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Reinterpretation of Late Quaternary Sediment Chronology of Lake Biwa, Japan, from Correlation with Marine Glacial–Interglacial Cycles

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A review of published stratigraphic records of pollen, sediment grain size, diatoms, and organic matter composition from Lake Biwa, Japan, identifies four pre-Holocene episodes of milder climate, increased surface runoff, and enhanced aquatic productivity, indicating intervals of warmer and wetter conditions which are interpreted as being interglacial. Correlation of these episodes to times of marine interglacial periods revises the age scale of the Lake Biwa sediment sequence which has been based on fission-track dating. The revised chronostratigraphic scale proposes an age of ca. 430,000 yr B.P. for the base of the 250-m-thick T Bed instead of the former age of ca. 700,000 yr B.P. ©1993 University of Washington.

INTRODUCTION

Japan's largest lake, Biwa-ko, has a geologically long history and has been the subject of many paleolimnological studies. Detailed investigations have been done on sediment, floral, and faunal contents, grain size distributions, mineralogy, physical and geophysical properties, and geochemistry (e.g., Horie, 1984). Determination of the age of various sediment depths has been attempted using a number of dating methods, but problems with these methods have complicated paleolimnogical reconstructions which ultimately depend on chronostratigraphy. We propose a new age scale for the late Quaternary sediments of Lake Biwa which we have devised by establishing a paleoclimatic linkage between the lacustrine sediment record and the well-dated marine record of glacial–interglacial cycles.

SEDIMENTARY RECORD OF LAKE BIWA

Lake Biwa is located on the island of Honshu between Kyoto and the Sea of Japan (Fig. 1) in the asymmetrically faulted Ohmi Basin. The lake has an area of 674 km^2 and a maximum water depth of 104 m. The main North Basin has two depressions >70 m deep and an average depth of 48 m, making much of the basin deep enough that bottom sediments are not easily disturbed by wave turbulence.

Lake Biwa has existed in its downfaulted basin for ca. 6 myr, although major tectonic movements have evidently occurred and have left their marks on the sedimentary record (e.g., Takemura, 1990). Deposition began in the predecessor of modern Lake Biwa to form the Miocene–Pleistocene Kobiwako Group, which is found uplifted in hills mostly to the south of the present lake but also to the west (Yokoyama, 1984). The history of the lake basin is generally one of deeper subsidence to the west accompanied by uplift along fault boundaries.

Sediment cores have been obtained (Table 1) from four sites within a 350-m-diameter area near the center of the southern depression in the North Basin (Fig. 1). Water depths at the four sites are between 65 and 70 m. Piston coring recovered 6 m of sediment in 1965 and 11.5 m in 1967. Drilling was done to a sediment depth of 200 m in 1971 and to a combined sediment plus basement rock depth of 1422 m during 1982–1983. Sediment recovery was poor in the upper 60 m of the latter core (Takemura, 1990). The existence of the four cores provides the opportunity to splice together the Lake Biwa paleolimnological record if a combined chronostratigraphy can be devised.

The 1982–1983 coring revealed that the southern basin of modern Lake Biwa contains five sedimentary units that total 911 m in thickness and which overlie Paleozoic–Mesozoic basement rocks (e.g., Takemura and Yokoyama, 1989; Takemura, 1990). The oldest of these units is Pliocene in age. The downward sequence consists of (1) the T Bed, a 250-m-thick unit composed of lacustrine deepwater clays; (2) the S Bed, a 332-m-thick unit

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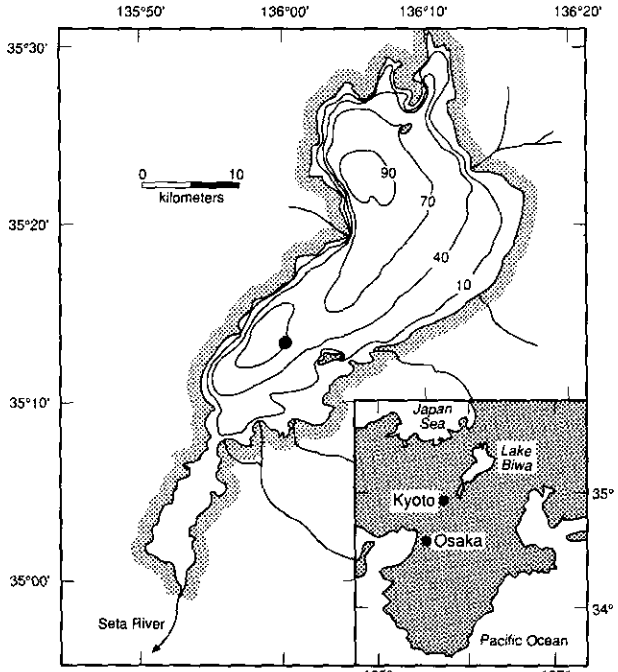

FIG. 1. Map showing location of Lake Biwa on Honshu, Japan, and general site of piston cores of 1965 and 1967 and of drilled cores obtained in 1972 and 1982–1983. Depth contours of the Northern Basin are in meters. The Southern Basin is less than 10 m deep. Mountains border the lake on the west and northeast; broad plains are present along most of the eastern shore. The major rivers entering the lake and the Seta River, the only river draining the lake, are shown.

containing alternations of shallow-water sands and silts; (3) the R Bed, a 150-m-thick unit made up of clay, sand, and gravel subunits representing fluctuating deep and shallow depositional conditions; (4) the Q Bed, a 72-m-thick unit composed of layers of silt, sand, and gravel laid down under shallow lacustrine or fluvial conditions; and (5) the P Bed, a 107-m-thick unit containing poorly sorted pebbles and gravels representing a fluviodeltaic environment. These units record stages in the drowning of a former lacustrine shore as the lake depocenter migrated to the northwest in response to tectonic rearrangements of the basin. The T Bed represents attainment of deep-lake depositional conditions which have prevailed since middle to late Pleistocene times with no major interruptions evident in either seismic or core records (Takemura, 1990). This unit has been the focus of Lake Biwa paleolimnological studies because of its apparent continuity.

CHRONOSTRATIGRAPHY

Various chronostratigraphic methods have been previously applied to the Lake Biwa sediment cores (Table 1). These include radiocarbon dating, tephrochronology, fission track dating of zircon crystals, and magnetostratigraphy (Takemura, 1990). ^{14}C dating is typically limited to sediments younger than ca. 30,000 yr; recycling of detrital carbon in lakes commonly renders ^{14}C ages 1000 to 2000 yr older than actual sediment ages (e.g., Stuiver, 1975; Rea *et al.*, 1980). The uncorrected radiocarbon age for the 11.5-m horizon of the 1967 piston core is 14,980 yr (Horie *et al.*, 1971), yielding an average sedimentation rate of ca. 0.84 m/yr.

TABLE 1

Cores Obtained from the Southern Depression of the North Basin of Lake Biwa for Paleolimnological Study

Year of coring	Type of core	Maximum depth (mblf)	Stratigraphic units encountered
1965	Piston	6.0	Lacustrine clays
1967	Piston	11.5	Lacustrine clays
1971	Drilled	200	Lacustrine clays
1982–83	Drilled	1422	0–250 m, Lacustrine clays (T Bed)
			250–582 m, Sands and Silts (S Bed)
			582–732 m, Clays sands and gravel (R Bed)
			732–804 m, Silt, sands and gravel (Q Bed)
			804–911 m, Pebbles and gravel (P Bed)
			911–1422 m, Paleozoic–Mesozoic basement rocks

Note. The core locations are within a 350 m diameter area approximated in Figure 1. Core depths given in meters below lake floor (mblf).

Tephrochronology is particularly useful in dating Japanese sediments. The volcanic activity characteristic of the Japanese Archipelago has produced multiple, widely dispersed layers of tephra and volcanic ash in the sediments of the lakes and marine waters around Japan. The major layers can be identified by their mineral and chemical compositions and by the refractive indices of their glasses. Table 2 includes 11 well-known tephra layers deposited in Japan during the late Quaternary, along with four other fission-track-dated ash layers from the drilled Lake Biwa cores. Taishi *et al.* (1986) integrated the fission track dates with porosity and compaction estimates to arrive at an age–depth curve. This age scale projects that the 250-m-thick T Bed represents ca. 700,000 yr of lake history, giving an average sedimentation rate of 0.36 m/1000 yr. As shown in Table 2, however, the relative uncertainty of the fission track ages of sediment is great. For example, the sediment horizon at 237 m may be as old as 950,000 yr or as young as 430,000 yr. This uncertainty seems to be a common problem for fission track dating of sediments less than 1 myr old.

Paleomagnetic measurements show normal polarity until a subbottom depth of 469 m, which is in the shallow-water S Bed (Torii *et al.*, 1986; Takemura, 1990). The continuity of this bed is uncertain, but if no major hia-

TABLE 2

Discordance of Radiocarbon Dates, Tephrochronology of Major Quaternary Ash Layers in Japan, and Fission Track Dating of Zircon Crystals from Other Ash Layers in the T Bed of Lake Biwa Sediments

Depth (m)	Core	Age (years)	Measurement
0.8	1965	1430 ± 95	Radiocarbon
4.5	1965	3650 ± 105	Radiocarbon
10	1982–1983	6300	Akahoya ash (Ah)
11.5	1967	14,980 ± 460	Radiocarbon
13	1982–1983	9300	Ulreung-Oki ash
26	1982–1983	140,000 ± 100,000	Fission track
27	1982–1983	25,000	Aira-Tanzawa ash (AT)
—	—	33,000 ± 2000	Yamato ash (Ym)
—	—	70,000 ± 3000	Aso-4 ash
37	1971	80,000 ± 26,000	Fission track
62	1971	110,000 ± 22,000	Fission track
82	1971	170,000 ± 31,000	Fission track
99	1971	180,000 ± 41,000	Fission track
110	1971	270,000 ± 63,000	Fission track
132	1982–1983	170,000 ± 100,000	Fission track
159	1982–1983	280,000 ± 130,000	Fission track
181	1971	460,000 ± 41,000	Fission track
182	1982–1983	450,000 ± 100,000	Fission track
237	1982–1983	690,000 ± 260,000	Fission track

Note. Radiocarbon dates are from Horie *et al.* (1971); fission track ages are from Nishimura (1984) and Takemura (1990). —, Not found.

tuses exist, then the magnetic reversal at 469 m corresponds to the Brunhes–Matuyama boundary of 730,000 yr B.P., and the base of the T Bed at 250 m must be considerably younger than this age. The average sedimentation rate to the Brunhes–Matuyama boundary at 469 m calculates to 0.64 m/1000 yr, but we suspect that the accumulation rates of the S Bed sand and gravel layers were faster than the deep water clays of the T Bed and more likely to be interrupted by erosion.

The results of the various direct methods that have been used to date the sediments of Lake Biwa give poor agreement (Table 2). The problem may arise partly from the procedures that could be used, partly from incomplete core recoveries, and partly from core-to-core variability. A more satisfactory age scale for these lake sediments clearly is needed. We have therefore sought evidence of climatic changes in the depositional history of the lake that could be correlated with the established marine chronostratigraphic record and could thereby lead to an improved Lake Biwa sedimentary age scale.

GLACIAL–INTERGLACIAL MARINE INFLUENCES ON JAPANESE CLIMATE

Ocean currents exert a large influence on the weather and climate of Japan (Heusser and Morley, 1990). The warm western boundary Kuroshio Current, also called the Japan Current, flows northward along the Pacific coast, turning eastward off central Honshu at about 36°N. The cold Oyashio, or Kurile, Current flows south to this latitude to meet the Kuroshio Current. This juncture, the North Pacific Polar Front, shifts farther to the south during glacial maxima (Thompson, 1981; Chinzei *et al.*, 1987). The modern climate of Japan is moist and mild. A rainy season associated with the east Asian monsoon exists during June and July. During the last glaciation, the climate was drier and cooler (Tsukada, 1983). For our correlation to the marine stratigraphic record, we assume that earlier glaciations were similar to the most recent, i.e., drier and cooler than the modern climate.

POLLEN RECORD OF PALEOCLIMATES IN JAPAN

The Japanese Archipelago has experienced major changes in plant distribution as a result of glacial–interglacial climatic cycles. Pollen-based reconstructions of past vegetation show predictably that cooler climates prevailed during glacial times (e.g., Tsukada, 1983, 1985; Sohma, 1984; Morley and Heusser, 1989). The magnitude of the cooling was greater in Hokkaido (9°C) than in Kyushu (6°C) because of the southward migration of the North Pacific Polar Front. Relatively stable glacial-age conditions existed from 80,000 to 20,000 yr B.P. (Heusser and Morley, 1985). During this time the climate of Japan was generally cold and wet, but with less precipitation than during interglaciations (Heusser and Morley, 1990). Coniferous forests covered most of Japan. Northward migration of the polar front by the beginning of the Holocene led to warmer conditions, and forests shifted to deciduous types ca. 10,000 yr B.P. (Sohma, 1984).

Precipitation patterns were modified by glacial–interglacial cycles. Although rainfall on the Pacific coast of Japan was equivalent to that of modern times because of proximity to relatively warm ocean waters, Tsukada (1983) concludes that land areas bordering the Sea of Japan received less rain during the last glaciation than they do today. The Sea of Japan was at least partially isolated from the Pacific by eustatic lowering of sea level and consequently had colder surface waters (Oba *et al.*,1991), thus contributing less moisture to the atmosphere during glacial times. In addition, Yasuda (1990) concludes that the southwest monsoons, which provide most of the summer precipitation to Japan, were weaker from 70,000 to 50,000 yr B.P., from 33,000 to 28,000 yr B.P., and from 25,000 to 13,000 yr B.P. During these times, drier and cooler climates existed, and coniferous forests prevailed.

The pollen records from the 1971 and 1982–1983 Lake Biwa cores provide an extended history of vegetational change in central Japan. Paleoclimatic reconstructions of Fuji (1980, 1983, 1986, 1988) employ the pollen contents of the T Bed and the age-scale of Taishi *et al.* (1986) to identify alternating warm and cold periods extending back an estimated 700,000 yr. Fluctuations in the concentrations of total pollen in the two cores are compared in Figure 2, along with the corresponding climate type inferred from the pollen assemblage present at the various core depths. Pollen concentrations are generally elevated when assemblages indicate that climates were mild or warm. Exceptions to this relationship are the mild interval between 40 and 50 m core depth, which is not accompanied by enhanced amounts of pollen, and the beginning of the cold interval between 145 and 170 m, which has high pollen concentrations in both cores.

Pollen concentrations in sediments depend on the type and abundance of plants, as well as on the transport of pollen from land areas to the lake. Each factor is affected by precipitation, especially transport. The pollen-concentration record in Lake Biwa sediments may be a gauge of paleo-precipitation, showing times of wetter climate and greater land runoff to the lake at core depths of 235 to 220 m, 170 to 160 m, 145 to 130 m, 95 to 70 m, and in the top 5 m. These core depths correspond to periods of warm or mild climate (Fig. 2). The pollen record in North Pacific sediments shows the present and preceding interglacial episodes to be wetter and milder than during the last glacial interval (Heusser, 1989; Heusser and Morley, 1985, 1990; Morley and Heusser, 1989). The five pollen concentration peaks present in the 1982–83 core probably record these two and three earlier interglacial conditions and thereby provide a paleoclimatic link between the marine and the Lake Biwa chronostratigraphic records.

THE DIATOM RECORD OF LAKE BIWA PALEOPRODUCTIVITY

The sediments of Lake Biwa contain less than 1% $CaCO_3$ (Horie *et al.*,1971) because the igneous bedrock of the surrounding watershed leaves the freshwater lake undersaturated with respect to preservation of biologically produced carbonates. The small carbonate component is detrital dolomitic limestone washed into the lake (Yamamoto, 1976). The microfossil floral record in Lake Biwa consequently consists principally of diatom cells.

The diatom assemblages reported for the 1971 core record several paleolimnological changes. The large centric diatom *Melosira solida,* for example, appears to be an indicator of enhanced productivity (E. G. Stoermer, personal communication, 1991). This species becomes dominant at four main levels in the 1971 core (Mori and Horie, 1975, 1884). These intervals are accompanied by increases in the number of total diatom cells per volume of sediment (Fig. 2), which can be another indicator of enhanced productivity. These episodes of enhanced productivity occur at core depths of 190 to 180 m, 140 to 130 m, 75 to 60 m, and in the top 20 m.

SEDIMENT GRAIN SIZE VARIATIONS

The majority of the sediments in the 1971 core have particle grain sizes in the clay range of 7 to 8 Φ (Yamamoto, 1984). The fraction of particles coarser than 4.5 Φ (silt) increases in sediments deposited slightly later

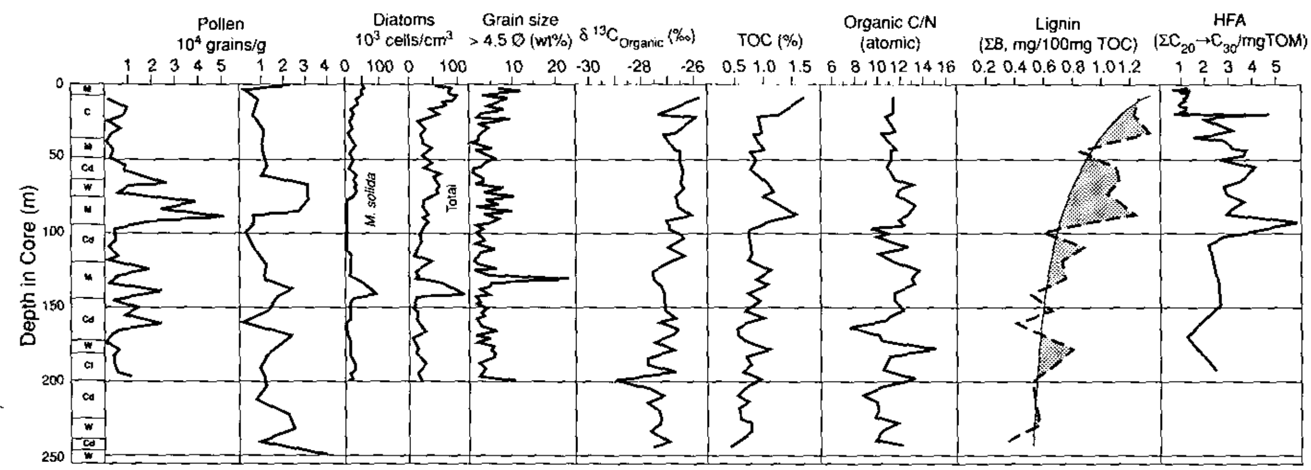

FIG. 2. Summary of information used to link the Lake Biwa sedimentary record to the marine chronostratigraphic record. Climate types inferred from pollen assemblages are shown (C and Cd, cold; Cl, cool; M, mild; W, warm). Pollen concentrations from the 1971 200-m core and the 250-m-thick T Bed of the 1982–1983 core are generally concordant. Pollen data are from Fuji (1980, 1983, 1986, 1988). Concentrations of diatom cells and of coarse particles are in the 1971 core. The diatom species *Melosira solida* is an indicator of enhanced aquatic productivity, as is total cell concentration. Particles coarser than 4.5 Φ are larger than 44 μm in diameter (silt) and record times of greater fluvial transport (Kashwaya *et al.*, 1987). Diatom productivity and coarse sediment roughly correlate. Data are from Mori and Horie (1975) and Yamamoto (1984). Organic carbon $\delta^{13}C$ values, total organic carbon (TOC) concentrations, and organic matter C/N ratios of sediments are from 250-m-thick T Bed of the 1982–1983 core. Data are from Nakai (1973, 1986). The sum of the eight major lignin components relative to TOC concentrations are Ishiwatari and Uzaki (1987). Postulated first-order degradation curve of lignin is shown; lignin concentrations in excess of the expected amount record higher contributions of land-derived organic matter. Higher contributions of long chainlength waxy fatty acids (HFA) to total organic matter (TOM) similarly record episodes of enhanced inputs of land-derived organic matter (Kawamura and Ishiwatari, 1984).

than at times of enhanced aquatic productivity (Fig. 2). The surrounding terrain is hilly and mountainous; thus, an increase in precipitation rates would increase the transport capacity of the streams and rivers feeding Lake Biwa (Kashiwaya *et al.*, 1987). Diatom maxima and increased grainsize show positive correlation, although slightly out of phase, which suggests that greater riverflow occurred approximately at the times of diatom abundance. Because dissolved materials from the watershed are an important source of nutrients to many lakes, the increases in diatom productivity may result from increases in regional precipitation, soil erosion, and rock weathering. Washout of nutrients contained in soils evidently preceded delivery of coarser detrital sediment particles as river transport capacity increased during wetter intervals.

ORGANIC CARBON STRATIGRAPHIC RECORD IN LAKE BIWA SEDIMENTS

The amount and isotopic composition of autochthonous carbon in sediments provide an integrated record of lacustrine biological carbon assimilation and production. Dissolution of biogenic carbonates and recycling of inorganic carbon occur within the Lake Biwa water column. The only important process removing carbon from the waters of this lake is burial of organic carbon in bottom sediments. Biota selectively take up ^{12}C during formation of organic matter, typically fractionating the isotopes by −20‰ from the isotopic content of the carbon source. When lake productivity is high, preferential biotic uptake of ^{12}C can shift the isotopic ratio of dissolved CO_2 toward heavier values, i.e., less negative $\delta^{13}C$ values (McKenzie, 1985; Hollander and McKenzie, 1991), and this isotopic shift ultimately appears in the organic carbon record.

Downcore changes in the organic carbon $\delta^{13}C$ values of Lake Biwa sediments have been reported by Nakai (1973, 1986). We present here data only from the T-bed of the 1982–83 core, because those from the 1971 core were affected by analytical problems that made them systematically too light (N. Nakai, personal communication, 1990). Variations in the two data sets are nonetheless similar, although displaced by ca. 8‰. Two types of changes appear in the organic carbon isotope ratios (Fig. 2). First, $\delta^{13}C$ values generally become heavier in younger sediments. Second, $\delta^{13}C$ values roughly covary with total organic carbon (TOC) concentrations and atomic C/N ratios.

Several possible causes of the shift toward heavier values in more recent times have been considered by Ishiwatari and Uzaki (1987). A progressive shift in the proportions of land-derived and aquatic contributions of organic matter is discounted on the basis of organic geochemical molecular evidence. Selective diagenetic removal of isotopically heavy components of the total organic matter can also be discounted, even though concentrations of organic carbon are lower where $\delta^{13}C$ values are lighter, because removal of a small amount of unrealistically heavy organic matter would be required. On the basis of kinetics of CO_2 photosynthetic uptake, Nakai (1972) proposes that progressive warming of the local climate has produced the observed shift to heavier, modern isotope ratios, but this hypothesis is not supported by pollen data (Fuji, 1988). Another possible explanation for the isotopic shift is a gradual increase in lake productivity, which is consistent with the general increases in the concentrations of diatom microfossils and TOC (Fig. 2) toward modern times. A fully satisfactory explanation of the isotopic shift remains to be found.

Relationships among fluctuations in $\delta^{13}C$, TOC concentration, and C/N are not as obvious as the depth-related isotopic trend. TOC concentrations and C/N values both increase between 70 and 100 m. The $\delta^{13}C$ is heaviest (−25.4‰) in concert with the peak of 1.56% TOC in this interval. This is consistent with a period of enhanced productivity in the lake. The higher C/N values reflect times of greater wash-in of land organic matter (Nakai, 1986), probably accompanied by dissolved nitrates and phosphates weathered from the watershed soils. This core interval corresponds to a time of mild-to-warm climate (Fuji, 1988). This relationship among elevated TOC concentrations, higher C/N ratios, and climate warming also appears at core depths of 130 to 140 m, 185 m, 240 m. At the 185-m event, $\delta^{13}C$ becomes heavier, as at the 70- to 100-m depth, but the isotope ratios become lighter in the other two warm periods. This is perplexing, and it is inconsistent with the expected pattern of heavier isotope values in times of enhanced lake productivity. The concentration and consequently the $^{13}C/^{12}C$ ratio of atmospheric CO_2 change between glacial and interglacial times, and the magnitude of these changes is not constant (Shackleton *et al.*, 1983; Shackleton and Pisias, 1985; Barnola *et al.*, 1987). Although the Lake Biwa isotope record would seem to be simplified by reflecting mainly organic carbon production, global factors such as changes in atmospheric CO_2 concentration may complicate the regional isotopic history of climate transitions. This problem remains unresolved.

ORGANIC BIOMARKERS AND PALEOCLIMATE INDICATORS IN LAKE BIWA SEDIMENTS

Organic matter present in lake sediments comprises the residue of former aquatic and watershed biota. Molecular investigations of the organic geochemical sedimentary record of Lake Biwa help identify biotic types significant to the paleoclimate history of this region (Ishiwatari and Ogura, 1984). We cite herein examples of fatty acid distributions and lignin composition specifically related to regional climate history.

Fatty acids are biosynthesized in a broad range of carbon chainlengths. Long chainlength biomarker compounds, having 24, 26, 28, and 30 carbon atoms, are created by land plants for use as waxy protective coatings on their leaves, stems, and flowers. Compounds having 14, 16, and 18 carbon atoms are principally synthesized by aquatic algae, but also by plants on land and by animals. These chainlength differences can be used in several ways. For example, the proportion of longchain acids can be used as an indicator of how much of the fatty acid fraction of sediment organic matter has been derived from land plants.

Kawamura and Ishiwatari (1984) divided the fatty acid contents of the Lake Biwa sediment core into short chainlength and long chainlength groups to identify paleosource changes. Concentrations of the shortchain acids are high in the top 20 m of the core and then decrease with depth. The high proportion of the short chainlength compounds agrees with the indication from diatom content that algal productivity has been enhanced during the past ca. 20,000 yr. Concentrations of long chainlength acids begin to increase at 20 m core depth and continue to do so to about 100 m, then return to values equivalent to near surface sediments (Fig. 2). The downcore plot of land plant fatty acid contributions to sediment organic matter resembles the pollen profile and to some degree follows the TOC profile.

An important and abundant component of the organic matter of vascular land plants is lignin, the macromolecular material that binds together the cellulose fibers of woody tissue. Like the longchain fatty acids, the amount of lignin in lake sediments is an indication of the proportion of organic matter derived from watershed biota. The concentration of lignin components relative to the total organic carbon content of T Bed sediments decreases irregularly with depth (Fig. 2). Ishiwatari and Uzaki (1987) interpret the general decrease in the lignin contribution as postdepositional diagenetic degradation. They calculate a half-life for lignin of 400,000 yr based on this assumption and the age scale of Taishi *et al.* (1986). We present a projected concentration curve based on the first-order degradation of lignin in Figure 2, assuming an unvarying land plant contribution. Lignin contributions in excess of the projected amounts are to the right of this curve. These excess amounts may be residues of larger-than-average deliveries of land-derived organic matter to Lake Biwa sediments. From core depths of 60 to 90 m, in particular, the lignin enhancements correlate with the long chainlength fatty acids in indicating increases in land plant organic matter in the lake sediments. An increase in land plant material can arise from increased runoff from land areas as a result of higher amounts of precipitation.

DISCUSSION

Annual precipitation in Japan varies considerably from place to place, but averages about 2 m near the Sea of Japan and 1.4 m near the Pacific coast (Hirao *et al.*, 1984). Pollen data indicate that during the last glacial age the annual rainfall decreased and temperatures fell (Heusser and Morley, 1985). These changes correlate with a decrease in sea-surface temperature as the Pacific Polar Front shifted southward (Thompson, 1981; Chinzei *et al.*, 1987). The absence of warm surface waters, which are required to warm air masses and to add large amounts of moisture to the air, produced the drier, cooler glacial climate of the Japanese Archipelago.

Many of the components of the T Bed sediments of Lake Biwa that would be enhanced by greater stream flow have several maxima corresponding to times of wetter interglacial climate. Mean grain size of sediment increases, presumably because transport capacities of rivers were greater during times of greater precipitation. Other indicators of greater amounts of land runoff are higher concentrations of pollen and, in the organic geochemical identifiers of more land-derived organic matter, the C/N ratio, the proportion of longchain fatty acids, and lignin concentrations. The concentrations of total organic carbon and of total diatom cells also increase during wetter times. Their values reflect the rate of aquatic productivity, which is accelerated by greater erosion of nutrients from watershed soils when precipitation increases during warmer interglaciations.

Figure 3 summarizes five intervals in the upper 250 m of Lake Biwa sediments which contain enhanced values of sediment parameters we interpret as indicative of increased runoff. One interval is at the top of the core and corresponds to the current interglaciation. Assuming that the deeper maxima represent earlier interglaciations, we postulate a revised time scale for the T Bed. Marine oxygen-isotope maxima, which correspond to interglaciations (Imbrie *et al.*, 1984), are correlated in this time scale with the onset of the four Lake Biwa intervals showing strongest indications of greater precipitation. The core depths in Lake Biwa and their corresponding marine time scale ages are: 85 to 90 m, 120,000 yr B.P.; 130 to 140 m, 240,000 yr B.P.; 180 to 185 m, 325,000 yr B.P.; 230 to 235 m, 400,000 yr B.P. This revised time scale predicts a basal age of ca. 430,000 yr B.P. for the T Bed, which is substantially younger than the ca. 700,000 yr estimated by Taishi *et al.* (1986).

We have four reasons for believing a younger basal age is more reasonable:

1. Taishi *et al.* (1986) assumed a constant linear sedimentation rate for the T Bed. They then adjusted this to compensate for compaction. We think the observed variation in grain size and the evidence for changing amounts of precipitation make a constant sedimentation rate unlikely, although determining mass accumulation rates remains unrealistic from the available data.
2. The only sediment ages available to Taishi *et al.* (1986) were the various dates listed in Table 2; these ages

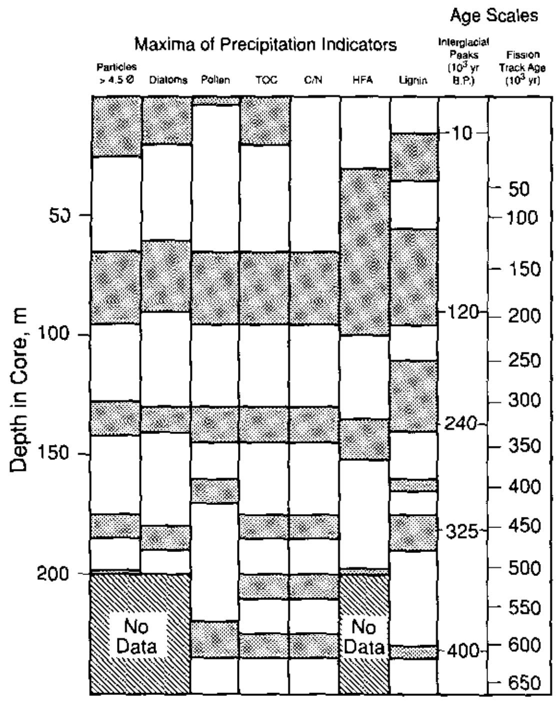

FIG. 3. Comparison of times of high precipitation as indicated by sediment components of Lake Biwa cores. Present conditions are wetter than those during the last glacial age, and four similar wetter episodes can be identified in the Pleistocene part of the section. Correlating these episodes with peak interglacial times recorded in marine sediments (Imbrie *et al.*, 1984) creates a revised age scale that is markedly younger than the fission-track-based age scale of Taishi *et al.* (1986). The proposed new age scale is compared here to the older one.

include substantial uncertainties in their age assignments. Our younger age scale actually fits within uncertainty ranges of most of these ages.

3. Paleomagnetic data show a reversal at 469 m subbottom in the S Bed (Torii *et al.*, 1986; Takemura, 1990). The continuity of the S Bed is not certain, but if it contains no major hiatuses, then the magnetic reversal at the 469 m depth corresponds to the Brunhes-Matuyama boundary of 730,000 yr B.P., and the base of the 250 m-thick T Bed must be considerably younger than this age.

4. Adams (1988) has examined the pollen data of Fuji (1983, 1986) and concludes that conditions corresponding to the last interglaciation (120,000 yr B.P.) existed during the time when sediments at ca. 80 m were deposited. Adams further notes conflicts with the fission track dates, which suggest an age of 170,000 yr for this pollen zone. Our revised chronology agrees with Adams' interpretation.

Our reinterpretation of the Lake Biwa chronostratigraphy has several implications. First, the sediment accumulation rates indicated by our correlations to the times of marine interglaciations are not constant over the last four glacial–interglacial cycles. Between 400,000 and 325,000 yr B.P., the rate averaged 0.67 m/1000 yr. It decreased to 0.56 m/1000 yr during the next younger cycle and decreased again to 0.39 m/1000 yr in the penultimate cycle. From 120,000 yr B.P. to the end of the last glacial event, the average rate was 0.68 m/1000 yr. Since the last glaciation, sediments have accumulated at 1.38 m/1000 yr. This variability may reflect actual changes in lake productivity and in erosion of surrounding countryside, but we recognize the dangers in overinterpreting linear sedimentation rates.

A second implication of the revised age scale is that the entire sediment column is younger than formerly believed. The absence of the prominent Yamato and Aso-4 ash layers from the sediments of Lake Biwa (Table 2) may be an artifact of incomplete core recovery, inasmuch as the upper 50 to 60 m of both drilled cores were not fully recovered. The Aso-4 layer, in particular, is widely distributed in Japan and surrounding marine sediments, such as near Lake Biwa in the Sea of Japan (e.g., Oba *et al.*, 1991). Our age scale would place these layers within the upper 50 m of the T Bed. This age adjustment should enable new correlations between the Lake Biwa sediment record and global glacial–interglacial paleoclimatic changes.

An important further implication of our reinterpretation is that it reinforces the critical need for new methods to obtain absolute age determinations in Quaternary sediments such as those cored from Lake Biwa. Advances in $^{40}Ar/^{39}Ar$ dating may help to solve this problem (A. N. Halliday and C. M. Hall, personal communication, 1991).

Detailed comparison of Holocene conditions in the 1982–1983 drilled Lake Biwa core to previous interglacial conditions is constrained by poor core recovery in the upper 60 m of this core. The enhanced concentrations of diatom cells in the upper 15 m of the 200-m core (Fig. 2) suggests, however, that lake productivity may have increased to its greatest levels after the beginning of the Holocene. This enhancement may be partly because of human activities. Agriculture began to disrupt natural ecosystems in Japan beginning ca. 2000 yr B.P. (Yasuda, 1990), when anthropogenic factors added other elements of complexity to interpreting lacustrine sedimentary records of climate change here and elsewhere.

SUMMARY AND CONCLUSIONS

Our review of paleolimnologic information from Lake Biwa sediment cores clarifies potential glacial–interglacial signatures of climate change in Japan. The signatures and their consequence are:

1. Four episodes of greater precipitation typical of the Holocene interglaciation are recorded in the 250-m-thick T Bed of Lake Biwa sediment. They are indicated by increased sediment grain size, enhanced aquatic productivity from land-eroded nutrients, and larger amounts of washed-in pollen and land-derived organic matter.

2. Correlation of the lake record to the marine record of past interglaciations enables us to propose an improved age scale for the Lake Biwa sediment record. The basal age of the T Bed is estimated to be ca. 430,000 yr, significantly younger than the previous estimate of ca. 700,000 yr.

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