Journal of Nepal Geological Society, 2011, Vol. 43 (Special Issue), pp. 103–113

Diatom flora assemblage composition in Lake Aoki sediment during the last 43 ka and its paleoenvironmental significance

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ABSTRACT

Diatom assemblage changes over the last 43 ka were examined from a tephra and ^{14}C-dated sediment core retrieved from Lake Aoki, central Japan to understand the environmental changes in and around the lake. Twenty-two common diatom taxa belonging to 11 genera were identified, and these genera (species) included *Cyclotella (radiosa)*, *Aulacoseira (ambigua, valida)*, *Fragilaria (pinnata, capucina var. mesolepta)*, *Denticula (lauta, elegans* Kützing*)*, *Pinnularia (termitina, stomatophora)*, *Navicula (radiosa var. tenella, subconcentrica)*, *Cymbella (cistula var. gibbosa, sp.)*, *Tabellaria (sp.)*, *Diploneis (ovalis)*, *Gomphonema (germainii, globiferum, acuminatum,* and *truncatum)*, and *Epithemia (adnata, sorex* Kützing*, turgid)*, and *Cyclotella radiosa* was the most dominant and only species continuous throughout the core. Based on the major shifts in their relative abundance, four major diatom zones were detected. The earliest (43-35 ka cal BP) diatom assemblages were dominated by *C. radiosa* with sporadic and less frequent benthic taxa. A shift to dominance by diatoms other than *C. radiosa* followed during 35-26 ka cal BP where the benthic communities showed record high presence. *C. radiosa* returned as a dominant component again during 26-13 ka cal BP at the expense of other diatoms, and amid the dominance of *C. radiosa*, a continuous and better presence of other diatoms marked a uniform composition after 13 ka cal BP. The compositional shifts indicate fluctuating lake environment with four distinct lake stands. The diatom record also suggests that Lake Aoki has been oligotrophic and alkaline throughout its history, but some indication of human influence in the lake environment is evident in recent time.

Keywords: Diatom flora assemblage, diatom taxa, alkaline, oligotrophic, Lake Aoki

Recieved: 14 November 2010 **revision accepted:** 10 March 2011

INTRODUCTION

Diatom and environment

Diatoms are species-rich siliceous algae which are found in virtually every habitat where water is present. They are sensitive to a range of ecological variable, including temperature, salinity, pH, trophic status, and water depth (Gasse et al. 1995), and the environmental optima and tolerances of many diatom taxa are generally well known, at least on a broad scale (Stoermer et al. 1999). These variables are directly or indirectly affected by climatic factors and human activities, and therefore change in diatom assemblage composition provides important information on environmental conditions. As the silica cell walls of diatoms do not decompose, they preserve well in lake and marine sediments and changes in their species composition serve as paleolimnological and paleoclimate proxy indicator. Fossil evidence suggests that diatom originated during, or before, the early Jurassic Period (Battarbee 2000). Little or no change in diatom composition for long time may indicate stable environmental conditions for extended period of time.

Transfer functions, based on the relationship between the species composition of modern diatom assemblages and the chemistries of the waters from which they were collected, allow quantitative reconstruction of past variations in lake chemistry from counts of fossils diatoms in lake sediment cores (Fritz et al. 1991; Gasse et al. 1995; Laird et al. 1996). Lake depth may be gauged qualitatively from the relative proportions of diatoms of different life forms (Round et al. 1990); planktonic species indicate deep water; benthic and periphytic species suggest shallow water. Certain diatom species are characteristic of oligotrophic water, others of eutrophic waters; this allows the qualitative reconstruction of lake nutrient status.

Environmental issues, especially those that concern freshwater resources, are currently at the forefront of both scientific and public concerns. Diatom assemblages provide the basis for many important assessments of trends in the status of freshwater ecosystems. These versatile indicators tell us about the acidification of lakes caused by acidic deposition, the eutrophication of lakes caused by human impacts and changing land use, improvements and declines in the quality of our rivers and streams, and changes in climate over the past thousands of years. Lakes those are more eutrophic now than in pre-settlement times are being obtained from analyses of diatom assemblages from recent and preindustrial levels of sediment cores (e. g., Dixit and Smol 1994). The approach of examining lake eutrophication by using diatom assemblages has been widely applied throughout the world.

Study area

Lake Aoki (36°36'32"N, 137°51'14"E), the object of this study, is located in an intermontane valley north of Omachi City near the northern Japanese Alps, central Japan (Fig. 1). The valley hosts a series of three freshwater bodies (Lake Aoki, Lake Nakatsuna, and Lake Kizaki from north to south), which are known by the 'Nishina Three Lakes'. With a perimeter of 6.5 km, Lake Aoki is intermediate in size (1.86 km^2), but the deepest (58 m) and largest water body (53,940×10^3 m^3) among the three lakes (Adhikari et al. 2002). The residence time of water in the lake is 193 days (Horie 1962). Lake Aoki lies at 822 m elevation, with catchment peak elevation of 1599 m and maximum relief of 777 m. The lake has topographic closures in the east, west, and north and draws runoff from 9.2 km^2 area.

In modern-days, forest (including minor grass land), residential area, and cultivated land occupy ca. 74.1 %, 4.2 %, and 1.4 % of the total catchment area, respectively and it may have been far less or nil in the past. The modern vegetation around the area is mainly of cool-temperate deciduous (broadleaf) type forest (Adhikari 2002). It has nice clean water with little macrophyte at the marginal part, and is categorized as an oligotrophic lake (Horie 1962; Saijo 2000). Bedrocks in the catchment area consist of Cretaceous granite, welded tuffs, Tertiary sedimentary rocks (Omine Formation), and Quaternary terrace deposits (Kosaka 1983). The Itoigawa-Shizuoka Tectonic Line, a well-known boundary fault, runs through this valley, and the formation of the Nishina Three Lakes have a genetic relation with the active fault system (Kumon and Inouchi 2002).

Bathymetric features of Lake Aoki form a main-basin and a sub-basin which are separated by a steep slope (Fig. 2). The main basin has roughly a rectangular outline and reaches a maximum depth of about 58 m. The eastern one-third part of the lake appears gently sloping westward with a narrow flat area lying under the maximum water depth of about 32.5 m and abutting one of the bathymetric highs in the south above the main basin (Fig. 2). 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. In the eastern part of the lake some terraces are also present.

Streams draining the catchment are few and small relative to the lake dimensions, and hence no specific names are given (Fig. 2). Amount of natural inflow into the lake is estimated at 0.58 m^3 s^{-1} (Watanabe et al. 1987), and an artificial flow (2.69 m^3 s^{-1}) from the electric power plant at Aoki Power station has been mixed into the lake since 1954. Surface outflow from Lake Aoki flows into Lake Nakatsuna to the south through the Upper Nogu River (Fig. 2).

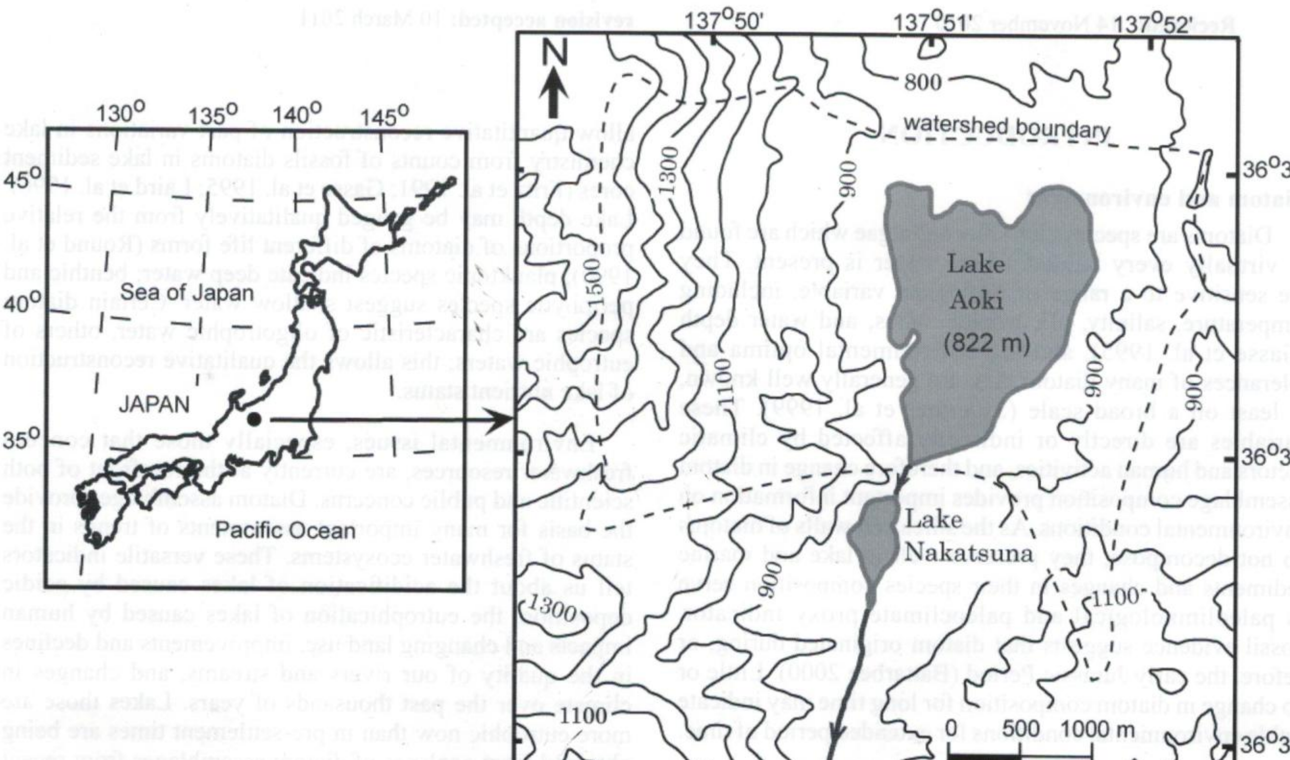

Fig. 1: Location of Lake Aoki and the topographic features around it. Lake Kizaki and the Omachi City are to the south of the map. Topographic contours are at 100 m intervals (adopted from the Geographical Survey Institute of Japan, Kamishiro, 1:25,000).

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Modern climate in the area is characterized by cold dry winters and moist hot summers. Annual average temperature 3 km south at Omachi Meteorological Station varied from 8.3 °C to 10.5 °C, with an average summer temperature in the range from 18 °C to 21 °C and winter average between 1.1 °C and -5.5 °C (average from 1971-2000, Omachi City Office). Annual average precipitation for that period was 2000 mm, with a large variation from year to year (Adhikari and Kumon 2001). The lake and the surrounding area experiences more than 1 m thick snowfall in winter, making the mountain slopes suitable for skiing. During winter extremes, peripheral part of the lake sometimes undergoes freezing for a few weeks, but complete ice bounding rarely occurs.

Beginning of scientific investigation on Lake Aoki dates back to 1907 with the limnological works of Tanaka (1930). Sediment-based research began much later in 1987 when the Geological Survey of Japan extracted two sediment cores (17 m and 28 m) and made their lithological descriptions (Inouchi et al. 1987). Studies on the core sediment lithology along with their dating and geomorphic features around the lake (e.g., Adhikari 2011b; Ono et al. 2000; Manaka et al. 1998) suggest landslide damming as the process which created the lake ca. 43 ka cal BP. Using separate sediment core from the sub-basin of Lake Aoki, Adhikari et al. (2002) reconstructed the history of 10 ka climate variability in the region. Recently, Adhikari (2011d) investigated the 17 m

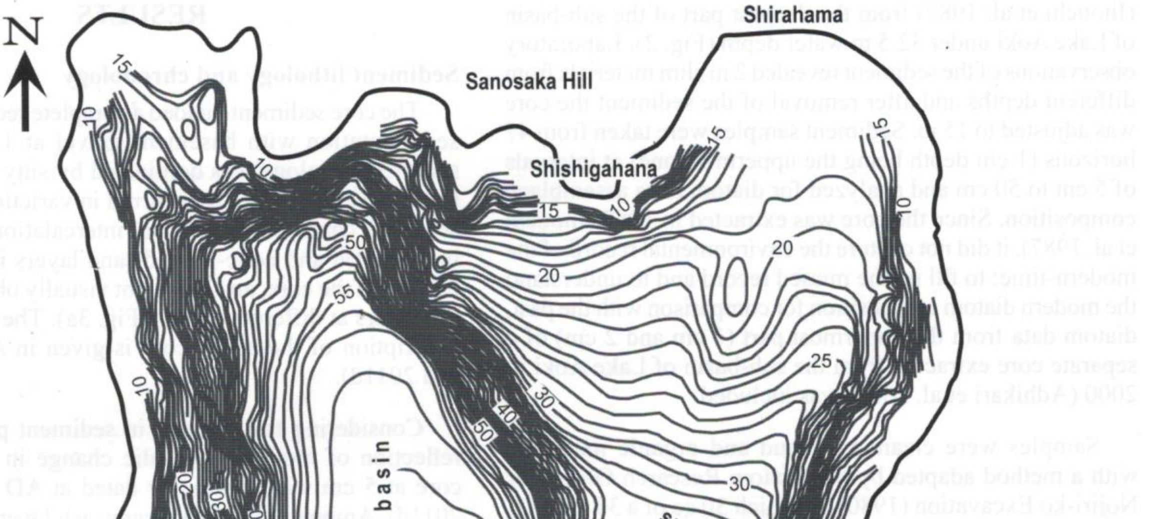

Fig. 2: Bathymetric map of Lake Aoki with the location of coring site. Contours are at 1 m interval. Bathymetric map is modified after Inouchi et al. (1987).

core for diatom abundance and proposed 13 ka cal BP as the timing of the last Glacial-Holocene transition in central Japan. As part of the ongoing works with the sediment on diatoms, this study for the first time, investigates diatom flora assemblage composition in Lake Aoki sediment. The objective of this study was to describe the diatom flora assemblage composition to evaluate the past environmental conditions in and around the lake using the autecological preferences of diatoms.

MATERIALS AND METHODS

The present study investigated the 17 m 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. 2). Laboratory observations of the sediment revealed 2 m slim materials from different depths and after removal of the sediment the core was adjusted to 15 m. Sediment samples were taken from 47 horizons (1 cm depth being the uppermost one) at intervals of 5 cm to 50 cm and analyzed for diatom flora assemblage composition. Since the core was extracted in 1987 (Inouchi et al. 1987), it did not capture the environmental record of the modern-time; to fill up the missed record and to understand the modern diatom composition for comparison with the past, diatom data from the uppermost part (1 cm and 2 cm) of a separate core extracted from the sub-basin of Lake Aoki in 2000 (Adhikari et al. 2002) was included.

Samples were cleaned of mud and organic materials with a method adapted by the Diatom Research Group for Nojiri-ko Excavation (1980), in which 30 cc of a 30 % H_2O_2 solution was added to 1 gm dry sediment and heated to boiling 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 using Naphrax (RI = 1.73). Diatom taxonomy followed Krammer and Lange-Bertalot (1986–1991), Krammer (2000, 2002, 2003), Lange-Bertalot (2001) and other specific taxonomic publications. Ecological preferences of detected taxa were established following van Dam et al. (1994), Krstiæ et al. (1998 and 2012), Battarbee et al. (2000), and Spalding et al. (2010).

Slides were examined under both low power (40×10) and oil immersion (100×10) of a canon microscope. Diatom frustules were examined under 100 sections along 10 vertical transects from each sediment sample at 100×10 magnification under light microscope and selected species were photographed. Broken fragments of the genera *Fragillaria* and *Tabellaria* were evident at several samples most probably due to the heating effects during slide preparation.

Sediment chronology was derived from six reference ages (3 tephra, 2 radiocarbon, and 1 known ages) and calibrated to calendar years by using INTCAL09 (Reimer et al. 2009) and INTCAL98 (Stuiver et al. 1998). Tephra ages were adopted from Machida and Arai (1992). Detail descriptions of the tephra identification and calibration procedures are available in Adhikari (2011b). Age boundaries of the diatom zones were derived by interpolating these reference ages, and age at the core bottom was estimated by extrapolating the overlying known age.

RESULTS

Sediment lithology and chronology

The core sediment yielded a complete record of lacustrine sedimentation with basement gravel at 15 m depth. The sediment lithology was dominated by silty clay throughout the core (Fig. 3a), but it occurred in varieties of colors. The sediment contained occasional intercalation of fine silt and both graded and none-graded sand layers in the lower half portion of the core, and had eight visually observed volcanic ash layers at different depths (Fig. 3a). The detail lithologic description of the entire core is given in Adhikari (2011b and 2011d).

Considering the changes in sediment properties as the reflection of modern hydraulic change in Lake Aoki, the core at 5 cm was previously dated at AD 1954 (Adhikari 2011d). Among the eight volcanic ash layers intercalated in the sediments, the three layers 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 calibrated ages established by Machida and Arai (1992), 7.3 ka cal BP, 21 ka cal BP, and 29 ka cal BP, are adopted in this study (Fig. 3b). Similarly, the plant materials at 2.1 m and 12.71 m yielded 9.4 ka cal BP and 36 ka cal BP, respectively.

Figure 3 shows the age-depth relationship of the sediment, where the calibrated five reference ages below 1.25 m falls almost on a line. It indicates that the available age yielded 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. 3b). The chronology yielded an average sedimentation rate of 0.156 mm yr^{-1} between 5 cm and 124 cm (K-Ah horizon) and 0.35 mm yr^{-1} below 124 cm (Adhikari 2011d).

Diatom assemblage composition

Twenty-two common diatom taxa belonging to 11 genera were identified in the sediment (Fig. 4), but their abundance fluctuated widely (Fig. 5). These genera (species) included *Cyclotella (radiosa)*, *Aulacoseira (ambigua, valida)*, *Fragilaria (pinnata, capucina var.*

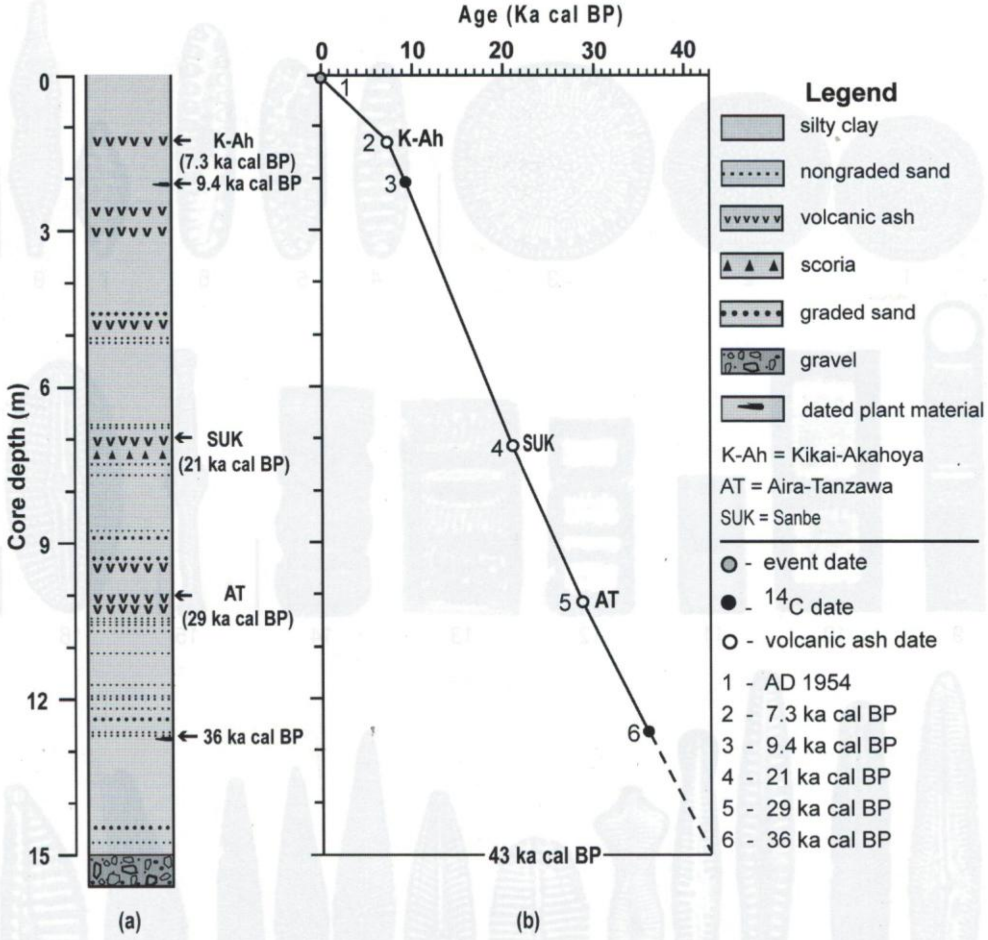

Fig. 3 (a): Lithology of the cored sediment along with the dated horizons and their calibrated ages; (b) Depth-age relationship of the sediment. The dashed portion of the line indicates extrapolation of the available oldest reference age.

mesolepta), *Denticula (lauta, elegans* Kützing*)*, *Pinnularia (termitina, stomatophora)*, *Navicula (radiosa var. tenella, subconcentrica)*, *Cymbella (cistula var. gibbosa, sp.)*, *Tabellaria (sp.)*, *Diploneis (ovalis)*, *Gomphonema (germainii, globiferum, acuminatum,* and *truncatum)*, and *Epithemia (adnata, sorex* Kützing*, turgida)* (Figs. 4 and 5a). Among the 22 taxa, *Cyclotella radiosa* (Fig. 4, Plates 1-3) was the most dominant and the only species continuous throughout the entire core (Fig. 5a); except a much reduced interval between 12.25-9.85 m where its abundance remained well below 45 % and dropped to a minimum of 4 %, the relative abundance of this species generally varied between 56-93 % with 70-90 % as the dominant range (Fig. 5a). The number of *Cyclotella radiosa* and total diatom abundance in the sediment yielded statistically significant positive correlation (r^2= 0.97) (Fig. 6).

The species of the genera *Aulacoseira*, *Fragilaria*, *Denticula*, *Pinnularia*, *Navicula*, *Cymbella*, *Tabellaria*, and *Diploneis* listed in Figure 4 rarely exceeded 10 % or tended to disappear, but they appeared with greater abundances, reaching up to 53 % (e.g. species of *Denticula*) when *C. radiosa* diminished (Fig. 5a). The species of some genera, such as, *Gomphonema* and *Epithemia* appeared only in certain sections of the core (Fig. 5a). In addition to the common diatoms, some other genera (species), which rarely appeared in some samples and represented <1 % of the total diatoms combined, were considered as rare diatoms; they comprised *Eunotia (praerupta)*, *Rhopalodia (gibba)*, *Asterionella (formosa hassall)*, *Caloneis (silicula)*, *Amphora*, *Gyrosigma*, *Surirella*, *Diatoma*, and *Encyonema (minuta)*. There were also a number of taxa that might be new to science, as they differ with respect to certain morphometrical features from the nominal forms that seen in the species mentioned above. Therefore, the diatom flora of Lake Aoki requires further detailed taxonomical research, which is likely to result in the description of some new species.

Diatom zonation

Based on the major shifts in the relative abundance of the most common genera and their species, the diatom flora assemblages were divided into four major zones (Fig. 5a). They are labeled Zones A through D to provide a common framework to discuss shift in environmental conditions with time.

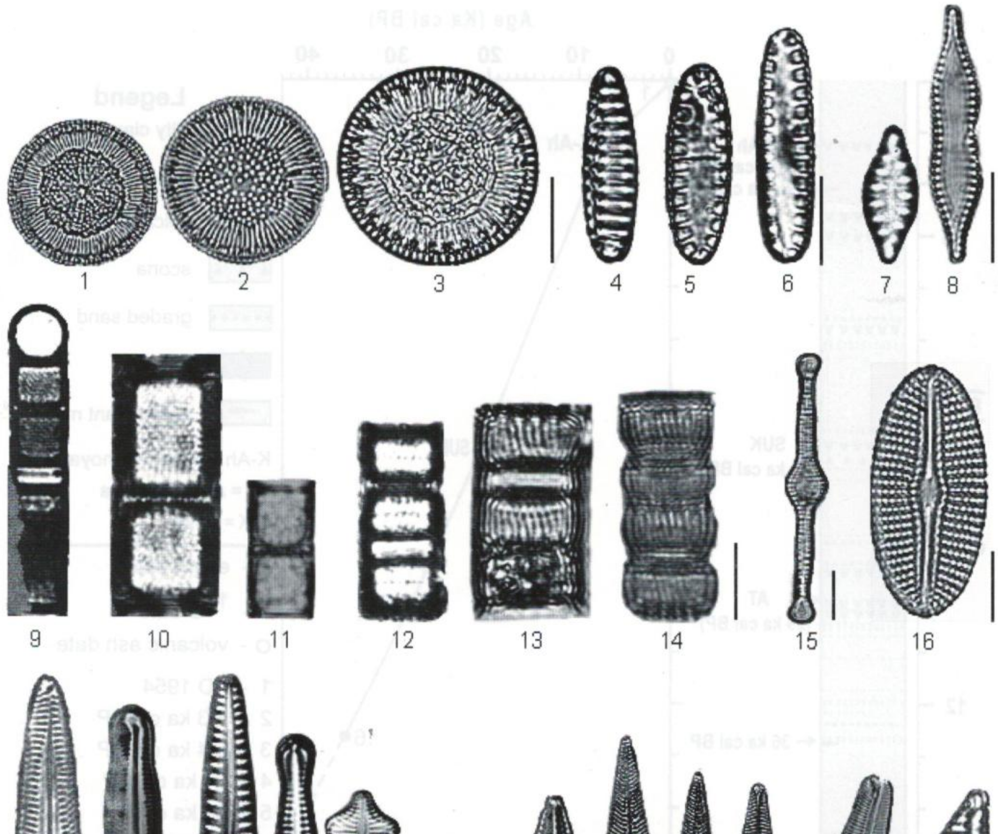

Fig. 4: Microphotograph of the most common diatom flora in the sediments of Lake Aoki; 1, 2, 3: *Cyclotella radiosa*; 4: *Denticula lauta*; 5, 6: *Denticula elegans Kützing*; 7: *Fragillaria pinnata*; 8: *Fragillaria capucina var. mesolepta*; 9, 10, 11: *Aulacoseira ambigua*; 12, 13, 14: *Aulacoseira valida*; 15: *Tabellaria species*; 16: *Diploneis ovalis*; 17: *Pinnularia stomatophora*; 18: *Pinnularia termitina*; 19: *Gomphonema germainii*; 20: *Gomphonema globiferum*; 21: *Gomphonema acuminatum*; 22: *Gomphonema truncatum*; 23: *Navicula radiosa var. tenella*; 24, 25, 26: *Navicula subconcentrica*, 27: *Cymbella cistula var. gibbosa*; 28: *Cymbella species*; 29, 30, 31: *Epithemia adnata*; 32, 33, 34, 35: *Epithemia sorex Kützing*; 36, 37: *Epithemia turgida*; 38, 39: *Ropalodia gibba var. gibba*; 40: *Eunotia praerupta*; 41: *Caloneis silicula* (HER) CLEVE. Scale bar =10 µm.

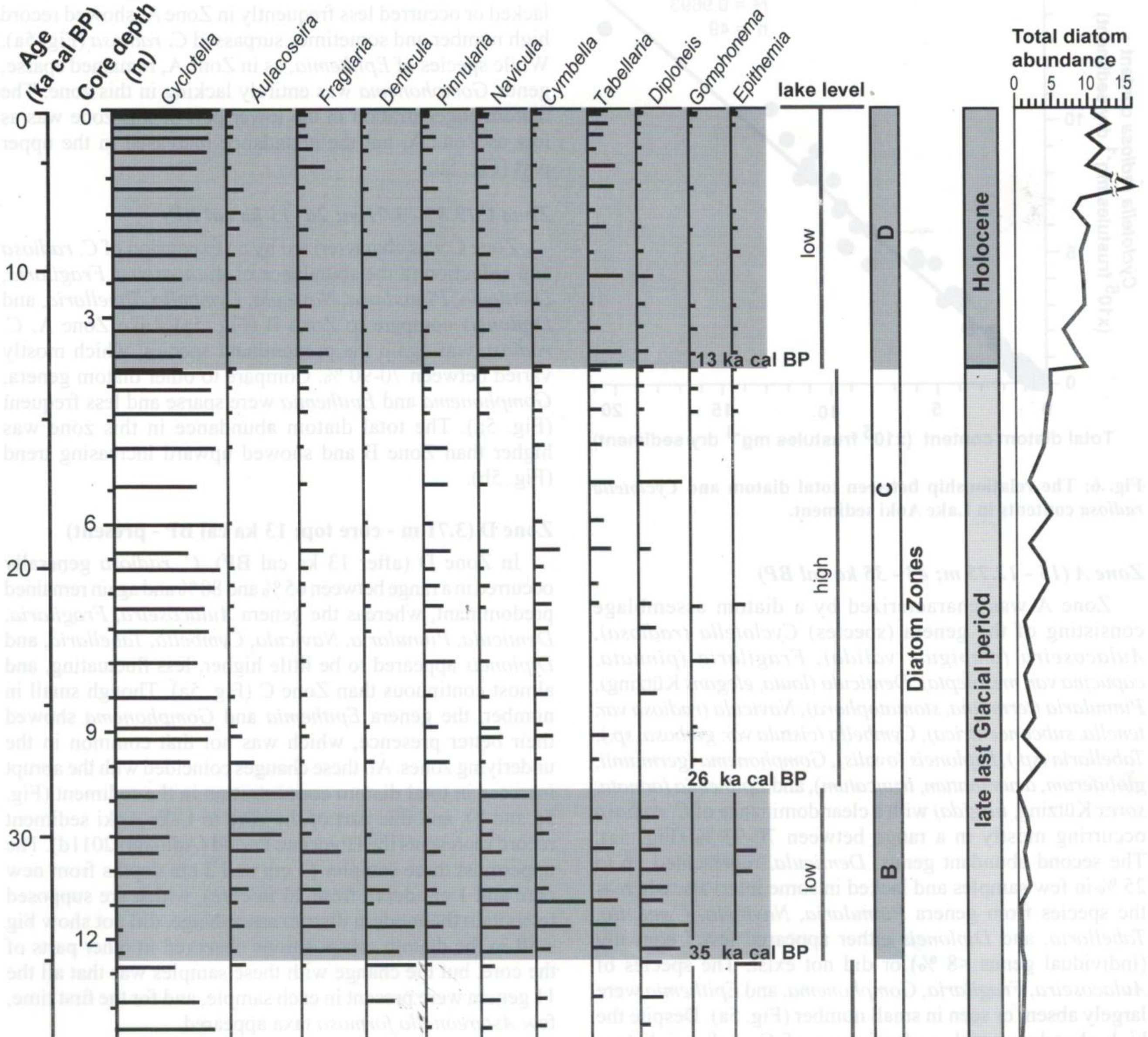

Fig. 5 (a): Stratigraphic profile of the relative abundances (%) of the most common diatom genera in Lake Aoki sediments with diatom zonation, lake level fluctuation, and sediment chronology. The genera include the species in parentheses: Cyclotella *(radiosa)*, *Aulacoseira (ambigua, valida)*, *Fragilaria (pinnata, capucina var. mesolepta)*, *Denticula (lauta, elegans* Kützing*)*, *Pinnularia (termitina, stomatophora)*, *Navicula (radiosa var. tenella, subconcentrica)*, *Cymbella (cistula var. gibbosa, sp.)*, *Tabellaria (sp.)*, *Diploneis (ovalis)*, *Gomphonema (germainii, globiferum, acuminatum, truncatum)*, and *Epithemia (adnata, sorex* Kützing*, turgida)*. The scales are getting larger to the right to make the less abundant genera visible; (b) Variation in total diatom concentration with core depth (after Adhikari 2011d).

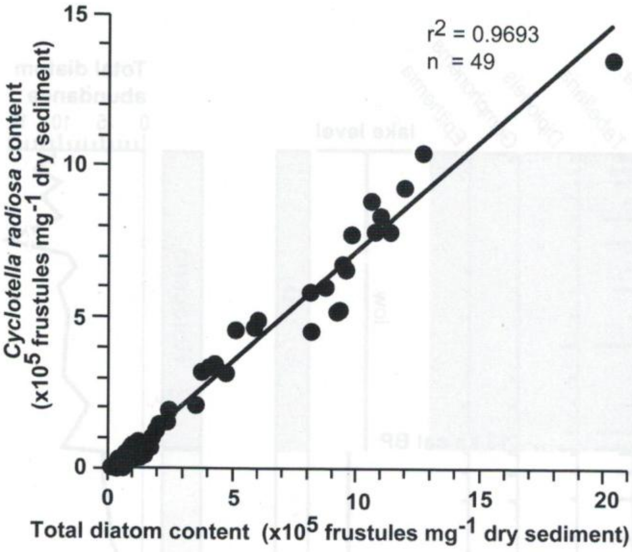

Fig. 6: The relationship between total diatom and *Cyclotella radiosa* contents in Lake Aoki sediment.

Zone A (15 - 12.25 m; 43 - 35 ka cal BP)

Zone A was characterized by a diatom assemblage consisting of the genera (species) *Cyclotella (radiosa)*, *Aulacoseira (ambigua, valida)*, *Fragilaria (pinnata, capucina var. mesolepta)*, *Denticula (lauta, elegans* Kützing*)*, *Pinnularia (termitina, stomatophora)*, *Navicula (radiosa var. tenella, subconcentrica)*, *Cymbella (cistula var. gibbosa, sp.)*, *Tabellaria (sp.)*, *Diploneis (ovalis)*, *Gomphonema (germainii, globiferum, acuminatum, truncatum)*, and *Epithemia (adnata, sorex* Kützing, *turgida)* with a clear dominance of *C. radiosa* occurring mostly in a range between 70-93 % (Fig. 5a). The second abundant genus, *Denticula,* represented up to 25 % in few samples and lacked in some intervals, whereas the species from genera *Pinnularia*, *Navicula*, *Cymbella*, *Tabellaria*, and *Diploneis* either appeared less frequently (individual genus <8 %) or did not exist. The species of *Aulacoseira*, *Fragilaria*, *Gomphonema*, and *Epithemia* were largely absent or seen in small number (Fig. 5a). Despite the high abundance and predominance of *C. radiosa*, diatom concentration in this zone was significantly lower relative to other three zones (Figs. 5a and b).

Zone B (12.25 - 9.85 m; 35 - 26 ka cal BP)

The diatom assemblage composition in Zone B remained more or less similar to Zone A, but it was distinct from the rest of the core that the relative abundance of all diatoms, except the genus *Gomphonema*, experienced marked changes (Fig. 5a). The species *C. radiosa* underwent sharp reduction; it appeared as low as 4 % at the bottom part, a record low content in the entire core, and remained below 40 % in the upper part. Other diatom genera, such as, *Aulacoseira, Fragilaria, Denticula, Pinnularia, Navicula, Cymbella, Tabellaria*, and *Diploneis* appeared almost continuous and dominated the zone at the expense of *C. radiosa*. Some diatom genera, such as, *Aulacoseira* and *Fragillaria,* which lacked or occurred less frequently in Zone A, showed record high number and sometimes surpassed *C. radiosa* (Fig. 5a). While species of *Epithemia*, as in Zone A, remained sparse, genus *Gomphonema* was entirely lacking in this zone. The diatom concentration in the lower part of this zone was as low as Zone A, but the abundance increased in the upper part (Fig. 5b).

Zone C (9.85 - 3.71 m; 26 -13 ka cal BP)

Zone C was characterized by an expansion of *C. radiosa* and reduction in the abundance of *Aulacoseira*, *Fragilaria*, *Denticula*, *Pinnularia*, *Navicula*, *Cymbella*, *Tabellaria*, and *Diploneis* compare to Zone B (Fig. 5a). Like Zone A, *C. radiosa* was again the predominant species, which mostly varied between 70-90 %. Compare to other diatom genera, *Gomphonema* and *Epithemia* were sparse and less frequent (Fig. 5a). The total diatom abundance in this zone was higher than Zone B and showed upward increasing trend (Fig. 5b).

Zone D (3.71 m - core top; 13 ka cal BP - present)

In Zone D (after 13 ka cal BP), *C. radiosa* generally occurred in a range between 65 % and 80 % and again remained predominant, whereas the genera *Aulacoseira*, *Fragilaria*, *Denticula*, *Pinnularia*, *Navicula*, *Cymbella*, *Tabellaria*, and *Diploneis* appeared to be little higher, less fluctuating, and almost continuous than Zone C (Fig. 5a). Though small in number, the genera *Epithemia* and *Gomphonema* showed their better presence, which was not that common in the underlying zones. All these changes coincided with the abrupt increase in total diatom concentration in the sediment (Fig. 5a and b), and this part of the core in Lake Aoki sediment record represents the Holocene Period (Adhikari 2011d). The uppermost three samples (1 cm and 2 cm depths from new core and 1 cm depth from 15 m core), which are supposed to contain the modern diatom assemblage, did not show big shift in the diatom compositions observed in other parts of the core, but the change with these samples was that all the 11 genera were present in each sample, and for the first time, few *Astereonella formosa* taxa appeared.

DISCUSSIONS

Diatom species identified, in this study, as *Cyclotella radiosa* was formerly reported as *Cyclotella comta* in Lake Aoki sediment (Adhikari et al. 2002) as they share similar morphological features. Following an extensive literature review in search for new changes and advances in algal taxonomy, the former *Cyclotella comta* is transferred into *Cyclotella radiosa*. Like the earlier autecological interpretation made for *C. comta* (e. g., Adhikari et al. 2002), the taxon *C. radiosa* is also recognized as an alkaliphilous, planktonic diatom characteristic of oligotrophic freshwater bodies (e. g., Smol et al. 2005; Rühland et al. 2008), and the similar interpretation is adopted in this study.

Zone A (43 - 35 ka cal BP)

The predominance of *C. radiosa,* a planktonic, alkaliphilous, and oligotrophic indicator (Smol et al. 2005; Rühland et al. 2008), combined with sporadic and less frequent number of *Aulacoseira (ambigua, valida), Fragilaria (pinnata, capucina var. mesolepta), Pinnularia (termitina, stomatophora), Navicula (radiosa var. tenella, subconcentrica), Cymbella (cistula var. gibbosa, sp.), Tabellaria (sp.), Diploneis (ovalis), Gomphonema (germainii, globiferum, acuminatum,* and *truncatum*), and *Epithemia (adnata, sorex* Kützing, *turgida)* and the corresponding low diatom concentration during 43-35 ka cal BP (Figs. 5a and b) indicates pristine environment deprived of significant nutrient loads (oligotrophic condition) to continuously support diverse taxa and large diatom population. The preponderance of the alkaliphilous plankton, *C. radiosa,* with little acidophilous, benthic species of *Pinnularia, Navicula, and Cymbella* may also suggest relatively higher lake level with alkaline water chemistry during 43-35 ka cal BP. Diatom plankton is poorly developed in acid lake and very acid or acidified lakes often completely lack a planktonic diatom component (Batterbee et al. 2000). The diatom record in Zone A suggests that the environment was not favorable for benthic and acid tolerant diatoms. The second abundant genus *Denticula,* widely known as characteristic of large oligotrophic lake (Spaulding and Edlund 2009), also supports the above interpretation that the lake was oligotrophic.

Zone B (35 - 26 ka cal BP)

The abrupt decrease in the relative abundance of *C. radiosa* to its record low content (<40 %) and the accompanied dominance of other diatoms, such as, *Aulacoseira (ambigua, valida), Fragilaria (pinnata, capucina var. mesolepta), Pinnularia (termitina, stomatophora), Navicula (radiosa var. tenella, subconcentrica), Cymbella (cistula var. gibbosa, sp.), Tabellaria (sp.),* and *Diploneis (ovalis)* in Zone B (Fig. 5a) indicates different environmental condition in and around the lake during 35-26 ka cal BP. The all time high abundance of the benthic diatoms, *Fragilaria, Denticula, Navicula, Cymbella,* and *Diploneis* (Fig. 5a), suggests the possibility of a lowering lake level. As lake level decreases, the littoral zone in which these benthic diatoms live would shift and bring the zone closer to the core site. Sediment grain-size distribution can provide supplementary information as increase in benthic diatoms should combine with sediment coarsening if lake level stands low.

Since 35-26 ka cal BP was part of the Glacial Period (Adhikari 2011d), it is likely that lake surface water temperature during that time declined and the lower temperatures leading to prolonged ice-cover may be responsible for the decrease in lake level and the planktonic diatom, *C. radiosa* content. As the lake and the surrounding area experiences thick snowfall in modern-winter and the peripheral part of the lake sometimes undergoes freezing during winter extreme, complete ice bounding on Lake Aoki surface would be a likely phenomena during the Glacial time. The nature of diatom composition and their proportion (record high content of benthic diatoms) may suggest that 35-26 ka cal BP was the coldest period with lowest lake level in the history of Lake Aoki. The Last Glacial Maximum (LGM) might have occurred at some point during this period. The domination of alkaliphilous genera, such as, *Cyclotella, Aulacoseira, and Fragilaria* over the acidophilous diatoms (Fig. 5a) suggests an alkaline condition in the lake.

Aulakoseira species are planktonic and have similar requirement as *Cyclotella* (Spaulding and Edlund 2009), but it needs a high amount of silica, as the valves are large and robust. *Aulakoseira* also requires wave action to keep them in the photoic zone; without waves, the heavy valves sink below the layer of water that is penetrated by sun light and die (Colman et al. 1995). The abundance of genus *Aulacoseira* can therefore be interpreted as a time of increased windiness or storminess; in Lake Aoki possibly it happened during summer time when the lake remained free from snow cover. The reduction in *C. radiosa* during 35-26 ka cal BP would have lead to the increased silica availability in lake water from which *Aulacoseira* benefited.

Zone C (26 -13 ka cal BP)

The return of *C. radiosa* again as a predominant component (70-90 %) of the diatom assemblage and the accompanying decrease of other diatom population during 26-13 ka cal BP (Zone C, Fig. 5a) suggests another major shift in the environmental condition. The condition that led to the above change would be a relatively longer ice-free period in the lake and its catchment and higher lake level than that during 35-26 ka cal BP (Fig. 5a), which was most likely mediated by climatic amelioration after 26 ka cal BP. However, the higher number and better continuation of some of the benthic diatoms, for example, *Fragilaria, Navicula, Cymbella,* and *Diploneis* (Fig. 5a) may imply better nutrient availability and lower lake level than that the case during 43-35 ka cal BP. Similarly, the reduced *Aulacoseira* content may suggest limited silica availability or reduction in storminess or their combination.

Zone D (13 ka cal BP - present)

Keeping *C. radiosa* as a predominant component again (65-80 %), the higher and almost continuous presence of *Aulacoseira (ambigua, valida), Fragilaria (pinnata, capucina var. mesolepta), Denticula (lauta, elegans* Kützing*), Pinnularia (termitina, stomatophora), Navicula (radiosa var. tenella, subconcentrica), Cymbella (cistula var. gibbosa, sp.), Tabellaria (sp.), Diploneis (ovalis)* and the better representation of *Gomphonema (germainii, globiferum, acuminatum,* and *truncatum*), and *Epithemia (adnata, sorex* Kützing, *turgid)* than Zone C (Fig. 5a) indicates new environmental shift after 13 ka cal BP, and is in good agreement with the earlier finding (e. g., Adhikari 2011d) that 13 ka cal BP marks the last Glacial-Holocene transition in central Japan. The small decrease in *C. radiosa* and the better presence of the benthic diatoms, *Fragilaria, Denticula, Pinnularia, Navicula, Cymbella, Diploneis, Gomphonema,* and *Epithemia)* hints some reduction in the lake level than that during 26-13 ka cal BP (Fig. 5a), but climatic factor leading to such reduction is not clear because the Holocene is widely accepted as a relatively wetter period than the last Glacial time (e. g., Alley et al. 1997).

If climate is not the causative factor for the proposed lake level decrease in Zone D, tectonic activities could have played some role as the Itoigawa-Shizuoka Tectonic Line runs through this valley (Kumon and Inouchi 2002) and there is a steep bathymetric gradient with about 25 m height difference between the main and sub basins (Fig. 2). The presence of well defined terraces in the eastern part of Lake Aoki could be the complementary evidence of the above interpretation that the lake level in the past was higher than the existing level. On the other hand, the highest diatom concentration in the lake history (Zone D, Fig. 5b), which Adhikari (2011d) interpreted as Holocene Period, in combination with the presence of the large number of diatom genera and taxa (Fig. 5a) allude that warm condition favors growth of diverse taxa.

The appearance of few *Astereonella formosa* taxon, which is known to be introduced by humans into new habitats and also to increase with anthropogenic nutrient loading to the lakes (Spaulding and Edlund, 2009), in the uppermost sample (representing time around AD 2000) suggests some indications of the beginning of human influence on the lake environment, but the diatom composition in the entire core has good analogs with the modern diatom assemblage, and that suggests similar water chemistry and nutrient loading throughout the entire lake history. In modern-days, residential area and cultivated land occupy ca. 4.2 % and 1.4 % of the total catchment area, respectively and it may have been far less or nil in the past. For this reason, there was no possibility of anthropogenic eutrophication of the lake in the past.

CONCLUSSIONS

The diatom record from the 15 m long sediment core retrieved from Lake Aoki, a freshwater body located close to the northern Japanese Alps, central Japan, provides important insights into the late last Glacial-Holocene (43 ka cal BP-present) environmental history in and around the lake. The fluctuations in the relative abundance of planktonic and benthic diatoms give pictures of multiple periods of water level fluctuations in the history of Lake Aoki. The relatively high stands during 43-35 ka cal BP and 26-13 ka cal BP and low stands during 35-26 ka cal BP and 13 ka cal BP-present are inferred, and these changes are likely to be mediated by the climatic and geological changes in the region. The diatom composition characterized by the dominance of *C. radiosa* throughout the core implies that the lake has been oligotrophic and alkaline, and there is no evidence of lake eutrophication during the course of its history. However, the appearance of few *Astereonella formosa* taxon in the most recent sediment indicates the beginning of human influence in the lake environment.

The paucity of acidophilous diatoms on the other hand suggests a non-acidic history of the lake, and it is most probably due to its isolation and lack of catchment changes. It is supported by the evidence that, in modern-days, the residential area and cultivated land occupy ca. 4.2 % and 1.4 % of the total catchment area, respectively and it may have been far less or nil in the past. There are also a number of diatom taxa that might be new to science, as they differ with respect to certain morphometrical features from the nominal forms that seen in the species listed in this paper. Therefore, the diatom flora of Lake Aoki requires further detailed taxonomical research, which is likely to result in the description of some new species and that may give a new picture of further detail environmental changes the lake has experienced in its history.

ACKNOWLEDGEMENTS

This paper contains part of the research works undertaken during JSPS postdoctoral fellowship in Yamanashi Institute of Environmental Sciences (YIES), Japan. The author is thankful to F. Kumon and S. Koshimizu, Japan for their various supports during the fellowship period. Diatom taxonomy was greatly improved from the discussion with H. Tanaka, Japan, P. Kociolek, USA, S. Krstiæ, Macedonia, M. Enache, USA, and A. Budzynska, Poland, who also provided helpful insights on the earlier draft of this manuscript. Thanks are also due to A. P. Gajurel, Department of Geology, Tri-Chandra Campus, Tribhuvan University, Nepal for his valuable and thoughtful comments that improved the quality and clarity of this manuscript.

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