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Diatom abundance in Lake Aoki sediment as a proxy in demarcating the timing of the last Glacial-Holocene transition in central Japan

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ABSTRACT

A 15 m long sediment core from Lake Aoki, central Japan was investigated for its diatom abundance to determine if the abundance change with time provides a reasonable basis to reconstruct the timing of the last Glacial-Holocene climate shift in central Japan. Silty clay dominated the sediment lithology, and the tephra and radiocarbon based age determinations provided an excellent sediment chronology extending back to the beginning of the lacustrine sedimentation ca. 43 ka cal BP. The diatom abundance in the sediment showed a marked change at 13 ka cal BP, with a mean concentration of ca. 1.8×10^5 frustules mg^{-1} dry sediment before and ca. 10.3×10^5 frustules mg^{-1} dry sediment after that time. This abrupt increase in abundance after 13 ka cal BP is attributed to the increase in diatom productivity in the lake due to the climate shift from the last Glacial cold to the Holocene warm condition. The timing of rapid diatom abundance rise, 13 ka cal BP, in Lake Aoki sediment record appears to be the last Glacial-Holocene transition in central Japan.

Keywords: Lake Aoki, diatom abundance, Glacial-Holocene transition, climate reconstruction, chronology

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INTRODUCTION

Climate proxy

Climate proxies are preserved physical characteristics of the past events that enable scientists to reconstruct the climatic conditions that prevailed during much of the Earth's history. As reliable modern records of climate only began in the 1860s, proxies provide a means for scientists to determine climatic patterns before record-keeping began. Examples of proxy sources include lake and ocean sediments, ice cores, tree rings, corals, etc. In lake sediments, contents of diatom, pollen, organic carbon and nitrogen, biogenic silica, ostracodes, eolian flux, and carbonate; variations in sediment grain-size and mineralogy, magnetic susceptibility, organic and sulfur geochemistry, and stable isotope (carbon and oxygen) ratios; and presence of varved sediments are reliable proxies for paleoclimate reconstruction (Adhikari 2011a). Deposition or growth rate of the proxy materials are influenced by the climatic conditions of the time in which they were laid down or grew.

Diatoms (Class Bacillariophyceae), a group of microscopic algae abundant in almost all aquatic habitats, are well preserved in lake sediments. They are species-rich, and estimates on the order of 10^4 are often given (Guillard and Kilham 1977), and Mann and Droop (1996) point out that this estimate would be raised to at least 10^5 by application of modern species concepts. Diatoms are characterized by a number of features, but are most easily recognized by their siliceous (opaline) cell walls, composed of two valves, that together form a frustule. The size, shape, and sculpturing of diatom cell walls are taxonomically diagnostic. Moreover, because of their siliceous composition, they are often very well preserved in lake sediments, provided salinity is not excessive. Because they can be identified to species level, and their distribution and abundance is sensitive to a range of ecological variables, including water depth, salinity, pH, and trophic status, diatoms preserved in lacustrine sediments are one of the most sensitive indicators of past lake conditions (Bradbury 1988). The reconstructed lake condition in turn can be directly or indirectly linked to the climatic condition at the time the sediments deposited. Besides the ecological dependency, diatom, as a climate proxy, can be studied for two aspects, abundance and type. Both the abundance and assemblage composition can be used as paleoclimate proxy.

Study area

A narrow intermontane valley in the Hakuba-Omachi City area, near the northern Japanese Alps, central Japan hosts a series of three fresh-water bodies, viz Lake Aoki, Lake Nakatsuna, and Lake Kizaki, which are known by the 'Nishina Three Lakes' (Fig.1). Lake Aoki, the study area, is intermediate in size (1.86 km^2), but the deepest (58 m) and largest water body (53940×10^3 m^3) among the three lakes (Adhikari et al., 2002). The lake has topographic closures

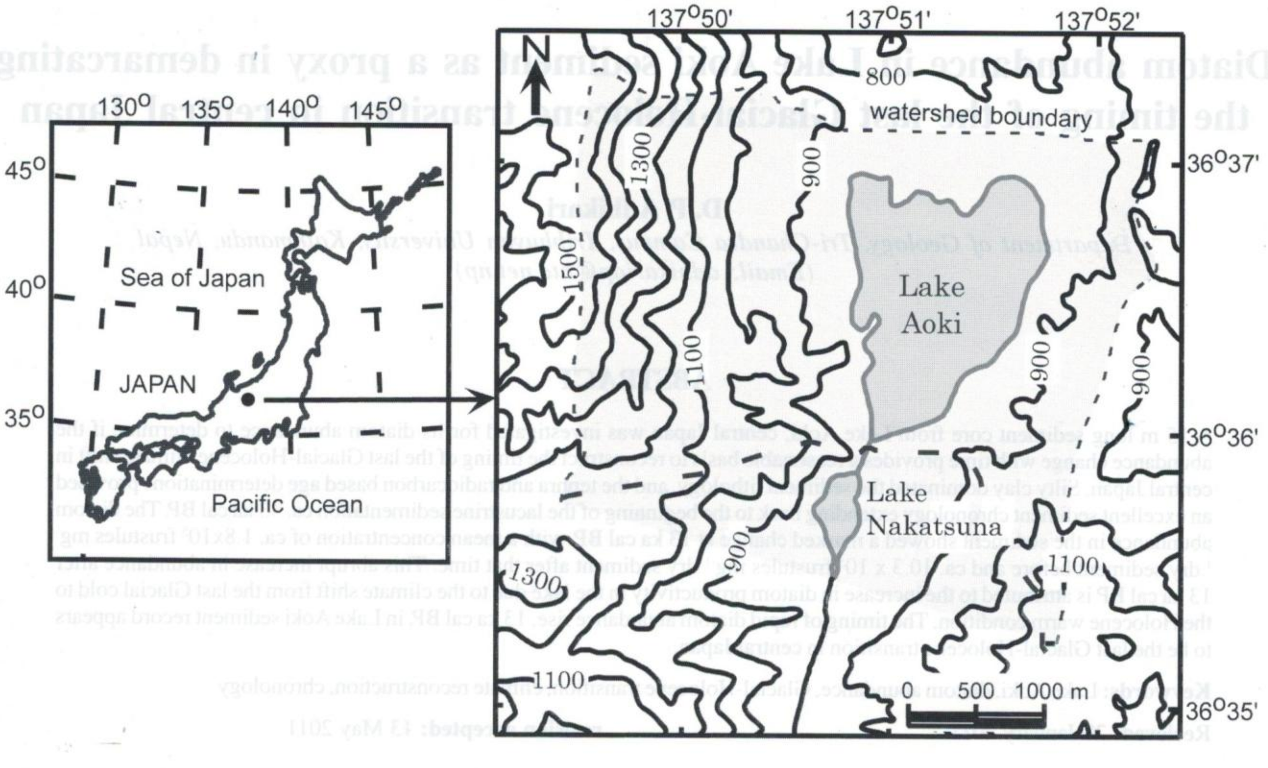

Fig. 1: Location of Lake Aoki and the topographic features around it. Lake Kizaki and Omachi City are to the south of the map. Topographic contours are at 100 m intervals (adopted from the topographic map, Geographical Survey Institute of Japan, Kamishiro, 1:25000).

in the east, west and north (Fig. 2), and draws runoff from 9.2 km^2 area. The peak elevation in the catchment area is about 1599 m with a maximum relief of 778 m. Bedrocks in the catchment area consist of Cretaceous granite, welded tuffs, Tertiary sedimentary rocks (Omine Formation), and Quaternary terrace deposits (Kosaka 1983). Some of the characteristic features of the lake are summarized in Table 1.

Lake Aoki has a main basin and a sub-basin which are separated by a steep slope (Fig. 3). The main basin has roughly a rectangular outline and reaches a maximum depth of about 58 m. It is symmetrically bounded by a steep bathymetric gradient to the north, south and west in the upper slope and a gentle slope merged to the basin plain in the foot slope. This gentle foot slope is wider in the axial ends of the basin than in the other two sides. The eastern one-third part of the lake appears gently sloping westward with a narrow flat area lying under the water depth of about 32.5 m and abutting one of the bathymetric highs in the south above the main basin (Fig. 3). This hanging portion of the lake is the sub-basin, which is bounded by steep gradient to the east and south, and gentle slope to the north.

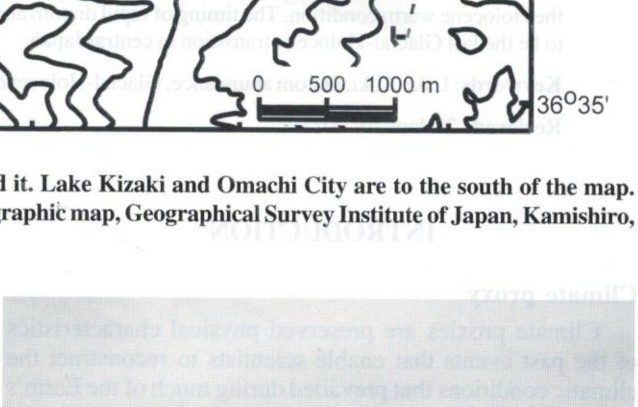

Fig. 2: Northward view of Lake Aoki and the surrounding area in winter. It is evident that snowfall is thick and widespread, and the peripheral part of the lake has undergone frozen.

The northern Japanese Alps region is characterized by monsoon-type climate, with cold dry winters and moist hot summers. The lake and the surrounding area experiences more than 1 m thick snowfall in winter and the shallow peripheral part of the lake undergoes ice bounding for a few weeks during winter extreme (Fig. 2), but the inner

Table 1: Characteristic features of Lake Aoki

Latitude and longitude	36° 36' 32" N 137° 51' 14" E
Mean annual temperature (°C)	9.4
Mean annual precipitation (mm)	2022
Surface elevation (m)	822
Drainage basin area (km^2)	9.2
Maximum relief in the drainage basin (m)	778
Perimeter (km)	6.5
Maximum depth (m)	58
Average depth (m)	29
Water volume (x 10^3 m^3)	53940
Water residence period (days)	193
Lake type	oligotrophic

***Note:** Location as well as lake and catchment characteristics were determined from topographic and bathymetric maps, and partly referred from Saijo (2001) and Horie (1962).*

lake surface rarely freezes (Adhikari et al. 2002). Amount of natural inflow into the lake is estimated at 0.58 m^3s^{-1} (Watanabe et al. 1987), and an artificial flow (2.69 m^{-3} s) from electric power plant at Aoki Power station has been mixed into the lake since 1954 (Fig. 3).

Tanaka (1930) made some limnological investigations of Lake Aoki as an opening of scientific work on this lake. The Geological Survey of Japan (Inouchi et al. 1987) began sediment-based research on this lake by extracting two sediment cores (17 m and 28 m) and making their lithological descriptions. Further studies on these sediments were limited to the grain-size analysis of the longer core (Manaka et al. 1998) from which several turbidite horizons were reported in the early history of the lake. Ono et al. (2000) studied the Late Quaternary sediment around the lake and suggested landslide damming of the pre-existing stream as the basin closure mechanism to give birth of the lake. Later, Adhikari et al. (2002) investigated a separate sediment core (2.25 m) from this lake for diatom and organic material contents and gave a picture of climatic variability of the last 10 ka in the region. However, climatic reconstruction beyond 10 ka and information on Last Glacial-Holocene transition is not available from Lake Aoki sediments until recently. In this study, 15 m long sediment core from Lake Aoki is investigated for its diatom abundance to determine if the abundance change in the sediment provides a basis to reconstruct the timing of the last Glacial-Holocene climate shift in central Japan. It is hypothesized that warm climate favors higher lake productivity, and hence higher diatom abundance.

METHODOLOGY

The 17 m long sediment core previously extracted by The Geological Survey of Japan (Inouchi et al. 1987) from the deepest part of the sub-basin of Lake Aoki under 32.5 m water depth (Fig. 3) was recovered and split lengthwise in the laboratory. Lithology of the sediment was described on the cut surface; colors were assigned using Munsell soil color charts and X-rayed to reveal internal sedimentary features. A total of 2 m thick slim material, identified from different depths of the core, was removed, and this removal reduced the core length to 15 m.

Sediment samples were taken from 48 horizons at intervals of 20 to 50 cm and analyzed for diatom abundance. Diatom slides were prepared following the standard methods (Diatom Research Group for Nojiri-ko Excavation 1980). From each sample, 1 g of dry sediment was heated to boiling in 30 cc (30 %) of H_2O_2 for 5 minutes to remove soluble minerals and organic matter. After cooling, the remaining material was diluted with 300 cc distilled water, well stirred using ultrasonic vibrator, and washed by settling and decantation (3 times every 4 hour intervals) to remove oxidation by-product. Diatoms were then collected from the leftover, washing 3 times with 50 cc distilled water each time, and then diluted to 200 cc. Finally, 2 cc of this liquid was again diluted to 20 cc by adding distilled water. After shaking it well, 3 cc aliquot was then transferred to a cover slip by pipette, dried on a hotplate, and mounted in mount media.

Slides were examined under both low power (40×10) and oil immersion (100×10) of a canon microscope. Diatom frustules were counted under 100 sections along 10 vertical transects from each sediment sample at 100×10 magnification under light microscope. When the number is too low (<500), valves were counted under 600 sections. Fragments that can be assigned to a taxon with reasonable confidence were reported in terms of whole valves, and fragments lacking morphological characteristics for identification, or simply too small to contain such features, were not counted. Diatom numbers were then calculated for one milligram (mg) dry sediment for each sample examined, and a graph was generated by plotting the abundance against core depth.

To determine the sediment age, volcanic ash and organic matters from the core sediments were used. The Japanese Archipelago has a well-known history of volcanic activities. Identification and characterization of volcanic ash layers in sediments thereby provide chronological precision. For that reason, volcanic glasses from three ash-fall horizons, 1.24-1.25 m, 7.15-7.16 m, and 10.21-10.22 m were extracted, cleaned, and observed under the microscope to determine the mineral composition, refractive index and morphology of the glass shards. Then the volcanic ash layers

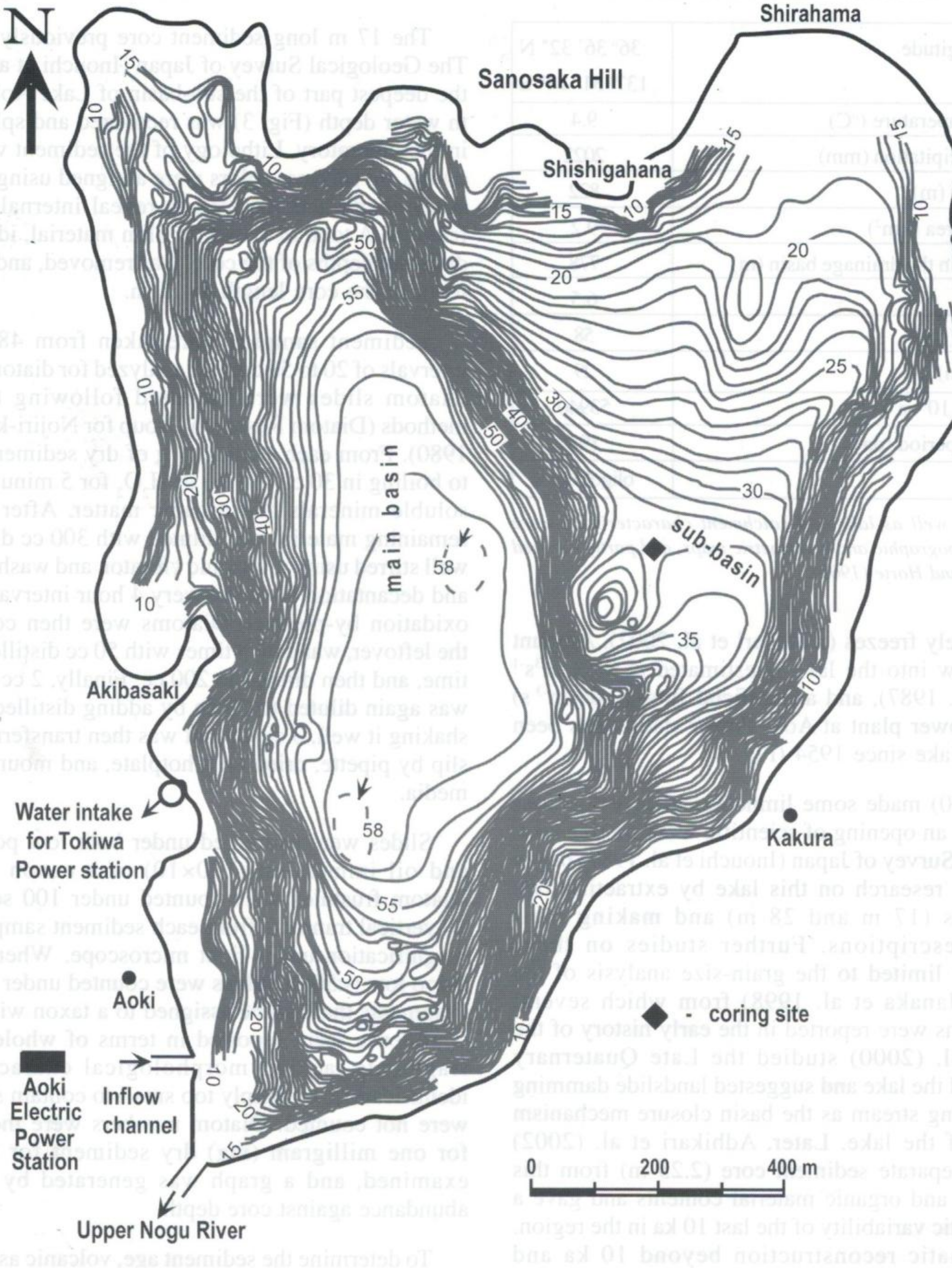

Fig. 3: Bathymetric map of Lake Aoki with the location of coring site. Contours are at 1 m interval. Bathymetric map is modified after Inouchi et al. (1987).

were correlated to the known widespread tephra based on the microscopic features and their stratigraphic position. For additional dates, radiocarbon dating was performed for two plant materials from 2.10 m and 12.71 m depths using a standard Accelerator Mass Spectrometer (AMS). Sediment chronology was derived from the six reference ages (3 tephra, 2 radiocarbon, and 1 known age) by calibrating to calendar years using INTCAL09 (Reimer et al. 2009) and INTCAL98 (Stuiver et al. 1998). Age of the sample horizons were derived by interpolating these reference ages, and age at the core bottom was estimated by extrapolating the overlying known age. The average sedimentation rates in different segments of the core were calculated by using the age-depth relationships.

RESULTS

Lithology and chronology

Silty clay dominated the lithology of the core sediment at all depths below 5 cm (Fig. 4). It occurred in varieties of colors (e.g. dusky yellowish black, olive black, olive gray, greenish gray, greenish black), and had occasional intercalation of fine silt and both graded and none graded sand layers in the lower half portion of the core. The sediment also contained eight visually observed volcanic ash layers at different levels (Fig. 4), the thickness of which ranged from 2 mm to 1 cm and two of them were coarse enough to be seen the larger grains. The core terminated on matrix supported angular gravel bed at 15 m depth, which is interpreted as the basement of the lacustrine sediment (Adhikari 2011b).

The sediment above 5 cm depth was coarser and lighter than the underlying sediments, and this difference is considered to indicate the modern hydraulic changes that have been imposed in the lake by diverting artificial flow since AD 1954 (Adhikari et al. 2002). The age of 5 cm depth is therefore AD 1954. The three ash layers intercalated at 1.24-1.25 m, 7.15-7.16 m, and 10.21-10.22 m were identified as Kikai-Akahoya (K-Ah), Sanbe (SUK), and Aira-Tanzawa (AT), respectively (Adhikari 2011b), and their corresponding ages, 7.3 ka cal BP, 21 ka cal BP, and 29 ka cal BP, as established by Machida and Arai (1992) is adopted in this study (Fig. 4). Similarly, the plant samples from depths 2.1 m and 12.71 m yielded 9.4 ka cal BP and 36 ka cal BP, respectively.

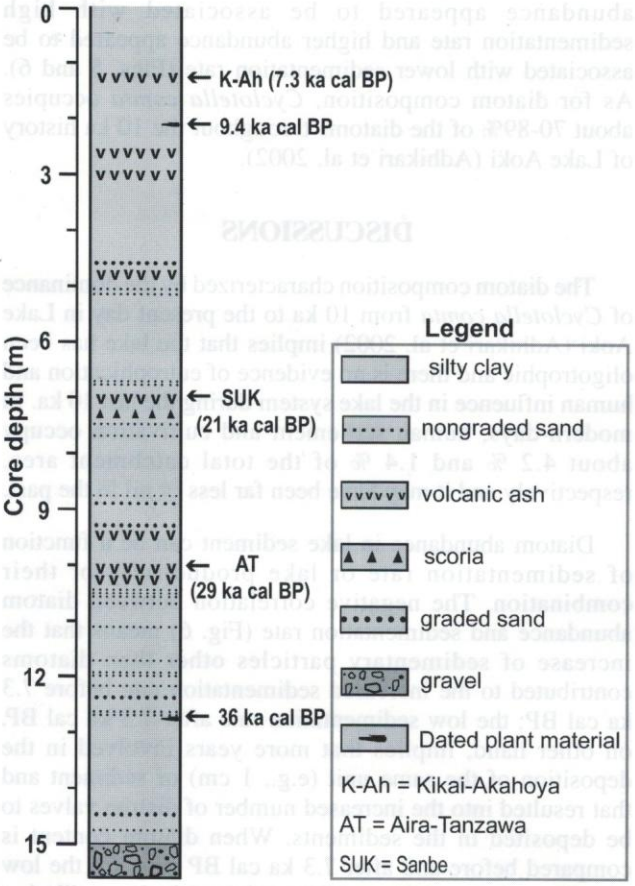

Fig. 4: Lithology of the cored sediment along with the dated horizons and their calibrated ages

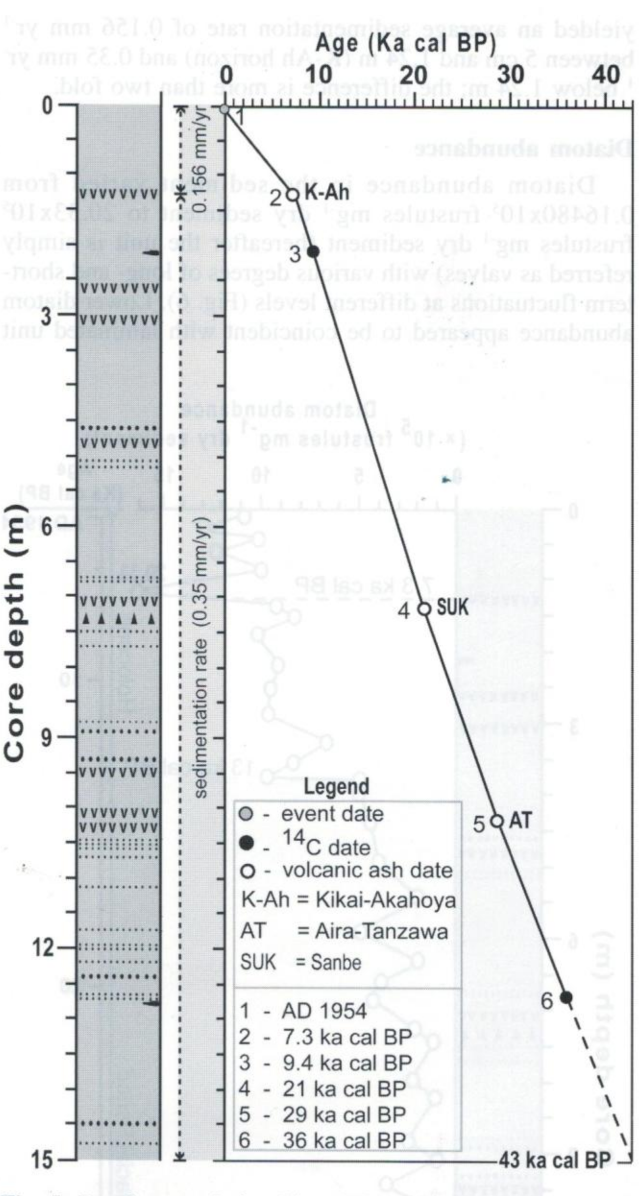

Fig. 5: Depth-age relationship of the sediments. The dashed portion of the line indicates extrapolation of the reference age. Sedimentation rates are also indicated.

The calibrated five reference ages below 1.25 m fell almost on a line in the age-depth plot (Fig. 5) and hence provided an excellent chronology of the sediment. Considering constant sedimentation rate further down from 12.71 m depth, the extrapolation placed the bottom sediment age at 43 ka cal BP (Fig. 5). The chronology yielded an average sedimentation rate of 0.156 mm yr^{-1} between 5 cm and 1.24 m (K-Ah horizon) and 0.35 mm yr^{-1} below 1.24 m; the difference is more than two fold.

Diatom abundance

Diatom abundance in the sediment varied from 0.16480x10^5 frustules mg^{-1} dry sediment to 20.33x10^5 frustules mg^{-1} dry sediment (hereafter the unit is simply referred as valves) with various degrees of long- and short-term fluctuations at different levels (Fig. 6). Lower diatom abundance appeared to be coincident with laminated unit below 3.71 m. A sharp break in the underlying gradual upward increasing trend occurred at 3.71 m when the concentration with a mean of about 1.8x10^5 valves below abruptly increased to a mean of 10.3x10^5 valves above 3.71 m (Fig. 6). Interpolation of the ages at 2.10 m (9.4 ka cal BP) and 7.16 m (21 ka cal BP) yielded an age of 13 ka cal BP at 3.71 m depth. The difference in abundance before and after 13 ka cal BP provided the basis to divide the core into low abundance (shaded) and high abundance (plain) units, respectively (Fig. 6).

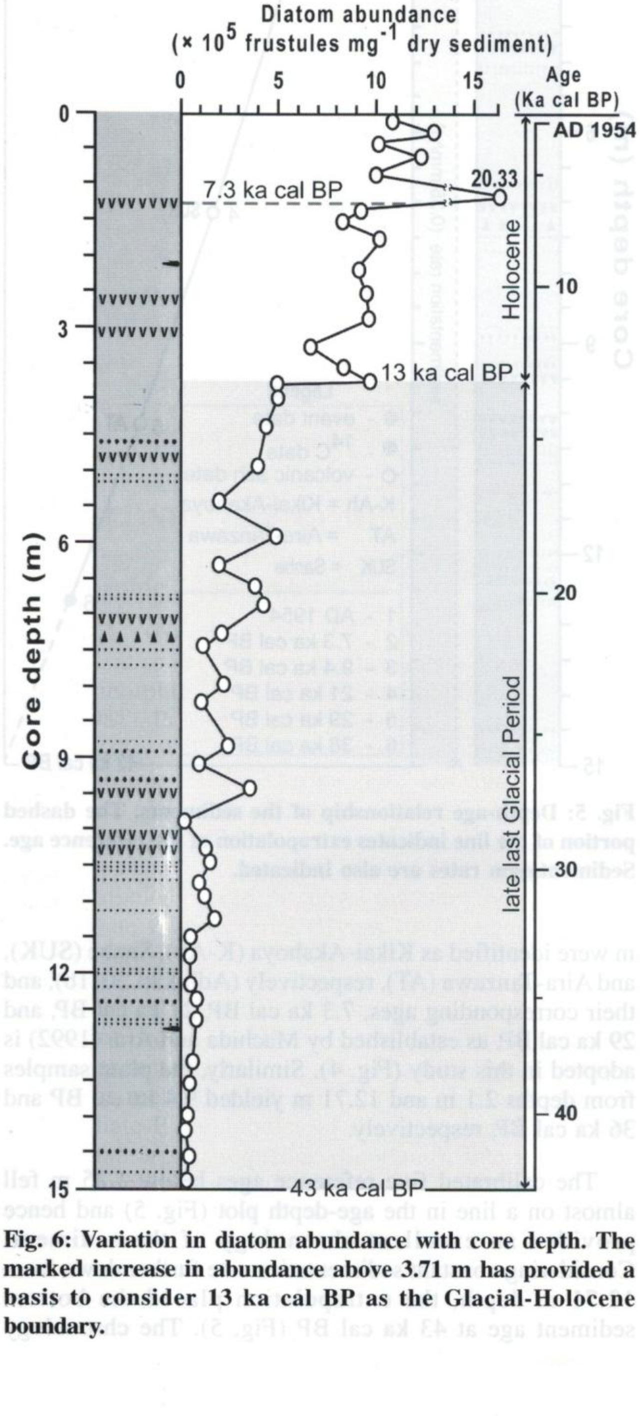

Fig. 6: Variation in diatom abundance with core depth. The marked increase in abundance above 3.71 m has provided a basis to consider 13 ka cal BP as the Glacial-Holocene boundary.

In the low abundance unit, diatoms remained <1.5x10^5 valves below 10 m, and it showed an upward increasing trend with considerable fluctuations between 1.5x10^5 valves and 5x10^5 valves above 10 m (Fig. 6). Following the marked increase at 13 ka cal BP, diatom numbers in the high abundance unit indicated a gradual upward decease at the beginning and an ensuing increase after 7.3 ka cal BP. An unusually high content of 20.33x10^5 valves around 6.3 ka cal BP punctuated the underlying trend, and a general upward increasing trend with some fluctuations followed upward (Fig. 6). The mean concentrations before and after 7.3 ka cal BP were 9x10^5 valves and 12x10^5 valves, respectively.

In general, there is a negative correlation between diatom abundance and sedimentation rate, i.e. lower abundance appeared to be associated with high sedimentation rate and higher abundance appeared to be associated with lower sedimentation rate (Figs. 5 and 6). As for diatom composition, *Cyclotella comta* occupies about 70-89% of the diatoms throughout the 10 ka history of Lake Aoki (Adhikari et al. 2002).

DISCUSSIONS

The diatom composition characterized by the dominance of *Cyclotella comta* from 10 ka to the present day in Lake Aoki (Adhikari et al. 2002) implies that the lake has been oligotrophic and there is no evidence of eutrophication and human influence in the lake system during the last 10 ka. In modern-days, human settlement and cultivation occupy about 4.2 % and 1.4 % of the total catchment area, respectively and it may have been far less or nil in the past.

Diatom abundance in lake sediment can be a function of sedimentation rate or lake productivity or their combination. The negative correlation between diatom abundance and sedimentation rate (Fig. 6) means that the increase of sedimentary particles other than diatoms contributed to the increased sedimentation rate before 7.3 ka cal BP; the low sedimentation rate after 7.3 ka cal BP, on other hand, implies that more years involved in the deposition of the same unit (e.g., 1 cm) of sediment and that resulted into the increased number of diatom valves to be deposited in the sediments. When diatom content is compared before and after 7.3 ka cal BP (Fig. 6), the low abundance before 7.3 ka cal BP can be partly due to dilution effect.

However, as the sedimentation rate is constant before 7.3 ka cal BP (Fig. 5) and there seems no factor(s) leading to differential preservation, the abrupt increase in mean diatom concentration after 13 ka cal BP can't be explained by dilution effect, but is exclusively the function of lake productivity. Similarly, as the anthropogenic perturbation, a common cause enhancing lake productivity, is also not evident as suggested by the diatom composition (Adhikari et al. 2002), only the possible candidate responsible for changing lake productivity is climatic factor. Alternative explanations do not appear likely.

Globally, biogenic productivity in lacustrine environment is largely controlled by nutrient supply and water temperature. If external nutrient loading is not evident, temperature would play bigger role as warm water temperature makes living things more active and enhances biogenic productivity. Water temperature is directly controlled by the atmospheric temperature. Therefore, warm climate may induce high biogenic productivity, resulting in high diatom abundance in lake sediment. For example, the productivity of Lake Suwa, as measured by *chlorophyll a* showed a distinct reduction in 1993 with cool summer, and indicated much increasing in 1994 with hot summer (Park et al. 1998). Some other studies have also shown that warm condition appears to have an important effect on the relative abundance of diatom and other freshwater algae (e.g. Stoermer and Ladewski 1976; Tilman and Kiesling 1984, Xiao et al. 1997).

Based on the above explanations, the abrupt increase in diatom abundance at 13 ka cal BP and its upward continuation (Fig. 6) suggests shifting of climate from a cold to a warm condition, a shift from the last Glacial to the Holocene. This interpretation agrees substantially with global records as 13 ka cal BP is widely referred as the time of rapid sea level rise (e. g., Bradley 1999). Consistent with the above explanation, the low diatom concentration before 13 ka cal BP is attributed to increased ice cover and turbidity from silt and clay introduced into the lake from glaciated drainage surrounding the basin and cold water temperature. In modern-days, the lake and surrounding area experiences abundant snowfall in winter and the shallow peripheral part of the lake undergoes ice bounding (Fig. 2), it may have been far more extensive during the Glacial time. It also holds true that the combination of low sedimentation and warm climate of the Holocene have made even higher diatom concentration after 7.3 ka cal BP.

CONCLUSSIONS

The 15 m long sediment core from the sub-basin of Lake Aoki yields a complete record of lacustrine sedimentation. The tephra and radiocarbon based age determinations have provided an excellent sediment chronology extending back to ca. 43 ka cal BP. Diatom productivity in Lake Aoki sediment appears to be climatically dependent; high concentration indicates elevated diatom productivity that characterized interglacial climates and the opposite relation characterized the glacial climate. The sudden increase in diatom abundance ca. 13 ka cal BP marks the last Glacial-Holocene transition and this finding agrees substantially with the global records. This study has contributed to the better understanding of the timing of the last Glacial-Holocene climate shift in central Japan and strengthen the belief that diatom abundance in lake sediment can be a reliable proxy of past climate change.

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