiwi cryomers and Boomli thermomers were at times quite abrupt; both sudden warmings and sudden coolings occurred. The most severe of these changes was the cooling that occurred at the end of the Konocti thermomer, when oak pollen frequencies decreased from more than 60 percent to about 25 percent in a stratigraphic interval of only 23 cm. These sudden changes were climatic catastrophes for the ecosystems that experienced them.

The record of acid-resistant algae in the sediments indicates that algal productivity was relatively high during warm intervals in the past, and that productivity increased as the lake became shallower and its thermal capacity decreased. The lake water was probably transparent during the cooler parts of the last glacial cycle, but Clear Lake has probably not been clear during the Holocene.

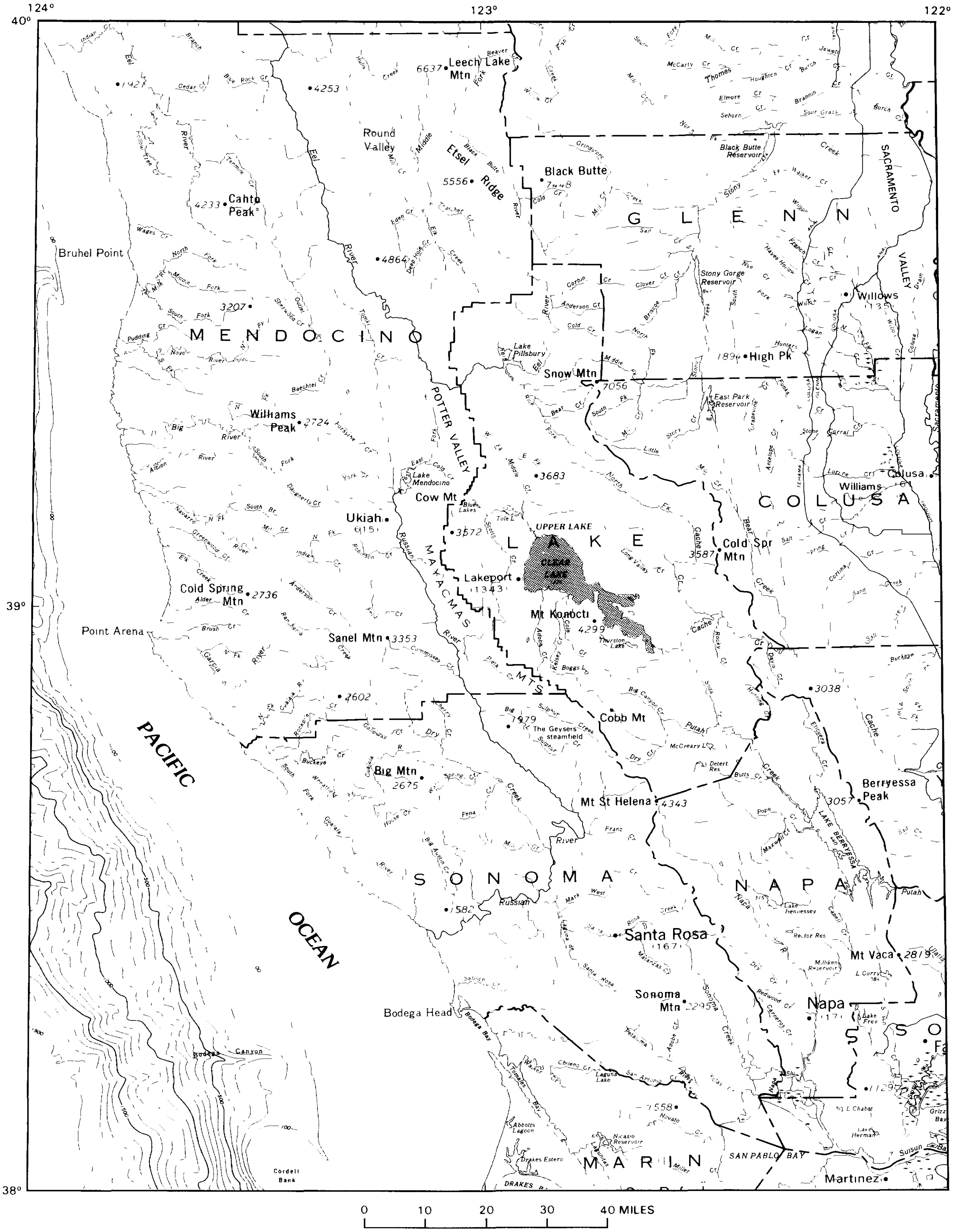
The Clear Lake pollen fluctuations correlate remarkably well with those from long cores at Grande Pile in France and Tenaghi Philippon in Macedonia, as well as with the oxygen-isotope record from deep-sea cores. Correlations with other long records, including Lake Biwa, Japan, and Sabana de Bogotá, Colombia, are not so clear. Correlation with the early Weichselian climatic sequence of northern Europe is excellent.

In North America, the Sangamonian Stage of the midcontinent area is correlated with the entire Konocti thermomer-early Pomo cryomer interval, and correlation with the glacial sequences of the Sierra Nevada and Rocky Mountains suggest that some of the deposits identified as Tahoe, Mono Basin, and Bull Lake moraines may be of Sangamonian age.

The sudden climatic changes require mechanisms in addition to the variations in orbital parameters of the earth that form the basis of the astronomical theory of climatic change. Some mechanism(s) must have threshold values which can trigger sudden shifts in climate. Major drainage shifts in the area of the developing Laurentide Ice Sheet are suggested as a possible cause for rapid changes. These might act through changing the thermal behavior of the North Atlantic Ocean or Hudson Bay.

INTRODUCTION

Clear Lake occupies a structural depression of complex origin in the northern Coast Ranges of California (fig. 1). The lake's long history has been influenced strongly by local and regional tectonism and volcanism. The present lake is the successor to many earlier lakes whose deposits



0 10 20 30 40 MILES

FIGURE 1.—Regional index map showing location of Clear Lake in northern California. For general location, see inset on figure 2. Bathymetric contours in 100-fathom intervals.

have been known collectively as the Cache Formation of Pliocene and Pleistocene age (Anderson, 1936; Rymer, 1981).

In the fall of 1973, an extensive program for coring the modern lake sediments was undertaken jointly by the U.S. Geological Survey and the Lake County Board of Supervisors. The eight cores recovered from the lake (fig. 2) contain a rich paleoecological record for the northern Coast Ranges area. One core (core 4) comprises one of the longest continuous sedimentary records of late Pleistocene events recovered within the United States as of that time.

This report presents the results of pollen analyses of cores 4 and 7. These analyses are the first pollen data for Wisconsinan events in California. They provide significant evidence for the correlation of climatic fluctuations between continental and marine environments and between the Atlantic and Pacific Oceans during the last major cycle of glaciation.

The work described here is independent of later work on cores collected in 1980. One of those cores, core CL–80–1, has been examined for diatoms by Bradbury (in press) and for pollen by L.E. Heusser (Heusser and Sims, 1981; 1983). Bradbury (in press) concludes that the lower part of the 177-m core CL–80–1 is probably correlative with the Kelseyville Formation, which is exposed south of Clear Lake (Rymer, 1981). Examination of tephra from cores CL–80–1 and CL–73–4 yields only one match; the tephra found at 67 m in core CL–73–4 is the same as the tephra found at a depth of 54 m in core CL–80–1. Other tephra layers found deeper in core CL–80–1 are not found in core CL–73–4, and one tephra at a depth of 155 m in core CL–80–1, identified as the Loleta ash bed, has an estimated age of about 360,000 years (Sarna-Wojcicki and others, in press). The limited tephra work available from the Clear Lake cores thus supports Bradbury's suggestion that there is a hiatus in core CL–80–1.

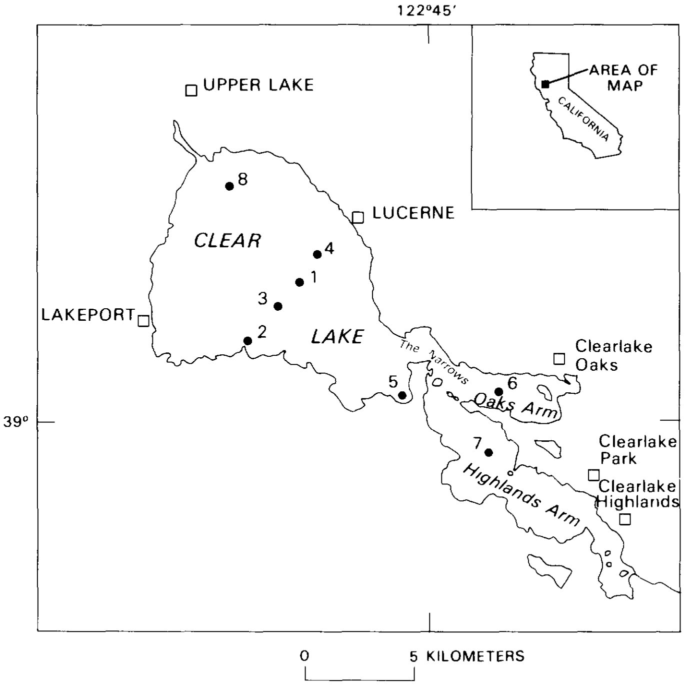


FIGURE 2.—Numbered localities of cores removed from Clear Lake in 1973 (Sims, 1976). Cores 4 and 7 were studied for this report.

I believe that no such hiatus is present in core CL–73–4. Continuity of the core is suggested by uniform very fine grain size throughout (Sims, 1982) and by a lack of weathering zones visible in either cross-sections or radiographs of the cores (Sims and Rymer, 1975c). The climatic sequence inferred from the pollen data appears to correlate remarkably well with numerous long climatic sequences elsewhere, and the timescale suggested by such correlations agrees well with age estimates based on extrapolation of radiocarbon-derived sedimentation rates (see below) and amino-acid racemization rates (Blunt and others, 1981). Also, etching of pyroxene and hornblende phenocrysts in the tephra layers in core CL–80–1, which suggests subaerial exposure of the deposits, is only observed below depths of about 115-120 m (Sarna-Wojcicki, written commun., 1983), deeper than the base of core CL–73–4. Because the tephra layer and Bradbury's correlative diatom floras found in both cores occur at a shallower depth in core CL–80–1 than in core CL–73–4, it is reasonable to infer that if correlative hiatuses are present at both sites, any resulting subaerially-exposed deposits in core CL–73–4 would also occur deeper than in core CL–80–1. If that is true, then the hiatus inferred in core CL–80–1 from such deposits would occur below the bottom of core CL–73–4. This paper therefore assumes that no significant hiatus exists in core CL–80–4. Bradbury (in press), however, feels that this assumption has not been rigorously tested.

ACKNOWLEDGMENTS

Drilling operations and overall supervision of the Clear Lake project were carried out by J.D. Sims. Core sampling and record keeping by C.K. Throckmorton and technical assistance by M.J. Rymer, R.L. Oscarson, Richard Carr, Marie Jackson, and John Olsen are acknowledged. Pollen extractions were done under the supervision of P.J. Mehringer, Jr., at the Laboratory of Anthropology at Washington State University, Pullman.

DESCRIPTION OF THE AREA

GEOGRAPHY AND CLIMATE

The geography of the Clear Lake area is summarized by Hopkirk (1973) and Lallatin (1975). The lake surface is at an elevation of 404 m, and the lake is divided into three parts by The Narrows (fig. 2). The main basin of Clear Lake is to the north of The Narrows; it is the largest of the basins and also the shallowest, with an average depth of only about 9 m (Sims, 1976). To the east and southeast of the Narrows are two smaller basins with maximum depths of as much as 13 m. The eastern basin is here informally called the Oaks Arm, after the town of Clearlake Oaks at its east end, and the southeastern basin is referred to as the Highlands Arm, after the town of Clearlake Highlands. The modern outlet of Clear Lake is at the southeast end of the Highlands Arm.

Water levels of Clear Lake for the period between 1874 and 1900, when there was no dam at the outlet of the lake, varied from a high of 33.92 m (arbitrary datum) in January 1890, to a low of 29.84 m in October 1899 (Chandler, 1901), a range of 408 cm. The lowest annual mean water level recorded was 30.21 m (1899). The two highest annual means reported, both near 32.46 m (1878 and 1895), were for years in which data were missing for the months that are normally characterized by low water levels; the highest mean annual water level using data for a full year was calculated as 31.90 m (1876). These data indicate that, under present climatic conditions and with the present configuration of the lake outlet without the dam, mean annual lake levels would fluctuate within about a 2-m range, and extreme high water would not rise more than about 5 m above extreme low water.

The Clear Lake basin has a drainage area of about 1370 km^2. The Mayacmas Mountains, on the west and south edges of the Clear Lake drainage, separate the region from the Russian River drainage and the Pacific Ocean, 50 to 80 km to the west (fig. 1). Elevations along the crest of the Mayacmas Mountains range from 600 to 1,440 m; to the south and west of the lake, only Cobb and Cow Mountains, both in the Mayacmas Mountains, and Mt. Konocti, just south of Clear Lake, have elevations greater than 1,200 m. To the north, elevations are generally more than 1,200 m, and the elevation of higher ground is commonly more than 1,500 m.

The Clear Lake area has a Mediterranean climate, with wet winters and dry summers. Summary temperature and precipitation data for Upper Lake Ranger Station and for Lakeport (fig. 3) are from sites near the lake. Mean annual temperatures are 13.2 °C and 13.7 °C; July is the warmest month and January the coldest. The diurnal temperature range is greater in summer than in winter. Annual precipitation is from 70 to 80 cm, nearly all of which occurs between October and April. A description of the climate of the Clear Lake area in relation to nearby areas is given by Major (1977), who shows evapotranspiration data for a transect from Point Arena to Williams across the northern Coast Ranges that includes two sites adjacent to Clear Lake (Lakeport and Clear Lake Park). According to his calculations, virtually no available soil moisture remains at the end of the summer season each year.

GEOLOGY

The regional geologic and tectonic setting of the Clear Lake area is described by McLaughlin (1981). The oldest rocks in the Clear Lake area belong to both the Mesozoic and Tertiary Great Valley sequence and the Franciscan assemblage. These rocks are deformed, partly metamorphosed, and uplifted as a result of interaction between the west edge of the North American plate and the Pacific and Farallon plates (fig. 4). Overlying these rocks are Paleocene and Eocene rocks exposed to the south of Lower Lake (Brice, 1953).

The Clear Lake basin itself is the result of an extensional tectonic regime associated with the San Andreas fault system and is probably less than 3 Ma old (McLaughlin, 1981). A thick series of alluvial and lacustrine sediments of Pliocene and Pleistocene age have been deposited within the Clear Lake Basin and ancestral basins. These deposits are designated the Cache Formation by Becker (1888), Anderson (1936), and Brice (1953). Rymer (1981) divides the Cache Formation into three units. The oldest unit, for which Rymer retains the name Cache Formation, is of Blancan (Pliocene and Pleistocene) age and is exposed along the North Fork of Cache Creek east of Clear Lake. Overlying the restricted Cache Formation is the rhyolitic tuff of Bonanza Springs of Hearn and others (1976). Rymer names the next youngest unit the Lower Lake Formation; it is of Pleistocene age, is locally at least 130 m thick, and crops out to the southwest of the restricted Cache Formation. Lacustrine and fluvial beds included in the Cache Formation by some geologists (California Department of Water Resources, 1957; McNitt, 1968) are named the Kelseyville Formation by Rymer (1981). The Kelseyville Formation is not exposed in contact with the older units and is found only on the west side of the Clear Lake volcanic field, about 10 to 20 km west of the nearest exposure of the Lower Lake Formation. Plant macrofossils and pollen recovered from the Kelseyville Formation lead Rymer (1981) to infer a late Illinoian age for the top of the Kelseyville. The upper part of the Kelseyville Formation is probably equivalent in age to lacustrine sediments of Clear Lake that are found below the base of core 4 (Rymer, 1981; Sims and others, 1981a). The base of the Kelseyville overlies volcanic units with K-Ar ages that range from 0.53 ± 0.02 to 0.64 ± 0.03 Ma (Rymer, 1981). Overlying the Kelseyville Formation (probably conformably) are the sediments of modern Clear Lake. Whether or not these sediments should be considered a separate unit from the Kelseyville Formation is not clear.

Extensive volcanic activity occurred episodically in the Clear Lake region during the past several million years.

Early activity produced the Sonoma Volcanics of Miocene and Pliocene age (fig. 4), which were deposited well to the south of the Clear Lake basin before 2.9 Ma. Younger volcanic rocks that comprise the Clear Lake Volcanics (Donnelly-Nolan and others, 1981) have been erupted in the southern part of the Clear Lake basin during the past 2 m.y. McLaughlin (1981) attributes the change from Sonoma Volcanics to the Clear Lake Volcanics to the passage of the Mendocino triple junction beneath the Clear Lake area, whereas Hearn and others (1981) prefer to explain the northward shift in volcanism through time to the passage of the North American plate over a mantle plume or hot spot. Past volcanism also produced the Geysers steam field, southwest of Clear Lake. Donnelly-Nolan and others (1981) emphasize that future volcanic activity in the Clear Lake region is probable, although the

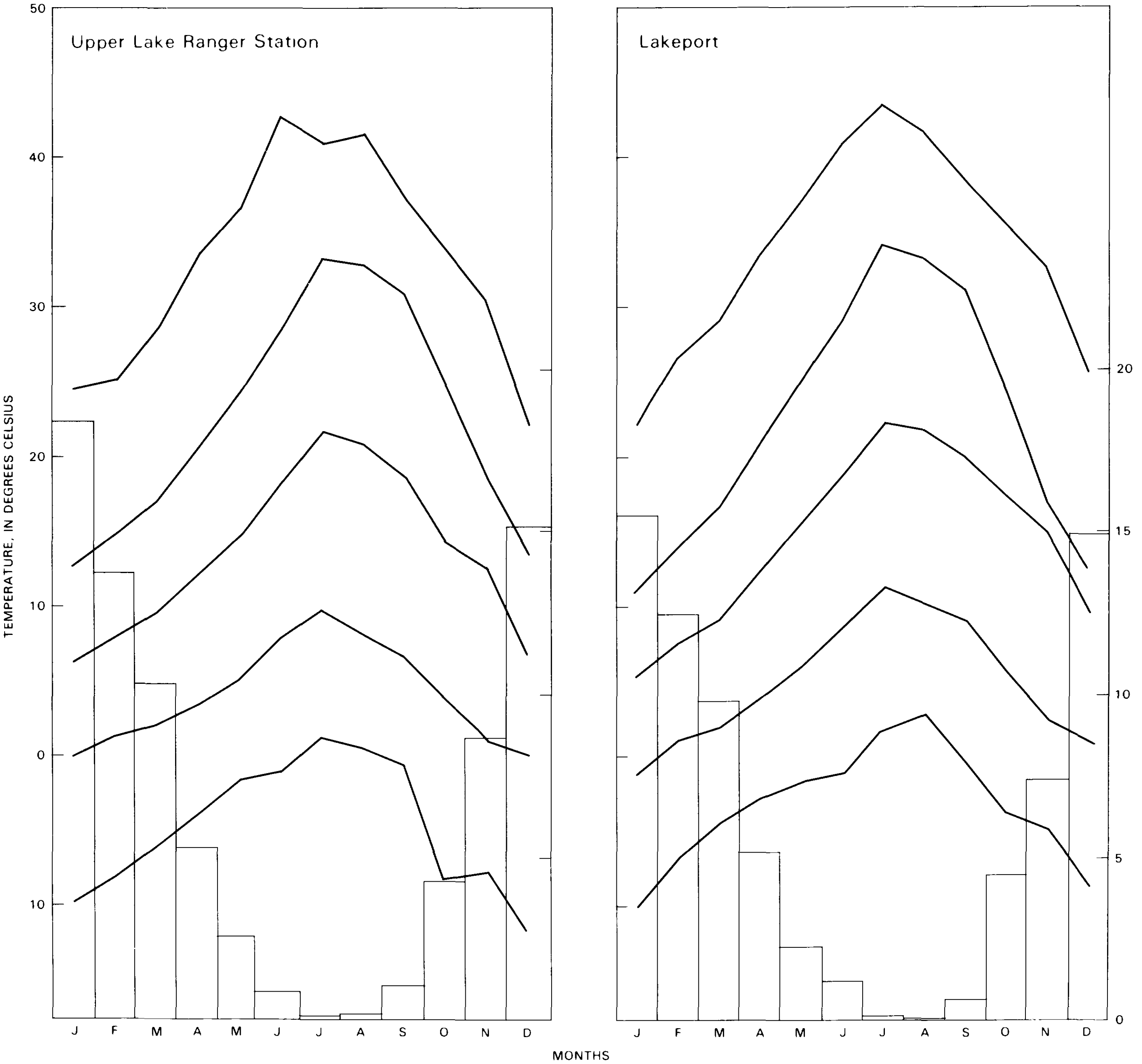


FIGURE 3.—Monthly average climatic data for Upper Lake Ranger Station and Lakeport. Data are from U.S. Department of Commerce (1964). Temperature data (shown by curves) are for a 17- to 19-year period ending in 1960; precipitation data (shown by bars) for Upper Lake Ranger Station are for a 58-year period ending in 1960, and precipitation data for Lakeport are standard climatic normal values for the period 1931–60. Temperature curves, from top to bottom, are maximum recorded temperature, mean monthly maximum, monthly mean, mean monthly minimum, and minimum recorded value.

episodic nature of past eruptive sequences makes prediction of the timing of future eruptions difficult. Further details on the geologic and geophysical setting of the Clear Lake area, and especially of the Geysers steam field, may be found in the volume by McLaughlin and Donnelly-Nolan (1981).

The Cenozoic geologic history of the northern Coast Ranges is summarized by Wahrhaftig and Birman (1965). The Clear Lake basin is just to the south of the southernmost-known Pleistocene glacier in the Coast Ranges, on Snow Mountain (fig. 1), where a small glacier had a cirque floor at an elevation of 1,700 m (Holway, 1911; Davis, 1958).

GEOMORPHOLOGY

The geomorphology of the Clear Lake basin is strongly controlled by geologic structure and by volcanic explosion and collapse features, cones, and lava flows. Mt. Konocti, the most prominent feature of the Clear Lake volcanic field, is a composite volcano less than one-half million years old that rises abruptly from the south shore of Clear Lake (Donnelly-Nolan and others, 1981).

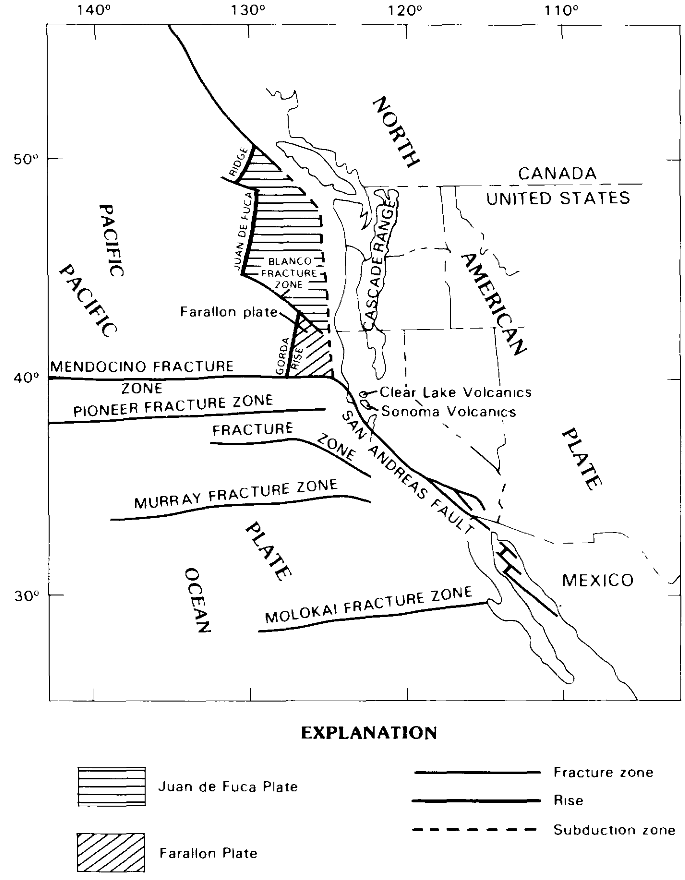


FIGURE 4.—Map showing location of Clear Lake with respect to the North American, Pacific, and Farallon plates. Adapted from Mankinen and others (1981, fig. 46).

Local faulting is dominantly northwest-southeast and follows the primary structural orientation of the underlying Franciscan (Jennings and Strand, 1960; Koenig, 1963). Faults are inferred to control shoreline orientation in the Oaks and Highlands Arms of Clear Lake (Hearn and others, 1975), and fault control of the main basin of Clear Lake was demonstrated by Sims and Rymer (1976a). Movement along faults bounding the lake may relate to the Quaternary volcanic activity described above. These fault movements have maintained the lake basin, resulting in a long-term record of Quaternary sedimentation (Rymer, 1981).

The geomorphic history of the Clear Lake basin is not clearly understood. Volcanic, tectonic, and climatic events and landslides have all affected the area, but it is not always possible to determine which events produced significant geomorphic changes or features.

The complexity of events at Clear Lake is illustrated in the explanation given by Davis (1931, 1933; see also Holway, 1907, and Hutchinson, 1957), who stated that the main body of the lake was originally a valley that drained west to the Russian River through the present site of Blue Lakes and upper Cold Creek, while the Oaks and Highlands Arms were valleys that drained to the east through Cache Creek. At an unspecified time, the Cache Creek drainage was blocked by a lava flow, ponding the Oaks and Highlands Arms and reversing their drainage into the valley now occupied by the main part of Clear Lake. At a later date, which Davis (1933) estimated as only a few hundred years ago, Cold Creek canyon was blocked by a large landslide, and this blockage restored the drainage into Cache Creek and formed Blue Lakes.

In the present study, the cores recovered from Clear Lake show that Clear Lake has been a lake for at least the past 130,000 years, and subsequent work by Heusser and Sims (1981) has extended the record to 175,000 years or more, confirming the view of Hinds (1952) that the lake is quite old. The lava flow that Davis claimed now dams the Clear Lake outlet is in fact only limonite-stained lake sediment, so parts of Davis's model are untenable (Donnelly-Nolan and others, 1981). However, modern fish distributions suggest that Clear Lake did once drain into the Russian River (Holway, 1907; Snyder, 1908; Hopkirk, 1973), and the landslide noted by Davis was probably the cause of a drainage reversal.

Cores from the Oaks and Highlands Arms of Clear Lake show that these parts of the lake have been deep-water areas only during the Holocene and latest Wisconsinan (Sims, 1976; Sims and others, 1981a). Before about 11,000 radiocarbon years ago, these areas were shallow-water swamps, and this suggests that tectonic activity has played an important part in determining local geomorphology.

The Clear Lake basin may at times have drained through outlets other than Cold Creek and the present Cache Creek outlet. Present topography and the tectonic changes inferred from changes in water depth in the Oaks and Highlands Arms of the lake lead to the speculation that Clear Lake may also have drained into the North Fork of Cache Creek near Clearlake Oaks at the east end of the Oaks Arm, as well as at some time into Putah Creek to the southeast.

LIMNOLOGY

The limnology of Clear Lake is described by Goldman and Wetzel (1963) in a study of the primary productivity of the lake and chemical composition of the water. They describe the lake as turbid and eutrophic, with moderately high salinity and hard water. The long fetch of the predominantly westerly winds across the lake generates enough turbulence to keep the entire water column mixed under most circumstances. The most abundant cations in the water follow the order $Ca>Mg>Na>K$; anions are dominated by bicarbonate, with $CO_3>Cl\geqslant SO_4$ (bicarbonate converted to carbonate). The primary productivity is mainly the result of algal growth because the high turbidity of the lake restricts higher plants to littoral habitats around the edge of the lake. The pH during the period from May 1959 to July 1960 varied between about 7.5 and 8.9.

Areal and average depth data for the three lake basins (Horne and others, 1971) are used to calculate volume estimates (Table 1). The area of the three arms of the lake is about 172.2 km^2 and the total volume is nearly 1.4 km^3. Because the main basin of the lake is shallower than the Oaks and Highlands Arms, it is relatively more significant in terms of surface area than in terms of volume.

ZOOGEOGRAPHY

The major study of the zoogeography of the Clear Lake region is on endemism in Clear Lake fish (Hopkirk, 1973). Hopkirk recognizes 14 native fish species, of which 5 are endemic lake-adapted derivatives of lowland river species. He also notes the presence of three endemic aquatic snails in the basin. Hopkirk (1973, p. 10) feels that "the extent of morphological differentiation in the endemic fishes of Clear Lake Basin indicates an age of many thousands of years for the lake." Comparison of the fish faunas of the Russian and Sacramento River drainages indicates that Clear Lake at some time drained into the Russian River through Blue Lakes and Cold Creek (Snyder, 1908; Hopkirk, 1973).

PHYTOGEOGRAPHY

The Clear Lake basin is at the south end of the main mountain mass of the inner Coast Ranges, so that high-elevation vegetation has ready access to the basin during times of cooler climate. The major potential paths of plant migration to and from lower elevations are to the east, through the Cache Creek canyon, which forms the modern outlet of Clear Lake, and through the Putah Creek drainage to the southeast. During warm periods, these routes provide for the rapid reestablishment of plant species displaced from the Clear Lake basin during cool periods, particularly oaks (*Quercus* spp.). Another access corridor to low elevations, probably of only minor biogeographic importance, is the canyon now occupied by Blue Lakes and upper Cold Creek.

The Clear Lake basin is in the Californian Floristic Province; this province includes parts of coastal Oregon, most of California, and parts of Baja California, Mexico (Raven, 1977). The flora is quite diverse; Raven (1977, p. 111) estimates that there are about 770 genera and 4,437 species of native vascular plants in the province, which has an area of about 324,000 km^2. The Clear Lake basin is at the north end of the Central Coast subdivision of the Californian Floristic Province of Stebbins and Major (1965). The boundary between the Central Coast and North Coast subdivisions runs through central Lake County along the south edge of the continuous pine-hardwood forest. Stebbins and Major recognize an important center of endemism in southern Lake and northern

TABLE 1.—*Area, depth, and volume of the three basins of Clear Lake*

[Areas and average depths from Horne and others (1971); other values calculated]

	Area (ha)	Area (pct.)	Average depth (m)	Volume km^3	Volume (pct.)
Main basin--------	12,700	73.75	7.1	0.902	65.47
Oaks Arm----------	1,250	7.26	11.1	.139	10.07
Highlands Arm----	3,270	18.99	10.3	.337	24.46
Total	17,220	100.00	8.0	1.378	100.00

Napa Counties and note that many of the soils in the area are formed on young volcanic rocks and are poorly developed.

DISTRIBUTION OF MAJOR VEGETATION TYPES

Vegetation maps that include the Clear Lake area include those of Clark (1937), Küchler (1964, 1977), Livingston and Shreve (1921), Benson (1957), and Knapp (1965); of particular interest are the species distribution maps in Little (1971, 1976), Fowells (1965), and Griffin and Critchfield (1972). The maps by Küchler (1964, 1977) describe the potential natural vegetation, that is, the vegetation that would ultimately prevail under the present climate in the absence of human influence. He recognizes four major vegetation types in the Clear Lake basin: (1) blue oak-digger pine forest (oak woodland in this paper); (2) mixed hardwood forest; (3) chaparral; and (4) Coast Range montane forest (Küchler, 1977).

The most recent version of the potential natural vegetation map (Küchler, 1977) shows Clear Lake surrounded by a belt of blue oak-digger pine forest several kilometers wide, except that chaparral is mapped along the south shore of the lake between Soda Bay and the outlet at Cache Creek. From the south shore of the lake, the chaparral extends southwest to the crest of the Mayacmas Mountains and then northwest along the crest of that range as far north as Blue Lakes. Northeast of the lake, a band of chaparral several kilometers wide lies above the blue oak-digger pine forest. Above the chaparral in this area is found the southernmost mapped patch of Coast Range montane forest. A small patch of mixed hardwood forest is mapped between 10 and 20 km south of the outlet of Clear Lake along the upper reaches of Putah Creek. The broad band of redwood forest that extends along the California coast does not extend inland far enough to affect the Clear Lake basin, although a few small stands are found along the Russian River in the next major valley to the west. At elevations below about 100 m, the blue oak-digger pine forest gives way to a valley oak savanna in the Santa Rosa-Healdsburg area to the south of Clear Lake and to California prairie in the Sacramento Valley to the east, but these vegetation types are not found in the Clear Lake basin itself.

Küchler (1964) shows the potential distribution of chaparral in the Clear Lake area as including the entire Mayacmas Range and the low ground between it and Clear Lake, with the single exception of an area of mixed coniferous forest extending from the outlet of Clear Lake to the top of Cobb Mountain. By contrast, Clark (1937, fig. 1) maps most of the low land within the Clear Lake basin as woodland and maps chaparral only as a narrow band along the ridgetops. Küchler's 1977 map shows chaparral reaching the shores of Clear Lake only along the west shore of the Highlands Arm.

OAK WOODLAND

The oak woodland found in the Clear Lake basin is mapped as blue oak-digger pine forest by Küchler (1977). California oak woodland in general is discussed by Griffin (1977), who notes that:

> Oak woodland can be viewed as a group of variable communities geographically placed between grassland or scrub and montane forests. The xeric lower border of oak woodland is easily defined by the absence of oak trees—where the savanna form of oak woodland becomes true grassland or scrub. The mesic upper border, where the increasingly dense woodland becomes forest, is more difficult to establish. The presence of the appropriate woodland indicator oaks is as important as the actual tree density. Where the proportion of live oaks becomes great, the oak woodland can be only arbitrarily separated from interior forms of the mixed hardwood forest ***. Often the upper woodland border is obscured by a chaparral zone between the typical woodland and the forest above (Griffin, 1977, p. 385).

MIXED HARDWOOD FOREST

The California mixed hardwood forest is dominated by *Arbutus menziesii* (madrone), *Chrysolepis chrysophylla* (golden chinquapin), *Lithocarpus densiflora* (tanbark oak), *Pseudotsuga menziesii* (Douglas fir), *Quercus chrysolepis* (canyon oak), *Quercus wislizenii* (interior live oak), and *Umbellularia californica* (California laurel); other components include *Acer macrophyllum*, *Aesculus californica*, *Corylus californica*, *Arctostaphylos manzanita*, *Ceanothus* spp., *Cornus nuttallii*, *Quercus douglasii*, *Q. garryana*, and *Q. kelloggii* (Küchler, 1964, 1977; Munz and Keck, 1959). Average annual rainfall ranges from 60 to 150 cm, and the maximum elevation is about 750 m (Munz and Keck, 1959).

CHAPARRAL

The chaparral vegetation type, which is well developed in California, is described by Küchler (1964, p. 33) as "very dense vegetation of broadleaf evergreen sclerophyll shrubs." It is dominated by *Adenostoma fasciculata* (chamise), *Arctostaphylos* spp. (manzanita), and *Ceanothus* spp.; other species include *Cercocarpus betuloides*, *Fremontia californica*, *Heteromeles arbutifolia*, *Pickeringia montana*, *Prunus ilicifolia*, *Quercus dumosa*, *Rhamnus californica*, *R. crocea*, and *Trichostema lanatum* (Küchler, 1964). Chaparral generally grows on dry slopes and ridges; average annual precipitation ranges from 35 to 64 cm, summers are hot and dry, and winters are cool but not cold (Munz and Keck, 1959, p. 17).

COAST RANGE MONTANE FOREST

The Coast Range montane forest has not been described in as much detail as the oak woodland, mixed hardwood forest, and chaparral. Küchler (1977) maps Coast Range montane forest at upper elevations between central Lake

TABLE 2.—_Tree and shrub species growing in or near Lake County, California_

[Names preceded by an asterisk are not recorded as growing in Lake County on distribution maps used to compile table, but they are found just beyond borders of county or are otherwise significant for interpretation of the Clear Lake pollen record. Four sources were used: 1, Little (1976); 2, Griffin and Critchfield (1972), which includes some annotation and is the most detailed in its geographic descriptions; 3, Fowells (1965), which includes ecological requirements but is rather general in terms of geographic distributions; and 4, Little (1971). Taxonomic nomenclature has been adjusted to conform to that used by Munz and Keck (1959) and Munz (1968). This list is not complete, especially with regard to shrubs]

Family		References
	Conifers	
Cupressaceae	_Cupressus macnabiana_ A. Murr.	2,4
	C. sargentii Jeps.	2,4
	Juniperus californica Carr.	4
	J. occidentalis Hook. ssp. _australis_ Vasek	2,3,4
	Calocedrus decurrens (Torr.) Florin	2,3,4
	Thuja plicata Donn ex D. Don in Lamb.	2,3,4
Pinaceae	_Abies concolor_ (Gord. & Glend.) Lindl.	2,3,4
	A. grandis (Dougl.) Lindl.	2,3,4
	A. magnifica A. Murr.	2,3,4
	A. procera Rehd.	2,3,4
	Pinus attenuata Lemmon	2,4
	P. balfouriana Grev. & Balf.	2,4
	P. jeffreyi Grev. & Balf. in A. Murr.	2,3,4
	P. lambertiana Dougl.	2,3,4
	P. monticola Dougl.	2,3,4
	P. ponderosa Lawson	2,3,4
	P. sabiniana Dougl.	2,4
	Pseudotsuga menziesii (Mirb.) Franco	2,3,4
	*_Tsuga heterophylla_ (Raf.) Sarg.	2,3,4
Taxaceae	_Taxus brevifolia_ Nutt.	2,4
	Torreya californica Torr.	2,4
	*_Sequoia sempervirens_ (D. Don) Endl.	2,3,4
	Angiosperms	
Aceraceae	_Acer circinatum_ Pursh	1
	A. macrophyllum Pursh	3,4
	A.negundo L. ssp. _californicum_ (T. & G.) Wesmael	2,4
Betulaceae	_Alnus rhombifolia_ Nutt.	1,2
	A. oregona Nutt.	2,3,4
	*_A. tenuifolia_ Nutt.	1
	Corylus cornuta Marsh. var. _californica_ (A. DC.) Sharp	1
Caprifoliaceae	_Sambucus caerulea_ Nutt.	1
Celastraceae	*_Euonymus occidentalis_ Nutt. ex Torr.	1
Cornaceae	_Cornus glabrata_ Benth.	1
	C. nuttallii Aud.	1,2
	C. occidentalis (T. & G.) Cov.	1
Ericaceae	_Arbutus menziesii_ Pursh	2,3,4
	Arctostaphylos manzanita Parry	---
Fagaceae	_Chrysolepis chrysophylla_ (Dougl. ex Hook.) Hjelmquist	2,4
	Lithocarpus densiflorus (H. & A.) Rehd.	2,3,4
	*_Quercus agrifolia_ Nee	2,4
	Q. chrysolepis Liebm.	2,4
	Q. douglasii H. & A.	2,4
	Q. garryana Dougl.	2,3,4
	Q. kelloggii Newb.	2,4
	Q. lobata Nee	2,4
	Q. wislizenii A. DC.	1,2
Hippocastanaceae	_Aesculus californica_ (Spach) Nutt.	1,2
Juglandaceae	_Juglans hindsii_ (Jeps.) Jeps.	1,2
Lauraceae	_Umbellularia californica_ (H. & A.) Nutt.	2,3,4
Leguminosae	_Cercis occidentalis_ Torr. ex Gray	1
Myricaceae	_Myrica californica_ Cham. & Schlecht.	1
Oleaceae	_Fraxinus dipetala_ H. & A.	1
	F. latifolia Benth.	2,4
Platanaceae	_Platanus racemosa_ Nutt.	1,2
Rhamnaceae	_Ceanothus cordulatus_ Kell.	---
	Rhamnus californica Esch.	1
	R. crocea Nutt. in T. & G.	1
	R. purshiana DC.	4
Rosaceae	_Cercocarpus betuloides_ Nutt. ex T. & G.	1
	Crataegus douglasii Lindl.	1
	Heteromeles arbutifolia M. Roem.	1
	Prunus emarginata (Dougl.) Walp.	1
	P. subcordata Benth.	1
	P. virginiana L. var. _demissa_ (Nutt.) Sarg.	1
	*_Sorbus californica_ Greene	1
Rubiaceae	_Cephalanthus occidentalis_ L. var. _californicus_ Benth.	1
Rutaceae	_Ptelea crenulata_ Greene	1
Salicaceae	_Populus fremontii_ Wats.	2,4
	P. trichocarpa T. & G.	2,3,4
	Salix hindsiana Benth.	1
	S. laevigata Bebb	1
	S. lasiandra Benth.	1
	S. lasiolepis Benth.	1
	S. gooddingii Ball var. _variabilis_ Ball	1
	S. tracyi Ball	1
Sterculiaceae	_Fremontodendron californicum_ Cov.	1

County and western Tehama and southern Trinity Counties, and also a few scattered occurrences as far north as central Humboldt County. The transition from a lower altitude digger pine-dominated forest to a higher ponderosa pine-dominated forest occurs at an elevation of about 1,100 m in a vegetation transect on the south side of Snow Mountain in northern Lake County (Gray, 1979). However, Gray notes that the boundary coincides with the upper limit of serpentine and is thus in part an edaphic boundary. At higher elevations in Gray's transect, sugar pine is dominant between 1,680 and 1,860 m, white fir is dominant at 1,950 m, and red fir is dominant at 2,040 m.

The Klamath Mountains flora, 135 km and more to the north of Clear Lake, includes many ecologically important tree species that do not grow in the Clear Lake region (Sawyer and Thornburgh, 1977). The vegetation of the Klamath Mountains is thus not a direct modern analog for interpreting the Clear Lake pollen record.

SIGNIFICANT SPECIES DISTRIBUTIONS

Although the vegetation types mapped by Küchler (1977) provide a helpful overview of the modern vegetation, they are of limited use in interpreting the Clear Lake fossil-pollen record, largely because of the inherent imprecision of pollen identifications and low representation of many pollen types in the pollen rain. Another view of the vegetation is available through published species-distribution maps, especially those of Little (1971, 1976), Griffin and Critchfield (1972), and Fowells (1965); table 2, a list of species that grow in Lake County, was compiled from these four atlases. A few species not presently growing in Lake County are also included, either because they have been found as macrofossils in the Kelseyville Formation (Rymer, 1981) or because their present distributions suggest that they probably grew in the Clear Lake basin during the last glacial period. The table is not complete; many shrubby species are not mapped in any of the references consulted.

Most arboreal pollen recovered from the Clear Lake cores represents three major plant groups—oaks, pines, and TCT—each with representatives in more than one of the four major vegetation types, as described below.

OAKS (*QUERCUS SPP.*)

The dominant oaks in the Clear Lake basin are *Quercus douglasii* (blue oak), which is the dominant element of the blue oak-digger pine forest, *Q. wislizenii* (interior live oak), and *Q. kelloggii* (California black oak) (Griffin and Critchfield, 1972). Blue oak tends to grow at the lowest elevations, interior live oak somewhat higher, and California black oak higher still, extending up into the lower parts of the montane coniferous forest. *Q. chrysolepis* (canyon live oak) is also common to the north of Clear Lake, and *Q. garryana* (Oregon oak) and *Q. lobata* are also found in the basin. Two shrubby species, *Q. sadleriana* (deer oak) and *Q. vaccinifolia* (huckleberry oak), are found at still higher elevations in the Klamath Mountains 130 to 200 km to the north. The altitude ranges of the oaks found in the Clear Lake basin are shown in table 3. A general discussion of the several different forms of oak woodland in California is given by Griffin (1977).

PINES

Of the five *Pinus* species in the Clear Lake area, four represent the subgenus *Diploxylon*: *Pinus sabiniana* (digger pine), *P. attenuata* (knobcone pine), *P. ponderosa* (ponderosa pine), and *P. jeffreyi* (Jeffrey pine). The only *Haploxylon* pine is *P. lambertiana*, the sugar pine.

Digger pine (*P. sabiniana*) is common on dry sites at elevations below about 1,000 to 1,500 m in the northern Coast Ranges and around the Sacramento Valley (Griffin and Critchfield, 1972). It is common to the east and south of Clear Lake and commonly occurs in association with both oak woodland and chaparral species. Digger pine does not form dense forests.

TABLE 3.—*Species of* Quercus *(oak) now growing in or near Clear Lake basin*

[Elevation ranges (Munz and Keck, 1959) are rounded to the nearest 5 m after conversion from feet]

Species (common name)	Elevation range (m)
Quercus lobata (valley oak)	<610
Q. agrifolia (coast live oak)	<915
Q. douglasii (blue oak)	<1,065
Q. wislizenii (interior live oak)	<1,525
Q. garryana (Oregon oak)	305-1,525
Q. garryana var. *breweri*	610-1,830
Q. chrysolepis (canyon oak)	<1,980
Q. sadleriana (deer oak)	945-2,135
Q. kelloggii California black oak)	305-2,440
Q. vaccinifolia (huckleberry oak)	915-3,050

The knobcone pine, *P. attenuata*, is less common than digger pine in the Clear Lake basin. According to the distribution maps of Griffin and Critchfield (1972), knobcone pine is missing from an area to the east of Clear Lake where digger pine is abundant, but it grows in small stands in the western part of the basin along the Mayacmas Mountains where digger pine is absent. They note that "In the Coast Ranges, this species forms dense stands on poor soils within the chaparral zone. Lake County has extensive areas of such frequently burned knobcone pine thickets" (Griffin and Critchfield, 1972, p. 25).

The most common pine at elevations above 1,100 m is *P. ponderosa*, a dominant species of the montane forest (Gray, 1979). To the north of Clear Lake, Griffin and Critchfield (1972) map a continuous band of ponderosa pine that covers the high ground of the northern Coast Ranges. The distribution is discontinuous in the immediate vicinity of Clear Lake, but a large stand occurs in southern Lake County. The remaining diploxylon pine, *P. jeffreyi*, is found only in a few relict stands in northernmost Lake County and is restricted in the Coast Ranges primarily to soils formed on serpentine.

The distribution of sugar pine (*P. lambertiana*) in the Clear Lake area is similar to the distribution of ponderosa pine but somewhat more restricted; sugar pine is distributed continuously only along the east side of the mountains, whereas ponderosa pine is continuously distributed farther to the west as well.

OTHER PINACEAE

The remaining member of the pine family common in the Clear Lake basin is the Douglas fir (*Pseudotsuga menziesii*). Although it is mapped in continuous stands on the mountains both north and south of Clear Lake (Griffin and Critchfield, 1972), it is poorly represented in the pollen record. Other members of the pine family are not now common in the Clear Lake area but may have been much more important during cooler periods. The two most important species of fir in California are white fir (*Abies concolor*) and red fir (*A. magnifica*). Both species are common in high elevation coniferous forests; red fir reaches its maximum development at somewhat higher elevations than white fir (Gray, 1979). Both species are important components of Küchler's (1977) Coast Range montane forest. The southern limit for both species in the Clear Lake area is on Snow Mountain, in northern Lake County. White fir is much more continuous in its distribution in the northern Coast Ranges than is red fir. An additional fir not now found in Lake County is the grand fir (*A. grandis*). Grand fir is currently found growing only within about 30 km of the coast and at elevations below about 600 m at the latitude of Clear Lake, although it extends farther inland near Eureka. Fossil needles recovered from the Clear Lake cores demonstrate that grand fir grew in the Clear Lake basin during the last glacial period.

The three California species of spruce are not found in the Clear Lake basin. The two inland species, Engelmann spruce (*Picea engelmannii*) and weeping spruce (*P. breweriana*), are found only north of about latitude 41° N. The coastal species, Sitka spruce (*P. sitchensis*), is common only along the coast north of Cape Mendocino, but a few scattered stands are found along the coast in central Mendocino County. Spruce is limited in its distribution by its inability to withstand prolonged drought (Adam, 1973a); the long, dry summers of California's Mediterranean climate prevent spruce from growing either in the Coast Ranges or the Sierra Nevada.

TCT SPECIES

The TCT pollen category is named for the families Taxodiaceae, Cupressaceae, and Taxaceae. The most important species in the forest vegetation of the northern Coast Ranges are the redwood, *Sequoia sempervirens*, and the California incense cedar, *Calocedrus* (*Libocedrus*) *decurrens*. Redwood does not grow in Lake County; it is generally confined to a belt that reaches inland no more than about 30 km along the Sonoma and Mendocino County coast. Redwood that grows farther inland in Napa County requires summer fog.

Incense cedar grows as scattered stands in the northern Coast Ranges as far south as northernmost Napa County. It is not a major component of the Coast Range coniferous forest at the present time; its major distribution in California is along the middle western slope of the Sierra Nevada. Griffin and Critchfield (1972, p. 22) note that "In the north Coast Ranges and western portion of the Klamath Ranges incense-cedar tends to be restricted to serpentine soils ***. To the east, particularly at higher elevations, incense-cedar gradually becomes less restricted to specialized soil situations and is a regular component of the Mixed Conifer Forest." In the southern Coast Ranges, incense-cedar is found between 36° N. and 36°30′ N. in the Santa Lucia Range and farther east on San Benito Mountain, and then in scattered small stands in the Transverse Ranges and south into San Diego County. These southern stands all are found south of 35° N.

The patchy distribution of incense-cedar in the Coast Ranges suggests that the present stands are relicts of a more widespread former distribution. This is supported by subfossil remains of incense-cedar foliage from below modern sea level at Mountain View, Calif., on the west margin of San Francisco Bay (Helley and others, 1972). These remains, which are associated with radiocarbon ages of 21 to 24 ka, suggest that during the last full glacial period incense-cedar may have been distributed much more continuously through the California Coast Ranges.

Two species of cypress are fairly common in Lake County, the MacNab cypress (*Cupressus macnabiana*) and the Sargent cypress (*C. sargentii*). Both favor serpentine soils, and both are generally restricted to elevations below 900 m (Munz and Keck, 1959).

Other Cupressaceae are not important today in the Clear Lake area. The California juniper, *Juniperus californica*, is listed by Munz and Keck (1959) as growing in the inner Coast Ranges as far north as Tehama County. Little (1971) mapped a single small stand to the west of Clear Lake in Lake County and a band along the eastern slope of the inner Coast Ranges from Colusa to Tehama Counties. The other two Cupressaceous genera in California, *Chamaecyparis* and *Thuja*, grow only in the northernmost part of the state.

There are only two members of the Taxaceae in California, yew (*Taxus brevifolia*) and California nutmeg (*Torreya californica*). Both are found in Lake County; California nutmeg is more common than yew, but neither one is an important component of the vegetation.

BACKGROUND AND PREVIOUS WORK

The cores studied for this report are part of a series of eight cores collected from Clear Lake by John D. Sims from June to November 1973 (Sims, 1974, 1976). Those cores are now designated formally as cores CL–73–1 through CL–73–8. Cores CL–73–1 and CL–73–2 are referred to by their full formal names to prevent any confusion with cores CL–80–1 and CL–80–2, two additional cores that were taken in 1980 (Rymer and others, 1981; Sims and others, 1981b; Sims and others, 1981c). Cores CL–73–3 through CL–73–8 will hereafter be referred to simply as cores 3 through 8. Detailed descriptions of all the 1973 cores, including color and black-and-white photographs and X-ray radiographs, are available in a series of reports by Sims and Rymer (1975a–g, 1976b). Samples removed from the cores are listed and the detailed sampling procedures are described by Beaver and others (1976). Most of the samples are as yet unprocessed.

The general stratigraphy, geochronology, and interpretation of the Clear Lake cores are described by Sims (1976) and Sims and others (1981a). Surficial sediments are nearly identical in all the cores; they represent the modern lake environment with its high algal productivity and resulting high organic content of the sediments. In cores CL–73–1 through 3, surficial lake muds are underlain by a wedge of sand and gravel that represents deltaic deposits of Kelsey Creek. The maximum observed thickness of this wedge is about 25 m in core 3. Core CL–73–2 is from the coarsest facies of the deltaic wedge;

that core did not penetrate the deltaic wedge completely, but core CL–73–1 and core 3 both passed through the wedge into underlying lake muds.

All the cores, except for CL–73–2, contain volcanic-ash layers visible either macroscopically or on the X-ray radiographs. Initial correlations between cores were made on the basis of these ash layers, using such correlation criteria as ordinal position, visual or radiographic appearance, thickness, and the occurrence of multiple layers (Sims, 1976). Subsequent studies show that the pollen stratigraphy from core 4 correlates quite closely with that from core 7, but the correlations based on pollen conflict with those based on ash layers. Sims and others (1981a) thus reject the ash correlations; they offer two possible explanations for the failure of the method. First, many of the ashes may represent local phreatomagmatic explosions. Such ashes could be of very limited extent and might be missing from some cores. Second, the drainage of Kelsey Creek includes many outcrops of tuffaceous beds, and runoff may have produced reworked tuff layers that are now indistinguishable from primary ash falls in some cores.

Core 4 was studied for paleomagnetism by J.W. Hillhouse. Because oriented cores were not collected, only changes in inclination could be studied. No paleomagnetic events were observed in the cores; in particular, there is no evidence of the Blake Event (Smith and Foster, 1969; Denham, 1976) in the part of the core that we believe to be correlative with deep-sea oxygen-isotope stage 5 (Adam and others, 1981; J.W. Hillhouse, oral commun., 1981).

Abundant fish remains were identified and analyzed by R.W. Casteel (Casteel and others, 1975, 1977a, 1977b, 1979; Casteel and Beaver, 1978). The first published references to the pollen work were in a series of abstracts by Adam (1976c, 1977) and Adam and Sims (1976). A preliminary description of the pollen work (Adam and others, 1981) describes pollen zones nearly the same as those reported here. Numerous chrysomonad cysts of Wisconsinan age were found in samples from core 7; these were illustrated in a report by Mahood and Adam (1979), but no attempt was made to interpret the significance of the cysts. Further references to the Clear Lake area may be found in the bibliography prepared by Adam (1979c).

METHODS AND PROCEDURES

Coring operations took place during June to November 1973. The cores were taken using a truck-mounted drilling rig on a barge (fig. 5). Nearly all the cores were taken in sections 15 cm in diameter and as much as 80 cm long. These core segments were extruded from the core barrel into plastic pipes as soon as they were recovered, and they were then labeled and sealed with paraffin to keep them moist until they could be split and sampled. The core sections were stored unrefrigerated for four to six months before they were unsealed in the laboratory for logging and sampling. The initial splitting, logging, and photography of the cores were carried out by John D. Sims; I was responsible for sampling the cores and the subsequent work reported here.

DESCRIPTION OF CORES 4 AND 7

The upper several meters of cores 4 and 7 consist of fine-grained, organic, open-water lake muds that commonly include scales and bones of large fish (Casteel and others, 1977a). These surficial muds have a thickness of about 20 m in core 4 and about 6.8 m in core 7.

The lithology of core 4 is nearly uniform below the surficial muds, except that the carbon content of the sediments decreases gradually with depth. The sediment in the core is predominantly fine-grained clastic material having a mean grain size of 2 to 5 μm (Sims 1982), and the sediment has an organic appearance only in the upper few tens of meters. The transition between the upper organic sediments and the lower nonorganic clays is very gradual.

The lithology of core 7 is strikingly different from core 4. Below a depth of 6.8 m, the sediment changes from open-water lake muds to interbedded, shallow-water lake muds and peats. Remains of large fish are no longer found, and spines and bones of sticklebacks (*Gasterosteus aculeatus*) are the only fish remains common in the lower

FIGURE 5.—Drilling rig used in the 1973 Clear Lake coring program. Rig was a truck-mounted version that was secured to a three-section steel barge. Photograph by J.D. Sims.

part of the core. Plant macrofossils, common in the lower part of the core, include seeds of *Zannichellia*, *Nuphar*, *Brasenia*, *Potamogeton*, and *Myriophyllum*, as well as seeds of aquatic Polygonaceae and Cyperaceae.

CORE SAMPLING

Cores were split lengthwise, inspected, logged, and photographed both in color and in black and white, and a 1-cm slice was removed from the middle of each core segment for X-ray radiography. After each core section was logged and radiographed, one half was sealed in a plastic bag and stored as a voucher specimen. The other half was sampled according to the protocol described by Beaver and others (1976). Samples were taken at 10-cm intervals wherever core recovery and preservation allowed. Samples were removed for analysis of pollen, diatoms, cladocera, sediment size, water content, and macrofossils wherever enough sediment was available, and additional samples were removed for volcanic-ash and radiocarbon studies when suitable material was present. The X-ray radiographs were often useful as a guide in sampling. Many of the samples removed from the cores have not yet been studied and are available for future use. A list of the samples studied for this report is given in table 4.

Core-section exteriors commonly showed signs of oxidation during storage, but the interiors appeared undisturbed; pollen samples were always taken from the undisturbed part of the core. Some decrease in sediment water content probably occurred during storage, but no significant desiccation was observed.

Pollen and weight-loss samples were removed from the cores using a cylindrical tube sampler fitted with a piston. A sample volume of 1.30 cm^3 was used for most of core 7; all the remaining samples were taken using a 2.19-cm^3 sampler. Sample volumes for the core 7 samples are given in Adam (1979b). Weight-loss samples were weighed as soon as they were removed from the cores and again after drying overnight at 110 °C.

POLLEN SAMPLE PREPARATION

Pollen extraction followed standard procedures for Quaternary pollen samples including hydrofluoric acid digestion, acetylation, and hydroxide dissolution of humates. Extracted samples were stored and mounted in silicone oil. Counting was done at a magnification of × 600 using a Leitz Ortholux[1] binocular microscope.

Pollen percentage data are affected by a constraint: the observations included within the pollen sum must add up to 100 percent. Under certain conditions, this constraint can produce percentage curves that do not accurately represent changes in amounts of a particular pollen type through time. For example, if two pollen types, A and B, add up to 100 percent, then an increase in the percentage of A could be a result of a simple increase in the amount of A (B constant), a decrease in the amount of B (A constant), A increasing more than B, or A decreasing less than B.

Quaternary palynologists commonly try to circumvent the percentage constraint problem by estimating either pollen concentrations (grains per gram or cubic centimeter of sediment) or pollen influx (grains per square centimeter per year). (See Colinvaux, 1978, for a critique of the "'absolute pollen frequency" terminology sometimes used for such data.) To calculate pollen concentrations, one must know the number of pollen grains in the sample, the sample volume, and the sample weight. To calculate pollen influx data one must also know the sedimentation rate for each sample. Sedimentation rates could not be determined accurately for the present study, particularly for core 4. The radiocarbon ages for the upper part of the core are suspect, and the dating for the lower part of the core rests upon correlation with dated series elsewhere; therefore, pollen influx data cannot be calculated. Pollen concentrations are calculated as grains per gram dry weight of sediment rather than as grains per cubic centimeter because of the great variation in dry sediment density with depth in core 4 (fig. 7; see also the discussion by Fletcher and Clapham, 1974).

Pollen samples of known volume were removed from the core as already described. Prior to pollen extraction, a known amount of exotic pollen was added to each sample to enable estimation of the amount of fossil pollen in each sample. The exotic tracer pollen types were added in the form of tablets containing either *Eucalyptus* pollen grains or *Lycopodium* spores.

The tracer added to the core 7 samples consisted of unweighed tablets containing approximately 15,833 grains of Eucalyptus pollen. Two tablets were added to each 1.3-cm^3 sample, and four tablets were added to each 2.19-cm^3 sample; sample volumes are given in Adam (1979b).

A more elaborate tracer procedure was followed for the core 4 samples. Two tracer types were used, *Eucalyptus* and *Lycopodium.* All core 4 samples had a volume of 2.19 cm^3. Four tablets of each tracer type were dried to constant weight before they were added to the sample. This method allowed each tracer to be used as a check on the other and made it possible to assess the variability of the amount of each tracer added to the samples. Totals of 16,346 *Eucalyptus* grains and 12,905 *Lycopodium* spores were counted along with the fossil pollen in the 166 core 4 samples. The best estimate of the ratio of *Eucalyptus*

---

[1] Any trade names and trademarks found in this publication are used for descriptive purposes only and do not constitute endorsement by the U.S. Geological Survey.

to *Lycopodium* is 1.267. The *Lycopodium* tablets were known to contain approximately 12,500 spores per tablet; the pollen content of the *Eucalyptus* tablets was calculated using the observed ratio of *Eucalyptus* to *Lycopodium.*

The counts of *Eucalyptus* and *Lycopodium* are plotted against each other in figure 6. There is considerable scatter of the observations away from the straight-line relation expected if the composition of the pollen tablets were homogeneous. The observations plotted in the figure are the raw numbers of grains counted, without correction for variations in the weight of the tablets. However, correction for tablet weight produces little difference in the appearance of the graph, indicating that variability in pollen concentration between tablets is a more significant source of variability than variation in tablet weight. The tracer pollen counts are not analyzed further here, but the scatter (fig. 6) suggests that between-tablet variability is significant enough to affect the results of pollen concentration and influx calculations.

Pollen counting criteria were designed for efficient estimation of frequencies of the various pollen types and nonpollen microfossils. In many samples, remains of algae (*Botryococcus, Coelastrum,* and several kinds of *Pedi-*

TABLE 4.—*Pollen sample numbers and depths*

[Sample numbers also shown on detailed lithological descriptions of cores (Sims and Rymer, 1975c, f)]

No.	Depth (m)	No.	Depth (m)	No.	Depth (m)	No.	Depth (m)	No.	Depth (m)	No.	Depth (m)
					Core 4						
2053	0.10	1665	27.00	1518	54.05	1340	81.85	1134	101.30	1189	108.17
2054	0.20	1660	28.00	1511	55.05	1342	82.05	1135	101.62	1190	108.27
2048	1.20	1650	29.40	1280	56.05	1459	83.28	1138	101.92	1191	108.37
2060	2.00	1655	29.90	1559	57.00	1462	83.58	1139	102.02	1192	108.47
2069	3.00	1643	30.30	1552	58.00	1465	83.88	1140	102.12	1193	108.57
1848	4.00	1649	30.90	1245	59.04	1467	84.25	1141	102.22	1194	108.67
1843	5.00	1639	31.50	1275	60.01	1470	84.55	1157	102.58	1526	108.90
1838	6.05	1630	32.10	1253	60.97	1473	84.85	1159	102.78	1124	109.85
1830	7.00	1623	33.00	1584	62.00	1315	85.21	1161	102.98	1125	110.00
1824	8.00	1616	34.00	1564	63.20	1308	86.07	1163	103.18	1127	110.20
1815	8.70	1746	35.05	1571	64.10	1445	87.04	1150	103.50	1195	110.71
1803	9.30	1730	35.95	1600	65.00	1453	88.00	1151	103.60	1198	111.01
1810	10.00	1724	37.00	1593	66.00	1432	89.07	1152	103.70	1200	111.21
1787	11.00	1718	38.00	1609	67.00	1440	90.00	1154	103.90	1202	111.41
1255	11.96	1712	39.00	649	68.06	1304	91.00	1156	104.10	1226	111.63
1287	13.02	1705	40.00	657	69.03	1483	91.96	1143	104.36	1228	111.83
1888	14.00	1698	40.95	1428	70.01	1486	92.26	1145	104.56	1230	112.03
1897	15.00	1778	42.10	1422	70.98	1294	92.62	1147	104.76	1231	112.13
1904	16.00	1736	43.10	1416	72.04	1296	92.82	1149	104.96	1232	112.23
1911	17.00	1743	44.30	1409	73.01	1298	93.02	1172	105.28	1212	112.64
1919	18.00	1753	46.00	1322	74.14	1479	93.95	1174	105.48	1216	113.04
1869	20.00	1762	47.00	1388	75.10	1501	94.90	1176	105.68	1219	113.51
1878	21.10	1769	48.05	1380	75.97	1494	95.82	1178	105.88	1224	114.01
1685	22.10	1775	49.00	1374	77.03	1504	96.78	1164	106.14	1205	114.57
1679	22.95	1239	50.00	1367	77.99	1505	98.51	1168	106.55	1210	115.07
1674	25.05	1269	51.01	1361	78.96	1507	99.28	1179	107.10		
1673	25.43	1541	52.00	1355	80.02	1487	100.15	1184	107.60		
1669	26.00	1527	53.15	1348	80.99	1131	101.00	1188	108.07		
					Core 7						
102	0.00	163	6.40	201	10.60	71	15.40	215	19.80	264	24.70
106	0.40	167	6.80	26	11.00	75	15.80	218	20.10	268	25.10
109	0.80	171	7.20	30	11.40	79	16.20	221	20.20	272	25.50
113	1.20	175	7.70	34	11.80	80	16.30	223	20.61	275	26.00
117	1.60	179	8.10	38	12.20	81	16.40	230	21.03	281	26.40
121	2.00	182	8.45	43	12.60	83	16.60	234	21.40	290	26.80
124	2.40	183	8.60	49	13.12	85	17.00	238	21.80	294	27.10
132	3.20	185	8.80	50	13.20	89	17.40	241	22.20		
140	4.00	187	9.00	52	13.40	94	17.80	246	22.60		
144	4.40	189	9.24	55	13.80	101	18.20	250	23.10		
148	4.80	191	9.40	59	14.20	204	18.57	254	23.50		
156	5.60	195	9.80	63	14.60	208	19.00	257	23.90		
160	6.00	197	10.20	67	15.00	211	19.40	261	24.30		

astrum) were so abundant that they slowed pollen counting significantly. Several approaches were tried as the magnitude of the algae problem became apparent. The first method, used for some core 7 samples, was to count all microfossils until at least 200 grains of fossil pollen had been counted. The next approach was to count each algal type until 100 individuals (or colonies in the case of *Pediastrum*) were counted and then to record the number of tracers together with the count; the rest of the algae of that type were then ignored. As it became apparent that fluctuations in algal frequencies were very large, less precision seemed necessary, and stopping criteria for algal counts were made less and less stringent. For some counts, frequencies of abundant algae were recorded whenever the most abundant type reached a count of 100 individuals. Eventually, the stopping criterion became a

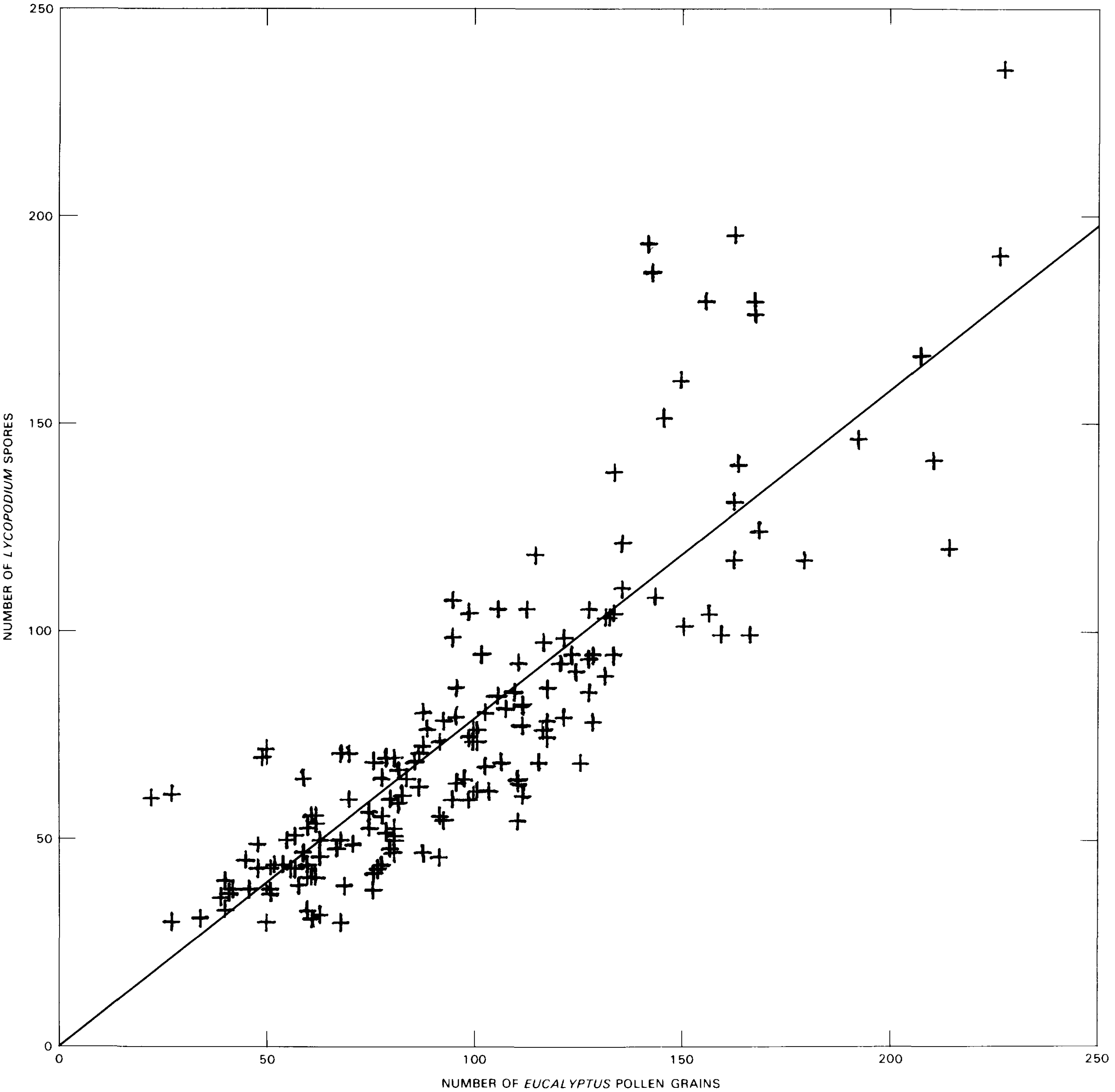


FIGURE 6.—Plot of raw counts of *Eucalyptus* tracer pollen versus *Lycopodium* tracer pollen for core 4. Straight line indicates expected relation in the absence of all errors.

total of at least 100 of all algae. The ratio of the number of tracers counted with the algae to the number of tracers counted with the pollen was then used to estimate how many algae would have been counted with the full sum. One result of this approach is that confidence limits for some estimates of algal abundance are very broad; however, this effect is only important when algae are extremely abundant.

STATISTICAL METHODS

The pollen samples from cores 4 and 7 are divided into a series of pollen zones using a procedure that involves first reducing the dimensionality of the data to five orthogonal factors and then using an iterative boundary-fitting process to zone the samples according to their factor loadings.

FACTOR ANALYSIS

Factor analysis is a multivariate statistical technique used to summarize patterns of behavior in large data sets. It consists of a number of techniques that are included in the larger field of multidimensional scaling (Prentice, 1980). These techniques enable description of the variations observed for a large number of variables (pollen types) in terms of a smaller number of uncorrelated variables (factors) that are linear combinations of the original variables. The first factor selected includes the maximum variance that can be accounted for by a single linear combination of the pollen types and represents a least-squares line drawn through a cloud of sample points in a multidimensional space whose axes are the original variables. Successive factors repeat the process, each one accounting for the maximum possible variance not included in previous factors. In this way, one can reduce the dimensionality of the data set from the number of original variables to a much smaller number of factors and still include nearly all the original variance.

Factor analysis results include a set of "factor loadings" and a set of "factor scores" for each factor. Each factor has one factor loading for each sample and one factor score for each variable. The greater the absolute value of the loading, the more important the factor is in describing the sample; the greater the absolute value of a factor score, the more important that pollen type is in determining the factor loadings for that factor. Positive and negative values indicate opposite effects.

The results presented in this paper as "scaled factor scores" are the result of a transformation that weights the results for each factor in proportion to the amount of the initial variance that is accounted for by that factor.

Once an appropriate number of factors is selected to describe a data set, the factors can be made easier to interpret by a procedure known as VARIMAX rotation. The amount of variance and the orthogonality of the factors are conserved in this transformation, but the factor scores are adjusted so that a given factor tends to be either very strongly or very weakly affected by any given original variable, and intermediate scores tend to be suppressed.

A further description of factor analysis in general may be found in Harman (1967), and applications to Quaternary pollen data are discussed by Adam (1974) and Prentice (1980) among others. The CABFAC computer program used here is described by Klovan and Imbrie (1971) and Adam (1976a).

I have previously suggested that pollen data should be subjected to a centering transformation in which the mean for each variable is subtracted from the observations of that variable before calculation of similarity matrices for Q-mode factor analyses (Adam, 1970, 1974). However, a centering transformation of the Clear Lake data produced factors more difficult to interpret than those presented below. CABFAC-type analysis appears to provide better results for uncentered than for centered data when two or more major variables or sets of variables replace each other in different parts of the data set.

ZONING ALGORITHM

The factor loadings are used as input to an interactive zoning algorithm that uses a least-squares measure to determine the optimum position for a single zone boundary within a given series of samples, subject to the constraint that every zone should contain at least two samples. Within a block of samples being zoned, all possible ways of dividing the block into two smaller blocks are considered, and the function

$$S=\sum_{k=1}^{2}\sum_{j=1}^{5}\sum_{i=\mathrm{top}_k}^{\mathrm{bottom}_k}(x_{ij}-\bar{x}_{jk})^2 \qquad (1)$$

is evaluated for each possibility, where x_{ij} is the value of the jth factor score for sample i, $\bar{x}_{jk}$ is the mean value of the observations of factor j in zone k, and top_k and bottom_k are the top and bottom samples included in zone k. The boundary chosen is the one that produces the minimum value of S.

The choice of the upper and lower bounds of the block of samples to be subdivided can significantly affect the position of the boundary selected, especially if the block being divided contains more than two acceptable zones. The initial choice of blocks to be subdivided is made by subjective inspection of the factor score curves; the resulting zone boundaries then define new blocks to be divided. After several iterations, this process should produce a series of boundaries that are stable and consistent—that is, each zone boundary is selected as the best dividing point for the two zones that it separates.

RESULTS

SEDIMENT DENSITY AND CARBON CONTENT

Dry sediment density is calculated from the weights of the dried samples. Quadratic regression against depth produces the equation

$$D(g\ \mathrm{cm}^{-3}) = 0.46018 + 0.02673d - 0.00012d^2 \qquad (2)$$

where D is the sample density and d is the sample depth in meters. The resulting quadratic curve (fig. 7*A*) fits the general trend of the data quite well, but there are some systematic departures of the observations from the curve, particularly below a depth of 80 m. These are discussed after the description of the climatic sequence.

Percent weight loss on ignition at 550 °C for samples from core 4 is shown in figure 7*B*. Weight loss declines from about 25 percent at the top of the core to about 10 percent at a depth of 30 m and then stays at about that percentage to the bottom of the core. The results of carbon analyses of core 7 sediment at 1-m intervals are shown in figure 8. The upper 7 m of the core, which consists of open-water lake muds similar to those found in the upper parts of all of the cores, has a carbon content of about 10 percent. Below a depth of 7 m, the sediments consist of interbedded peats and shallow-water lake muds that contain much more macroscopic plant debris than the open-water muds, and the carbon content is generally higher. The only exception is found at a depth of 16 m in clay (Sims and Rymer, 1975f), where the carbon content is the lowest observed in the core.

Mean sediment grain size for core 4 is plotted against depth in figure 7*C*, along with a three-level moving average of the same data. Average grain size ranges from about 2 μm to almost 5 μm. The small grain size reflects the distance of the core site from the lake shore, and the lack of major trends in the long-term behavior of the curve suggests that the distance of the site from shore has not altered greatly during the time the core was deposited. The short-term behavior of the data, especially as seen in the moving-average curve, suggests possible cyclical variations in grain size, but these possible cycles are not explored further here.

PALYNOLOGY

Core 4 was chosen for pollen analysis because it is the longest core and thus should span the longest time interval, and core 7 was chosen because it contains abundant plant remains for use in establishing a radiocarbon time scale.

All fossil pollen types are included in the pollen sum, as are microspores of *Isoetes* (quillwort). The inclusion of non-arboreal pollen (NAP) and aquatic pollen in the sum has very little effect on the core 4 data, because those types are scarce. In core 7, however, aquatic pollen types are abundant in the lower part of the section. The best estimates of the regional arboreal pollen (AP) rain therefore come from the core 4 record.

The pollen sum consists of at least 200 grains of fossil pollen. Pollen is well preserved throughout the core; the main hindrance to easy counting is the abundance of acid-resistant algal remains found near the tops of both cores. The pollen identification key of Kapp (1969) and a reference collection of California pollen types were the principal resources used to identify unknown pollen grains.

Diagrams for the basic percentage data include: (1) curves for the important non-aquatic pollen types, including both arboreal and non-arboreal types (pl. 1), (2) aquatic, unknown, miscellaneous, and tracer pollen types (pl. 2), and (3) curves for the various algae (pl. 3).

NOTES ON VARIABLES

The initial pollen counts included observations on 121 variables. Many are quite rare, with distributions that show no apparent stratigraphic pattern. This report is based on a summary data set of 51 variables that includes all fossil pollen, as well as several non-pollen variables and the counts of the tracer pollen types (*Eucalyptus* and *Lycopodium*). The original data are presented in Adam (1979a,b), and a list of the variables in the reduced data set is shown in table 5. Some of the variables in the summary data set include more than one variable from the original data; all such instances are described in the following section.

QUERCUS (OAKS)

Pollen grains identified as *Quercus* (oak) include not only the unmistakable *Quercus* grains that comprise the bulk of the group (fig. 9A), but also numerous "quercoid" grains that fail in some way to match the "textbook" type of *Quercus* grain but are less unlike *Quercus* than any other type. Quercoid grains could not be separated as a distinct type but were lumped with the other *Quercus* grains. No attempt was made to identify *Quercus* grains to species. Of the 16 species of *Quercus* in California (Munz and Keck, 1959), nine now grow in the Clear Lake area (see table 3).

PINUS (PINES)

No systematic attempt was made to separate the haploxylon and diploxylon groups within *Pinus*, although haploxylon grains were noted separately when they were obvious. The major species of pine naturally occurring in Lake County are *Pinus attenuata*, *P. ponderosa*, and *P. sabiniana*, all in the subgenus *Diploxylon*. Less important are *P. jeffreyi* (*Diploxylon*) and *P. lambertiana* (*Haploxylon*). Nearly all pine grains appeared to be of the diploxylon type (fig. 9*B*). Broken pine grains were counted as thirds.

ABIES (FIRS)

Fir pollen probably represents *Abies concolor* (white fir), *A. magnifica* (red fir), or *A. grandis* (grand fir). White and red fir are both found on the highest mountaintops in northern Lake County (Griffin and Critchfield, 1972; Gray, 1979) and undoubtedly participated in the expansion of high-elevation coniferous forests into the Clear Lake basin during the cooler parts of the last glacial cycle. Grand fir is presently found only much nearer to the Pacific coast, but it did grow in the Clear Lake basin during full glacial times, as evidenced by the recovery of distinctive grand fir needles from core CL-73-1 and core 4.

PICEA (SPRUCE)

Spruce pollen, rare in both cores, may consist mostly of redeposited grains from the Kelseyville Formation, from which both pollen grains and macrofossils of spruce are reported (Rymer, 1978, 1981).

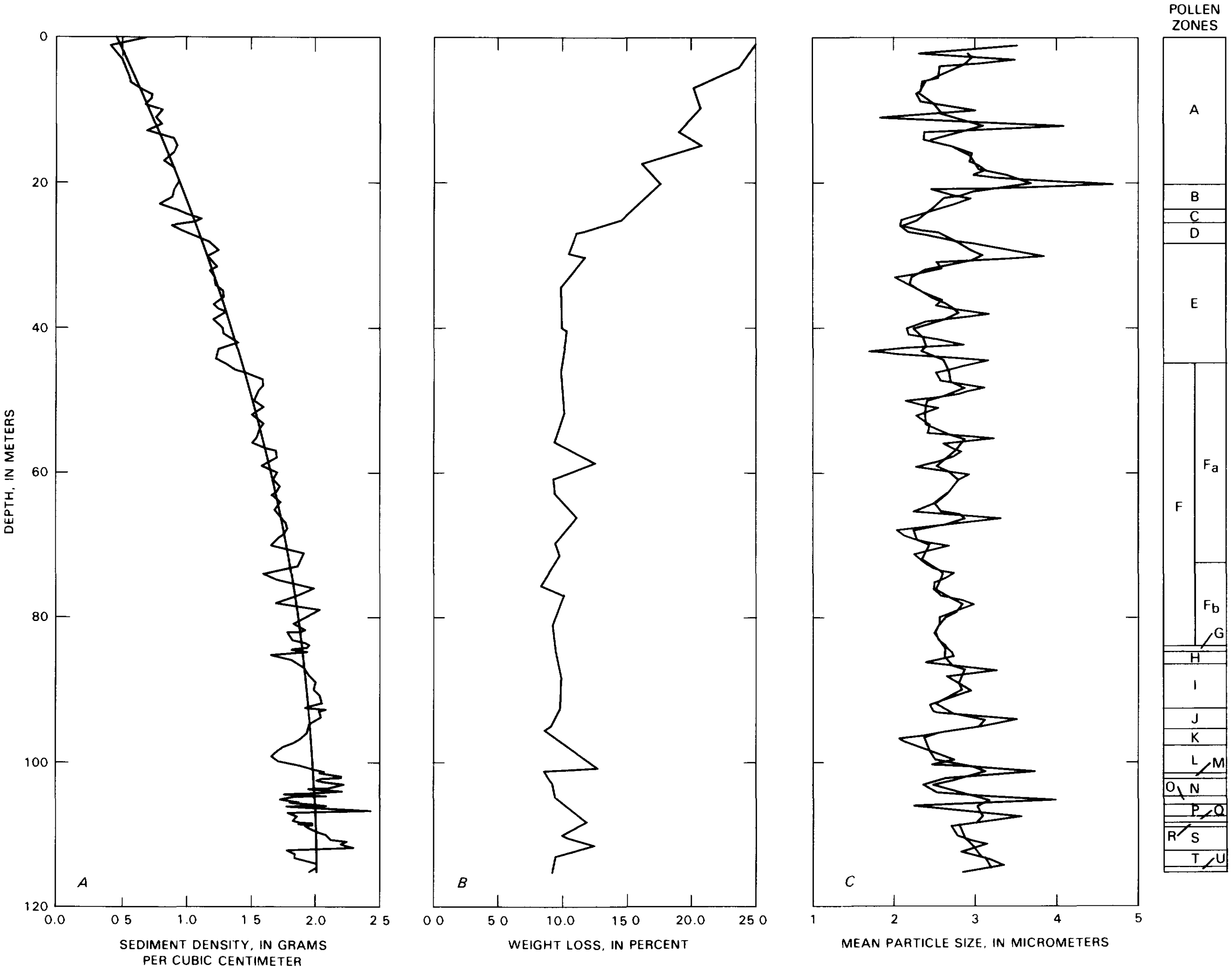


FIGURE 7.—Sample characteristics versus depth for core 4. *A*, Dry sediment density. Smooth curve is described in text. *B*, Weight loss on ignition. Data by S.W. Robinson. *C*, Mean sediment grain size (jagged curve) and three-level moving average of mean sediment grain size (smoothed curve), using data from Sims (1982).

TSUGA (HEMLOCK)

Hemlock pollen includes both *Tsuga heterophylla* (western hemlock) and *T. mertensiana* (mountain hemlock). Both types are rare.

TCT (TAXODIACEAE, CUPRESSACEAE, AND TAXACEAE)

The TCT category (fig. 9*C*) includes pollen of the families Taxodiaceae, Cupressaceae, and Taxaceae, and probably represents mostly the genera *Calocedrus*, *Cupressus*, and *Juniperus*. A few grains of Sequoia were identified on the basis of the papillae, and some TCT grains were tentatively identified as *Chamaecyparis*, but no systematic patterns were apparent for those types.

POLYGONACEAE (BUCKWHEAT FAMILY)

Polygonaceae pollen includes undifferentiated members of the family, and also *Polygonum californicum*, *P. persicaria*-type, *Eriogonum*, and *Rumex*.

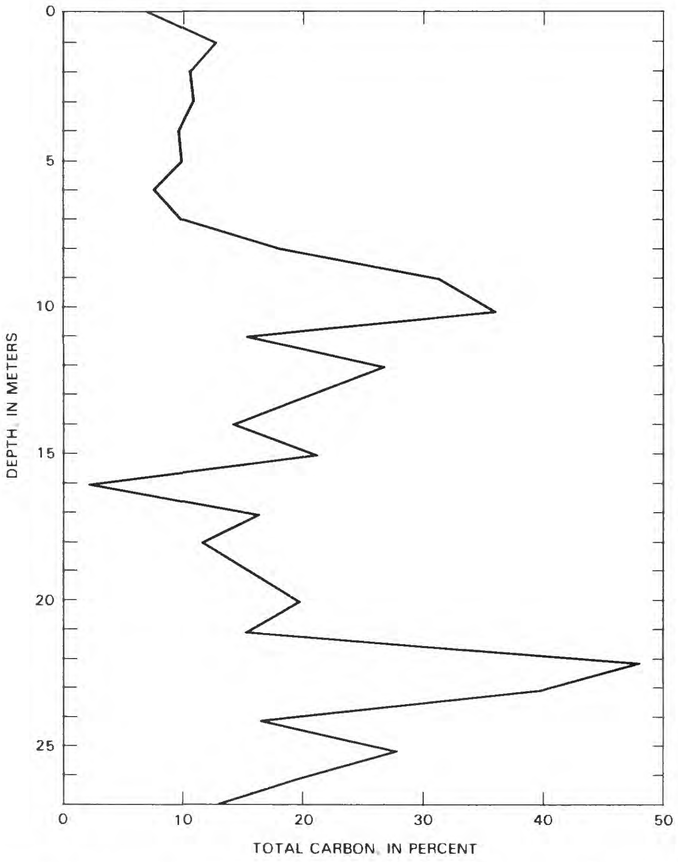


FIGURE 8.—Total carbon content plotted against depth for core 7. Carbon analyses by J.H. Tillman.

GRAMINEAE (GRASSES)

Most Gramineae grains could not be identified below the family level. However, a few very large grains near the top of the core represent the Cerealia.

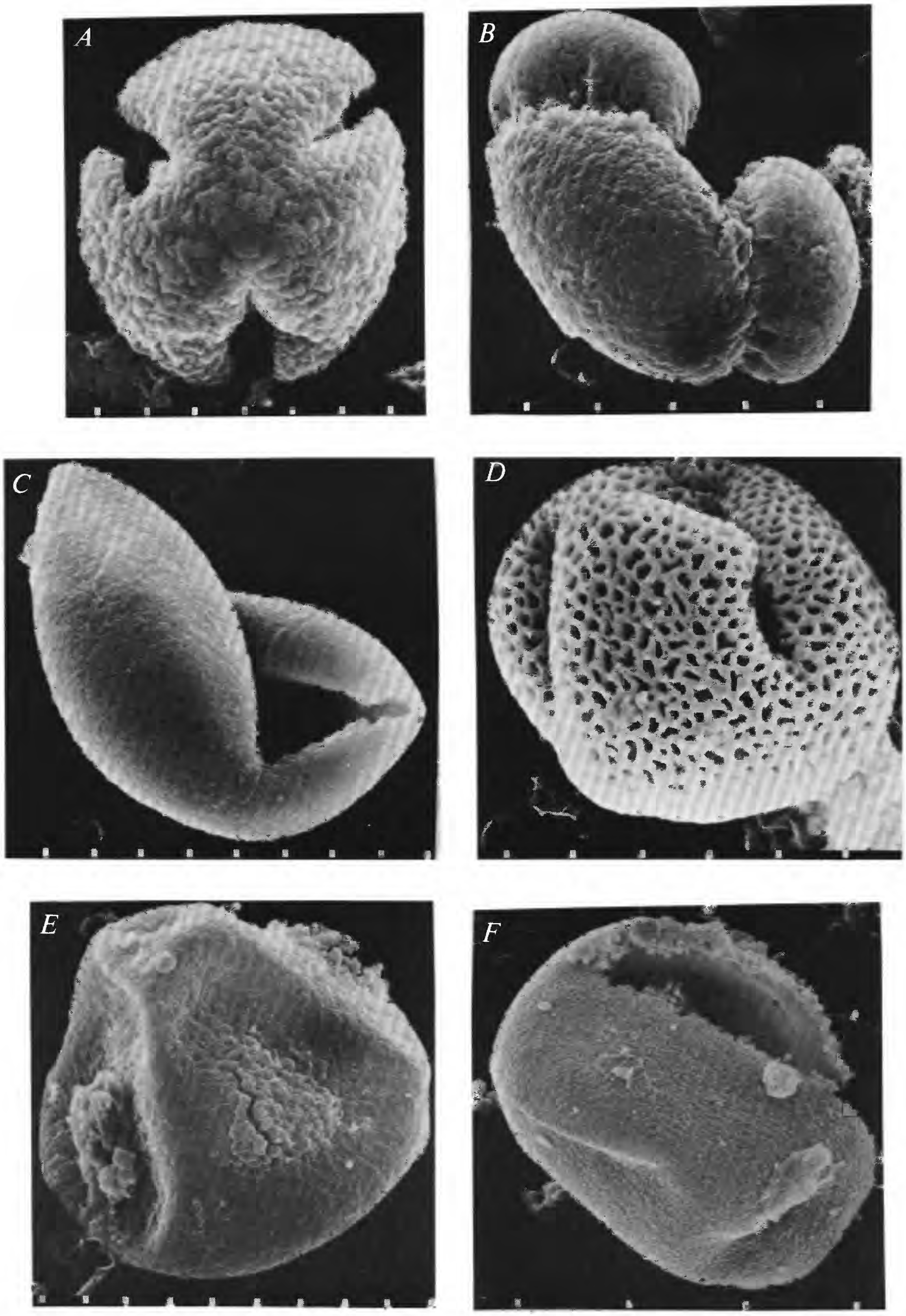
CHENO-AMS

The Cheno-ams include the Chenopodiaceae and the related genus *Amaranthus* (Martin, 1963a). A few grains of *Sarcobatus* (greasewood) pollen were found; they are included with the rest of the Cheno-ams.

TABLE 5.—*Variables included in the summary data set*

Variable No.	Variable name
1	*Quercus* (oaks)
2	*Pinus* (pines)
3	*Abies* (true firs)
4	*Picea* (spruce)
5	*Tsuga* (hemlock)
6	*Pseudotsuga* (Douglas fir)
7	TCT
8	*Alnus* (alder)
9	*Salix* (willow)
10	*Brasenia* (water-shield)
11	Cyperaceae (sedges)
12	*Typha* tetrads (cattails)
13	*Typha-Sparganium* (cattails and burreeds)
14	Cruciferae
15	*Potamogeton* (pondweeds)
16	*Isoetes* (quillwort)
17	Unknown A
18	*Artemisia* (sagebrush)
19	Rhamnaceae (buckthorn family)
20	Cheno-Ams
21	High-spine Compositae
22	Gramineae (grasses)
23	Polygonaceae
24	Caryophyllaceae
25	*Arceuthobium* (dwarf mistletoe)
26	Portulacaceae
27	Other trees & shrubs
28	Other aquatics
29	Umbelliferae
30	*Chrysolepis* (*Castanopsis*) (chinquapin)
31	*Corylus* (hazel)
32	*Juglans* (walnut)
33	cf. *Tilia*
34	*Fraxinus* (ash)
35	Nymphaeaceae leaf hairs[1]
36	*Lithocarpus* (tanbark oak)
37	Other Compositae
38	Unknown & unidentifiable
39	*Eucalyptus* (tracer pollen type)[1]
40	*Lycopodium* (tracer pollen type)[1]
41	*Pediastrum* A[1]
42	*Pediastrum* N[1]
43	*Pediastrum* O[1]
44	*Pediastrum* X[1]
45	*Pediastrum* Y[1]
46	*Pediastrum* K[1]
47	*Botryococcus*[1]
48	*Coelastrum*[1]
49	Hystrichosphaerids(?)[1]
50	*Peridinium* cysts[1]
51	Other pollen types

[1] Type excluded from pollen sum.


A
B
C
D
E
F

OTHER TREES AND SHRUBS

This group includes occasional grains of *Betula*, *Shepherdia*, *Ericaceae* (which might also have been assigned to the "other aquatics" group), and *Sambucus*.

OTHER AQUATIC AND EMERGENT PLANTS

The "other aquatics" category includes grains of *Myriophyllum*, *Nuphar*, *Sagittaria*, *Proserpinaca*, *Pedicularis*, *Menyanthes*, *Utricularia*, *Nymphaea*, and dyads of *Typha*. Nuphar pollen grains were uncommon even when Nymphaeaceae leaf hairs were abundant.

COMPOSITAE (SUNFLOWER FAMILY)

Compositae pollen are identified as high-spine Compositae, low-spine Compositae, *Artemisia*, and Liguliflorae, using the approach of Martin (1963a). Separate curves are shown for the high-spine Compositae and *Artemisia*, whereas the low-spine Compositae and Liguliflorae grains are grouped as "other Compositae."

UNKNOWN A

Unknown A (fig. 9*D*) is a stephanocolpate, reticulate grain of oblate shape. The size of the grain, about 15 μm in polar diameter by 22 μm in equatorial diameter, makes it too small for *Fraxinus*, which it otherwise resembles. The reticulum is uniform over the entire grain. There are four colpi, and the equatorial profile of the grain is slightly distended toward a square shape, with the colpi at the corners. In the description of the raw data (Adam, 1979a), this type was identified as "Unk., cf. *Acer negundo*," but it is definitely some other type.

OTHER POLLEN TYPES

Rare pollen types lumped into this category include Ranunculaceae, *Aconitum*, Rosaceae, *Galium*, Leguminosae, *Thalictrum*, *Gilia*, Geraniaceae, Liliaceae, cf. *Ilex*, Labiatae, Convolvulaceae, cf. *Morus*, Violaceae, Campanulaceae, Primulaceae, *Hedera*, *Dodecatheon*, *Fremontia*, Onagraceae, *Ailanthus*, Rubiaceae, Saxifragaceae, *Castanea*, Malvaceae, *Prunus*, and *Ephedra* (*nevadensis*-type).

FIGURE 9.—Scanning electron micrographs of pollen types. Distance between ticks along bottom of photograph indicates scale. *A*, Oak (*Quercus*) pollen grain, polar view. Grain is from core 7, sample 171, depth 7.20 m. Scale is 3 μm. *B*, Pine (*Pinus*) pollen grain, side view. Grain is from core 4, sample 1623, depth 33.00 m. Scale is 10 μm. *C*, TCT pollen grain, broken in typical fashion. Grain is from core 4, sample 1623, depth 33.00 m. Scale is 3 μm. *D*, Unknown A pollen grain, approximately in side view. Grain is from core 4, sample 1669, depth 26.00 m. Scale is 3 μm. *E*, Sedge (Cyperaceae) pollen grain. Grain is from core 7, sample 177, depth 7.90 m. Scale is 3 μm. *F*, Water-shield (*Brasenia*) pollen grain. Grain is from core 7, sample 177, depth 7.90 m. Scale is 10 μm.

PEDIASTRUM

Several types of the algal genus *Pediastrum* are abundant in both cores. The several forms recognized may or may not be taxonomically reasonable. Types are separated using several morphologic features, including the number of "horns" per cell, the surface sculpturing, and the presence or absence of holes between adjacent cells. The letters assigned to the different forms are arbitrary designations; "missing" letters have no significance.

The most important types are A, K, N, O, X, and Y. *Pediastrum* A (fig. 10) resembles *P. simplex* var. *duodenarium* as shown in Smith (1920) and is larger than most other forms. Only one form of *Pediastrum* A was recognized while counting, but comparison with scanning electron micrographs by Parra (1979) indicate that at least two varieties are present: *P. simplex* var. *pseudoglabrum* Parra (figs. 10*A–C*) and *P. simplex var. simplex* (figs. 10*D–E*).

Pediastrum N (fig. 11*A–C*) is much larger than all the other types and has a reticulum of triangles on the cell walls; it resembles *P. sculptatum* of Smith (1920, pl. 46, table 1) and *P. duplex* var. *punctatum* (Krieger) Parra of Parra (1979, pl. 37). *Pediastrum boryanum* is probably represented both by *Pediastrum* O (fig. 11*C*), which has holes between adjacent cells, and by *Pediastrum* X (figs. 11*D–F* and 12*A–B*), which lacks such holes; intermediate forms are also present. *Pediastrum* Y (fig. 12*E–F*) corresponds to *P. duplex* Meyen var. *duplex* (Parra, 1979, pl. 30); it has two long "horns" per cell, and each horn has a circular aperture with a slightly thickened rim at its tip. Cell walls are smooth and thin, and holes are present between cells. It may be equivalent to *P. duplex* var. *gracillimum* as described by Smith (1920, pl. 47, tables 8–11), but it is difficult to tell from Smith's illustrations just how close the match is. It also resembles *P. clathratum* as shown by Harper (1918, p. 226, tables 17 and 18).

Pediastrum K (fig. 12*C–D*) resembles *Pediastrum* X but has only a single horn. The taxonomic key presented by Parra (1979) identifies *Pediastrum* K as some form of *P. simplex*, along with *Pediastrum* A, but I consider *Pediastrum* K to be quite distinct both in its morphology and

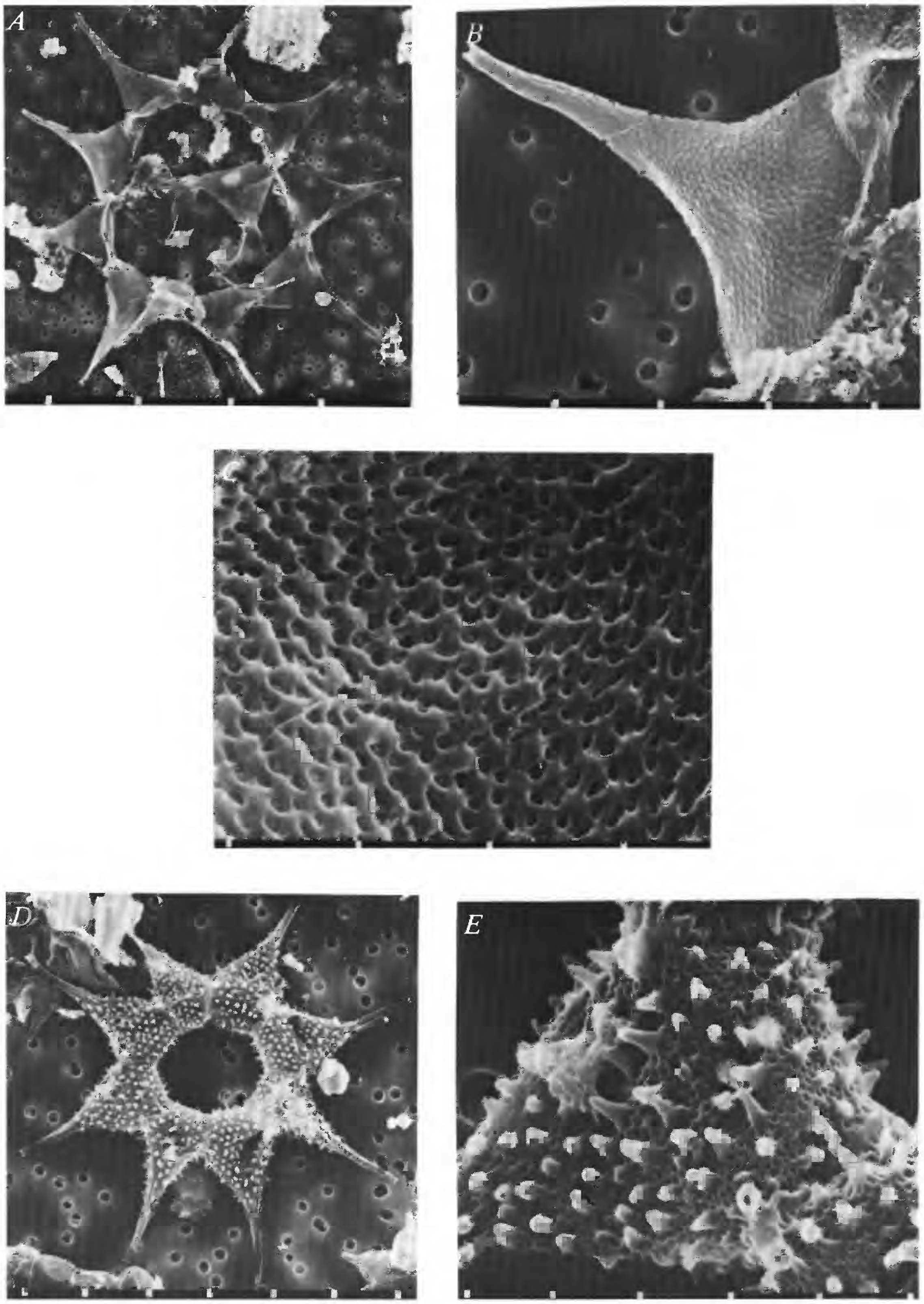


FIGURE 10.—Scanning electron micrographs of *Pediastrum*, type A. Distance between ticks along bottom of photograph indicates scale. *A*, Holes in substrate are 2 μm in diameter. From core 4, sample 2054, depth 0.20 m. Scale is 30 μm. *B*, Enlarged view of a single algal cell of the colony shown in *A*. Scale is 10 μm. *C*, Fine surface sculpturing of the cell shown in *B*. Scale is 3 μm. *D*, Another form. Scale is 10 μm. From core 4, sample 1869, depth 20.00 m. *E*, Enlarged view of surface sculpturing of the colony shown in *D*. Scale is 3 μm.

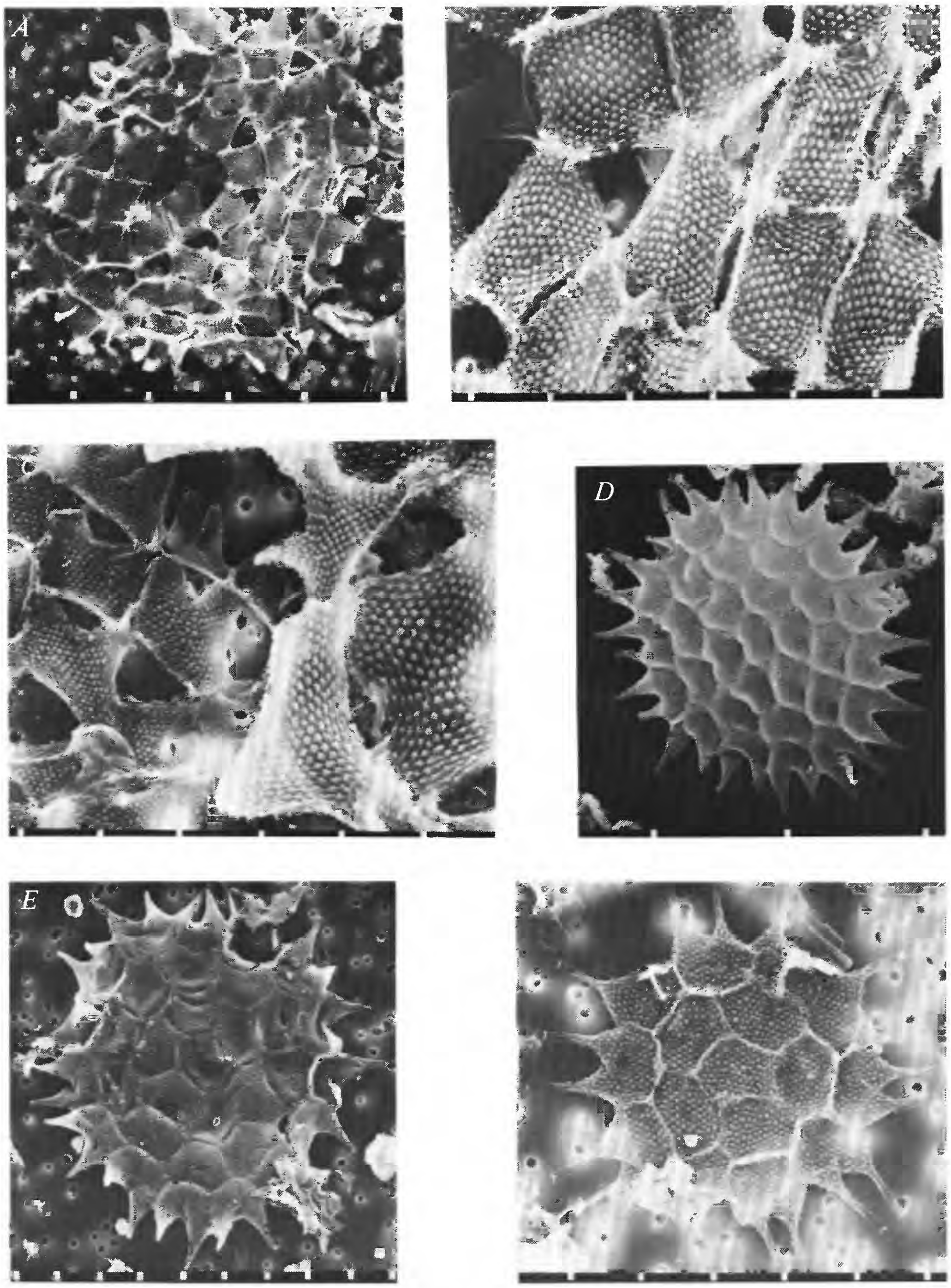


FIGURE 11.—Scanning electron micrographs of *Pediastrum*, types N, O, and X. Distance between ticks along bottom of photograph indicates scale. *A*, Colony of *Pediastrum* N from core 7, sample 171, depth 7.20 m. Holes in substrate are 2 μm in diameter. Scale is 30 μm. *B*, Enlarged view of *Pediastrum* N colony shown in *A*. Scale is 10 μm. *C*, Overlapping colonies of *Pediastrum* O (left) and *Pediastrum* N (right), from core 7, sample 171, depth 7.20 m. Holes visible in substrate are 2 μm in diameter. Scale is 10 μm. *D*, Colony of *Pediastrum* X, from core 7, sample 177, depth 7.90 m. Puffy appearance is because specimen was critical-point dried. Scale is 30 μm. *E*, Colony of *Pediastrum* X, from core 4, sample 2054, depth 0.20 m. Holes in substrate are 2 μm in diameter. Sample was critical-point dried; cracks in some cell walls are artifacts. Scale is 10 μm. *F*, Colony of *Pediastrum* X, showing longer 'horns' and coarser surface sculpturing than in the specimens shown above. From core 7, sample 171, depth 7.20 m. Holes in substrate are 2 μm in diameter. Scale is 10 μm.

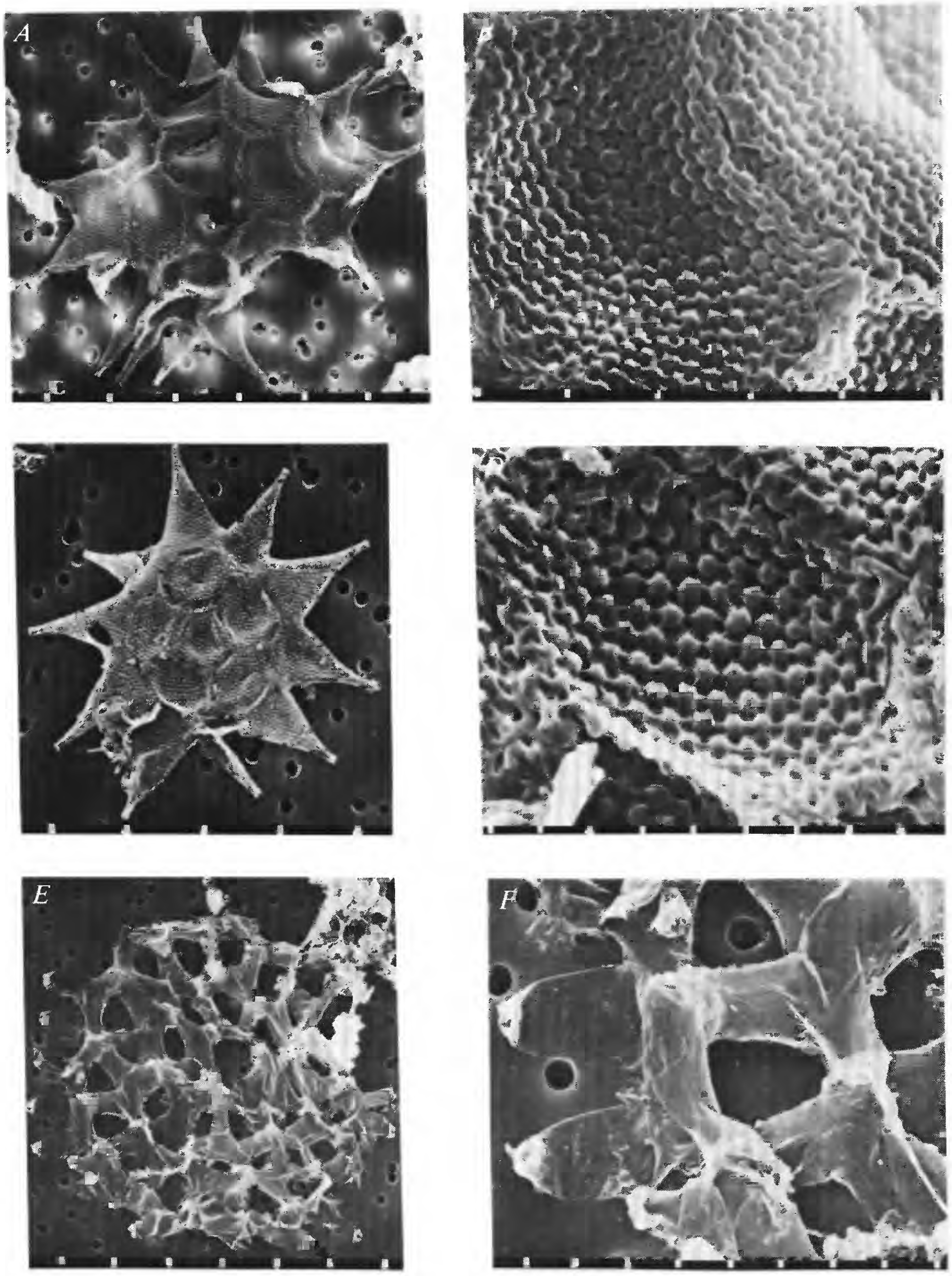


FIGURE 12.—Scanning electron micrographs of *Pediastrum*, types K, X, and Y. Distance between ticks along bottom of photograph indicates scale. *A*, Colony of *Pediastrum* X, from core 7, sample 171, depth 7.20 m. Cracks are artifacts. Holes in substrate are 2 μm in diameter. Scale is 10 μm. *B*, Enlarged view of surface sculpturing of cells of *Pediastrum* X colony in *A*. Scale is 3 μm. *C*, Colony of *Pediastrum* K, from core 4, sample 1623, depth 33.00 m. Holes visible in substrate are 2 μm in diameter. Scale is 10 μm. *D*, Enlarged view of surface sculpturing of *Pediastrum* K specimen shown in *C*. Scale is 1 μm. *E*, Colony of *Pediastrum* Y, from core 4, sample 1623, depth 33.00 m. Walls are very thin except for some thickening around apertures at ends of 'horns.' Holes in substrate are 2 μm in diameter. Scale is 10 μm. *F*, Enlarged view of part of *Pediastrum* colony shown in *E*. Note thickened apertures around pores at ends of 'horns' and absence of surface sculpturing. Holes in substrate are 2 μm in diameter. Scale is 3 μm.

in its stratigraphic distribution. Other *Pediastrum* types are rare and are not described here.

PERIDINIUM SPP. CYSTS

Under optical microscopy these *Peridinium* spp. cysts resemble TCT (fig. 9*C*) and sedge (fig. 9*E*) pollen grains as well as hystrichosphaerids (fig. 13*C*), but they can be

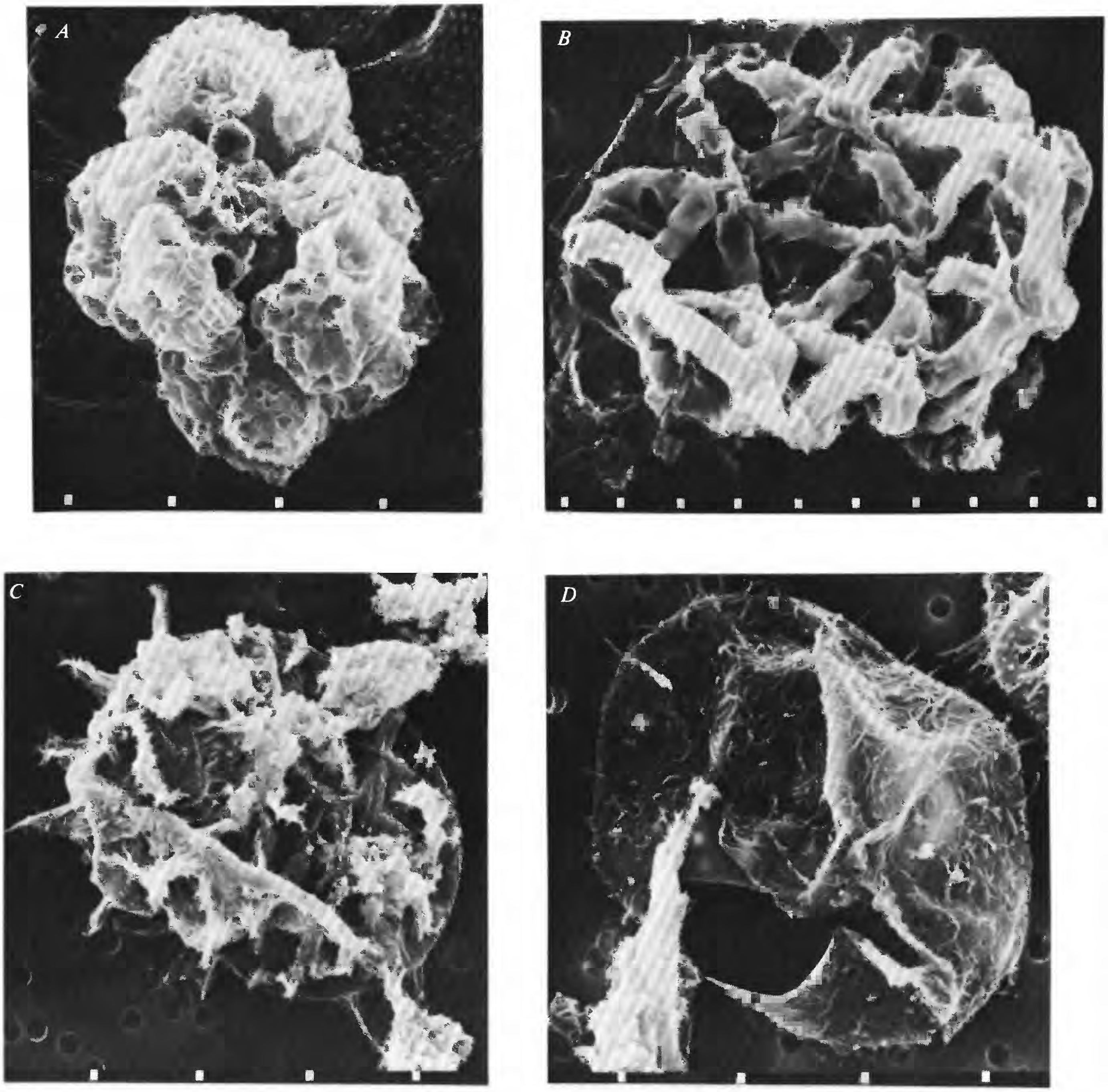


FIGURE 13.—Scanning electron micrographs of algal types. Distance between ticks along bottom of photograph indicates scale. *A*, Colony of *Botryococcus* (with part of a colony of *Pediastrum* N visible in background). From core 7, sample 171, depth 7.20 m. Holes visible in substrate at right are 2 μm in diameter. Scale is 10 μm. *B*, Partly collapsed colony of *Coelastrum*, from core 4, sample 2054, depth 0.20 m. Holes visible in substrate at left are 2 μm in diameter. Scale is 3 μm. *C*, Hystrichosphaerid(?) cyst. Specimen is partly collapsed as a result of drying. Holes in substrate are 2 μm in diameter. Scale is 10 μm. *D*, *Peridinium* cyst, from core 4, sample 2054, depth 0.20 m. Holes visible in substrate are 2 μm in diameter. Scale is 10 μm.

distinguished from those types after one becomes familiar with them. W.R. Evitt (oral commun., 1982), who examined cysts from sample 2054 (20 cm depth, core 4), reports that at least two species of *Peridinium* cysts are present. Circumstantial evidence, based on both the stratigraphic occurrence of the cysts and modern observations made at Clear Lake by Horne and others (1971), suggests that one possible species is *P. penardii*, but none of the cysts examined by Evitt matched the *P. penardii* cyst illustrated by Huber-Pestalozzi (1950).

POLLEN ZONE DEFINITION

FACTOR ANALYSIS RESULTS

The data used for the pollen factor analysis are the first 38 variables of the summary data set (table 5) and include all fossil pollen and also *Isoetes* spores and Nymphaeaceae leaf hairs. The latter two variables were included because they represent vascular plants. The reduced set of 38 variables and 237 samples (165 from core 4 and 72 from core 7) was subjected to a factor analysis as described

TABLE 6.—*Scaled pollen factor scores for percentage data, cores 4 and 7*

Variable name	VARIMAX factors				
	1	2	3	4	5
Quercus	-0.1083	0.9806	0.0004	-0.0510	-0.0563
Pinus	.4159	.0975	.0749	.1767	.8766
Abies	.0179	-.0037	.0058	.0135	.0071
Picea	.0020	.0007	.0018	.0054	.0035
Tsuga	.0063	-.0008	-.0007	.0063	.0039
Pseudotsuga	.0106	.0040	-.0005	-.0020	.0043
TCT	.8821	.0772	.0515	.0917	-.4500
Alnus	-.0117	.0530	.0018	-.0009	.0202
Salix	.0046	.0217	.0004	-.0025	.0029
Brasenia	-.0018	.0009	.0130	-.0008	-.0018
Cyperaceae	-.1683	.0192	.0139	.9707	-.1211
Typha tetrads	-.0088	.0044	.0022	.0309	.0005
Typha monads	-.0050	.0014	.0004	.0421	-.0006
Cruciferae	-.0007	.0119	.0014	.0008	.0013
Potamogeton	-.0033	.0070	.0121	.0236	-.0089
Isoetes	.0286	-.0096	.0034	-.0179	.0816
Unknown A	.0009	.0112	.0071	-.0026	.0075
Artemisia	.0209	-.0063	.0129	.0614	.0018
Rhamnaceae	-.0208	.0737	-.0015	.0024	.0233
Cheno-ams	-.0005	.0087	.0039	.0161	.0085
High-spine Compositae	.0140	.0474	-.0024	.0023	.0253
Gramineae	.0073	.0261	-.0001	.0070	.0102
Polygonaceae	.0031	.0028	-.0008	.0017	.0017
Caryophyllaceae	.0030	-.0007	-.0002	.0022	-.0009
Arceuthobium	.0002	.0015	.0005	.0012	.0005
Portulacaceae	.0071	-.0009	-.0010	-.0029	-.0019
Other trees and shrubs	-.0006	.0030	.0003	.0000	.0031
Other aquatics	-.0023	.0005	.0170	.0137	-.0033
Umbelliferae	-.0091	.0021	.0006	.0502	-.0094
Chrysolepis	-.0065	.0237	-.0006	.0008	-.0088
Corylus	-.0002	.0060	.0001	-.0008	.0010
Juglans	.0005	.0021	.0001	-.0004	.0008
cf. *Tilia*	.0020	.0020	.0002	-.0007	.0105
Fraxinus	.0036	.0051	-.0007	-.0022	.0047
Nymphaeaceae leaf hairs	-.0749	-.0124	.9953	-.0333	-.0412
Lithocarpus	-.0022	.0027	-.0003	.0053	.0012
Other Compositae	.0010	.0052	.0006	-.0005	.0019
Unknowns	.0177	.0981	.0042	.0602	.0237

above; this analysis produced five VARIMAX factors that together account for more than 98 percent of the variance in the data set. Each factor is dominated by only a few variables. These factors are shown in plate 4*A*, and the scaled factor scores are shown in table 6. The five pollen factors are described here because they are used to define the zone boundaries in the following sections, but interpretation of the factors is deferred until the pollen zones are described.

Factor 1 accounts for nearly half of the variance; it responds primarily to TCT (factor score, 0.88) and *Pinus* (0.42), with smaller negative scores for Cyperaceae (−0.17), *Quercus* (−0.11), and Nymphaeaceae leaf hairs (−0.07) (table 6). High factor loadings for factor 1 identify the most common type of sample in the data set. The negative factor loadings for factor 1 are for variables that have high loadings on subsequent factors that identify various other kinds of samples.

Factor 1 produces high factor loadings (>0.60) at depths of 26.00 to 108.67 m in core 4, as well as below 112.13 m, and low loadings above 26.00 m and between 108.00 and 112.00 m. In core 7, loadings above 7.20 m are generally comparable to those at the top of core 4. From 7.70 to 9.00 m slightly negative values are found. Below 9.00 m is a series of oscillations between low and high values unlike any found in core 4 (pl. 4*A*).

Factor 2, which accounts for about one-fourth of the total variance, is dominated by *Quercus* (factor score, 0.98), with lesser contributions from *Pinus* (0.10), TCT (0.08), and Rhamnaceae (0.07) (table 6). Factor 2 produces high factor loadings in the upper 20.00 m of core 4 and the upper 6.80 m of core 7 and also between 108.90 and 112.03 m in core 4. Generally low values are found between 27.00 and 84.00 m in core 4, although some systematic fluctuations that affect groups of adjacent samples are found in this interval and below 112.00 m. Low values are also found below 7.20 m in core 7. Between 84.00 and 108.00 m in core 4, factor 2 shows a series of wide oscillations that change gradually with depth (pl. 4*A*).

Factor 3 responds primarily to Nymphaeaceae leaf hairs (factor score, 0.99), and to a lesser extent to *Pinus* (0.07) and TCT (0.05) (table 6). Loadings are low throughout core 4 except between 21.10 and 27.00 m. The upper 7.00 m of core 7 show similar low loadings, as does the interval between 9.80 and 16.40 m; high loadings are found between 7.20 and 9.40 m. Below a depth of 16.60 m is a series of oscillations between high and low loadings (pl. 4*A*).

Factor 4 responds mostly to Cyperaceae (factor score, 0.97) but also to *Pinus* (0.18) and TCT (0.09) (table 6). *Typha* tetrads and monads also have low positive factor scores, whereas Nymphaeaceae leaf hairs and *Isoetes* spores show low negative scores. Factor loadings are low throughout core 4 and for the upper 9.40 m of core 7. Between 9.80 and 15.80 m in core 7 the factor 4 loadings are consistently high; below 15.80 m is a series of oscillations that appear to be inversely related to the oscillations of factor 3 within this interval (pl. 4*A*).

Factor 5, which accounts for only 4 percent of the variance in the data, is more complex than the first four factors. The variables that contribute positively to factor 5 are dominated by *Pinus* (factor score, 0.88) with a smaller contribution by Isoetes (0.08) (table 6). Negative-effect variables include TCT (−0.45) and Cyperaceae (−0.12). High factor loadings for factor 5 are found for samples that have a high frequency of *Pinus* pollen relative to TCT pollen.

ZONE BOUNDARIES

The factor loadings were used to select boundaries between pollen assemblage zones using the procedure described earlier. These zones are listed in table 7 and are shown on the pollen, algal, and factor diagrams (pls. 1, 2, 3, and 4). These zone boundaries account for 92.4 per-

TABLE 7.—*Numbers of samples and depth ranges of the Clear Lake pollen assemblage zones*

Pollen zone	Number of samples in zone	Depth (m) Top sample	Depth (m) Bottom sample
	Core 4		
A	22	0.10	20.00
B	3	21.10	22.95
C	2	25.05	25.43
D	3	26.00	28.00
E	18	29.40	44.30
F_a	27	46.00	72.04
F_b	14	73.01	83.88
G	2	84.25	84.55
H	3	84.85	86.07
I	8	87.04	92.62
J	4	92.82	94.90
K	2	95.82	96.78
L	5	98.51	101.30
M	4	101.62	102.12
N	11	102.22	104.36
O	6	104.56	105.68
P	4	105.88	107.10
Q	2	107.60	108.07
R	6	108.17	108.67
S	12	108.90	112.13
T	5	112.23	114.01
U	2	114.57	115.07
	Core 7		
A7	15	0.00	6.80
B7	9	7.20	9.40
C7	20	9.80	16.40
D7	28	16.60	27.10

cent of the variance of the core 4 factor loadings and for 67.0 percent of the core 7 variance.

One zone (F) has been further subdivided empirically. When the zone boundary between zones F_a and F_b was included in the zonation scheme, the boundary between zones F and G became unstable. The F_a–F_b boundary is useful for interpretation, but it is treated as a different class of boundary because of this stability problem.

ZONE DESCRIPTIONS

Once the zone boundaries were determined, mean values and standard deviations were calculated for each pollen type present in the zone. In the following section, standard deviations are estimated values for each zone rather than calculated values for a population consisting of the samples in the zone.

CORE 4

ZONE A

Pollen zone A extends from the top of the core to a depth of 20.00 m and is represented by 22 samples. Loadings are high (>0.90) for factor 2 and low for the other factors (pl. 4*A*). The dominant pollen type, *Quercus*, has a frequency of 59.0 ± 5.0 percent. *Pinus* and TCT frequencies are less than 20 percent. Other relatively common pollen types are Rhamnaceae (6.0 ± 4.0 percent), *Alnus* (5.2 ± 1.4 percent), high-spine Compositae (3.2 ± 1.6 percent), Gramineae (2.6 ± 1.4 percent, pl. 1), and Cyperaceae (3.3 ± 1.9 percent, pl. 2). Two types show systematic variations within zone A. Rhamnaceae pollen is present in only minor amounts in the bottom six samples of zone A and rises in frequency above a depth of 13.00 m (pl. 1). *Chrysolepis* is absent from the bottom three samples but is present in low frequencies above a depth of 16.00 m.

ZONE B

Zone B is represented by three samples that range in depth from 21.10 to 22.95 m. Loadings for factor 2 are lower than in zone A and decrease with increasing depth from 0.66 at 21.10 m to 0.39 at 22.95 m (pl. 4*A*). The factor loadings for the other factors are higher than in zone A, and the factor loadings for factor 5 are the highest observed in either core. *Pinus* is the most common pollen type in zone B (52.5 ± 12.8 percent), followed by *Quercus* (23.2 ± 7.7 percent) and TCT (14.4 ± 2.9 percent) (pl. 1). *Isoetes* spores (11.1 ± 3.1 percent), Nymphaeaceae leaf hairs (8.2 ± 4.4 percent), and Cyperaceae pollen (3.6 ± 0.4 percent) are the most common aquatic elements (pl. 2). Significant minor types are *Alnus* (4.0 ± 2.3 percent), which triples in frequency from the bottom to the top of zone B, and high-spine Compositae (2.1 ± 1.4 percent) (pl. 1).

ZONE C

Zone C is represented by only two samples, at 25.05 m and 25.43 m. Loadings for factors 2 and 5 are lower than in zone B, factor 1 loadings are about the same, and factors 3 and 4 have the highest values observed in core 4 (pl. 4*A*). *Pinus* (45.4 ± 3.4 percent) and TCT (32.2 ± 5.5 percent) are the most common AP (arboreal pollen) types, followed by *Quercus* (15.2 ± 0.8 percent) (pl. 1). Aquatic types are important in zone C and include Nymphaeaceae leaf hairs (53.7 ± 5.6 percent of AP), Cyperaceae pollen (15.7 ± 5.3 percent), *Isoetes* spores (9.0 ± 3.9 percent), and *Typha-Sparganium* type (2.3 ± 0.6 percent) (pl. 2). Cruciferae pollen (2.8 ± 3.9 percent) may also represent aquatic species. Minor types include high-spine Compositae (3.0 ± 0.7 percent) and *Alnus* (2.0 ± 1.1 percent) (pl. 1). Within and above zone C, *Alnus* is consistently present in core 4; below zone C, it is found only sporadically. Another minor component of the zone C assemblage is Unknown A (4.6 ± 1.5 percent).

ZONE D

The three samples in zone D are from depths of 26.00 to 28.00 m. Factor loadings for factor 1 are higher than in zones A–C (0.70–0.84), and loadings for factor 2 are lower (<0.28) (pl. 4*A*). Loadings for factor 3 are fairly high (0.17–0.40) and increase upward toward the peak in zone C. Factor 4 loadings are similar to those in zones B and C. Factor 5 loadings are higher than those in zone C (0.42–0.54) but not so high as those in zone B.

Pinus is the most common pollen type (51.4 ± 4.4 percent), followed by TCT (34.5 ± 5.7 percent) and *Quercus* (5.0 ± 4.6 percent) (pl. 1). *Abies* (2.1 ± 1.9 percent) is present as a minor element, along with Gramineae (1.6 ± 1.0 percent) and *Salix* (1.1 ± 1.1 percent). Both *Abies* and *Salix* are missing from the top sample. Nymphaeaceae leaf hairs (12.6 ± 7.5 percent), Cyperaceae pollen (3.4 ± 0.7 percent), and *Isoetes* spores (3.4 ± 3.0 percent) are significant, although much less common than in zone C (pl. 2). Unknown A is also a minor component of the zone D assemblage (3.4 ± 5.9 percent).

ZONE E

Zone E is represented by 18 samples ranging in depth from 29.40 to 44.30 m. Loadings are high for factor 1 (mostly >0.90) and low for factors 2 and 3 (<0.17) (pl. 4*A*). Factor 4 loadings are fairly high compared to the rest of core 4 (0.17–0.25) but not so high as in parts of core 7. Loadings for factor 5 are systematically positive within zone E but vary considerably (0.07–0.61). The most common pollen types are TCT (51.9 ± 6.7 percent) and *Pinus* (42.5 ± 6.8 percent) (pl. 1). Minor types include *Artemisia* (3.9 ± 2.0 percent), Gramineae (2.3 ± 1.2 percent), *Abies* (1.8 ± 1.2 percent), and high-spine Compositae (1.6 ± 1.1 percent). *Quercus* is rare (1.2 ± 0.7 percent). Aquatic types (pl. 2) include *Isoetes* (8.9 ± 6.1 percent), Cyperaceae (2.5 ± 1.5 percent), and Nymphaeaceae leaf hairs (1.6 ± 1.1 percent). Nymphaeaceae leaf hairs are less abundant than Cyperaceae or *Isoetes*, in contrast to zones C and D.

ZONE F

Zone F, the thickest zone recognized in the data set, is represented by 41 samples ranging in depth from 46.00 to 83.88 m. The factor loadings for factors 1, 3, and 4 show very little variability within the zone, except for a single-sample local minimum for factor 1 at a depth of 59.04 m (pl. 4*A*). Factor 2 shows a series of low-amplitude oscillations above a depth of 70.98 m, and factor 5 fluctuates in an apparently random way throughout the zone. The dominant pollen type is TCT (62.3 ± 6.1 percent), and the other major type is *Pinus* (29.5 ± 6.2 percent) (pl. 1). *Quercus* is a minor type in zone F (4.1 ± 3.2 percent); other minor types include *Artemisia* (2.5 ± 1.7 percent), Cyperaceae (2.0 ± 1.3 percent), high-spine Compositae (1.8 ± 1.1 percent), *Abies* (1.4 ± 1.0 percent), and Gramineae (1.2 ± 0.9 percent). *Artemisia* is in general more common in the upper third of the zone, as is *Abies* to a lesser extent. Three local maxima of *Isoetes* spores occur in the upper half of the zone, including the prominent peak (48.9 percent) at 59.04 m (pl. 2).

As noted above, pollen zone F is further subdivided empirically to facilitate discussion. The upper part of zone F shows several systematic fluctuations in the *Quercus* pollen curve, but the zoning algorithm did not produce useful and stable boundaries within zone F. The zone is divided into an upper part (F_a) and a lower part (F_b) using a criterion of 5 percent *Quercus* pollen; the boundary between the two subzones lies between samples 1409 (73.01 m) and 1416 (72.04 m). The same criterion is used later to define subunits within subzone F_a.

ZONE G

Zone G is represented by two samples at 84.25 and 84.55 m. The primary feature setting the zone apart from those on either side is relatively high factor loadings for factor 2 (about 0.43) and slightly lower loadings for factor 1 (<0.90) (pl. 4*A*). The lower sample also shows a sharp peak for factor 5 (0.40). Loadings for factors 3 and 4 are similar to those of adjoining zones. TCT (40.9 ± 9.5 percent) and *Pinus* (37.7 ± 10.5 percent) are the most common pollen types, but *Quercus* is also important (18.3 ± 0.2 percent) (pl. 1). Minor types include Cyperaceae (2.3 ± 1.8 percent), Gramineae (2.1 ± 0.7 percent), high-spine Compositae (1.5 ± 0.01 percent), and *Abies*, *Artemisia*, and other Compositae (each 1.0 ± 0.7 percent).

ZONE H

Zone H is represented by three samples from depths between 84.85 and 86.07 m. Loadings are similar to those in zone F. TCT (58.3 ± 1.9 percent) and *Pinus* (32.7 ± 2.5 percent) are the most common pollen types, followed by *Quercus* (5.1 ± 2.8 percent) (pl. 1). Minor types include high-spine Compositae (2.6 ± 1.0 percent), *Abies* (2.4 ± 1.3 percent), Gramineae (2.0 ± 1.6 percent), Cyperaceae (1.5 ± 0.8 percent), and Portulacaceae (1.4 ± 1.9 percent).

ZONE I

Zone I is represented by eight samples that range in depth from 87.04 to 92.62 m. Loadings for factor 1 are <0.80, and loadings for factor 2 are >0.40 (pl. 4*A*). These joint criteria distinguish zone I samples from samples in the adjacent zones. TCT is the most common pollen type (44.0 ± 4.3 percent), followed by *Quercus* (28.1 ± 4.9 percent) and *Pinus* (22.7 ± 5.9 percent) (pl. 1). *Quercus* frequencies decrease upward within zone I, whereas *Pinus* and TCT increase. Small amounts of *Alnus* and *Salix* pollen are found in the lower half of the zone but not in the upper half. Minor pollen types include Cyperaceae (1.3 ± 0.7 percent, pl. 2) and high-spine Compositae (1.1 ± 0.7 percent) and *Abies* (1.0 ± 0.5 percent) (pl. 1).

ZONE J

Zone J is represented by four samples ranging in depth from 92.82 to 94.90 m. Factor loadings are similar to those of zone E (pl. 4*A*). TCT (51.0 ± 2.3 percent) and *Pinus* (40.6 ± 3.3 percent) account for most of the AP; *Quercus* is scarce (4.0 ± 2.2 percent) (pl. 1). Minor types include *Abies* (1.9 ± 0.4 percent, pl. 1) and Cyperaceae (1.6 ± 0.7 percent, pl. 2).

ZONE K

Zone K is represented by two samples at depths of 95.82 and 96.78 m. Factor loadings are generally similar to those of zone J, except that loadings for factor 5 are negative instead of positive (pl. 4*A*). TCT pollen is very common (68.6 ± 1.0 percent), much more so than *Pinus* (19.7 ± 5.1 percent) or *Quercus* (8.8 ± 6.1 percent) (pl. 1). Minor types include Cyperaceae (2.6 ± 1.2 percent, pl. 2), *Artemisia* (1.7 ± 1.8 percent), and high-spine Compositae (1.1 ± 0.2 percent) (pl. 1).

ZONE L

Zone L is represented by five samples at depths between 98.51 and 101.30 m. Factor loadings are similar to those of zone I, but factor 5 has more positive loadings in zone L, notably in the lowest two samples (pl. 4*A*). TCT (39.1 ± 6.2 percent), *Pinus* (28.8 ± 8.0 percent), and *Quercus* (27.5 ± 6.4 percent) are all important pollen types (pl. 1). Minor types include *Fraxinus* (1.4 ± 1.3 percent) and high-spine Compositae (1.2 ± 1.2 percent).

ZONE M

Zone M is represented by four samples from the 50-cm interval between 101.62 and 102.12 m. The main feature that sets zone M apart from adjacent zones is the low loadings for factor 2 (<0.27); those loadings contrast with values >0.45 throughout zones L and N (pl. 4*A*). TCT (46.0 ± 6.2 percent) and *Pinus* (43.7 ± 7.2 percent) are nearly equally common, whereas *Quercus* (7.1 ± 1.6 percent) is much reduced from its frequency in the adjoining zones (pl. 1). Minor types include high-spine Compositae (1.7 ± 0.8 percent) and Cyperaceae (1.2 ± 0.5 percent).

ZONE N

Zone N is represented by 11 samples between 102.22 and 104.36 m. The most common type is TCT (40.5 ± 6.0 percent), and *Quercus* (31.7 ± 5.7 percent) is more common than *Pinus* (23.7 ± 6.4 percent) (pl. 1). Minor types include high-spine Compositae (1.5 ± 1.1 percent), Cyperaceae (1.0 ± 0.8 percent), and *Alnus* (1.0 ± 0.8 percent). Small amounts of *Corylus* appear irregularly in zone N but are not found in adjacent zones.

ZONE O

Zone O is represented by six samples at depths between 104.56 and 105.68 m. Loadings for factors 1, 3, and 4 are slightly higher in zone O than in zone N (pl. 4*A*). The distinctive factor patterns for zone O are for factor 2, which has much lower loadings than in the adjacent zones, and factor 5, which has much higher loadings. The most common pollen type is *Pinus* (55.6 ± 5.3 percent), followed by TCT (33.0 ± 4.6 percent) (pl. 1). *Quercus* is relatively scarce (7.2 ± 3.3 percent). Minor types include high-spine Compositae (1.9 ± 1.2 percent), Cyperaceae (1.6 ± 1.5 percent), *Artemisia* (1.2 ± 0.5 percent), and *Abies* (1.1 ± 1.1 percent). Smaller amounts of *Salix, Pseudotsuga*, and *Fraxinus* are also present.

ZONE P

Zone P is represented by four samples that range in depth from 105.88 to 107.10 m. Loadings for factor 2 are in the range 0.33–0.52, higher than in the adjoining zones O and Q but lower than in zones I, L, N, and S (pl. 4*A*). Loadings for factor 5 are low (<0.31) in contrast to zone O. Loadings for factors 3 and 4 differ little from those of adjacent zones. The most common pollen types are TCT (42.7 ± 2.9 percent) and *Pinus* (37.1 ± 5.1 percent) (pl. 1). *Quercus* is more common in zone P than in the adjacent zones O and Q. Less common types include Cyperaceae (3.4 ± 0.8 percent), high-spine Compositae (2.3 ± 1.3 percent), *Artemisia* (1.2 ± 0.9 percent), *Fraxinus* (1.0 ± 0.9 percent), and Cheno-ams (1.0 ± 0.9 percent).

ZONE Q

Zone Q is represented by two samples at depths of 107.60 and 108.07 m. The zone is separated from the adjoining zones on the basis of low (<0.25) loadings for factor 2 (pl. 4*A*). There is also a peak value of 0.64 (pl. 4*A*) for factor 5 in the lower sample of zone Q, but that value appears to be more closely related to the values in zone R than to the other zone Q value. The dominant pollen type is *Pinus* (52.8 ± 16.8 percent); TCT pollen is also common (36.6 ± 16.2 percent) (pl. 1). Minor types include high-spine Compositae (4.1 ± 5.1 percent), *Fraxinus* (3.4 ± 1.7 percent), and Cyperaceae (2.4 ± 1.0 percent).

ZONE R

Zone R is represented by six samples at 10-cm intervals between the depths of 108.17 and 108.67 m. These samples plus the lower sample of zone Q came from a single segment of the core. Loadings for factor 1 are in the range 0.70–0.79, somewhat lower than in the two overlying zones but much higher than in zone S (pl. 4*A*). Factor 2 loadings range from 0.38 to 0.58, again intermediate between the overlying and underlying zones. Loadings for factor 5 reach a local maximum if the lower sample of zone Q is included, and factors 3 and 4 both show increases above the values found in zone S. *Pinus* and TCT (42.2 ± 4.6 and 33.3 ± 2.3 percent) are the major pollen types, but *Quercus* (18.7 ± 4.2 percent) is also fairly common (pl. 1). This zone also includes the highest percentages of high-spine Compositae (7.5 ± 2.6 percent) found in either core 4 or core 7. Minor types include Rhamnaceae (3.5 ± 1.0 percent), Cyperaceae (3.3 ± 1.3 percent), cf. *Tilia* (2.9 ± 1.0 percent), *Chrysolepis* (1.6 ± 1.6 percent), Gramineae (1.3 ± 1.1 percent), and Cruciferae (1.1 ± 0.8 percent), as well as *Salix* (1.0 ± 0.4 percent) and *Pseudotsuga* (0.8 ± 0.7 percent).

ZONE S

Zone S is represented by 12 samples that range in depth from 108.90 to 112.13 m. Loadings for factor 1 are similar to those for zone A, but even smaller values are found in the middle of this zone (pl. 4*A*). Loading values for factor 2 increase from 0.80 for the lowest sample to more than 0.95 for the upper eight samples. The dominant pollen type is *Quercus* (66.9 ± 12.8 percent); in the middle of zone S it reaches its highest frequencies found in either core (pl. 1). TCT is fairly common (20.7 ± 7.2 percent), but *Pinus* is less frequent (8.4 ± 5.4 percent) than in any other part of the core. Pollen of the high-spine Compositae (3.3 ± 1.9 percent) and Cyperaceae (1.8 ± 0.8 percent) are found throughout the zone. Several minor types are found primarily in the upper half of zone S, including Cruciferae, *Chrysolepis*, *Fraxinus*, and *Juglans*. *Salix* is more common in the upper and lower parts of zone S than in the middle.

ZONE T

Zone T is represented by five samples ranging in depth from 112.23 to 114.01 m. Although loadings for factor 1 are high, they decline from a value of 0.97 at the base of the zone to 0.85 at the top (pl. 4*A*). Factor 2 loadings are quite low at the base of the zone (0.12) but increase to a value of >0.45 at the top. Loadings for factors 3 and 4 are comparable to those in zones O–R, and loadings for factor 5 are positive but small. The most common pollen types are TCT (48.3 ± 8.8 percent) and *Pinus* (32.8 ± 2.5 percent) (pl. 1). TCT values reach a local maximum in zone T, whereas *Pinus* values are steady within the zone, and *Quercus* values increase almost steadily through time. Zone T is notable for the uncommon but consistently present pollen of several conifers in addition to *Pinus* and TCT: these include *Pseudotsuga* (2.7 ± 0.7 percent), *Tsuga* (1.8 ± 0.9 percent), *Picea* (0.9 ± 0.8 percent), and *Abies* (0.9 ± 0.4 percent). Other minor types include high-spine Compositae (1.1 ± 0.7 percent) and Cyperaceae (1.0 ± 0.6 percent).

One problematical sample (1233) from zone T has been excluded from the core 4 data. This sample, which was recorded from a depth of 112.33 m, was taken from the lowermost part of core slug 123 (Sims and Rymer, 1975c). This sample contained abundant *Quercus* pollen comparable to that found in zone S but from a depth within zone T. The resulting fluctuations in the pollen curves appeared much more likely to be the result of an error in the laboratory than the result of climatic changes, so the sample has been excluded from this analysis. The data for the missing sample are presented in Adam (1979a).

The most likely cause of the irregular results for sample 1233 is that it and the sample above it were reversed, either during the initial sampling or during the processing of the pollen samples. An alternative explanation, since the suspect sample came from the lowest part of a core section, is that the base of the section somehow became contaminated with sediment from zone S before the core section was removed from the hole. The degree of consolidation of the sediments near the bottom of the core makes this seem unlikely.

ZONE U

Zone U is represented by the bottom two samples of core 4 at depths of 114.57 and 115.07 m. Loadings for factors 1, 3, and 4 are similar to those found in zone T (pl. 4*A*), factor 2 loadings are lower than those in zone T (and among the lowest found in the core), and factor 5 loadings are high (>0.40). The zone is dominated by *Pinus* (54.5 ± 1.6 percent) and TCT (39.5 ± 0.3 percent) pollen, followed by *Tsuga* (1.9 ± 0.7 percent), *Pseudotsuga* and Gramineae (both 1.7 ± 0.4 percent), and *Abies* (1.0 ± 0.8 percent) (pl. 1). Only a single grain of *Quercus* was found in the zone.

CORE 7

ZONE A7

Zone A7 is represented by the top 15 samples in core 7 and ranges in depth from 0.00 to 6.80 m. The dominant factor pattern is one of high loadings for factor 2 (pl. 4*A*). The other factors all show higher loadings in the upper and lower parts of the zone than in the middle. The most common pollen type is *Quercus* (41.5 ± 5.2 percent), followed by *Pinus* (15.5 ± 3.9 percent) and TCT (9.7 ± 2.1 percent) (pl. 1). Rhamnaceae pollen is common above a depth of 4.40 m, and *Chrysolepis* pollen is present throughout the upper half of the zone. *Alnus* (2.1 ± 0.8 percent) is present throughout the zone, and high-spine Compositae are most common below a depth of 2.00 m. Gramineae pollen shows two peaks, a broad one in the middle of the zone and a sharper one in the topmost sample. Cyperaceae pollen is most frequent in the lower half of the zone, and there is a single-sample peak of *Potamogeton* pollen at 6.40 m (pl. 2).

ZONE B7

Zone B7 is represented by nine samples between the depths of 7.20 and 9.40 m. The zone is characterized by factor 3 loadings >0.90 and loadings near zero for the other four factors (pl. 4*A*). The dominant microfossils in this zone are Nymphaeaceae leaf hairs (506.8 ± 396.2 percent of AP), which are several times as abundant as pollen grains (pl. 2). *Brasenia* pollen (pl. 9*F*) is also common (16.5 ± 18.3 percent), and probably represents the same plants as the leaf hairs. The most common tree pollen types are *Pinus* (27.7 ± 11.1 percent) and TCT (15.6 ± 4.1 percent), but *Quercus* is also present in quantity (10.1 ± 5.7

percent) (pl. 1). Other aquatic pollen types include Cyperaceae (12.1 ± 7.4 percent), Unknown A (1.9 ± 1.6 percent), other aquatics (1.9 ± 1.6 percent), and *Potamogeton* (1.0 ± 1.1 percent) (pl. 2).

ZONE C7

Zone C7 is represented by 20 samples at depths between 9.80 and 16.40 m. Loadings for factor 4 are consistently high in this zone, whereas loadings for factor 3 are generally low (pl. 4*A*). Loadings for factor 1, which are as high or higher than in zone A7, show the highest values in the middle of the zone. Factor 5 increases irregularly to values >0.40 near the top of the zone. Only factor 2 is consistent throughout the zone, and it generally has low values. The most common pollen type in zone C7 is Cyperaceae (38.1 ± 12.9 percent, pl. 2), in marked contrast to all other zones in both cores; zone C7 is the only zone not dominated by *Quercus*, *Pinus*, or TCT (pl. 1). Other aquatic types present in zone C7 are *Typha*, *Typha-Sparganium*, and Umbelliferae (pl. 2; Umbelliferae are shown on pl. 1). The major AP types are *Pinus* (20.3 ± 7.3 percent) and TCT (20.1 ± 8.0 percent). Small amounts of *Abies* (1.0 ± 0.8 percent) are also present as well as occasional grains of *Picea*, *Tsuga*, and *Pseudotsuga*.

ZONE D7

Zone D7 is represented by the lowest 28 samples in core 7 and extends from a depth of 16.60 m to the bottom of the core at 27.10 m. The zone is characterized by abrupt short-term fluctuations in factors 1, 3, and 4, and somewhat smaller fluctuations in factor 5 (pl. 4*A*). Although zone D7 could easily be subdivided into several smaller zones, the general appearance of the zone suggests that this would not be useful, so this zone is characterized here by its variability rather than by its uniformity. TCT (32.7 ± 8.1 percent) and *Pinus* (28.4 ± 8.5 percent) are the most common AP types, and *Quercus* (2.0 ± 1.7 percent) and *Abies* (1.5 ± 1.2 percent) are also present (pl. 1). *Artemisia* (4.3 ± 2.4 percent) is also rather common, and there are a few minor peaks in the Cheno-ams curve. Aquatic types (pl. 2) are both common and highly variable, and include Nymphaeaceae leaf hairs (96.8 ± 106.2 percent), Cyperaceae (17.1 ± 14.5 percent), *Potamogeton* (2.7 ± 4.5 percent), and "Other Aquatics" (2.4 ± 1.8 percent). *Typha* and *Typha-Sparganium* also appear intermittently, especially in the lower part of the zone.

POLLEN CONCENTRATION

Two independent pollen concentration curves were constructed for oak, pine, TCT, and total pollen in core 4 using the *Eucalyptus* and *Lycopodium* tracer counts (fig. 14). Where the two curves agree, their average value is taken as a good estimate of the pollen concentration. Where they disagree, the disagreement is taken as a warning that the amount of tracer pollen added to the sample was not what would have been expected on the basis of the weight of the tablets. Such discrepancies are not uncommon, as the scatter of the data points in figure 6 suggests. The dual-tracer technique allows one to distinguish variations in the fossil pollen content of the sediments from spikes caused by errors in the amount of tracer pollen added to a sample.

Although pollen concentration data in many cases provide better estimates than percentage data of the amount of a particular pollen type incorporated into sediment as a function of time, such data are subject to more statistical "noise" than percentage data. Both types of data are subject to statistical errors of estimation in counting a particular pollen type. Additional sources of error for pollen concentration data include (1) variations in the amount of tracer pollen added to the sample, (2) statistical counting errors in estimating the amount of tracer pollen, and (3) errors in measuring sample volume or weight.

The pollen concentration curves represent the integrated effects of three potentially independent factors: pollen influx, sediment density, and sedimentation rate. More sources of variability for both signal and noise affect concentration data, and thus the pollen concentration curves are not so smooth and regular as the corresponding pollen percentage curves.

The statistical errors associated with the tracer pollen counts are greatest where the counts are smallest. Tracer counts are generally smaller at greater depths because of the constant estimated number of tracer grains added to each sample. At shallow depths, much of the initial sample volume is water, and the tracers are thus added to a relatively small number of fossil grains. At greater depths, the water content decreases and the volumetric pollen content increases (figs. 7 and 14*E*).

The number of tracer grains recovered per sample ranges from 22 to 228 for *Eucalyptus* and from 30 to 236 for *Lycopodium*. The frequencies of the tracers, expressed as percentages of the fossil pollen sum (pl. 2), are generally less than 100 percent of the pollen sum except near the top of core 4. The narrowest confidence limits for estimated pollen concentrations are obtained when the fossil and tracer pollen types are equal (Regal and Cushing, 1979). The estimates of total fossil-pollen concentrations are therefore probably most accurate near the top of core 4, but the concentration estimates for individual pollen types may be better estimated at greater depths.

Before the differences between the pollen percentage and concentration curves can be evaluated, it is necessary to evaluate the reliability of the concentration curves themselves. This has been done by plotting the *Eucalyptus*-based and *Lycopodium*-based curves for a given type

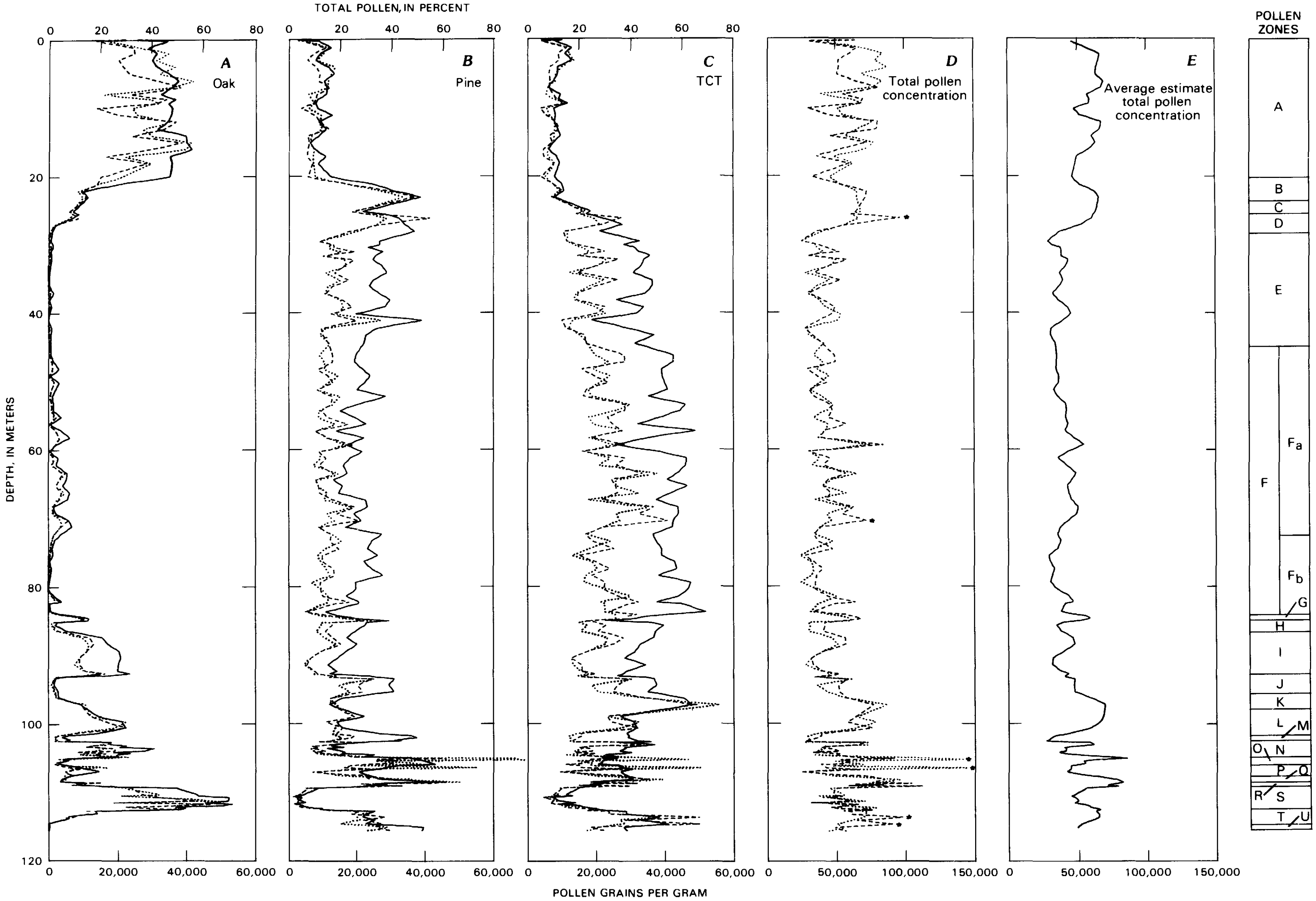


FIGURE 14.—Concentration and percentage data plotted against depth for oak, pine, and TCT pollen, core 4. *A*, Oak pollen; *B*, Pine pollen; *C*, TCT pollen. *A–C*, Solid line indicates pollen percentage; dashed line, pollen concentration estimate based on *Lycopodium* tracer counts; and dotted line, pollen concentration based on *Eucalyptus* tracer counts. *D*, Estimate for total pollen concentration; dashed line, pollen concentration estimate based on *Lycopodium* tracer counts; dotted line, pollen concentration based on *Eucalyptus* tracer counts; asterisks indicate concentration estimates ignored in calculating values for *E* because of probable errors. *E*, Averaged estimate of total pollen concentration.

against the same depth scale (dotted and dashed lines in figs. 14*A*–*C*).

Inspection of the two curves for TCT concentration (fig. 14*C*) reveals several prominent peaks that appear in only one curve. For the *Eucalyptus*-based curve, there are two spurious peaks at depths of 104.76 and 105.88 m; for the *Lycopodium*-based curve, there are six apparently spurious peaks at depths of 26.00, 46.00, 47.00, 70.01, 113.04, and 114.01 m. These same false peaks are also seen in the curves for pine (fig. 14*B*) although the peaks are not so prominent when concentrations are relatively low (for example, the 113.04- and 114.01-m samples).

The oak curves (fig. 14*A*) show only one clearly false peak, at 105.88 m; it is also observed in the pine and TCT curves. In addition, there is also a rather wide range between the two estimates of oak-pollen concentration near the top of the core between depths of 2 and 5 m. Within that depth range, estimates of oak-pollen concentration based on *Eucalyptus* average 50 percent higher than those based on *Lycopodium.* Both *Eucalyptus* and *Lycopodium* curves increase with decreasing depth in that interval (pl. 2), but *Lycopodium* increases faster than *Eucalyptus*. The reason for the "extra" *Lycopodium* is uncertain. Statistical errors are unlikely to produce such a well-defined peak that includes several adjacent samples. Furthermore, the distribution of *Lycopodium* in California suggests that the plant was not growing around Clear Lake in the upper Holocene (Munz and Keck, 1959).

A curve (fig. 14*E*) showing the estimated total concentration of fossil pollen in core 4 plots the average of the *Eucalyptus*- and *Lycopodium*-derived values except for the eight anomalous samples noted above that showed spurious peaks in one curve. For those eight samples, only the concentration value from the curve that lacked the anomalous peak is used. The concentration curve in figure 14*E* has been smoothed using a three-level weighted moving average of the form

$$y_i = (x_{i-1} + 2x_i + x_{i+1})/4, \qquad (3)$$

where y_i is the smoothed value for sample i, and the x's are the data values for sample i and the samples above and below it. No correction was made to compensate for the varying stratigraphic distance between samples.

To test the possibility that the total pollen concentration fluctuations (fig. 14*E*) are the result of variations in sediment density, a revised pollen concentration curve (not shown) was prepared by correcting each observation to compensate for differences of sediment density from the expected values shown by the calculated depth versus density curve in figure 7. The corrected curve differs little from the concentration curve shown in figure 14E; a few of the maxima and minima of the curve are slightly decreased in amplitude. The agreement between the two curves is evidence that the concentration curve shown in figure 14*E* primarily reflects variations in pollen influx and sedimentation rate and not variations in sediment density. The uniform lithology of the core also supports this conclusion.

Pollen concentrations are highest near the top and bottom of core 4. A number of sharp peaks below a depth of 80 m indicate pollen concentrations of more than 50,000 grains per gram. Between 27 and 80 m, concentrations are generally less than 50,000 grains per gram. Above a depth of 27 m in the core, pollen concentrations are again generally greater than 50,000 grains per gram.

Below a depth of about 95 m, total pollen concentration appears negatively related to sediment-density residuals. This suggests that at those times when the sediment density was relatively high, the sedimentation rate was also high, so that the pollen was diluted to lower concentrations. Above 95 m, there is no apparent relation between the total pollen concentration and sediment-density residual curves.

COMPARISON OF PERCENTAGE AND CONCENTRATION CURVES

Core 4 factor scores from a principal component factor analysis on the *Eucalyptus*- and *Lycopodium*-based pollen concentration estimates for oak, pine, and TCT pollen, using the CABFAC program (Klovan and Imbrie, 1971; Adam, 1976a), are shown in table 8. The first three factors accounted for 98.75 percent of the variance and correspond to factors 1, 2, and 5 in the factor analysis of the pollen percentage data (pl. 4*A*). Factors 3 and 4 of the percentage data respond mainly to aquatic variables that are not included in the concentration data. The remaining factors account for the variability that results from differences between the *Eucalyptus*- and *Lycopodium*-based estimates of pollen concentration. A VARIMAX rotation of the first three factors produced the factor scores shown in table 9 and the factor diagram shown in plate 4*B*. The responses of factors 1 through 3 are dominated by TCT, oak, and pine, respectively. The differences between the three pollen concentration factors and the corresponding percentage curves of their dominant pollen types are relatively minor.

The overall similarity between the first three factors of the pollen concentration data and the corresponding factors (1, 2, and 5) of the percentage data for all pollen types in the summary data set is illustrated in figures 15, 16, and 17. For each pair of factors, a perfect linear relation would produce a straight line of plotted data points; this condition is most nearly satisfied in figure 16, which compares the two factors that mimic the oak curve. Only three data points in figure 16 depart markedly from the straight line formed by the rest of the sample points.

TABLE 8.—*Scaled factor scores for pollen concentration data for oak, pine, and TCT pollen in core 4*

[Data are both *Eucalyptus*- and *Lycopodium*-based concentration estimates for oak, pine, and TCT pollen in core 4]

Pollen concentrations	factors					
	1	2	3	4	5	6
Oak, based on *Eucalyptus* counts	0.227	0.700	-0.014	-0.216	-0.642	-0.004
Oak, based on *Lycopodium* counts	.221	.639	-.043	.272	.684	-.001
Pine, based on *Eucalyptus* counts	.388	-.093	.624	-.390	.155	-.524
Pine, based on *Lycopodium* counts	.401	-.125	.524	.491	-.174	.526
TCT, based on *Eucalyptus* counts	.527	-.172	-.344	-.555	.189	.481
TCT, based on *Lycopodium* counts	.557	-.221	-.464	.422	-.172	-.466
Percent of variance	77.38	17.17	4.21	.96	.23	.05
Cumulative percent of variance	77.38	94.55	98.75	99.72	99.95	100.00

TABLE 9.—*Scaled factor scores for VARIMAX rotation of first three factors for oak, pine, and TCT pollen concentration data in core 4*

Pollen concentrations	VARIMAX factors		
	1	2	3
Oak, based on *Eucalyptus* counts	-.240	1.786	-.018
Oak, based on *Lycopodium* counts	-.161	1.649	-.072
Pine, based on *Eucalyptus* counts	.295	.103	1.788
Pine, based on *Lycopodium* counts	.447	.063	1.583
TCT, based on *Eucalyptus* counts	1.563	.221	-.250
TCT, based on *Lycopodium* counts	1.786	.163	-.481
Percent of variance	56.286	28.017	14.450
Cumulative percent of variance	56.286	84.304	98.754

Those samples are anomalous for all three pairs of factors; the depths associated with those sample points are noted on figures 15, 16, and 17. The oak percentage curve differs very little from the oak-pollen concentration curve for core 4 (fig. 15). Much of the interpretation of the pollen record is based on the fluctuations in the oak percentage curve, so it is reassuring that except for three data points, the oak percentage curve is apparently free of spurious fluctuations introduced by the conversion of the pollen counts to percentages.

The three anomalous samples are from depths of 25.05, 25.43, and 101.30 m. The upper two samples, which are both from pollen zone C, contain the highest sedge (Cyperaceae) pollen frequencies found in core 4. The "extra" sedge pollen introduced a constraint on the oak-pollen percentages for pollen zone C that was not present elsewhere in core 4. The sample at 101.30 m is the bottommost sample of pollen zone L and is discussed in subsequent sections. The first factors for percentage and concentration data sets are similar (fig. 15), but the correspondence is not so close as that for factor 2 (fig. 16). In addition to the three anomalous points already noted, three distinct groups of points lie away from the perfect-fit straight line. The first consists of a single point for sample 1245, at a depth of 59.04 m. The high peak of *Isoetes* spores in that sample (pl. 3) accounts for the disparity between the percentage and concentration data. The second group consists of the three samples from pollen zone B, and the third consists of a long, somewhat sinuous cloud of points that fall well below the perfect-fit line in the top right part of figure 15. The third group consists primarily of samples from pollen zones O through R and from pollen zones D and E. These zones are characterized by high frequencies of pine pollen (pl. 1) and high factor loadings for percentage factor 5 (pl. 4*A*) and concentration factor 3 (pl. 4*B*). These characteristics indicate that high frequencies of pine pollen exert a constraint on the percentage values of oak and TCT that is not apparent at lower frequencies.

The third pollen concentration factor (pl. 4*B*) corresponds to factor 5 for the pollen percentage data (pl. 4*A*) and reflects the ratio of pine to TCT pollen. Values for the two sets of factor loadings are plotted against each other in figure 17. With the exception of the three anomalous points noted for figure 16, most of the points fall along a straight line. Although the best-fit line is offset well above a 1:1 relation, the fit is quite good. A group of points found below the main linear grouping consists of all the samples from pollen zones A and S. The significance of this is not clear but the separation is quite distinct, as shown by the dotted line (fig. 17).

The pollen percentage (solid lines) and concentration curves (dotted and dashed lines) for oak, pine, and TCT for core 4 are compared in figures 14*A*–*C*. The two curves for a given type should fluctuate together if the percentage curves are a faithful record of changes in the vegetation. In general, the pollen concentration curves do agree with the percentage curves, but not always.

The differences between the oak percentage and concentration curves (fig. 14*A*) are that (1) oak concentration falls more rapidly than oak percentage during the upper half of pollen zone S, (2) the oak percentage peaks during pollen zones I and N are significantly higher than the corresponding concentration peaks, (3) oak percentages rose more rapidly than oak concentrations at the start of pollen zone A, and (4) oak-pollen concentrations during pollen zone A were much more variable than oak percentages.

Comparison of the pine curves shows a more complicated pattern of real, exaggerated, and spurious peaks in the percentage curve. The general pattern of the percentage curve is best seen on plate 1. There is a series of wide oscillations during and before pollen zones *G–Q*. In pollen zones *F–B*, the oscillations become less systematic and are superimposed on a rising trend. In pollen zone A, pine percentages drop to between 10 and 20 percent.

The pattern shown by the pine-pollen concentration data differs significantly from the percentage data in some places (fig. 14*B*). The initial pine peak in pollen zone Q is real, and the following pine concentration minimum during pollen zone P was more than twice as intense as the percentage minimum.

The two curves do not match well at all in pollen zone O. The percentage curve shows a well-defined peak in pine pollen, whereas the concentration curve shows three

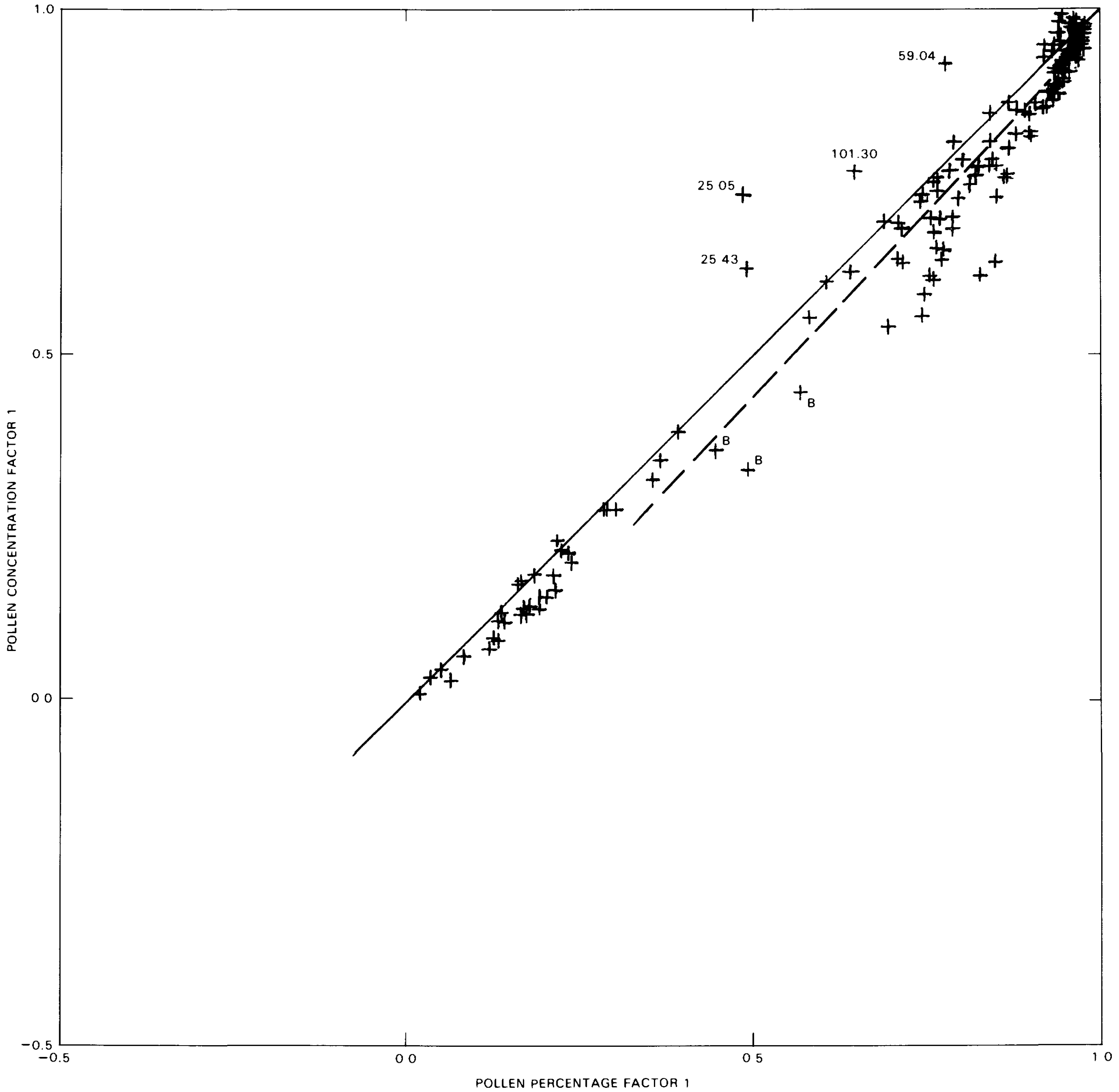


FIGURE 15.—Factor scores of pollen percentage factor 1 plotted against factor scores of pollen concentration factor 1 for core 4. Solid line indicates 1:1 relation between the two factors; points above the dashed line follow the 1:1 relation more closely than those below the dashed line. Numbers next to certain points are sample depths; points labeled B indicate samples from pollen zone B.

separate peaks. The two strongest peaks, however, are the spurious peaks in the *Eucalyptus*-derived curve at 104.76 and 105.88 m already noted. The *Lycopodium*-based curve shows a much smoother peak in pine-pollen concentration, and its maximum value is found slightly above the percentage maximum. Since the percentage curve and the *Lycopodium*-based concentration curve are in reasonable agreement, the wild oscillations in *Eucalyptus*-based pine concentration in pollen zone O are ignored hereafter.

The pronounced peak in pine-pollen percentages just below a depth of 100 m in pollen zone M does not have a counterpart in the concentration curves. The pine percentage peak is a result of decreases in the concentrations of oak and TCT pollen rather than a large increase in the concentration of pine pollen. The pine percentage peak in pollen zone J also appears to be an artifact. Pine concentrations rise somewhat during the last part of the interval but not nearly so much as the percentage curve would suggest.

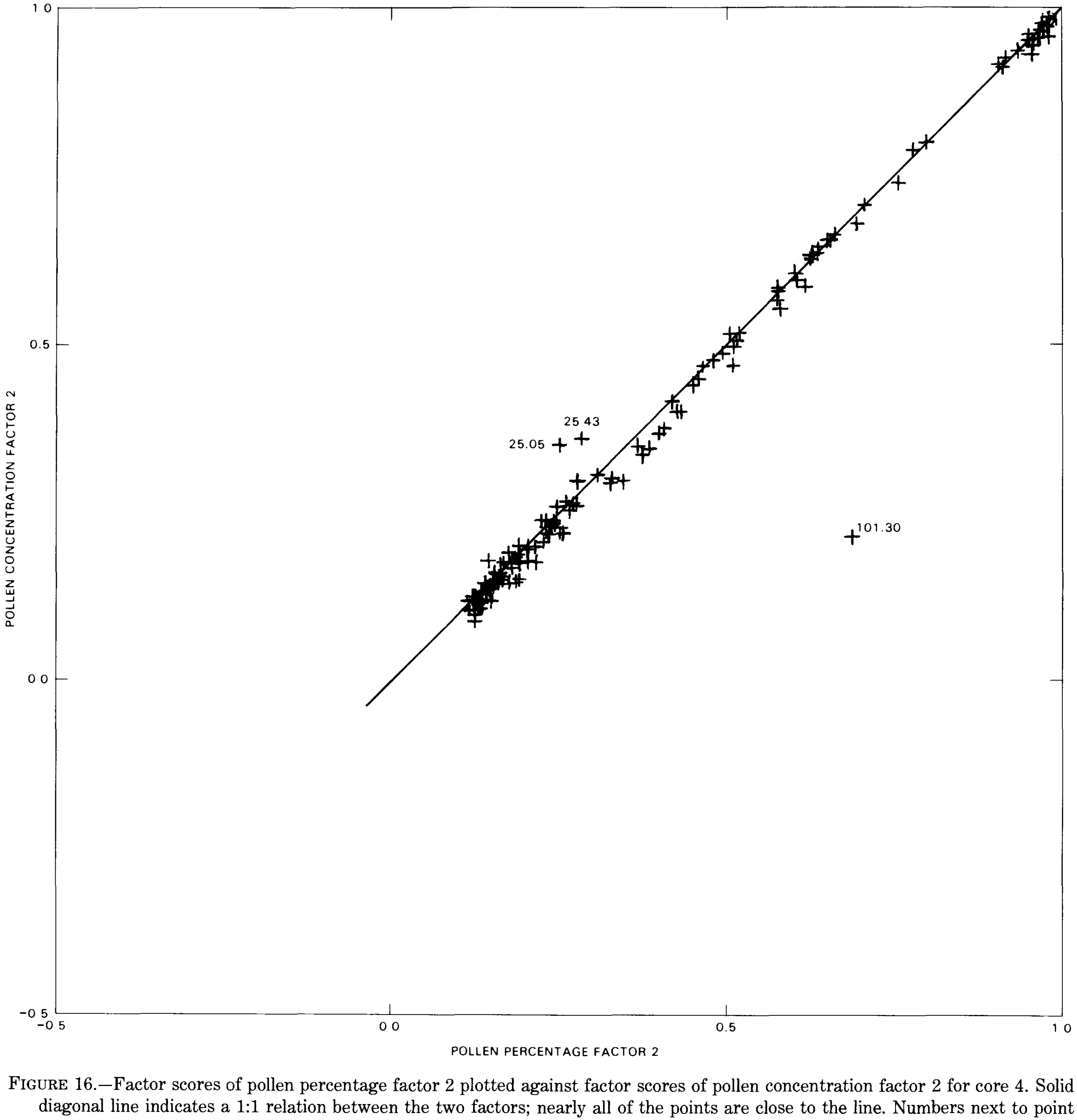


FIGURE 16.—Factor scores of pollen percentage factor 2 plotted against factor scores of pollen concentration factor 2 for core 4. Solid diagonal line indicates a 1:1 relation between the two factors; nearly all of the points are close to the line. Numbers next to point away from line are sample depths.

The final pine concentration peak of pollen zones *G–Q* occurred in pollen zone G, at a depth of 84.55 m. Although the peak is real, the steady rise in pine-pollen percentages that preceded it was not.

In zone F the fluctuations in the pine-pollen concentration curve are smaller than the fluctuations in the pine-percentage curve. In particular, there is no apparent trend in the data to match the rising trend seen in the percentage curve between 42 and 65 m. Zone E initially shows a short but strong peak in pine-pollen concentration, followed by concentrations throughout the zone that average somewhat more than those in pollen zone F, followed by a sharp increase in concentrations in zones B through D.

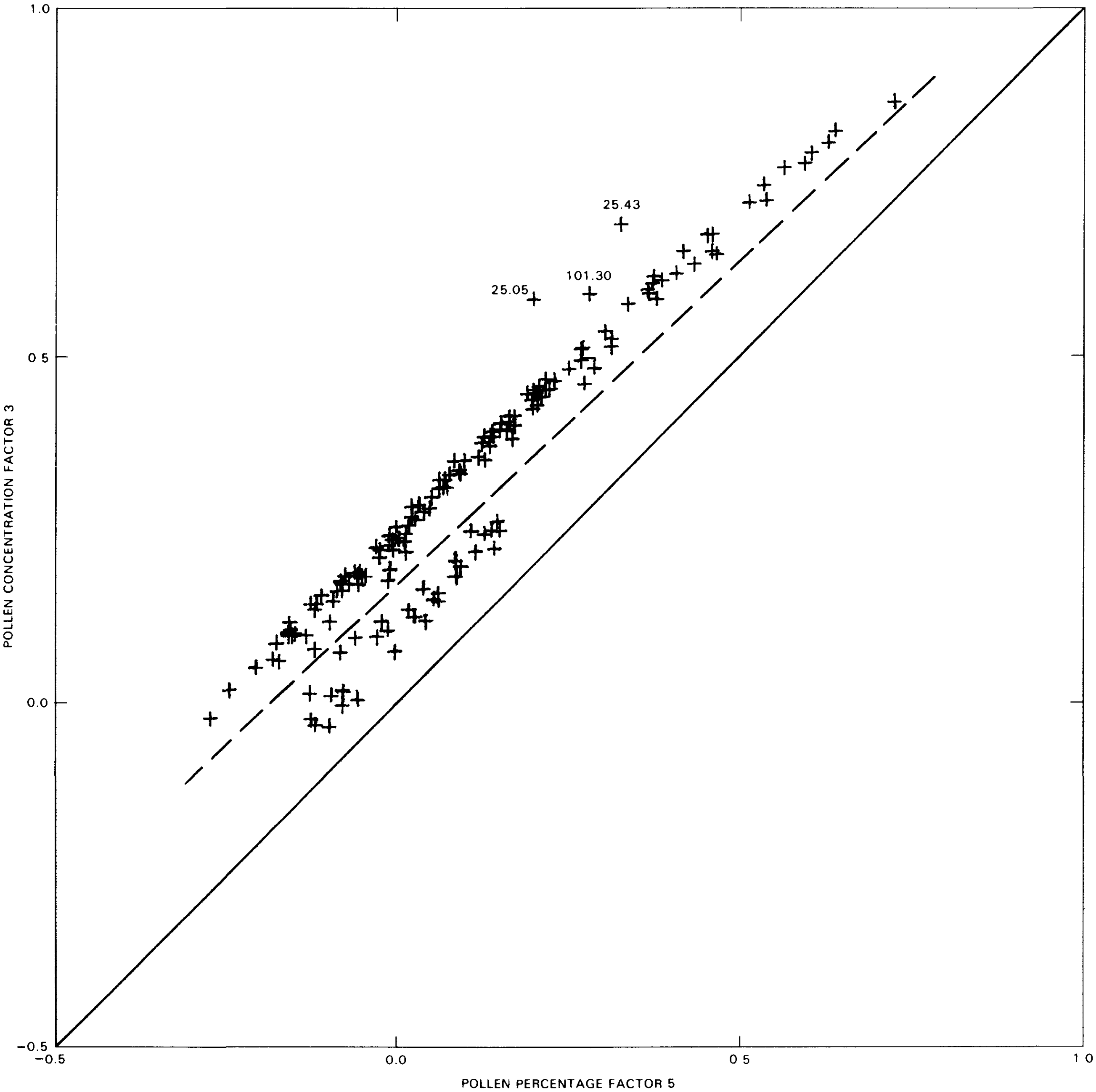


FIGURE 17.—Factor scores of pollen percentage factor 5 plotted against factor scores of pollen concentration factor 3 for core 4. Solid diagonal line indicates a 1:1 relation between the two factors. All points fall above the line but still show a linear relation between the two factors. Dashed line separates interglacial-age samples below from glacial-age samples above. Numbers next to certain points are sample depths.

The TCT concentration curve (fig. 14*C*) shows many high-frequency, high-amplitude fluctuations similar to those of the pine concentration curve. These short-term changes in pollen concentration are real because they are found in both the *Eucalyptus*- and *Lycopodium*-derived concentration curves. The origin of these high-frequency fluctuations is not clear. In some parts of the core, the pine and TCT peaks appear to be synchronous, but not always. Synchronous fluctuations could be explained in terms of changes in sedimentation rates, but the asynchronous and out-of-phase fluctuations must reflect vegetation dynamics in some way.

THE ALGAL RECORD

The sediments also include remains of numerous acid-resistant phytoplankton, which are in some samples far more abundant than pollen grains (figs. 18 and 19). These were counted using largely empirical taxonomy and counting methods that were in many cases less precise than those used for the pollen counts. The ten major phytoplankton variables include six forms of *Pediastrum*, as well as *Botryococcus*, *Coelastrum*, hystrichosphaerids, and *Peridinium* cysts (pl. 3).

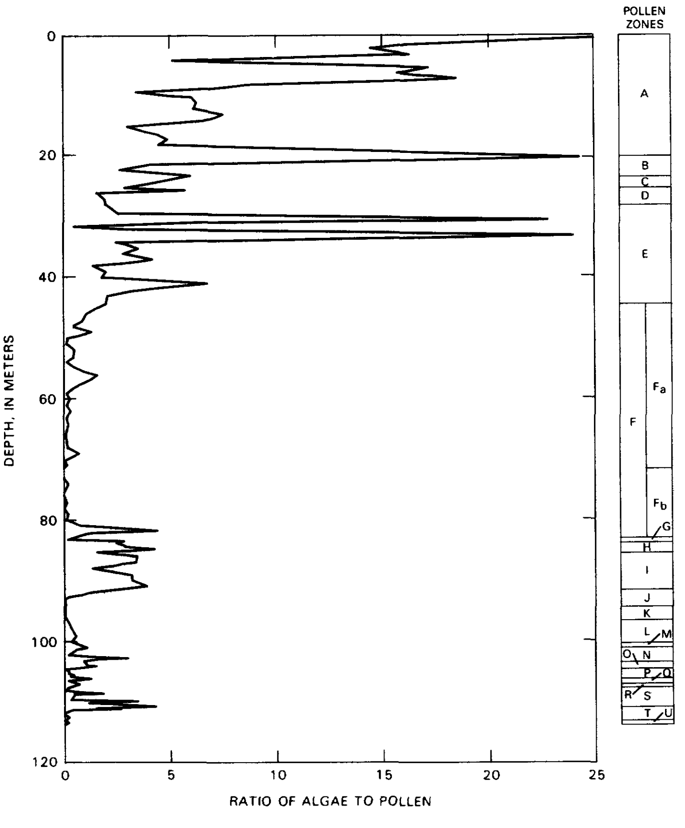


FIGURE 18.—Ratio of total acid-resistant algae (*Pediastrum*, *Botryococcus*, *Coelastrum*, hystrichosphaerids, and *Peridinium* cysts) to fossil pollen (including *Isoetes* microspores) plotted against depth for core 4.

FACTOR ANALYSIS

The algal data were subjected to a factor analysis independent of the other data, and the resulting nine factors are shown on plate 4*C*. These factors together account for nearly all (99.9 percent) of the variance in the algal data. The algal factors (pl. 4*C*) express the behavior of the various algal types with respect to each other and

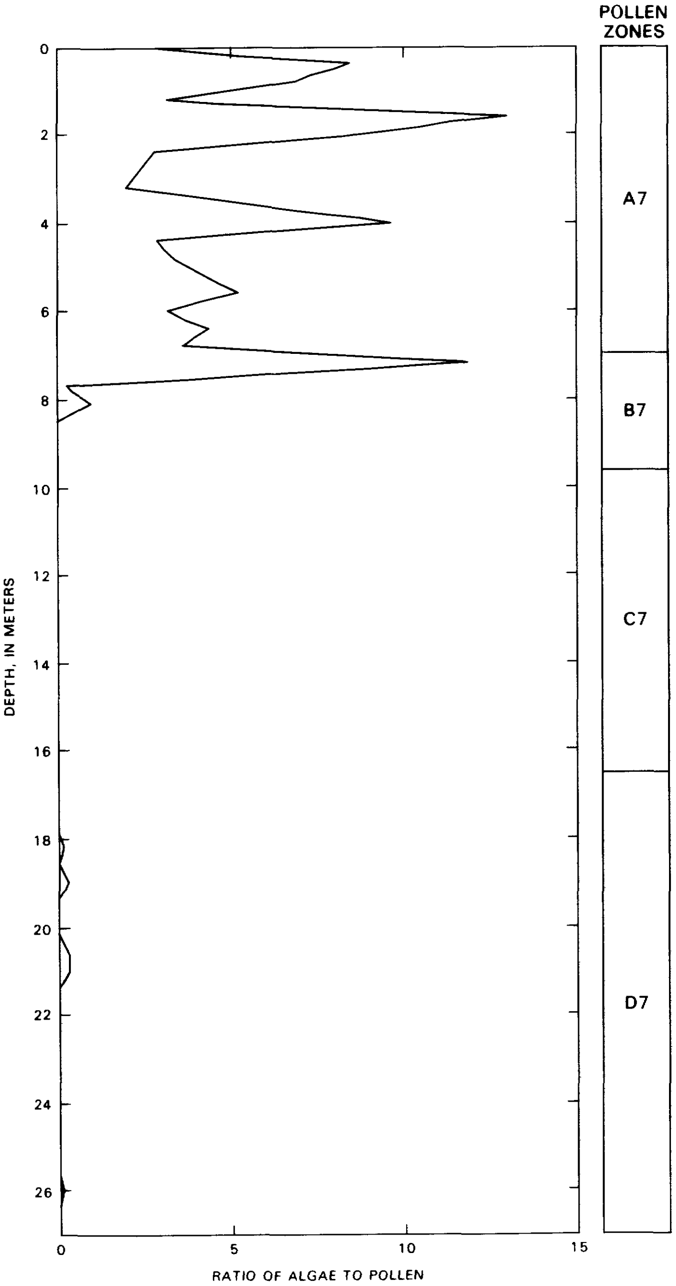


FIGURE 19.—Ratio of total acid-resistant algae (*Pediastrum*, *Botryococcus*, *Coelastrum*, hystrichosphaerids, and *Peridinium* cysts) to fossil pollen (including *Isoetes* microspores) plotted against depth for core 7.

are completely independent of the pollen data, whereas the algal percentages (pl. 3) express algal variability in terms of the pollen sum. The zone boundaries (pl. 4*C*) are derived from the pollen data. Although not all of the changes in the algal factors occur at pollen zone boundaries, there is considerable agreement. The changes that affected the vegetation of the Clear Lake region also affected the phytoplankton of the lake.

The factor analysis program is not nearly as effective in reducing the dimensionality of the algal data set as it is with the pollen data. Ten initial variables are reduced to nine factors, and each factor appears to show significant patterns in its variability with depth. However, most of the variance (61.7 percent) appears in the first factor, which responds most strongly to *Pediastrum* O and also significantly to *Coelastrum*, *Pediastrum* X, *Pediastrum* K, and *Peridinium* cysts (table 10). Factor 1 loadings are positive for all variables, unlike the rest of the factors. The strongly negative factor 1 loadings in zones F, J, K, L, T, U, C7, and D7 correspond to samples in which algae are scarce or absent, whereas those samples with strongly positive loadings have abundant algae. Factor 1 is thus interpreted as representing the overall favorability of conditions in the lake for the growth of the algal types that have been preserved as fossils. Negative loadings represent unfavorable conditions, and positive loadings represent favorable conditions.

Factor 1 loadings are consistently high throughout pollen zone A and generally high in zone A7. Below zone A7 in core 7, conditions were generally unfavorable for phytoplankton; the record of Cyperaceae pollen and Nymphaeaceae leaf hairs in zones B7 through D7 indicates that open-water conditions did not exist in the Highlands Arm of Clear Lake during deposition of those zones.

In the main basin of Clear Lake, favorable conditions for algal growth apparently began early in the deposition of pollen zone E, with the appearance of *Pediastrum* O, *Pediastrum* X, and *Pediastrum* Y. Factors 1, 2, 4, 5, 6, 7, and 9 all reflect this change.

Factor 2 responds positively only to *Peridinium* cysts; the strongest negative scores are for *Pediastrum* O and *Coelastrum*. High positive factor loadings are found in the upper half of pollen zone P and in pollen zones G, I, and O. The upper two samples of core 4 also have positive loadings. High positive loadings are conspicuously absent in pollen zone L; the rise in loadings does not begin immediately, and the low peak continues upward into the transitional conditions shown in pollen zone K. Negative factor loadings are present in the interval from pollen zones A through E in core 4 but only in pollen zone A7 of core 7.

Factor 3 responds mainly to *Pediastrum* K. High factor loadings are found in the lower part of pollen zone L, in pollen zone H, and then intermittently from pollen zone G through the upper part of pollen zone E. The changes in the *Pediastrum* K curve for zones E–G are matched by the *Botryococcus* curve in a general way, but this relation breaks down below zone I and above the top of zone E.

Negative loadings for factors 2 and 3 are nearly identical in pollen zones A and A7. The primary variables influencing these two factors, *Pediastrum* K and *Botryococcus*, are missing in these deposits; no significance is attached to the curves for these zones.

Factor 4 responds mostly to *Pediastrum* X. High factor loadings are found in the upper part of pollen zone S and in the lower parts of zones A and A7 and to a lesser extent in zone P. Comparison of the curve for algal factor 4 (pl. 4*C*) with the curve for *Pediastrum* X (pl. 3) shows some significant differences in the two curves. The algal curve shows the abundance of *Pediastrum* X relative to pollen for each sample, whereas the factor curve reflects the abundances of the various algae relative to each other.

Factor 5 responds positively to *Pediastrum* O and negatively to *Coelastrum*. Samples with positive factor loadings contain abundant *Pediastrum* O and little or no *Coelastrum*. Such conditions prevailed in the lower part of pollen zones E and C7 and were intermittent above the

TABLE 10.—*Scaled VARIMAX factor scores for algae in cores 4 and 7*

[Algae expressed as percent AP]

Variable	Factor								
	1	2	3	4	5	6	7	8	9
Pediastrum A	0.460	-0.176	-0.115	0.153	-0.370	-0.054	0.232	-0.096	3.051
Pediastrum N	.148	-.057	-.063	.259	-.128	-.045	.003	.120	.416
Pediastrum O	2.020	-.702	-.643	-.785	2.022	-.212	.205	-.457	-.110
Pediastrum X	1.055	-.351	-.289	2.878	-.236	-.123	.248	-.143	-.426
Pediastrum Y	.781	-.239	-.302	-.181	-.797	-.006	-2.914	-.279	-.025
Pediastrum K	1.010	-.168	2.960	-.151	-.269	-.099	.086	-.262	-.088
Botryococcus	.489	-.098	.131	.008	.244	-.077	-.236	3.097	.048
Coelastrum	1.164	-.753	-.745	-.968	-2.205	-.407	1.112	.082	-.559
Hystrichosphaerids(?)	.416	-.092	-.065	-.068	-.177	3.122	.168	.041	-.041
Peridinium cysts	1.085	2.946	-.239	-.103	-.212	-.085	.143	-.042	-.036

top of zone E in core 4 and in the upper half of pollen zone A7 in core 7.

Factor 6 responds positively only to hystrichosphaerids(?). High factor loadings are restricted to the middle part of pollen zone S, where high frequencies of hystrichosphaerids(?) are found in the near absence of other algae. Minor peaks also are found in the middle of zone L and the lower part of zone I. Hystrichosphaerids(?) also are present in substantial numbers in the lower half of zones A and A7, but they receive little emphasis in the factor analysis because of the overwhelming effect of other species.

Factor 7 responds negatively to *Pediastrum* Y and in a weaker positive way to *Coelastrum*. High-negative factor loadings are found in three main peaks in pollen zone E and in a single sample at the base of zone F_b; positive peaks are found in the lower part of zones A and A7.

Factor 8 responds mainly to *Botryococcus*, but factor loadings are high only when *Botryococcus* is present but other types are scarce. The *Botryococcus* percentage curve (pl. 3) is the most persistent of all the algal curves. Below pollen zone F_a, amounts of *Botryococcus* are fairly low; peak amounts do not exceed 50 percent of the pollen. Above pollen zone F_a, *Botryococcus* frequencies are generally higher.

Factor 9 responds primarily to *Pediastrum* A. Loadings are high in pollen zone B, low in the lower and middle parts of zones A and A7, and high once again in the upper part of zones A and A7. This pattern can also be seen in the curves for *Pediastrum* A, N, and X.

DISCUSSION

Pediastrum N is the only alga that has no high factor loadings, despite its generally clear pattern in the percentage curve (pl. 3). Two circumstances appear to account for these uniformly low factor loadings: *Pediastrum* N is found in relatively few samples, and it is always rather scarce compared to the other algae. Even the major peak of *Pediastrum* N at the top of pollen zone B7 is overshadowed by the much higher peak of *Pediastrum* X in the same sample.

The great increase in algal productivity that started during the deposition of pollen zone E must represent a profound change in the limnology of the basin. Contributing factors probably include the shallowing of the lake as a result of sediment accumulation and the climatic change from warm to cold conditions. The consistent presence of *Isoetes* spores throughout zones B–E indicates that the plants were probably growing on the bottom of Clear Lake. This implies that the water was clear enough for sunlight to reach the bottom. Another possible explanation is that the combination of a colder climate when zone E deposition began and the decreased thermal capacity of the shallowing lake caused the lake to change from monomictic to dimictic, so that the water column overturned twice a year instead of only once. Such a change would increase the recycling of nutrients from the lake sediment and thus would enhance algal productivity.

In an earlier paper describing the pollen record from Pearson's Pond on the San Francisco peninsula (Adam, 1975a), I interpreted high frequencies of *Botryococcus* to indicate wet conditions in which water persisted in an ephemeral pond long enough into the summer for water temperatures to rise and permit a *Botryococcus* bloom. This model cannot be applied directly at Clear Lake because of the great differences in lake size and permanence of open water between the sites.

DATING

By Stephen W. Robinson

Simple comparison of the lengths of cores 4 and 7 and comparison of the two pollen records (pl. 1) suggest that the core 4 sequence covers the longest time interval and is therefore the sequence for which time control is most needed. Early efforts to develop a time scale for core 4 (Sims, 1976; Adam and others, 1981; Sims and others, 1981a) led to the results shown in figure 20. The oak-pollen curves for core 7 and the upper part of core 4 are similar enough to enable correlation between the two records at some levels, but the radiocarbon ages for apparently correlative events are different in the two cores. Also, sediment age in core 4 does not appear to increase significantly below a depth of about 40 m. The age of the base of core 4 was estimated at about 130 ka, primarily on the basis of curve matching between the oak-pollen percent versus depth curve (fig. 21*A*) and the fluctuations in $\delta^{18}O$ recorded in deep-sea cores. Here, I present results of radiocarbon measurements on core 4 sediments that are consistent with the age estimate of the core described above.

RADIOCARBON

Because woody material is very rare in core 4, radiocarbon dating has been performed on disseminated organic matter, which amounted to approximately 9 to 25 percent of the dry weight. Detailed data on the genesis of this organic matter is not available, but I assume that it originated primarily from biological productivity in the lake and secondarily from productivity in the drainage basin. I further assume that the biological production of the organic matter was essentially contemporaneous with the deposition of the sediment.

The standard or "DeVries" method of chemical decontamination of samples for radiocarbon analysis consists of leaching the sample sequentially in acidic, basic, and finally acidic solutions at elevated temperatures for periods of 8 to 16 hours each. The initial acidification removes any carbonate detritus present; the basic leach removes organic decomposition products known as humic and fulvic acids which, by their mobility, may introduce carbon from other horizons. The final acid leach neutralizes any residual hydroxide and prevents subsequent absorption of carbon dioxide from the air.

All samples received acid treatment to remove carbonates, but for some samples the basic (sodium hydroxide) leach was omitted. Samples from three depths (0.7 m, 58 m, and 71 m) were split and analyzed both with and without the basic leach. For the 0.7-m sample, the sodium hydroxide-soluble fraction was also analyzed. The carbon in the pretreated sediments was combusted to carbon dioxide in a quartz tube under oxygen flow at a temperature of about 900 °C. The purified carbon dioxide was

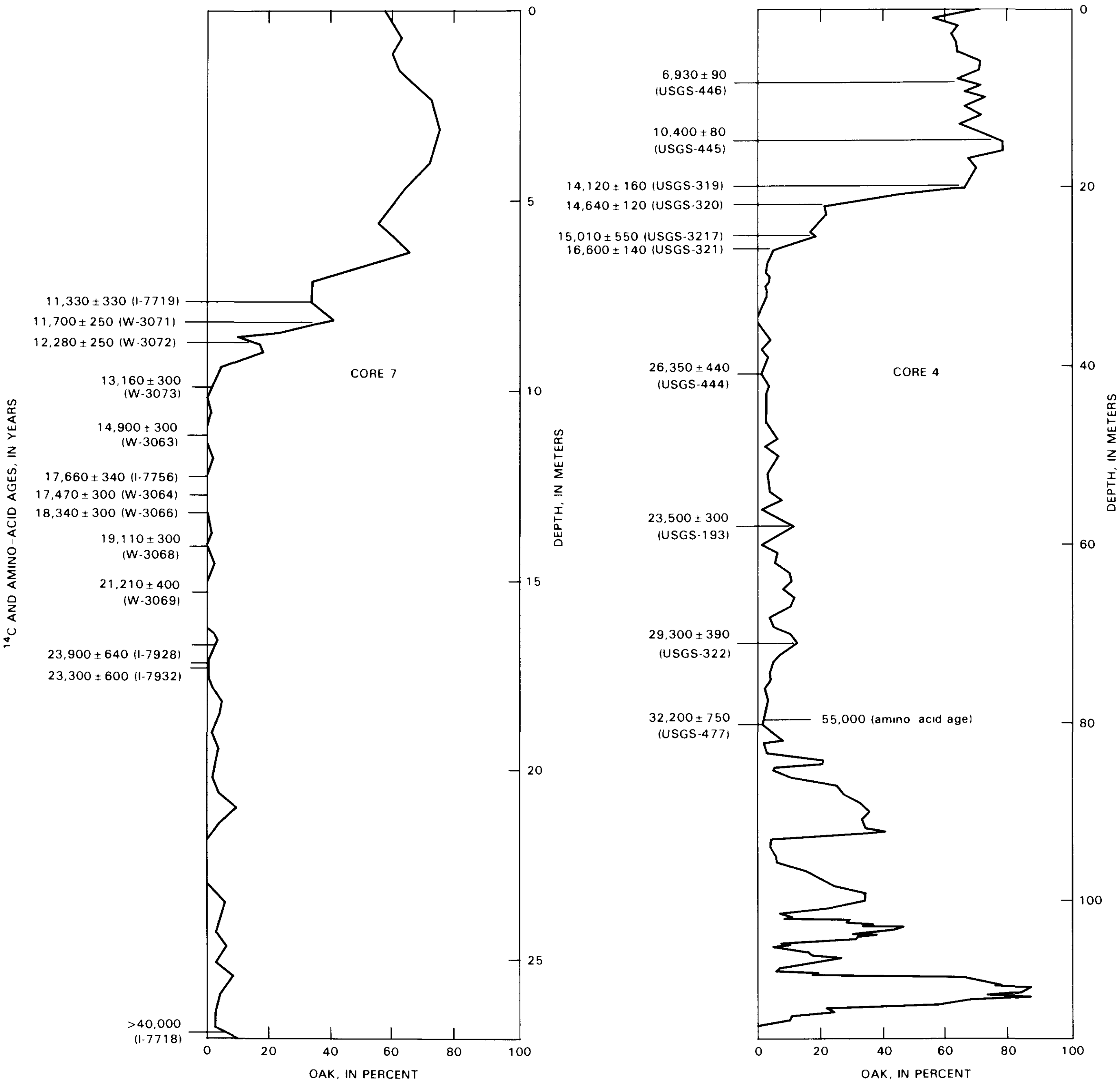


FIGURE 20.—Radiocarbon and amino-acid age determinations from cores 4 and 7, shown plotted on the oak-pollen percentage versus depth curves. Sample identification is given in parentheses following each age. From Adam and others (1981, fig. 3).

analyzed for radiocarbon by beta decay counting in an underground laboratory described earlier (Robinson, 1979). The results of core 4 radiocarbon dating are presented in table 11.

The relation between depth and age in a lacustrine deposit is controlled by (1) the rate of delivery of sediment to the core site, (2) diagenetic sediment compaction, and (3) variations in production of organic matter in the lake and its preservation in the sediment. To eliminate the effects of variables (2) and (3), one can replace the depth parameter by the mass of noncombustible sediment per unit area above a given depth (hereafter termed "noncombustible overburden"; fig. 21*B*). The new scale will deviate from linearity against age only if the inorganic-sediment influx changes with time. This technique has been applied by Stuiver (1970, 1971) in the investigation of atmospheric radiocarbon variation. He found that rates of accumulation of noncombustible sediment are remarkably uniform in lakes in equatorial Africa and Taiwan, far from the geomorphic and climatic influence of ice sheets. However, he did observe a significant change in sedimentation rate in the one lake record that includes the major glacial-nonglacial transition at 14–15 ka.

The bulk dry density of the core 4 deposits varies fairly smoothly from about 0.5 g/cm^3 in the upper part to about 2.0 g/cm^3 in the lower part of the core (fig. 7*A*). Thirty-eight of the original bulk density samples were selected for measurement of weight loss on combustion in order to construct a noncombustible overburden scale for the core. The sediment pellets (2 to 4 g) were powdered, then roasted at 550 °C for 35 minutes to oxidize the organic matter to carbon dioxide. The weight-loss results (fig. 7B) appear to show a rapid diagenetic loss of organic matter in the upper part of the core, and below a depth of 30 m, a uniform organic content of 9 to 10 percent. The relation between noncombustible overburden (X) and core depth (z) is given by

$$X(z) = \int_0^z \rho(z')[1-F(z')]dz', \qquad (4)$$

where ρ is the bulk density of dry sediment and F is the fractional loss on ignition. For X we adopt units of kilograms of noncombustible sediment per square centimeter. It should be noted that this noncombustible sediment also contains minor amounts of biogenic silica and carbonates, which we assume are negligible.

Conventional radiocarbon ages are plotted against the noncombustible overburden scale in figure 22. Prominent features of figure 22 are (1) the linear relation between X and radiocarbon age for the upper five samples, (2) the core-top age of about 4,200 radiocarbon years, (3) the deviation of the deeper ages from the straight line fitted

TABLE 11.—*Radiocarbon analyses of sediment in core 4*

[References for age calibrations: a, Stuiver (1982), b, Klein and others (1982), c, Stuiver (1971). Dashes indicate calibration was not used]

Sample no. USGS-	Core depth (m)	Non-combustible overburden	Sample pretreatments (kg/cm^2)	Conventional ^{14}C age	Age adjusted by subtraction of core-top age (geothermal effect)	Age calibrated to dendrochronological (absolute) time scale
614A	0.68	0.029	Acid only	4,560±90	----	---
614B	.68	.029	Base soluble	4,230±110	----	---
614C	.68	.029	Acid and base	4,475±50	260	310-430 (a)
446	8.1	.340	Acid and base	6,930±90	2,715	2,750-3,000 (b)
445	15.0	.775	Acid and base	10,400±80	6,185	6,910-7,230 (b)
319	19.8	1.133	Acid only	14,120±160	9,905	10,600 (c)
320	22.1	1.309	Acid only	14,460±120	10,245	11,000 (c)
321	26.9	1.702	Acid only	16,600±140	----	---
444	41.0	3.245	Acid and base	26,350±440	----	---
193A	58.0	5.527	Acid only	23,500±300	----	---
193B	58.0	5.527	Acid and base	29,600±580	----	---
322A	71.0	7.532	Acid only	29,300±390	----	---
322B	71.0	7.532	Acid and base	32,650±670	----	---
447	80.1	9.217	Acid and base	32,200±750	----	---

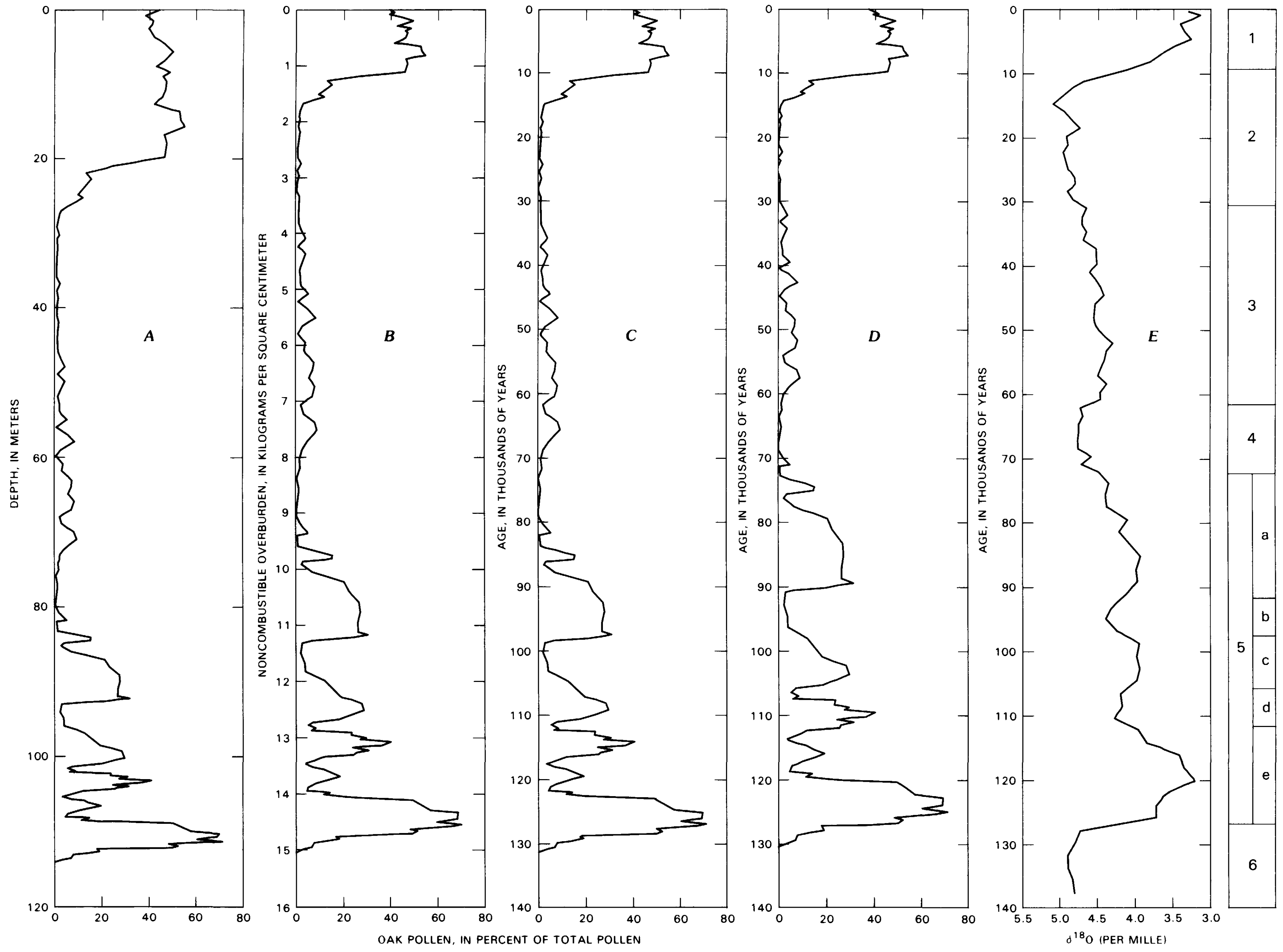


FIGURE 21.—Core 4 oak pollen percentage versus four characteristics, with a deep-sea oxygen-isotope curve shown for comparison. *A*, Oak pollen versus depth. *B*, Oak pollen versus weight of non-combustible overburden. *C*, Oak pollen versus age in calendar years as calculated by extrapolating ^{14}C-derived sedimentation rates to base of core. *D*, Age in calendar years after adjusting age of boundary we correlate with the stage 4/5 boundary in deep-sea record to 73 ka, and age of the stage 5/6 boundary to 127 ka. *E*, Age versus $\delta^{18}O$ record from deep-sea core V19-29 in the Panama basin (modified from Ninkovitch and Shackleton, 1975). Deep-sea oxygen isotope stages and substages are shown at the right.

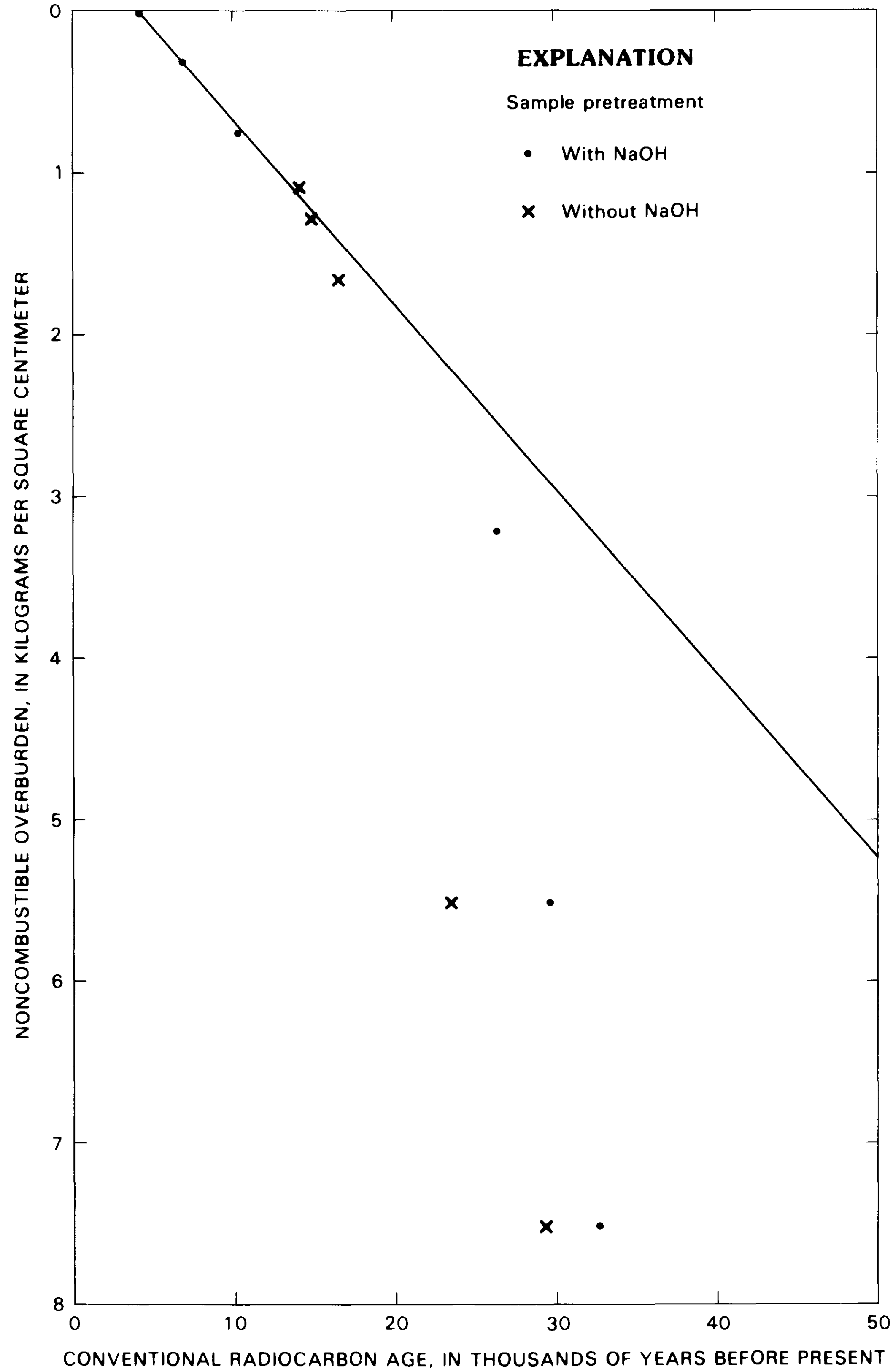


FIGURE 22.—Conventional radiocarbon age plotted against weight of noncombustible overburden for Clear Lake core 4. Solid line indicates regression of age against weight of noncombustible overburden as calculated from uppermost five radiocarbon ages.

to the observations for the upper five samples, and (4) the older ages obtained for NaOH-treated sediment samples.

THE OLD-CARBON EFFECT

Clear Lake has an alkalinity of about 2.5 moles of carbon per cubic meter and an average depth of about 8 m, so the mean residence time of dissolved inorganic carbon in the lake due to gas exchange (5 to 30 moles/m^2/yr; Peng and Broecker, 1980) with atmospheric carbon dioxide is of the order of one year. With such a short residence time, the radiocarbon content of the lake's dissolved inorganic carbon and hence of the phytoplankton would be expected to yield a conventional radiocarbon age very close to zero years. The unusually old core-top age is due to two factors: old inorganic carbon from the sediments and even older carbon entering the lake from subaqueous springs beneath the lake. The flux of inorganic carbon from the mineralization of organic matter in the sediments may be estimated from the variation of organic matter (weight loss) with depth, and its radiocarbon content is approximately 25 percent of that of modern carbon. The effect of this carbon source is significant in Clear Lake because of the exceptionally high primary productivity in its waters. Clear Lake overlies a large number of subaqueous springs (Sims and Rymer, 1976a) that emit carbon dioxide gas and bicarbonate-rich waters (Thompson and others, 1981). The inorganic carbon contained in geothermal fluids is known to contain very little or no radiocarbon because of its apparent isolation from the atmosphere for many half-lives. For example, six measurements performed in the U.S. Geological Survey Menlo Park Radiocarbon Laboratory on geothermal fluids from Steamboat Springs, Nevada, Yellowstone Park, Wyoming, and Cerro Prieto, Mexico, have yielded radiocarbon contents ranging from 0.09 percent to 1.64 percent of modern activity, corresponding to apparent ages of from 56 to 33 ka.

A further test of the existence of an old-carbon effect on radiocarbon in dissolved inorganic carbon in Clear Lake was provided by analysis of the shell of a modern pelecypod provided by Barry Roth of the California Academy of Sciences, San Francisco, that was collected in 1922 at an unknown location in the lake. The apparent age of the shell is 6,300 ± 50 radiocarbon years (USGS–644).

There are two possible interpretations of the discrepancy between this result and the core-top age of 4,200 years. One is that the mollusk lived closer to sources of geothermal carbon than the phytoplankton whose debris reached the lake bottom at the core site. The other is that the lake may be well mixed with respect to the geothermal input and the discrepancy due to terrigenous organic detritus. This organic component would have zero-effective-age carbon and would reduce the apparent core-top age. If this is the case, it implies that about 24 percent of the core organic carbon is terrigenous. To use the radiocarbon measurements on the core as age indicators, it is necessary to subtract this net 4,200-year-old carbon effect from each date, assuming a constant old-carbon effect over the period for which the radiocarbon ages are used.

The upper five radiocarbon ages from core 4 (fig. 23) indicate a sediment accumulation rate of 0.1224 ± 0.0014 kg/cm^2/1,000 yr (1,000 conventional radiocarbon years) and a core-top age of 4,215 ± 60 years. This accumulation rate would give an age of 123 ± 1.4 ka (conventional radiocarbon years) for the lowest part of the core.

Below 1.309 kg/cm^2 the radiocarbon ages suggest a markedly greater rate of sediment accumulation (fig. 22). In addition, the samples pretreated with NaOH plot closer to the line of constant accumulation rate than the samples not so treated. This younger age of the samples not subjected to NaOH leaching is an indication of contamination with younger carbon, because in an uncontaminated sample all the chemical species of organic carbon would have the same radiocarbon age. Unfortunately, there is no assurance that the NaOH treatment removed all the contaminant carbon, and the ages below the $X = 1.309$ kg/cm^2 level are discarded as unreliable. In the sample pairs USGS-193A and B and USGS-322A and B, the excess activities of the splits not treated with NaOH are 0.9 and 2.8 percent, respectively, of modern activity level. The most likely cause of this contamination is the incorporation of modern carbon by bacterial activity during the 4 to 6 years that the sediment was stored in a wet condition before the radiocarbon analyses were performed. A similar case of contamination of a marine core has been documented by Geyh and others (1974), who believe that atmospheric carbon dioxide is absorbed by the core pore water and subsequently assimilated into the cells of sulfate-reducing bacteria. The ages of the younger samples will be less affected by the incorporation of the same amount of younger contamination because of their higher radiocarbon and carbon contents. Because of the excess radiocarbon in the atmosphere from nuclear weapons testing, the atmospheric CO_2 contamination could have contained as much as 50 percent more radiocarbon than did the 1950 modern standard.

Because the deeper part of the core appears to extend well beyond the range of the radiocarbon dating method, it is desirable to convert the chronological data thus far obtained from conventional radiocarbon years (Stuiver and Polach, 1977) into absolute years so that they can be compared to time scales based upon other dating methods. This is done by using calibration data for radiocarbon in tree-ring-dated wood over the last 8,000 years (Stuiver, 1982; Klein and others, 1982). For the two older samples, an approximate extrapolation is used from the calibration of radiocarbon in Lake of the Clouds (Minnesota) sediments against a varve chronology that extends back 9,200

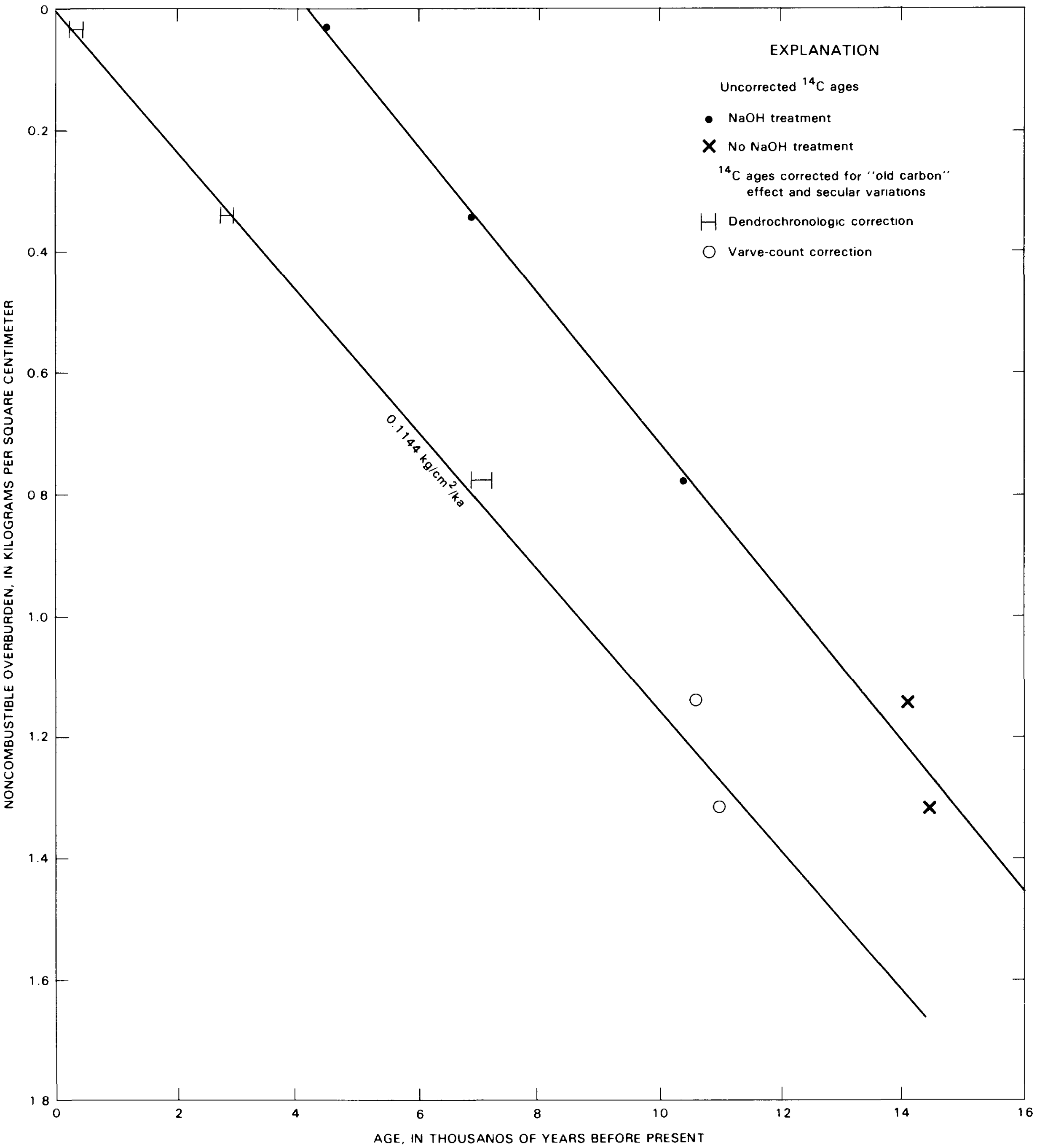


FIGURE 23.—Conventional radiocarbon ages from core 4 (upper curve) and same data after correction for apparent reservoir age ("old carbon" effect, explained in text) and secular variations in atmospheric radiocarbon activity (lower curve). Dendro-calibration of Klein and others (1982) was used for the three younger dates and Lake of the Clouds varve-count data of Stuiver (1971) were used to approximately calibrate two oldest dates. Curves are straight lines fitted to two sets of data points. Sedimentation rate shown by lower curve is used to estimate age at base of core.

conventional radiocarbon years (Stuiver, 1971). The conversion formula used here for ages in the range of 8,000 to 13,000 conventional radiocarbon years is

$$T_{\mathrm{absolute}} = 1.029\ T_{\mathrm{radiocarbon}} + 700, \qquad (5)$$

where T_{absolute} is the estimated absolute age and $T_{\mathrm{radiocarbon}}$ is the conventional radiocarbon age. The upper five ages converted to absolute years in this manner give a noncombustible sediment accumulation rate of 0.1144 ± 0.0019 kg/cm^2/ka, and this rate projects back to a core bottom (15 kg/cm^2) age of 132.9 ± 2.2 ka (fig. 21*C*).

CORRELATION WITH DEEP-SEA RECORD

The calculations of the previous section assume an approximately uniform sediment accumulation rate over the period of deposition of Clear Lake core 4. This assumption can be tested by comparing the climatic signal of the oak-pollen curve with the marine isotopic record for which a time scale has been more firmly established (fig. 21). The $\delta^{18}O$ record of benthic foraminifera in deep-sea cores has been dated by uranium-series disequilibrium, correlation with high sea levels, magnetostratigraphy, and by comparison with the periodicities of the earth's orbital mechanics (Hays and others, 1976; Kominz and others, 1979). If the oak-pollen curve (fig. 21*C*) is compared with $\delta^{18}O$ in core V19–29 from the Panama Basin in the eastern equatorial Pacific Ocean (fig. 21*E*; Ninkovitch and Shackleton, 1975), we find good general agreement with high oak-pollen percentage correlating with low $^{18}O/^{16}O$ ratio (interglacials). However, the last interglacial period (isotope stage 5) seems too short in the Clear Lake core, while the Wisconsin glacial (isotope stages 2–4) seems too long. This is probably a consequence of our projecting the accumulation rate derived for the present interglacial stage through the last glacial. We can now refine our estimates of Clear Lake sediment accumulation rates by correlation with isotope-stage boundaries 4/5 and 5/6, which are dated (Hays and others, 1976; Kominz and others, 1979) at 73 and 127 ka, respectively. The stage 1/2 boundary is chosen at $X = 1.309$ kg/cm^2; this boundary has an age of 11.44 ka on the time scale of figure 21*C*, derived from the Holocene sedimentation rate. Choosing the Clear Lake stage 4/5 boundary at $X = 9.7225$ kg/cm^2 and the stage 5/6 boundary at $X = 14.7125$ kg/cm^2 from the oak-pollen curve (fig. 21*B*), we obtain an accumulation rate of 0.1367 kg/cm^2/ka for the last glacial period (isotope stages 2 through 4) and a rate of 0.0924 kg/cm^2/ka for the last interglacial period (isotope stage 5). The refined sedimentation rates give rise to the oak-pollen curve of figure 21*D*. A higher accumulation rate during the last glacial period is not unreasonable in a regime of higher precipitation and greater geomorphic instability. It is not clear why the rate during the last interglacial should have been so much less than during the present one. The relation between age and weight of noncombustible overburden for the entire core is summarized in table 12.

Other possibilities for comparison are the Bølling-Dryas-Allerød complex of climatic oscillations and the middle Wisconsin interstadials. The Bølling-Dryas-Allerød complex is dated at 10.0 to 12.5 ka (conventional radiocarbon years) in northwestern Europe (Andersen, 1981). Correlative events may be present in the Clear Lake oak-pollen record between $X = 1.3$ and 1.65 kg/cm^2 just before the onset of the present interglacial period. For purposes of comparison, the European radiocarbon ages are approximately converted to absolute ages by the same procedure (eqn. 5) used for Clear Lake samples USGS–319 and 320. The comparisons (table 13, fig. 24) show general agreement, although a gap between samples in the core 4 pollen record between 1.37 and 1.54 kg/cm^2 probably included most of Allerød time.

In table 14, the ages of events in the Clear Lake oak-pollen record are compared with correlative interstadials radiocarbon dated at Grande Pile in northeastern France (Woillard and Mook, 1982) and relatively high sea-level stands dated by uranium-series disequilibrium in corals from raised terraces in the Huon Peninsula, New Guinea (Chappell and Veeh, 1978; Bloom and others, 1974; Chappell, 1974). The conventional radiocarbon ages from Grande Pile have been converted to a half-life of 5,730 years, but no further data are available to enable conversion to absolute years. Again, if the correlations are accepted, the

TABLE 12.—*Summary of the relation between age (T, in ka) and weight of noncombustible sediment overburden (X, in kg/cm²) in core 4*

Formula	Range
$T = X / .1144$	$X \leq 1.309$
$T = 11.44 + (X - 1.309) / .1367$	$1.309 < X \leq 9.723$
$T = 73.0 + (X - 9.7225) / .0924$	$X > 9.723$

agreement is excellent. Although at Grande Pile the Denekamp or "30 ka event" is the most prominent interstadial, it is the least pronounced in the Clear Lake oak curve. Another comparison would be the uranium-series-dated high sea-level stands at 82, 105, and 125 ka (Bender and others, 1979); these ages correspond to values of $X = 10.4$, 12.5, and 14.4 kg/cm^2 in the Clear Lake core. Each corresponds to a time of high oak-pollen percentage, but one major and one minor oak peak in stage 5 are left without an associated high sea stand. The age of the apparent location of the isotopic stage 3/4 boundary (close to the 8.0 kg/cm^2 level) agrees well with the age of 61 ka assigned to it by Kominz and others (1979).

The radiocarbon data presented here require extrapolation of sedimentation rates far beyond the range of the valid data in order to estimate the age of the base of core 4. The extrapolated age of 133 ka for the base of the core is nevertheless remarkably consistent with the age obtained by matching the oak-pollen curve with well-dated deep-sea oxygen-isotope records. I interpret the consistency of the results obtained by the two independent methods as confirmation of a last-interglacial age for the high oak-pollen zone just above the base of the core.

TABLE 13.—*Age comparison of Bølling-Dryas-Allerød complex in Europe and in core 4*

[A, Conventional ^{14}C age of boundary in Europe (Andersen, 1981). B, Estimated absolute ages of the boundaries shown in column A, using formula $T_{absolute} = 1.029\ T_{radiocarbon} + 700$ (see text). C, estimated absolute ages of pollen samples that appear to correlate with European intervals, calculated from rate of noncombustible sediment accumulation]

Climatic interval	A (ka)	B (ka)	C (ka)	C (kg/cm^2)
—	10.0	11.0	—	—
Younger Dryas (cold)			11.4	1.31
—	11.0	12.0	—	—
Allerød (warm)			11.9	1.37
—	11.8	12.8	—	—
Older Dryas (cold)			13.2	1.54
—	12.0	13.0	—	—
Bølling (warm)			13.4	1.58
—	12.5	13.6	—	—

AMINO-ACID RACEMIZATION

The only other age determination available for the Clear Lake cores is an amino-acid racemization age of 55 ± 13 ka at a depth of 79.55 m in core 4 (Blunt and others, 1981, 1982; Dungworth, 1982). This age is consistent with the age of 67.3 ka for this level ($X = 8.95$ kg/cm^2) given by the time scale derived above.

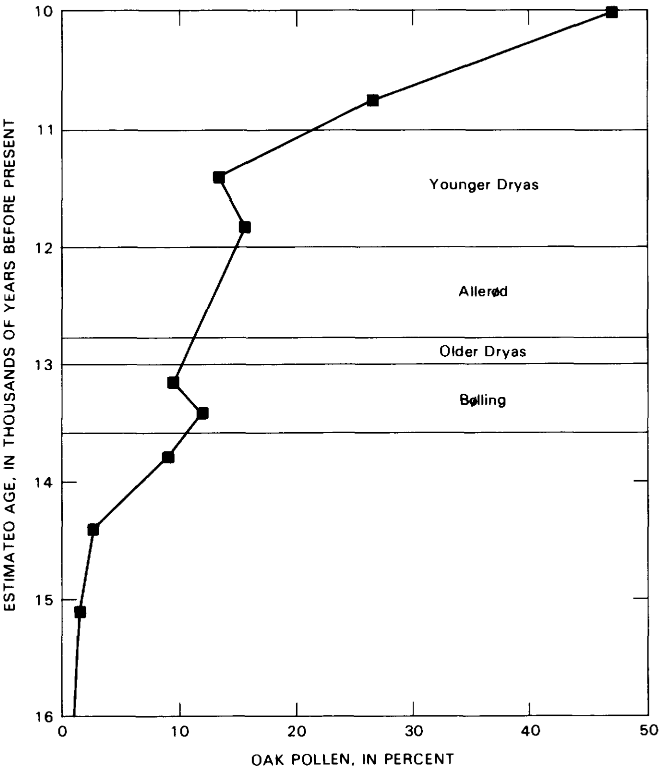


FIGURE 24.—Oak pollen percentage versus estimated age in calendar years for Clear Lake core 4 for period 16 to 10 ka. Ages of Younger Dryas, Allerød, Older Dryas, and Bølling periods of northwestern Europe have been converted from radiocarbon to calendar years using the same method as was used for Clear Lake ages (eq. 1). Data points indicate samples.

TABLE 14.—*Comparison of ages of climatic events in deep-sea isotopic stage 3*

Clear Lake minor oak peaks[1]		Grand Pile Interstadials[2]		Huon Peninsula high sea stands[3]
(ka)	(kg/cm^2)	Interval	(ka)	(ka)
32.3-34.3	4.1-4.4	"Denekamp"	29.8-31.9	31.0±2.5
39.6-42.8	5.1-5.5	"Hengelo"	41.2	40.0±3.0
48.6-57.6	6.3-7.5	"Moershoofd"	48-62	ca. 60

[1] Based on Clear Lake time scale $T=11.36 + (X-1.3)/0.1347$, T (ka), X (kg/cm^2)

[2] Woillard and Mook, 1982, with ^{14}C ages recomputed using a half-life of 5.73 ka

[3] Chappell and Veeh, 1978; Chappell, 1974; and Bloom and others, 1974 (uranium-series disequilibrium dating)

INTERPRETATION OF THE FOSSIL RECORD

POLLEN FACTORS

The first two pollen factors account for nearly three-fourths of the variance in the pollen data. The highest scores for these two factors are for the three major pollen variables, *Pinus*, *Quercus*, and TCT. The two factors taken together provide a summary of the forest vegetation history of the Clear Lake region. Scores for factor 1 are highest for TCT and *Pinus* (table 6). Samples with high loadings for factor 1 represent times when the forest vegetation surrounding Clear Lake was dominated by some combination of members of the TCT group and *Pinus* spp. There are two reasonable possibilities for the vegetation that produced high factor 1 loadings: montane coniferous forest dominated by *Pinus ponderosa* and *Calocedrus decurrens*, or a closed-cone-pine/cypress forest dominated by *Pinus attenuata* and *Cupressus* spp., most likely *C. sargentii* and *C. macnabiana.*

The interpretation preferred here is that high factor 1 loadings represent montane coniferous forest; this interpretation is based on factor scores for *Abies* and *Pseudotsuga* and on modern pollen surface-sample data from the Coast Ranges and the Sierra Nevada. The factor 1 scores for *Abies* and *Pseudotsuga* are small but positive and are larger for factor 1 than for any other factor. Relatively high frequencies of these uncommon pollen types should be found in a montane coniferous forest but not in a pine/cypress forest.

Modern pollen surface-sample data from the northern Coast Ranges (Adam and West, 1983) show that the highest pine pollen percentages in the Clear Lake area are found at high elevations in the montane coniferous forest. The modern pollen rain of the California montane coniferous forest is also known from surface transects of soil-surface pollen samples across Carson and Tioga Passes in the Sierra Nevada (Adam, 1967). In those transects, associated high frequencies of *Pinus* and TCT pollen are found in a belt along the lower western slope of the Sierra, where TCT frequencies were between 20 and 30 percent and *Pinus* frequencies were 40 to 60 percent. Above the high-TCT belt was a belt in which *Pinus* frequencies were even higher and low amounts of *Abies* pollen were consistently present; below the high-TCT belt was a belt bordering the Central Valley in which oak pollen was consistently present, although the frequencies were not nearly so high as the *Quercus* frequencies observed at Clear Lake. Also of interest is the upper Holocene pollen record from Hodgdon Ranch in Yosemite National Park, Calif. (Adam, 1967), in which TCT frequencies of as much as 80 percent are found at an elevation of about 1,300 m.

The similarity between high-TCT surface samples from the Sierra Nevada and the pollen spectra with high loadings for factor 1 at Clear Lake suggests that high factor 1 loadings at Clear Lake represent a mixed coniferous forest containing a strong admixture of *Calocedrus*. Such a forest is presently found on the lower western slope of the Sierra Nevada.

A regional *Pinus attenuata*/*Cupressus* spp. forest is not likely because of the rather restricted environmental preferences of the plants. Although they can tolerate a wide range of conditions, they are easily excluded by more aggressive competitors. The modern pine/cypress forests of California are generally found in areas where serpentine-derived soils or other poor substrates exclude their competitors (Vogl and others, 1977), and they also depend on recurrent fires for favorable reproduction. The distribution of serpentine in the Clear Lake area probably did not change much during the interval recorded in core 4, and it thus seems unlikely that pine/cypress forest was more widespread than at present.

The scanty macrofossil evidence available from core 4 is not sufficient to provide a definite interpretation of the TCT-pollen record. Both *Calocedrus* and *Cupressus*/*Juniperus* leaves are present in core 4, but remains are scarce and generally poorly preserved. *Juniperus* leaves were not distinguished from *Cupressus* because of poor preservation.

The scores for factor 2 are very low for all variables except *Quercus*, which has a score of 0.98 (table 6). Several other types have scores for factor 2 that are higher than their scores on any other factor. These include *Alnus*, *Salix*, Cruciferae, high-spine Compositae, Gramineae, *Chrysolepis*, and Rhamnaceae. Although *Pinus* and TCT have scores for factor 2 that are higher than the other secondary types, their scores on factors 1 and 5 are greater than their scores on factor 2. Factor 2 is interpreted here to represent primarily an oak woodland such as that which now grows in the lower parts of the Clear Lake basin.

The remaining factor that represents the behavior of the forest vegetation is factor 5. The highest factor 5 score is for *Pinus* (0.88), which is counterbalanced in part by a negative score of −0.45 for TCT. The pattern summarized in factor 5, which is independent of factors 1 and 2, describes a tendency for samples with the highest TCT-pollen frequencies to have relatively low pine-pollen frequencies and vice versa. This pattern is interpreted here in terms of the Sierra Nevada pollen surface transect described previously to mean that times of high factor 5 scores were periods in which the vegetation belts of the Coast Ranges were vertically depressed a maximum amount, so that the high-TCT vegetation belt was growing largely below the Clear Lake basin. Such times probably represent the maximum cooling observed in the pollen record.

This interpretation of factor 5 may be in error for the peaks recorded in the lower half of core 4. In that part of the section, there were a number of apparently quite rapid climatic shifts that may well have occurred faster than the vegetation was able to respond to them. Some of the high pine-pollen frequencies observed below a depth of 90 m may be the result of pine pollen blown in from a distance at a time when local pollen production was inhibited by sudden climatic changes.

The two remaining factors, 3 and 4, summarize the behavior of aquatic and riparian vegetation. Factor 3 is dominated by Nymphaeaceae leaf hairs; *Brasenia* pollen also has its highest score on factor 3 and probably represents the same plants. High loadings on factor 3 indicate that *Brasenia* or *Nuphar*, or both, were growing in the vicinity and thus indicate fairly shallow standing water, probably with a depth of about 0.5 to 2.0 m.

Factor 4 has its highest score for Cyperaceae, and *Typha* also has its highest scores for factor 4. Factor 4 is therefore interpreted to represent a reed/cattail marsh, with little or no open standing water.

CLUSTERING OF ZONES

The relations between zones are shown in figure 25, a mean-linkage clustering tree based on Euclidean distances between the centroids of the zones in a five-dimensional factor score space. The distances were divided by the maximum distance observed and then subtracted from 1.0 to yield a similarity coefficient that ranges from a value of 1.0 for identical zones to a value of 0.0 for the most dissimilar pair of zones in the analysis.

Several groups of zones are apparent (fig. 25). Six groups have mean similarity coefficients of at least 0.9 among their members. These include zones G and P, zones E, J, and M, zones O, Q, and U, zones F and H, zones I, L, and N, and zones A and A7.

The clusters of samples summarized in the dendrogram (fig. 25) are shown in greater detail in figure 26, in which the centroids of the zones are plotted against all combinations of the five summary factors. The broadest dispersion of zones occurs along factors 1, 2, and 5. Though factors 3 and 4 are useful in separating zones B–D and B7–D7 from each other and from the other zones, they offer little discrimination elsewhere. The groups of zones that have mean similarity coefficients >0.8 can be recognized easily in the plots of factor 1 compared to factor 5 and factor 2 compared to factor 5, and somewhat less clearly in the plot of factor 1 compared to factor 2, where there is some overlap.

The clusters represent groups of similar samples, and presumably similar environmental conditions, that are found in different parts of cores 4 and 7. The most prominent separation is the one that separates zones A, A7, and S from the rest of the zones. The degree of separation is apparent on the clustering dendrogram, on the plot of factor 1 compared to factor 2 (which accounts for 72 percent of the variance), and by direct inspection of the pollen diagram (pl. 1).

Zone A represents the upper 20 m of core 4 and zone A7 the top 6.8 m of core 7. The youngest radiocarbon age in core 7, 11.220±0.330 ka, comes from 7.63–7.71 m, some 80 cm below the base of zone A7. The relative positions of the date and the A7/B7 boundary suggest that the age of the boundary lies somewhere between 10 and 10.6 ka. Because of the stratigraphic position of zone A7 in the uppermost part of the core and because the core 7 radiocarbon ages are more reliable than those in core 4, zone A7 is interpreted here as corresponding to the Holocene. Zone A is correlated directly with zone A7 on the basis of the curves for factor 2 and the similar stratigraphic position. The radiocarbon ages for core 4 support a Holocene age for zone A.

The other member of the cluster containing the two Holocene zones is zone S. This zone is the only interval in either core in which the pollen spectra resemble those of the Holocene, and this resemblance is a primary reason for correlating zone S with the last interglacial period, together with the sedimentation-rate-based extrapolation described previously.

PALEOCLIMATIC UNITS

The pollen zones described above form the stratigraphic basis for the division of the Clear Lake record into a series of informal paleoclimatic units. The approach used here was proposed by Lüttig (1965) and followed by Menke (1976), who recognizes cold periods as cryomers (German = Kryomer) and warm periods as thermomers in the early Weichselian climatic record of West Holstein.

As used here, a cryomer is a period that is interpreted to be cooler than the periods that precede and follow it; a thermomer is warmer. Either unit may contain lesser cryomers and thermomers within it. If a cryomer or thermomer includes the present, it is defined only by comparison with the preceding climate, and without any implications for the future climate that will follow. Names used here have been selected from the ethnogeography of the Pomo and neighboring Indians (Barrett, 1908). Locations of the former Indian villages and landmarks whose names are used in this report are shown in figure 27. Spelling follows the Barrett versions, with the exception of Mt. Konocti (Barrett: Kanaktai), for which the current spelling is used.

The pollen frequencies used to characterize the climatic units are pollen percentages based on the sum of all fossil pollen. However, the core 4 pollen record consists almost entirely of arboreal pollen. It will probably be necessary to define a pollen sum that excludes nonarboreal pollen

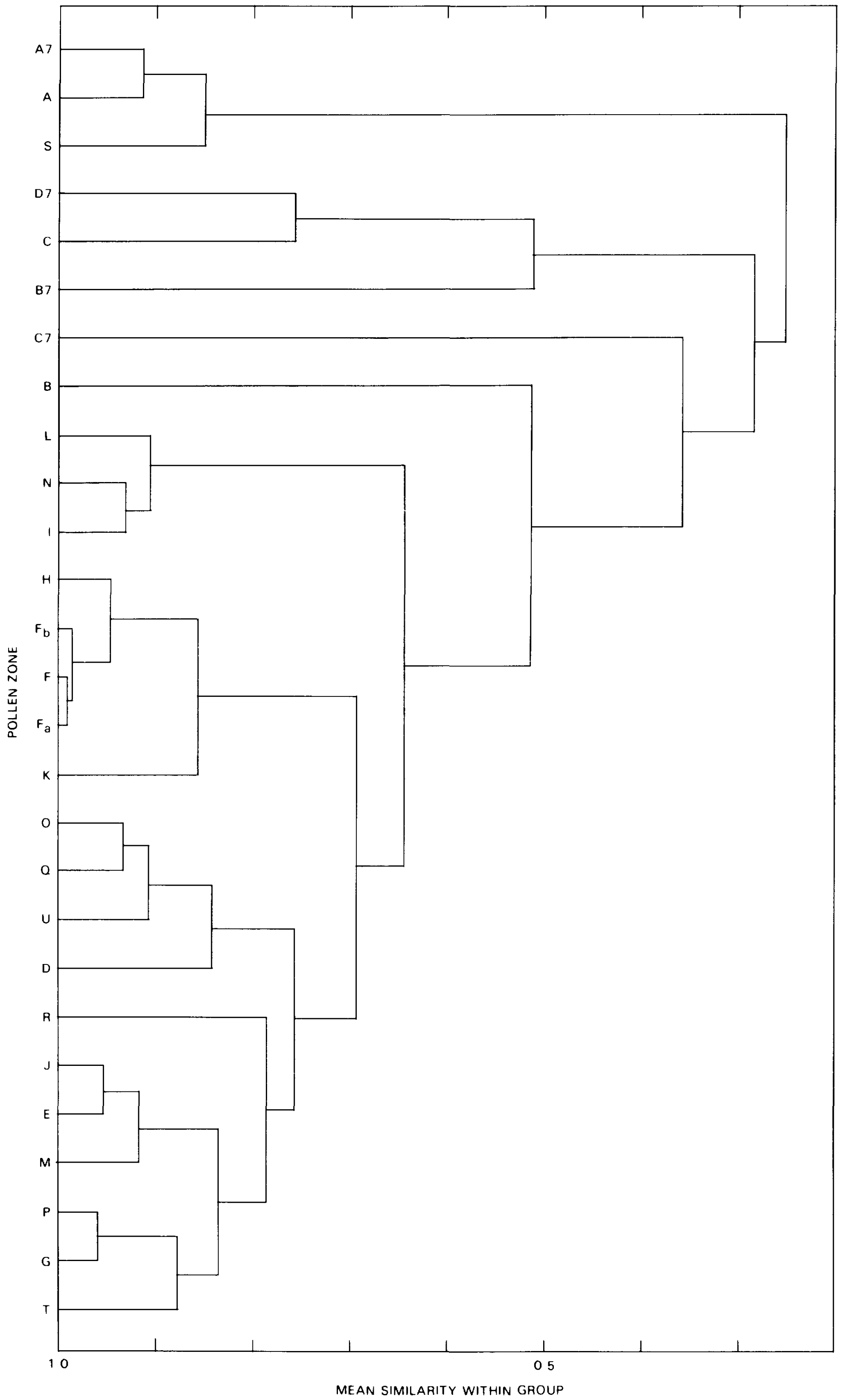


FIGURE 25.—Dendrograph of Clear Lake pollen zones, clustered on basis of Euclidean distance between zone centroids in a five-dimensional factor space. Mean-linkage clustering was used. See figure 26.

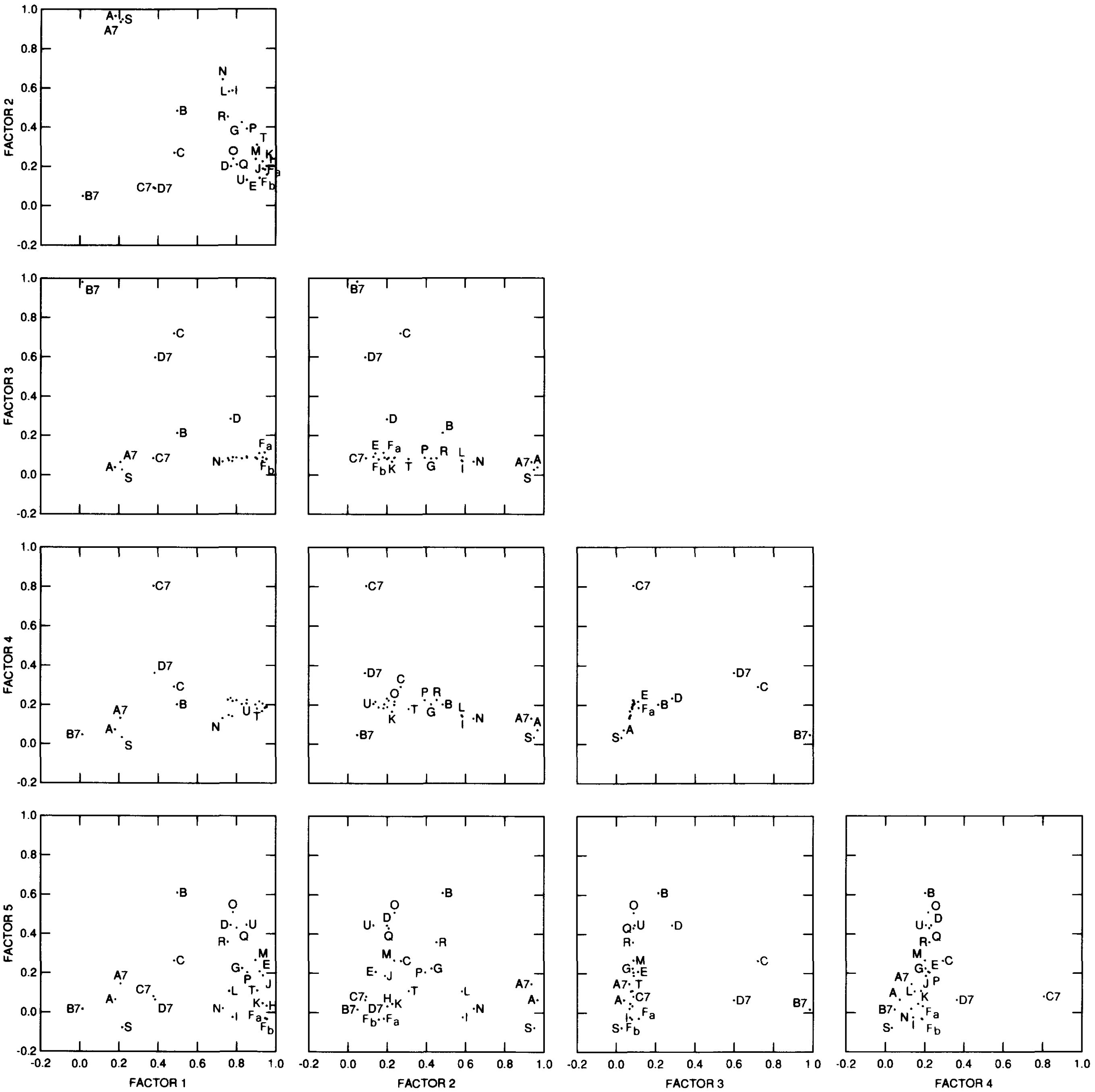


FIGURE 26.—Plots of zone centroids of pollen zones in two-dimensional cross sections through the five-dimensional factor space. Comparison of various sections shows which factors are responsible for clustering patterns summarized in figure 25. Not all points are labeled on some subsurfaces.

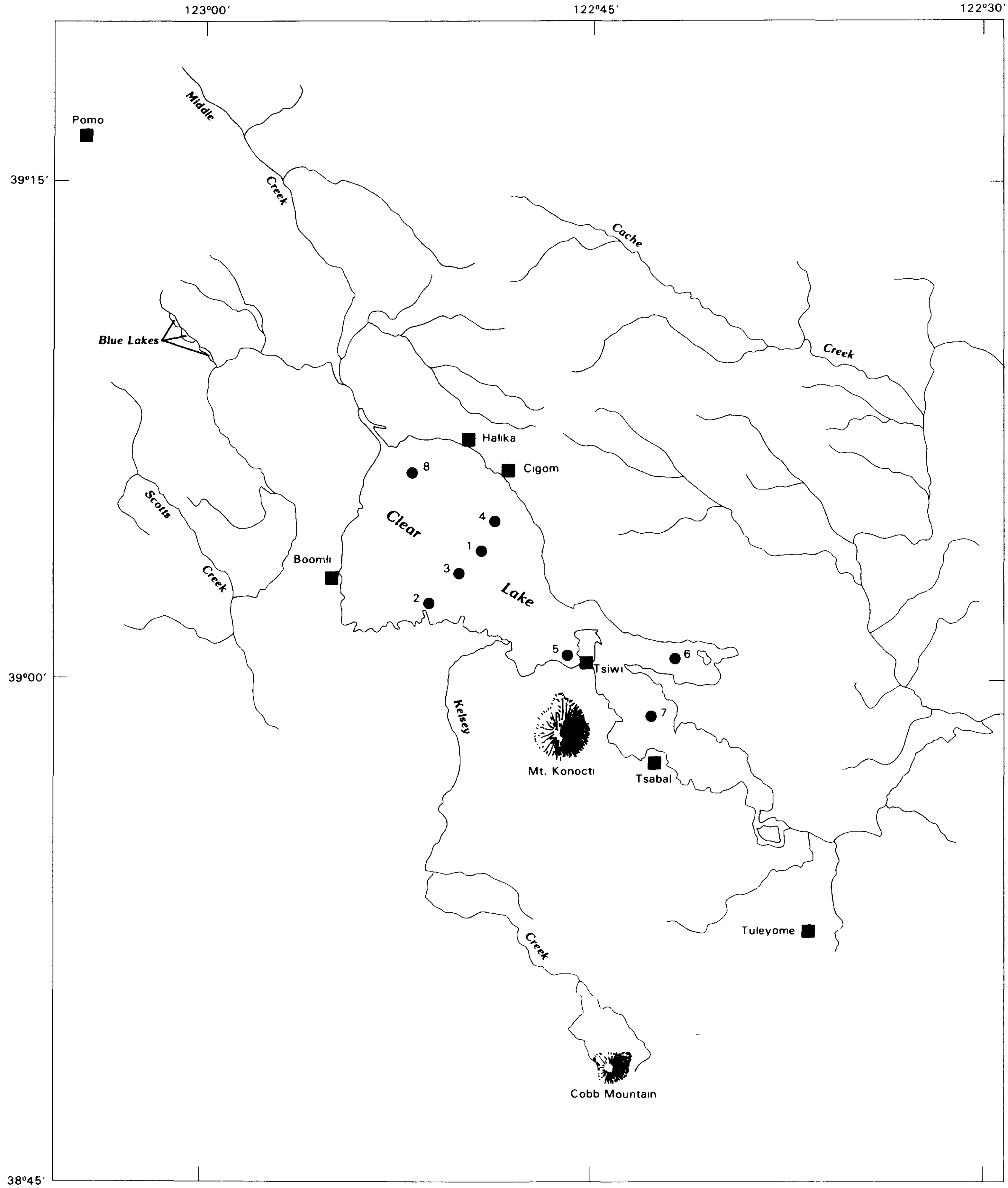


FIGURE 27.—Locations of former Indian villages whose names have been used to designate the paleoclimatic units defined in this report. Locations from Barrett (1908). Numbered localities are cores 1-8 (Sims, 1976).

if an attempt is made to recognize the climatic units in other cores that represent environments nearer to the shore of the lake.

REFERENCE SECTION

The reference section for all the climatic units described below is core 4, taken from beneath 8.4 m of water in the main basin of Clear Lake, about 2.5 km southwest of the town of Lucerne (fig. 2), between September 25 and October 17, 1973. The 115.2-m core, which has been described in detail by Sims and Rymer (1975c), is presently stored at the U.S. Geological Survey in Menlo Park, Calif., under the custody of J.D. Sims.

DEFINITION OF PALEOCLIMATIC UNITS

TSABAL CRYOMER

The oldest unit is the Tsabal cryomer, named after the Southeastern Pomo Indian camp of Tsabal on the south shore of the Highlands Arm of Clear Lake (fig. 27). The unit includes pollen zones T and U and is characterized in the type section by *Quercus*-pollen frequencies of less than 20 percent, *Pinus* frequencies of greater than 30 percent, and TCT frequencies of greater than 40 percent, as well as minor amounts of *Abies*, *Picea*, *Tsuga*, and *Pseudotsuga*. The upper boundary is defined on the basis of an abrupt increase in the frequency of *Quercus* pollen to greater than 50 percent between the depths of 112.23 and 112.13 m. The lower boundary has not been defined. The presently known thickness of the deposits is less than 3 m, but the unit is probably much thicker. Recent work on core CL-80-1 indicates little change in pollen content in that core below the level of pollen zone S (Heusser and Sims, 1981). The deposits of the Tsabal cryomer thus are probably at least 50 m thick (Sims and others, 1981b).

KONOCTI THERMOMER

The Konocti thermomer consists of the interval represented by the deposits of pollen zone S; those deposits are characterized by *Quercus*-pollen frequencies of more than 50 percent. Both the upper and lower boundaries are placed at abrupt changes in oak-pollen frequency. The thickness of the deposits of the Konocti thermomer in core 4 is about 3.5 m. These deposits are the first deposits below those of the Holocene that contain *Quercus*-pollen frequencies that equal or exceed those of the Holocene; on that basis, the Konocti thermomer is correlated with the last interglaciation. The unit is named after Mt. Konocti, a large volcano of middle and late Pleistocene age that dominates the Clear Lake basin.

POMO CRYOMER

The Pomo cryomer, as proposed here, consists of the interval represented by pollen zones B through R in core 4 and is characterized by *Quercus*-pollen frequencies of less than 50 percent. Pollen zones B7, C7, and D7 are also included in the Pomo cryomer. The unit is named after the Pomo Indian village of Pomo (fig. 27) in Potter Valley (fig. 1). The deposits of the Pomo cryomer extend from 21.10 to 108.67 m in core 4, and many climatic fluctuations are recorded within the unit. Both the lower and upper boundaries are defined by abrupt changes in *Quercus*-pollen frequency (pl. 1). The upper boundary is somewhat more gradual on the pollen diagrams, probably because the sediments at the upper boundary are not so compact as those at the lower boundary.

BOOMLI THERMOMERS

The climate during the early part of the Pomo cryomer oscillated several times between relatively warm conditions, characterized by *Quercus*-pollen frequencies greater than 10 percent, and relatively cool conditions, characterized by *Quercus*-pollen frequencies less than 10 percent. Five local maxima of *Quercus* pollen, corresponding to pollen zones G, I, L, N, and P, are designated here the Boomli thermomers. They are named after the Pomo Indian village of Boomli, whose site was within the present town of Lakeport (fig. 27). The thermomers are numbered from Boomli 1 (oldest) to Boomli 5 (youngest).

TSIWI CRYOMERS

The deposits of the Boomli thermomers are separated from each other and from the underlying deposits of the Konocti thermomer by a series of beds that contain local minima for *Quercus* pollen, usually associated with local maxima for *Pinus* as well. *Quercus*-pollen frequencies within these deposits are less than 10 percent. These *Quercus* minima are attributed to relatively cold conditions that are here designated the Tsiwi cryomers, named after the Pomo Indian village of Tsiwi at Little Borax Lake (fig. 27). The cryomers are numbered from Tsiwi 1 cryomer (oldest) to Tsiwi 5 cryomer (youngest); each Tsiwi unit underlies the Boomli unit with the same number. The correlation between the cryomers and thermomers and the pollen zones is shown in table 15.

CIGOM CRYOMERS

The sediments overlying the Tsiwi cryomers and Boomli thermomers include two units, pollen zones E and F_b, which contain the lowest percentages of *Quercus* pollen found in the Pomo cryomer and are interpreted to represent the two major glacial maxima of the last glacial cycle.

These deposits were produced under cool conditions during two cryomers that are designated here as the Cigom 1 and Cigom 2 cryomers; they are named after the Pomo Indian village of Cigom on the northeast shore of Clear Lake (fig. 27). *Quercus*-pollen frequencies within the deposits of the Cigom cryomers are less than 5 percent, except for a single sample in the Cigom 1 deposits. The reference section for Cigom 1 is pollen zone F_b, and the type section for Cigom 2 is pollen zone E. The boundaries of the Cigom cryomers are less well defined than those of the units defined above. Pollen zone C7 is also correlated with the Cigom 2 cryomer. The Cigom 1 cryomer is not represented in core 7.

HALIKA THERMOMERS

The interval between the Cigom 1 and Cigom 2 cryomers was characterized by climatic conditions that were somewhat more moderate. *Quercus*-pollen frequencies increased above 5 percent during three separate intervals, and each such interval is recorded by more than one sample in core 4. These intervals are here designated as the Halika thermomers after the Pomo Indian village of Halika, which was located near Cigom on the northeast shore of Clear Lake (fig. 27). The three intervals are designated as Halika 1, 2, and 3, from oldest to youngest. The samples attributed to the Halika thermomers are listed in table 16. They are separated from each other by sediments with *Quercus*-pollen frequencies less than 5 percent. All three thermomers are found within pollen zone F_a.

TULEYOME THERMOMER

The Tuleyome thermomer (equivalent to Holocene) is here named after the Northern Moquelumnan Indian village of Tuleyome, which was located about 3.2 km south of the town of Lower Lake (fig. 27). Pollen zone A is designated as the reference section, and zone A7 is also correlated with the Tuleyome thermomer. The reference section is characterized by *Quercus*-pollen frequencies greater than 40 percent and almost always greater than 50 percent. Both *Pinus* and TCT pollen frequencies are generally less than 20 percent. Remains of the algae *Pediastrum* spp., *Botryococcus*, and *Coelastrum* are abundant.

ENVIRONMENTAL HISTORY OF CLEAR LAKE BASIN

TSABAL CRYOMER

The few samples from the Tsabal cryomer suggest that the climate was quite cold, because oak pollen is almost completely absent from the lowest samples in core 4. The major pollen types, TCT and pine, indicate that a mixed conifer forest surrounded Clear Lake at that time. The highest observed frequencies of spruce, hemlock, and Douglas fir are found in the deposits of the Tsabal cryomer, and these suggest that the character of the forest may have been somewhat different from that of the forests that occupied the area during the Pomo cryomer. Minor amounts of *Botryococcus* and *Pediastrum* K were growing in the lake, especially during the transitional conditions of pollen zone T. The slight local maximum in the grass-pollen curve for the bottom three samples (pl. 1) may indicate either more open conditions in some areas or the presence of some riparian grasses.

TABLE 15.—*Correlation between informal climatic units and pollen zones of this study*

Informal climatic unit	Pollen zones	
	Core 4	Core 7
Tuleyome thermomer	A	A7
Pomo cryomer:		
Late:	B, C, D	B7
Cigom 2 cryomer	E	C7
Middle:		
Halika thermomers	F_a (in part)	D7
Cigom 1 cryomer	F_b	
Early:		
Boomli 5 thermomer	G	
Tsiwi 5 cryomer	H	
Boomli 4 thermomer	I	
Tsiwi 4 cryomer	J	
(Unnamed transitional interval)	K	
Boomli 3 thermomer	L	
Tsiwi 3 cryomer	M	
Boomli 2 thermomer	N	
Tsiwi 2 cryomer	O	
Boomli 1 thermomer	P	
Tsiwi 1 cryomer	Q	
(Unnamed transitional interval)	R	
Konocti thermomer	S	
Tsabal cryomer	T, U	

TABLE 16.—*Sample data for the Halika thermomers*

Thermomer	Depth (m)		Number of samples	*Quercus* (max. pct.)
	Top sample	Bottom sample		
Halika 1	57.00	58.00	2	9.5
Halika 2	63.20	67.00	5	9.7
Halika 3	70.01	72.04	3	10.4

KONOCTI THERMOMER

The Konocti thermomer began with a sudden doubling of oak-pollen frequencies at the end of the transitional pollen zone T. This increase probably represents a very sudden climatic amelioration. Small abrupt increases in the frequencies of Cyperaceae and high-spine Compositae pollen are present at the beginning of the Konocti, together with sudden decreases in the frequencies of pine and TCT.

The marked shift in vegetational types at the onset of the Konocti thermomer was accompanied by an abrupt increase of more than 25 percent in sediment density (fig. 7). This increase was probably the result of increased soil erosion in the Clear Lake watershed at a time when warmth-loving plant communities had not yet become well established. After the initial peak in sediment density at the onset of the Konocti, sediment density decreased throughout the thermomer, probably in response to a decreasing input of clastic sediment from the watershed and a somewhat increased productivity of the lake as it reached higher summer temperatures.

The middle of the Konocti thermomer was significantly warmer than the early and late phases, judging from the frequency of oak pollen. During the middle part of the Konocti, oak-pollen frequencies exceeded 80 percent and pine-pollen frequencies decreased to well below 10 percent. These conditions are not matched anywhere else in the record. It seems likely that the middle part of the Konocti thermomer was significantly warmer and (or) drier than the warmest part of the Tuleyome thermomer (Holocene) at Clear Lake and that the role of *Pinus* in the vegetation was less important than it is today. Adam and West (1983) estimate that temperatures were as much as 1.5 °C warmer than at present during the Konocti thermomer. Because the amount of grass pollen reaching the lake sediments was very low, the high oak-pollen frequencies probably do not represent oak grassland in the Clear Lake basin.

The middle of the Konocti thermomer is also distinguished from the early and late phases by high frequencies of hystrichosphaerids(?); throughout the middle Konocti, they are more abundant than pollen grains. Hystrichosphaerids are the resting stages of dinoflagellate algae (Evitt, 1969), but the Clear Lake specimens have not been identified.

Freshwater "red tides" of the dinoflagellate *Peridinium pernardii*, with cell densities of at least 5,000/cm^3, have been reported in Clear Lake (Horne and others, 1971). If the hystrichosphaerids found in the Konocti thermomer and the lower part of the Tuleyome thermomer represented *P. pernardii*, however, then one would also expect to find high frequencies of the cysts in modern Clear Lake sediments, but this is not the case for either core 4 or core 7 (pl. 3). Large numbers of *Peridinium* cysts are found in the surficial sediments of core 4, and these may be cysts of *P. pernardii.*

Hutchinson (1967) recognizes both oligotrophic and eutrophic dinoflagellate plankton associations, so the simple presence of abundant hystrichosphaerids does not reveal anything about the character of the lake during the warmest part of the Konocti thermomer. Conditions were clearly different from those of the early part of the Tuleyome thermomer, when hystrichosphaerids were again fairly common but were much less frequent than the other algae.

POMO CRYOMER

The Pomo cryomer is here divided into three main phases that differed significantly in their climatic responses. Early Pomo time consists of the Tsiwi cryomers and the Boomli thermomers as well as the transitional interval represented by pollen zone R; it is characterized by numerous systematic oscillations of large amplitude in the frequency of *Quercus* pollen. Middle Pomo time consists of the Cigom 1 cryomer and the succeeding Halika thermomers up to the base of the Cigom 2 cryomer, and upper Pomo time consists of the Cigom 2 cryomer and the overlying pollen zones up to the base of the Holocene or Tuleyome thermomer.

EARLY POMO CRYOMER

ONSET OF THE POMO CRYOMER

The transition from the end of the Konocti thermomer to the start of the Pomo cryomer was quite sudden. *Quercus* frequencies decreased rather slowly from a maximum of about 80 percent to about 60 percent during the latter half of the Konocti thermomer. The sudden decrease in *Quercus* frequencies that marks the onset of the Pomo cryomer occurs over a stratigraphic interval of from 23 to 96 cm. The interval cannot be determined exactly because of poor core recovery in the critical part of the section (fig. 28). The uppermost sample of the Konocti thermomer, sample 1526, was taken from core segment 120 (Sims and Rymer, 1975c). The coring device penetrated 86 cm of sediment when core segment 120 was drilled; however, only 13 cm of sediment was recovered. The recovered sediment probably represents the upper part of the interval sampled, and the missing sediment probably represents the lower part. If this is not so, then sample 1526 may have come from a depth as great as 109.63 m, instead of from its recorded depth of 108.90 m. It is thus possible that the end of the Konocti thermomer was somewhat less abrupt than it appears on the pollen diagram (pl. 1).

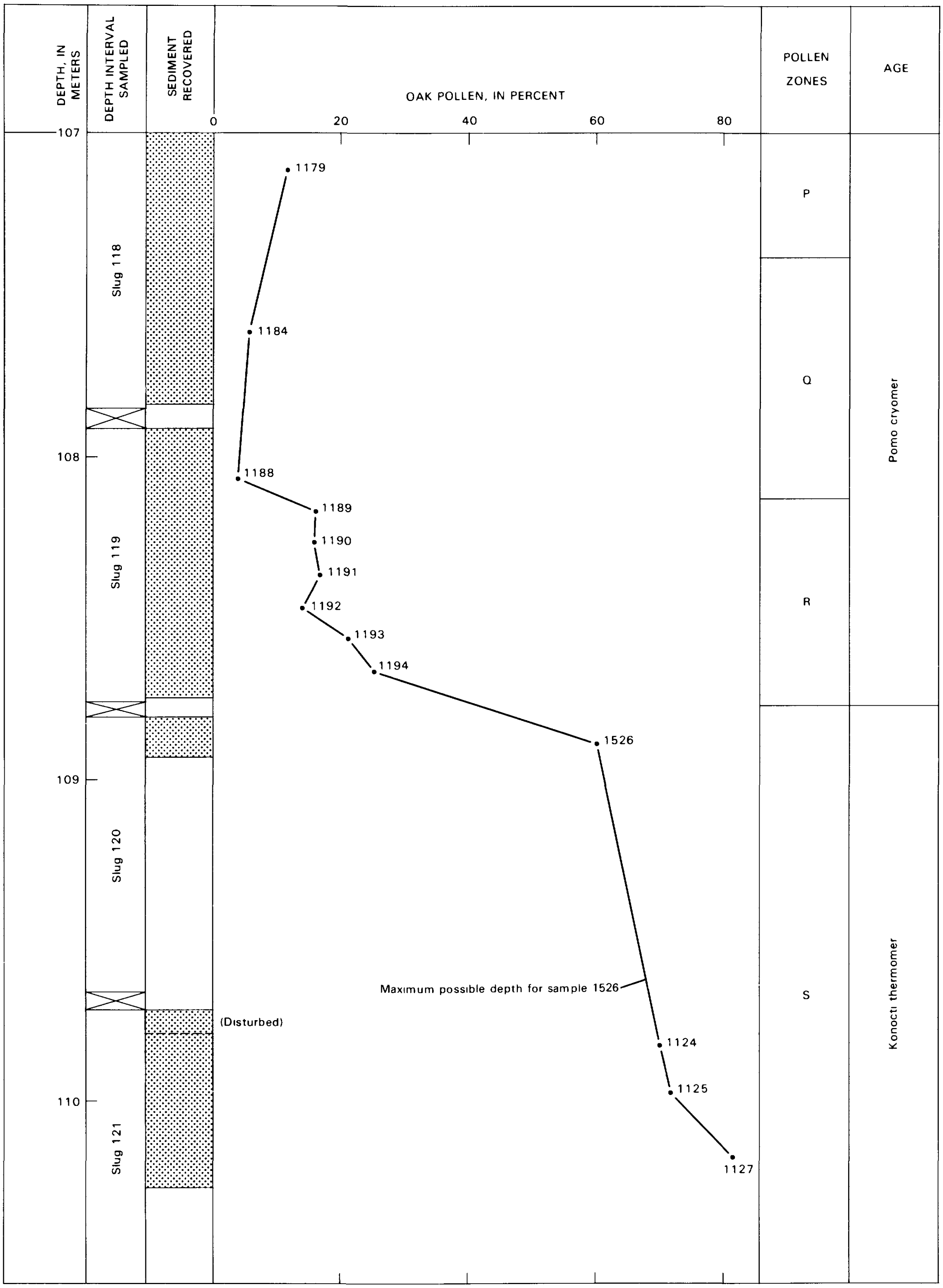


FIGURE 28.—Coring intervals, sediment recovery, and oak percentages across transition from Konocti thermomer to Pomo cryomer. Data for coring intervals and sediment recovery from Sims and Rymer (1975c). Numbers next to data points are sample numbers. Depth intervals marked by X were not sampled.

The shift from about 60 percent *Quercus* pollen at the end of the Konocti thermomer to about 25 percent at the onset of the Pomo cryomer probably occurred over a stratigraphic interval of no more than 23 cm. This shift represents an abrupt change, particularly since the sediments are not laminated and the sharpness of the shift has probably been blurred through bioturbation. However, the sudden end of the Konocti thermomer did not immediately lead to full glacial conditions. The *Quercus* frequencies of pollen zone R decrease from 25 percent at the base of the zone to values near 15 percent in the middle and upper parts of the zone. Not until the onset of the Tsiwi 1 cryomer, about 60 cm above the top of the Konocti deposits, do *Quercus*-pollen frequencies decrease below 5 percent.

A slight reversal of the decline in sediment density occurred at the end of the Konocti thermomer (fig. 7), but it was not nearly so large as the earlier change at the start of that interval. The climatic change at the end of the thermomer was in the direction of more moisture and cooler conditions, so that the stabilizing effect of plant cover on the soil probably increased. Within the lake, the hystrichosphaerids that dominated the algal flora during the middle part of the Konocti thermomer were replaced by low frequencies of *Botryococcus* and *Pediastrum* X.

The response of the vegetation of the Coast Ranges to the climatic change at the end of the Konocti thermomer was dramatic. The oaks clearly responded suddenly; probably many were killed by the change, whereas others perhaps stayed alive for a time but were unable to reproduce. The proportions of different species of *Quercus* contributing pollen to Clear Lake sediments also probably changed significantly at the onset of the Pomo cryomer.

The decrease in *Quercus*-pollen frequencies was matched by dramatic increases in the frequencies of TCT and *Pinus* pollen (fig. 14). The more rapid increase of *Pinus* than TCT frequencies may represent in part a more rapid migration of *Pinus* than TCT species into habitats suddenly made suitable for them. It may also represent the ability of *Pinus* pollen to disperse great distances; if local pollen production were suppressed by a sudden climatic shift, then wind-transported pollen blown in from distant forests could become an important part of the pollen rain until the vegetation was able to adjust to the new climate.

THE TSIWI CRYOMERS AND BOOMLI THERMOMERS

The Tsiwi cryomers and Boomli thermomers represent a series of broad oscillations of the regional climate of the Clear Lake area during a period of 40,000 to 50,000 years. The total thickness of the deposits is about 25 m; sediment density (fig. 7) shows both regular and erratic changes. The climatic fluctuations of the early Pomo cryomer appear to have an amplitude of about half that observed for glacial/interglacial changes, on the basis of changes in oak-pollen percentages. Adam and West (1983) estimate that the Boomli 2, 3, and 4 temperature maxima were about 1-2 °C cooler than at present and that minimum temperatures during the Tsiwi cryomers were about 7 °C cooler.

The Tsiwi 1 cryomer was of short duration, and less than 1 m of sediment was deposited. *Quercus*-pollen frequencies decreased to about 5 percent, or 5,000 grains/gram, whereas *Pinus* and TCT frequencies increased abruptly. A small but systematic peak of *Fraxinus* (ash) began during the Tsiwi 1 cryomer and persisted throughout the first half of the Boomli 1 thermomer that followed; a similar peak occurred for the high-spine Compositae.

Tsiwi 1 through Tsiwi 3

The interval from the beginning of the Tsiwi 1 cryomer through the end of the Tsiwi 3 cryomer was a period of marked climatic and environmental instability in the Clear Lake basin. The sediment-density curve (fig. 7A) shows many rapid oscillations that relate in a general way to the three cycles of pollen concentration changes during the same interval (101.62 to 108.07 m). During the initial phases of both the Tsiwi 1 and Tsiwi 2 cryomers, there was a rise in pollen concentration in the sediment and an accompanying decrease in sediment density, suggesting in each case that a shift to cooler, moister conditions led to an increase in vegetative cover and a decrease in the erosion rate. These conditions were reversed during the warming conditions that led to the Boomli 1 and 2 thermomers.

Tsiwi 1 and 2 are both characterized by high frequencies of pine pollen and low frequencies of oak. Small amounts of *Botryococcus* are found in Tsiwi 1 deposits, and in Tsiwi 2 deposits minor amounts of both *Botryococcus* and *Pediastrum* K are found.

Boomli 1 Thermomer

The Boomli 1 thermomer was a minor warm period during the early Pomo cryomer. Oak-pollen frequencies increased from 5 percent to almost 20 percent, and the ratio of pine to TCT pollen decreased (pls. 1 and 4). Inspection of the pollen-concentration data (fig. 14) indicates that the percentage figures shown on plate 1 do not provide an adequate view of the Boomli 1 thermomer. The percentage peak for oak pollen during the Boomli 1 peak (fig. 14*A*) clearly occurs before the peak in oak pollen concentration. Between depths of 107.60 and 106.55 m, pollen concentrations of both TCT and pine pollen decrease by more than two-thirds, whereas oak concentrations increase by almost 30 percent. These data suggest that the climatic warming that produced the Boomli 1 thermomer may have been too sudden for the oaks to adjust, and that the sudden decreases in pine and TCT frequencies represent a sudden restriction in their ranges. The highest oak concentration was found in the uppermost sample of the interval, so apparently the oaks were still migrating into the area and becoming established when the Boomli 1 thermomer came to an end. The first peak of *Peridinium* cysts is found near the end of the Boomli 1 thermomer; its significance is not clear.

TSIWI 3 CRYOMER

The Tsiwi 3 cryomer is perhaps the most remarkable period during the early Pomo cryomer because of its short duration and its abrupt start and end. Tsiwi 3 deposits consist of a stratigraphic interval of at least 50 cm but no more than 92 cm, and both the lower and upper boundaries are sharply defined in the percentage data (pl. 1). The upper boundary is somewhat less sharp in the pollen concentration data than in the percentage data (fig. 14*A*–*C*), but the concentration data still indicate a rapid change.

A small but distinct increase in sediment density at the start of Tsiwi 3 time was the last of the rapid density fluctuations observed during the early part of early Pomo time (fig. 7*A*). Total pollen concentration in the sediment decreased to the lowest values observed in the core. Although sediment density increased by only 8.5 percent, total pollen concentration decreased by 59 percent. Concentrations of oak, pine, and TCT pollen all decreased abruptly, but the decrease was proportionally the greatest for oak and the least for pine, so that constraint effects produced a percentage peak for pine. The changes in pollen concentration recorded during the Tsiwi 3 cryomer result from some combination of changes in sediment density, sedimentation rate, and pollen influx. Changes in sediment density are of sufficient magnitude to account for only a small part of the changes, so pollen influx and sedimentation-rate changes must have been the primary causes.

Because the decreases in the concentrations of pine, oak, and TCT pollen are not proportional, it seems unlikely that a simple increase in sedimentation rate could alone account for the changes in pollen concentration. However, both the higher sediment density and the lack of an increase in pine pollen accompanying the decrease in oak suggest that the sedimentation rate during the Tsiwi 3 cryomer was probably higher than usual (pine and oak show an inverse relation in the samples below the Tsiwi 3 deposits). If the sedimentation rate was in fact higher than normal, then the Tsiwi 3 cryomer was even shorter and more abrupt than its appearance in the pollen diagrams would indicate.

Within the lake, the *Peridinium* cysts were replaced by a small but persistent population of *Pediastrum* K. Early in the succeeding Boomli 3 thermomer, *Pediastrum* K became more abundant than the pollen grains; it then declined gradually in frequency until the end of the thermomer, when it almost disappeared.

BOOMLI 3 THERMOMER

The onset of the Boomli 3 thermomer was nearly as sudden as the start of the Tsiwi 3 cryomer that preceded it. Dry sediment density decreased by nearly 20 percent, and total pollen concentration more than doubled relative to the extreme conditions of the Tsiwi 3 cryomer; these changes suggest that sedimentation and erosion rates were relatively low. The Boomli 3 thermomer, as defined here, is represented by the samples between 98.51 and 101.30 m (pollen zone L). The interval was unusual among the events of the early Pomo cryomer in that it did not end suddenly; the transition from the oak maximum of Boomli 3 to the oak minimum of Tsiwi 4 is spread over a stratigraphic interval of 6.20 m. The upper part of the transition (pollen zone K) is marked by a great increase in TCT pollen at a time when oak pollen is decreasing. Pine-pollen frequencies change little within the two zones. The upper part of the Boomli 3 thermomer is also characterized by low peaks of Douglas fir (*Pseudotsuga*), ash (*Fraxinus*), and high-spine Compositae pollen (pl. 1).

Lake vegetation changed during the Boomli 3 thermomer and the succeeding Boomli 3-Tsiwi 4 transition. A low peak of unknown A during early Boomli 3 time was replaced by *Typha-Sparganium* and *Potamogeton* during upper Boomli 3 time, and then by sedge (Cyperaceae) pollen (pl. 2). Among the algae (pl. 3), the early Boomli 3 peak of *Pediastrum* K was replaced by low peaks of *Botryococcus* and *Peridinium* cysts. The frequencies involved in these shifts are very low, but the overall impression is that the lake became shallower during the transition from Boomli 3 warmth toward the colder conditions of the Tsiwi 4 cryomer. Because the shallow-water indicators do not persist, the low lake levels are probably the result of climatic shifts rather than irreversible changes such as faulting.

TSIWI 4 CRYOMER

The Tsiwi 4 cryomer was the longest and most severe cold interval of the early Pomo cryomer. Sediment density for the Tsiwi 4 deposits is near normal but shows a tendency to increase with time. Oak pollen is quite scarce, pine pollen increases somewhat, and TCT frequencies decrease greatly from their peak in pollen zone K. Fir (*Abies*) pollen, which is also present, suggests distinctly cool conditions in the basin. The pronounced pine-pollen percentage peak (pl. 1) during the Tsiwi 4 cryomer is apparently largely an artifact of the percentage constraint.

BOOMLI 4 THERMOMER

The Boomli 4 thermomer is the longest of the warm intervals during the early Pomo cryomer. Warm conditions appeared suddenly; the transition from maximum cold conditions to the maximum in oak pollen is found over a stratigraphic interval of 76 cm. Total pollen densities were relatively low at the start of the interval but increased with time. Sediment density was higher than normal at the beginning but decreased with time.

The comparatively low oak-pollen concentration (fig. 14*A*) raises the possibility that conditions during the Boomli 4 thermomer (pollen zone I) were significantly cooler than during the Boomli 2 and 3 thermomers (pollen zones N and L), in spite of the fact that the oak percentages are roughly equal. Inspection of figure 7, however, indicates that the differences in oak concentration during those intervals were the result of differences in sediment density. The sediments deposited during pollen zones N and I were of normal or slightly higher than normal density, whereas pollen zone L sediments are much less dense than normal. It seems unnecessary to resort to climatic differences to explain the differences between the oak percentage and concentration curves in this part of the core.

A gradual cooling occurred during the latter half of the Boomli 4 thermomer. During this cooling, pine and TCT concentrations increased. Though there was also a small increase in oak concentrations, it was not enough to keep up with the increases in pine and TCT, so oak percentages fell.

Low but persistent peaks in alder (*Alnus*) and willow (*Salix*) pollen during the first half of the Boomli 4 thermomer indicate that these plants grew around the margin of the lake. Somewhat more fir pollen is present in the Boomli 4 samples than in samples from the previous warm periods; perhaps stands of fir that became established in the mountains around Clear Lake during the Tsiwi 4 cryomer may have persisted during the Boomli 4 thermomer as relict stands in protected habitats.

Aquatic plants contributed minor amounts of pollen to Boomli 4 deposits. There is a distinct peak of unknown A during the first half of the interval, as well as traces of *Potamogeton* and minor amounts of sedge pollen. At the beginning and end of Boomli 4, *Pediastrum* K is present in small amounts. During the middle of the interval, it is replaced by abundant *Peridinium* cysts, which are about twice as common as pollen in most samples.

TSIWI 5 CRYOMER

The Tsiwi 5 cryomer is marked by a decrease in oak pollen and an increase in fir. High-spine Compositae and grasses also increased. Sediment density and total pollen concentration were relatively low. *Pediastrum* K became abundant for the first time, attaining frequencies of as much as three times that of the fossil pollen.

BOOMLI 5 THERMOMER

The Boomli 5 thermomer, a relatively minor event, is comparable in magnitude to the earlier Boomli 1 thermomer but of shorter duration and lower amplitude than the other Boomli intervals. Concentrations of oak, pine, and TCT pollen in the sediment increased; sediment density was about normal. In the lake, *Pediastrum* K persisted as the major acid-resistant planktonic form and was accompanied by minor peaks of *Botryococcus* and *Peridinium* cysts.

MIDDLE POMO CRYOMER

In contrast with the early Pomo cryomer, the middle Pomo cryomer was a time of relative climatic stability. The climate was much colder than at present, but there is no record of repeated sudden changes from one climatic regime to another. In part, this may be a result of the low frequencies of oak pollen during middle Pomo time. Oak is the most sensitive recorder of climatic changes in the lower part of the core, but at low frequencies the sensitivity to climatic changes is suppressed. Both pine and TCT pollen show changes in frequency, but the general impression is that most of those changes represent statistical noise rather than systematic climatic signals.

CIGOM 1 CRYOMER

The Cigom 1 cryomer is marked by low pollen concentrations for pine, oak, and TCT and by oak-pollen frequencies at or near zero. These values must represent the total or near-total elimination of oak from the Clear Lake basin and the establishment of a mixed coniferous forest down to elevations of 400 m or less. The relatively low ratio of pine to TCT pollen during Cigom 1 time suggests that incense-cedar was able to compete successfully against the pines around Clear Lake and that the cooling did not depress the incense-cedar distribution below 400 m.

The record of aquatic plants and algae for Cigom 1 time is uneventful. Sedge grains are present in low numbers but show no particular pattern. A prominent peak in the frequency of *Pediastrum* K matches the very minor oak-pollen peak at a depth of 80 m; there are no other records of aquatic events during Cigom 1.

POLLEN ZONE F_A AND THE HALIKA THERMOMERS

The environmental complacency established during the Cigom 1 cryomer persisted throughout the middle Pomo cryomer with only a few perturbations. Three brief intervals with oak-pollen percentages more than 5 percent are designated the Halika thermomers. These thermomers were all cooler than even the coolest of the Boomli thermomers and were marginally warmer than the warmest of the Tsiwi cryomers on the basis of their oak pollen percentages. TCT-pollen percentages and concentrations were high throughout middle Pomo time, whereas pine-pollen concentrations record little change. The sharp peak in *Isoetes* microspores in pollen zone F_a marks the beginning of a period during which the quillwort was a common aquatic plant in the lake.

The lowermost part of the core 7 pollen record corresponds to the upper part of the middle Pomo cryomer. Pollen zone D7 is correlated with the upper part of pollen zone F_a using the resemblance of the *Quercus*, TCT, and *Artemisia* curves. Unfortunately, the lack of both sensitivity and detail preclude a precise correlation of the base of core 7 with the core 4 sequence. The most likely guess is that the core 7 oak peak at 21.03 m corresponds to the core 4 peak at 58.00 m, and the pair of peaks at 24.70 and 25.50 m in core 7 correspond to the peaks at 64.10 and 66.00 m in core 4.

The Highlands Arm of Clear Lake was a shallow swamp during the last part of the middle Pomo cryomer. Sedge (Cyperaceae) pollen was abundant. Standing water is indicated by relatively high percentages of *Potamogeton* (pondweed) and other aquatic pollen and by Nymphaeaceae leaf hairs. *Typha* (cattail) pollen is also found in a few levels. The factor analysis results (pl. 4) indicate that shallow-water conditions fluctuated considerably during middle Pomo time, as shown by the curves for factors 3 and 4. Shallow submerged vegetation was displaced several times by emergent vegetation, mostly sedges. Whether these water-level fluctuations were the result of climatic changes or variations in the overflow (sill) level for the swamp is not clear.

LATE POMO CRYOMER

CIGOM 2 CRYOMER

The Cigom 2 cryomer was the time of maximum development of the cold climatic conditions of the last glacial cycle. This inference is based on the low incidence of oak pollen, the high ratio of pine to TCT pollen, and the relatively high frequencies of *Abies* (fir), *Artemisia* (sagebrush), and Gramineae (grass) pollen. The high ratio of pine to TCT pollen suggests that incense-cedar was not able to compete as successfully with the pines in the Clear Lake basin as it did earlier, and that most incense-cedars grew below the elevation of Clear Lake. This interpretation is supported by the occurrence of subfossil incense-cedar foliage at Mountain View, along the west margin of San Francisco Bay, in deposits radiocarbon-dated between 21 and 24 ka (Helley and others, 1972).

A prominent feature of the pollen record during the Cigom 2 cryomer is the consistent presence of *Isoetes* (quillwort) spores. These plants probably grew on the lake bottom in a fairly wide belt around the edge of the lake. The spore record is interpreted here to mean that the waters of Clear Lake were probably much more transparent during the Cigom 2 cryomer than during the Holocene, and that Clear Lake was actually clear at that time. The lake may have been clear in earlier times as well but too deep to support a bottom flora of quillworts.

An increase in the algal flora at the start of late Pomo time marks a fundamental change in the limnology of Clear Lake. During and prior to early Pomo time, the ratio of acid-resistant algal remains to pollen grains in the sediment sometimes reaches values as much as four, but during middle Pomo time the ratio does not exceed two (fig. 18). At the start of the Cigom 2 cryomer, the ratio increases to seven, and algae are more common than pollen in all but one of the samples of Cigom 2 and younger ages. The increase in algal remains is more likely the result of a major increase in lake productivity than of a shift in lake productivity from species that do not survive pollen extraction techniques to species that do.

The inferred increase in productivity can best be explained as the result of three interacting factors—decreased thermal inertia, increased wind-generated turbulence, and a shift from monomixis to dimixis—whose joint effect was to increase the supply of nutrients in the lake. The gradual shallowing of the lake as sediment accumulated in the basin produced at least the effects of decreased thermal inertia of the lake and increased wind-generated turbulence, the latter resulting in more effective mixing of the lake water. Also, because the climate became cooler at the onset of the Cigom 2 cryomer, a shift from monomixis to dimixis in the water column would have occurred if the surface water temperature dropped below 4 °C in the winter. In the Highlands Arm, the shallow standing water of late middle Pomo time gave way to emergent swampy vegetation during the Cigom 2 cryomer. Pondweed pollen, Nymphaeaceae leaf hairs, and other aquatic pollen are absent from Cigom 2 samples, whereas sedge pollen is abundant.

END OF THE POMO CRYOMER

The final stages of the Pomo cryomer occurred after the end of the Cigom 2 cryomer. In core 4, three pollen zones (B, C, and D) are recognized during the transition from the Cigom 2 cryomer to the Tuleyome thermomer, but only one zone (B7) is recognized in core 7. Oak pollen begins to increase in frequency at the start of pollen zone D, and by the end of zone D time it is more common than at any time during the preceding 50,000 years.

Pollen zone D has much lower frequencies of *Artemisia* pollen than pollen zone E. This decrease, together with the decrease in TCT percentages and the beginning of the increase in oak pollen, marks the end of full glacial conditions in the Clear Lake basin, dated by radiocarbon at about 13 ka.

However, not all of the pollen types diagnostic of full glacial conditions disappeared immediately at the start of pollen zone D. In particular, relatively high frequencies of fir (*Abies*) and Douglas fir (*Pseudotsuga*) persisted until the end of pollen zone D. Two pollen types that are common in pollen zones A through C, *Alnus* and high-spine Compositae, are very scarce in pollen zone D.

I interpret the successive increases in concentrations of pine, TCT, and oak pollen in pollen zone D (fig. 29) in terms of an initial release of the pines from climatic constraints on their growth and pollen production, followed by the arrival of competitors (incense-cedar and oaks) from lower elevations and the eventual displacement of the pines and incense-cedar by the oaks. The TCT increase is more than offset by the increase in pine-pollen concentration, so that there is no prominent peak in the TCT percentage curve. Incense-cedar apparently did not become a well-established part of the forest around Clear Lake during the glacial-to-interglacial transition. The peak in TCT-pollen concentration in pollen zone D is a relatively minor one, comparable to the three preceding minor peaks during the Cigom 2 cryomer (fig. 14).

Pollen zone C is characterized by pollen frequencies unlike those found anywhere else in core 4. Pine-pollen frequencies decreased below the levels found in the adjoining pollen zones B and D, whereas oak and TCT frequencies did not change markedly from those found in the uppermost part of pollen zone D. *Alnus* (alder) and high-spine Compositae pollen appeared in significant numbers as arriving members of the developing Holocene vegetation.

The most remarkable feature of pollen zone C is the record of aquatic and riparian plants. Sedge pollen attained a frequency of almost 20 percent, and there are peaks of cattails (*Typha* and *Typha-Sparganium*), Cruciferae, other aquatic pollen, and Nymphaeaceae leaf hairs as well. Taken together, these types suggest that the main basin of Clear Lake was shallower during pollen zone C time than it was before or after. Common *Isoetes* spores indicate clear water; Nymphaeaceae leaf-hair frequencies of as much as 57 percent of total pollen indicate standing water no more than a few meters deep.

The sediment-density curve for core 4 (fig. 7*A*) does not show any sign of desiccation at the core 4 site nor does the core lithology (Sims and Rymer, 1975c). The relatively high frequencies of aquatic indicators in pollen zone C are interpreted here as the result of a decrease in water depth that exposed mud flats around the margin of the lake, increased the littoral-zone area near core 4, and thus allowed heavy growth of sedges and water lilies. The deposits of pollen zone B7 in core 7 also reveal changes in water level but in an opposite direction from that observed in core 4. At the start of pollen zone B7, sedge pollen decreased abruptly in frequency and was replaced by abundant pollen of *Brasenia* (the water-shield) and by aquatic pollen such as *Potamogeton* (pondweed). Leaf hairs of Nymphaeaceae are as much as ten times as common as pollen. They are probably from the *Brasenia* plants.

The opposite changes in water level between the two core sites suggest regional tilting or faulting, rather than climatic change, as the cause of the shifts in aquatic vegetation. Shallower conditions in the main body of the lake (core 4) were only temporary; the aquatic pollen peaks disappeared at the end of pollen zone C. The shallow-water plants also diminished at the end of pollen zone B7 in core 7, but at that site the water became still deeper. The peats and shallow-water muds of the lower part of the core were replaced by open-water lake muds containing the bones of large fish (Casteel and others, 1975, 1977a). Lithologic and faunal changes similar to those observed in core 7 were also observed in core 6 (Sims, 1976; Casteel and others, 1977b; Casteel and Beaver, 1978), so whatever mechanism caused the hydrographic changes must have acted on the Highlands and Oaks Arms of the lake as a unit.

An alternative explanation is that the increase in shallow-water indicators in core 4 could be the result of a drainage shift that caused the flooding of the Oaks and Highlands Arms and diverted their outflow from Cache Creek into the main body of Clear Lake, then into the Russian River through Blue Lakes and Cold Creek. According to this hypothesis, the landslide that presently blocks the head of Cold Creek would not have been formed at the time represented by pollen zone C. Some local tilting or faulting would still be required to initiate the drainage change.

The final phase of the Pomo cryomer, during pollen zone B, is characterized by high frequencies of pine pollen and low frequencies of both TCT and oak pollen. Toward the end of the interval, the high pine frequencies diminished and oak pollen resumed its rapid increase toward postglacial levels. Alder pollen increased in frequency, and by the start of the Tuleyome thermomer it was fully established as a member of the vegetation.

THE TULEYOME THERMOMER

The Tuleyome, or present-day, thermomer was fully established in the Clear Lake basin by about 10,000 ka. This age estimate is based on interpolation between the uppermost radiocarbon age in core 7 and the top of the core; it is in agreement with an age of 9.990 ± 0.800 ka reported by Adam (1967) for the establishment of postglacial vegetation at Osgood Swamp, 250 km to the east in the Sierra Nevada.

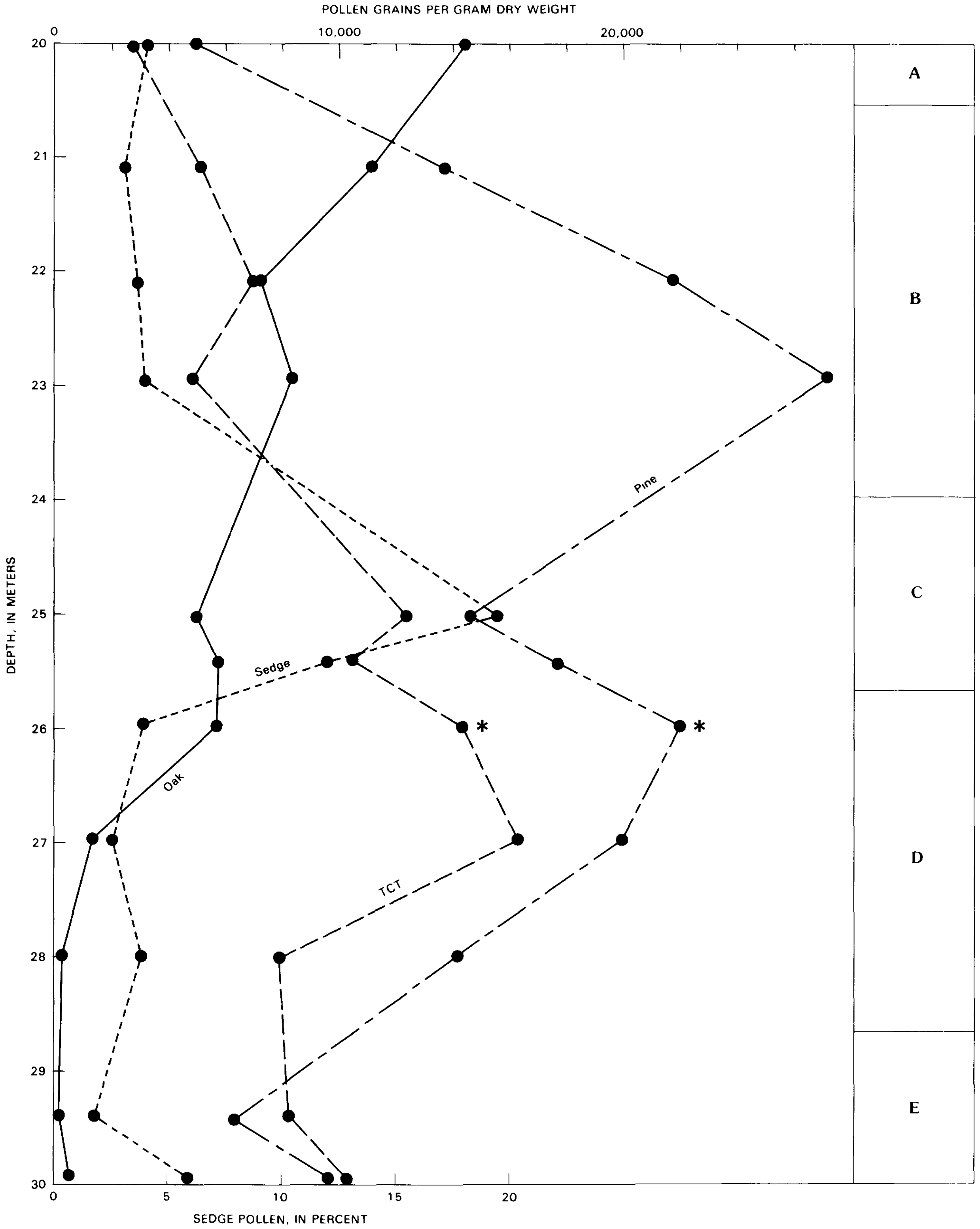


FIGURE 29.—Oak-, pine-, and TCT-pollen concentration curves and sedge percentage curve plotted against depth for part of core 4. Pollen zones are those defined in this report. Sample points are indicated by dots; asterisks indicate values based on a single tracer pollen count (see fig. 14).

There are no apparent systematic changes in the frequencies of oak, pine, or TCT during the Tuleyome thermomer in core 4. The area that contributes pollen to the main basin of Clear Lake is so large that the core 4 pollen record was insensitive to minor climatic fluctuations during the Holocene. The core 7 pollen record, however, which shows a pronounced maximum in the oak percentage curve during the middle of the Tuleyome, suggests a warmer and(or) dryer interval during the middle Holocene in the northern Coast Ranges (Adam and West, 1983).

A warm interval during the middle Holocene is also supported by variations in growth annulus measurements of tule perch scales from cores CL-73-6 and CL-73-7 (Casteel and others, 1977a; Casteel and Beaver, 1978). In those studies, fish scales from the middle part of the Holocene were found to have wider growth annuli than scales from the early or late Holocene. Wider growth rings were interpreted to mean warmer water temperatures, although no absolute temperatures were given.

Two pollen types may have stratigraphically useful distributions within the Tuleyome thermomer. The chinquapin, *Chrysolepis* (*Castanopsis*), does not appear until well after the beginning of the Holocene, but the timing of its initial appearance is not consistent between cores 4 and 7. The highest frequencies of chinquapin are found in the upper half of the Holocene deposits. Pollen of the Rhamnaceae (buckthorn family) appears irregularly throughout the pollen record of both cores, but its first appearance in substantial frequency appears to coincide with the oak pollen maximum of core 7. Rhamnaceae pollen may thus be a useful stratigraphic indicator for samples of middle Holocene ("altithermal") or younger age.

The ratio of algae to pollen is high throughout the Holocene. Acid-resistant algal remains range from twice as abundant as pollen in parts of core 7 to more than 25 times as abundant at a depth of 20 cm in core 4 (fig. 18). Low frequencies of *Isoetes* spores suggest that quillworts were restricted to very shallow submerged and emergent habitats at the edge of the lake.

Although the acid-resistant algal forms recorded in this study are not the major planktonic forms found in Clear Lake at present (Sandusky and Horne, 1978), they are found in large numbers in modern sediment, and their presence in older sediments is taken as an index of high lake productivity not only for themselves but probably also for other more abundant but non-acid-resistant forms. High frequencies of algae throughout the Holocene are taken to mean that the productivity of the lake has been high throughout the last 10,000 years and that the transparency of the waters of Clear Lake has probably not been high during that interval.

Several algal types appear to have responded to the warm period during the middle Holocene. *Pediastrum* A, N, and X all show relative maxima both before and after the middle of the Holocene and minima in between. The hystrichosphaerids show a single maximum early in the Holocene, followed by a decline during the middle Holocene warm period and very low or zero frequencies during the late Holocene. *Botryococcus* and *Pediastrum* O increased in frequency during the warm period and have generally maintained a dominant position since then. *Coelastrum* and *Pediastrum* Y both reached their postglacial maxima just after the start of the decline in oak frequencies following the middle Holocene maximum.

CORRELATIONS

The Clear Lake pollen record is of considerable interest because it covers a long time span, is a continuous record, and comes from a drainage basin that has never been glaciated. The record is particularly important because of the detailed sequence of climatic changes recorded during the Konocti thermomer and the early Pomo (equivalent to Wisconsinan) cryomer. Pollen records of various parts of this period have been available for many years, but correlation of the various overlapping sequences has been difficult, largely because no reliable radiometric age-dating methods were available for events prior to 50 ka. The primary emphasis in the correlations given here is on the lower part of the record, and many of the proposed correlations with this part of the section appear to be almost inescapable. In the upper part of the Clear Lake record, however, the character of the minor climatic fluctuations is not so well defined, and the correlations proposed with other parts of the world are more tentative.

The Konocti thermomer is first established as equivalent to deep-sea oxygen-isotope substage 5e and to the Eemian Stage of northern Europe. Next, the detailed correlations of the Clear Lake record with five long, continuous climatic sequences are examined (fig. 30). Finally, I propose correlations (pl. 5) of the Clear Lake record with other selected Northern Hemisphere climatic records that include the early part of the last glacial cycle.

AGE OF THE KONOCTI THERMOMER

The correlations shown in figure 30 critically depend on the correctness of the correlation of the Konocti thermomer with deep-sea oxygen-isotope substage 5e and with the Eemian Interglaciation of Europe. The most direct link between the Konocti thermomer and substage 5e is through correlation of the Clear Lake record with the pollen and oxygen-isotope record described by Heusser and Shackleton (1979) from an oceanic sediment core taken off the Oregon coast. They established that the first pollen assemblage zone below the Holocene that resembles the Holocene is the same unit as oxygen-isotope substage

5e. Pollen zone S (which defines the Konocti thermomer) is the only pollen zone that closely resembles the Holocene deposits of pollen zones A and A7 (figs. 25 and 26); the high oak-pollen zones that correspond to the Boomli thermomers are clearly different from zones A and A7. The correlations obtained by matching the Konocti thermomer with deep-sea oxygen-isotope substage 5e are the same as those that one would obtain from simple curve matching. The correlation of oxygen-isotope substage 5e with the Eemian was demonstrated by Mangerud and others (1979) at Fjøsanger in Norway. Thus the Konocti thermomer at Clear Lake can be reliably correlated with the Eemian Stage in Europe.

LONG CONTINUOUS SEQUENCES

The Clear Lake core 4 oak-pollen curve is compared to four long paleoclimatic curves that span the full last glacial

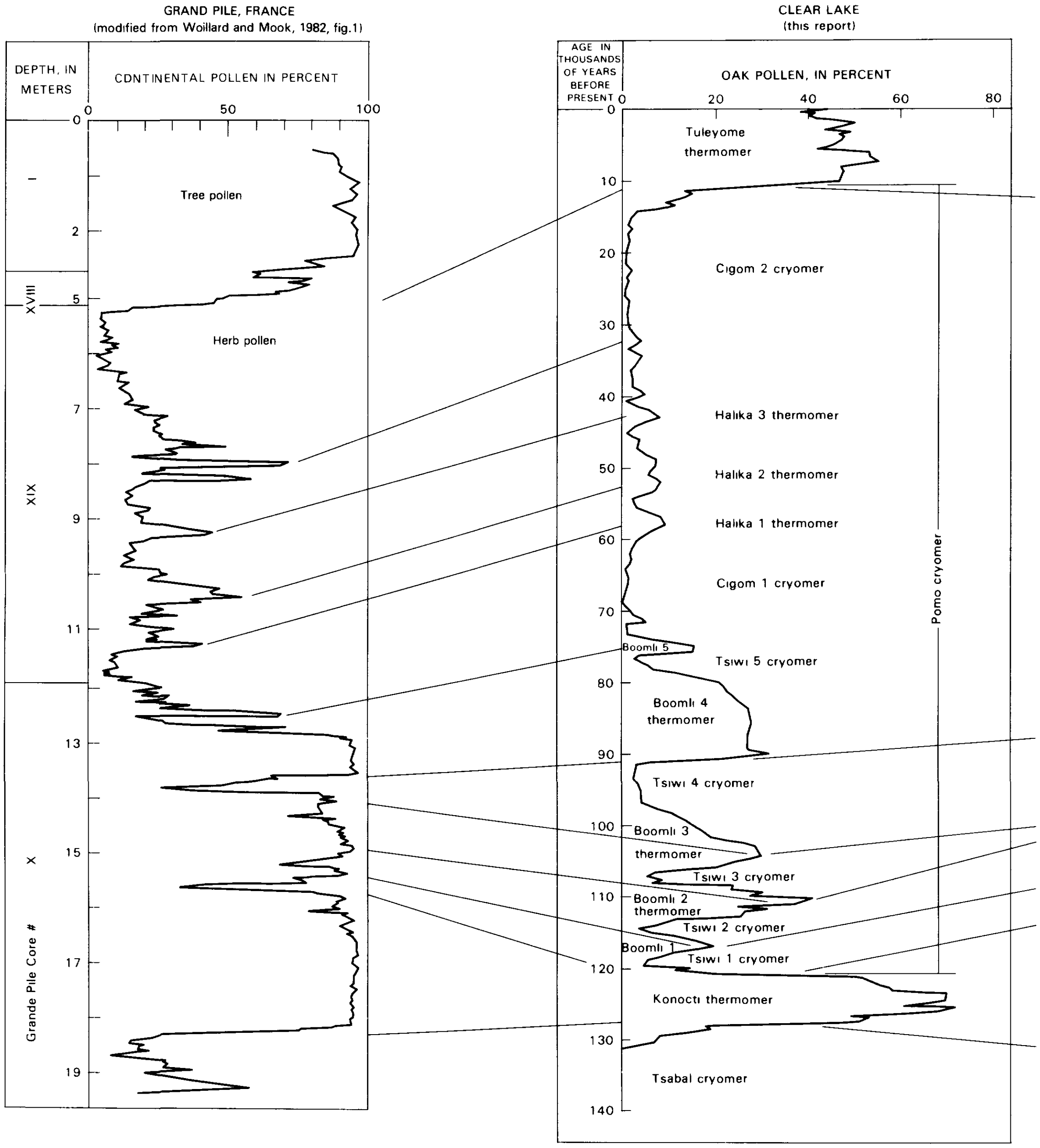
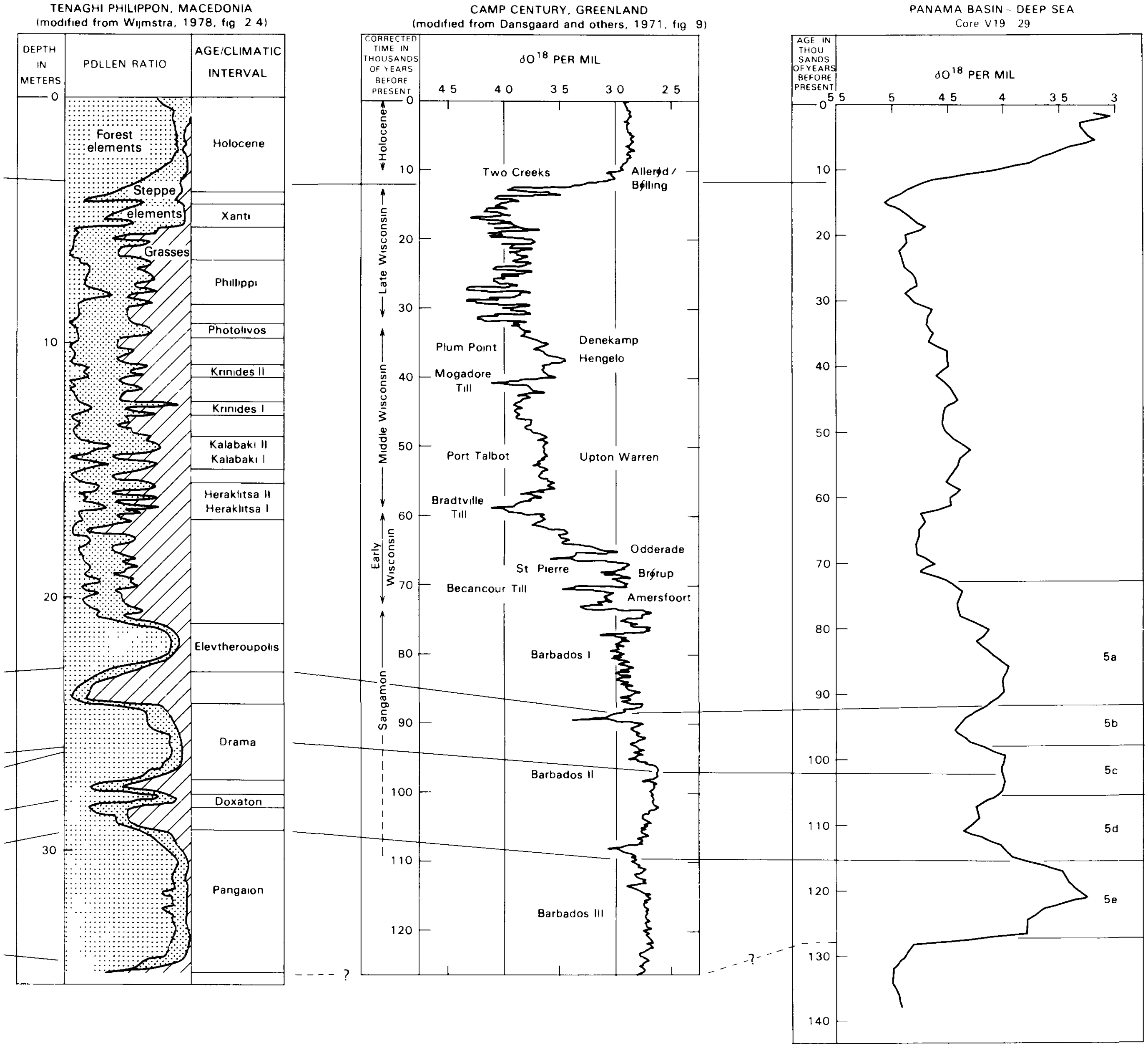


FIGURE 30.—Correlation of the Clear Lake oak-percentage curve with long climatic sequences from France, Macedonia, Camp Century, Greenland, and Panama basin deep-sea core V19-29. The section from Grande Pile in France is a composite section from four different cores; the samples are in inferred stratigraphic order, and the depth scales are for depth within each core.

cycle (fig. 30). Two curves (Grande Pile, France, and Tenaghi Philippon, Macedonia) present pollen data; the other two curves present oxygen-isotope data from deep-sea core V19–29 (Ninkovich and Shackleton, 1975) and the Greenland Camp Century ice core (Dansgaard and others, 1971). The locations range from the equator to 77° N. latitude at widely spaced longitudes. From Clear Lake (long 119° W.), the Camp Century ice core locality (long 61° W.) is located 3200 km NNE, and the V19–29 deep-sea locality (lat 3°35′ S., long 83°56′ W.) is located 4000 km to the southeast. The five curves thus provide a summary of the climatic behavior of much of the northern hemisphere during the last full glacial cycle.

The Eemian Stage in the Grande Pile pollen record and substage 5e in core V19–29 are identified unequivocally (Woillard, 1977; Ninkovich and Shackleton, 1975). The correlations of the Grande Pile and V19–29 records with the Macedonia and Camp Century curves (fig. 30) are somewhat less certain. The Macedonia curve is dated by extrapolation of estimated sedimentation rates beyond the range of radiocarbon dating; Wijmstra and van der Hammen (1974) estimated that the age of the base of the


TENAGHI PHILIPPON, MACEDONIA (modified from Wijmstra, 1978, fig 2 4)

CAMP CENTURY, GREENLAND (modified from Dansgaard and others, 1971, fig 9)

PANAMA BASIN - DEEP SEA Core V19 29

FIGURE 30.—Continued.

Pangaion interval is about 115 ka. Correlation of the Pangaion interval with the Eemian Stage is thus not unreasonable. The dating of the Camp Century record is based on an ice-flow model of the ice sheet; the age of the base of the core is estimated at about 120 ka (Dansgaard and others, 1971). The correlations of the Macedonia and Camp Century curves with the other curves (fig. 30) are thus based on estimated ages of the lowest warm periods in the curves rather than on direct correlations.

The detail shown in the three pollen sections is in part a function of the sedimentation rate. The Eemian and early Weichselian deposits are about 6 m thick at Grande Pile, 14 m thick in the Macedonia section, and almost 29 m thick at Clear Lake. It is therefore not surprising that the Clear Lake record shows more detail than the other pollen records.

GRANDE PILE, FRANCE, TENAGHI PHILIPPON, MACEDONIA, AND CAMP CENTURY, GREENLAND

The first few, long, continental sequences to record the entire last glacial cycle were from Spain (Florschütz and others, 1971), South America (Van der Hammen and Gonzalez, 1960, 1964), and Macedonia (Wijmstra, 1969). Correlations of these sequences with the pollen sequences of the early Weichselian of northern Europe and with each other were somewhat equivocal because of the great distances and vegetational differences involved. A continuous pollen sequence was needed that would cover the entire last glacial cycle from a site closer to northern Europe.

Such a site was found at Grande Pile, in northeastern France (Woillard, 1975, 1977, 1978a, 1978b, 1979a; Woillard and Mook, 1982). The Grande Pile record provides a continuous climatic sequence since the beginning of the last interglacial period (Eemian). The site is close enough to northern Europe to enable reliable correlations with the many short pollen records that cover various parts of the early Weichselian Glaciation, and the entire sequence of climatic fluctuations provides a reasonable basis for correlation with the long Macedonian pollen record (Woillard, 1977).

The Grande Pile pollen record is a critical link in establishing the correlations among the relatively few, long, continuous pollen sequences from extraglacial areas and the more abundant short pollen sequences from sites near the continental ice sheets that cover at most only a few stadial-interstadial fluctuations. Many of the correlations of the Grande Pile sequence with other sequences and events have been summarized by Woillard (1977), and the correlations described in this paper draw extensively on her work.

The correspondence between the fluctuations of the Clear Lake oak-pollen curve and the fluctuations in the other curves (fig. 30) is particularly remarkable in the lower part of the section (the Konocti thermomer and the early Pomo cryomer). The fluctuations in the oak curve are wide, clearly defined, and always involve at least two samples.

The pollen curves (Grande Pile, Clear Lake, and Macedonia) show a set of three broad peaks in the frequency of the pollen of warmth-loving plants, starting with the Eemian Stage and its equivalents; the Camp Century record shows three isotopically heavy peaks in a comparable position in the sequence. In the Grande Pile, Macedonia, and Camp Century records these three broad warm peaks appear to be of nearly equal magnitude. Woillard (1978b) therefore described the latter two warm phases at Grande Pile (St. Germain I and II) as interglacial periods. Oak-pollen frequencies for what are considered equivalent intervals at Clear Lake (the Boomli thermomers) are clearly different from those of both the underlying Konocti thermomer and the Holocene, and it would not be reasonable to give the warmer Boomli intervals (Boomli 2, 3, and 4) interglacial rank at Clear Lake. The correlative St. Germain intervals are considered of interstadial rank in this paper.

The similarity between the Clear Lake, Grande Pile, and Macedonia pollen records during the interval correlated with oxygen-isotope stage 5 (fig. 30) is remarkable. The broad climatic changes that produced these curves must have affected at least most of the Northern Hemisphere and perhaps the entire world. If the changes that produced similar climatic curves for France and Macedonia are also found in California, then the rationale for using long-distance climatic correlations is greatly enhanced.

The climatic sequence of the Eemian and early Weichselian Stages is of particular interest because, although many pollen studies in northern Europe cover parts of this interval (for a summary, see Menke and Behre, 1973), the proper correlation of the various interstadial intervals (Amersfoort, Brørup, Odderade, and so forth) has been unclear.

The Eemian Stage at Grande Pile, the correlative Konocti thermomer at Clear Lake, and the Pangaion interval in Macedonia are easily recognizable. After the Eemian, the correlations are not quite so clear. The Tsiwi I cryomer at Clear Lake is equivalent to the Melisey I interval at Grande Pile, and the Boomli I thermomer corresponds to the Doxaton interval in Macedonia and to St. Germain IA at Grande Pile.

The problem in correlation appears to result from the presence of the Tsiwi 3 cryomer at Clear Lake. If the Boomli 2 and 3 thermomers are together correlated with oxygen-isotope substage 5c, one is left with a short but very distinct cold interval in the middle of the substage 5c sediments in the Clear Lake record. This unit, which is only 50 cm thick, must represent a brief event, especially considering that it was deposited at the relatively high sedimentation rate of the Clear Lake core.

Two different correlations of the Grande Pile record with the Clear Lake units between the Tsiwi 1 cryomer and the Tsiwi 4 cryomer appear possible (table 17). The Grande Pile climatic periods (fig. 30) were named and described according to their apparent importance at that site. The St. Germain I warm interval was divided into three parts: the St. Germain IA and IC warm intervals and the intervening Montaigu cold interval (= St. Germain IB). Another minor drop in arboreal pollen within the St. Germain IC warm interval is found at a depth of 1,427.5 cm (fig. 30). This drop (St. Germain IC–5b) affected only a single pollen sample (Woillard, 1975).

If St. Germain IC-5b is recognized as a separate cool interval, it is possible to match up the cryomer and thermomer intervals between the Eemian Stage and the Tsiwi 4 cryomer-Melisey II cold period on a one-to-one basis. The correlations that result are shown in the left-hand column of table 17 (version A). An alternative correlation (version B), shown in the right column of table 17, attempts to force both the Clear Lake and Grande Pile records into a system in which there are three major warm periods that correspond to oxygen-isotope stages 5a, 5c, and 5e. If St. Germain I is taken as the equivalent of Boomli 2-Tsiwi 3-Boomli 3 and stage 5c, then no equivalent for the Boomli 1 and Tsiwi 2 intervals in the Grande Pile record is possible.

The version A correlation in table 17 is preferred here because it produces a much better match between the two records. The correlations shown for Grande Pile on plate 5 include the preferred correlations for the early Pomo cryomer shown in table 17. The Ognon I oscillation is correlated with the Boomli 5 thermomer, and Ognon II is correlated with the minor peak in oak pollen that is found just above the Boomli 5 deposits in core 4. The correlations shown for the upper Pomo cryomer are much more tentative than those shown for the older deposits.

The correlation of the Clear Lake and Tenaghi Philippon records is not so detailed as the correlation with the Grande Pile record. There are four major warm-cold cycles between the Pangaion (equivalent to the Eemian) and Elevtheroupolis intervals. The correlations preferred here are shown on plate 5. The Tsiwi 3 cryomer does not have an unequivocal match in the Macedonia record, but there is a sudden decline in the percentage of pollen of forest elements near the middle of the Drama interval that may represent the same event (fig. 30). No attempt is made here to correlate the Clear Lake record with any of the events between the end of the Elevtheroupolis interval and Holocene in the Macedonian core. The two curves do not match well, probably because the Macedonian site was a more sensitive recorder of climatic changes during that period than the Clear Lake site.

TABLE 17.—*Correlations between the Grande Pile and Clear Lake pollen records*

Grande Pile preferred correlation (A)	Clear Lake	Grande Pile alternative correlation (B)
Ognon I	Boomli 5	Ognon I
Lanterne I, stadial I	Tsiwi 5	Lanterne I, stadial I
St. Germain II	Boomli 4	St. Germain II
Melisey II	Tsiwi 4	Melisey II
St. Germain IC-5c, IC-5d	Boomli 3	St. Germain IC
St. Germain IC-5b	Tsiwi 3	Montaigu
St. Germain IC-1 through IC-5a	Boomli 2	St. Germain IA
Montaigu (St. Germain IB)	Tsiwi 2	(not recognized)
St. Germain IA	Boomli 1	(not recognized)
Melisey I	Tsiwi I	Melisey I
Eemian	Konocti	Eemian

V19–29 AND CAMP CENTURY OXYGEN-ISOTOPE RECORDS

The oxygen-isotope curves (fig. 30) vary greatly in the amount of detail shown, but broad features similar to those observed in the three pollen records are present. The correlations of the Camp Century curve with the Barbados I, II, and III sea-level maxima of Broecker and others (1968) are accepted here, but the correlations of the Amersfoort, Brørup, and Odderade interstadials given by Dansgaard and others (1971) are probably not correct in light of the correlations proposed in this paper. The oxygen-isotope record from core V19–29 (Ninkovich and Shackleton, 1975) shows the broad features of the last glacial cycle in a more compressed and blurred form than the other curves (fig. 30) because of the much lower sedimentation rate. The record of the past 130,000 years in core V19–29 is compressed into a <9-m sequence.

OTHER CORRELATIONS

Suggested correlations of the Clear Lake climatic sequence with other sequences of various kinds (shown on pl. 5) demonstrate that the Clear Lake record can be correlated in a plausible way with a variety of climate-related sequences from many localities. Each sequence is correlated with the Clear Lake oak-pollen curve independently of the others. These correlations are based mainly on curve matching and on the assumption that the Clear Lake record is continuous through the last glacial cycle. The correlations with the Clear Lake record shown on plate 5 have not been proven independently of climatic inferences, but the general agreement among the many records as seen in the light of the Clear Lake record provides a coherent framework for climatic evolution during the last glacial cycle for much of the Northern Hemisphere.

DEEP-SEA RECORD

Generalized oxygen-isotope curves for the Caribbean Sea and the Atlantic Ocean (Emiliani, 1958, 1966) were originally interpreted as a record of past fluctuations in surface-water temperatures. Emiliani's odd-numbered stages correspond to warm stages and his even-numbered stages to cold stages. Stage 1 corresponds to the Holocene, stage 2 to the full-glacial conditions of the last major continental glaciation of the Northern Hemisphere, stage 3 to the interstadial conditions that prevailed on the continents before the last major ice advance, stage 4 to the first major continental ice advance of the last full glacial cycle, and stage 5 to the last interglacial period. Three warm phases within stage 5 were clearly recognized by Emiliani (1958, fig. 5). Shackleton (1969) formally divided stage 5 into five substages from 5a (youngest) to 5e (oldest); those subdivisions are now in general use and can be readily recognized in many cores (see Emiliani, 1958, and Shackleton, 1975, 1977).

The interpretation of the deep-sea oxygen-isotope record as a simple function of sea surface temperature was challenged by Shackleton (1967), who pointed out that much of the range observed in the isotopic composition of foraminifera through time could be accounted for by the varying isotopic composition of the water in which they lived. Evaporation at the sea surface preferentially extracts ^{16}O and leaves the surface water enriched in ^{18}O. During times of growth of continental ice sheets, isotopically light water removed from oceans by evaporation becomes bound in ice sheets, and this results in an increase in the proportion of ^{18}O in the oceans. Shackleton (1967) thus interpreted the oceanic oxygen-isotope curves largely as a measure of the amount of ice bound in glaciers rather than as a paleotemperature curve. Dansgaard and Tauber (1969) estimated that at least 70 percent of the variability of the deep-sea curves can be attributed to changes in oceanic isotopic composition and at most 30 percent to changes in sea surface temperature.

The problem is not yet completely resolved. The fluctuations of the Clear Lake oak-pollen curve closely resemble fluctuations of the deep-sea oxygen-isotope curves. However, there is no feasible mechanism by which oak-pollen frequencies at a continental site could be directly controlled by the isotopic composition of oceanic surface waters. Climate is a more likely controlling mechanism for both curves, and the surface temperature of the ocean may be highly correlated with isotopic composition of the water, at least in some areas (Adam and others, 1981).

My correlation of the Clear Lake climatic record with the deep-sea oxygen-isotope stages is shown on figure 30 and plate 5. The particular oxygen-isotope curve shown on figure 30 is from core V19–29, described by Ninkovich and Shackleton (1975; data are given in Shackleton, 1977); the ages for the boundaries between stages (pl. 5) are those proposed by Shackleton and Opdyke (1973).

MARINE TERRACES

On the marine terraces of Barbados, three well-dated high stands of sea level that correlate with deep-sea oxygen-isotope substages 5a, 5c and 5e are recognized (Bender and others, 1979). The high stands were long referred to as Barbados I through Barbados III, and Barbados III has been correlated with stage 5e; Bender and others (1979) have renamed the terraces as shown on plate 5. The radiometric control for the estimated ages (pl. 5) is among the best available for stage 5.

Along the U.S. Atlantic Coastal Plain between Virginia and South Carolina, marine terraces formed during the high sea-level stands associated with warm periods. Cronin and others (1981) used uranium-disequilibrium-series dating of fossil corals to define three terraces formed during the early part of the last glacial cycle. Their 120 ka terrace is correlated here with the Konocti thermomer. The two younger terraces, with ages of about 94 and 72 ka, are correlated with the Boomli 2–3 and Boomli 4 thermomers, respectively.

The marine terraces of the Huon Peninsula, New Guinea, have been described by Chappell (1974) and dated by Bloom and others (1974). The numbered terraces in their sequence are plotted (pl. 5) according to their ages. Respectively, terraces V, VI, and VIIb correlate with the Boomli 4, Boomli 2–3, and Konocti thermomers, and terraces IIIa and IIIb correlate with the Halika 2 and Halika 3 thermomers. Terraces II and IV (pl. 5) do not have any matching warm periods in the Clear Lake record.

NORTHWESTERN EUROPE

Four versions of the early Weichselian sequence from northwestern Europe (pl. 5) are composite sequences for the West Holstein region of Germany (Menke, 1976), Denmark (Anderson, 1980), and the Netherlands (van der Hammen and others, 1971), and the sequence from Samerberg in Upper Bavaria (Grüger, 1979).

WEST HOLSTEIN AND DENMARK

The most detailed sequence, the composite record from West Holstein (Menke, 1976, p. 54), matches the Clear Lake sequence in remarkable detail. The Roedebaek Interstadial is described as "very short and unimportant," in agreement with the correlative Boomli 1 thermomer; the final warm phase, the "Keller Interstadial" (also a minor unit) matches the Boomli 5 thermomer. The Brørup Interstadial is divided by a short cold period into three phases; the younger warm phase is the longer one. This sequence matches the Boomli 2-Tsiwi 3-Boomli 3 series of events at Clear Lake. The other main interstadial, the Odderade, which lies above the Brørup, is not interrupted by any cold periods and corresponds to the Boomli 4 thermomer. In short, both the major and minor fluctuations in Menke's early Weichselian climatic history of West Holstein have direct counterparts in the Clear Lake record, both in their durations and their relative magnitudes.

The Early Weichselian sequence in nearby Denmark is incomplete; no deposits younger than the Brørup Interstadial have been described. However, the sequence described by Anderson (1980) is in agreement with the other European sequences (pl. 5) for the period between the Eemian Stage and the Brørup Chronozone.

BAVARIA

The sequence at Samerberg in Bavaria is of special importance because it established that the palynological Riss-Würm Interglacial of the Alps is the same as the Eemian Interglacial of northern Europe (Grüger, 1979). The sequence in Bavaria is similar to that from West Holstein, though there are problems in detailed correlations with the Clear Lake record. Two broad interstadial periods follow the Riss-Würm Interglacial (=Eemian), and the older of the two is interrupted by a cold period. There is also a final small interstadial, incompletely developed at Samerberg, which is found above the two main interstadials. These changes are found in a section about 15 m thick. The pollen diagram is divided into 32 zones; zone 1 is the oldest.

The problems in correlating the Samerberg record with the Clear Lake record are found in Grüger's zones 12 through 19. That part of his section appears to correlate with the Tsiwi 1-Boomli 3 interval (the same part of the Clear Lake section that posed problems in correlating with the record at Grande Pile). Grüger (1979, table 1) correlated his zone 17 with St. Germain IB (Montaigu) at Grande Pile. This correlation then matches Samerberg zones 18 and 19 with the Boomli 2-Tsiwi 3-Boomli 3 sequence at Clear Lake, but the Samerberg record has no zonal equivalent for the Tsiwi 3 cryomer.

In particular, the cold periods in the Samerberg record all show high frequencies of non-arboreal pollen (NAP), but NAP frequencies are close to zero throughout zones 18 and 19. At the base of zone 19, however, there is an oscillation in which the frequency of *Picea* decreases and the frequency of *Pinus* increases during a stratigraphic interval of about 15 cm. This change reverses itself, so it is unlikely to be the result of succession or soil depletion. This change in the lower part of zone 19 is tentatively correlated here with the Tsiwi 3 period at Clear Lake in order to obtain the same number of cold-warm fluctuations at both sites. This procedure would not be justified if the Samerberg record were the only one available for Europe, because one should not assume that the records from two such distant sites should match. However, the remarkable similarity between the other European records discussed here and the Clear Lake record during the early Weichselian provides some justification for forcing a match.

THE NETHERLANDS

The sequence of climatic stages for the Netherlands is taken from the summary paper of van der Hammen and others (1971); the correlations of the Netherlands and Macedonia sequences are also from that paper. The Amersfoort Interstadial is correlated with Boomli 1, the Brørup with the Boomli 2-Tsiwi 3-Boomli 3 sequence, and the Odderade with Boomli 4. There is no equivalent in the Netherlands record for the minor Boomli 5 thermomer.

The correlations discussed previously show that the Clear Lake pollen record corresponds much better than might be expected to the available long climatic records from Europe, Greenland, the equatorial Pacific Ocean, and South America. The correlations proposed among the various records appear to be reasonably sound, although independent age dating should be done whenever possible.

The Clear Lake pollen record is of major importance because (1) it provides a continuous sequence through the last glacial cycle against which shorter climatic sequences may be evaluated; (2) it demonstrates that the oxygen-isotope curves measured on deep-sea cores are recording global climatic changes that also had profound effects on terrestrial vegetation; and (3) it establishes the validity of the general sequence observed at Grande Pile and in Macedonia as a paleoclimatic sequence for at least most of the Northern Hemisphere.

SABANA DE BOGOTÁ, COLOMBIA

The correlation of the Sabana de Bogotá record with the sequences previously described is rather poorly controlled; the only finite radiocarbon ages are from fairly near the surface. Van der Hammen and Gonzalez (1960) originally correlated the sediments at a depth of 22 to 24 m with the Eemian Stage. However, they later considered that the interval from 22 to 31 m probably corresponded with oxygen-isotope stage 5, and that the Eemian Stage was represented from 29 to 31 m (van der Hammen and Gonzalez, 1964, p. 114). This interpretation was apparently later abandoned, because the summary curve for Bogotá shown by van der Hammen and others (1971, fig. 12) shows only the 22 to 24 m portion of the section as correlated with the Eemian.

The correlation preferred here is the one given by van der Hammen and Gonzalez in 1964. When that correlation is used, a series of five cold-warm cycles is found above the end of the Eemian Stage equivalent and below the first main cold phase; these stages are correlated here with the Tsiwi-Boomli cycles in the Clear Lake record. Better age control and more rigorous criteria for correlation than simple curve matching would be desirable, but the correlations shown on plate 5 appear to provide a good match between the various sequences.

LAKE BIWA, JAPAN

The correlation of the Clear Lake pollen record with the record from Lake Biwa, Japan (Fuji, 1976a, 1976b, 1978), is much less clear than the correlations with Europe, Greenland, and the deep-sea oxygen-isotope records. The original interpretations of the Lake Biwa record were given primarily in floristic rather than climatic terms, and the summary diagram curves are for plant groups. The pollen zones shown on plate 5 are from the initial description of the detailed pollen diagram (Fuji, 1976a, 1978). These zones are not those used by Fuji (1976b).

Because the climatic interpretation of the Lake Biwa record is not clearly stated by Fuji (1976a, 1976b, 1978), I attempt to correlate it with the Clear Lake record using the apparent occurrence of the paleomagnetic Blake Subchron of the Brunhes Normal Polarity Chron in the Lake Biwa core at a depth of 50 to 55 m (Fuji, 1976a, 1976b, Kobayashi, 1978). The Blake event, as originally described by Smith and Foster (1969), occurs within faunal zone X of Ericson and others (1961). Smith and Foster (1969) estimated that the Blake event extended from 108 to 114 ka ±10 percent. A similar age for the Blake event at Lake Biwa is supported by fission-track age determinations of 80 ka at a depth of 37 m and 110 ka at a depth of 62 m, as determined by Nishimura and Yokoyama (1975), who estimated that the fission-track ages from Lake Biwa are accurate to ±20 percent.

More recently, Prell and Hays (1976) estimated that faunal zone X extended from 130 to 84 ka; the upper boundary of zone X as shown on their figure 2 corresponds approximately with the boundary between oxygen-isotope stages 5a and 5b. If the 50 to 55 m reversal in the Lake Biwa core in fact represents the Blake Event, then the Lake Biwa pollen zones Z–1–a and Z–1–b that correspond to it should have ages near the middle of the 130 to 84 ka period and correspond to some part of the Clear Lake record between the start of the Konocti thermomer and the end of the Boomli 3 thermomer. Most of the Blake event records illustrated by Smith and Foster (1969) show the event approximately in the middle of faunal zone X after turbidites are taken into account, and it thus seems unlikely that the event occurred during the Konocti thermomer. It is more likely that Lake Biwa pollen zones Z–1–a and Z–1–b should correlate with some part of the Tsiwi 1-Boomli 3 interval.

If the Blake episode is properly identified in the Lake Biwa core, then the sediments deposited during the last interglacial period must lie below a depth of 55 m. Inspection of the summary pollen diagram for that section of the core (Fuji, 1978, fig. 1) indicates that at only one time during the interval 55 to 110 m was there a major peak in the frequency of warmth-loving plants—during pollen zone Y–2–d, which occurs between depths of about 79 and 82 m. Lesser amounts of pollen of warmth-loving plants are also found in pollen zones Y–2–a through Y–2–c at depths between 82 and 97 m.

The interpretation offered here is that Lake Biwa pollen zone Y–2–d, and perhaps zones Y–2–a through Y–2–c as well, should be correlated with the last interglacial period and thus with the Konocti thermomer at Clear Lake. However, this correlation is in conflict with two fission-track ages from the Lake Biwa core. A sample at the base of pollen zone Y–2–d has an age of 170 ka at a depth of 82 m, and a sample at the top of pollen zone Y–1 at a depth of 99 m has an age of 180 ka. If the correlation suggested here based on pollen is correct, then something is wrong with the Lake Biwa fission-track ages.

Because of the apparent difficulties in correlating the Clear Lake record with that of Lake Biwa, no detailed correlations of the Lake Biwa section above pollen zone Y–2–d with the Clear Lake record are shown on plate 5. A paleoclimatic interpretation of the important Lake Biwa record is badly needed.

NORTH AMERICA

Whereas the Clear Lake record can be correlated with remarkable success with the long, continuous records from distant locations described above, correlations with other climatic sequences in North America are much less certain. This is in large part because very few continuous climatic sequences are available for North America; most sequences are defined on the basis of paleosols, tills, and depositional units that cover only relatively short time periods.

According to the rather ill-defined conventional wisdom, the last glacial cycle in North America consists of the Sangamon interglacial, followed by the Wisconsin glacial, followed by the Holocene or postglacial. These terms are widely used in an informal sense throughout North America (Nelson and Locke, 1981), and the Sangamonian and Wisconsinan Stages are formal units in the midcontinent area (Frye and others, 1965, 1968).

THE SANGAMONIAN STAGE

The Sangamonian Stage of Frye and others (1965) is based on the Sangamon Soil of Worthen (1873); it encompasses the interval from the retreat of the youngest Illinoian glacier in Sangamon County, Illinois, to the onset of the deposition of the Roxana Silt. The status of the Sangamon Soil in its type area has been reviewed by Follmer (1978). The Wisconsinan Stage of Frye and others (1968) includes "all deposits from the contact of Roxana Silt on the A-horizon of the Sangamon soil to the top of the Cochrane till and its contact with the overlying thin discontinuous post-Cochrane deposits in the James Bay Lowland of Ontario, Canada" (Frye and others, 1968, p. E1). The Wisconsinan Stage is divided into the Altonian, Farmdalian, Woodfordian, Twocreekan, and Valderan Substages, (pl. 5).

Given the similarities observed between the Clear Lake record and the other long, continuous climatic sequences already described, the conclusion seems inescapable that the same series of climatic events must have affected the North American midcontinent area in some way. The time-stratigraphic subdivisions (pl. 5), however, do not appear to support this conclusion. The transition from the Sangamonian Stage to the Wisconsinan Stage appears to be much too simple in the light of the complex oscillations observed in the Clear Lake and other long sequences.

The problem lies in the common practices of equating the Sangamonian Stage with the last interglacial period and regarding the Sangamonian as though it were based on a depositional sequence rather than on a weathering event. The last interglacial period at Clear Lake, which is equated here with the Konocti thermomer, includes only a small part of the time between the end of the penultimate (Illinoian) glaciation and the onset of cold conditions (correlated here with the development of full continental glaciation) at the end of the Tsiwi-Boomli oscillations. The Sangamonian Stage, on the other hand, includes the entire period from the last departure of the Illinoian ice sheet to the first arrival of the Altonian ice sheet, as represented by the deposition of wind-blown silt derived from glacial outwash trains. I conclude that the Sangamonian Stage must represent more than the last interglacial period in the strict sense (oxygen-isotope Stage 5e); it must be, in at least a general way, correlative with all of oxygen-isotope Stage 5 (pl. 5; see also Pierce and others, 1976).

LONG NORTH AMERICAN SEQUENCES

Long sediment cores have been studied from several localities in North America, including south-central Illinois (Grüger, 1970, 1972), Searles Lake, Calif. (Smith, 1979), Willcox Playa, Ariz. (Martin, 1963b), San Augustin Plain, N. M. (Clisby and Sears, 1956), and the Valley of Mexico, Mexico (Clisby and Sears, 1955; Sears and Clisby, 1955). Age determinations for the bottoms of these cores are all somewhat equivocal; all these cores with the exception of the Illinois core are from pluvial lakes.

ILLINOIS

Grüger (1970, 1972) describes a pollen sequence from the Pittsburg basin in south-central Illinois that he interprets to span the period from late Illinoian time through the Holocene. The age of the bottom of the core, inferred on botanical grounds to be below the Sangamon, is based largely on the inferred presence of large amounts of *Taxodium* (bald cypress) pollen in his pollen zones 2a and 2c. The deposits of pollen zone 2 probably do correlate with the upper part of the Sangamonian Stage of Frye and others (1965). However, this does not require that they be correlative with the last interglacial period in the strict sense (stage 5e). It seems more likely that Grüger's zones

2a and 2c postdate stage 5e and are correlative with the Clear Lake Boomli 4 and Boomli 2–3 thermomers (pl. 5). Grüger (1972) specifically acknowledges this possibility, and Frye and Willman (1973) prefer it to Grüger's interpretation.

It is worth noting that if Clear Lake core 4 had been only 10 m shorter, my interpretation of the Clear Lake record would have been much like that given by Grüger for the Pittsburg basin. In the absence of the deposits of the Konocti thermomer and their unequivocal interglacial aspect, the most reasonable interpretation of the rest of the record would have been to interpret the Boomli events as the record of the last interglacial period.

PUGET SOUND REGION

Several long pollen sequences estimated to cover the past 80,000 years have been described from the Puget Sound and Olympic Peninsula region of western Washington (Heusser, 1972, 1977). One important stratigraphic unit, the Salmon Springs Drift, was thought to be middle Wisconsinan in age, but it is now believed to be of middle Pleistocene age at its type locality on the basis of fission-track and zircon ages and magnetic polarity data (Easterbrook and others, 1981). Some of Heusser's pollen zones were attributed to the Salmon Springs glaciation. Because of the present uncertainty concerning the local correlation of stratigraphic units in the western Washington area, no attempt is made to correlate Heusser's important sections with the Clear Lake record.

PLUVIAL LAKES

In many areas pluvial lakes are the only sites where it is possible to recover a relatively continuous record of sedimentation covering a long time period. For purposes of pollen analysis, however, pluvial lakes present many difficult problems which confound the interpretation of pollen diagrams from their sediments. Such lakes are found in areas where present-day precipitation is not great enough to keep lake basins overflowing regularly. When the ratio between precipitation (P) and evaporation (E) drops below a critical value, the lake ceases to overflow, and the lake level then drops below the level of the outlet until a balance is reached between the amount of evaporation from the (reduced) lake surface and the amount of water reaching the lake through precipitation and inflow from the drainage basin. If the P/E ratio is sufficiently low, the lake will dry up completely.

The size of a lake influences the way in which the lake incorporates pollen from various components of the surrounding vegetation into its sediments (see Faegri and Iversen, 1964, p. 104; Moore and Webb, 1978, p. 108; Jacobson and Bradshaw, 1981). Thus climatic changes that cause pluvial lakes to change size and the vegetation around them to shift also change the way in which the pollen record is related to the vegetation. These processes interact to make pollen records from fluctuating pluvial lakes difficult to interpret.

The other major difficulty faced in dealing with pluvial-lake pollen records is that when a lake dries up, the pollen in the surficial sediments becomes exposed to oxidation, and the sediments themselves may be subjected to wind erosion. Hiatuses in such pollen records are thus not uncommon.

WILLCOX PLAYA

Martin (1963b) described a long pollen record from a 42-m core from the Willcox Playa in southeastern Arizona. The upper 2 m of the core did not contain pollen because of surface oxidation. Below the oxidized zone was a thick sequence of reduced, pollen-bearing sediments that ranged in depth from 2 to 21 m. Between the depths of 21 and 29.3 m, there were four oxidized zones separated by three reduced zones; the middle reduced zone, at a depth of 24.4 m, consisted of only a single sample, but all the other zones were at least a meter thick. Martin (1963b, fig. 3) correlated the interval between 23.5 and 29.3 m containing the lowest three of the four oxidized zones just mentioned with the Sangamon interglacial, assuming that the oxidized zones represented times when the lake was dry and interglacial conditions prevailed. He included the oxidized zone at 21 to 22 m within the Wisconsin glaciation.

In the light of the correlations of the Clear Lake record already discussed, it now seems reasonable that the oxidized zones in the Willcox Playa core correspond to the Konocti thermomer and the Boomli 2, 3, and 4 thermomers at Clear Lake. If so, then the minor Boomli 1 and 5 thermomers were not warm or dry enough to allow Willcox Playa to dry up. The suggested correlations are shown on plate 5, along with Martin's division of his sequence into the Illinoian, Sangamon, and Wisconsin.

SAN AUGUSTIN PLAINS

A long (150 m) pollen profile (not shown on pl. 5) from the San Augustin Plains in western New Mexico was described by Clisby and Sears (1956) in very general terms. High frequencies of spruce (*Picea*) pollen were equated with relatively cold periods, and high frequencies of non-arboreal pollen types (NAP) were taken as a measure of aridity; no other curves were shown. The section was not well dated, but the upper 15.24 m (50 ft) of the core was shown to correspond to the full glacial conditions of the late Wisconsinan and the Holocene. It appears likely that the upper 91.46 m (300 ft) of the San

Augustin Plains core covers about the same period as the Clear Lake record, but the original diagram for the San Augustin Plains record is not detailed enough to permit precise correlations.

SEARLES LAKE

The Quaternary sequence of lacustrine and playa sediments from Searles Lake, Calif., has been summarized by Smith (1979). He presents a summary curve of lake fluctuations during the last full glacial cycle; unfortunately, the summary curve is not shown in relation to the stratigraphy of the core, and the various lake phases are unnamed. His correlations of the Searles Lake record with other long records are shown using a series of six low stands labeled A through F. Low stand A is correlated here with the early part of the Tuleyome thermomer at Clear Lake; low stands B and C are correlated with the Halika thermomers; low stands D and E are correlated with the Boomli 4 and 3 thermomers respectively; and low stand F is correlated with the Konocti thermomer.

LAKES BONNEVILLE AND LAHONTAN

The Lake Bonneville and Lake Lahontan sequences correlated here with the Clear Lake record are taken from the summary paper by Morrison and Frye (1965, fig. 2). The lower half of the two sequences shown on their figure 2 shows a lower soil, correlated with the last interglaciation, overlain by a series of five lacustrine units and then by an alluvial-colluvial-aeolian unit upon which is developed another soil.

The lower soil units (Dimple Dell and Cocoon soils) are correlated with the Sangamonian Stage of the midcontinent by Morrison and Frye (1965), and the succeeding five lake phases are correlated with the Altonian Substage. A different interpretation is offered here: the lower soils are correlated with the Konocti thermomer at Clear Lake and thus with isotope substage 5e, rather than with the entire Sangamonian Stage. At least some of the overlying lake deposits thus are correlative with the upper part of the midcontinent Sangamonian Stage and the Tsiwi cryomers at Clear Lake.

The correlation of the series of climatic fluctuations above the Dimple Dell and Cocoon Soils with the Clear Lake record depends on how one chooses to correlate the middle Wisconsinan Promontory and Churchill soils. Two reasonable possibilities exist, but each creates some problems. The first possibility is to consider the Promontory and Cocoon soils as correlative with the soil-forming period that occurred between the Tahoe and Tioga glaciations in the Sierra Nevada (Burke and Birkeland, 1979). In this case, the middle soils are considered correlative with the Boomli 4 thermomer at Clear Lake, and the pluvial periods recorded by the Alpine and Eetza Formations are correlative as a group with the Tsiwi 1 through 4 cryomers. The two prominent lake phases above the middle soils would then be correlative with the Cigom 1 and Cigom 2 cryomers. This correlation seems unlikely for several reasons. Radiocarbon ages for the Churchill soil indicate an age of about 25 ka for the end of the soil-forming period (Morrison and Frye, 1965); such an age seems much too young to allow interpretation of the Churchill as equivalent to the Tahoe-Tioga soil-forming period. This correlation would also require that the five lake advances of the Alpine and Eetza Formations correlate with only three apparent cool periods at Clear Lake.

The other interpretation, which I prefer, is that the Promontory and Churchill soils are correlative with the Halika thermomers. The lacustrine advances of the Alpine and Eetza Formations would then correlate with the Tsiwi cryomers and possibly with the Cigom 1 cryomer, and the lake deposits of the Bonneville and Sehoo Formations would correlate with the Cigom 2 cryomer. This interpretation is consistent with that proposed by Davis (1978, fig. 3). It is not clear in this interpretation whether the Wyemaha Formation, which lies below the Churchill soil and above the lacustrine units of the Eetza Formation, should be considered the equivalent of the Cigom 1 cryomer. If it is, then climatic conditions during Cigom 1 were presumably much less pluvial than during the other stadial phases, either because of low precipitation or high evaporation (or both). If it is not, then not all of the Tsiwi cryomers were matched by high lake levels in the Bonneville and Lahontan basins, or not all of the Boomli thermomers produced lake recessions. The latter seems more likely; in particular, the Boomli 5 thermomer might not have been long enough to produce a significant lake recession.

YELLOWSTONE NATIONAL PARK

The Yellowstone Park area is chosen here to represent the glacial sequence of the Rocky Mountains because of the series of age determinations available for deposits formed early in the last glacial cycle (Richmond, 1976; but see also Pierce, 1979). The Yellowstone record, even though not based on a continuous depositional sequence, is important here because it reports at least two major glacial advances during oxygen-isotope stage 5. Richmond (1976) correlated these advances with the Bull Lake glaciation, which has long been assumed to be the equivalent of the Tahoe glaciation in the Sierra Nevada.

Richmond's till 5 is correlated here with the Tsabal cryomer, till 6 with the Tsiwi 1-Tsiwi 2 period, till 7 with the Tsiwi 4 cryomer, Till 8 with the Tsiwi 5 cryomer(?), and till 9 with the Cigom 1 cryomer (pl. 5). Caldera lake silt D is correlated with the Konocti thermomer, lake silt

E with the Boomli 2–3 period, and lake silt F with the Boomli 4 thermomer. The age estimates available for the lake silt units are in good agreement with the other correlations proposed for the Clear Lake record.

The summary of the Yellowstone record (pl. 5) also shows Richmond's correlations of the Yellowstone tills with the glacial deposits of the Wind River Range, Wyoming (Sacagawea Ridge, Bull Lake, and Pinedale glaciations). The correlations given here do not necessarily apply to all Rocky Mountain glacial deposits that have been correlated with the Bull Lake and Pinedale deposits, but only to the Yellowstone sequence. Some deposits that have been correlated with the Bull Lake glaciation may well predate the Konocti thermomer, and the correlation of the Yellowstone sequence with the Clear Lake record should not be used to refute such a possibility.

CALIFORNIA

SIERRA NEVADA

The climatic sequence of the last glacial cycle in the Sierra Nevada is still far from being well understood. Two largely independent glacial histories have been developed for the west and east slopes of the range. The east side has been more intensively studied than the west (Russell, 1887; Blackwelder, 1931; Putnam, 1949; Sharp and Birman, 1963; Birkeland, 1964; Birman, 1964; Dalrymple, 1964; Sharp, 1969, 1972; Curry, 1971; Birkeland and others, 1976; Burke and Birkeland, 1979). Vegetation is sparser because of the climatic rain shadow, and active tectonism and volcanism have helped to preserve a more detailed record of glacial advances on the east side than on the west side.

Unfortunately, the detail preserved on the east side of the range has not produced a definitive glacial sequence. Burke and Birkeland (1979) concluded that the criteria used to separate many of the previously described glacial advances along the east side of the Sierra Nevada are not adequate to enable reliable definition of those advances as separate events. They (1979, p. 49) "suggest mapping only multiple Tioga and Tahoe deposits until better criteria for further subdivision are developed." Burke and Birkeland (1979) were concerned primarily with relative dating techniques and the problems involved in correlating glacial sequences from one drainage basin to another along the east side of the Sierra, and thus placed only minor emphasis on geomorphological criteria that can only be used to provide relative ages for different deposits within a single basin.

Given the warning by Burke and Birkeland (1979) that many of the glacial advances previously recognized as separate events in the Sierra Nevada cannot be distinguished from each other on the basis of weathering criteria, it should be clear that any attempt to correlate the Sierra Nevada glacial record with the continuous climatic sequence at Clear Lake must be regarded as tentative.

The degree of weathering of Tahoe moraines in the Sierra Nevada is much greater than for Tioga-age moraines. Potassium-argon ages from Sawmill Canyon indicate that the Tahoe glaciation occurred before 53±44 ka (Dalrymple and others, 1982), and Bailey and others (1976) reported ages of 62±13 and 126±25 ka for two basalt flows that overlie and underlie the Casa Diablo Till of Birkeland and Janda (1971) near Mammoth, Calif. Burke and Birkeland (1979) stated that the Casa Diablo Till is of Tahoe age.

The available radiometric ages are thus consistent with either a pre-Konocti or a post-Konocti age for the Tahoe glaciation. A post-Konocti age is preferred here, primarily in order to provide enough glacial events to match the cryomers in the Clear Lake record. However, not all workers would agree with a post-Konocti age for the Tahoe; for example, Colman and Pierce (1981) assumed that the Tahoe is pre-Konocti, with an age of about 140 ka. When interpreting the Clear Lake record, the difficulty with a pre-Konocti age for the Tahoe glaciation is that one is left with a complicated series of events that had a major impact on the vegetation of the Coast Ranges and yet left little or no record in the glacial history of the Sierra Nevada. The present climate is marginally able to support tiny glaciers in the Sierra Nevada, and it seems probable that climatic changes such as those recorded during the early Pomo cryomer at Clear Lake would have produced sizeable glaciers in the Sierra.

One of the most detailed morainal sequences exposed along the east side of the Sierra Nevada is in the Bloody Canyon-Sawmill Canyon area near the south end of Mono Lake (Sharp and Birman, 1963; Wahrhaftig and Sharp, 1965; Burke and Birkeland, 1979). At that locality, both the Tahoe- and Tioga-age deposits as defined by Burke and Birkeland (1979) are represented by multiple moraines. The Mono Basin moraine of Sharp and Birman (1963) is the oldest. It forms the sides of Sawmill Canyon and was originally deposited by a glacier that flowed out of Bloody Canyon. The post-Mono Basin moraines were deposited after a drainage shift diverted the ice flowing out of Bloody Canyon northeast, away from Sawmill Canyon and into the present course of Walker Creek. The moraines along Walker Creek are the Tahoe, Tenaya, and Tioga moraines of Sharp and Birman (1963). Burke and Birkeland (1979) considered the Tenaya moraine to be of Tioga age.

The Mono Basin moraine cannot be distinguished from the Tahoe moraine that cuts across it by using the relative age-dating techniques of Burke and Birkeland (1979). Thus it is unlikely that a major period of weathering occurred between the deposition of the two moraines. However, enough time elapsed between the two glacial advances for a significant change in local drainage to occur. Moreover, a significant period of weathering affected both the Tahoe and the Mono Basin moraines but did not affect the Tenaya or Tioga moraines.

The Mono Basin advance most probably correlates with the Tsiwi 1, 2, or 3 cryomers (pl. 5). These periods are all relatively brief at Clear Lake, and their oak-pollen frequencies are all somewhat higher than during the Tsiwi 4 cryomer, which is correlated here with the Tahoe advance. The short duration of the cold periods and the oscillations of climate during the Tsiwi 1-Tsiwi 3 period probably account for the fact that the Mono Basin advance was not so large as the subsequent Tahoe advance and thus was overridden in most localities. Assuming that the thickness of the intervals in the Clear Lake section provides a reasonable estimate of their duration, the Tahoe advance was larger than the Mono Basin advance because conditions were somewhat cooler and its duration was somewhat longer.

The Boomli 4 thermomer was the longest of the warm periods during the early Pomo cryomer; therefore significant weathering during that period seems likely. Climatic conditions at Clear Lake appear to have been similar to those that prevailed during the Boomli 2 and 3 thermomers, but those periods apparently did not persist long enough to produce a significant difference between the weathering characteristics of the Mono Basin and Tahoe moraines in the Sierra Nevada.

The Tenaya and Tioga advances are correlated here with the Cigom 1 and 2 cryomers, respectively. The Tioga advance is generally recognized as the latest major ice advance in the Sierra Nevada, so correlation of that advance with the Cigom 2 cryomer seems straightforward. The Tenaya advance is still not well understood in the Sierra Nevada, but where Tenaya deposits are found, they are clearly older than Tioga deposits and younger than Tahoe deposits. The Tenaya advance is correlated here with the Cigom 1 cryomer because that seems to be the most reasonable solution, rather than because of any compelling data or arguments.

If the Tahoe and Mono Basin glacial advances are both older than the Konocti thermomer, then the glacial advances of the Tenaya and Tioga glaciations must have been large enough to obliterate any deposits left by the glacial advances of the first half of the last glacial cycle. If that is so, then the morainal deposits that have been used to infer the glacial history of the Sierra Nevada are in fact poorly suited to that task. The glacial history of the Sierra must instead be developed by using well-dated sedimentary sequences (preferably continuous) that include outwash deposits of upstream glaciations. Such deposits are present on both sides of the Sierra, although they will be difficult to sample. Atwater and others (1986) have shown the feasibility of such an approach.

SAN JOAQUIN VALLEY

The alluvial stratigraphy of the San Joaquin Valley has been described by Marchand and Allwardt (1981). They described a series of alluvial deposits of Wisconsinan and earlier age that they designated the Modesto and Riverbank Formations. Periods of coarse alluviation probably correspond to deglacial phases in the Sierra Nevada. Interglacial periods were characterized by erosional periods and soil formation on the alluvial deposits.

The Modesto Formation appears to correspond with the middle and late Pomo cryomer at Clear Lake. The Modesto is divided into an upper and a lower member that are separated by a soil-forming period. The members probably correlate with the Cigom 2 and Cigom 1 cryomers. As noted above, maximum alluvial deposition occurred during glacial melting, so each Modesto member probably corresponds with the latter half of the correlative Cigom unit.

The Modesto Formation is underlain by the Riverbank Formation, which Marchand and Allwardt (1981) subdivided into three members. The age of the Riverbank Formation is not well established, but Marchand and Allwardt stated that it probably is between about 130 and 450 ka. Soils developed on the upper member of the Riverbank suggested to Marchand and Allwardt that the upper member was deposited before the last interglaciation, which they correlated with marine oxygen-isotope stage 5.

Hansen and Begg (1970) reported open-system uranium-series ages averaging 103 ± 6 ka on vertebrate remains from the Teichert gravel pits east of Sacramento, Calif. The age was regarded as too young by Marchand and Allwardt (1981), in part because the bones were attributed to the middle member of the Riverbank Formation. However, the site was attributed to the upper part of the Riverbank Formation by Shlemon (1972). Study of pollen and plant macrofossils from the site indicated a somewhat cooler climate (Ritter and Hatoff, 1977); such a climate would be consistent with an interstadial environment of the early Pomo cryomer.

The interpretation preferred here is that the uranium-series ages of Hansen and Begg (1970) are valid and that the upper part of the Riverbank Formation includes deposits that postdate the last interglacial in the strict sense. The upper part of the Riverbank would thus include sediments produced by the melting of the Tahoe and Mono Basin glaciers in the Sierra Nevada, and the soil-forming period recorded at the top of the Riverbank would correspond to the weathering period that separates Tahoe-age deposits from younger deposits in the Sierra (see following section). The preferred correlation of the upper part of the Riverbank with the Sierran glacial sequence is the same as that given by Ritter and Hatoff (1977).

Atwater and others (1986), in a reconnaissance study of the sediments of Tulare Lake in the southern San Joaquin Valley, described a lacustrine section about 30 m thick that included significant lithologic variation through time and was estimated to span about the past 100 ka. However, that study was not based on continuous cores, and the sampling interval reported for pollen is not detailed enough to enable accurate correlations with the Clear Lake section. A 40- to 50-m continuous core from near the site of Atwater's core 8 would provide a valuable reference section for comparison with the Clear Lake record.

DISCUSSION

The Clear Lake pollen record is remarkable for its length, stratigraphic continuity, and high temporal resolution. Furthermore, it provides a climatic sequence for the early part of the last glacial cycle for an area from which no such records were previously available. The pollen record is also remarkable in that the curve for a single pollen type (oak) forms the basis for climatic interpretation.

The interpretation of the Clear Lake pollen record presented here provides the basis for a substantially different view of the last glacial cycle in North America than has existed previously. The Clear Lake record faithfully follows the same series of climatic events that has been observed in northern Europe, and the conclusion seems inescapable that the same series of events must have affected at least the northern part of North America. The present state of understanding of the last glacial cycle in the midcontinent area, however, does not provide a clear indication of the complex series of events during the early part of the cycle that is now recorded both in California and in Europe. The correlation of the Clear Lake record with the glacial and interglacial stratigraphy of the North American midcontinent thus raises significant questions concerning the nature of the Sangamonian Stage and of the last interglaciation.

THE LAST INTERGLACIAL PERIOD

Suggate (1974) reviewed the terminological confusion centered around the definition and duration of the last interglacial. He advocated dividing each major glacial cycle into glacial and interglacial half-cycles and placing the boundary between half-cycles at the midpoint in temperature between the coldest and warmest parts of the full cycle. According to his rules, the last interglacial at Clear Lake would include both the Konocti thermomer and the early Pomo cryomer. However, a temperature interpretation of the oak and pine pollen curves (Adam and West, 1983) indicates that the Boomli thermomers were definitely not as warm as the unequivocally interglacial Konocti and Tuleyome thermomers; in addition, the Tsiwi cryomers were so cold that it seems unreasonable to include them within an interglacial period. At Grande Pile, Woillard (1979b) recognized a series of three separate interglacial periods during the interval correlative with oxygen-isotope stage 5, but her approach does not seem appropriate for the Clear Lake sequence.

The Sangamonian Stage of Frye and others (1965) is clearly a useful time-stratigraphic unit in the midcontinent area of North America, but it has not been generally recognized that the Sangamonian had a complex and oscillatory climatic history. The concept of an interglacial period characterized by a single warming followed by a single cooling and the return of the continental ice sheet to the midcontinent area can no longer be sustained. The Sangamonian Stage must have included several warm cycles. This greatly increases the problems of interpretation of deposits that have been identified as "Sangamon" in the literature (see Kapp, 1965; Hibbard, 1955; Lindberg and others, 1980), as such deposits could represent either the last interglacial in the strict sense or one of the later interstadial periods corresponding to the Boomli thermomers. Clearly, the practice of referring to deposits of the last interglaciation as Sangamonian Stage equivalents should be greatly restricted from its present usage.

A particularly interesting conclusion of this work is that some of the montane glaciations of the Western United States may well be Sangamonian in age. If the correlations (pl. 5) are correct, then at least some of the moraines classed as Tahoe and Mono Basin in the Sierra Nevada and as Bull Lake in the Rocky Mountains are middle and late Sangamonian in age. Independent confirmation of this conclusion is needed.

ABRUPT CLIMATIC EVENTS

A striking feature of the climatic sequence of the early Pomo cryomer is the rapidity with which most of the changes occurred. Only at the ends of the Boomli 3 and Boomli 4 thermomers are fairly slow and systematic changes observed; the other transitions appear to be quite sudden. From the point of view of the environmental status quo that preceded them, these sudden changes must have been nothing less than climatic catastrophes. Local vegetation was largely destroyed, and different vegetation grew to replace it.

The nature of the sudden climatic changes raises profound biologic and climatic questions. What were the ecologic effects, and how did such rapid climatic changes come about?

Little is known about the response of vegetation to climatic catastrophes of the sort inferred from the Clear Lake record. Raup (1981, p. 11) notes that "To consider crises as a legitimate and important part of the formative processes in ecology and evolution is new to many and anathema to some." After a climatic catastrophe, each species must suddenly be unsuited to its changed habitat throughout much of its range. Some previously marginal populations will be wiped out, whereas others will be in a much more favorable environment, with their competitors also affected in various ways by the change. Work dealing with catastrophes such as hurricanes and forest fires (see Bormann and Likens, 1979) may provide some insight, but those events are not strictly comparable. Hurricanes and forest fires act to displace local vegetation away from a hypothetical steady state, and subsequent recovery from the catastrophe involves a slow restoration of prior conditions. Climatic catastrophes, however, involve the sudden displacement of the steady state itself. If the displacements are great enough to kill established plants, then conditions for plant dispersal may be quite favorable for plants that can spread their seeds widely. If the displacements do not kill most existing plants, but rather shift the competitive advantages of different species, then competition between established vegetation and new species better adapted to the new conditions may retard the adjustment of the vegetation somewhat.

Climatic changes at Clear Lake cannot have been severe enough to kill all the members of any species; the distributions before and after sudden changes must have overlapped at least slightly or some extinctions would be observed in the record. The rapidity of the shifts observed in many cases, however, does suggest that vegetation shifts were able to proceed rapidly even in the case of plants with rather long life cycles (oak, pine, and TCT species, for example). Evolutionary pressures at such times must have been much different than during most of the last glacial cycle, when climate was either stable or changed much more slowly.

Both rapid coolings and rapid warmings are observed in the Clear Lake record. Gradual coolings are observed at the end of the Boomli 3 and Boomli 4 thermomers; however, no gradual warmings are recorded. (The Boomli 1 thermomer is ignored here; it seems incomplete when compared with the other Boomli thermomers, as though something interrupted it.)

The suddenness of the early Pomo climatic changes and their apparent reversibility, as in the case of the Tsiwi 3 cryomer, pose difficult climatic questions. How could such changes be explained in terms of the global energy budget? Sudden climatic changes seem particularly hard to explain at Clear Lake because of the climatic buffering effect of the Pacific Ocean.

I have previously suggested (Adam, 1969, 1973b, 1975b) that the presence or absence of surface layers of low-salinity glacial meltwater on the oceans can have important climatic effects, and also that the freezing of Hudson Bay would have a pronounced cooling effect because of the increase in albedo (Adam, 1976b). In addition, the major cycles of climate associated with oxygen-isotope substages 5a through 5e have been strongly linked with variations in insolation as explained by the astronomical or Milankovitch theory (see Kukla and others, 1981; Imbrie and Imbrie, 1980; Hays and others, 1976).

The astronomical theory is accepted here as the most reasonable explanation of the three broad warm cycles of the Konocti thermomer, the Boomli 2-Boomli 3 interval, and the Boomli 4 thermomer. However, there are also features of the climatic record during this time that the astronomical theory cannot explain. These features are the short Boomli 1, Tsiwi 3, and Boomli 5 intervals and the suddenness of many of the climatic shifts. The shortest periodicity in the astronomical model is about 19,000 yr (Imbrie and Imbrie, 1980). If the astronomical theory accounted for all of the climatic variability observed in the fossil record, we would observe neither sudden climatic shifts nor climatic cycles less than 19,000 yr long.

The suddenness of the observed climatic shifts indicates that there must be critical thresholds somewhere in the global climatic system that can trigger rapid shifts from one climatic mode to another. Flohn (1979) has speculated that mechanisms such as solar changes, volcanic dust in the stratosphere, and ice sheet surges could have produced such sudden changes.

Major drainage shifts also deserve careful attention as a possible cause of sudden climatic changes. Hydrologic changes associated with the growth of the Laurentide ice sheet must have caused major changes in the rate of delivery of glacial meltwater to the North Atlantic Ocean that could have significantly changed its climatic behavior by affecting the rate of formation of sea ice in the winter. A high rate of inflow of glacial meltwater through Davis or Hudson Straits could have caused sudden climatic changes through albedo effects.

Increased meltwater influx might explain why the climatic sequence in the Camp Century core from Greenland (fig. 30; Dansgaard and others, 1971) has a character markedly different from the pollen records from Clear Lake, France, and Macedonia. The cool intervals recorded at Camp Century are all very brief events in the lower half of the record. These brief cool intervals may represent changes in the surface conditions of Baffin Bay and Davis Strait near the end of periods of glacial growth. At such times, increased meltwater influx may have been important both as a stabilizer of the surface density profile (promoting winter freezing) and perhaps also as a partial source for the precipitation at Camp Century.

The circulation of the North Atlantic Ocean did not shift from an interglacial to a glacial mode until the end of oxygen-isotope stage 5; relatively warm temperatures prevailed during stage 5 (Ruddiman and McIntyre, 1977, 1979). Under such conditions, much of the precipitation that fell at Camp Century may have had its source in evaporation from Baffin Bay, Davis Strait, or the Labrador Sea. A surface layer of glacial meltwater under such conditions could draw heat for evaporation from the underlying warm ocean water, but the higher salinity of the ocean water would inhibit mixing of the isotopically light surface water with the isotopically heavier ocean water.

If isotopically light glacial meltwater did form a surface layer in the Baffin Bay-Labrador Sea area during stage 5 glacial maxima, and if evaporation from the area covered by the meltwater layer contributed significantly to precipitation at Camp Century, then the sudden short "cold intervals" observed in the Camp Century record may in fact not represent temperature changes but rather the recycling of glacial meltwater back to the ice sheet. Some isotopic fractionation could be driven not by temperature, but by variations in the relative amounts of isotopically light glacial meltwater and isotopically heavy sea water serving as vapor sources for the ice sheet.

The Tsiwi 3 cryomer may well correspond with the abrupt cooling intervals noted in the Gulf of Mexico (Kennett and Huddlestun, 1972) and at Orgnac, France (Duplessy and others, 1970). Hollin (1980) has argued for an east Antarctic ice surge at about 95 ka, and the Tsiwi 3 cryomer and the other brief cold events noted above could all be in response to such a surge. The mechanism is attractive because it provides not only for a sudden cooling but also for a sudden warming following the surge.

CONCLUSIONS

The pollen record of Clear Lake cores 4 and 7 provides a continuous climatic record covering the entire last glacial cycle from a continental environment that is well to the south of the continental ice sheets. Changes in the frequency of oak pollen through time provide a measure of the severity of the climate—high percentages of oak pollen correspond to interglacial conditions that are relatively warm and dry, whereas low percentages of oak pollen correspond to relatively colder and wetter glacial conditions. The sensitivity of oak-pollen frequency to changes in climate is much greater during the interglacial and interstadial parts of the record than during the glacial periods.

The period following the last interglacial at Clear Lake was characterized by several drastic climatic shifts, including both sudden coolings and sudden warmings. These shifts are interpreted as climatic catastrophes for the ecosystems that they affected. The most extreme change occurred at the end of the last interglaciation.

The climatic fluctuations at Clear Lake during the Konocti thermomer and the early Pomo cryomer follow the sequence of stadials and interstadials observed in northern Europe during the correlative Eemian and early Weichselian stages with remarkable fidelity. This result establishes that the Clear Lake and northern European sequences are of more than regional importance.

Correlation of the Clear Lake record with other climatic sequences has been done primarily from the point of view of the Clear Lake record. Individual sites have been made to correlate so that the sequence of stadial (cryomer) and interstadial (thermomer) events produced the best subjective match with Clear Lake without regard to the other correlations implied by such matching. In general, the other sequences seem to correlate among themselves rather well at the times suggested by the Clear Lake record, but some correlations may distress other workers. In particular, the suggestion is made that some of the montane glaciations of the Western United States may be of Sangamonian age. If this conclusion can be corroborated, then the general stratigraphic framework of the last glacial cycle in North America will require substantial revision.

The Clear Lake results show that long cores from extraglacial areas can provide long climatic records from continental sites that have not been forthcoming using more traditional (and less expensive) field methods. Such long and continuous records are invaluable in providing a context in which to evaluate the shorter climatic records of various ages that will always constitute the bulk of the paleoclimatic record. Long and continuous records are now very scarce. Many parts of our complex modern society are strongly influenced by climate, including such important components as agriculture, water supply, energy needs, and susceptibility to natural hazards. We cannot accurately assess the risks we face from future climatic changes until we understand the long-term behavior and mechanisms of climate. Prompt study of additional long, continuous climatic sequences from continental environments is of great importance for developing that understanding.

REFERENCES CITED

Adam, D.P., 1967, Late Pleistocene and Recent palynology in the central Sierra Nevada, California, *in* Cushing, E.J., and Wright, H.E., Jr., eds., Quaternary paleoecology: New Haven, Yale University Press, p. 275–301.

——— 1969, Ice ages and the thermal equilibrium of the earth: Tucson, University of Arizona, Geochronology Department, Interim Research Report 15, 26 p.

——— 1970, Some applications of multivariate statistics in palynology: Tucson, University of Arizona, Ph.D. dissertation, 120 p.

——— 1973a, Early Pleistocene(?) pollen spectra from near Lake Tahoe, California: U.S. Geological Survey Journal of Research, v. 1, no. 6, p. 691–693.

——— 1973b, Ice ages and the thermal equilibrium of the earth: U.S. Geological Survey Journal of Research, v. 1, no. 6, p. 587–596.

——— 1974, Palynological applications of principal component and cluster analyses: U.S. Geological Survey Journal of Research, v. 2, no. 6, p. 727–741.

——— 1975a, A Late Holocene pollen record from Pearson's Pond, Weeks Creek Landslide, San Francisco Peninsula, California: U.S. Geological Survey Journal of Research, v. 3, no. 6, p. 721–731.

——— 1975b, Ice ages and the thermal equilibrium of the earth, II: Quaternary Research, v. 5, no. 2, p. 161–171.

——— 1976a, CABFAC/USGS, a FORTRAN program for Q-mode factor analysis of stratigraphically ordered samples: U.S. Geological Survey Open-File Report 76-216, 27 p.

——— 1976b, Hudson Bay, Lake Zissaga, and the growth of the Laurentide Ice Sheet: Nature, v. 261, no. 5562, p. 679–680.

——— 1976c, Climatic fluctuations during the transition from the last interglacial to the last glacial: pollen evidence from Clear Lake, California [abs.]: Geological Society of America Abstracts with Programs, v. 8, no. 6, p. 749.

——— 1977, A continuous pollen record through the last glacial/interglacial cycle from Clear Lake, California [abs.]: International Quaternary Congress, 10th, Birmingham, England, p. 3.

——— 1979a, Raw pollen counts from core 4, Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 79-663, 181 p.

——— 1979b, Raw pollen counts from core 7, Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 79-1085, 92 p.

——— 1979c, Bibliography for the Clear Lake-Geysers area, *in* Crow, N.B., An environmental overview of Geothermal development: the Geysers-Calistoga KGRA, Volume 4. Environmental Geology: Livermore, California, University of California, Lawrence Livermore Laboratory Publication UCRL-52496, p. 38–56.

Adam, D.P., and Sims, J.D., 1976, A long, continuous pollen record from Clear Lake, California [abs.]: Geological Society of America Abstracts with Programs, v. 8, no. 3, p. 349.

Adam, D.P., Sims, J.D., and Throckmorton, C.K., 1981, 130,000-yr continuous pollen record from Clear Lake, Lake County, California: Geology, v. 9, no. 8, p. 373–377.

Adam, D.P., and West, G.J., 1983, Temperature and precipitation estimates through the last glacial cycle from Clear Lake, California, pollen data: Science, v. 219, no. 4581, p. 168–170.

American Commission on Stratigraphic Nomenclature, 1970, Code of stratigraphic nomenclature: Tulsa, Okla., American Association of Petroleum Geologists, 22 p.

Andersen, B.J., 1981, Late Weichselian ice sheets in Eurasia and Greenland, *in* Denton, G.H., and Hughes, T.J., eds., The last great ice sheets: New York, Wiley-Interscience, p. 3–65.

Anderson, C.A., 1936, Volcanic history of Clear Lake, California: Geological Society of America Bulletin, v. 47, no. 5, p. 629–664.

Anderson, S.T., 1980, Early and Late Weichselian chronology and birch assemblages in Denmark: Boreas, v. 9, p. 53–69.

Atwater, B.F., Adam, D.P., Bradbury, J.P., Forester, R.M., Mark, R.K., Lettis, W.R., Fisher, G.R., Gobalet, K.W., and Robinson, S.W., 1986, A fan dam for Tulare Lake, California, and implications for the Wisconsin glacial history of the Sierra Nevada: Geological Society of America Bulletin, v. 97, no. 1, p. 97–109.

Bailey, R.A., Dalrymple, G.B., and Lanphere, M.A., 1976, Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California: Journal of Geophysical Research, v. 81, no. 5, p. 725–744.

Barrett, S.A., 1908, The ethno-geography of the Pomo and neighboring Indians: Berkeley and Los Angeles, University of California Publications in American Archaeology and Ethnology, v. 6, no. 1, 332 p.

Beaver, C.K., Adam, D.P., Sims, J.D., and Rymer, M.J., 1976, Sampling procedures and catalogue of samples for eight boreholes at Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 76-157, 14 p.

Becker, G.F., 1888, Geology of the quicksilver deposits of the Pacific slope: U.S. Geological Survey Monograph 13, 486 p.

Bender, M.L., Fairbanks, R.G., Taylor, F.W., Matthews, R.K., Goddard, J.G., and Broecker, W.L., 1979, Uranium-series dating of the Pleistocene reef tracts of Barbados, West Indies: Geological Society of America Bulletin, pt. I, v. 90, no. 6, p. 577–594.

Benson, Lyman, 1957, Plant classification: Boston, D.C. Heath & Co., 688 p.

Birkeland, P.W., 1964, Pleistocene glaciation of the northern Sierra Nevada, north of Lake Tahoe, California: Journal of Geology, v. 72, no. 6, p. 810–825.

Birkeland, P.W., and Janda, R.J., 1971, Clay mineralogy on soils developed from Quaternary deposits of the eastern Sierra Nevada, California: Geological Society of America Bulletin, v. 82, p. 2495–2514.

Birkeland, P.W., Burke, R.M., and Yount, J.C., 1976, Preliminary comments on Late Cenozoic glaciations in the Sierra Nevada, *in* Mahaney, W.C., ed., Quaternary stratigraphy of North America: Stroudsburg, Pa., Dowden, Hutchinson and Ross, p. 283–295.

Birman, J.H., 1964, Glacial geology across the crest of the Sierra Nevada, California: Geological Society of America Special Paper 75, 80 p.

Blackwelder, E., 1931, Pleistocene glaciation in the Sierra Nevada and Basin Ranges: Geological Society of America Bulletin, v. 42, no. 4, p. 865–922.

Bloom, A.L., Broecker, W.S., Chappell, J.M.A., Matthews, R.K., and Mesolella, K.J., 1974, Quaternary sea level fluctuations on a tectonic coast: New ^{230}Th/^{234}U dates from the Huon Peninsula, New Guinea: Quaternary Research, v. 4, p. 185–205.

Blunt, D.J., Kvenvolden, K.A., and Sims, J.D., 1981, Geochemistry of amino acids in sediments from Clear Lake, California: Geology, v. 9, no. 8, p. 378–382.

——— 1982, Reply to comment on "Geochemistry of amino acids in sediments from Clear Lake, California": Geology, v. 10, no. 3, p. 124–125.

Bormann, F.H., and Likens, G.E., 1979, Catastrophic disturbance and the steady state in northern hardwood forests: American Scientist, v. 67, no. 6, p. 660–669.

Bradbury, J.P., in press, Diatom biostratigraphy and the paleolimnology of Clear Lake, Lake County, California, *in* Sims, J.D., ed., Late Quaternary climate, tectonism, and lake sedimentation in Clear Lake, northern California Coast Ranges: Geological Society of America Special Paper 214.

Brice, J.C., 1953, Geology of Lower Lake Quadrangle, California: California Division of Mines Bulletin 166, 72 p.

Broecker, W.S., Thurber, D.L., Goddard, J., Ku, T.L., Matthews, R.K., and Mesolella, K.J., 1968, Milankovitch hypothesis supported by precise dating of coral reefs and deep-sea sediments: Science, v. 159, no. 3812, p. 297–300.

Burke, R.M., and Birkeland, P.W., 1979, Reevaluation of multiparameter relative dating techniques and their application to the glacial sequence along the eastern escarpment of the Sierra Nevada, California: Quaternary Research, v. 11, no. 1, p. 21–51.

California Department of Water Resources, 1957, Lake County investigation: California Department of Water Resources Bulletin 14, 191 p.

Casteel, R.W., Adam, D.P., and Sims, J.D., 1975, Fish remains from core 7, Clear Lake, Lake County, California: U.S. Geological Survey

Open-File Report 75-173, 67 p.

——— 1977a, Late-Pleistocene and Holocene remains of *Hysterocarpus traski* (tule perch) from Clear Lake, California, and inferred Holocene temperature fluctuations: Quaternary Research, v. 7, no. 1, p. 133–143.

Casteel, R.W., and Beaver, C.K., 1978, Inferred Holocene temperature changes in the North Coast Ranges of California: Northwest Science, v. 52, no. 4, p. 337–342.

Casteel, R.W., Beaver, C.K., Adam, D.P., and Sims, J.D., 1977b, Fish remains from core 6, Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 77-639, 154 p.

Casteel, R.W., Williams, J.H., Throckmorton, C.K., Sims, J.D., and Adam, D.P., 1979, Fish remains from core 8, Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 79-1148, 98 p.

Chandler, A.E., 1901, Water Storage, Cache Creek, California: U.S. Geological Survey Water-Supply and Irrigation Papers, no. 45, 46 p.

Chappell, John, 1974, Geology of coral terraces, Huon Peninsula, New Guinea: A study of Quaternary tectonic movements and sea-level changes: Geological Society of America Bulletin, v. 85, no. 4, p. 553–570.

Chappell, J., and Veeh, H.H., 1978, ^{230}Th/^{234}U age support of an interstadial sea level of −40m at 30,000 yr BP: Nature, v. 276, no. 5688, p. 602–604.

Clark, H.W., 1937, Association types in the north Coast Ranges of California: Ecology, v. 18, p. 214–230.

Clisby, K.H., and Sears, P.B., 1955, Palynology of southern North America, Part III: Microfossil profiles under Mexico City correlated with the sedimentary profiles: Geological Society of America Bulletin, v. 66, p. 511–520.

——— 1956, San Augustin Plains—Pleistocene climatic changes: Science, v. 124, no. 3221, p. 537–539.

Colinvaux, P.A., 1978, On the use of the word "absolute" in pollen statistics: Quaternary Research, v. 9, no. 1, p. 132–133.

Colman, S.M., and Pierce, K.L., 1981, Weathering rinds on andesitic and basaltic stones as a Quaternary age indicator, western United States: U.S. Geological Survey Professional Paper 1210, 56 p.

Cronin, T.M., Szabo, B.J., Ager, T.A., Hazel, J.E., and Owens, J.P., 1981, Quaternary climates and sea levels of the U.S. Atlantic Coastal Plain: Science, v. 211, no. 4479, p. 233–240.

Curry, R.R., 1971, Glacial and Pleistocene History of the Mammoth Lakes Sierra, California—A Geologic Guidebook: Missoula, Montana Department of Geology, Geological Serial Publication 11, Field Conference of Pacific Coast Section, Friends of the Pleistocene, Mammoth Lakes, Calif., Sept. 11-12, 1971, 49 p.

Dalrymple, G.B., 1964, Potassium-argon dates of three Pleistocene interglacial basalt flows from the Sierra Nevada, California: Geological Society of America Bulletin, v. 75, no. 8, p. 753–758.

Dalrymple, G.B., Burke, R.M., and Birkeland, P.W., 1982, Note concerning K-Ar dating of a basalt flow from the Tahoe-Tioga Interglaciation, Sawmill Canyon, southeastern Sierra Nevada, California: Quaternary Research, v. 17, no. 1, p. 120–122.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., and Langway, C.C., Jr., 1971, Climatic record revealed by the Camp Century ice core, *in* Turekian, K.K., ed., The Late Cenozoic glacial ages: New Haven, Conn., Yale University Press, p. 37–56.

Dansgaard, W., and Tauber, Henrik, 1969, Glacier oxygen-18 content and Pleistocene ocean temperatures: Science, v. 166, no. 3904, p. 499–502.

Davis, J.O., 1978, Quaternary tephrochronology of the Lake Lahontan area, Nevada and California: Nevada Archeological Survey, Research Paper 7, 137 p.

Davis, S.N., 1958, Glaciated peaks in the northern Coast Ranges, California: American Journal of Science, v. 256, no. 9, pp. 620–629.

Davis, W.M., 1931, Clear Lake, California: Science, v. 74, no. 1927, p. 572–573.

——— 1933, The lakes of California: California Journal of Mines and Geology, v. 29, p. 175–236.

Denham, C.R., 1976, Blake polarity episode in two cores from the Greater Antilles Outer Ridge: Earth and Planetary Science Letters, v. 29, p. 422–434.

Donnelly-Nolan, J.M., Hearn, B. Carter, Jr., Curtis, G.H., and Drake, R.E., 1981, Geochronology and evolution of the Clear Lake Volcanics, *in* McLaughlin, R.J., and Donnelly-Nolan, J.M., eds., Research in the Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, p. 47–60.

Dungworth, G., 1982, Comment on "Geochemistry of amino acids in sediments from Clear Lake, California": Geology, v. 10, no. 3, p. 124.

Duplessy, J.C., Labeyrie, J., Lalou, C., and Nguyen, H.V., 1970, Continental climatic variations between 130,000 and 90,000 years B.P.: Nature, v. 226, no. 5246, p. 631–633.

Easterbrook, D.J., Briggs, N.D., Westgate, J.A., and Gorton, M.P., 1981, Age of the Salmon Springs Glaciation in Washington: Geology, v. 9, no. 2, p. 87–93.

Emiliani, Cesare, 1958, Paleotemperature analysis of core 280 and Pleistocene correlations: Journal of Geology, v. 66, no. 3, p. 264–275.

——— 1966, Paleotemperature analysis of Caribbean cores P6304-8 and P6304-9 and a generalized temperature curve for the past 425,000 years: Journal of Geology, v. 74, no. 2, p. 109–126.

Ericson, D.B., Ewing, Maurice, Wollin, Goesta, and Heezen, B.C., 1961, Atlantic deep-sea sediment cores: Geological Society of America Bulletin, v. 72, no. 12, p. 193–286.

Evitt, W.R., 1969, Dinoflagellates and other organisms in palynological preparations, *in* Tschudy, R.H., and Scott, R.A., eds., Aspects of palynology: New York, Wiley-Interscience, p. 439–479.

Faegri, Knut, and Iverson, Johannes, 1964, Textbook of pollen analysis, [2d ed., rev.]: New York, Hafner, 237 p.

Fletcher, M.R., and Clapham, W.B., Jr., 1974, Sediment density and the limits to the repeatability of absolute pollen frequency determinations: Geoscience and Man, v. 9, p. 27–35.

Flint, R.F., 1971, Glacial and Quaternary geology: New York, John Wiley and Sons, 892 p.

Flohn, Hermann, 1979, On time scales and causes of abrupt paleoclimatic events: Quaternary Research, v. 12, no. 1, p. 135–149.

Florschütz, F., Menendez Amor, Josefina, and Wijmstra, T.A., 1971, Palynology of a thick Quaternary succession in southern Spain: Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 10, p. 233–264.

Follmer, L.R., 1978, The Sangamon Soil in its type area—a review, *in* Mahaney, W.C., ed., Quaternary Soils: Norwich, England, Geo Abstracts Ltd., p. 125–165.

Fowells, H.A., 1965, Silvics of the forest trees of the United States: U.S. Department of Agriculture Handbook 271, 762 p.

Frye, J.C., and Willman, H.B., 1973, Wisconsinan climatic history interpreted from Lake Michigan Lobe deposits and soils: Geological Society of America Memoir 136, p. 135–152.

Frye, J.C., Willman, H.B., and Black, R.F., 1965, Outline of glacial geology of Illinois and Wisconsin, *in* Wright, H.E., Jr., and Frey, D.G., eds., The Quaternary of the United States: Princeton, New Jersey, Princeton University Press, p. 43–61.

Frye, J.C., Willman, H.B., Rubin, Meyer, and Black, R.F., 1968, Definition of Wisconsinan Stage: U.S. Geological Survey Bulletin 1274-E, 22 p.

Fuji, N., 1976a, Palaeoclimatic and palaeovegetational changes around Lake Biwa, central Japan during the past 100,000 years, *in* Horie, Shoji, ed., Paleolimnology of Lake Biwa and the Japanese Pleistocene, v. 4, p. 316–356.

——— 1976b, Palynological investigation on a 200-meter core samples from Lake Biwa in central Japan, *in* Horie, Shoji, ed., Paleolimnology of Lake Biwa and the Japanese Pleistocene, v. 4, p. 357–421.

——— 1978, Paleovegetational and paleoclimatic changes around Lake Biwa, central Japan, during the past 100,000-270,000 years, *in* Horie, Shoji, ed., Paleolimnology of Lake Biwa and the Japanese Pleistocene, v. 6, p. 235-262.

Geyh, M.A., Krumbein, W.E., and Kudrass, H.-R., 1974, Unreliable C-14 dating of long-stored deep-sea sediments due to bacterial activity: Marine Geology, v. 17, p. M45-M50.

Goldman, C.R., and Wetzel, R.G., 1963, A study of the primary productivity of Clear Lake, Lake County, California: Ecology, v. 44, p. 283-294.

Gray, J.T., 1979, The vegetation of two California mountain slopes: Madroño, v. 25, p. 177-185.

Griffin, J.R., 1977, Oak woodland, *in* Barbour, M.G., and Major, Jack, eds., Terrestrial vegetation of California: New York, John Wiley, p. 383-415.

Griffin, J.R., and Critchfield, W.B., 1972, The distribution of forest trees in California: U.S. Department of Agriculture, Forest Service Research Paper PSW-82, 114 p.

Grüger, Eberhard, 1970, Development of the vegetation of southern Illinois since late Illinoian time (preliminary report): Revue de Geographie Physique et de Geologie Dynamique, v. 12, pt. 2, p. 143-148.

——— 1972, Late Quaternary vegetation development in south-central Illinois: Quaternary Research, v. 2, no. 2, p. 217-231.

——— 1979, Die Seeablagerungen vom Samerberg/Obb. und ihre Stellung im Jungpleistozän: Eiszeitalter und Gegenwart, v. 29, p. 23-34.

Hansen, R.O., and Begg, E.L., 1970, Age of Quaternary sediments and soils in the Sacramento area, California, by uranium and actinium series dating of vertebrate fossils: Earth and Planetary Science Letters, v. 8, p. 411-419.

Harman, H.H., 1967, Modern Factor Analysis (2d ed., rev.): Chicago, University of Chicago Press, 474 p.

Harper, R.A., 1918, The evolution of cell types and pressure responses in *Pediastrum*: Memoirs of the Torrey Botanical Club, v. 17, p. 210-240.

Hays, J., Imbrie, J., and Shackleton, N., 1976, Variations in the earth's orbit: Pacemaker of the ice age: Science, v. 194, no. 4270, p. 1121-1132.

Hearn, B.C., Jr., Donnelly, J.M., and Goff, F.E., 1975, Preliminary geologic map of the Clear Lake volcanic field, Lake County, California: U.S. Geological Survey Open-File Report 75-391, scale 1:24,000.

——— 1976, Preliminary geologic map and cross-section of the Clear Lake volcanic field, Lake County, California: U.S. Geological Survey Open-File Map 76-751, scale 1:24,000.

——— 1981, The Clear Lake Volcanics: tectonic setting and magma sources, *in* McLaughlin, R.J., and Donnelly-Nolan, J.M., eds., Research in the Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, p. 25-45.

Helley, E.J., Adam, D.P., and Burke, D.B., 1972, Late Quaternary stratigraphic and paleoecological investigations in the San Francisco Bay area, *in* Frizzell, V.A., ed., Unofficial progress report on the USGS Quaternary studies in the San Francisco Bay area: Friends of the Pleistocene meeting, October 6-8, 1972, Guidebook, p. 19-30.

Heusser, C.J., 1972, Palynology and phytogeographical significance of a Late-Pleistocene refugium near Kalaloch, Washington: Quaternary Research, v. 2, no. 2, p. 189-201.

——— 1977, Quaternary palynology of the Pacific Slope of Washington: Quaternary Research, v. 8, no. 3, p. 282-306.

Heusser, L.E., 1983, Contemporary pollen distribution in coastal California and Oregon: Palynology, v. 7, p. 19-42.

Heusser, L.E., and Shackleton, N.J., 1979, Direct marine-continental correlation: 150,000-year oxygen isotope-pollen record from the North Pacific: Science, v. 204, no. 4395, p. 837-839.

Heusser, L.E., and Sims, J.D., 1981, Palynology of core CL-80-1, Clear Lake, California [abs.]: Geological Society of America Abstracts with Programs, v. 13, no. 2, p. 61.

——— 1983, Pollen counts for core CL-80-1, Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 83-384, 28 p.

Hibbard, C.W., 1955, The Jinglebob interglacial (Sangamon?) fauna from Kansas and its climatic significance: University of Michigan Museum of Paleontology Contributions, v. 12, no. 10, p. 179-228.

Hinds, N.E.A., 1952, Evolution of the California landscape: California Division of Mines Bulletin 158, 240 p.

Hollin, J.T., 1980, Climate and sea level in isotope stage 5: an East Antarctic ice surge at ~95,000 BP?: Nature, v. 283, no. 5748, p. 629-633.

Holway, R.S., 1907, Physiographic changes bearing on the faunal relationships of the Russian and Sacramento Rivers, California: Science, v. 26, no. 664, p. 382-383.

——— 1911, An extension of the known area of Pleistocene glaciation to the Coast Ranges of California: Bulletin of the American Geographical Society, v. 43, no. 3, p. 161-170.

Hopkirk, J.D., 1973, Endemism in fishes of the Clear Lake region of central California: Berkeley, Los Angeles, and London, England, University of California Publications in Zoology, v. 96, 135 p.

Horne, A.J., Javornicky, Pavel, and Goldman, C.R., 1971, A freshwater "red tide" on Clear Lake, California: Limnology and Oceanography, v. 16, no. 4, p. 684-689.

Huber-Pestalozzi, G., 1950, Phytoplankton des Süsswassers, Systematik und Biologie: Cryptophyceen, Chloromonadinen, Peridineen: Die Binnengewässer, v. 16, pt. 3, 310 p.

Hutchinson, G.E., 1957, A treatise on limnology; volume I, Geography, physics and chemistry: New York, John Wiley, 1015 p.

——— 1967, A treatise on limnology; volume II, Introduction to lake biology and the limnoplankton: New York, John Wiley, 1115 p.

Imbrie, John, and Imbrie, J.Z., 1980, Modeling the climatic response to orbital variations: Science, v. 207, no. 4434, p. 943-953.

Jacobson, G.L., Jr., and Bradshaw, R.H.W., 1981, The selection of sites for paleovegetational studies: Quaternary Research, v. 16, no. 1, p. 80-96.

Jennings, C.W., and Strand, R.G., 1960, Geologic map of California (Olaf P. Jenkins edition), Ukiah Sheet: California Division of Mines and Geology, scale 1:250,000.

Kapp, R.O., 1965, Illinoian and Sangamon vegetation in southwestern Kansas and adjacent Oklahoma: University of Michigan Museum of Paleontology Contributions, v. 19, no. 14, p. 167-255.

——— 1969, How to know the pollen and spores: Dubuque, Iowa, W.D. Brown, 249 p.

Kennett, J.P., and Huddlestun, Paul, 1972, Abrupt climatic change at 90,000 yr BP: faunal evidence from Gulf of Mexico cores: Quaternary Research, v. 2, no. 3, p. 384-395.

Klein, Jeffrey, Lerman, J.C., Damon, P.E. and Ralph, E.K., 1982, Calibration of radiocarbon dates: Radiocarbon, v. 24, p. 103-150.

Klovan, J.E., and Imbrie, J., 1971, An algorithm and FORTRAN-IV program for large-scale Q-mode factor analysis and calculation of factor scores: Mathematical Geology, v. 3, p. 61-77.

Knapp, Rüdiger, 1965, Die Vegetation von Nord- und Mittelamerika: Stuttgart, Fischer, 375 p.

Kobayashi, Kazuo, 1978, Correlation of short geomagnetic polarity episodes between Lake Biwa and deep-sea sediments, *in* Horie, Shoji, ed., Paleolimnology of Lake Biwa and the Japanese Pleistocene, v. 6, p. 88-100.

Koenig, J.B., 1963, Geologic map of California (Olaf P. Jenkins edition), Santa Rosa Sheet: California Division of Mines and Geology, scale 1:250,000.

Kominz, M.A., Heath, G.R., Ku, T.-L., and Pisias, N.G., 1979, Brunhes time scales and the interpretation of climatic change: Earth and Planetary Science Letters, v. 45, p. 394-410.

Küchler, A.W., 1964, Manual to accompany the map "Potential natural vegetation of the conterminous United States": American Geographical Society Special Publication 36, 39 p., 116 pls., 1 map.

—— 1977, The map of the natural vegetation of California, *in* Barbour, M.G., and Major, Jack, Terrestrial vegetation of California: New York, John Wiley, p. 909–938, scale 1:1,000,000.

Kukla, G., Berger, A., Lotti, R., and Brown, J., 1981, Orbital signature of interglacials: Nature, v. 290, no. 5804, p. 295–300.

Lallatin, R.D., 1975, Clear Lake water quality data: California Department of Water Resources, Northern District, 321 p.

Liddicoat, J.C., Sims, J.D., and Bridge, W.D., 1981, Paleomagnetism of a 177-m-long core from Clear Lake, California [abs.]: Geological Society of America Abstracts with Programs, v. 13, no. 2, p. 67.

Lindberg, D.R., Roth, Barry, Kellogg, M.G., and Hubbs, C. L., 1980, Invertebrate megafossils of Pleistocene (Sangamon Interglacial) age from Isla de Guadelupe, Baja California, Mexico, *in* Power, D.M., ed., The California Islands: Proceedings of a multidisciplinary symposium: Santa Barbara, Santa Barbara Museum of Natural History, p. 41–70.

Little, E.L., Jr., 1971, Atlas of United States Trees, Volume 1: Conifers and important hardwoods: U.S. Department of Agriculture Miscellaneous Publication 1146, 8 p. and 200 maps.

—— 1976, Atlas of United States Trees, Volume 3: Minor Western Hardwoods: U.S. Department of Agriculture Miscellaneous Publication 1134, 13 p. and 213 maps.

Livingston, E.B., and Shreve, Forrest, 1921, The distribution of vegetation in the United States as related to climatic conditions: Carnegie Institution of Washington Publication 284, 284 p.

Lüttig, Gerd, 1965, Interglacial and interstadial periods: Journal of Geology, v. 73, no. 4, p. 579–591.

Mahood, A.D., and Adam, D.P., 1979, Late Pleistocene chrysomonad cysts from core 7, Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 79-971, 11 p.

Major, Jack, 1963, Vegetation mapping in California: Bericht über das Internationale Symposion für Vegetationskartierung vom 23.-26.3. 1959 in Stolzenau/Weser, p. 195–218.

—— 1977, California climate in relation to vegetation, *in* Barbour, M.G., and Major, Jack, eds., Terrestrial vegetation of California: New York, John Wiley, p. 11–74.

Mangerud, Jan, Sønstegaard, Eivind, and Sejrup, Hans-Petter, 1979, Correlation of the Eemian (interglacial) Stage and the deep-sea oxygen-isotope stratigraphy: Nature, v. 277, p. 189–192.

Mankinen, E.A., Donnelly-Nolan, J.M., Gromme, C.S., and Hearn, B.C., Jr., 1981, Paleomagnetism of the Clear Lake Volcanics and new limits on the age of the Jaramillo normal-polarity event, *in* McLaughlin, R.J., and Donnelly-Nolan, J.M., eds., Research in the Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, p. 67–95.

Marchand, D.E., and Allwardt, Alan, 1981, Late Cenozoic stratigraphic units, northeastern San Joaquin Valley, California: U.S. Geological Survey Bulletin 1470, 70 p.

Martin, P.S., 1963a, The last 10,000 years, a fossil pollen record of the American Southwest: Tucson, University of Arizona Press, 87 p.

—— 1963b, Geochronology of pluvial Lake Cochise, southern Arizona, II: Pollen analysis of a 42-meter core: Ecology, v. 44, p. 436–444.

McLaughlin, R.J., 1981, Tectonic setting of pre-Tertiary rocks and its relation to geothermal resources in the Geysers-Clear Lake area, *in* McLaughlin, R.J., and Donnelly-Nolan, J.M., eds., Research in the Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, p. 3–23.

McLaughlin, R.J., and Donnelly-Nolan, J.M., eds., 1981, Research in the Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, 259 p.

McNitt, J.R., 1968, Geology of the Kelseyville quadrangle, Sonoma, Lake, and Mendocino Counties, California: California Division of Mines and Geology Map Sheet 9, scale 1:250,000.

Menke, Burchard, 1976, Neue Ergebnisse zur Stratigraphie und Landschaftsentwicklung im Jungpleistozän Westholsteins: Eiszeitalter und Gegenwart, v. 27, p. 53–68.

Menke, Burchard, and Behre, Karl-Ernst, 1973, History of vegetation and biostratigraphy: Eiszeitalter und Gegenwart, v. 23/24, p. 251–267.

Moore, P.D., and Webb, J.A., 1978, An illustrated guide to pollen analysis: New York, Halstead, 133 p.

Morrison, R.B., and Frye, J.C., 1965, Correlation of the Middle and Late Quaternary successions of the Lake Lahontan, Lake Bonneville, Rocky Mountain (Wasatch Range), southern Great Plains, and eastern Midwest areas: Nevada Bureau of Mines Report 9, 45 p.

Munz, P.A., 1968, Supplement to A California flora: Berkeley, University of California Press, 224 p.

Munz, P.A., and Keck, D.D., 1959, A California flora: Berkeley, University of California Press, 1681 p.

Nelson, A.R., and Locke, W.W., III, 1981, Quaternary stratigraphic usage in North America: a brief survey: Geology, v. 9, p. 134–137.

Ninkovitch, D., and Shackleton, N.J., 1975, Distribution, stratigraphic position, and age of ash layer "L" in the Panama Basin region: Earth and Planetary Science Letters, v. 27, p. 20–34.

Nishimura, Susumu, and Yokoyama, Takuo, 1975, Fission-track ages of volcanic ashes of core samples of Lake Biwa and the Kobiwako Group (2), *in* Horie, Shoji, ed., Paleolimnology of Lake Biwa and the Japanese Pleistocene, v. 4, p. 138–142.

Parra, O.O., 1979, Revision der Gattung *Pediastrum* Meyen (Chlorophyta): Bibliotheca Phycologica, v. 48, 186 p., 55 pls.

Peng, T.-H., and Broecker, W.S., 1980, Gas exchange rates for three closed-basin lakes: Limnology and Oceanography, v. 25, p. 789–796.

Pierce, K.L., 1979, History and dynamics of glaciation in the northern Yellowstone National Park area: U.S. Geological Survey Professional Paper 729-F, p. F1–F90.

Pierce, K.L., Obradovich, J.D., and Friedman, Irving, 1976, Obsidian hydration dating and correlation of Bull Lake and Pinedale glaciations near West Yellowstone, Montana: Geological Society of America Bulletin, v. 87, p. 703–710.

Prell, W.L., and Hays, J.D., 1976, Late Pleistocene faunal and temperature patterns of the Colombia Basin, Caribbean Sea: Geological Society of America Memoir 145, p. 201–220.

Prentice, I.C., 1980, Multidimensional scaling as a research tool in Quaternary palynology: a review of theory and methods: Review of Palaeobotany and Palynology, v. 31, p. 71–104.

Putnam, W.C., 1949, Quaternary geology of the June Lake district, California: Geological Society of America Bulletin, v. 60, no. 8, p. 1281–1302.

Raup, D.M., 1981, Introduction: What is a crisis?, *in* Nitecki, M.H., ed., Biotic crises in ecological and evolutionary time: New York, Academic Press, p. 1–12.

Raup, H.M., 1981, Physical disturbance in the life of plants, *in* Nitecki, M.H., ed., Biotic crises in ecological and evolutionary time: New York, Academic Press, p. 39–52.

Raven, P.H., 1977, The California flora, *in* Barbour, M.G., and Major, Jack, eds., Terrestrial vegetation of California: New York, John Wiley, p. 109–137.

Regal, R.R., and Cushing, E.J., 1979, Confidence intervals for absolute pollen counts: Biometrics, v. 35, p. 557–565.

Richmond, G.M., 1976, Pleistocene stratigraphy and chronology in the mountains of western Wyoming, *in* Mahaney, W.C., ed., Quaternary stratigraphy of North America: Stroudsburg, Pa., Dowden, Hutchinson and Ross, p. 353–379.

Ritter, E.W., and Hatoff, B.W., 1977, Late Pleistocene pollen and sediments: an analysis of a central California locality: Texas Journal of Science, v. 29, p. 195–207.

Robinson, S.W., 1979, Radiocarbon dating at the U.S. Geological Survey, Menlo Park, California, *in* Berger, Rainer, and Suess, H.E, eds., Radiocarbon dating: Los Angeles, University of California Press,

p. 268–273.

Ruddiman, W.F., and McIntyre, Andrew, 1977, Late Quaternary surface ocean kinematics and climatic change in the high latitude North Atlantic: Journal of Geophysical Research, v. 82, no. 27, p. 3877–3887.

—— 1979, Warmth of the subpolar North Atlantic Ocean during northern hemisphere ice-sheet growth: Science, v. 204, no. 4389, p. 173–175.

Russell, I.C., 1887, Quaternary history of Mono Valley, California: U.S. Geological Survey 8th Annual Report, pt. 1, p. 261–394.

Rymer, M.J., 1978, Stratigraphy of the Cache Formation (Pliocene and Pleistocene) in Clear Lake Basin, Lake County, California: U.S. Geological Survey Open-File Report 78-924, 102 p.

—— 1981, Stratigraphic revision of the Cache Formation (Pliocene and Pleistocene), Lake County, California: U.S. Geological Survey Bulletin 1502-C, 35 p.

Rymer, M.J., Sims, J.D., Hedel, C.W., Bridge, W.D., Makdisi, R.S., and Mannshardt, G.A., 1981, Sample catalog for core CL–80–1, Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 81-245, 53 p.

Sandusky, J.C., and Horne, A.J., 1978, A pattern analysis of Clear Lake phytoplankton: Limnology and Oceanography, v. 23, no. 4, p. 636–648.

Sawyer, J.O., and Thornburgh, D.A., 1977, Montane and subalpine vegetation of the Klamath Mountains, *in* Barbour, M.G., and Major, Jack, eds., Terrestrial vegetation of California: New York, John Wiley, p. 699–732.

Sarna-Wojcicki, A.M., Meyer, C.E., Adam, D.P., and Sims, J.D., in press, Correlation and age estimates of ash beds in late Pleistocene sediments of Clear Lake, California, *in* Sims, J.D., ed., Late Quaternary climate, tectonism, and lake sedimentation in Clear Lake, northern California Coast Ranges: Geological Society of America Special Paper 214.

Sears, P., and Clisby, K.H., 1955, Palynology in southern North America, pt. 4: Pleistocene climates in Mexico: Geological Society of America Bulletin, v. 66, no. 5, p. 521–530.

Shackleton, N.J., 1967, Oxygen isotope analyses and Pleistocene temperatures re-assessed: Nature, v. 215, no. 5096, p. 15–17.

—— 1969, The last interglacial in the marine and terrestrial records: Royal Society of London Proceedings, ser. B., v. 174, no. 1034, p. 135–154.

—— 1975, The stratigraphic record of deep-sea cores and its implications for the assessment of glacials, interglacials, stadials, and interstadials in the Mid-Pleistocene, *in* Butzer, K.W., and Isaac, G.L., eds., After the Australopithecines: Stratigraphy, ecology, and culture change in the Middle Pleistocene: The Hague, Netherlands, Mouton, p. 1–24.

—— 1977, The oxygen isotope stratigraphic record of the Late Pleistocene: Philosophical Transactions of the Royal Society of London, ser. B, v. 280, no. 972, p. 169–182.

Shackleton, N.J., and Opdyke, N.D., 1973, Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a 10^5 year and 10^6 year scale: Quaternary Research, v. 3, no. 1, p. 39–55.

Sharp, R.P., 1969, Semiquantitative differentiation of glacial moraines near Convict Lake, Sierra Nevada, California: Journal of Geology, v. 77, no. 1, p. 68–91.

—— 1972, Pleistocene glaciation, Bridgeport Basin, California: Geological Society of America Bulletin, v. 83, no. 8, p. 2233–2260.

Sharp, R.P., and Birman, J.H., 1963, Additions to classical sequence of Pleistocene glaciations, Sierra Nevada, California: Geological Society of America Bulletin, v. 74, no. 8, p. 1079–1086.

Shlemon, R.J., 1972, The lower American River area, California: A model of Pleistocene landscape evolution: Association Pacific Coast Geographers Yearbook, v. 34, p. 62–86.

Sims, J.D., 1974, Searching for prehistoric earthquakes in Lake sediments: Earthquake Information Bulletin, v. 6, no. 1, p. 3–9.

—— 1976, Paleolimnology of Clear Lake, California, U.S.A., *in* Horie, Shoji, ed., Paleolimnology of Lake Biwa and the Japanese Pleistocene, v. 4, p. 658–702.

—— 1982, Granulometry of core CL–73–4 Clear Lake, California: U.S. Geological Survey Open-File Report 82–70, 7 p.

Sims, J.D., Adam, D.P., and Rymer, M.J., 1981a, Late Pleistocene stratigraphy and palynology of Clear Lake, *in* McLaughlin, R.J., and Donnelly-Nolan, J.M., eds., Research in the Geysers-Clear Lake Geothermal Area, northern California: U.S. Geological Survey Professional Paper 1141, p. 219–230.

Sims, J.D., and Rymer, M.J., 1975a, Preliminary description and interpretation of cores and radiographs from Clear Lake, Lake County, California: Core 1: U.S. Geological Survey Open-File Report 75-665, 19 p.

—— 1975b, Preliminary description and interpretation of cores and radiographs from Clear Lake, Lake County, California: Core 2: U.S. Geological Survey Open-File Report 75-266, 13 p.

—— 1975c, Preliminary description and interpretation of cores and radiographs from Clear Lake, Lake County, California: Core 4: U.S. Geological Survey Open-File Report 75-666, 19 p.

—— 1975d, Preliminary description and interpretation of cores and radiographs from Clear Lake, Lake County, California: Core 5: U.S. Geological Survey Open-File Report 75-381, 15 p.

—— 1975e, Preliminary description and interpretation of cores and radiographs from Clear Lake, Lake County, California: Core 6: U.S. Geological Survey Open-File Report 75-569, 18 p.

—— 1975f, Preliminary description and interpretation of cores and radiographs from Clear Lake, Lake County, California: Core 7: U.S. Geological Survey Open-File Report 75-144, 21 p.

—— 1975g, Preliminary description and interpretation of cores and radiographs from Clear Lake, Lake County, California: Core 8: U.S. Geological Survey Open-File Report 75-306, 15 p.

—— 1976a, Map of gaseous springs and associated faults, Clear Lake, California: U.S. Geological Survey Miscellaneous Field Investigations Map MF–721, scale 1:48,000.

—— 1976b, Preliminary description and interpretation of cores and radiographs from Clear Lake, Lake County, California: Core 3: U.S. Geological Survey Open-File Report 76-208, 18 p.

—— 1981, Deep coring of Quaternary sediment in Clear Lake, California [abs.]: Geological Society of America Abstracts with Programs, v. 13, no. 2, p. 106.

Sims, J.D., Rymer, M.J., and Perkins, J.A., 1981b, Description and preliminary interpretation of core CL–80–1, Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 81-751, 175 p.

Sims, J.D., Rymer, M.J., Perkins, J.A., and Flora, L.A., 1981c, Description and preliminary interpretation of core CL–80–2, Clear Lake, Lake County, California: U.S. Geological Survey Open-File Report 81-1323, 112 p.

Smith, G.I., 1979, Subsurface stratigraphy and geochemistry of Late Quaternary evaporites, Searles Lake, California: U.S. Geological Survey Professional Paper 1043, 130 p.

Smith, G.M., 1920, Phytoplankton of the inland lakes of Wisconsin, pt. 1: Myxophyceae, Heterokontae, and Chlorophyceae exclusive of the Desmidiaceae: Wisconsin Geological and Natural History Survey Bulletin 57, Scientific Series No. 12, p. 1–243.

Smith, J.D., and Foster, J.H., 1969, Geomagnetic reversal in Brunhes Normal Polarity Epoch: Science, v. 163, no. 3867, p. 565–567.

Snyder, J.O., 1908, The fauna of Russian River, California, and its relation to that of the Sacramento: Science, v. 27, p. 269–271.

Stebbins, G.L., and Major, Jack, 1965, Endemism and speciation in the California flora: Ecological Monographs, v. 35, no. 1, p. 1–35.

Stuiver, Minze, 1970, Long-term C-14 variations, *in* Olsson, I.U., ed., Radiocarbon variations and absolute chronology: Almqvist and Wiksell, Stockholm, Nobel Symposium 12, p. 197–213.

——— 1971, Evidence for the variation of atmospheric C^{14} content in the Late Quaternary, *in* Turekian, K.K., ed., The Late Cenozoic glacial ages: New Haven, Connecticut, Yale University Press, p. 57–70.

——— 1982, A high-precision calibration of the AD radiocarbon time scale: Radiocarbon, v. 24, p. 1–26.

Stuiver, Minze, and Polach, H.A., 1977, Reporting of ^{14}C data: Radiocarbon, v. 19, p. 355–363.

Suggate, R.P., 1974, When did the last interglacial end?: Quaternary Research, v. 4, no. 3, p. 246–252.

Thompson, J.M., Sims, J.D., Yadav, S., and Rymer, M.J., 1981, Chemical composition of water and gas from five nearshore subaqueous springs in Clear Lake, *in* McLaughlin, R.J., and Donnelly-Nolan, J.M., eds., Research in the Geysers-Clear Lake Geothermal Area, northern California: U.S. Geological Survey Professional Paper 1141, p. 215–218.

U.S. Department of Commerce, 1964, Decennial census of United States climate—Climatic summary of the United States—Supplement for 1951 through 1960, California: Climatography of the United States No. 86-4, 214 p.

van der Hammen, Th., and Gonzalez, E., 1960, Upper Pleistocene and Holocene climate and vegetation of the "Sabana de Bogotá" (Colombia, South America): Leidse Geologische Mededelingen, v. 25, p. 261–315.

——— 1964, A pollen diagram from the Quaternary of the Sabana de Bogotá (Colombia) and its significance for the geology of the Northern Andes: Geologie en Mijnbouw, v. 43, no. 3, p. 113–117.

van der Hammen, Th., Wijmstra, T.A., and Zagwijn, W.H., 1971, The floral record of the late Cenozoic of Europe, *in* Turekian, K.K., ed., The Late Cenozoic glacial ages: New Haven, Connecticut, Yale University Press, p. 391–424.

Vogl, Richard J., Armstrong, W.P., White, K.L., and Cole, K.L., 1977, The closed-cone pines and cypress, *in* Barbour, M.G., and Major, Jack, eds., Terrestrial vegetation of California: New York, John Wiley, p. 295–358.

Wahrhaftig, Clyde, and Birman, J.H., 1965, The Quaternary of the Pacific mountain system in California, *in* Wright, H.E., Jr., and Frey, D.G., eds., The Quaternary of the United States: Princeton, New Jersey, Princeton University Press, p. 229–340.

Wahrhaftig, Clyde, and Sharp, R.P., 1965, Sonora Pass Junction to Bloody Canyon, *in* Wahrhaftig, Clyde, Morrison, R.B., and Birkeland, P.W., eds., Guidebook for Field Conference I, Northern Great Basin and California: INQUA Congress, 7th, Lincoln, Nebraska, Nebraska Academy of Sciences, Guidebook, p. 71–88.

Wijmstra, T.A., 1969, Palynology of the first 30 metres of a 120 m deep section in northern Greece: Acta Botanica Neerlandica, v. 18, p. 511–527.

——— 1975, Palynology and palaeoclimatology of the last 100,000 years: WMO/IAMAP Symposium on Long-term Climatic Fluctuations, Norwich, England, 18-23 August 1975, Proceedings, p. 5–20.

——— 1978, Palaeobotany and climatic change, *in* Gribbin, John, ed., Climatic Change: Cambridge, England, Cambridge University Press, p. 25–45.

Wijmstra, T.A., and van der Hammen, T., 1974, The last interglacial-glacial cycle: state of affairs of correlation between data obtained from the land and from the ocean: Geologie en Mijnbouw, v. 53, no. 6, p. 386–392.

Willman, H.B., and Frye, J.C., 1970, Pleistocene stratigraphy of Illinois: Illinois State Geological Survey Bulletin 94, 204 p.

Woillard, G.M., 1975, Recherches palynologiques sur le Pleistocene dans l'est de la Belgique et dans les Vosges Lorraines: Acta Geographica Lovaniensia, v. 14, 118 p.

——— 1977, Comparison between the chronology from the beginning of the classical Eemian to the beginning of the classical Wurm in Grande Pile peat-bog, and other chronologies in the world: International Geological Correlation Program, Project 73/1/24, Session in Stuttgart, W. Germany, Quaternary glaciations in the Northern Hemisphere, September 5-13, 1976, Report 4, p. 72–82.

——— 1978a, The last interglacial-glacial cycle at Grande Pile in northeastern France: Belgium, Université de Louvain, Travaux du Laboratoire de Palynologie et Phytosociologie, (Belgium), 21 p.

——— 1978b, Grande Pile peat bog: A continuous pollen record for the last 140,000 years: Quaternary Research, v. 9, no. 1, p. 1–21.

——— 1979a, Abrupt end of the last interglacial s.s. in north-east France: Nature, v. 281, no. 5732, p. 558–562.

——— 1979b, The last interglacial-glacial cycle at Grande Pile in northeastern France: Bulletin of the Geological Society of Belgium, v. 88, no. 1, p. 51–69.

Woillard, G.M., and Mook, W.G., 1982, Carbon-14 dates at Grande Pile: Correlation of land and sea chronologies: Science, v. 215, no. 4529, p. 159–161.

Worthen, A.H., 1873, Geology of Sangamon County: Illinois Geological Survey, v. 5, p. 306–319.

Zagwijn, W.H., 1974, Vegetation, climate, and radiocarbon datings in the Late Pleistocene of the Netherlands, pt. 2: Middle Weichselian: Mededelingen Rijks Geologische Dienst, Nieuwe Serie v. 25, no. 3, p. 101–111.

GPO 685-041/9778