#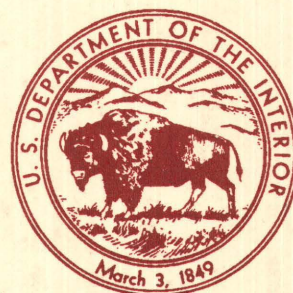 Environmental Changes in the Tule Lake Basin, Siskiyou and Modoc Counties, California, from 3 to 2 Million Years Before Present

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Environmental Changes in the
Tule Lake Basin,
Siskiyou and Modoc Counties, California,
from 3 to 2 Million Years Before Present

By DAVID P. ADAM, J. PLATT BRADBURY, HUGH J. RIECK,
and ANDREI M. SARNA-WOJCICKI

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, Jʀ., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

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*By* David P. Adam, J. Platt Bradbury, Hugh J. Rieck, *and* Andrei M. Sarna-Wojcicki

## Abstract

Pollen and diatom analyses of a core from the town of Tulelake, Siskiyou County, California, for the period between 3 and 2 Ma reveal a paleoclimatic and paleolimnologic sequence recording a long, warm time interval that lasted from about 2.9 to 2.6 Ma and had a short, cooler interval within it. During this warm interval, the regional vegetation surrounding ancient Tule Lake was a mixed coniferous forest, and Tule Lake was a warm monomictic lake. Approximate modern analogs for this Pliocene fossil record at Tulelake are found at least 2 degrees farther south. The Tulelake warm interval appears to have correlatives in the North Atlantic oxygen isotope record and in the pollen record of the Reuverian in the Netherlands. An interval beginning at about 2.4 Ma was characterized at Tule Lake by slow sedimentation, by changes in the relative amounts of algae in the lake, and by an increase in the maximum percentages of *Artemisia* pollen.

## INTRODUCTION

The upper Klamath River drainage basin, in northernmost California and south-central Oregon, is physiographically part of the Basin and Range province. Several factors make it well suited for paleoclimatic and paleolimnologic studies: A number of modern and older depositional basins within this region contain thick sedimentary sequences that span much of the Quaternary and perhaps reach well back into the late Cenozoic. The present climate is less arid than in the Great Basin proper, and modern lakes in many of these depositional basins provide habitats suitable for environmentally sensitive organisms such as ostracodes and diatoms as well as depositional environments suitable for the preservation of pollen. Numerous tephra layers, mostly from the volcanoes of the southern Cascades, can be used to correlate both between basins and with sequences in more distant areas.

This paper describes results of diatom and pollen analyses of sediment deposited during the interval from 3 to 2 Ma at what is now the town of Tulelake, Siskiyou County, California (fig. 1). The town lies within the bed of ancient Tule Lake, now largely reclaimed for agriculture. Diatoms and pollen grains are well preserved and abundant in sediments cored from the ancient lake bed, and their biostratigraphy documents limnological and environmental changes in this region for the last 3 million years. The interval between 3 and 2 Ma is of special interest because significant climatic changes during that interval have been inferred from the foraminiferal and oxygen isotope stratigraphy of marine cores (Loubere and Moss, 1986). Specifically, $\delta^{18}O$ values of $\leq 3.5$ per mil characterize the marine record earlier than about 2.4 Ma, and these are interpreted to represent reduced extent of continental ice and consequently higher sea levels and generally warmer temperatures (Ruddiman and Raymo, 1988). Warmer climates in the future may be a result of the current increase in atmospheric $CO_2$ released by the burning of fossil fuels. Late Pliocene warm climates may be relevant analogs for a $CO_2$-enhanced world, and hence it is important to document their characteristics.

The biostratigraphy of the Tulelake core provides an opportunity for such documentation. This core, dated by paleomagnetic reversals and tephrochronology (Adam and others, 1989), includes a continuous lacustrine stratigraphic record between 3 and 2 Ma. Changes in the relative abundance of pine pollen versus pollen of the Taxodiaceae, Cupressaceae, and Taxaceae (TCT) group[1] reflect changes in the composition of the regional forest through time; proportional shifts between planktonic diatoms (*Aulacoseira solida* and large species of

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[1] Pollen grains of genera and species within the TCT group cannot be reliably distinguished in most cases, so they are lumped in a group for this study. Species that are particularly relevant to the interpretation of the Tulelake core include *Juniperus occidentalis* (western juniper) and *Calocedrus decurrens* (incense-cedar).

*Stephanodiscus*) and benthic diatoms (*Fragilaria species*) can be interpreted in terms of past changes in lake depth, open-water turbulence, and seasonal thermal structure. These parameters are potentially under climatic control and therefore may provide terrestrial paleoclimatic insights that can be compared with data from marine records for the same time interval.

## SITE DESCRIPTION

The study area is a part of the Modoc Plateau (Hinds, 1952; Macdonald, 1966), physiographically transitional between the Great Basin to the east and the Cascade Range to the west (McKee and others, 1983). The region is underlain by Tertiary and Quaternary volcanic rocks broken by prominent normal faults that strike mostly north and north-northwest. The Tule Lake and Klamath basins are bounded by normal fault scarps to the west, by the Devils Garden and Medicine Lake



Figure 1. Core was drilled in town of Tulelake, shown by dot. Line pattern indicates historic lakes; single-headed arrows indicate flow direction; double-headed arrow indicates region of bidirectional flow between Lost and Klamath Rivers; heavy line across Klamath River indicates probable location of sill over which ancient lake system first spilled into Klamath drainage. Dot pattern indicates portions of Medicine Lake highland and Mt. Shasta region with elevations in excess of 1,525 m. From Adam and others (1989).

volcanic fields to the southeast and south, by normal scarps to the east, and by irregular highlands to the north. Volcanism and tectonism are both active processes in the region today; the Glass Mountain obsidian flow on the northeast flank of the Medicine Lake highland was erupted about 1 ka (Heiken, 1981), and Holocene lava flows are offset by the Gillems Bluff fault, which forms the western margin of the Tule Lake basin (Donnelly-Nolan and Champion, 1987).

The Tule Lake basin, along with the Klamath basin to the north, was a part of the larger pluvial Lake Modoc of Dicken (1980). The maximum lake level, as determined from the elevations of lake deposits exposed around the edge of the lake basin, was about 1,292 m according to Dicken. This level is about 50 m higher than the present lake outlet and about 64 m higher than the lowest part of the Tule Lake basin. Much of Tule Lake was drained for agriculture by the 1920's (Turner, 1988); before that time, historic lake levels were as high as approximately 11 m above the present lake level (Cleghorn, 1959).

Dicken (1980), although rather vague about the genesis of Lake Modoc, implied that it behaved like other Great Basin pluvial lakes, waxing and waning in response to climatic changes. However, the basin that once contained Lake Modoc is not now topographically closed at the high elevations the lake is known to have reached; given the present topography, lake water would drain into the Klamath River before rising to the elevations at which many lake deposits are now exposed. In addition, there is no evidence in the upper Klamath River gorge of ancient processes—such as low-elevation glaciation or major landsliding—that could have confined the lake at its maximum level.[2] Therefore, we believe that tectonic and volcanic factors, as well as climatic factors, contributed to the formation of Lake Modoc. Very likely the lake was formed when a closed basin was created either (1) by faulting or (2) by blocking of an original southward drainage to an ancestral Pit River system by the eruption of the Medicine Lake volcanic field (see fig. 1). Once the closed basin was formed, it filled until the impounded lake overflowed to the west, cutting the present gorge of the Klamath River. Exposed benches of lake sediment stranded around the margins of the basin suggest that the lake eroded its outlet rather slowly, allowing time for the deposition of considerable amounts of diatomite at high lake levels. The diatoms found in these higher elevation deposits indicate that the time of maximum lake extent may be much older than the poorly defined Pleistocene age implied by Dicken (1980); the deposits we have examined all appear to be at least 3 m.y. old.
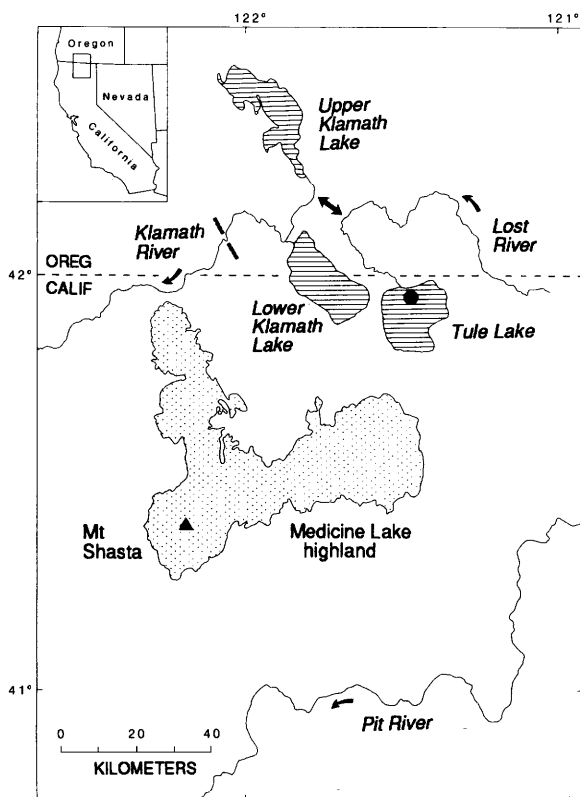
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[2]The major landslide on the north side of Secret Spring Mountain has blocked the Klamath River at times, but at too low an elevation to have affected the Klamath Lake and Tule Lake basins.

## METHODS

We selected a drill site at the town of Tulelake, in northeastern Siskiyou County, California (lat 41°57.27′ N., long 121°28.83′ W., elevation 1,229 m; fig. 1), near the Tulelake municipal water well. The water-well log records shallow-water sediments (lakebottom mud, pumice, sand, and shale) from the surface to a depth of 491 m; these are underlain by interbedded volcanic and sedimentary rocks that extend to a depth of at least 816 m (Hotchkiss, 1968). A 334-m-long sediment record (fig. 2) was cored at a location about 250 m south of the municipal water well. For the section described in this paper, 2.875-in wireline equipment was used down to a depth of 234.75 m; the interval below that depth was sampled using 2.25-in wireline equipment. The stratigraphic intervals from which core was recovered are shown in figure 3. Overall recovery within this interval was about 75.8 percent, with poorer recovery between 231.70 and 279.57 m (56.4 percent) than above or below that interval (87.4 and 86.2 percent, respectively). Drilling was terminated at a depth of 334 m when the drill stem became too heavy to lift safely with our equipment. An additional 155 m of sediment lies beneath the cored section above the first occurrence of "rock" noted in the log of the municipal water well (Hotchkiss, 1968).

Sediments from the Tulelake deposits are highly diatomaceous and largely unconsolidated. Samples for diatom analysis were taken from 49 stratigraphic levels (fig. 3) and then were disaggregated in distilled water. After settling, supernatant water was decanted and one drop of water-saturated diatomaceous sediment was resuspended in 50 mL of distilled water. Diatoms were settled onto coverslips (Battarbee, 1973). At least 300 diatom valves were counted from each sampled stratigraphic level to obtain percentages of taxa present.

Pollen samples were processed using standard techniques for Quaternary materials and then were mounted in silicone oil for counting. At least 200 fossil pollen grains were counted to estimate the percentages of taxa present. Algae were counted outside the pollen sum. For samples in which algae were much more abundant than pollen, the counts for all algae were recorded when the most common algal type reached a count of 100, along with the number of pollen grains recorded up to that point. Estimates of the numbers of the various algae were then calculated using the formula

$$N_{est} = N_{observed} * S_{pollen} / S_{algae} \, ,$$

where $N_{est}$ is the estimated total number of a particular alga that would have been counted if counting had continued until the pollen sum was reached, $N_{observed}$ is the number of that alga counted when the algal counts were recorded, $S_{pollen}$ is the total number of pollen grains counted, and $S_{algae}$ is the number of pollen grains counted at the time the algal counts were recorded. This system produces rather wide confidence limits on the estimates of algal frequencies when algae are abundant, but also requires counting fewer algae (Adam, 1988). All percentages are expressed with respect to the pollen sum, $S_{pollen}$.

## RESULTS

### Lithology

The part of the core described here consists of interbedded lake sediment and tephra. The lake sediment includes (1) olive-gray algal muds and marly units that are primarily massive but sometimes laminated and (2) darker gray to black silts and clays. Tephra units are found throughout the core and range from less than 1 mm to as much as 1.4 m in thickness. The interval between 220.77 and 234.4 m is characterized by a well-developed platy structure that is not found in the adjacent parts of the section.

### Dating

The core has been dated primarily through paleomagnetic and tephra studies (Adam and others, 1989). The upper part of the section contains numerous volcanic ash layers and records many paleomagnetic reversals, whereas the lower part of the section contains no widespread tephra layers and only a sparse record of reversals (fig. 2). The time scale used here for the Pliocene record is based on linear interpolation between the six ages listed in table 1. The sedimentation rate established for the Gauss Normal-Polarity Chron (the interval from 2.92 to 2.48 Ma) is in general agreement with rates observed higher in the section, but sedimentation rates varied greatly within the interval from 2.48 to 2.01 Ma (see table 1 and the age scale on fig. 3). In particular, sedimentation was very slow near the base of the Matuyama Reversed-Polarity Chron (in the interval from 2.48 to 2.12 Ma; 229.68 to 219 m depth). The low sedimentation rate inferred from the paleomagnetic data is corroborated by the lithology of the section, which shows a platy fracture pattern between 234.4 and 220.77 m depth that is not present above or below that interval. The platy fracture may be a result of early soil development caused by alternate wetting and drying of the sediment surface; thus it suggests that the lake bottom was frequently exposed during the cited interval.

### Biostratigraphy

Pollen is present in most of the section (fig. 2), and diatoms are abundant throughout. Other microfossils include sponge spicules, chrysophyte cysts, acid-resistant algae, and ostracodes; these other microfossils are not as abundant or as commonly preserved as the diatoms and pollen. Macrofossils include gastropods and fish remains.
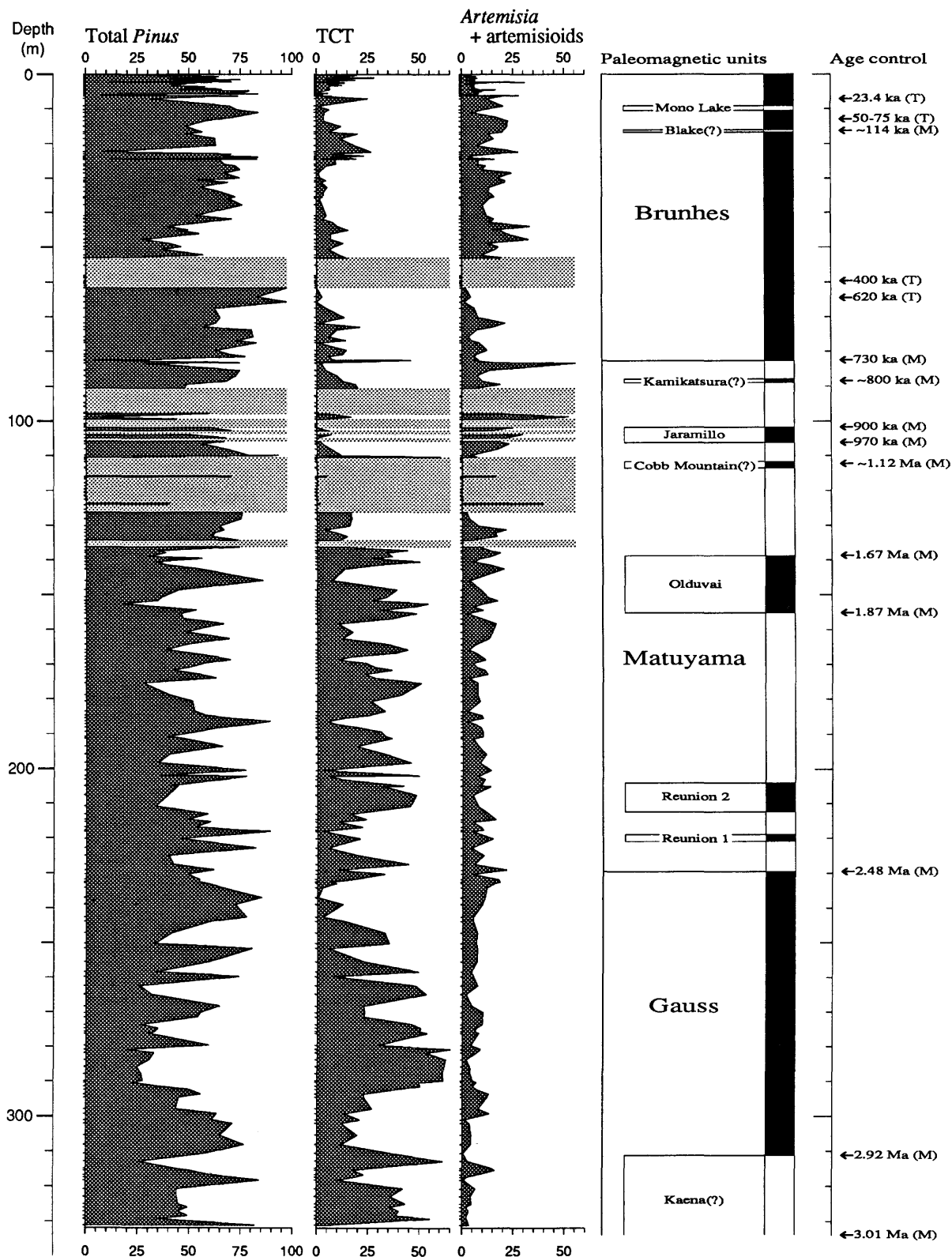
**Figure 2.** Percentages of *Pinus* (pine), TCT (Taxodiaceae, Cupressaceae, and Taxaceae), and *Artemisia* pollen plotted against depth for entire Tulelake section. Tick marks to left of vertical axes show locations of analyzed samples. Lightly shaded rectangles indicate intervals where pollen was absent or too sparse to count. In "Age control" column, ages derived from paleomagnetic data are indicated by "M" and ages derived from tephra by "T" (from Adam and others, 1989). Paleomagnetic units in black are normal polarity, those in white are reversed polarity. Depth scale (unlabeled) added to left of "Age control" column to facilitate comparison of ages with depths.
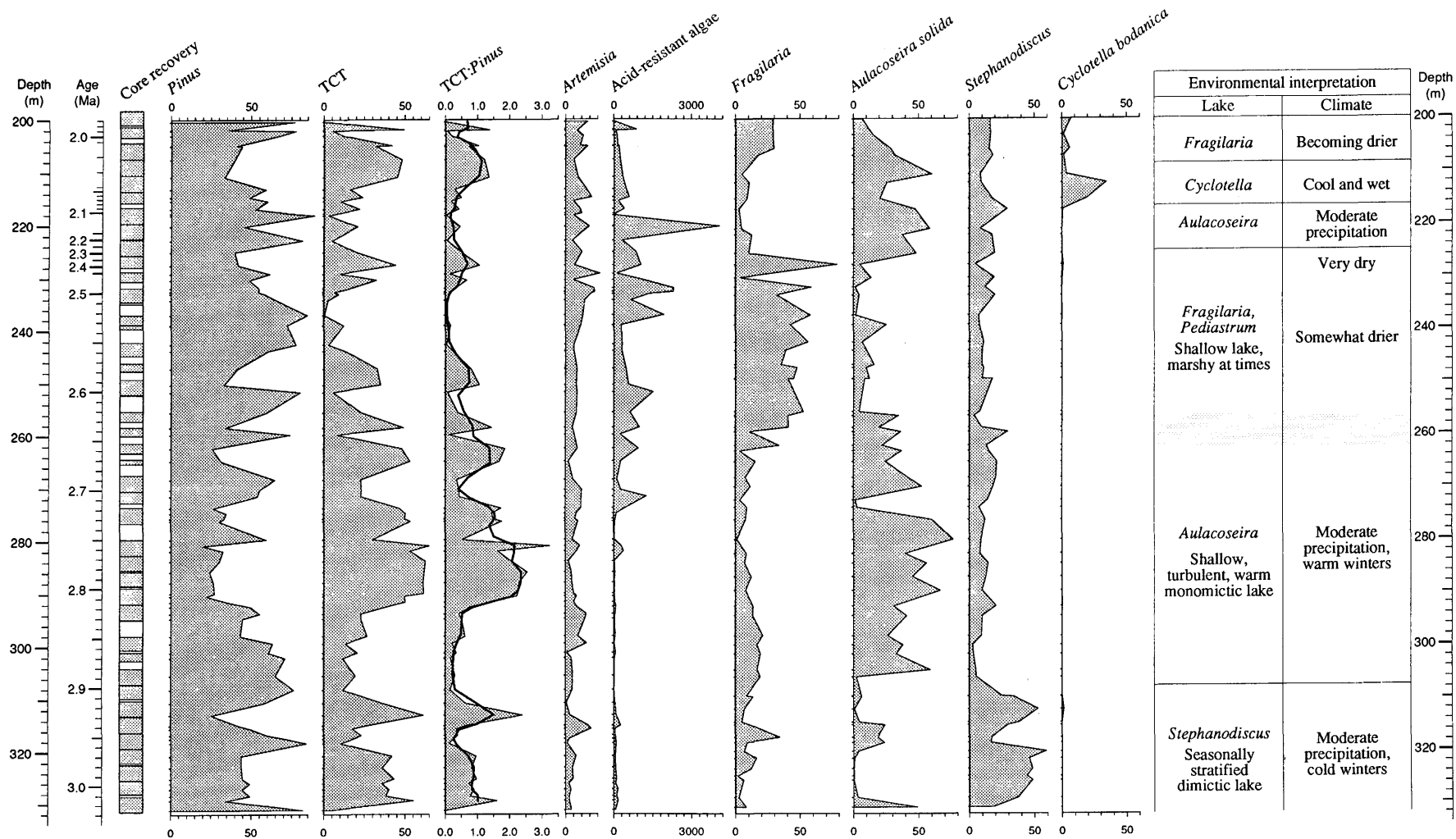
**Figure 3.** Selected variables plotted against depth and inferred age for the 3- to 2-Ma part of the Tulelake section. Tick marks to left of vertical axes show locations of analyzed samples. TCT indicates Taxodiaceae, Cupressaceae, and Taxaceae group. Pollen percentages expressed as percent of total pollen; TCT:*Pinus* ratios dimensionless. Curve for acid-resistant algae (those algae that survived pollen extraction process) derived from pollen counts and expressed as percent of total pollen; diatom percentages expressed as percent of total diatoms. Smoothed curve (heavy line) shown for TCT:*Pinus* calculated as weighted three-level moving average, with both TCT:*Pinus* and depth values smoothed. Shaded areas in "Core recovery" column show intervals from which core was recovered, and white spaces show intervals from which no core was recovered; horizontal lines within shaded areas represent boundaries between core segments. Shaded rectangle in "Environmental interpretation" column indicates transitional interval.

## Palynology

The general character of the pollen record from the Pliocene part of the section is markedly different from that in the younger part of the section. The two most important pollen types in the Pliocene section are pine and TCT, which are plotted against age and depth in figure 3 and with respect to each other in figure 4. Within the Pliocene, pine and TCT pollen show a well-developed inverse relation (fig. 4A), and the highest TCT frequencies commonly exceed 50 percent. By contrast, in the younger part of the section the highest TCT frequencies are significantly lower (fig. 4B), and other pollen types, particularly *Artemisia* (sagebrush), become more important (fig. 2).

Significant glacial activity in the North Atlantic ocean began about 2.37 Ma, not far above the Gauss/Matuyama boundary (Shackleton and others, 1984). The pollen record in the Tulelake core does not show major changes at that time. Pollen samples within the Matuyama (dots, fig. 4A) are somewhat lower in maximum TCT frequency and somewhat higher in minimum pine frequency, but they display the same basic pattern as that displayed by the samples from the Gauss (open hexagons, fig. 4A).

The strong inverse relationship between pine and TCT pollen in the Pliocene sediments of the Tulelake core (fig. 4A) is distinctly different from the pattern recorded in the section of the core that spans the past 1 m.y. (fig. 4B), but is generally similar to the pattern observed in Holocene deposits at Hodgdon Ranch, lat 38° N., on the lower western slope of the Sierra Nevada in Yosemite National Park (fig. 4C; Adam, 1967), and to selected parts of the upper Pleistocene pollen record from Clear Lake, Lake County, California, lat 39° N. (fig. 5; Adam, 1988). A reasonable assumption is that regional environmental conditions at ancient Tule Lake (lat 42° N.) between about 3 and 2 Ma were more similar to conditions on the lower western slope of the Sierra Nevada today and to the regional environment around Clear Lake during the cooler parts of the last glacial cycle (roughly the last 125,000 yr) than they were to modern conditions near the town of Tulelake.

At Hodgdon Ranch (elevation 1,400 m), increases in TCT pollen at the expense of pine pollen were interpreted by Adam (1967) to represent warming during middle Holocene time; the increase in TCT pollen was attributed to an upward migration of the ecotone between a lower elevation forest dominated by *Calocedrus decurrens* (incense-cedar) and a higher elevation pine forest. The Hodgdon Ranch section is not entirely satisfactory as a modern analog for the Tulelake Pliocene section, because it is from valley-bottom alluvial fill in a fairly small meadow, whereas both the diatom evidence and the regional geomorphology at the Tulelake site indicate that the Pliocene sediments there were deposit-

ed in a large basin much like the modern one, so that surrounding forests must have been at least several kilometers away, across a stretch of open water.

A better geomorphic analog is represented by the Clear Lake section, which records regional climatic history near the middle of a large lake during the past 130,000 years (Adam, 1988). The pollen rain at Clear Lake (elevation 400 m) has been dominated by oak pollen throughout the Holocene; conifer pollen is dominant only at higher elevations. During the cooler parts of the last glacial cycle, however, the oaks in the Clear Lake basin were largely or entirely displaced by a mixed coniferous forest. The pattern displayed by the full set of observations of pine and TCT percentages (fig. 5A) does not match the Tulelake Pliocene pattern displayed in figure 4A, but there is considerable overlap in the two distributions. When the samples from the warm intervals (thermomers) dominated by oak (*Quercus*) pollen at Clear Lake are excluded, the comparison is much better (figs. 5B, C). The cooler intervals (cryomers) at Clear Lake during the past glacial cycle appear to provide a reasonably good match for the regional conditions that prevailed at ancient Tule Lake during the late Pliocene (figs. 4A, 5D).

We assume that the same general biogeographic model used at Hodgdon Ranch and Clear Lake can be used for the Pliocene section at Tulelake. According to this model, the belt of highest percentages of TCT pollen is found at elevations below the belt of highest pine pollen percentages, so increases in the ratio of TCT to pine pollen correspond to upslope migrations of the ecotone between the two belts and, by inference, to warming and (or) drying conditions.

If this model is correct, then the ratio of TCT to pine pollen may be used as a proxy measure of relative warmth and (or) dryness. The smoothed curve for TCT:*Pinus* in figure 3 shows a weighted three-level moving average of the observations. Using the model described above, we infer from the pollen data a period of relative warmth that began about 2.8 Ma and persisted until shortly after 2.6 Ma. The magnitude of the inferred temperature oscillations is not known.

An alternative interpretation would attribute the TCT pollen in the Tulelake core primarily to *Juniperus occidentalis* (western juniper), which currently forms extensive open woodlands to the south of Tulelake (Küchler, 1977). However, *Artemisia* (sagebrush) is a major associate of western juniper in the juniper woodlands, and there was no apparent increase in *Artemisia* pollen to accompany the higher TCT frequencies during the Pliocene (fig. 2). Also, because Tule Lake was probably a fairly large lake, the pollen record probably represents the vegetation over a large area, and it seems unlikely that a relatively sparse juniper woodland could produce enough pollen to supplant pine as a dominant pollen type over a wide area, given the prodigious amounts of pollen produced by most pines and the ability of pine pollen to disperse widely by air transport. For these reasons, we prefer to interpret the TCT pollen record of the Tulelake Pliocene section as representing primarily *Calocedrus*.

One of the most striking features of the Pliocene pollen record in the Tulelake core is the extent to which it is dominated by pine and TCT pollen. The vegetation surrounding the lake must have been coniferous forest, which contrasts sharply with the sagebrush steppe that Küchler (1977) mapped as the present natural vegetation of the lower parts of the Tule Lake basin. The climatic rain shadow of the southern Cascade Range makes the modern climate at Tulelake quite arid; only at elevations well above the valley floor is there enough precipitation to sustain a vigorous conifer forest. It is likely that aridity was not as pronounced during the late Pliocene in the Tulelake area as it is today. Volcanic, tectonic, and climatic causes probably all contributed to a more humid climate, but we lack the data to determine to what extent each factor operated.

## Diatoms

The dominant diatoms in the Tulelake core consist of species of *Fragilaria, Aulacoseira,* and *Stephanodiscus* (fig. 3). At some levels, especially near the base of the core, *Cyclotella elgeri* and related forms are common.

Three major diatom zones characterize the Tulelake paleolimnological record between 3.0 and about 2.4 Ma: a basal zone, 3.0 to 2.9 Ma, dominated by *Stephanodiscus*; an intermediate zone, 2.9 to 2.65 Ma, characterized by *Aulacoseira solida* (=*Melosira solida* Eulenstein);

and an upper zone, 2.65 to 2.4 Ma, dominated by *Fragilaria* (fig. 3). After 2.4 Ma, *Aulacoseira solida* again dominated, but the trend was interrupted by significant percentages of *Cyclotella bodanica* between about 2.08 and 2.03 Ma (215 to 210 m depth). *Aulacoseira solida* returned to dominance by 2.02 Ma, but at the end of the Pliocene, *Fragilaria* species became dominant once more (fig. 3).

The large, heavily silicified *Stephanodiscus* species at the base of the Tulelake core are unidentified but are closely related to *S. asteroides* Gasse, *S. carconensis* Grunow, and *S. subtransylvanicus* Gasse. The taxonomy of these species is unresolved, and its resolution will require detailed scanning electron microscope work because the forms vary morphologically, perhaps in relation to nutrient supplies (for example, Theriot and Stoermer, 1984; Hakansson, 1986). For the purposes of this paper, these forms are referred to simply as *Stephanodiscus*, and the assumption is made that because they are morphologically similar, they have similar nutrient requirements and paleolimnological significance (for example, Kilham and others, 1986).

*Aulacoseira solida* and *Stephanodiscus* (identified as *S. carconensis*) live today in Lake Biwa, Japan (Mori, 1975; Mori and Horie, 1975, 1984). Their paleolimnological significance can be tentatively inferred from their occurrence in that lacustrine system, although in recent years *S. carconensis* has become rare in Lake Biwa, perhaps as a result of pollution (Nakanishi, 1984). The Lake Biwa *Stephanodiscus* blooms between January and March, whereas *Aulacoseira* (= *Melosira*) *solida* thrives in November, December, and April (Negoro, 1960).

The diatom succession of Lake Biwa has not been studied in relation to lake circulation and nutrient fluxes, but the temporal distribution of the dominant species fits with current ideas on the relationship between diatom abundance and lake nutrient dynamics. The growth of *Stephanodiscus* is known to be favored by high phosphorus:silicon ratios (Kilham and others, 1986). Phosphorus enters lake water most readily by dissolution from anoxic sediments and decomposition of organic remains during periods of stagnation. Thus, the growth of *Stephanodiscus* is likely to be favored in a lake that is stratified for part of the year—a dimictic lake that freezes in the winter, for example—giving the stagnant (anoxic) bottom waters time to acquire abundant phosphorus. *Stephanodiscus* will bloom when this phosphorus-rich water is brought to the surface, during spring, for example, when vertical mixing resumes. The nutrient requirements of *Aulacoseira* are not so well known, but *Aulacoseira* tends to be abundant in turbulent lakes, possibly because turbulence continually brings nutrient-rich bottom waters to the surface and because it keeps the diatoms in the photic zone. In any case, *Aulacoseira* will be favored in lakes that experience substantial vertical mixing throughout the open-water season.

Lake Biwa is a warm monomictic lake. Typically, such lakes begin to circulate when falling autumn air temperatures cool the epilimnion and the thermocline deepens. As water from the hypolimnion is brought to the photic zone, nutrients (nitrogen, phosphorus, and silicon) become available for diatom growth. At Lake Biwa, the increased turbulence and availability of nutrients, especially silicon, appear to provide conditions favorable for *Aulacoseira solida*, which dominates the lake in November and December. Its heavy cells presumably extract silicon rapidly from the lake water during those months. Progressively deeper mixing prob-

ably occurs in midwinter (January and February) and supplies additional nutrients, including phosphorus from the profundal zone of the lake. At that time, phosphorus:silicon ratios are likely to be high and thus to facilitate the bloom of *Stephanodiscus* that occurs between January and March. The observed increase in *A. solida* in April may result in part from nutrients, especially silicon, supplied by runoff during the early spring (Kotoda and Mizuyama, 1984; Koyama and others, 1984).

In this Lake Biwa scenario, any climatic change toward warmer winters would permit more continuous vertical mixing and thus favor *Aulacoseira solida*. Climat-
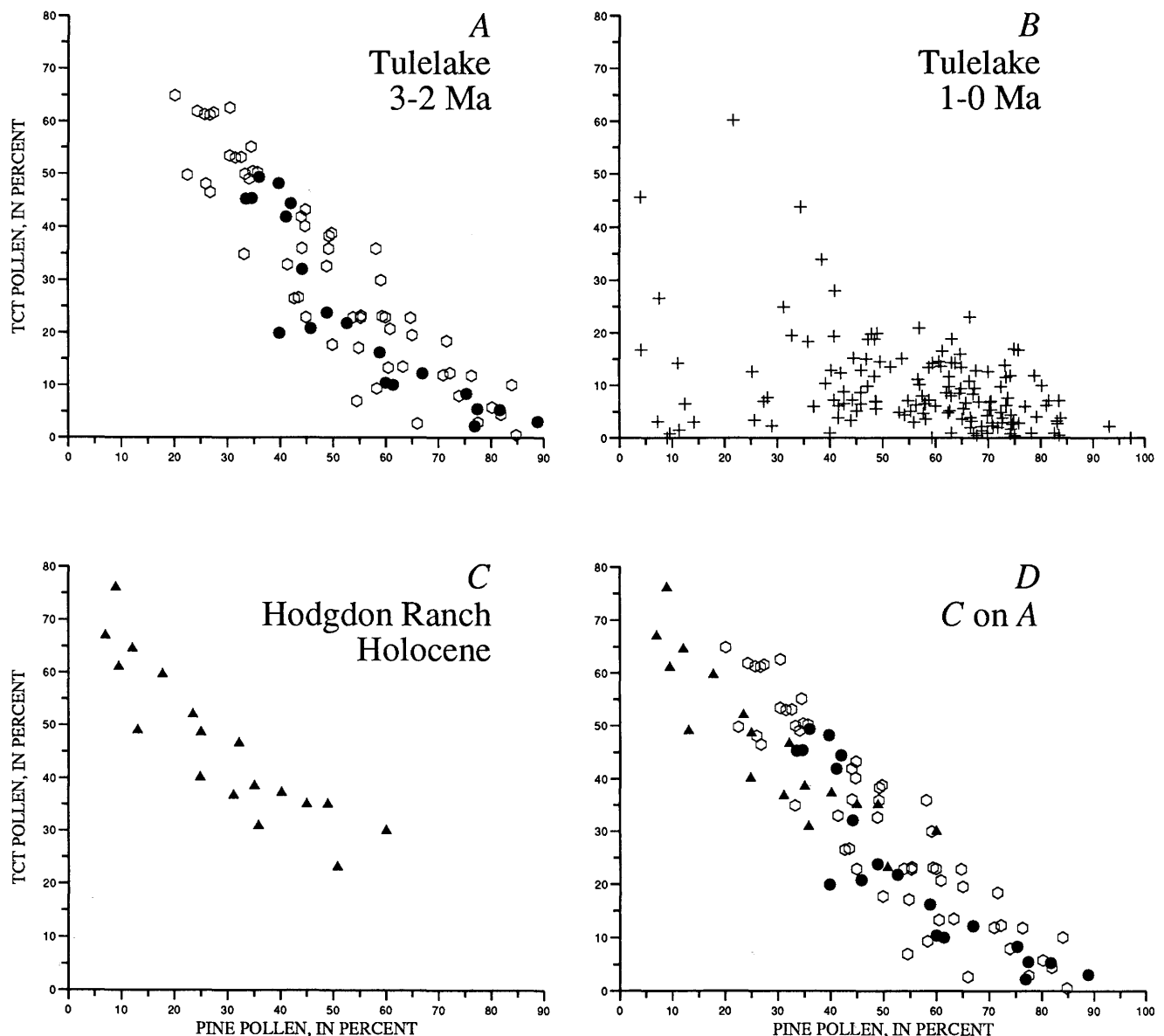
**Figure 4.** Pine pollen plotted against TCT (Taxodiaceae, Cupressaceae, and Taxaceae) pollen, both expressed as percent of total pollen. *A*, Tulelake, Siskiyou County, California, 3 to 2 Ma. Open hexagons represent samples within Gauss Normal Polarity Chron (>2.48 Ma), and dots repre-

sent samples within Matuyama Reversed Polarity Chron (<2.48 Ma); *B*, Tulelake, 1 Ma to present; *C*, Hodgdon Ranch, Yosemite National Park, California, Holocene (Adam, 1967); *D*, superimposition of *C* on *A*.

ic change toward colder winters would produce a period of stagnation while the lake lay frozen and stratified; this period would allow bottom waters to become rich in phosphorus and enable the growth of *Stephanodiscus* when the lake circulated again in the spring. The stratigraphic record of Lake Biwa supports this hypothesis: *A. solida* predominates today and dominated during the warm climate phases of the Holocene, whereas *Stephanodiscus* dominated the colder late Pleistocene levels (Mori and Horie, 1984). Pollen studies of the Lake Biwa core (Fuji, 1976) suggest a 7 °C lowering of mean annual temperature about 25 ka when *Stephanodiscus* dominat-

ed this record (see also Tsukada, 1986), and it is quite probable that Lake Biwa froze in the winter and became a dimictic lake at that time.

The general character of the Lake Biwa diatom record, with its alternation between an *Aulacoseira*-dominated warm monomictic lake during warm periods and a *Stephanodiscus*-dominated dimictic lake during cooler periods, makes it a reasonable qualitative analog for the Tulelake diatom record, even though the exact climatic and limnologic characteristics of Lake Biwa during the late Quaternary may not match those of Tule Lake in the Pliocene. Although the dominant species of
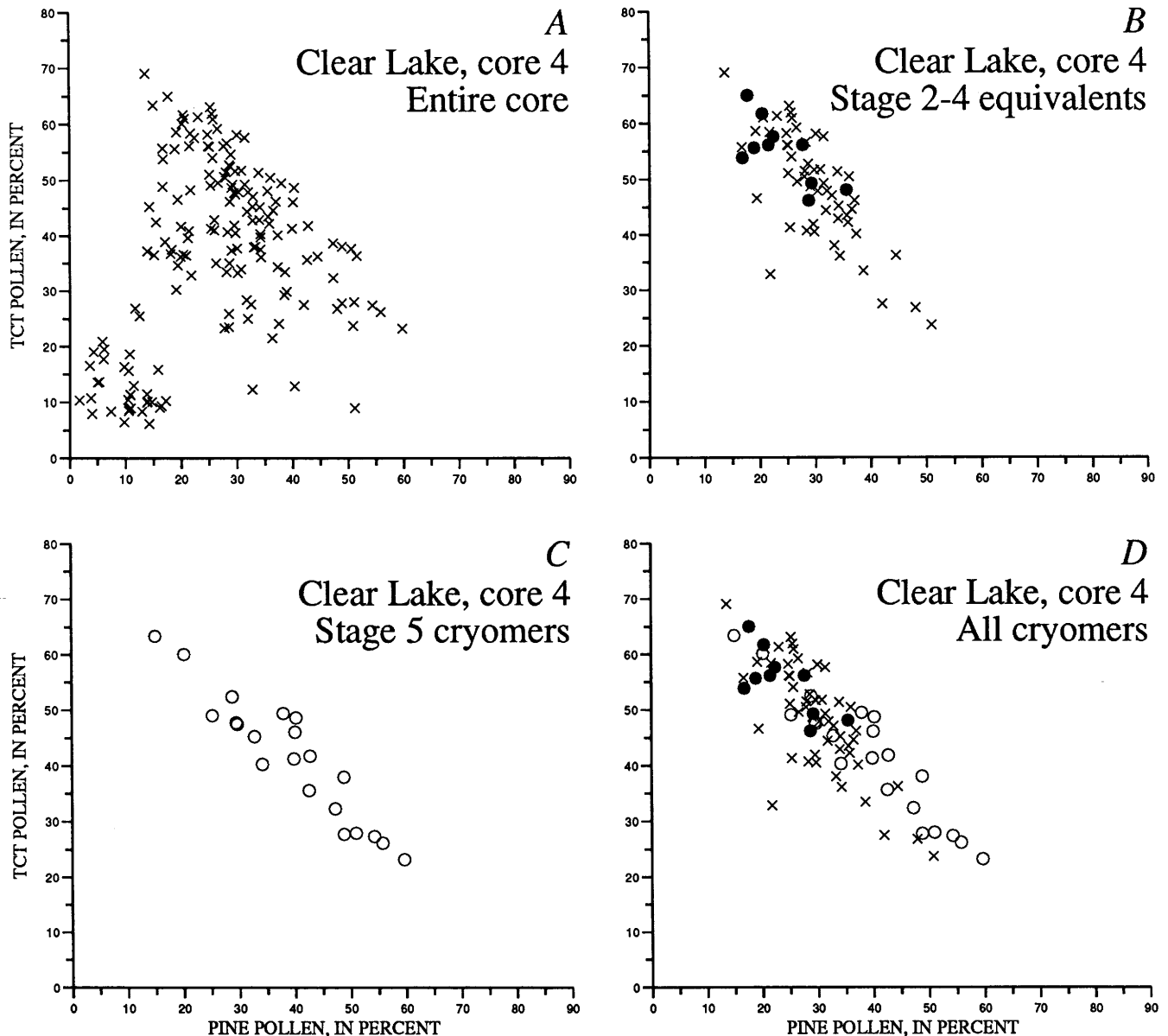


**Figure 5.** Pine plotted against TCT (Taxodiaceae, Cupressaceae, and Taxaceae) pollen for Clear Lake, Lake County, California, core 4, (130 to 0 ka) (Adam, 1988). Variables expressed as percent of total pollen. *A*, all of core 4; *B*, middle and late Pomo cryomers, correlative with deep-sea oxygen isotope stages 2–4 (solid dots represent the Halika thermomers, which are subunits within the middle Pomo cryomer); *C*, Tsiwi cryomers, correlative with the cooler parts of deep-sea oxygen isotope substages 5a through 5d; *D*, superimposition of *B* and *C*.

Quaternary diatoms at the two lakes are different, the genera are the same: *Aulacoseira* dominated the Holocene and *Stephanodiscus* the late Pleistocene at both Lake Biwa and Tule Lake. From the Lake Biwa analogy, we infer that a warm climate prevailed at Tule Lake between 2.9 and 2.65 Ma, whereas colder climates were dominant between 3.0 and 2.9 Ma. Within the colder interval, one distinct climatic reversal to warm, mild winters occurred between 2.96 and 2.94 Ma (fig. 3).

The section of the Tulelake core that spans the period from 2.65 to 2.4 Ma is dominated by *Fragilaria* species (principally *F. pinnata*, *F. construens* and varieties, and *F. brevistriata*). These benthic diatoms live loosely attached to submerged aquatic vegetation or to sand grains in the shallow, sunlit areas of lakes. However, they can become opportunistically planktonic with sufficient turbulence and enter shallow, open-water environments far from shore. Plankton and modern surface sediment samples of Upper Klamath Lake, Oregon, about 56 km northwest of the Tule Lake basin, are commonly dominated by these *Fragilaria* species (fig. 6).

Today, Upper Klamath Lake has a mean depth of about 2.5 m and an area of 31,000 ha (Sanville and others, 1974). This lake is in the same structural basin (a graben) as was ancient Tule Lake and in the past may have been part of the same lacustrine system (for example, Dicken, 1980). Therefore, present-day Upper Klamath Lake makes a reasonable analog for *Fragilaria*-dominated intervals in the Tulelake core. By this analogy, Tule Lake was a shallow, eutrophic, marsh-fringed freshwater lacustrine system between 2.65 and 2.4 Ma.
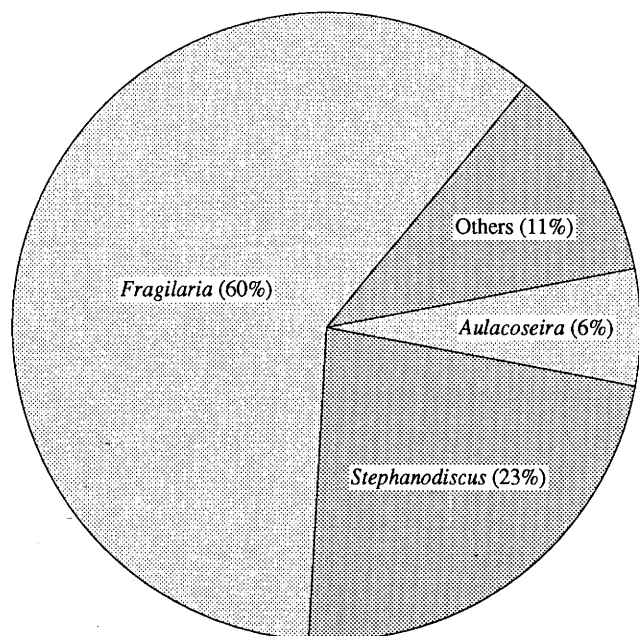
*Fragilaria* species were especially abundant between 2.4 and 2.3 Ma (inferred from a single sample at 227 m, fig. 3). The diatoms within this interval are poorly preserved and suggest unusually low lake levels and therefore dry conditions at this time. In some marine records (for example, Shackleton and others, 1984), high $\delta^{18}O$ values and low carbonate percentages between 2.4 and 2.3 Ma suggest a brief period of increased continental ice volume. Because dry and cold conditions characterized some climates during the Wisconsin full glacial period in the northwestern United States (Barnosky and others, 1987), it is possible that some Pliocene glacial climates were also dry. Perhaps the Tulelake and marine records from 2.4 to 2.3 Ma correspond to and reflect global cooling.

The reappearance of *Aulacoseira solida* after 2.3 Ma indicates the return of higher lake levels and generally warm climatic conditions until near the close of the Pliocene. *Cyclotella bodanica* first appears in the Tulelake core at about 217 m, or shortly before 2.0 Ma. Today this species characterizes temperate and north temperate lakes with reasonably abundant precipitation, cold winters, and warm summers. In Finland and northern Europe it is typically found in relatively deep, transparent, oligotrophic lakes (Huber-Pestalozzi, 1942; Molder and Tynni, 1968). The closely related species *Cyclotella comta* lives in similar habitats in Minnesota (Brugam, 1983). The presence of *Cyclotella bodanica* near the top of the Pliocene in the sediments of the Tulelake core may record a shift to cooler and moister climates that presaged the climate of some parts of the Pleistocene.

As at 2.4 Ma, marine oxygen-isotope records also reflect glacial climates around 2.0 Ma (for example, Shackleton and others, 1984). In the Tulelake record, however, the inferred climatic changes are not the same as those at 2.4 Ma, demonstrating that the continental climatic response to glaciation can be variable. Other long paleolimnological records will be required to document this variability through space and time before it can be explained in climatic terms.

At the generic level, changes in the diatom stratigraphy of the Tulelake core between 3.0 and 2.4 Ma are similar in character to changes at the Pleistocene-to-Holocene transition both at Tulelake and at other sites, for example at Clear Lake, California (Bradbury, 1988). These similarities indicate that Pliocene terrestrial limnologic and climatic changes were not drastically different from Quaternary climatic changes. They were somewhat different, however, because the planktonic diatom species dominant in ancient Tule Lake between 3.0 and 2.4 Ma do not live there today but disappeared from this record by 1.4 Ma.

*Aulacoseira solida* was present in Clear Lake, California (lat 39° N.), until about 100 ka. Lake Biwa (lat 35° N.), however, still contains *Aulacoseira solida*. The *Steph-*



**Figure 6.** Mean percentages of diatom groups in plankton and surface sediment of Upper Klamath Lake, Oregon (based on data from 3 samples).

Fragilaria (60%)

Others (11%)

Aulacoseira (6%)

Stephanodiscus (23%)

*anodiscus* species there is also quite similar to the Tulelake and Clear Lake forms and invites the comparison of these respective limnologic environments. Lake Biwa has been a stable, deep lacustrine environment for more than 500,000 years (Ueno, 1975; Nishimura and Yokoyama, 1975), whereas the paleolimnologic records at both Tulelake (Adam and others, 1989) and Clear Lake (Sarna-Wojcicki and others, 1988) include hiatuses that probably resulted from desiccation and absence of lacustrine deposition (for example, Bradbury, 1988). Such desiccation events, whether resulting from climate change or from tectonism, caused the local extinction of planktonic diatoms. Repopulation of the lakes by the same species could occur only under climatic and (or) limnologic environments closely similar to previous conditions. The permanent disappearance of these species from the Clear Lake and Tulelake records probably indicates changes to inhospitable climatic and (or) limnologic conditions following desiccation events. In contrast, climatic and limnologic change at Lake Biwa was not so extreme as to permanently eliminate populations of *Aulacoseira solida* and *Stephanodiscus* (for example, Ueno, 1975), although these populations fluctuated in abundance, apparently under the effects of modest climate change on lake circulation (Mori, 1974).

The abundance of *Aulacoseira* during the warm climatic interval at ancient Tule Lake from about 2.9 to 2.6 Ma implies a deep, warm monomictic lake. According to Hutchinson and Löffler (1956, fig. 1), modern warm monomictic lakes are not found farther than 40° from the equator, except near sea level. We see no reason to postulate a low elevation for the Tule Lake basin (lat 42° N.) during the late Pliocene; rather, we infer that the Pliocene climate recorded by the Tulelake core has its best modern analogs at lower latitudes. Pliocene climatic conditions at ancient Tule Lake must have required substantially increased annual precipitation and mean annual temperatures warmer and more equable than present. By analogy with Lake Biwa, Japan (mean annual temperature about 14 °C), the Tulelake area (present mean annual temperature about 9 °C) may have been about 5 °C warmer in the late Pliocene than at present. Higher sea levels implied by oxygen isotope records at 2.8 Ma (Shackleton, 1986), different circulation patterns in the North Pacific from those at present (Sancetta and Silvestri, 1986), and reduced rain shadow effects (lower elevations of the Coast Ranges) may have combined to create these climatic conditions.

## DISCUSSION

Comparison of the pollen and diatom records for the Pliocene section of the Tulelake core indicate general agreement that a relatively warm interval occurred between about 2.9 and 2.6 Ma. The lake in the basin was fairly deep and monomictic, so winter temperatures must have been much milder than at present. The proposed modern and Pleistocene analogs for the fossil pollen spectra lie within a Mediterranean climate, several degrees of latitude south of Tulelake, and above the low-elevation band of high frequencies of oak (*Quercus*) pollen. The general absence of spruce (*Picea*) pollen in the pollen spectra is also consistent with a Mediterranean climate and indicates that summers were dry.

Although the pollen and diatom records are in general agreement in recording a pronounced warm interval between about 2.9 and 2.6 Ma, some changes in the diatom record occurred tens of thousands of years earlier than changes of similar magnitude in the pollen record (fig. 3). These lags indicate that the limnological system and the regional vegetation responded differently to environmental changes. In particular, changes in basin morphology and sill depths may have produced changes in the heat storage capacity and chemical behavior of the lake that caused the lacustrine system to behave independently of climate. Tectonic, volcanic, or depositional processes could all have thus affected the lake.

On the basis of $\delta^{18}O$ analyses of foraminifers of the *Globorotalia inflata* group, Loubere and Moss (1986, fig. 2) proposed a warm interval between 3.2 and 2.4 Ma for DSDP Site 548 in the North Atlantic. This warm interval also affected the limnology of ancient Tule Lake and the composition of the regional forest in the surrounding area, as inferred from pollen and diatom stratigraphy in the Tulelake core. Although Loubere and Moss do not present a detailed time scale for their warm interval, the brief cool interval that appears at the top of their core 25 may well correlate with the relatively cool interval at about 2.7 Ma that is found in the Tulelake record in both the TCT:*Pinus* and *Aulacoseira solida* curves (fig. 3).

The Tulelake warm period lies within the Gauss Normal Polarity Chron (Adam and others, 1989) and can be correlated on that basis with the Reuverian deposits of the Netherlands. The Reuverian B deposits record a three-part warm interval consisting of two thermomers separated by a cryomer (Zagwijn, 1974; Suc and Zagwijn, 1983, fig. 2). This sequence may be correlative with the similar sequence observed in the Tulelake record.

## SUMMARY

The Pliocene sequence in a core from the town of Tulelake, California, records a three-part warm period that occurred between about 2.9 and 2.6 Ma. Changes in regional vegetation, as recorded in the pollen record, are offset from the lacustrine changes recorded by the diatom record by tens of thousands of years. The three-part nature of the warm interval is consistent with other records from both continental and marine environments. A marked decrease in sedimentation rate is observed in

the Tulelake record near the time of the onset of glacial sedimentation observed in the North Atlantic at about 2.37 Ma. The pattern of variation of regional vegetation was not strongly affected at this time; however, significant changes, such as a sharp increase in the abundance of the diatom genus *Fragilaria*, did occur within the lacustrine environment.

# REFERENCES

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.

Adam, D.P., 1988, Palynology of two upper Quaternary cores from Clear Lake, Lake County, California: U.S. Geological Survey Professional Paper 1363, 86 p.

Adam, D.P., Sarna-Wojcicki, A.M., Rieck, H.J., Bradbury, J.P., Dean, W.E., and Forester, R.M., 1989, Tulelake, California—The last 3 million years: Palaeoclimatology, Palaeogeography, Palaeoecology, v. 72, p. 89–103.

Barnosky, C.W., Andersen, P.M., and Bartlein, P.J., 1987, The northwestern U.S. during deglaciation, vegetational history and paleoclimatic implications, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation, v. K–3 *of* The Geology of North America: Boulder, Colorado, Geological Society of America, p. 289–321.

Battarbee, R.W., 1973, A new method for the estimation of absolute microfossil numbers, with reference especially to diatoms: Limnology and Oceanography, v. 18, p. 647–653.

Bradbury, J.P., 1988, Diatom biostratigraphy and the paleolimnology of Clear Lake, Lake County, California, *in* Sims, J.D., ed., Late Quaternary climate, tectonism, and sedimentation in Clear Lake, Northern California Coast Ranges: Geological Society of America Special Paper 214, p. 97–129.

Brugam, R.B., 1983, The relationship between fossil diatom assemblages and limnological conditions: Hydrobiologia, v. 98, p. 223–235.

Cleghorn, J.C., 1959, Historic water levels of Tulelake, California-Oregon, and their relation to the petroglyphs: Klamath County Museum Research Papers, No. 1, 10 p.

Dicken, S.N., 1980, Pluvial Lake Modoc, Klamath County, Oregon, and Modoc and Siskiyou Counties, California: Oregon Geology, v. 42, no. 11, p. 179–187.

Donnelly-Nolan, J.M., and Champion, D.E., 1987, Geologic map of Lava Beds National Monument, northern California: U.S. Geological Survey Miscellaneous Investigations Map I–1804, scale 1:24,000.

Fuji, N., 1976, 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: Otsu, Japan, Kyoto University, p. 316–356.

Hakansson, Hannelore, 1986, A taxonomic reappraisal of some *Stephanodiscus* species (Bacillariophyta): British Phycological Journal, v. 21, p. 25–37.

Heiken, Grant, 1981, Holocene Plinian tephra deposits of the Medicine Lake highland, California, *in* Johnston, D.A., and Donnelly-Nolan, Julie, eds., Guides to some volcanic terranes in Washington, Idaho, Oregon, and northern California: U.S. Geological Survey Circular 838, p. 177–181.

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

Hotchkiss, W.R., 1968, A geologic and hydrologic reconnaissance of Lava Beds National Monument and vicinity, California: U.S. Geological Survey open-file report, 30 p.

Huber-Pestalozzi, G., 1942, Das Phytoplankton des Süßwassers; Systematik und Biologie, *in* Thienemann, A., ed., Die Binnengewässer, v. xvi, Teil 2, Hälfte 2: Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung, p. 367–549.

Hutchinson, G.E., and Löffler, H., 1956, The thermal classification of lakes: Proceedings of the National Academy of Sciences, v. 42, p. 84–86.

Kilham, Peter, Kilham, S.S., and Hecky, R.H., 1986, Hypothesized resource relationships among African planktonic diatoms: Limnology and Oceanography, v. 31, p. 1169–1181.

Kotoda, Kazuo, and Mizuyama, Takayuki, 1984, Water balance, *in* Horie, Shoji, ed., Lake Biwa: Dordrecht, Netherlands, Dr. W. Junk, p. 165–174.

Koyama, Mutsuyo, Kawashima, Munetsugu, and Takamatsu, Takejiro, 1984, Inorganic chemical aspects, *in* Horie, Shoji, ed., Lake Biwa: Dordrecht, Netherlands, Dr. W. Junk, p. 257–271.

Küchler, A.W., 1977, The map of the natural vegetation of California [scale 1:1,000,000], *in* Barbour, M.G., and Major, Jack, eds., Terrestrial vegetation of California: New York, Wiley/Interscience, p. 909–938.

Loubere, Paul, and Moss, Kevin, 1986, Late Pliocene climatic change and the onset of Northern Hemisphere glaciation as recorded in the northeast Atlantic Ocean: Geological Society of America Bulletin, v. 97, p. 818–828.

Macdonald, G.A., 1966, Geology of the Cascade Range and Modoc Plateau, *in* Bailey, E.H., ed., Geology of Northern California: California Division of Mines and Geology Bulletin 190, p. 65–96.

McKee, E.H., Duffield, W.A., and Stern, R.J., 1983, Late Miocene and early Pliocene basaltic rocks and their implications for crustal structure, northeastern California and south-central Oregon: Geological Society of America Bulletin, v. 94, p. 292–304.

Mankinen, E.A., and Dalrymple, G.B., 1979, Revised geomagnetic polarity time scale for the interval 0–5 m.y. B.P.: Journal of Geophysical Research, v. 84, p. 615–626.

Molder, Karl, and Tynni, Risto, 1968, Über Finnlands recente und subfossile Diatomeen II: Bulletin of the Geological Society of Finland, v. 40, p. 151–170.

Mori, Shinobu, 1974, Diatom succession in a core from Lake Biwa, *in* Horie, Shoji, ed., Paleolimnology of Lake Biwa and the Japanese Pleistocene, v. 2: Otsu, Japan, Kyoto University, p. 247–254.

——1975, Vertical distribution of diatoms in core samples from Lake Biwa, *in* Horie, Shoji, ed., Paleolimnology of Lake Biwa and the Japanese Pleistocene, v. 3: Otsu, Japan, Kyoto University, p. 368–391.

Mori, Shinobu, and Horie, Shoji, 1975, Diatoms in a 197.2 meters core sample from Lake Biwa-ko: Proceedings of the Japan Academy of Sciences, v. 51, no. 8, p. 675–679.
——1984, Diatom analysis, in Horie, Shoji, ed., Lake Biwa: Dordrecht, Netherlands, Dr. W. Junk, p. 531–543.

Nakanishi, Masami, 1984, Phytoplankton, in Horie, Shoji, ed., Lake Biwa: Dordrecht, Netherlands, Dr. W. Junk, p. 281–290.

Negoro, Ken-ichiro, 1960, Studies on the diatom vegetation of Lake Biwa-ko (First report): The Japanese Journal of Limnology, v. 21, no. 3–4, p. 200–220.

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. 3: Otsu, Japan, Kyoto University, p. 138–142.

Ruddiman, W.F., and Raymo, M.E., 1988, Northern hemisphere climate regimes during the past 3 Ma; possible tectonic connections, in Shackleton, N.J., West, R.G., and Bowen, D.Q., eds., The past 3 million years; evolution of climatic variability in the North Atlantic region; a discussion: Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences, v. 318, no. 1191, p. 411–430.

Sancetta, Constance, and Silvestri, ShayMaria, 1986, Pliocene-Pleistocene evolution of the North Pacific ocean-atmosphere system, interpreted from fossil diatoms: Paleoceanography, v. 1, p. 163–180.

Sanville, W.D., Powers, C.F., and Gahler, A.R., 1974, Sediments and sediment-water nutrient interchange in Upper Klamath Lake, Oregon: Environmental Protection Agency Ecological Research Series, EPA 660/3–74-015, 45 p.

Sarna-Wojcicki, A.M., Meyer, C.E., Adam, D.P., and Sims, J.D., 1988, Correlations and age estimates of ash beds in late Quaternary sediments of Clear Lake, California, in Sims, J.D., ed., Late Quaternary climate, tectonism, and sedimentation in Clear Lake, northern California Coast Ranges: Geological Society of America Special Paper 214, p. 141–150.

Shackleton, N.J., 1986, The Plio-Pleistocene ocean—Stable isotope history, in Hsü, K.J., ed., Mesozoic and Cenozoic oceans: Geodynamics Series, American Geophysical Union and Geological Society of America, v. 15, p. 141–153.

Shackleton, N.J., Backman, J., Zimmerman, H., Kent, D.V., Hall, M.A., Roberts, D.G., Schnitker, D., Baldauf, J.G., Desprairies, A., Homrighausen, R., Huddlestun, P., Keene, J.B., Kaltenback, A.J., Krumsiek, K.A.O., Morton, A.C., Murray, J.W., and Westberg-Smith, J., 1984, Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region: Nature, v. 307, p. 620–623.

Suc, Jean-Pierre, and Zagwijn, W.H., 1983, Plio-Pleistocene correlations between the northwestern Mediterranean region and northwestern Europe according to recent biostratigraphic and palaeoclimatic data: Boreas, v. 12, p. 153–166.

Theriot, E.C., and Stoermer, E.F., 1984, Principal component analysis of character variation in Stephanodiscus niagarae Ehrenb.—Morphological variation related to lake trophic status, in Mann, D.G., ed., Proceedings of the 7th International Diatom Symposium, Philadelphia, 22–27 August, 1982: Koenigstein, West Germany, Koeltz, p. 97–111.

Tsukada, Matsuo, 1986, Altitudinal and latitudinal migration of Cryptomeria japonica for the past 20,000 years in Japan: Quaternary Research, v. 26, p. 135–152.

Turner, Stan, 1988, The years of harvest—A history of the Tule Lake Basin (2d ed.): Eugene, Oregon, 49th Avenue Press, 452 p.

Uéno, Masuzo, 1975, Evolution of life in Lake Biwa—A biogeographical observation, in Horie, Shoji, ed., Paleolimnology of Lake Biwa and the Japanese Pleistocene, v. 3: Otsu, Japan, Kyoto University, p. 5–13.

Zagwijn, W.H., 1974, Bemerkungen zur stratigraphischen Gliederung der plio-pleistozänen Schichten des niederländisch-deutschen Grenzgebietes zwischen Venlo und Brüggen: Zeitschrift des Deutsches Geologisches Gesellschaft, v. 125, p. 11–16.

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