DIATOM TRANSPORTATION IN SHALLOW LAKES BASED ON TAPHONOMIC, GEOCHEMICAL, MINERALOGICAL, AND GRAIN SIZE ANALYSIS IN MODERN SURFACE SEDIMENTS FROM LAKE KITAURA, JAPAN

組坂, 健人

https://hdl.handle.net/2324/7363597

出版情報：Kyushu University, 2024, 博士（理学），課程博士
バージョン：
権利関係：

DIATOM TRANSPORTATION IN SHALLOW LAKES BASED ON TAPHONOMIC, GEOCHEMICAL, MINERALOGICAL, AND GRAIN SIZE ANALYSIS IN MODERN SURFACE SEDIMENTS FROM LAKE KITAURA, JAPAN

by

KENTO KUMISAKA

B. Sc., Kyushu University

(2014)

M. Sc. Kyushu University

(2016)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

at the

DEPARTMENT OF EARTH AND PLANETARY SCIENCES, GRADUATE SCHOOL OF SCIENCE, KYUSHU UNIVERSITY

March 2025

Abstract

Diatoms are phytoplankton distributed globally in aquatic environments from terrestrial to marine. Diatoms form biogenic opal frustules composed of two valves. Fossil diatom assemblages preserved in sediments have been used to reconstruct past environmental changes. However, fossil diatom assemblages are usually exposed to taphonomic processes, such as dissolution, fragmentation, and transportation. The taphonomic processes mix autochthonous and allochthonous diatom valves. Therefore, we must distinguish between autochthonous and allochthonous diatom valves when reconstructing paleoenvironmental changes based on fossil diatom assemblages. Although allochthonous diatom valves are often found in terrestrial and coastal sediment samples, our knowledge of the depositional processes of diatom assemblages is limited. In this study, we investigate allochthonous diatom valves in shallow lake sediments from Lake Kitaura, Japan, to understand the transportation of diatom valves in terrestrial water. The fragmentation (*Fr*) and co-existence ratios (*Cv*) of diatom valves were used to distinguish between autochthonous and allochthonous diatom valves. To evaluate the transportation processes of diatom valves, we conducted X-ray fluorescence (XRF) and grain size distribution (GSD) analyses.

Surface sediment samples at 22 sites in Lake Kitaura were collected by gravity sampler during August and September 2014. Three hundred diatom valves were identified and counted in each slide using a light microscope with magnification ×1000. Then, 50 valves of the genus *Cocconeis*, a representative benthic taxon, were counted separately to estimate the *Cv*. To clarify the relationships between the *Fr* and *Cv* and environmental variables, we conducted correlation and univariate analyses for the *Fr*, *Cv*, water depth, distance to nearshore, and distance to vegetation. Sediment samples for XRF and GSD were treated to remove calcium carbonate, organic matter, and biogenic opal. The treated samples were analyzed using the loose powder method using XRF (Rigaku, ZSX Primus) and a laser-diffraction particle-size analyzer (SHIMADZU, SALD-2300). The polymodal GSDs were separated into 5 or 6 normal distributions based on the expectation-maximization algorithm. The XRF and GSD results were employed for logarithmic ratio analysis to evaluate the influence of inflow rivers on the study sites.

In Lake Kitaura, *Aulacoseira* spp., a planktonic diatom taxa, were dominant in the central part of the lake, whereas benthic diatom taxa increased near the inflow-river mouths and the southern littoral area. Benthic diatom taxa such as *Planothidium lanceolata* and *Cocconeis placentula* distributions in Lake Kitaura indicated that the benthic autochthonous valves deposited mostly near river mouths and the littoral sites. The *Cv* values of *P. lanceolatum* and *C. placentula* showed different patterns in Lake Kitaura. *Planothidium lanceolatum*, a fluvial benthic species, was abundant at the northern sites near the Tomoe River mouth with high *Cv* values, suggesting the transportation from the inflow river. *Cocconeis placentula*, an epiphytic species, was widely distributed in Lake Kitaura, and its fragmentation ratios increased with distance from the lakeshore. The *Cv* of *C. placentula* decreased with distance from the lakeshore and from macrophytic vegetation. The transportation of the clastic sediment corresponded to the spatial variations of *Fr* and *Cv* of the benthic diatoms. The GSD results indicated that coarse clastic particles (3.7-5.0 phi) were supplied from inflow rivers and littoral areas, consistent with the high *Cv* values of *P. lanceolatum* and *C. placentula* at the sites near the river mouths and littoral areas. The silty clastic particles (5.3-6.0 phi) indicated the transportation from the lakeshore and the difference in transportation by wave disturbance between the north and south basins. The *Fr* of *C. placentula* was negatively correlated to the log-ratio of silty clastic particles. The XRF results indicated the high log ratio of Fe_2O_3 to Al_2O_3 at the northern sites near the Tomoe River mouth. The geology around Lake Kitaura is late Pleistocene to Holocene sediments. Granite and metamorphic rocks distribute upstream of the Tomoe River. The Tomoe River transported Fe-rich sediments to the northern part of Lake Kitaura. The geochemical property suggested that the inflowing river transported *P. lanceolatum* valves from the Tomoe River to offshore.

This study demonstrates that the benthic diatoms' valve fragmentation and frustule separation occur by diatom valve transportation from inflowing rivers and macrophytic vegetation on the lakeshore. The *Fr* and *Cv* are useful for estimating the provenances of the benthic diatoms to discriminate the autochthonous and allochthonous valves in shallow lakes. Discriminating allochthonous valves help to reconstruct paleoenvironmental changes based on diatom assemblages in sediments.

Acknowledgements

I express my hearty thanks to my supervisor Prof. Yusuke Okazaki for his continuous and valuable support to complete my study. He gave me countless chance for participating papers. I am appreciating for his great effort to improving my manuscript. I sincerely appreciate my thesis advisory committee Dr. Naofumi Yamaguchi of Ibaraki University for providing the sediment samples, his constructive reviews, and suggestions for improving the manuscript. The grain size analysis in this study was performed at Water Environmental Field Station, Global and Local Environment Co-creation Institute, Ibaraki University under the support of Dr. Yamaguchi. Without their constant support, assistance and advise, this thesis never would have been written. I thank Prof. Tetsuji Onoue for accepting my advisory committee member and suggesting to improve the manuscript.

I am grateful to Ryosuke Hiroyama, the graduate of Ibaraki University. He collected the sediment samples and used them in this study. I also thank Dr. Kana Nagashima of JAMSTEC for providing information about preparation of sediment samples.

I am grateful to the members of the Paleoenvironmental Science Laboratory at the Graduate School of Science, Kyushu University for their assistance and numerous discussions in my study. I would like to thank the members of Fourth Chemical Section of National Research Institute of Police Science for their numerous supports to allow me to devote my time for the Ph.D. project.

Finally, I deeply appreciate my family for their understanding and encouragement.

This work was partly supported by JSPS KAKENHI Grant Number JP18K12578 and 21K12222.

TABLE OF CONTENS

List of Figures

Chapter 2.

Figure 2-1. Field setting. (A) Location of Lake Kitaura, Japan. (B) Map of the sampling sites (numbered) of lakebed-surface sediments in Lake Kitaura in 2014. Black solid and dashed lines denote inflowing rivers with watershed areas greater than and less than 8 km^2, respectively. The River Wani (dotted line) is the only outflowing river. (C) Lake bathymetry. Points denote the sampling sites shown in (B).

Figure 2-2. Light microscopic and SEM images of diatoms from lakebed-surface sediments. (A) Planktonic taxa: (1a, 1b, 8) *Aulacoseira ambigua*, sites kt02 and kt03; (2, 9) *A. granulata*, kt02; (3) *A. pusilla*, kt08; (4) *Actinocyclus normanii* f. *subsalsa*, kt20; (5, 10) *Cyclostephanos dubius*, kt02; (6) *Cyclotella meneghiniana*, kt02; (7, 11) *Stephanodiscus hantzschii* f. *tenuis*, kt11 and kt02. (B) Tychoplanktonic and benthic taxa: (1a) *Staurosira venter*, site kt03; (1b) *Pseudostaurosira* spp., kt17; (2) *Staurosirella berolinensis*, kt21; (3) *Staurosira leptostauron* var. *dubia*, kt03; (4) *Gomphonema truncatum*, kt02; (5) *Navicula lanceolata*, kt02; (6) *Navicula amphiceropsis*, kt02; (7) *Cocconeis placentula*, kt02 (a, araphid valve; b, raphid valve); (8) *Planothidium lanceolatum*, kt01 (a, araphid valve; b, raphid valve); (9) *Nitzschia amphibia*, kt03; (10) *Nitzschia perminuta*, kt01; (11) *Nitzschia subacicularis*, kt02.

Figure 2-3. Distributions of the relative abundances of (A) planktonic taxa, (B) tychoplanktonic taxa, and (C) benthic taxa in Lake Kitaura.

Figure 2-8. *Cv* and *Fr* values for *Cocconeis placentula*. (A) *Cv* values obtained by counting 50 valves in each sample. (B) *Fr* values obtained by counting 50 valves in each sample. (C) *Fr* values of the araphid valves. (D) *Fr* values of the raphid valves.

Figure 2-9. Univariate regression of distance to nearshore and *Fr* values of (A) *Aulacoseira ambigua*, (B) *Aulacoseira granulata*, and (C) *Cocconeis placentula*. (D) Univariate regression of distance to vegetation and *Cv* values of *Cocconeis placentula*. The solid lines show the regression lines, and the dotted lines denote 95% confidence intervals.

Chapter 3.

Figure 3-1. Field setting. (A) Geological map around Lake Kitaura. (B) Map of the sampling sites (numbered) of lakebed-surface sediments in Lake Kitaura. Black solid and dashed lines denote inflow rivers with watershed areas greater than and less than 8 km2, respectively. The Wani River (dotted line) is the only outflowing river.

Figure 3-2. Microscopic observations from lake center (kt14). (A) the smear slide of an unprepared sample. (B) preparation of organic matter, carbonate, and biogenic opal. White allows were point out clastic particles, and black arrows indicated diatom valves. Black bars in A and B are 50 μm.

Figure 3-3. Spatial variation of log-ratio of the mass percentage of (A) Na_2O, (B) MgO, (C) SiO_2, (D) K_2O, (E) CaO, (F) TiO_2, and (G) Fe_2O_3 to Al_2O_3.

Figure 3-4. (A) X-ray diffraction patterns of clastic fraction in lake surface sediments. Q: quartz, Pl: plagioclase, S: smectite group, Ch: chlorite, M: mica, H: hornblende, K: kaoline group. (B) Scatter plot of the peak area of albite (3.21 Å) and anorthite (3.19 Å).

Figure 3-5. Grain-size distributions of surface sediments in Lake Kitaura. The grain size distributions of surface sediments from kt01, kt07, kt16, and kt22 were the magenta, orange, green, and blue lines, respectively.

Figure 3-6. Spatial variation of median, mean, mode, coefficient of variation, skewness, and kurtosis of grain size distribution of surface sediments in Lake Kitaura.

Figure 3-7. The examples of separated components. (A) kt01 with six components, and (B) kt14 with five components. Gray density plots show individual components.

Figure 3-8. Proportions and mean grain size of separated components by expectation-maximization algorithm. (A) Original proportions and mean grain size of each component. (B) Re-synthesized proportions and mean grain size of Comp1&2. (C) Log-ratio of proportions of Comp1&2–5 relative to Comp6.

Figure 3-9. Spatial variation of separated components of surface sediments in Lake Kitaura.

List of Tables

Appendices

CHAPTER 1

INTRODUCTION

1. Diatoms

Diatoms (Bacillariophyceae), unicellular orgasm, are common and widespread algae in aquatic environments from terrestrial to marine settings (Smol and Stoermer 2010; Watanabe 2005). Diatoms are diverse and primary producers in water environments, living as plankton, tychoplankton, or benthos attached to the substrate. The lifeform of benthic diatoms are mainly classified into three types: the slide type, which slides along the surface of the substrata; the upright type, which attaches to the substrata with a mucilage stalk; and the prostrate type, which attaches to the substrata directly. The substrata to which diatoms attach are variable, such as stones, sand, mud, and macrophytes. The diatoms also indicate the present aquatic environments they prefer to live in. Diatoms have different tolerances to salinity, pH, and pollution in different species. Thus, the diatom communities reflect their habitat, light, turbulence, and water quality (Bennion et al. 2010) and are used for monitoring water environments worldwide (Flower 1991). Diatoms form a silica cell wall ($SiO_2 \cdot nH_2O$) called a frustule. The frustule is composed of two valves and girdle components. The frustule and valve structure varies among species, and diatom species are classified by their morphology (Round et al. 1990). The biogenic opal frustules often remain and are identified as fossil diatom assemblages.

Fossil diatom assemblages in sediments have been employed to reconstruct past water environments such as pH, salinity, nutrient status, and lake-level changes (Battarbee and Flower 2003; Chiba et al. 2016; Kashima 1990; Sato et al. 2016; Vos and Wolf 1993) The fossil diatom assemblages were classified into ecological groups based on the diatom community in the modern environment in which they live (Chiba and Sawai 2014; Kosugi 1988b; Sherrod 1999; Vos and Wolf 1988; Vos and Wolf 1993). The ecological groups mean the diatom assemblages is unique to a particular environment, such as open sea, inner bay, and tidal flat with marine or brackish water (Chiba and Sawai 2014). Naya et al. (2007a) is one study that reported recent environmental changes inferred from the fossil diatom assemblages in Lake Kitaura. The fossil diatom assemblage in Lake Kitaura mainly reflected salinity changes during the last 300 years with the regression. In addition, quantitative reconstructions using diatoms and statistical techniques were also performed (e.g., ter Braak and Juggins 1993). The statistical models were constructed based on modern diatom assemblages and their ecology to quantify the changes in past water qualities. The diatom-based model studies contributed to estimating changes in water environments, such as the nutrient state in lakes (Birks 2010).

2. Diatom taphonomy

Fossil diatom assemblages have been used to reconstruct past water environments, but there is a fundamental problem on the differences between modern and fossil diatom assemblages (Chiba 2014). The modern diatom assemblages change during the taphonomic processes; some species disappear on the surface sediments by dissolution, fragmentation, or transportation, and others are incorporated from other water environments or fossil origins. Sediment trap studies in Omura Bay demonstrated that the diatom composition changed between the diatom flora in the water column and the fossil diatom assemblages (Kato et al. 2000; Kato et al. 2003). After the deposition, the modern diatoms can be partially preserved, and the preservation ratio differs in diatom species (Kato et al. 2000; 2003). For example, the coastal benthic taxa *Entomoneis* and *Tryblionella* taxa, which have fragile valves, are dissolved immediately after death and are not likely to remain in the sediment (Sawai 2001). Hirose and Gotoh (2009) also found that *Skeletonema costanum* and *Chaetoceros* taxa, which were commonly observed in the water column, were rarely preserved in the surface sediment, except for the resting spore of *Chaetoceros* taxa (Suto 2006). On the other hand, *Cyclotella litoralis* was reported to be abundant in the sediments, although the species was infrequent in the water column (Hirose and Gotoh 2009). *Palaria sulcata*, marine tychoplanktonic or benthic diatom species, forms a chain-linking structure with thickly silicified valves (Hemphill-Haley 1995; Sawai 2001; Sherrod et al. 1989). Thus, Hemphill-Haley (1995) excluded *P. sulcata* from paleoenvironmental reconstructions because they are easily transported by tidal currents and distributed widely in tidal flats. In short, diatom assemblages in modern sediments are exposed to taphonomic processes, such as chemical dissolution, physical breakage, and incorporation of allochthonous diatoms or reworked fossil diatom taxa. The autochthonous diatoms that live in places of sediments provide information about the in-situ environments. On the other hand, the allochthonous diatoms, transported from their habitats to other environments, bias the compositions of autochthonous diatoms. Mixing autochthonous and allochthonous diatoms complicates the interpretation of the fossil diatom assemblages. Therefore, the allochthonous diatoms may mislead paleoenvironmental reconstructions.

It is necessary to discriminate between autochthonous and allochthonous diatoms in order to interpret fossil diatom assemblages. Vos and Wolf (1993) summarized the criteria of autochthonous and allochthonous diatoms. For example, the different ecological groups, such as freshwater or marine, did not overlap in the habitats, and thus, at least one of the two groups must be allochthonous. However, the criteria by Vos and Wolf (1993) could be more practical because the different ecological groups can be observed at intertidal zones. In practice, the autochthonous or allochthonous diatom is clarified by discriminating between the living and dead diatom in surface sediments (Gotoh 1978; Gotoh 1988a; Gotoh 1988b; Kosugi 1985; Kosugi 1986a; Kosugi 1986b; Kosugi 1989; Sawai 2001). The discrimination of living or dead diatom was developed using hematoxylin and eosin stains, dying the nucleus and chromatophore, respectively (Gotoh 1978). The comparison of the distribution of living diatom cells and dead diatom valves in each species allows us to estimate whether the species are allochthonous diatoms (Kosugi 1985). Kosugi (1986a; 1986b) applied the staining method for the sediments of the coastal setting in the mouth of the Obitsu River, Chiba Prefecture, Japan, and estimated diatom preservation based on the ratio between complete and fragmented diatom valves to discuss diatom transportation and sedimentation. In the tidal flat, intact and fragmented diatom valves experimented with different transportation processes (Kosugi 1986a; 1989). These studies found that the relative abundance of intact valves of autochthonous diatoms decreased with increasing of allochthonous diatoms deposition. Incorporating of allochthonous diatoms increased in the river mouth and tidal flats of the Obitsu River, where water movements by river and tidal currents were active. Based on the autochthonous diatoms in the river mouth of Obitsu River, Kosugi (1988a; 1988b) suggested that the diatom assemblages indicated salinity and substratum. Sawai (2001) classified the diatom assemblages based on vegetation, substratum, and tide level by recognizing the autochthonous diatom in tidal marshes of eastern Hokkaido, northern Japan. The ecological group in the salt marsh showed that the ratio of autochthonous and allochthonous diatom differed depending on the local environments. Chiba et al. (2021) reported the allochthonous diatoms in the coastal lowland of the Toberi River area, Hokkaido using hematoxylin-eosin stains. The allochthonous diatom and Neogene extinct diatom in the Toberi River area were excluded from the paleoenvironmental reconstruction (Chiba et al. 2021). Recognizing autochthonous and allochthonous diatom valves is essential issue to reconstruct paleoenvironments using diatom valves.

The modern and fossil diatoms are altered in taphonomic processes, such as chemical dissolution (Flower 1993; Ryves et al. 2003; Shimada et al. 2003) and physical breakage (Beyens and Denys 1981; Kosugi 1986a; Scherer et al. 2004). The dissolution of diatom valves is strongly dependent on the valve surface area and volume ratio in saline lakes (Flower and Ryves 2009; Reed 1998; Ryves et al. 2009). Fragile diatoms such as fine *Nitzschia* and *Rhizosolenia* taxa readily dissolve and rarely remain in sediments, significantly affecting fossil diatom assemblages and their ecological interpretation (Flower 1993; Ryves et al. 2009; Ryves et al. 2013). The laboratory experiments on diatom dissolution indicated that saline and alkali water promoted diatom dissolution

(Flower 1993; Kamatani et al. 1980). The physical breakage of diatom valves results from sample preparation, bioturbation (Austin et al. 2005), compaction, and long-distance transport (Beyens and Denys 1981; Kosugi 1986a). Macrofauna, such as amphipods and gastropods, and zooplanktons, such as benthic foraminifera, can be considered to be grazers of diatoms (Austin et al. 2005; Haberyan 2003; Hagerthey et al. 2002; Jewson et al. 1981).

The diatom transportation can play a large part in the diatom valve fragmentation. The allochthonous diatoms widely distribute beyond their habitats because of water movement in rivers and tides (Kosugi 1986a; Sherrod et al. 1989). On the other hand, tsunami also transport diatom assemblages to form tsunami sediments (Sawai 2014). Dawson (2007) demonstrated that the diatom assemblages in the tsunami sediments were composed of marine and freshwater diatoms with highly fragmented greater than 75%. However, the degree of diatom valve fragmentation varied among the tsunami sediments (Dura et al. 2016). Some tsunami sediments have relatively well-preserved diatom valves rather than intertidal areas (Dura et al. 2016).

Diatom transportation is also important for diatom taphonomy (Chiba et al. 2011; Tilstone et al. 2000). For example, Sagayama (2006) reported that freshwater diatoms were found in the marine sediments. The relative abundances of the freshwater diatoms decreased with the distance from river mouths, indicating the riverine transporation. In addition, the transportation by waves and tidal currents causes the separation of diatom frustule (Sawai 2001). *Cocconeis scutellum*, living on seagrass, was allochthonous diatom valves in the tidal flat (Sawai 2001). *Cocconeis scutellum* strongly attaches on seagrass by the raphid valve, and their rapheless valves are readily separated from the raphid valve and widely spread in the tidal flat. Therefore, the raphid valves of *C. scutellum* are found in the seagrass vegetation zones, whereas the rapheless valves are widely spread in intertidal areas (Sawai, 2001). There are few previous studies evaluating diatom frustule separation because it is necessary to distinguish between the upper and lower valves, and only some taxa can be applied. The transportation of diatom valves caused changes from modern to fossil diatom assemblages and distorted the interpretation of fossil diatom assemblages based on modern diatom ecology.

Allochthonous diatoms occurrences in studies on sea-level change, geomorphological development, and tectonics in coastal areas employing diatom assemblages (Chiba 2014; Hassan et al. 2006). As described above, allochthonous diatoms in sediment is a noise to obscure paleoenvironmental reconstructions. However, there is a considerable room for diatom taphonomy particularly in freshwater areas. In terrestrial settings, a diatom-salinity transfer function model incorporating the diatom dissolution was developed (Ryves et al. 2009). The taphonomic signatures related to the dissolution highlight that the understanding the taphonomic process along the pathway from the living diatom assemblages to the fossil assemblages preserved in sediment is necessary to utilize diatom taphonomy. The taphonomic processes result in not only dissolution and also fragmentation and frustule separation, and our knowledge about this complex process should be improved to clarify the diatom taphonomy in terrestrial settings.

3. Significance of shallow lakes in diatom taphonomic study

Hassan et al. (2018) applied diatom taphonomic analysis based on valve fragmentation and dissolution to paleoenvironmental reconstruction in Lake Nahuel Rucá, Argentina. They showed the usefulness of taphonomic indices for paleoenvironmental reconstruction in the heterogenous shallow lake. In shallow lakes, vertical mixing, wave action, and inflow rivers provide a chance to estimate how diatom valves are transported in different sedimentary environments. Hassan et al. (2018) implied the importance of investigating diatom taphonomy in shallow lakes. The heterogenous environment, such as water quality and vegetation and sedimentological parameters were variable locally within shallow lakes. The diatom diversity and preservation also have variability within the local scale, such as differences in the aquatic vegetation (Rojas and Hassan 2017). In littoral areas in shallow lakes, the abundance of epiphytic or benthic diatoms promote benthos productivity. The productivity of planktonic diatoms develops by vertical mixing of lake water. Although the diatoms with high species diversity in shallow lakes are useful for ecological and paleoenvironmental studies, the diatom taphonomy in shallow lakes has been overlooked.

Interpretation of fossil diatom assemblages in shallow lakes is complex due to the heterogeneous water movement, such as vertical mixing within lakes. Lake Kitaura exhibits the typical physical characteristics of shallow lakes, constituting a good model for investigating of diatom transportation. The distribution of sediments is controlled by erosion, transportation, and resuspension (Naya et al. 2004a). The bottom sediments in the lake basin consist of silty clay, whereas sandy sediments occur in the littoral parts. The sedimentary distribution is predominantly affected by wind-induced waves, wind direction, and wind velocity due to the lake’s shallowness (Naya et al. 2004a). The northeast wind prevailing drives surface water and waves, and thus, vertical mixing of the lake water occurs. The waves transport silty-clayey sediment particles to the lake basin, and the fine sediments deposit during calm conditions. The sandy sediment particles tend to deposit in the littoral areas selectively. The northern part of Lake Kitaura contains a shallow basin (water depth 2.5 m) with clay to silt deposits. In addition, the indented shoreline in the northern part results in a short fetch, leading to the deposition of fine silty clay. Except for the Tomoe River, the distribution of sandy sediment near inflowing rivers is limited, indicating that most inflow rivers transport a small amount of sediment (Naya et al. 2004a). The heterogeneous sediment distribution resulting from water movement can relate to the transport of diatoms in the lake. Moreover, the availability of previous works on the modern diatom assemblages in Lake Kitaura demonstrates its heterogeneity and variability in diatom composition (Naya et al. 2007b), implying its usefulness for studying of within-lake diatom taphonomy.

4. The goal of this study

This study aims to understand the diatom transportation process in a shallow lake using diatom valve fragmentation and frustule separation. Chapter 2 discussed the diatom transportation estimated by valve fragmentation and frustule separation in Lake Kitaura. In Chapter 3, the diatom transportation of benthic diatom valves was confirmed by the transport and provenance of other sedimentary particles in the lake-surface sediments.

Reference

Austin HA, Austin WEN, Paterson DM (2005) Extracellular cracking and content removal of the benthic diatom pleurosigma angulatum (quekett) by the benthic foraminifera haynesina germanica (ehrenberg). Marine Micropaleontology 57: 68-73

Battarbee RW, Flower RJ (2003) The inwash of catchment diatoms as a source of error in the sediment ‐ based reconstruction of ph in an acid lake1. Limnology and Oceanography 29: 1325-1329

Bennion H, Sayer CD, Tibby J, Carrick HJ (2010) Diatoms as indicators of environmental change in shallow lakes. In: J. P. Smol and E. F. Stoermer The diatoms: Applications for the environmental and earth sciences.Cambridge University Press, Cambridge, 152-173

Beyens L, Denys L (1981) Problems in diatom analysis of deposits: Allochtonous valves and fragmentation. Geologie en Mijnbouw 61: 159-162

Birks HJB (2010) Numerical methods for the analysis of diatom assemblage data. In: J. P. Smol and E. F. Stoermer The diatoms: Applications for the environmental and earth sciences.Cambridge University Press, Cambridge, 23-54

Chiba T, Endo K, Masubuchi K (2011) Size distribution of diatom frustules and sedimentary process of dead diatoms in a tidal zone. The Quaternary Research 50: 279-293 [(in Japanese)]

Chiba T (2014) Taphonomy of diatoms and problems of paleoenvironmental reconstruction in coastal areas using diatom assemblages. Diatom 30:

Chiba T, Sawai Y (2014) Reexamination and updating of diatom species for paleoenvironmental reconstructions. Diatom 30: 17-30 [in Japanese]

Chiba T, Sugihara S, Matsushima Y, Arai Y, Endo K (2016) Reconstruction of holocene relative sea-level change and residual uplift in the lake inba area, japan. Palaeogeography, Palaeoclimatology, Palaeoecology 441: 982-996

Chiba T, Nishimura Y, Yanagisawa Y (2021) Distinguishing reworked diatoms derived from neogene marine strata in modern coastal assemblages for understanding taphonomic processes and reconstructing holocene paleoenvironments in the tokachi coastal area, hokkaido, japan. Marine Micropaleontology 164: 101970

Dawson S (2007) Diatom biostratigraphy of tsunami deposits: Examples from the 1998 papua new guinea tsunami. Sedimentary Geology 200: 328-335

Dura T, Hemphill-Haley E, Sawai Y, Horton BP (2016) The application of diatoms to reconstruct the history of subduction zone earthquakes and tsunamis. Earth-Science Reviews 152: 181-197

Flower RJ (1991) Seasonal changes in sedimenting material collected by high aspect ratio sediment traps operated in a holomictic eutrophic lake. Hydrobiologia 214: 311-316

Flower RJ (1993) Diatom preservation: Experiments and observations on dissolution and breakage in modern and fossil material. Hydrobiologia 269-270: 473-484

Flower RJ, Ryves DB (2009) Diatom preservation: Differential preservation of sedimentary diatoms in two saline lakes.

Gotoh T (1978) On a judging method of living cells or non-living cells in the study of the diatom vegetation. The Japanese Journal of Phycology 26: 68 [in Japanese]

Gotoh T (1988a) Dead cell content in diatom samples. Japanese Journal of Water Treatment Biology 24: 132-134 [in Japanese]

Gotoh T (1988b) Analysis of diatom community by the cell nucleus staining method. Diatom 4: 67-72 [in Japanese]

Haberyan KA (2003) The role of eopepod fecal pellets in the deposition of diatoms in lake tanganyika1. Limnology and Oceanography 30: 1010-1023

Hagerthey SE, Defew EC, Paterson DM (2002) Influence of corophium volutator and hydrobia ulvae on intertidal benthic diatom assemblages under different nutrient and temperature regimes. Marine Ecology Progress Series 245: 47-59

Hassan GS, Espinosa MA, Isla FI (2006) Modern diatom assemblages in surface sediments from estuarine systemsin the southeastern buenos aires province, argentina. Journal of Paleolimnology 35:

Hassan GS, Rojas LA, De Francesco CG (2018) Incorporating taphonomy into community-based paleoenvironmental reconstructions: Can diatom preservation ddiscriminate among shallow lake sub-environments? Palaios 33: 376-392

Hemphill-Haley E (1995) Diatom evidence for earthquake-induced subsidence and tsunami 300 yr ago in southern coastal washington. Geological Society of America Bulletin 107: 367-378

Hirose K, Gotoh T (2009) Horizontal distribution of diatom remains in the northeastern part of osaka bay. Diatom 25: 21-36

Jewson DH, Rippey BH, Gilmore WK (1981) Loss rates from sedimentation, parasitism, and grazing during the growth, nutrient limitation, and dormancy of a diatom crop. Limnology and Oceanography 26: 1045-1056

Kamatani A, Riley JP, Skirrow G (1980) The dissolution of opaline silica of diatom tests in sea water. Journal of the Oceanographical Society of Japan 36:

Kashima K (1990) Holocene environmental change in some brackish lakes in japan, presumed by fossil and sedimentary analyses of lake sediments. J. Sed. Soc. Japan 32: 31-32 [Japanese]

Kato M, Tanimura Y, Matsuoka K, Fukusawa H (2000) Diatom flora in sinking particles and coastal marine sediments, examined by sediment trap method in omura bay, western japan. LAGUNA 7: 53-60 [Japanese]

Kato M, Tanimura Y, Matsuoka K, Fukusawa H (2003) Planktonic diatoms from sediment traps in omura bay, western japan with implications for ecological and taphonomic studies of coastal marine environments. Quaternary International 105: 25-31

Kosugi M (1985) Discrimination of living or dead cells of diatom based on the stained images - its meod and significance -. The Quaternary Research 24: 139-147 [in Japanese]

Kosugi M (1986a) Transportation and sedimentation patterns on dead diatoms in a tidal area - a case study in the lower reach of the obitsu river -. Geographical Review of Japan 59: 37-50 [in Japanese]

Kosugi M (1986b) Some fundamental problems on paleoecology of diatoms. Diatom 2: 169-174 [in Japanese]

Kosugi M (1988a) Method for paleoenvironmental reconstructions based on the similarities between present communities and fossil assemblages of diatom. Diatom 4: 89-98

Kosugi M (1988b) Classification of living diatom assemblages as the indicator of environments, and its application to reconstuction of paleoenvironments. The Quaternary Research 27: 1-20

Kosugi M (1989) Processes of formation on fossil diatom assemblages and the paleoecological analysis. Benthos research 35/36: 17-28 [in Japanese]

Naya T, Amano K, Okada M, Nakazato R, Kumon F, Nirei H (2004a) Characteristics of bottom surface sediments in relation to wind and wave action in lake kitaura, central japan. Journal of Geological Society of Japan 110: 1-10

Naya T, Tanimura Y, Kanai Y, Kumon F, Amano K (2007a) Natural and anthropogenic aquatic environmental changes reconstructed by paleolimnological analyses in lake kitaura, central japan. Journal of Paleolimnology 37: 547-563

Naya T, Tanimura Y, Nakazato R, Amano K (2007b) Modern distribution of diatoms in the surface sediments of lake kitaura, central japan. Diatom 23: 55-70

Reed JM (1998) Diatom preservation in the recent sediment record of spanish saline lakes: Implications for palaeoclimate study. Journal of Paleolimnology 19: 129-137

Rojas LA, Hassan GS (2017) Distribution of epiphytic diatoms on five macrophytes from a pampean shallow lake: Host-specificity and implications for paleoenvironmental reconstructions. Diatom Research 32: 263-275

Round FE, Crawford RM, Mann DG (1990) Diatoms biology and morphology of the genera. Cambridge university press, Cambridge

Ryves DB, Jewson DH, Sturm M, Battarbee RW, Flower RJ, Mackay AW, Granin NG (2003) Quantitative and qualitative relationships between planktonic diatom communities and diatom assemblages in sedimenting material and surface sediments in lake baikal, siberia. Limnology and Oceanography 48: 1643-1661

Ryves DB, Battarbee RW, Fritz SC (2009) The dilemma of disappearing diatoms: Incorporating diatom dissolution data into palaeoenvironmental modelling and reconstruction. Quaternary Science Reviews 28: 120-136

Ryves DB, Anderson NJ, Flower RJ, Rippey B (2013) Diatom taphonomy and silica cycling in two freshwater lakes and their implications for inferring past lake productivity. Journal of Paleolimnology 49: 411-430

Sagayama T (2006) Distribution of fresh water diatom valves in the surface sediments off the tokachi-gawa, teshio-gawa and ishikari-gawa, hokkaido, japan. Jour. Geol. Soc. Japan 112: 594-607 [(in Japanese)]

Sato Y, Matsuoka H, Okamura M, Kashima K (2016) Late holocene environmental changes of coastal lagoon inferred from a fossil diatom analysis of sediment core from lake hamana, central japan. Quaternary International 397: 317-329

Sawai Y (2001) Distribution of living and dead diatoms in tidal wetlands of northern japan: Relations to taphonomy. Palaeogeography, Palaeoclimatology, Palaeoecology 173: 125-141

Sawai Y (2014) Diatom fossil analysis as an aid for paleoseismology. Diatom 30: 57-74 [in Japanese]

Scherer RP, Sjunneskog CM, Iverson NR, Hooyer TS (2004) Assessing subglacial processes from diatom fragmentation patterns. Geology 32: 557

Sherrod BL, Rollins HB, Kennedy SK (1989) Subrecent intertidal diatoms from st. Catherines island, georgia; taphonomic implications. Journal of coastal research 5: 665-677

Sherrod BL (1999) Gradient analysis of diatom assemblages in a puget sound salt marsh: Can such assemblages be used for quantitative paleoecological reconstructions? Palaeogeography, Palaeoclimatology, Palaeoecology 149: 213-226

Shimada C, Hasegawa S, Tanimura Y, H. BL (2003) A new index to quantify diatom dissolution levels based on a ratio of neodenticula seminae frustule components. micropaleontology 49: 267-276

Smol JP, Stoermer EF (2010) The diatoms applications for the environmental and earth sciences. Cambrige university press, Cambridge

Suto I (2006) The explosive diversification of the diatom genus chaetoceros across the eocene/oligocene and oligocene/miocene boundaries in the norwegian sea. Marine Micropaleontology 58: 259-269

ter Braak CJF, Juggins S (1993) Weighted averaging partial least squares regression (wa-pls): An improved method for reconstructing environmental variables from species assemblages. Hydrobiologia 269/270: 485-502

Tilstone GH, Míguez BM, Figueiras FG, Fermín EG (2000) Diatom dynamics in a coastal ecosystem affected by upwelling: Coupling between species succession, circulation and biogeochemical processes. Marine Ecology Progress Series 205: 23-41

Vos PC, Wolf Hd (1988) Methodological aspects of paleo-ecological diatom research in coastal areas of the netherlands. Geologie en Mijnbouw 67: 31-40

Vos PC, Wolf Hd (1993) Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects. Hydrobiologia 269/270: 285-296

Watanabe T (2005) Picture book and ecology of the freshwater diatoms. Uchida Rokakuho publishing co., LTD., Tokyo [in Japanese]

CHAPTER 2

Fragmentation and separation of diatom valves in modern shallow lake sediments: A case study in Lake Kitaura, Japan

Abstract

We investigated diatom-valve fragmentation and frustule separation in bottom surface sediments in Lake Kitaura, a shallow lake in Japan, to clarify how sedimentation processes affect diatom assemblages. Twenty-two surface-sediment samples were collected from Lake Kitaura in 2014. *Aulacoseira* spp. were characteristic planktonic taxa, and *Cocconeis placentula* and *Planothidium lanceolatum* were characteristic benthic taxa, both with monoraphid valves. The fragmentation ratios of *Aulacoseira* spp., the most abundant taxon, were higher nearshore than in the central part of the lake. *Cocconeis placentula*, an epiphytic species, was widely distributed in Lake Kitaura, and its fragmentation ratios increased with distance from the lakeshore. The coexistence ratios of the two valve types of this species decreased with distance from the lakeshore and from macrophytic vegetation. *Planothidium lanceolatum*, a fluvial benthic species, was abundant at the three northernmost sites near a river mouth, and the frustules of this species were seldom separated. These results suggest that long-distance transport promotes fragmentation and separation of benthic diatom valves in shallow lakes.

2.1. Introduction

Diatoms are common and widespread algae in aquatic environments from terrestrial to marine settings (Smol and Stoermer 2010). They form a silica frustule composed of two valves, which is preserved in sediments. The diatom communities indicate their habitat, ecology, and water environment in lakes (Bennion et al. 2010). Fossil diatom assemblages in lake sediments have been employed to reconstruct past water environments such as pH, salinity, and lake-level changes (Chiba et al. 2016; Sato et al. 2016; Vos and Wolf 1993).

Diatom assemblages in lake sediments are also altered by taphonomic factors such as chemical dissolution and the physical breakage of diatom valves (Flower 1993; Hassan et al. 2018). Dissolution of diatom valves is primarily controlled by salinity and pH in lake waters (Ryves et al. 2001, 2009, 2013). Bioturbation (Austin et al. 2005), compaction, and long-distance transport (Kosugi 1986) play a large part in the physical breakage and fragmentation of diatom valves. Although the breakage process has been estimated from the ratio of complete to fragmented valves (Beyens and Denys 1981), our knowledge of the physical breakage and fragmentation of diatom valves during transport still needs improvement.

The robustness of diatom frustules varies between species, and thus also influences fragmentation, complicating the physical breakage process. For monoraphid diatom species, in which one valve differs from the other morphologically (i.e., they possess araphid and raphid valves), the different valves may experience different taphonomic processes (Hassan et al. 2018). The raphid and araphid valves show different distributions, as reported by Sawai (2001) for *Cocconeis scutellum*. After separation of the valves, waves, currents, and bioturbation disperse araphid valves, whereas raphid valves become concentrated near the substrata. Thus, the ratio of araphid to raphid valves is a promising indicator for assessing the transport process.

The aim of this study was to examine how diatom fragmentation and frustule separation proceed in a shallow lake. In shallow lakes, riverine inflows and waves generally affect the bottom sediment, and may also influence fragmentation and separation during the transport of diatom frustules. The diatom assemblages in Lake Kitaura sediments provide an excellent chance to assess how transportation processes alter the diatom fragmentation and separation in the shallow lake sediments through transport from riverine and lakeshore inputs and via wind-driven sediment resuspension.

2.2. Study area

Lake Kitaura is a freshwater lagoon lake located in the southeastern part of Honshu Island, Japan (Fig 2-1. Appendix A 1A). The lake has an area of 35.2 km^2, a perimeter of 64 km, a maximum water depth of 7 m, and an average water depth of 4.5 m with the northern part relatively shallow. Among the twenty-two river inflows, the Rivers Tomoe and Hokota at the northernmost part of the lake have the highest and second-highest flow rates, with catchment areas of 131.8 km^2 and 52.7 km^2, respectively (Fujita et al. 2006). The River Wani is the sole outflow from Lake Kitaura to the south, and connects to Lake Sotonasakaura. Reed vegetation occurs around part of the lakeshore, particularly near the mouths of the Rivers Tomoe, Hokota, and Yamada.

The Pleistocene plain around Lake Kitaura formed mainly during the last interglacial. The incision of the River Tomoe formed the basin of Lake Kitaura during the last glacial period (Kashima 1990; Saito et al. 1990). Lake Kitaura was a bay during the mid-Holocene transgression at 10,000–5500 yr BP, and burial of the bay mouth by a tidal flood delta began at 4500–2500 yr BP. In the 17th century, redirection of the River Tone to its present-day path buried the bay mouth completely. As a result, the lake water changed from brackish to fresh–brackish. In the 1970s, the River Hitachi tide gate was constructed (Fig. 2-1A) and the lake water became fresh, with a present-day salinity of

0.06 ‰ and pH of 8.8 (Ibaraki Prefectural Government 2021; Naya et al. 2007a).

Lake Kitaura is a good model area to study shallow lake environments because of the extensive knowledge available about its sediments and diatoms. The distribution of Lake Kitaura sediments is determined by erosion, transportation, and resuspension (Naya et al. 2004a). The bottom sediments in the lake basin consist of silty clay. Sandy sediments occur in the littoral parts at 0.5–3.5 m water depth. The sediment distribution is predominantly affected by wind-induced waves, wind direction, and wind velocity because of the lake's shallowness (Naya et al. 2004a). The northeast wind prevailing around Lake Kitaura drives surface waves and thus vertical mixing of the lake water. The waves transport silty-clayey sediment particles to the lake basin, whereas sandy sediment particles are left in the littoral areas. The northern part of Lake Kitaura contains a shallow basin (water depth 2.5 m) with clay to silt deposits. The short fetch by the indented shoreline leads to deposition of fine silty clay. Except for the Tomoe River, the distribution of sandy sediment near inflowing rivers is limited, indicating a small riverine influence on the grain-size distribution (Naya et al. 2004a). The heterogeneous sediment distribution resulting from water movement can be relevant for the transport of diatoms in the lake.

Naya et al. (2007b) reported the taxonomy and spatial distribution of diatoms in the bottom surface sediments of Lake Kitaura and suggested that the diatom assemblages comprised a mixture of taxa that originated from different habitats (water column, shoreline macrophyte zone, and inflowing rivers). The diatom assemblages imply the existence of autochthonous and allochthonous diatoms. Autochthonous diatoms are deposited in their habitat. In contrast, allochthonous diatoms are affected by transportation. Some benthic diatoms attached to substrata in littoral areas are carried to offshore locations, and then they can be regarded as allochthonous valves. The 22 rivers that flow into Lake Kitaura carry suspended particles, including allochthonous diatom valves. A sediment-trap study demonstrated that sediments and diatom valves are resuspended and laterally transported by the wind-driven lake circulation (Naya et al. 2004b). These reworked diatoms may also represent allochthonous valves.

2.3. Materials and methods

2.3.1. Sample collection

Surface-sediment samples were collected at 22 sites (called "kt01–kt22" from north to south) in Lake Kitaura during August and September 2014 using a gravity short corer with a diameter of 7 cm (Fig. 2-1B, C, Appendix A). Water depths at the sampling sites were measured with a sounding lead and ranged from 1.6 to 7.3 m (Appendix A).

Distance of sampling sites from the nearest lakeshore (called “distance to nearshore”) ranged from 100 to 930 m, and from the nearest aquatic vegetation zone (called “distance to vegetation”) ranged from 114 to 1623 m (Geospatial Information Authority of Japan, 2018). The top 5 cm of the sediment samples were placed in plastic bags, and each sample was stored in a laboratory refrigerator. Subsequently, wet samples were freeze-dried with a freeze dryer (FDU-1200, EYELA, Tokyo, Japan).

2.3.2. Diatom analysis

Approximately 0.05 g of freeze-dried sample was put into a 50-mL plastic tube and treated with 2 mL of 15% hydrogen peroxide in a water bath at 80 °C for 1 h to decompose organic matter. The suspended sample was diluted with distilled water to 20 mL to stop the reaction. For each suspended sample, 1 mL was dropped onto a coverslip and dried at room temperature. The dried samples were mounted on glass slides with Pleurax (Mount media, Fujifilm Wako Chemicals Corp., Osaka, Japan). Three hundred diatom valves were identified on each slide using a light microscope equipped with a 100× magnification oil immersion objective lens (BX53, Evident Co, Tokyo, Japan). Diatom taxa were identified following Round et al. (1990), Idei (2000), Watanabe (2005), Kobayasi et al. (2006), and Naya et al. (2007b). The diatom lifeform and habitat were based on Naya et al. (2007b) and Vos and Wolf (1993). Each diatom valve was classified as complete or fragmented. A fragmented valve was defined as a partially broken valve if at least 60% of the valve was present. Araphid and raphid valves of monoraphid taxa (i.e., *Cocconeis* and *Planothidium*) were counted separately. Additional counting of fifty valves of *Cocconeis placentula* was performed for each site to exclude the effect of differences in relative abundance.

We performed scanning electron microscopy (SEM) observation of the fine structures of diatom valves. The pretreated suspensions were filtered through a membrane filter (Advantech Co. Ltd., 0.45 μm pore size, 25 mm diameter) and dried at room temperature. The filtered samples were cut into 5-mm squares, taped onto an aluminum stub, and coated with OsO_4 using an osmium coater (Neoc-ST, Meiwafosis Co. Ltd., Tokyo, Japan). SEM observations were performed using a field-emission SEM (Regulus 8230, Hitachi High-Tec Co, Tokyo, Japan) with a 1 kV acceleration voltage, 10 μA emission current, and a working distance of 1.3 mm.

The diatom-valve-fragmentation ratio (*Fr*), the ratio of fragmented valves to total counted valves, was calculated for each diatom taxon (Supplementary data) as:

$$Fr = \frac{D}{Nv}$$

where *D* is the number of fragmented valves and *Nv* is the total number of valves for each diatom taxon. *Fr* values range from zero to one: zero means that no fragmented valves are present, whereas one means that all valves are fragmented. *Fr* values were calculated for species with an abundance of more than five valves in at least one sample. We selected *Aulacoseira* spp., *Cyclostephanos dubius*, *Cyclotella meneghiniana*, *Actinocyclus normanii* f. *subsalsa*, *Stephanodiscus hantzschii* f. *tenuis*, *Staurosira venter*, *Navicula* spp., *Achnanthidium* spp., *Planothidium* spp., *Psammothidium* spp, and *Cocconeis placentula* for *Fr* analysis in this study.

For monoraphid taxa, the raphid and araphid valves were counted separately. The coexistence ratio of raphid and araphid valves (*Cv*) was calculated for each taxon as:

$$Cv = 1 - \frac{|A - R|}{Nc}$$

where *A* and *R* are the counts of araphid and raphid valves, respectively, and *Nc* is the total population of each taxon (Shimoyama 1989), i.e., the greater number of araphid and raphid valves in each sample. The *Cv* index ranges from zero to one. If the counts of araphid and raphid valves are the same, the *Cv* index is one. If all valves in a sediment sample are araphid (or raphid), the *Cv* index is zero. Sawai (2001) demonstrated that the distribution patterns of raphid and araphid valves of *Cocconeis scutellum* differed in a tidal marsh: raphid valves were attached to the substrata and were more abundant near habitats, whereas araphid valves were moved easily by water movements (e.g., tidal action) and were widely dispersed. The *Cv* index increases when more autochthonous diatoms accumulate near their habitat. We selected two benthic monoraphid taxa, *Cocconeis placentula* and *Planothidium lanceolatum*, for the *Cv* analysis of Lake Kitaura samples.

We conducted the following data analyses using R software (version 4.0.4) with the 'stats' and 'vegan' packages. Hierarchical cluster analysis was conducted for the relative abundances of encountered diatom taxa at the species or genus level to identify the major environmental gradient underlying variation of diatom assemblages in the lake. The Bray–Curtis dissimilarity matrix and unweighted pair group method with arithmetic mean were used for the cluster analysis. Spearman's correlation analysis was applied to examine the relationship between *Fr* and *Cv* for each diatom taxon and the distance tonearshore, water depth, and distance from macrophytic vegetation. In addition, univariate regression analysis was conducted with *Fr* or *Cv* as the independent variable and distance to nearshoreas the dependent variable to show the relationships between taphonomic signatures of planktonic and benthic diatoms and environmental variables.

2.4. Results

2.4.1. Diatom assemblages in Lake Kitaura

Fifty diatom taxa were identified in the surface sediments at 22 sites in Lake Kitaura (Fig. 2-2, Appendix B). Planktonic taxa dominated the surface sediments of Lake Kitaura, exceeding 70% of the assemblages except at the northern sites kt01–kt03 (Fig. 2-3A). The abundances of tychoplanktonic taxa increased near the River Tomoe (Fig. 2-3B). Similarly, the relative abundances of benthic taxa were greater than 15% in the northern part of the lake (kt01–kt03; Fig. 2-3C). At these three sites near the mouth of the River Tomoe, 19–57% of the diatom assemblages consisted of benthic taxa. Relatively abundant benthic taxa were found at southern sites kt20–kt22.

Fifteen diatom taxa each formed more than 5% of the assemblage in at least one sample of Lake Kitaura's surface sediments. Of these taxa, *Aulacoseira ambigua*, *Aulacoseira granulata*, *Aulacoseira pusilla*, *Actinocyclus normanii* f. *subsalsa*, *Cyclostephanos dubius*, *Cyclotella meneghiniana*, and *Stephanodiscus hantzschii* f. *tenuis* are planktonic; *Staurosira venter*, *Pseudostaurosira* spp., and *Staurosirella* spp. are tychoplanktonic; and *Nitzschia* spp., *Gomphonema* spp., *Navicula* spp., *Cocconeis placentula*, *Achnanthidium* spp., *Planothidium* spp., and *Psammothidium* spp., are benthic (Fig. 2-4). *Aulacoseira ambigua* and *A. granulata* were the representative planktonic taxa in Lake Kitaura's surface sediments, but not at the four northern sites (kt01–kt04; Fig. 2-4A, B). The relative abundances of *A. pusilla* were lower than those of *A. ambigua* and *A. granulata* (Fig. 2-4 C). The relative abundances of *Cyclostephanos dubius* was higher in the southern part of the lake (Fig. 2-4E). *Cyclotella meneghiniana* was distributed mainly in the center of the lake, and was much less abundant at sites near river mouths (kt01, kt04, kt07, kt12, and kt16) and southern sites kt20–kt22 (Fig. 2-4F). *Staurosira venter* was the major tychoplanktonic taxon (Fig. 2-4H–J). *Navicula* spp., *Achnanthidium* spp., *Planothidium* spp., and *Psammothidium* spp. were the major benthic taxa (Fig. 2-4M, O). *Planothidium lanceolatum* was the most abundant taxon at the three northernmost sites. *Cocconeis placentula* showed a maximum abundance at the mouth of the River Tomoe (kt02; Fig. 2-4N). *Navicula* spp. was abundant at site kt01 at the mouth of the River Tomoe (Fig. 2-4M).

The 22 sites were divided into two clusters: cluster I and cluster II, with a dissimilarity of 0.5 (Fig. 2-5, Appendix A). The results of the hierarchical cluster analysis reflected that diatom assemblages at sites kt01–kt03 were abundant benthic and tychoplanktonic taxa (Fig. 2-4, Appendix C). Cluster I consists of samples from water shallower than 4 m depth. Cluster II contains sites deeper than 4 m water depth on a flat plain: kt06–k22.

2.4.2. Valve fragmentation and frustule separation

The range of *Fr* in Lake Kitaura sediments differed among diatom species and sampling sites (Fig. 2-6). *Aulacoseira* species and *Stephanodiscus hantzschii* f. *tenuis* showed low *Fr* values compared to the other planktonic taxa, i.e., *Cyclostephanos dubius*, *Cyclotella meneghiniana*, and *Actinocyclus normanii* f. *subsalsa* (Fig. 2-6). *Staurosira venter* had a low *Fr* value (<0.1) at almost all sites. *Navicula* spp. and *Cocconeis placentula* were highly fragmented. The spatial patterns of the *Fr* values of *Aulacoseira ambigua* and *A. granulata* showed that they tended to increase at relatively shallow sites (Fig. 2-7). The *Fr* values of *Aulacoseira ambigua* and *A. granulata* showed peaks at the Rivers Tomoe (kt02) and Gantsu (kt16), and at the southern littoral site (kt20). *Fr* of *A. ambigua* was also high at site kt10.

The *Cv* variations in *C. placentula* and *P. lanceolatum* showed different patterns (Fig. 2-7C and D). The *Cv* values of *C. placentula* were highest at the northern site kt03 and the southernmost site kt22. In contrast, *Planothidium lanceolatum* showed sporadically high *Cv* values at sites kt01, kt07, kt17, and kt20.

We focused on the valve fragmentation and frustule separation of *Cocconeis placentula*, which occurred ubiquitously in the sediments of Lake Kitaura. *Fr* and *Cv* values were calculated from data on 50 *C. placentula* valves for each sample (Fig. 2-8). The *Fr* values increased from north to south, and the lowest values were found at sites kt02 and kt07, which are close to river mouths. The *Fr* values of araphid valves exhibited a trend similar to that of *Fr* of whole valves, but *Fr* of raphid valves was different. The *Cv* values were higher at river mouths (kt02 and kt07) and the southernmost site (kt22). The spatial pattern of *Fr* values was a mirror image of that of the *Cv* values ($R = -0.64$).

2.4.3. The relationships of valve fragmentation, frustule separation, and environmental variables

The *Fr* values of *A. ambigua* and *A. granulata* showed a weak negative correlation with distance to nearshore ($R = -0.25$ and -0.44, respectively; Fig. 2-9A and B, Table 2-1). The highest correlation with *Fr* of *A. granulata* was distance to nearshore (Fig. 2-9B). In addition, *Fr* and *Cv* of *C. placentula* were correlated with water depth ($R = 0.42$ and -0.30, respectively), distance to nearshore ($R = 0.80$ and -0.47, respectively), and distance from neighboring aquatic macrophytic vegetation (distance to vegetation, $R = 0.57$ and -0.52, respectively). Thus, the highest correlation with *Fr* of *C. placentula* was distance to nearshore (Fig. 2-9C).

2.5. Discussion

2.5.1. Diatom distribution in Lake Kitaura

Diatom assemblages in the surface sediments of Lake Kitaura were composed of autochthonous and allochthonous specimens. Abundant *Aulacoseira* at most sites indicate a high contribution of autochthonous planktonic taxa in the diatom assemblages. Naya et al. (2007b) also reported that *Aulacoseira* taxa were the dominant diatoms in the surface sediments of Lake Kitaura, suggesting that this group is the major primary producer. A sediment-trap study observed flux peaks of both vegetative cells and empty valves of *Aulacoseira* taxa during spring and fall (Naya et al. 2004b). *Aulacoseira* taxa (*A. ambigua*, *A. granulata*, and *A. pusilla*) form resting spores after the spring bloom, which sink to the lake bottom in the oligotrophic summer (Kilham and Kilham 1975; Tsukada et al. 2006). The restarting of lake-water circulation in the fall brings the *Aulacoseira* resting spores to the surface water, where they revert to vegetative cells. Therefore, *Aulacoseira* taxa in Lake Kitaura's sediments are a mixture of autochthonous specimens that have sunk directly from the surface water and reworked valves that were transported by lake-sediment resuspension.

Benthic diatom taxa, such as *Navicula*, *Cocconeis*, *Achnanthidium* spp., *Planothidium* spp., and *Psammothidium* spp., in Lake Kitaura's sediments were transported from inflowing rivers and littoral areas. In particular, notable contributions of autochthonous benthic taxa were found at the northern sites (cluster I) near the mouth of the River Tomoe (Figs. 2-4 and 2-5). In contrast, the allochthonous valves are transported offshore (Naya et al. 2007b). *Planothidium lanceolata* and *Cocconeis placentula* dwell on substrata of inflowing rivers or on macrophytes. Thus, the presence of these benthic taxa can indicate transport of material from rivers and littoral areas. The presence of autochthonous diatoms (*Planothidium* and *Cocconeis*) in an assemblage can be explained by transport by inflowing water and valve fragmentation and frustule separation.

2.25.2. Fragmentation of planktonic diatoms

We discuss the sedimentation of *Aulacoseira* taxa as representative of planktonic diatoms in Lake Kitaura. The *Fr* values of *Aulacoseira* taxa were lower than those of other planktonic taxa—*Cyclostephanos dubius*, *Cyclotella meneghiniana*, and *Actinocyclus normanii* f. *subsalsa* (Fig. 2-6)—because of differences in valve shape and silicification. *Aulacoseira* taxa have heavily silicified cylindrical valves, whereas the other planktonic taxa have less silicified discoid valves, leading to selective valve fragmentation and dissolution (Ryves et al. 2001). Remains of *Aulacoseira pusilla*, which is a small species with valves measuring less than 10 μm in both diameter and height, were less fragmented than remains of *A. ambigua* and *A. granulata*. The *Fr* values of the discoid valves of *Stephanodiscus hantzschii* f. *tenuis* are lower than those of the discoid valves of other planktonic taxa such as *Cyclostephanos dubius*, *Cyclotella meneghiniana*, and *Actinocyclus normanii* f. *subsalsa*. Naya et al. (2007b) reported that the relative abundances of *A. pusilla* and *Stephanodiscus* species were positively correlated with sand content, and were high in littoral areas despite disturbance by wave erosion. *Aulacoseira pusilla* and *Stephanodiscus* spp. may be less influenced by wave action than other taxa (Naya et al. 2007b), and so the *Fr* values of these taxa were lower. Among the *Aulacoseira* taxa, the *Fr* values of *A. ambigua* and *A. granulata* were weakly correlated with distance to nearshore (Fig. 2-9A and B, Table 2-1). Naya et al. (2004a) suggested that lake currents and waves resuspend sediments in the lake basin; however, the *Fr* values of *Aulacoseira* taxa were lower in the center of the lake (sites kt13–kt15, kt17, and kt19) regardless of the influence of resuspension. The ecological features of requirement of turbulence (Hassan et al. 2018) and formation of resting spores (Anderson 2010; Hassan 2013; Schelske et al. 1995) suggest that vertical mixing is unimportant for valve fragmentation of *Aulacoseira* taxa. *Aulacoseira* valve fragmentation is likely to take place in river mouths and littoral areas where littoral erosion and wave-related transport occur (Fig. 2-7). However, the correlation between *Fr* and distance to nearshore was not strong (Fig. 2-9A and 2-9B). *Aulacoseira* taxa can also be found as tychoplanktonic species (Kobayasi et al. 2006), which may have caused the weak correlation between *Aulacoseira Fr* and distance to nearshore.

2.5.3. Transportation of benthic diatoms

Monoraphid diatom species provide clues for estimating the transport of allochthonous diatoms because of the differing in the attachment to the substrata between the raphid and araphid valves (Sawai 2001). The high abundances and *Cv* values of *P. lanceolatum* at sites near river mouths suggest transport of this species from the inflowing rivers, such as the rivers Tomoe and Hokota (kt01; Fig. 2-7). *Planothidium lanceolatum* may be attached to the substrata by the raphid valve in streams (Chen et al. 2017). The decrease in both *Cv* and abundance from kt01 to kt02 suggests frustule separation (Fig. 2-7). The high *Cv* values of *P. lanceolatum* in the offshore sites (kt17 and kt20; Fig. 2-7) indicate transport of valves as frustules. In contrast, the wide distribution of *C. placentula* suggests that remains of this species are transported from the inflowing rivers and littoral areas. The southernmost site (kt22) showed a high *Cv* value that is comparable to those of the northern sites (kt02 and kt07; Fig. 2-8). *Cocconeis placentula* lives attached to macrophytes by its raphid valve (Rojas and Hassan 2017), and has been demonstrated to dominate emergent, submersed, and rooted floating macrophytes in a shallow eutrophic lake (Hassan et al. 2018). The reed vegetation of Lake Kitaura is a potential habitat for *C. placentula* and source of autochthonous valves. Overall, the *Cv* trends reflect the origin and transport of *P. lanceolatum* and *C. placentula* in the lake sediments.

The negative correlation between *Fr* and *Cv* of *C. placentula* in Lake Kitaura indicates that transport affects the valve fragmentation and frustule separation. The difference between the *Fr* values of raphid and araphid *C. placentula* valves suggests that valve fragmentation mainly occurs during transport. Diatom-valve fragmentation is controlled by long-distance transportation (Dawson 2007; Kosugi 1989), bioturbation (Austin et al. 2005), and chemical dissolution (Ryves et al. 2006). Hassan et al. (2018) showed that the preservation of *C. placentula* was better in the macrophyte zone than in open-water environments. Bioturbation should not affect the araphid and raphid valves selectively, and chemical dissolution is unlikely in freshwater lakes with a near-neutral pH. Considering the correlation between *Fr* of the araphid valve and distance to nearshore, we suggest that valve fragmentation of *C. placentula* in Lake Kitaura is mainly caused by long-distance transport, demonstrating the importance of *Fr* and *Cv* as autochthonous indicators.

2.5.4. Diatom taphonomic process and implications for shallow lakes

The *Fr* and *Cv* values of benthic diatom taxa in surface sediments, particularly for monoraphid taxa such as *Planothidium* and *Cocconeis* species, are feasible indicators of the provenance and transport of diatom valves. The monoraphid *Cocconeis* and *Planothidium* taxa are often found in sediment samples from shallow lakes (Dong et al. 2007; Rojas and Hassan 2017; Ryves et al. 2009). These diatoms are attached to substrata, especially macrophytes, so they are a means of detecting the localities where those diatoms live. The high *Cv* values of *C. placentula* based on counting 50 valves per sample showed that autochthonous valves accumulated at sites near river mouths (Figs. 2-7 and 2-8A). The *Fr* index is helpful for indicating the transport distance: higher values suggest a greater transport distance. However, the *Fr* values of the raphid valves were weakly correlated with distance to nearshore because these valves, being attached to macrophytes, are difficult to transport. The positive correlation between the araphid valve *Fr* values and distance to nearshore suggests that these valves become fragmented during transport.

The *Fr* values of *Aulacoseira* taxa indicate the sedimentation process in the shallow lake regardless of the complex ecology. *Aulacoseira* taxa commonly live in shallow freshwater lakes (Anderson and Odgaard 1994; Dong et al. 2007; Flower 1991; Ryves et al. 2013). They dominate in the lake center but also dwell in littoral areas

(Kobayasi et al. 2006). *Aulacoseira ambigua*, *A. granulata*, and *A. pusilla* form thick, robust resting spores (Kilham and Kilham 1975; Tsukada et al. 2006). In shallow lakes, resuspension causes reworking of diatom assemblages (Hassan et al. 2018; Naya et al. 2004b). The consistently low *Aulacoseira Fr* values suggest that most *Aulacoseira* specimens in Lake Kitaura are autochthonous. A slight increase in the *Fr* values of *Aulacoseira* in the littoral area reflects lateral movement of valves by resuspension. *Aulacoseira* taxa grow in the water column and are deposited in central areas of the lake as autochthonous valves. The reworked valves of *Aulacoseira* were transported to a littoral area with fragmentation. However, *Aulacoseira* taxa can live in the littoral area as tychoplankton, and thus, the *Aulacoseira Fr* patterns can sometimes be equivocal compared to those of benthic taxa (kt01; Fig. 2-7).

Benthic diatom taxa can help to understand diatom taphonomy in shallow lakes because of their specific habitats and behaviors related to riverine inflow and aquatic vegetation. Benthic diatoms living in shore regions or rivers are transported into the lake and spread to the lake center. Autochthonous valves of benthic diatoms are mainly deposited near areas of reed vegetation (Flower 1993) and are well preserved (Hassan et al. 2018). Without vegetation in littoral areas, fine-grained benthic diatom valves are readily washed out by waves. Monoraphid benthic diatom taxa demonstrate how transport of benthic diatoms from the lakeshore to offshore regions results in selective removal of the araphid valves, causing the coexistence ratio of the paired valves to decrease (Sawai 2001). The *Cv* and *Fr* taphonomic indices can help to interpret diatom-assemblage data, and thus improve paleoenvironmental reconstructions based on diatom assemblages from sediments of shallow lakes.

2.6. Conclusions

We studied diatom assemblages in surface sediments from Lake Kitaura, and found that valve fragmentation and frustule separation differed by species, habitat, and ecology. Valve fragmentation of *Aulacoseira* taxa likely occurs in river mouths and lakeshore areas, not the lake center. Vertical mixing and resuspension in the water column are unlikely to promote fragmentation of *Aulacoseira* valves. Benthic diatom taxa for which both valves coexist in river mouths and lakeshore areas are autochthonous. The raphid valves of *Cocconeis placentula* were restricted to areas near the shore with reed vegetation, whereas the araphid valves were spread from the shore to offshore. The species' ecology and habitat caused both valves to behave differently and become separated. The *Fr* of *C. placentula* was more sensitive to the distance from the nearest shore and can be a good indicator of diatom transport from littoral areas. The *Cv* values also indicated transport of diatoms from their life habitat. However, the relationships between diatom-transport processes and sediments need to be clarified. In the future, sedimentological and chemical analyses should be conducted to confirm diatom-transport processes.

References

Anderson NJ (2010) Miniview: Diatoms, temperature and climatic change. Eur J Phycol 35: 307-314

Anderson NJ, Odgaard BV (1994) Recent palaeolimnology of three shallow danish lakes. Hydrobiologia 275-276:411-422

Austin HA, Austin WEN, Paterson DM (2005) Extracellular cracking and content removal of the benthic diatom *Pleurosigma angulatum* (Quekett) by the benthic foraminifera *Haynesina germanica* (Ehrenberg). Mar Micropaleontol 57:68-73

Bennion H, Sayer CD, Tibby J, Carrick HJ (2010) Diatoms as indicators of environmental change in shallow lakes. In: Smol JP and Stoermer FE (eds) The diatoms: Applications for the Environmental and Earth Sciences.Cambridge University Press, Cambridge, 152-173

Beyens L, Denys L (1981) Problems in diatom analysis of deposits: allochtonous valves and fragmentation. Geol Mijnbouw 61:159-162

Chen X, Stevenson MA, Zeng L, Qiao Q (2017) Diatom distribution in an alpine basin (central China) in relation to environmental factors and substrata. Diatom Res 32:251-262

Chiba T, Sugihara S, Matsushima Y, Arai Y, Endo K (2016) Reconstruction of holocene relative sea-level change and residual uplift in the lake Inba area, Japan. Palaeogeogr Palaeoclimatol Palaeoecol 441:982-996

Geospatial Information Authority of Japan (2018) Lake data of Kitaura and Sotonasakaura. https://www1.gsi.go.jp/geowww/lake/download/kitaura-sotonasakaura/kitaura-sotonasakaura-2018.zip

Dawson S (2007) Diatom biostratigraphy of tsunami deposits: examples from the 1998 Papua New Guinea tsunami. Sediment Geol 200:328-335

Dong X, Bennion H, Battarbee R, Yang X, Yang H, Liu E (2007) Tracking eutrophication in Taihu lake using the diatom record: Potential and problems. J Paleolimnol 40:413-429

Flower RJ (1991) Seasonal changes in sedimenting material collected by high aspect ratio sediment traps operated in a holomictic eutrophic lake. Hydrobiologia 214:311-316

Flower RJ (1993) Diatom preservation: Experiments and observations on dissolution and breakage in modern and fossil material. Hydrobiologia 269-270:473-484

Fujita K, Ito H, Oro T, Anma T (2006) A study on evaluation of water environment policy through watershed-scale - hydrological & material cycle simulation models to Kasumigaura lake and its watershed. Tech Note Nat Inst Land Infrastruct Manage 299: 3-20 [in Japanese]

Hassan GS (2013) Diatom-based reconstruction of middle to late Holocene paleoenvironments in lake Lonkoy, southern Pampas, Argentina. Diatom Res 28:473-486

Hassan GS, Rojas LA, De Francesco CG (2018) Incorporating taphonomy into community-based paleoenvironmental reconstructions: can diatom preservation discriminate among shallow lake sub-environments? Palaios 33:376-392

Ibaraki Prefectural Government (2023) Results of water quality measurements in public waters. https://www.pref.ibaraki.jp/seikatsukankyo/kantai/suishitsu/water/kokyoyosuiiki.html

Idei M (2000) Diatom from Kasumigaura. Ann Rep Stud 44:1-12 [in Japanese]

Kashima K (1990) Holocene environmental change in some brackish lakes in Japan, presumed by fossil and sedimentary analyses of lake sediments. J Sed Soc Jpn 32:31-32 [in Japanese]

Kilham SS, Kilham P (1975) *Melosira granulata* (Her.) Ralfs: morphology and ecology of a cosmopolitan freshwater diatom. Verh Int Ver Theor Angew Limnol 19:2716-2721

Kobayasi H, Idei M, Mayama S, Nagumo T, Osada K (2006) H. Kobayasi's atlas of Japanese diatoms based on electron microscopy. Uchida Rokakuho publishing co., LTD., Tokyo [in Japanese]

Kosugi M (1986) Transportation and sedimentation patterns on dead diatoms in a tidal area - a case study in the lower reach of the Obitsu River. Geogr Rev Jpn 59:37-50 [in Japanese]

Kosugi M (1989) Processes of formation on fossil diatom assemblages and the paleoecological analysis. Benthos Res 35/36:17-28 [in Japanese]

Naya T, Amano K, Okada M, Nakazato R, Kumon F, Nirei H (2004a) Characteristics of bottom surface sediments in relation to wind and wave action in lake Kitaura, central Japan. J Geol Soc Jpn 110:1-10

Naya T, Tanimura Y, Tsuchiya T, Abekawa H, Nakazato R, Amano K (2004b) Behavior of sinking particles and depositional processes o diatom frustules in shallow lake, examined by sediment trap in lake Kitaura, central Japan. Jpn J Limnol 65:203-213

[in Japanese]

Naya T, Tanimura Y, Kanai Y, Kumon F, Amano K (2007a) Natural and anthropogenic aquatic environmental changes reconstructed by paleolimnological analyses in lake Kitaura, central Japan. J Paleolimnol 37:547-563

Naya T, Tanimura Y, Nakazato R, Amano K (2007b) Modern distribution of diatoms in the surface sediments of lake Kitaura, central Japan. Diatom 23:55-70

Rojas LA, Hassan GS (2017) Distribution of epiphytic diatoms on five macrophytes from a pampean shallow lake: host-specificity and implications for paleoenvironmental reconstructions. Diatom Res 32:263-275

Round FE, Crawford RM, Mann DG (1990) Diatoms biology and morphology of the genera. Cambridge university press, Cambridge

Ryves DB, Anderson NJ, Flower RJ, Rippey B (2013) Diatom taphonomy and silica cycling in two freshwater lakes and their implications for inferring past lake productivity. J Paleolimnol 49:411-430

Ryves DB, Battarbee RW, Fritz SC (2009) The dilemma of disappearing diatoms: incorporating diatom dissolution data into palaeoenvironmental modelling and reconstruction. Quat Sci Rev 28:120-136

Ryves DB, Battarbee RW, Juggins S, Fritz SC, Anderson NJ (2006) Physical and chemical predictors of diatom dissolution in freshwater and saline lake sediments in north America and west Greenland. Limnol Oceanogr 51:1355-1368

Ryves DB, Juggins S, Fritz SC, Battarbee RW (2001) Experimental diatom dissolution and the quantification of microfossil preservation in sediments. Palaeogeogr Palaeoclimatol Palaeoecol 172:99-113

Saito Y, Inouchi Y, Yokota S (1990) Coastal lagoon evolution influenced by Holocene sea-level changes, Lake Kasumigaura, central Japan. Mem Geol Soc Jpn 36:103-118 [in Japanese]

Sato Y, Matsuoka H, Okamura M, Kashima K (2016) Late Holocene environmental changes of coastal lagoon inferred from a fossil diatom analysis of sediment core from Lake Hamana, central Japan. Quat Int 397:317-329

Sawai Y (2001) Distribution of living and dead diatoms in tidal wetlands of northern Japan: relations to taphonomy. Palaeogeogr Palaeoclimatol Palaeoecology 173:125-141

Schelske CL, Carrick HJ, Aldridge FJ (1995) Can wind-induced resuspension of meroplankton affect phytoplankton dynamics? J North Am Benthol Soc. 14:616-630

Shimoyama S (1989) Primary information and modification of fossil shell assemblages. Benthos Res 37:11-34 [in Japanese]

Smol JP, Stoermer EF (2010) The diatoms applications for the environmental and earth sciences. Cambrige university press, Cambridge

Tsukada H, Tsujimura S, Nakahara H (2006) Seasonal succession of phytoplankton in Lake Yogo over 2 years: effect of artificial manipulation. Limnology 7:3-14

Vos PC, Wolf H (1993) Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects. Hydrobiologia 269/270:285-296

Watanabe T (2005) Picture book and ecology of the freshwater diatoms. Uchida Rokakuho publishing co., LTD., Tokyo [in Japanese]

Table 2-1 Spearman's correlation coefficients between taphonomic signatures (*Fr* and *Cv*) of *Cocconeis placentula* and *Aulacoseira* taxa and water depth, distance to nearshore, and distance to vegetation

	Fr of *Cocconeis placentula*	Water depth (m)	Distance to nearshore (m)	Distance to vegetation
Fr of *Cocconeis placentula*	-	0.42	0.80	0.57
Cv of *Cocconeis placentula*	-0.62	-0.30	-0.47	-0.52
Fr (Araphid valve)	0.83	0.34	0.74	0.57
Fr (Raphid valve)	0.65	0.33	0.43	0.24
Fr of *Aulacoseira ambigua*	-	-0.04	-0.25	-
Fr of *Aulacoseira granulata*	-	-0.22	-0.44	-

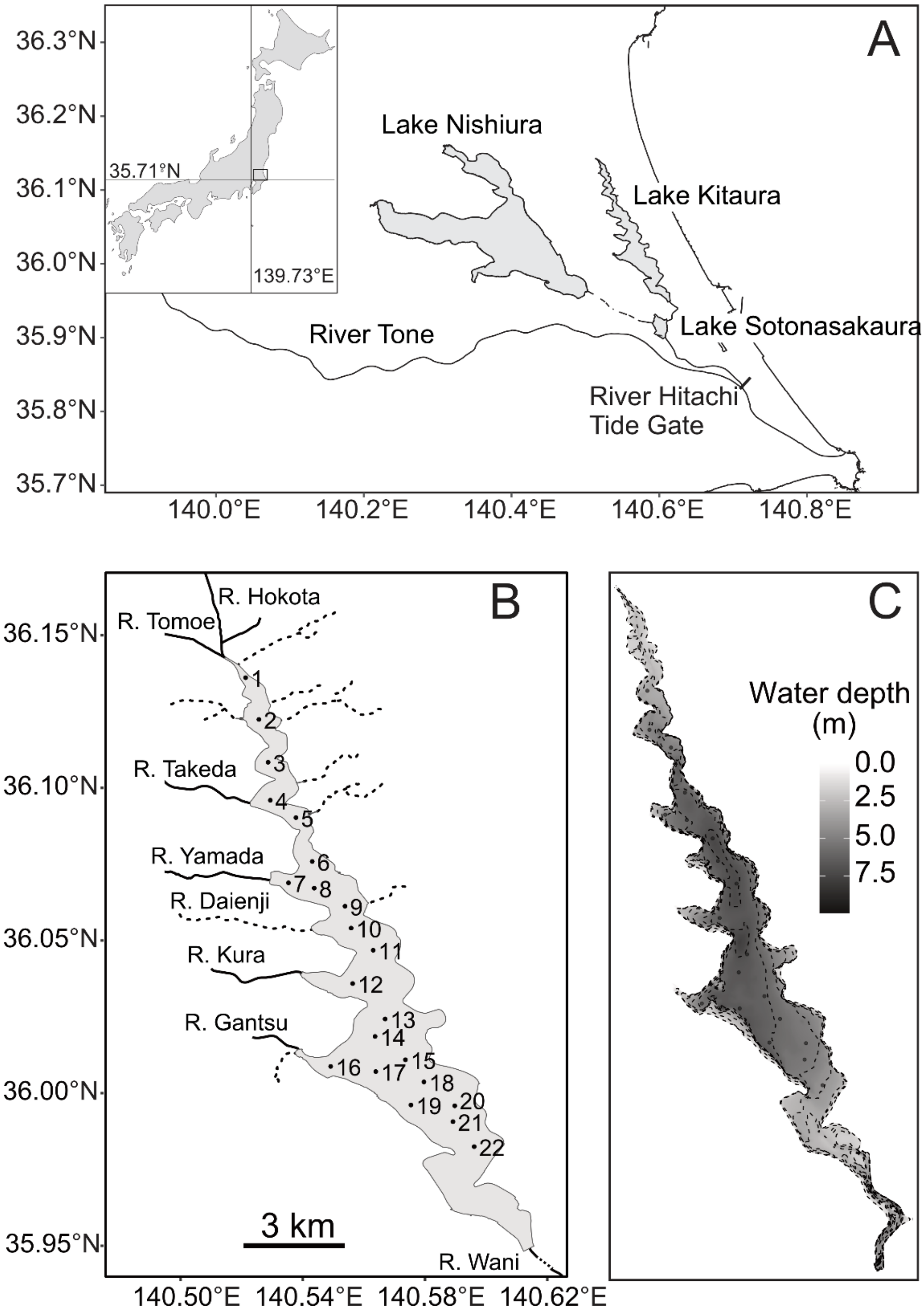

Fig. 2-1. Field setting. (A) Location of Lake Kitaura, Japan. (B) Map of the sampling sites (numbered) of lakebed-surface sediments in Lake Kitaura in 2014. Black solid and dashed lines denote inflowing rivers with watershed areas greater than and less than 8 km^2, respectively. The River Wani (dotted line) is the only outflowing river. (C) Lake bathymetry. Points denote the sampling sites shown in (B).

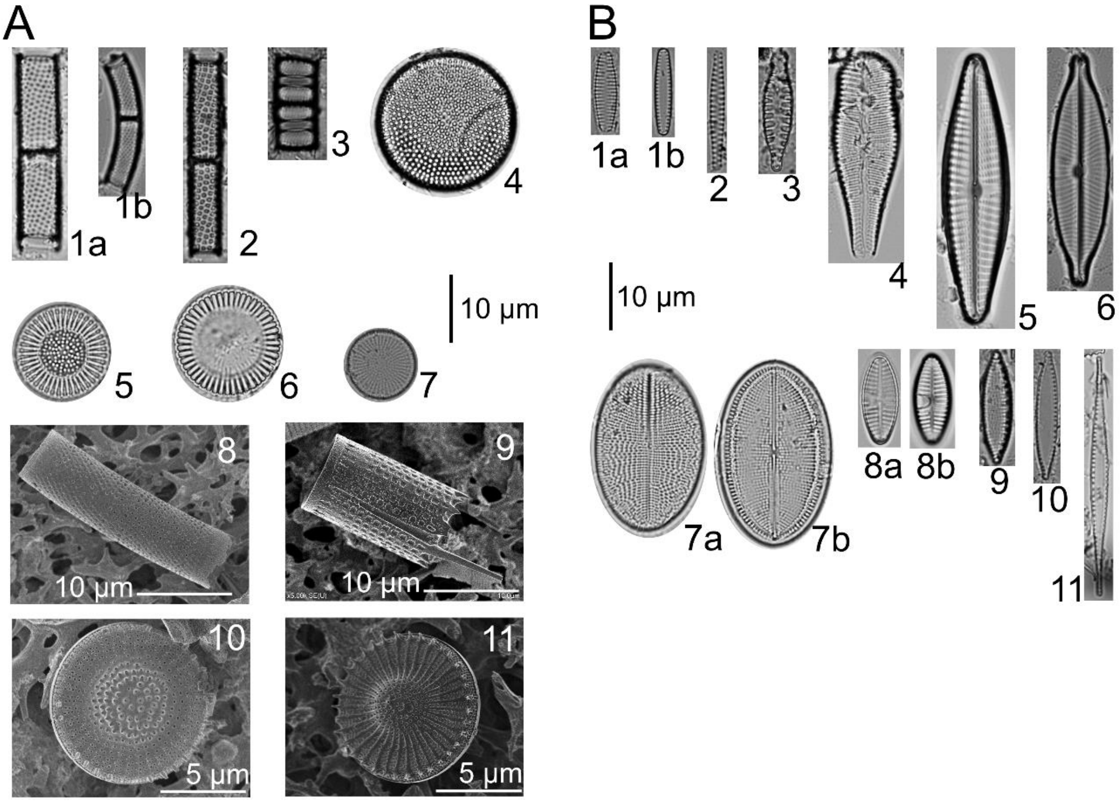

Fig. 2-2. Light microscopic and SEM images of diatoms from lakebed-surface sediments. (A) Planktonic taxa: (1a, 1b, 8) *Aulacoseira ambigua*, sites kt02 and kt03; (2, 9) *A. granulata*, kt02; (3) *A. pusilla*, kt08; (4) *Actinocyclus normanii* f. *subsalsa*, kt20; (5, 10) *Cyclostephanos dubius*, kt02; (6) *Cyclotella meneghiniana*, kt02; (7, 11) *Stephanodiscus hantzschii* f. *tenuis*, kt11 and kt02. (B) Tychoplanktonic and benthic taxa: (1a) *Staurosira venter*, site kt03; (1b) *Pseudostaurosira* spp., kt17; (2) *Staurosirella berolinensis*, kt21; (3) *Staurosira leptostauron* var. *dubia*, kt03; (4) *Gomphonema truncatum*, kt02; (5) *Navicula lanceolata*, kt02; (6) *Navicula amphiceropsis*, kt02; (7) *Cocconeis placentula*, kt02 (a, araphid valve; b, raphid valve); (8) *Planothidium lanceolatum*, kt01 (a, araphid valve; b, raphid valve); (9) *Nitzschia amphibia*, kt03; (10) *Nitzschia perminuta*, kt01; (11) *Nitzschia subacicularis*, kt02.

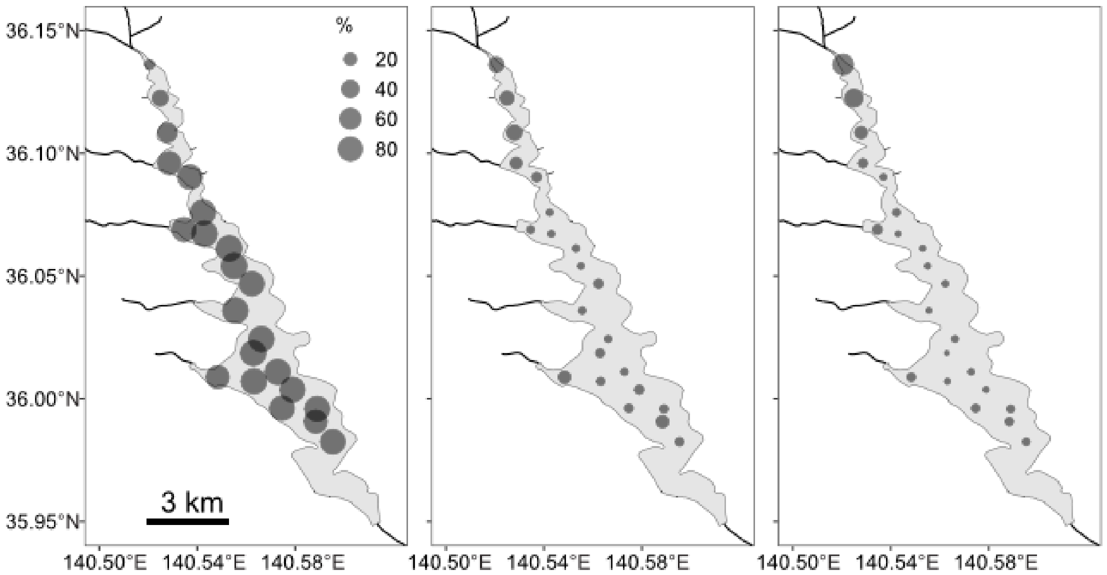

Fig. 2-3. Distributions of the relative abundances of (A) planktonic taxa, (B) tychoplanktonic taxa, and (C) benthic taxa in Lake Kitaura.

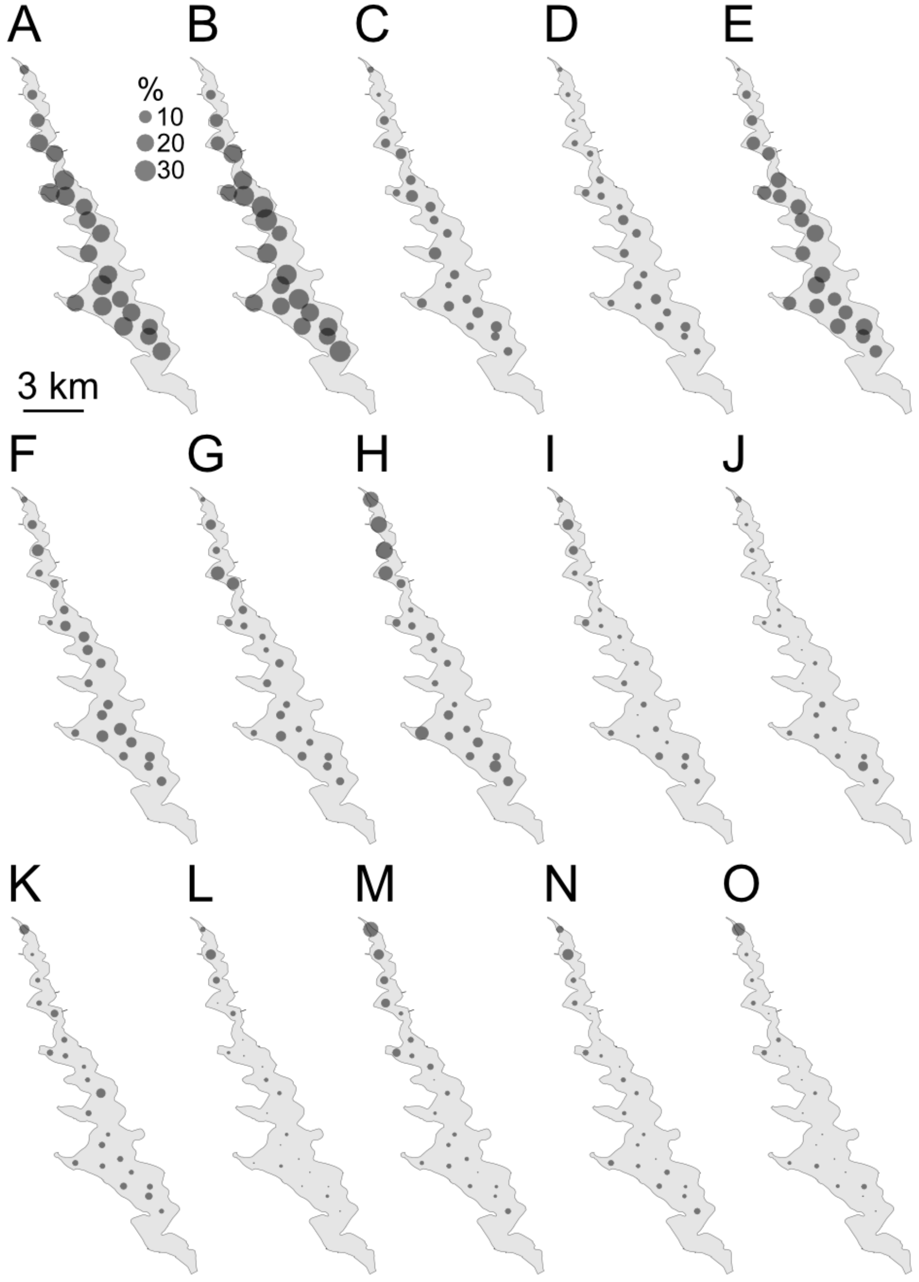

Fig. 2-4. Relative abundances of diatom taxa in surface sediments for taxa that constituted more than 5% of the assemblage at at least one site. Planktonic taxa: (A) *Aulacoseira ambigua*, (B) *Aulacoseira granulata*, (C) *Aulacoseira pusilla*, (D) *Actinocyclus normanii* f. *subsalsa*, (E) *Cyclostephanos dubius*, (F) *Cyclotella meneghiniana*, and (G) *Stephanodiscus hantzschii* f. *tenuis*. Tychoplanktonic taxa: (H) *Staurosira venter*, (I) *Pseudostaurosira* spp., and (J) *Staurosirella* spp. Benthic taxa: (K) *Nitzschia* spp., (L) *Gomphonema* spp., (M) *Navicula* spp., (N) *Cocconeis placentula*, and (O) *Achnanthidium* spp., *Planothidium* spp., and *Psammothidium* spp.

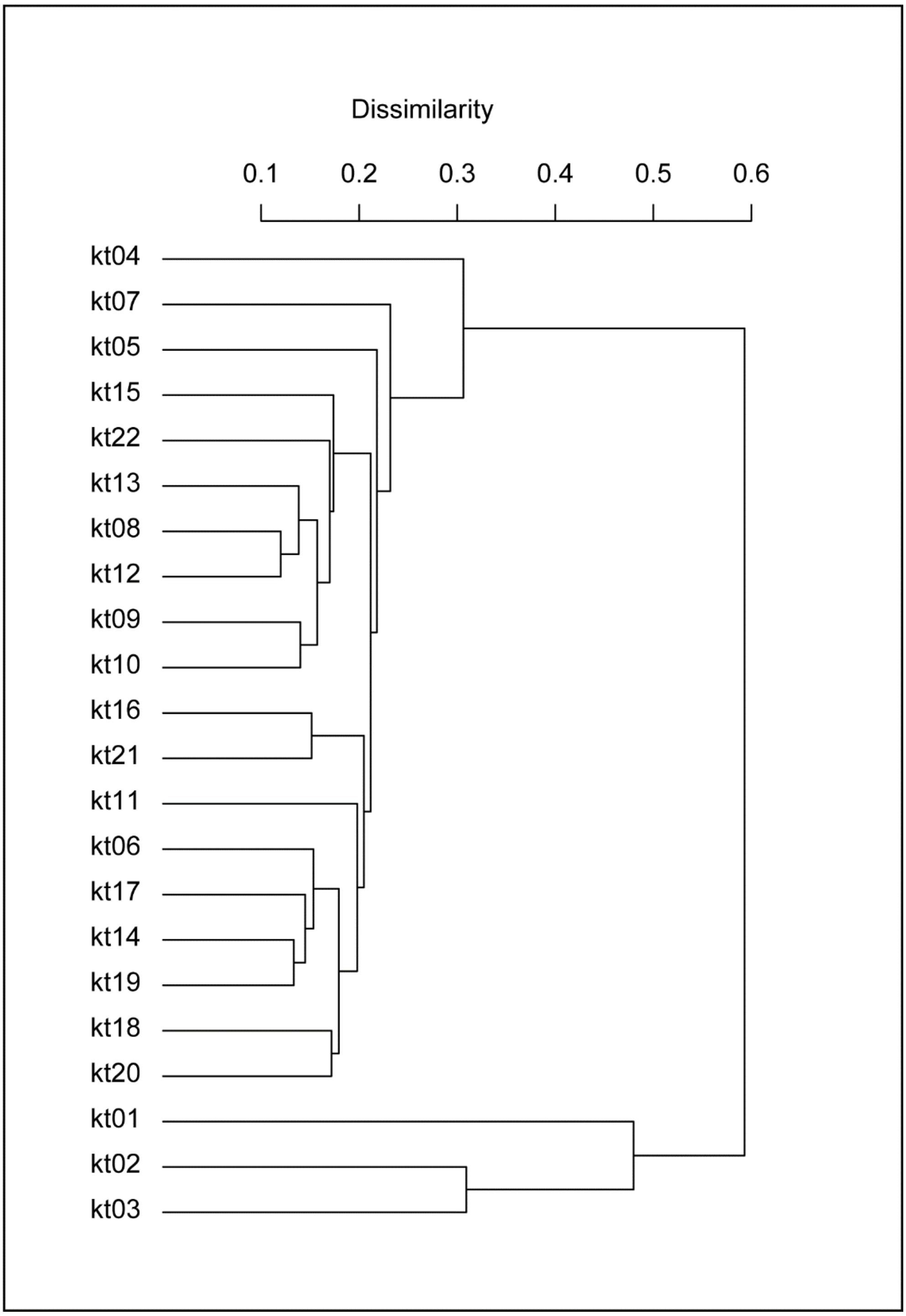

Fig. 2-5. Dendrogram of diatom assemblages in Lake Kitaura calculated by hierarchical cluster analysis. Sample dissimilarities of each sample calculated by the Bray–Curtis distance for diatom abundance.

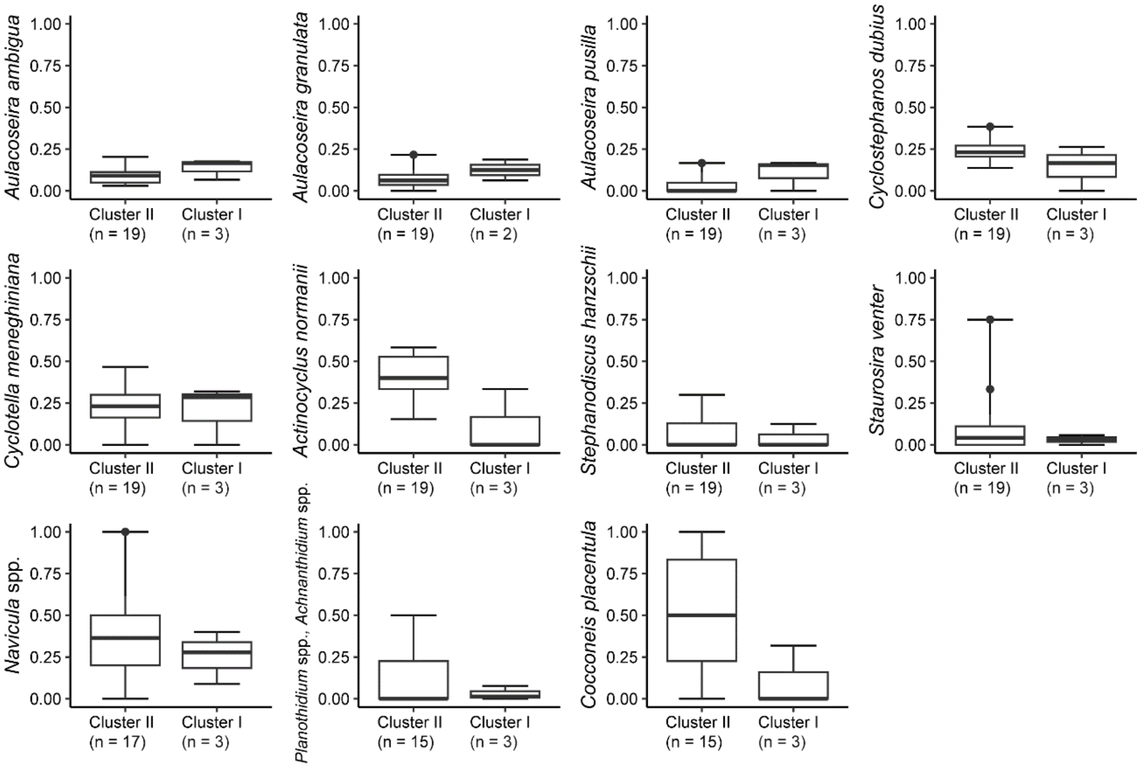

Fig. 2-6. Boxplots of *Fr* values in dominant diatom species. Boxes denote 25–75 percent quartiles. Vertical lines show the median. Error bars indicate maximum and minimum values. The *n* values denote sample sizes in clusters I and II.

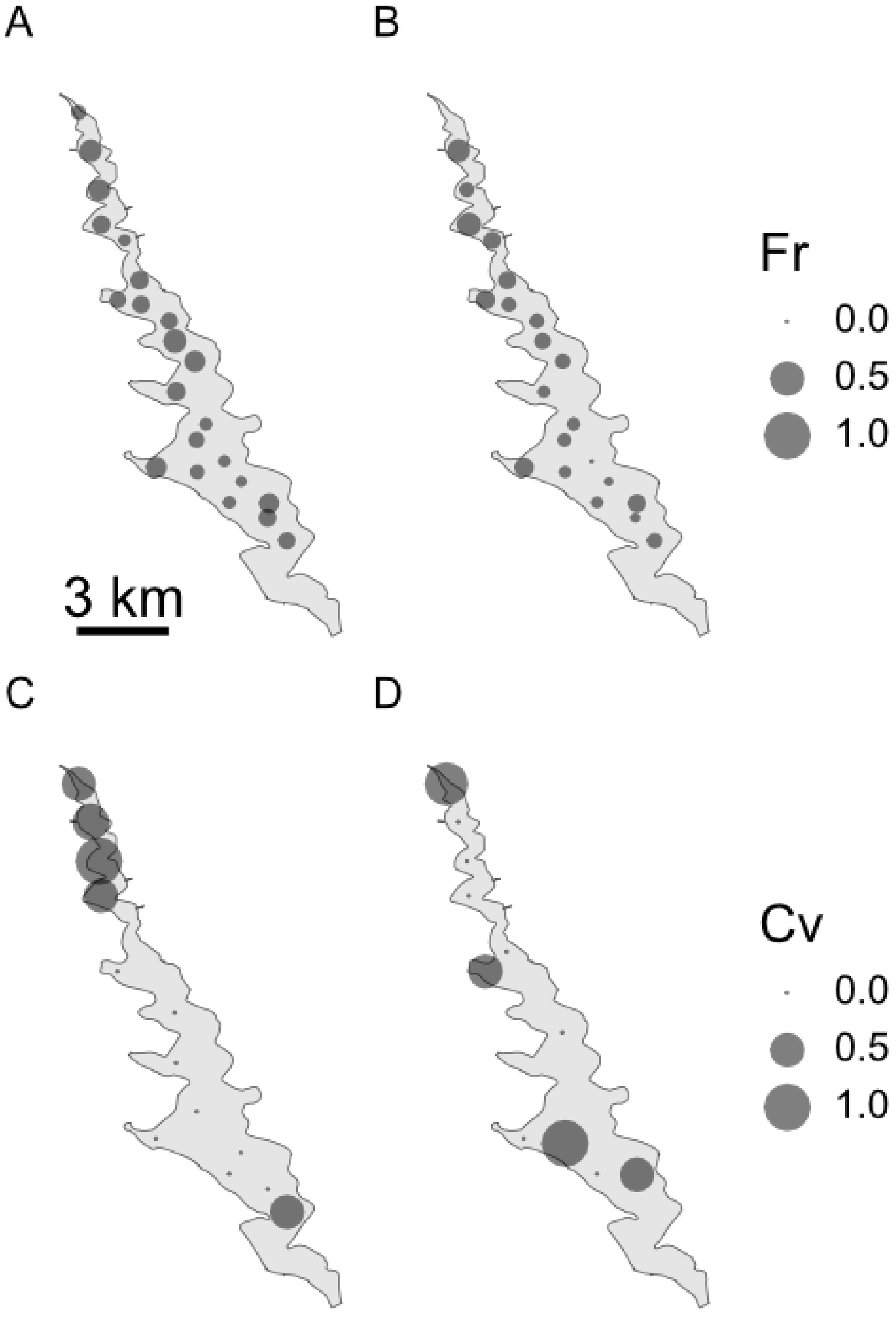

Fig. 2-7. *Fr* values of (A) *Aulacoseira ambigua* and (B) *A. granulata*, and *Cv* values of (C) *Cocconeis placentula* and (D) *Planothidium lanceolatum* at each sample site. Gray circles show the *Fr* and Cv values.

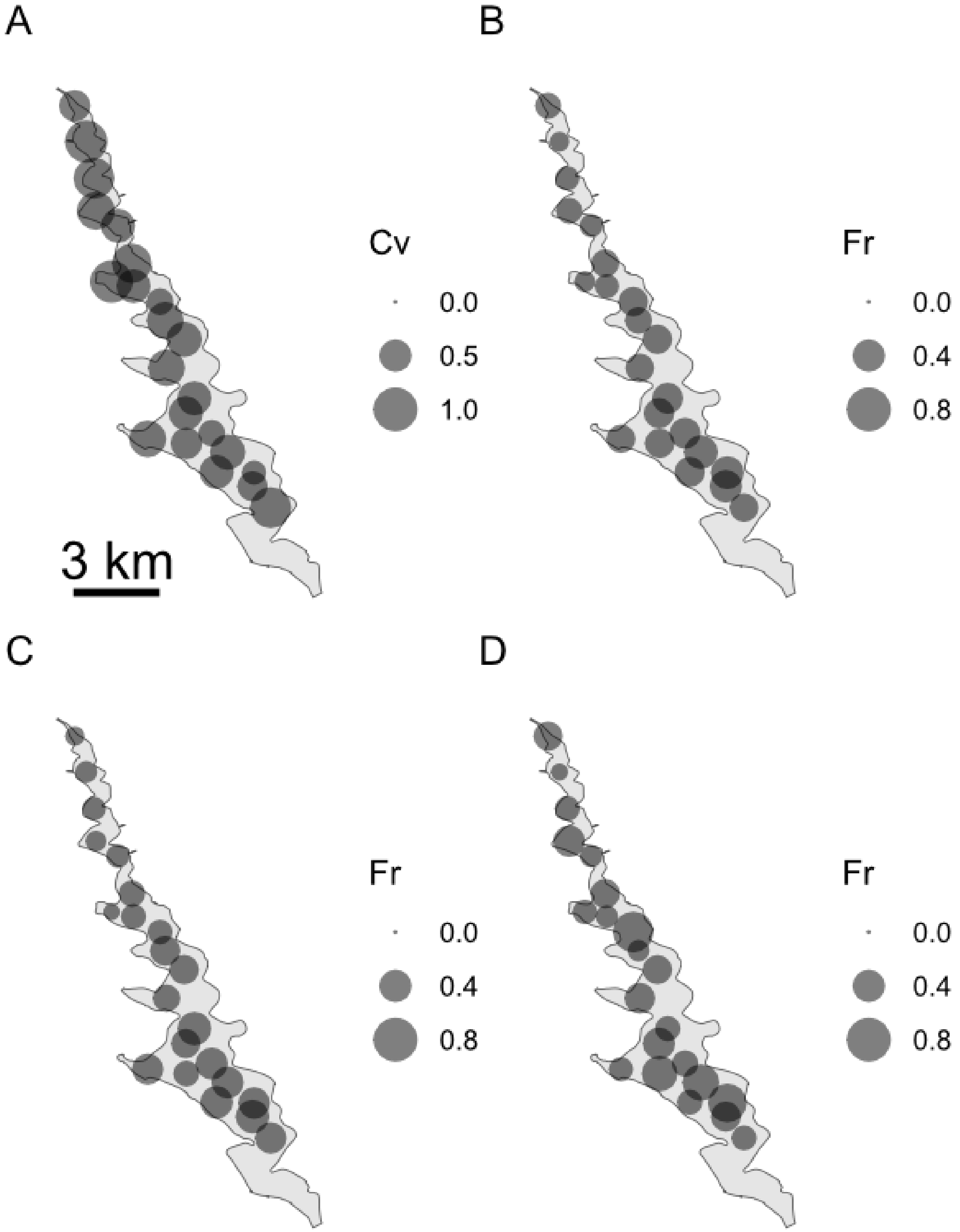

Fig. 2-8. *Cv* and *Fr* values for *Cocconeis placentula*. (A) *Cv* values obtained by counting 50 valves in each sample. (B) *Fr* values obtained by counting 50 valves in each sample. (C) *Fr* values of the araphid valves. (D) *Fr* values of the raphid valves.

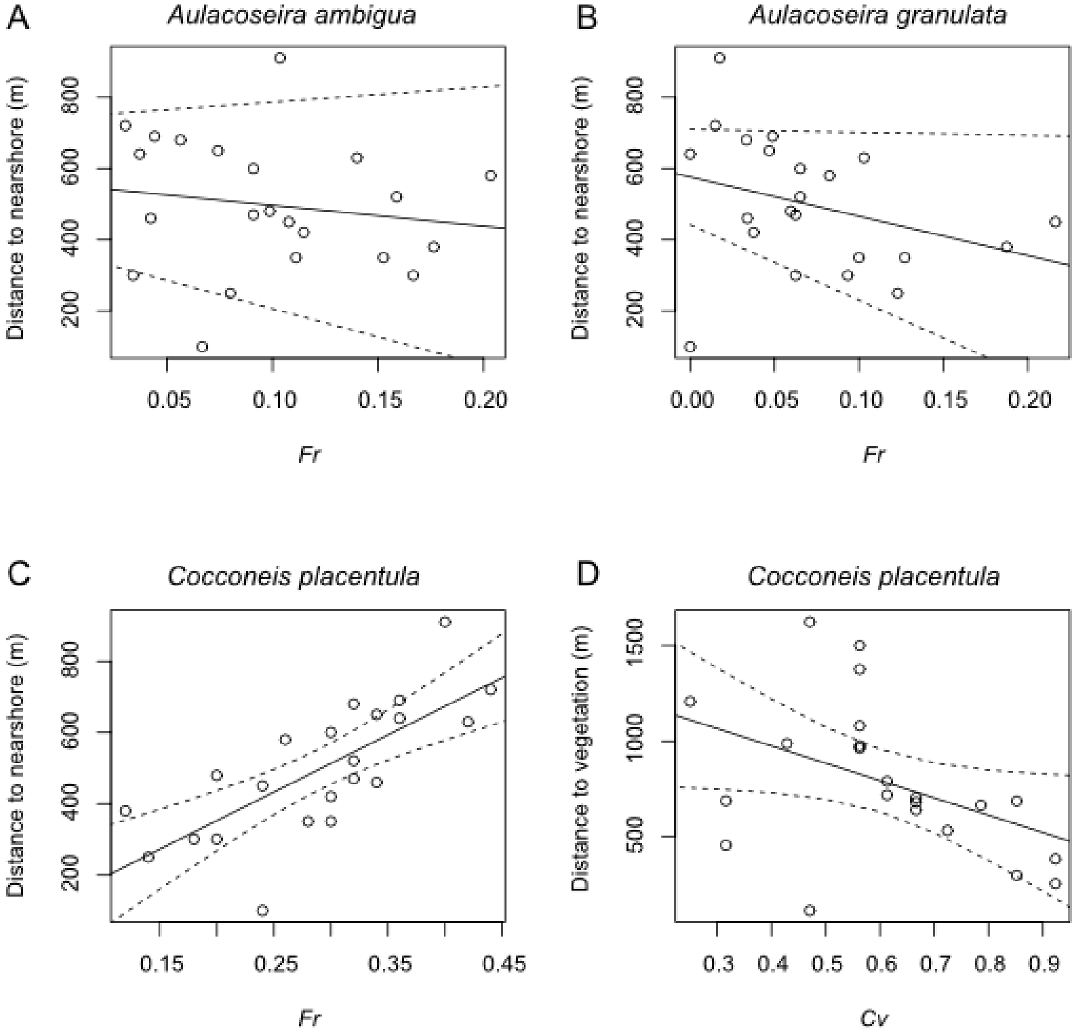

Fig. 2-9. Univariate regression of distance to nearshore and *Fr* values of (A) *Aulacoseira ambigua*, (B) *Aulacoseira granulata*, and (C) *Cocconeis placentula*. (D) Univariate regression of distance to vegetation and *Cv* values of *Cocconeis placentula*. The solid lines show the regression lines, and the dotted lines denote 95% confidence intervals.

CHAPTER 3

Transportation process of diatom valves revealed by geochemical, mineralogical, and grain size analysis in modern shallow lake sediments from Lake Kitaura, Japan

Abstract

The diatom transportation discussed in the previous chapter has yet to demonstrate its relationship with other sedimentary particles. In this chapter, the relationships between diatom-taphonomic signatures and transportation processes of clastic sediments were investigated using geochemical, mineralogical, and grain-size analysis of the lake sediments. Twenty-two surface-sediment samples in Lake Kitaura were prepared sequentially to remove carbonate, organic matter, and biogenic opal, and then, X-ray fluorescence, X-ray diffraction, and grain size distribution were analyzed. The chemical and mineral composition implied the supplies of clastic sediments from the inflow rivers and the difference in sources of the sediments. The grain size distributions contained five or six distinct log-normal grain-size distributions and were separated to discuss the sedimentary process in each component. The log-ratio transformation of the components demonstrated two coarser components were varied, reflecting the sources and sedimentary transport of clastic sediments. The agreement of clastic sediment behavior and diatom valve fragmentation or frustule separation demonstrated that benthic diatom valves had been transported offshore from their habitat by hydraulic transportation and were highly fragmented by wave disturbance. This study can contribute to the discrimination of allochthonous diatoms and provenance studies of benthic diatoms in shallow lakes.

3.1. Introduction

Diatoms are unicellular algae with biogenic silica frustules preservable in sediments. Fossil diatom assemblages have been used for paleoenvironmental reconstructions based on the knowledge of modern diatom assemblages and their habitats (Chiba et al. 2016; Sawai et al. 2016; Vos and Wolf 1993). Taphonomic processes must be assessed when reconstructing the paleoenvironmental changes based on fossil diatom assemblages (Chiba et al. 2021; Hassan et al. 2018; Vos and Wolf 1993). The diatom valves alter due to chemical dissolutions, bioturbation, and physical breakage (Beyens and Denys 1981; Flower 1993; Ryves et al. 2003; Shimada et al. 2003). The physical breakage makes diatom valves fragmented during transportation (Beyens and Denys 1981; Kosugi 1986). Most diatom frustules would separate into valves during transportation in a tidal flat (Sawai 2001) and a shallow lake. The diatom fragmentation and frustule separation can indicate the incorporation of allochthonous diatom valves or provenance from their habitats. Kumisaka et al. (2024) discussed the transportation process of diatoms in Lake Kitaura, a shallow lake in Japan, based on the spatial variation of the diatom valve fragmentation ratio (*Fr*) and frustule separation ratio (*Cv*) of benthic diatoms. The *Fr* and *Cv* varied by long-distance transportation and the incorporation of autochthonous diatom in Lake Kitaura. However, the transportation of diatom valves in Lake Kitaura has not yet to be demonstrated their relationship with other sedimentary particles, such as clastic sediments. Sedimentological studies investigating sediment properties and processes are necessary to confirm the transport and provenance of diatom valves. Geochemical, mineralogical, and grain-size analyses of lake sediments can reveal the provenance and transportation processes of sediments. The grain size distribution of lake sediments provides the depositional environments, hydrodynamics, and provenances (Dietze et al. 2012; Dietze et al. 2014; Kumon et al. 1993), suggesting the hydraulic transportation of sediments. The transportation of sediments improves the interpretation of the incorporation and long-distance transportation of diatom valves that involved valve fragmentation and frustule separation.

This study aims to clarify the relationships between diatom-taphonomic signatures and transportation processes of clastic sediments. We compare clastic particles with the diatom *Fr* and *Cv* to assess the transportation of diatom valves in Lake Kitaura. In shallow lakes, inflow rivers and waves often affect sediment compositions and sedimentary processes. The diatom assemblages in Lake Kitaura sediments provide an opportunity to assess the diatom transportation in shallow lake sediments because of the heterogeneity of sediment transport. This study can contribute to the diatom transportation and provenance in the diatom taphonomic study in shallow lakes.

3.2. Material and methods

3.2.1. Study area

Lake Kitaura is a freshwater lagoon lake in the southeastern part of Honshu Island, Japan, with a 35.2 km^2 surface area, a 7 m maximum water depth, and a 4.5 m average depth. The twenty-two river inflows, and one river, the Wani River, outflows. The Tomoe River at the northernmost part of the lake has the highest flow rates, with catchment areas of 131.8 km^2 (Fujita et al. 2006). Most of the catchment area of Lake Kitaura mainly consists of Late Pleistocene sediments and Holocene deposits (Fig. 3-1A). Sedimentary rocks around Mt. Tsukuba are distributed upstream of the Tomoe River. The other inflow rivers flow into Lake Kitaura from Pleistocene sediments.

The sedimentary process in Lake Kitaura is controlled by erosion, transportation, and resuspension derived from prevailing winds (Naya et al. 2004a). The wind direction and wind velocity affect the wave and vertical mixings of the lake water because of the lake's shallowness. (Naya et al. 2004a). The water movements transport silty-clayey sediment offshore, leaving sandy sediment in the littoral areas. A sediment-trap study demonstrated that sediments and diatom valves are resuspended and laterally transported by the wind-driven lake circulation (Naya et al. 2004b). On the other hand, the shallow basin in the northern part of Lake Kitaura has clay-to-silt sediments because the wave disturbances become weaker in the short fetch areas. The inflowing rivers, especially the Tomoe River, also supply coarser sediments (Naya et al. 2004a).

3.2.2. Sample collection and preparation

Surface sediment samples were collected at 22 sites (called "kt01–kt22" from north to south; Fig. 3-1B) in Lake Kitaura (details in Kumisaka et al. (2024)). The wet sediment samples were dried at 40ºC overnight with a natural convection oven.

The surface sediments were sequentially subjected to carbonate removal, organic matter decomposition, and biogenic opal removal to extract clastic sediments. Each sediment was weighted about 0.5 g for grain-size analysis and 0.1 g for X-ray fluorescence analysis (XRF) and X-ray diffraction analysis (XRD). Firstly, 40 mL of 20% acetic acid was added to the sediment to remove carbonates. The carbonate removal was carried out for 8 hours at room temperature and stirred with a glass rod every 2 hours. The suspension was centrifuged at 3000 rpm for 30 minutes, and the supernatant was decanted to remove reagent residuals. The sample was washed with 40 mL of distilled water and centrifuged twice at the same condition. Secondly, 40 mL of 30% hydrogen peroxide was added to the washed sediment to remove organic matter. The organic matter decomposition was carried out for 2 hours at 80 ºC in a water bath. Then, the suspension was washed as in the previous procedure. Finally, 40 mL of 2 mol/L sodium carbonate solution was added to the washed sample to remove biogenic opals. The opal removal was carried out for 9 hours at 80 ºC in a water bath and stirred with a glass rod every 2 hours. As in the previous procedure, the prepared sample was washed with distilled water. Before air drying, the prepared samples for XRF and XRD analyses were replaced with water and ethanol. The dried prepared samples were powdered with an agate mortar and pestle. A part of the kt14 sample after organic matter, carbonate, and biogenic opal removal was observed using a light microscope with 400x magnification to observe the prepared sample. The smear slide observations of the prepared and unprepared samples of kt14 were conducted to check whether the clastic particles were extracted.

3.2.3. Elemental analysis

The quantitative analyses of major elements were performed using a wavelength-dispersive X-ray fluorescence spectrometer (ZSX Primus, Rigaku Corp., Tokyo, Japan). The powder sample was measured using a loose powder method with 10 mm aperture (Takahashi 2015). Analytical errors were estimated on external reference material of JSd-2 (Geological Survey of Japan, AIST, Tsukuba, Japan).

3.2.4. XRD

The prepared samples were measured using an X-ray diffractometer (SmartLab, Rigaku Corp., Tokyo, Japan) equipped with a Cu tube (Kα, $\lambda = 1.541$, 45 kV, 200 mA), a 48-sample changer, and a semiconductor detector. Samples were mounted into the depression of a glass sample holder for XRD. The measurements were performed from 3.2° to 70° 2-theta with a step size of 0.02° and a step speed of 10°/minute. Mineral identification was carried out using the software PDXL2 (Rigaku Corp., Tokyo, Japan) and the pdf2 database (ICDD 2020, Newton Square, PA, USA).

3.2.5. Grain size distribution

The prepared sample was dispersed with 40 ml of 5.5 g/L sodium hexametaphosphate solution. The grain size was measured using a laser diffraction particle size analyzer (SALD-2300, Shimadzu Corp., Kyoto, Japan) with a refractive index 1.65. During the measurement, ultrasonic waves were applied to the suspension. The grain size was converted to the phi scale as:

$$D_{\varphi} = -log_2 \frac{D}{D_0}$$

where D is the grain size in millimeter scales and D_0 is a 1 mm.

3.2.6. Data analysis

The grain size distribution often exhibits a polymodal distribution and is represented by medians, mean grain size, skewness, and kurtosis. However, the representative parameters can be appropriate because the polymodal grain size distribution reflect multiple sediment provenance and sedimentary processes. The polymodal distribution of sediments is regarded as a mixture of several lognormal distributions (Ashley 1978). Several statistical analyses were conducted to separate and interpret the grain size components individually (Gammon et al. 2017; Yamaguchi et al. 2024).

The expectation-maximization (EM) algorithm was performed to separate mixed lognormal distributions in the previous study (Yamaguchi 2023; Yamaguchi et al. 2024). The EM algorithm is an iterative method to find the maximum likelihood estimation of unknown parameters in statistic models (Dempster et al. 1977). This algorithm estimates the mixing proportions, means, and standard deviation of the lognormal distributions composed of the grain size distribution. The analysis was performed in R version 4.3.2 (R Core Team (2023)) using the package "mixR" (Yu 2022). Two criteria were calculated to determine the number of components: the Bayesian information criteria (BIC) and the Akaike information criteria (AIC). For estimating the number of components of grain size distributions, the highest-ranked AIC included higher ranked BIC models can be appropriate and valid to avoid the possibility of overestimating the number of components (Yamaguchi 2023). This study adopted the number of components with highest-ranked AIC within the top three BIC.

The chemical composition and mixing proportion obtained by the EM algorithm were compositional data, sum to 100%. Due to the compositional data having a problem with subject statistical analysis (Aitchison 1986), log-ratio analysis was conducted to avoid the constant sum constraint. The present study transformed the compositional data to additive log-ratio (ALR) as follows:

$ALR(i|reference) = \ln\,(X_i/X_{reference})$ for $i = 1,\ldots, n$; $i \neq reference$

where X_i means the variables of compositional data, and n means the number of variables. It is important to select one reference component to calculate the ALR. Ohta et al. (2011) suggested the appropriate estimation of the unchanging component based on the coefficients of variation of each variable combination. In the present study, the reference component of the chemical composition and mixing proportion were regarded as unchanging components according to the statistical estimation (Ohta et al. 2011). We conducted Spearman's correlation analysis to examine the relationship between the log-ratio values of separated grain-size components, water depth, distance to nearshore, and *Fr* and *Cv* shown in Kumisaka et al. (2024).

3.3. Results

3.3.1. Smear slides observation

Smear slides observation of the prepared sample indicated that sediment particles after organic matter, carbonate, and biogenic opal removal were almost clastic particles rather than the unprepared sediment (Fig. 3-2). The smear slides contained clastic particles, diatom valves, and other debris (Fig. 3-2A). In contrast, the prepared sample rarely contained diatom valves (Fig. 3-2B). From now on, the prepared samples will be discussed as clastic fractions.

3.3.2. Chemical and mineral composition

The spatial distributions of major elements of the prepared samples in Lake Kitaura differed between the northern and southern areas (Appendix H). The Al_2O_3 was determined as the most unchanging component of major elements by the coefficient of variation method (Ohta et al. 2011). Based on this estimation, the ALR for each major element was calculated. ALR(Na_2O) was spatially homogenized (Fig. 3-3A). ALR(MgO), ALR(SiO_2), ALR(K_2O), and ALR(CaO) increased from the north to south (Fig. 3-3B, C, D, and E). ALR(CaO) also increased at the mouth of Yamada River and Gantsu River(kt07 and kt16). ALR(Fe_2O_3) show high values at the mouth of the Tomoe River (Fig. 3-3F and G).

The mineral compositions of the lake surface samples were similar. The peaks of quartz and plagioclase were observed in all samples (Fig. 3-4A). Clay minerals with peaks at 14–12 Å, 10 Å, and 7.1 Å were detected; they were smectite group or chlorite, mica, and kaolinite, respectively. The kt01 had only individual peaks at the 14-12 Å without the broad peak. The diffraction peaks of feldspar were identified as a mixture of albite (3.21 Å) and anorthite (3.19 Å). The peak area of albite was high at kt01–kt02 and that of anorthite was low at kt01–kt05 (Fig. 3-4B).

3.3.3. Grain size distribution

The prepared samples of surface sediments in Lake Kitaura consisted mainly of silt to clay particles, with a median grain size ranging from 6.5 to 7.6 phi (Fig. 3-5). Sand size fractions (coarser than 4 phi) were higher at the mouths of inflow rivers (kt01, kt07, and kt16) and the southern littoral site (kt22). The median and mean grain size at the inflow rivers and the southern littoral site was coarser than the other offshore sites (Fig. 3-6). The mode grain size was homogeneous, ranging from 7.4 to 7.8 phi, while kt01 was a coarse value of 5.7 phi. The grain size distributions were poorly sorted at the inflow rivers and the southern littoral site. The shapes of the grain size distributions exhibited polymodal distributions. They had common peaks at around 5.6 and 7.4 phi and common inflection points at around 4.2, 8.6, and 9.3 phis (Fig. 3-5). The peaks and inflection points of finer fractions of more than 7 phi were low varied in the position, whereas those of coarser fractions varied in the positions.

3.3.4. Separation of grain size components

The grain size distributions of the clastic fractions have polymodal distributions and were regarded as a mixture of several unimodal distributions. The separation of grain size distributions using the EM algorithm was conducted to decompose each component and discuss sedimentary processes in each component. The number of components separated from grain size distribution in the clastic fractions from Lake Kitaura was estimated to be 6 at kt01, kt07, kt16, and kt22 and 5 at the other sites (Fig. 3-7; Appendix G). The separated components in the present study were called Comp6–1, starting from the finest mean grain size (Fig. 3-7; 3-8A; Table 3-1). The coarse component with a mean grain size of 3.4–3.6 phi (Comp1) occurred in the river mouths of Tomoe River (kt01), Yamada River (kt07), and Gantsu River (kt16), and the southern littoral site (kt22). The Comp2 has a mean grain size ranging from 3.7–5.0 phi and is highly varied in the proportions among the samples. The mean grain size and the proportions of Comp3 were varied. Comp4, with a mean grain size of 7.3–7.5 phi, was the most abundant proportion except for kt01. The mean grain sizes of Comp5 and Comp6 were 8.5–8.7 phi and 9.3–9.4 phi, respectively. The variations in the mean grain size of fine components (Comp4–6) were minor, with less than 1%. The inflection points around 3.4–3.6 phi in kt01, kt07, kt16, and kt22 were indistinct compared to the inflection points around 4 phi, 8.6 phi, and 9.3 phi. Therefore, the Comp1 and Comp2 were re-synthesized into a single component (called Comp1&2) with a median grain size of 3.7–5.0 phi. The mean grain size and proportion of Comp1&2 were highly varied, as were Comp2 (Fig. 3-7B).

The spatial variations of the proportion of Comp1–6 were differentiated between the sample sites (Fig. 3-8). The Comp1 and Comp2 characterized the mouths of the inflow rivers and the southern littoral site. The Comp3 showed high proportions in the northern areas and low proportions in the southern offshore areas. In contrast, the proportions of Comp4–6 were relatively high in the southern offshore areas and low in the northern and southern littoral areas.

The Comp6 was determined as the most unchanging component by the coefficient of variation method. The additive log-ratio of the proportions of Comp1&2–5 to that of Comp6 were calculated (ALR(Comp1&2), ALR(Comp3), ALR(Comp4), and ALR(Comp5)). The ALR(Comp4) and ALR(Comp5) values were low variability, whereas the ALR(Comp1&2) and ALR(Comp3) were highly variable (Fig. 3-7C). The ALR(Comp1&2) values were increased at the river mouths (kt01, kt07, and kt16) and southernmost site (kt22; Fig. 3-9A). The mean grain size of Comp1&2 was coarse in the northern area (kt01–kt09) and the southern littoral area (kt16-kt22). The ALR(Comp3) values were also increased at the river mouths and the southern littoral site and were higher the northern area (kt01–05) than in the southern area (Fig. 3-9B). The mean grain size of Comp3 was coarse at the river mouth of the Tomoe River and became finer downstream (kt02–kt05). In the central to southern areas, the mean grain size of Comp3 was low variation around 5.6 phi, and relatively coarse Comp3 was distributed in the Gantsu River (kt16) and southern littoral area (kt17–kt22).

The ALR(Comp3) and ALR(Comp1&2) exhibited different correlation to water depth, distance to nearshore, and diatom taphonomic signatures (Figs. 3-10 and 3-11). The ALR(Comp3) has significant correlations with water depth, distance to nearshore, and *Fr* of *Cocconeis placentula* (R = –0.80, –0.66, and –0.70, respectively; Fig. 3-10C and D and Fig. 3-11C). In contrast, ALR(Comp1&2) was not correlated with water depth, distance to nearshore, *Fr*, and *Cv* of *C. placentula* (R = –0.23, –0.26, 0.00, and 0.14, respectively; Fig. 3-10A, B, and D, Fig. 3-11A, and B).

3.4. Discussion

We discuss the sediment distribution in Lake Kitaura based on geochemical properties, mineral compositions, and gran-size distributions: (1) the effectiveness of the separated components of the clastic sediments by comparing the conventional grain-size distribution parameters; and (2) diatom taphonomy in shallow lakes based on the transportation of benthic diatom valves and clastic particles.

3.4.1. Characteristics of sediment distribution in Lake Kitaura

The inflow rivers and littoral areas are potential source regions of the clastic particles in Lake Kitaura. The high values of ALR(Fe) and ALR(Ca) at the sites near the inflowing rivers suggest the riverine transportation of clastic particles. In particular, the northern sites kt01–kt03 near the Tomoe River mouth had high Fe (Fig. 3-3G), consistent with the high Fe contents in the suspended materials in Tomoe River water (Tagiri et al. (2009) from the granite distributed in the upstream (Fig. 3-1; Fig. 3-2B–E). The Pleistocene sediments surrounding Lake Kitaura can be transported from the Yamada and Gantsu Rivers and littoral areas. The mineral compositions at 22 sites in Lake Kitaura surface sediments were almost similar except for mica and albite. Mica intensities at sites k02–kt04 were lower than at other sites. Albite intensities at kt01–kt06 were higher than the south of kt07. In the south, the Yamada River and the Gantsu River, which have their upstream Pleistocene sediments, flow into Lake Kitaura. The difference in watershed and geological background between the northern and southern areas of Lake Kitaura may result in the chemical properties (log-ratio of Fe and Ca) and mineral composition (mica and albite) of sediments from inflow rivers and littoral areas.

The fine and well-sorted sediments were distributed in the offshore area, whereas the coarse and poorly sorted were limited to the inflowing rivers and the southern littoral site (Fig. 3-6). The grain size distributions also suggested the coarse clastic sediment supply from the inflow rivers to Lake Kitaura, the Tomoe River (kt01–kt03), the Yamada River (kt07), and the Gantsu River (kt16). At the southern littoral site (kt22), coarse particles are likely to be supplied from the nearshore by wave disturbance because there is no inflow river. Naya et al. (2004a) reported that the coarse sediments distributed at the Tomoe River and the littoral areas. On the other hand, the wave disturbance was the primary factor of the sedimentation processes in Lake Kitaura (Naya et al. 2004a). The waves driven by prevailing wind have washed the sediments in littoral areas: The coarser particles can deposit rapidly, and the finer grains move easily (Naya et al. 2004a). The fetch, driven by the wave disturbance, wind direction, and lake topography, controls the silty clay and clay sediment transportation in Lake Kitaura (Naya et al. 2004a). The mean and median grain sizes showed low variation in the central and southern sub-lacustrine plains despite the difference in distances to nearshore (kt06–kt12 and kt13–18; Fig. 3-6). The central sub-lacustrine plain has a shorter fetch than the southern. Thus, the mean and median grain sizes in the central part should be coarser than in the southern part.

The conventional parameters of grain-size distributions did not different between the central and the southern sub-lacustrine plains (Fig. 3-6) and would not reflect the difference in the sedimentary process within the lake. The shapes of grain-size distributions showed polymodal distributions (Figs. 3-5 and 3-6), suggesting the mixing of several log-normal distributions. The polymodal distributions can result from multiple sources of supply and the sedimentary process (Ashley 1978). The polymodal grain-size distributions should be separated into single log-normal distributions to discuss the sedimentary process in each component.

The separated grain-size components indicated the sedimentary processes in Lake Kitaura. Comp1&2 and Comp3, which increased mainly in the river mouths and littoral areas, were interpreted as components transported from the inflow rivers and southern littoral area. The increasing trends of Comp3 in the northern areas (kt01–kt05) showed the transportation of clastic particles from the Tomoe River (Fig. 3-10). The correlation between ALR(Comp3) and water depth and distance nearshore showed that the clastic particles with 5.3–6.0 phi had been transported from littoral to offshore areas (Fig. 3-11C and D). In addition, log-ratio of Comp1&2 demonstrated the supply of coarse grains from inflow rivers (kt01, kt07, and kt16) and the southern littoral site (kt22; Figs. 3-9 and 3-10A). Although Naya et al. (2004a) found sandy sediments in Lake Kitaura were few supplied from the inflow rivers, Yamaguchi et al. (2024) implied coarse sediments were to be transported from the inflow river. The distribution of Comp1&2 and Comp3 suggested transportation of clastic particles from the inflow rivers and littoral areas.

On the other hand, the separation of grain-size distributions showed the difference in the sedimentary processes between the northern and southern sub-lacustrine plains. The mean grain size of Comp3 was finer from kt01 to kt05 in the fluvial fans of the Tomoe River, whereas that of Comp3 was coarser in the south of kt05, especially the southern littoral site (kt22; Fig. 3-8). The northern part, shallower than 2.5 m, had fine sediments resulting from short fetch and weak or infrequent wave disturbance (Naya et al. 2004a). The finer mean grain size of Comp3 in the northern area may reflect the weak hydraulic regime by wave disturbance in the northern part of the lake. The mean grain sizes of Comp1&2 were relatively coarse in the northern area (kt01-kt09) and the southern littoral area (kt16-kt22), whereas they were relatively fine at the offshore sites (kt11, kt13-kt15; Fig. 3-10A), suggesting the Comp1&2 may be transported and get finer to offshore in the southern area. Yamaguchi et al. (2024) indicated the effectiveness of separation of grain-size distribution and the spatial characteristics of separated components in the southern sub-lacustrine plain of Lake Kitaura. The grain size components of 5.8–6.0 phi, corresponding to Comp3 in this study, were spatially homogenous. The medium silty component was considered to be resuspended in the southern sub-lacustrine basin (Yamaguchi et al. 2024). The grain size components of 4.0 to 4.4 phi in Yamaguchi et al. (2024), which corresponds to Comp1&2, were correlated with distance nearshore, suggesting transportation distance from their source. The correlation between the separated components and the water depth and distance nearshore differed between the previous and present studies, implying that the sedimentation processes in the southern and northern areas differ.

Our separated components of the grain size distributions were consistent with a previous study in Lake Kitaura. Yamaguchi (2023) simulated the appropriate number of components in the EM algorithm and applied it to two surface sediments at the lake basin in Lake Kitaura. The number of components of the lake sediments in Yamaguchi (2023) was 5. The proportions and mean grain sizes of the Comp2–6 in the present study corresponded to those in Yamaguchi (2023). However, Comp1, which had a mean grain size of 3.4–3.6 phi, was not separated in the previous study. The difference in the coarsest component between the present results and the previous study may be due to different sampling areas, as discussed above. The separation of grain size components in this study demonstrated that Comp1&2 and Comp3 were exposed to different sedimentary transport from inflow rivers and littoral areas and the difference in wave disturbance between the northern and southern areas.

3.4.2. Relationship between diatom transportation and grain size components

The diatom valve fragmentation and frustule separation of the benthic diatom were comparable to the coarse clastic components in Lake Kitaura. The benthic diatom, *Cocconeis placentula*, has valves of 20 to 80 µm length (3.6 to 5.6 phi) and 8 to 40 µm width (4.6 to 7.0 phi; Kobayashi et al., 2006). The valve size is finer than Comp1&2 and is considered to be transported offshore easily. The grain size of Comp3 is relatively similar to the valve size of *C. placentula*, and thus, the transportation of clastic particles with 5.3 to 6.0 phi and the diatom valves can be compared.

The diatom valve fragmentation and the grain-size distribution of surface sediments from Lake Kitaura show the transportation of sediments from the inflow rivers and littoral areas. Comp3 in the river mouths and littoral area reflected the sediment transport from their sources, whereas Comp3 in the southern sub-lacustrine plain indicated the resuspended components. The correlation between *Fr* and ALR(Comp3) (R = -0.70) suggested the transportation from inflow rivers and wave disturbance caused the diatom valve fragmentation. The decrease of *Fr* values in the inflow rivers and the southern littoral site indicated the incorporation of autochthonous benthic diatom valves (Fig. 3-13A). The log-ratio of Fe and Ca also supported the sediment supply from the inflow rivers, and the diatom valves can be transported with the sediments.-In addition, Comp3 relates to the difference in transportation processes between the northern and southern areas. The *Fr* has higher values in the southern part of the lake, which is dominated by wave disturbance. Thus, the diatom valve can also be fragmented by the transportation by the waves. The coarser Comp1&2 in the north of kt09 suggested that the wave disturbance weakly affected the transportation of clastic particles due to the shorter fetch (Fig. 3-10A). The low frequency of wave disturbance and large supply from inflow rivers showed the transportation of autochthonous benthic diatoms and the preservation of the diatom valves. Overall, this study demonstrated that the diatom valve fragmentation in Lake Kitaura was controlled by transportation by wave disturbance and incorporation from the inflow rivers.

The uncorrelation between *Cv* values and log-ratio of Comp1&2 and Comp3 implied that the transportation of clastic particles differed in behavior from the frustule separation of the *Cocconeis placentula* valves. The coarse components (Comp1&2 and Comp3) indicated the transportation from inflow rivers and wave disturbance, whereas the *Cv* can be mainly influenced by the habitat of *C. placentula* (Chapter2; Kumisaka et al., 2024). The high *Cv* values matched with the increase of ALR(Comp1&2) and ALR(Comp3) in the inflow rivers (kt01–03, kt07 and kt16) and southern littoral site (kt22; Fig. 3-12B, D). In the mouth of the Tomoe River (kt02–04), the *Cv* values and ALR(Comp3) were similar trends (Fig. 3-13D) and suggested the transportation from the Tomoe River. In the mouth of the Tomoe River (kt01), *Planothidium lanceolatum* showed high relative abundance and the *Cv* value (Kumisaka et al. 2024). The incorporation of *P. lanceolatum*, which was fluvial diatom valves, agreed with the inputs of Comp1&2 at kt01. The coarsest clastic component occurred near the river mouths and littoral areas, and matched with local diatom transportation. In addition, the *Cv* value of the kt22 samples from a shallow water area near the southern littoral area was higher when compared with the other samples around the southern sub-lacustrine plain (kt13–kt15 and kt17–kt21; Fig. 3-13B, D). These areas can supply the autochthonous *C. placentula* from littoral vegetation and the coarse clastic particles from the southern littoral areas. The agreement on the transportation of clastic particles and the *Cv* values at the adjacent sites of inflow rivers and littoral area indicated *Cocconeis placentula* was specific to their habitat. The correlation between the *Cv* and log-ratio of Comp1&2 and Comp3 would have become unclear because the raphe valves of *C. placentula* were difficult to be transported to offshore areas (Sawai, 2011; Kumisaka et al., 2024).

The agreement of sediment behavior and diatom valve fragmentation or frustule separation demonstrated that benthic diatom valves had been transported offshore from their habitat by hydraulic transportation and were highly fragmented by wave disturbance. We attributed the autochthonous diatom in the mouths of inflow rivers and the southern littoral site to transportation that also caused significant inflows of sediments.

3.4.3. Implication for diatom taphonomy in shallow lakes

Diatom taphonomic study is an essential consideration for sources of diatom valves in sediments (Chiba et al. 2021; Hassan et al. 2018). The autochthonous diatom valves of *Cocconeis placentula* in Lake Kitaura were transported in the mouths of inflow rivers, and both raphe and rapheless valves were found with a high fragmentation ratio in the southern littoral site (Fig. 3-13). The distribution of *C. placentula* was mainly in the mouth of the Tomoe River and southern littoral areas (Naya et al. 2007b). The multiple sources of *C. placentula* should indicate individual productivity, suggesting that the abundance of diatom valves supplied from the Tomoe River and the southern vegetation zone differed. This study highlighted how differences in the source of valves change the valve fragmentation and frustule separation ratio of lake surface sediments. Further investigations are required to assess the relationship between the diatom taphonomic signatures and diatom valve abundance in lake surface sediments.

The combination of *Fr* and *Cv* can contribute to the transport and provenance study of the benthic diatoms in shallow lakes. The diatom taphonomic signatures would provide insights into interpreting fossil diatom assemblages in modern and core sediments. The *Fr* and *Cv* may help determine whether the diatom valves are to be autochthonous or not. The *Cv* values demonstrated inflows of autochthonous diatoms. The allochthonous diatom may also be helpful for sedimentological analysis for the incorporation of sediments. In addition, the discrimination of autochthonous diatom valves allows for a less noisy paleoenvironmental reconstruction. Naya et al. (2007a) have reconstructed the water environment in Lake Kitaura based on the fossil diatom assemblages. The diatom assemblages of Lake Kitaura contained benthic diatoms such as *Cocconeis* taxa. The benthic diatoms were not assessed for their taphonomy, which may help reconstruct sedimentary environments or the benthic diatom provenance. The diatom taphonomy can be applied in sedimentology and provenance studies because diatom valve fragmentation and frustule separation help identify and differentiate source areas and transportation in shallow lakes. The diatom valve fragmentation and separation show the transportation of autochthonous diatom valves and their provenance in shallow lakes.

3.5. Conclusion

We studied the chemical properties, mineral compositions, and grain size distribution in surface sediments from Lake Kitaura and discussed the relationship between the distribution of clastic sediments and transportation of benthic diatoms in the shallow lake. The grain size distributions demonstrated the different sedimentary processes, such as transport from inflow rivers and transport by wave disturbances. The component separation of grain size distributions effectively clarified the sedimentary processes in the lake. The coarsest component with a mean grain size of 3.7–5.0 phi was considered to result mainly in transporting clastic particles from inflowing rivers and littoral areas. The coarse silty components with a mean grain size of 5.3–6.0 phi showed the transportation of clastic particles and the difference in the wave disturbance between the north and south area. The difference in the transportation of these grain-size components was obscure in the conventional grain-size parameters: mean, median, mode, coefficient of variations, skewness, and kurtosis of grain size distributions.

The diatom valve fragmentation of *Cocconeis placentula* is related to the sedimentary processes of silty clastic particles, and thus, the fragmentation can occur by transportation from inflow rivers and wave disturbance. Although the frustule separation of *Cocconeis placentula* was uncorrelated with the spatial variations of clastic components, the increasing trends of frustule separation were consistent with the transportation of fine sand to coarse silt components at river mouths and littoral areas. They indicated the incorporation of autochthonous valves from their habitat. The frustule separation of *Cocconeis placentula* indicate the incorporation of autochthonous valves from their habitat. The present study demonstrated that the diatom transportation revealed by valve fragmentation and frustule separation can be confirmed by grain size distributions.

Acknowledgement

We thank Ryosuke Hiroyama for his help in collecting lake-bottom sediments and Kana Nagashima (Japan Agency for Marine Earth Science and Technology) for providing information on preparation of sediments. This study was supported by JSPS KAKENHI Grant Number JP18K12578.

Reference

Aitchison J (1986) The statistical analysis of compositonal data. Chapman & Hall, London

Ashley GM (1978) Interpretation of polymodal sediments. The Journal of Geology 86: 411-421

Beyens L, Denys L (1981) Problems in diatom analysis of deposits: Allochtonous valves and fragmentation. Geol Mijnbouw 61: 159-162

Chiba T, Sugihara S, Matsushima Y, Arai Y, Endo K (2016) Reconstruction of holocene relative sea-level change and residual uplift in the Lake Inba area, Japan. Palaeogeogr Palaeoclimatol Palaeoecol 441: 982-996

Chiba T, Nishimura Y, Yanagisawa Y (2021) Distinguishing reworked diatoms derived from Neogene marine strata in modern coastal assemblages for understanding taphonomic processes and reconstructing Holocene paleoenvironments in the Tokachi coastal area, Hokkaido, Japan. Mar Micropaleontol 164: 101970

Dempster AP, Laird NM, Rubin DB (1977) Maximum likelihood from incomplete data via the em algorithm. J R Stat Soc B: Statistical Methodology 39: 1-22

Dietze E, Hartmann K, Diekmann B, Ijmker J, Lehmkuhl F, Opitz S, Stauch G, Wünnemann B, Borchers A (2012) An end-member algorithm for deciphering modern detrital processes from lake sediments of Lake Donggi cona, NE Tibetan plateau, China. Sediment Geol 243-244: 169-180

Dietze E, Maussion F, Ahlborn M, Diekmann B, Hartmann K, Henkel K, Kasper T, Lockot G, Opitz S, Haberzettl T (2014) Sediment transport processes across the tibetan plateau inferred from robust grain-size end members in lake sediments. Climat Past 10: 91-106

Flower RJ (1993) Diatom preservation: Experiments and observations on dissolution and breakage in modern and fossil material. Hydrobiologia 269-270: 473-484

Fujita K-i, Ito H, Oro T, Anma T (2006) A study on evaluation of water environment policy through watershed-scale - hydrological & material cycle simulation models to Kasumigaura Lake and its watershed. Technical note of National Institute for Land and Infrastructure Management 299: 3-20 [in Japanese]

Gammon PR, Neville LA, Patterson RT, Savard MM, Swindles GT, Ariztegui D (2017) A log‐normal spectral analysis of inorganic grain-size distributions from a canadian boreal lake core: Towards refining depositional process proxy data from high latitude lakes. Sedimentol 64: 609-630

Hassan GS, Rojas LA, De Francesco CG (2018) Incorporating taphonomy into community-based paleoenvironmental reconstructions: Can diatom preservation ddiscriminate among shallow lake sub-environments? Palaios 33: 376-392

Kosugi M (1986) Transportation and sedimentation patterns on dead diatoms in a tidal area - a case study in the lower reach of the obitsu river -. Geogr Rev Jpn 59: 37-50 [in Japanese]

Kumisaka K, Yamaguchi N, Okazaki Y (2024) Fragmentation and separation of diatom valves in modern shallow lake sediments: A case study in lake kitaura, japan. J Paleolimnol [in Press]:

Kumon F, Kamitani T, Sutoh K, Inouchi Y (1993) Grain size distribution of the surface sediments in Lake Biwa, Japan. Mem.Geol Soc Jpn 39: [in Japanese]

Naya T, Amano K, Okada M, Nakazato R, Kumon F, Nirei H (2004a) Characteristics of bottom surface sediments in relation to wind and wave action in Lake Kitaura, central Japan. J Geol Soc Jpn 110: 1-10

Naya T, Tanimura Y, Tsuchiya T, Abekawa H, Nakazato R, Amano K (2004b) Behavior of sinking particles and depositional processes o diatom frustules in shallow lake, examined by sediment trap in Lake Kitaura, central Japan. Jpn J limnol 65: 203-213 [in Japanese]

Naya T, Tanimura Y, Kanai Y, Kumon F, Amano K (2007a) Natural and anthropogenic aquatic environmental changes reconstructed by paleolimnological analyses in Lake Kitaura, central Japan. J Paleolimnol 37: 547-563

Naya T, Tanimura Y, Nakazato R, Amano K (2007b) Modern distribution of diatoms in the surface sediments of Lake Kitaura, central Japan. Diatom 23: 55-70

Ohta T, Arai H, Noda A (2011) Identification of the unchanging reference component of compositional data from the properties of the coefficient of variation. Math Geosci 43: 421-434

Ryves DB, Jewson DH, Sturm M, Battarbee RW, Flower RJ, Mackay AW, Granin NG (2003) Quantitative and qualitative relationships between planktonic diatom communities and diatom assemblages in sedimenting material and surface sediments in Lake Baikal, Siberia. Limnol Oceanogr 48: 1643-1661

Sawai Y (2001) Distribution of living and dead diatoms in tidal wetlands of northern Japan: Relations to taphonomy. Palaeogeogr Palaeoclimatol Palaeoecol 173: 125-141

Sawai Y, Horton BP, Kemp AC, Hawkes AD, Nagumo T, Nelson AR (2016) Relationships between diatoms and tidal environments in Oregon and Washington, USA. Diatom Res 31: 17-38

Shimada C, Hasegawa S, Tanimura Y, H. BL (2003) A new index to quantify diatom dissolution levels based on a ratio of neodenticula seminae frustule components. Micropaleontol 49: 267-276

Tagiri M, Naya T, Nagashima M, Negishi M (2009) Chemical composition and origin of suspended solids in Lake Kasumigaura and its tributaries. Jpn J Limnol 70: 87-98 [in Japanese]

Takahashi G (2015) Sample preparation fo X-ray fluorescence analysis; pressed and loose powder methods. Rigaku J 31: 26-30

Vos PC, Wolf Hd (1993) Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects. Hydrobiologia 269/270: 285-296

Yamaguchi N (2023) Validation of appropriate estimation criteria for the number of components for separating a polymodal grain-size distribution into lognormal distributions. Prog Earth Planet Sci 10: 70

Yamaguchi N, Ando T, Enokida H, Nakada N, Yamaki S, Ohta T (2024) Logratio analysis of components separated from grain-size distributions and implications for sedimentary processes: An example of bottom surface sediments in a shallow lake. Sedimentol 71: 1291-1304

Yu Y (2022) MixR: an R package for finite mixture modeling for both raw and binned data. J Open Sour Software 7: 723-741

Table 3-1 Separated components from the grain-size distributions from Lake Kitaura.

Component	Mean grain size (φ)	Proportion (%)
Comp1	3.4–3.6	2.2–5.0
Comp2	3.7–5.0	0.7–12.1
Comp1&2	3.7–5.0	0.7–16.3
Comp3	5.3–6.0	16.0–43.1
Comp4	7.3–7.5	33.7–58.9
Comp5	8.5–8.7	8.6–16.9
Comp6	9.3–9.4	3.3–7.5

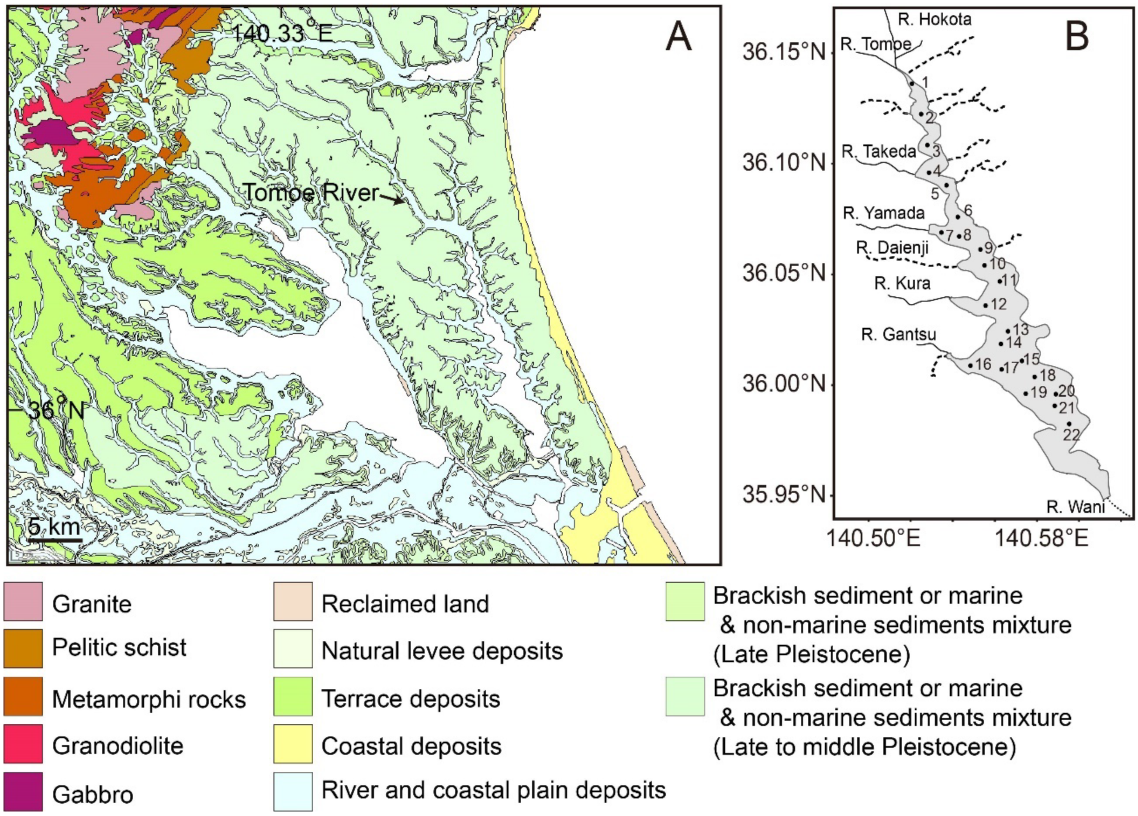

Fig. 3-1 Field setting. (A) Geological map around Lake Kitaura. (B) Map of the sampling sites (numbered) of lakebed-surface sediments in Lake Kitaura. Black solid and dashed lines denote inflow rivers with watershed areas greater than and less than 8 km2, respectively. The Wani River (dotted line) is the only outflowing river.

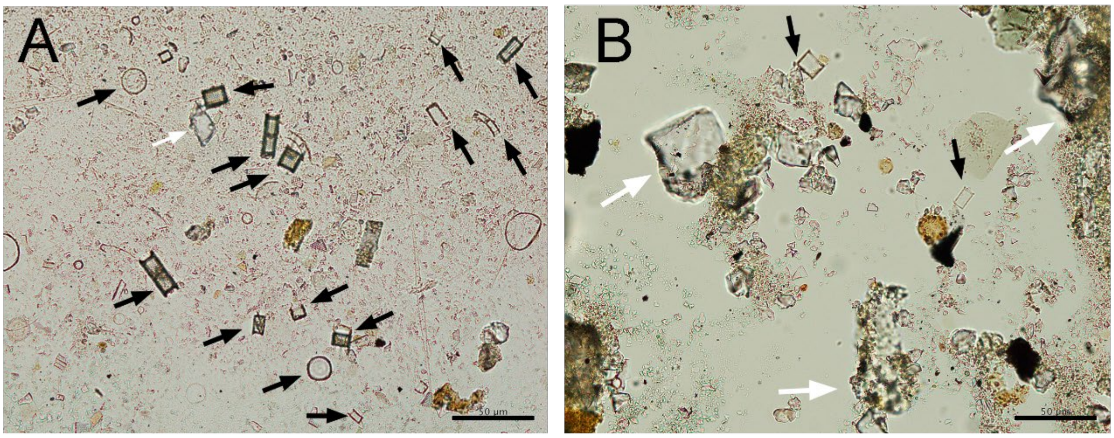

Fig. 3-2 Microscopic observations from lake center (kt14). (A) the smear slide of an unprepared sample. (B) preparation of organic matter, carbonate, and biogenic opal. White allows were point out clastic particles, and black arrows indicated diatom valves. Black bars in A and B are 50 µm.

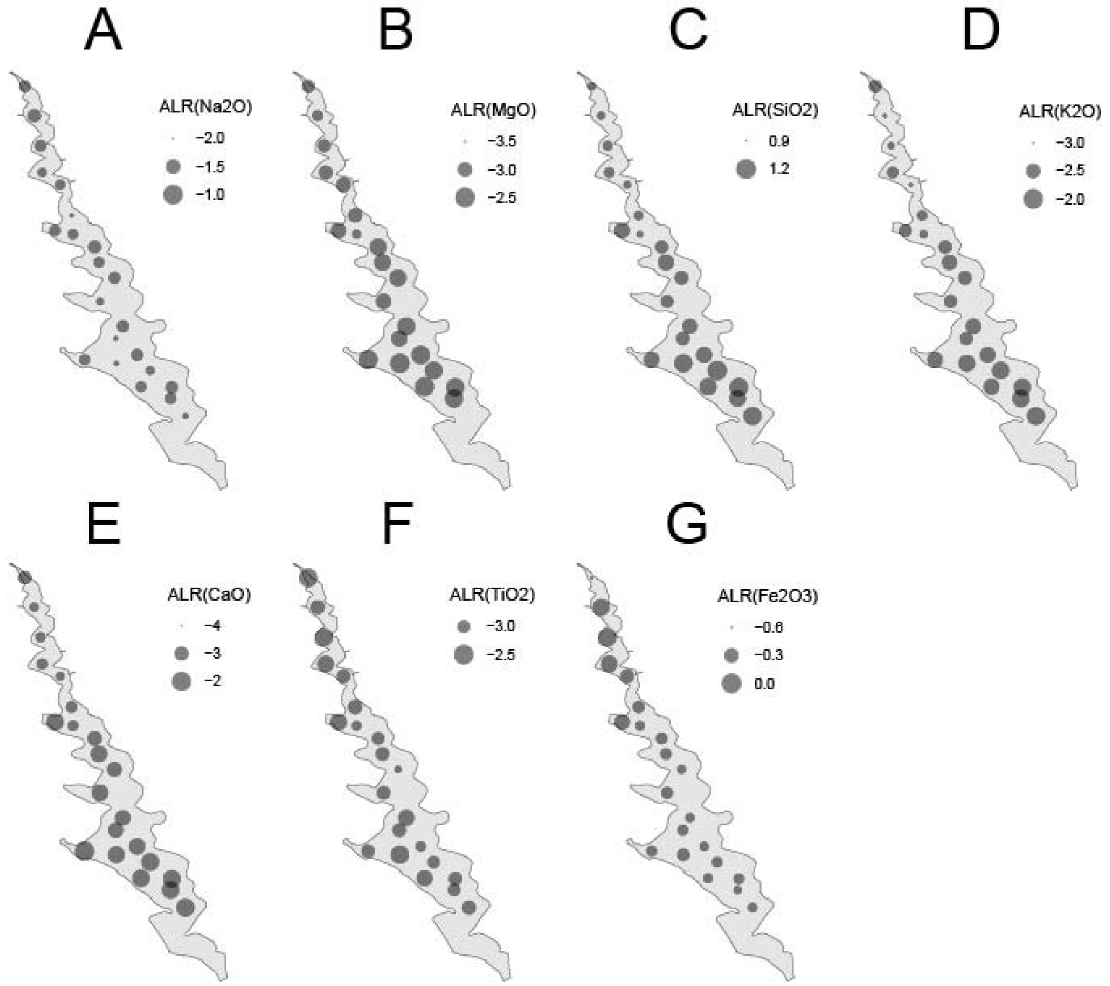

Fig. 3-3. Spatial variation of log-ratio of the mass percentage of (A) Na_2O, (B) MgO, (C) SiO_2, (D) K_2O, (E) CaO, (F) TiO_2, and (G) Fe_2O_3 to Al_2O_3.

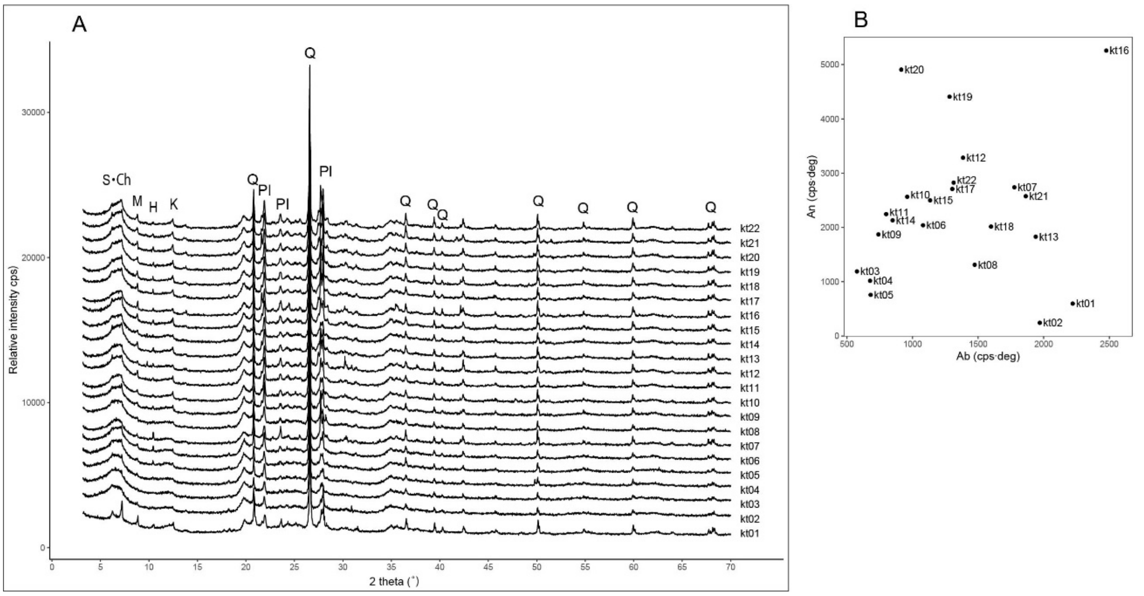

Fig. 3-4 (A) X-ray diffraction patterns of clastic fraction in lake surface sediments. Q: quartz, Pl: plagioclase, S: smectite group, Ch: chlorite, M: mica, H: hornblende, K: kaoline group. (B) Scatter plot of the peak area of albite (3.21 Å) and anorthite (3.19 Å).

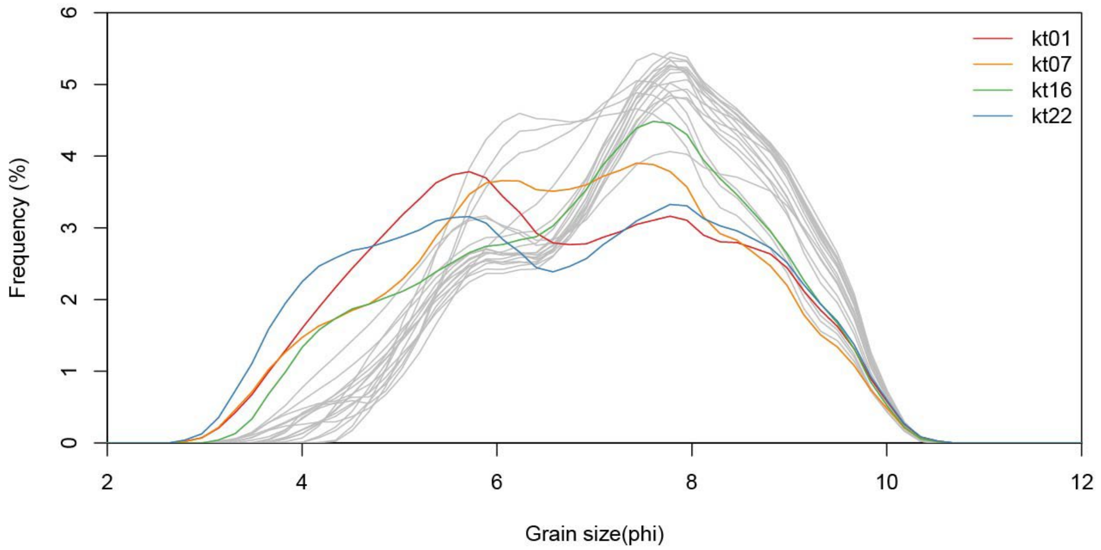

Fig. 3-5. Grain-size distributions of surface sediments in Lake Kitaura. The grain size distributions of surface sediments from kt01, kt07, kt16, and kt22 were the magenta, orange, green, and blue lines, respectively.

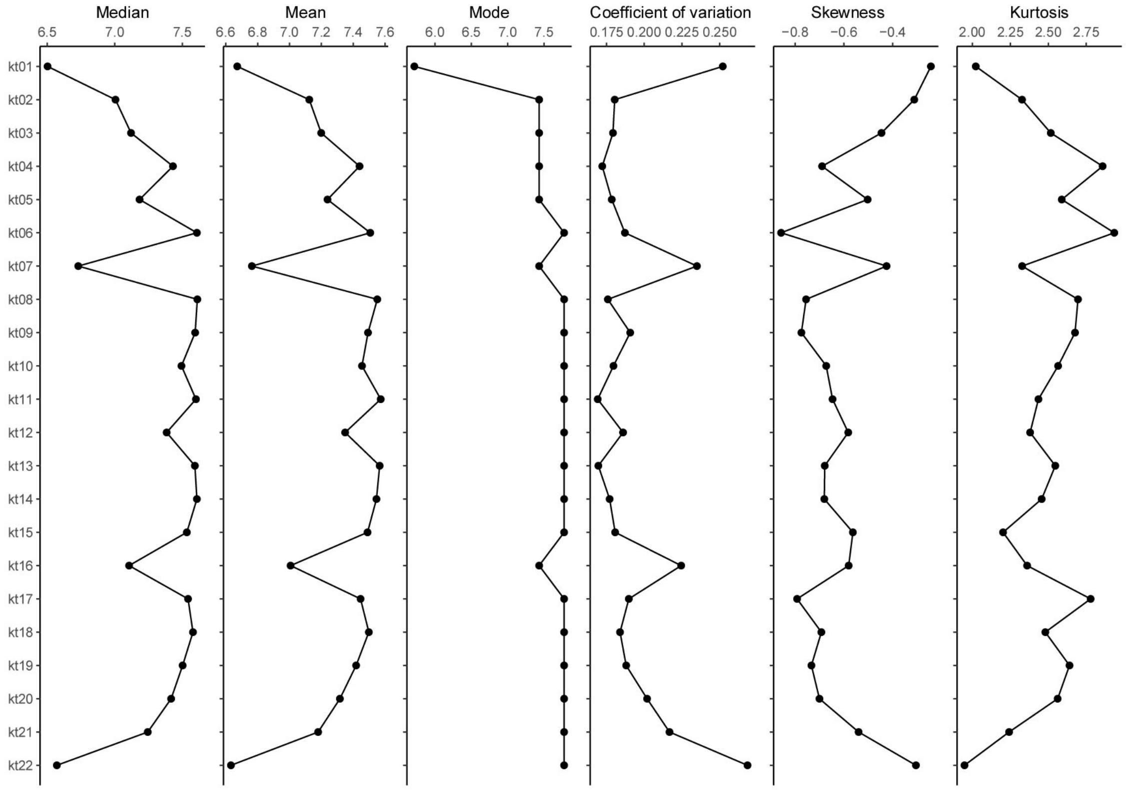

Fig.3-6. Spatial variation of median, mean, mode, coefficient of variation, skewness, and kurtosis of grain size distribution of surface sediments in Lake Kitaura

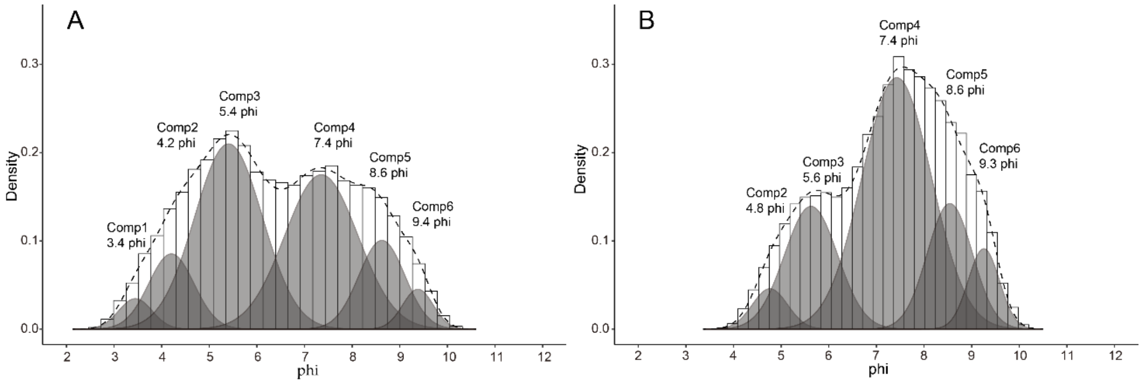

Fig. 3-7. The examples of separated components. (A) kt01 with six components, and (B) kt14 with five components. Gray density plots show individual components.

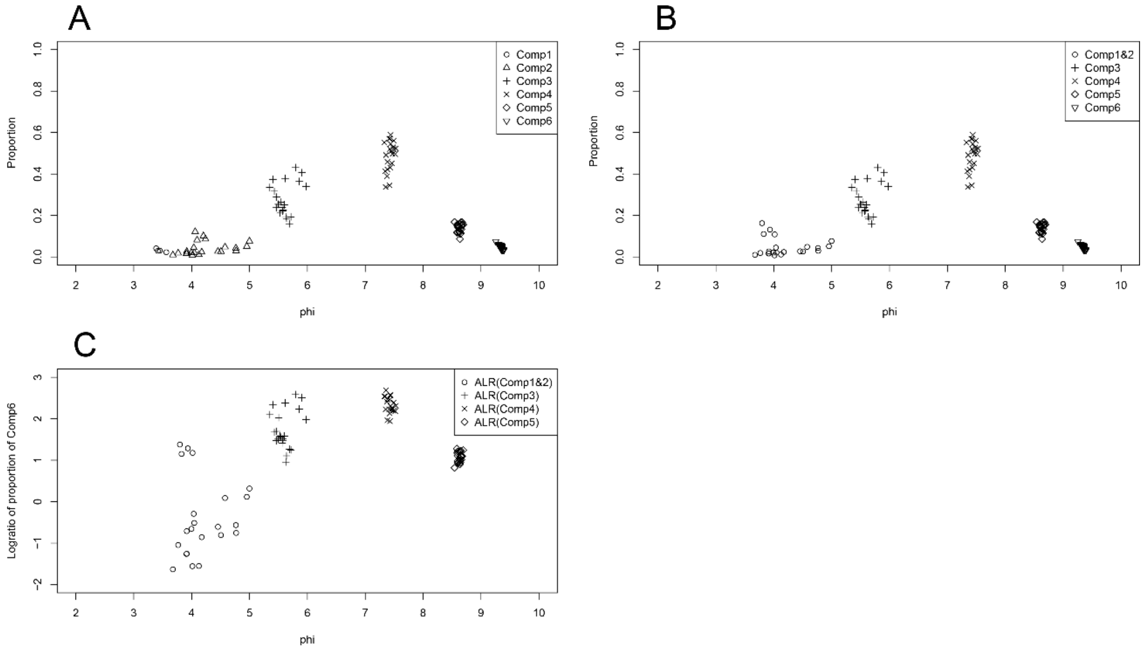

Fig. 3-8. Proportions and mean grain size of separated components by expectation-maximization algorithm. (A) Original proportions and mean grain size of each component. (B) Re-synthesized proportions and mean grain size of Comp1&2. (C) Log-ratio of proportions of Comp1&2–5 relative to Comp6.

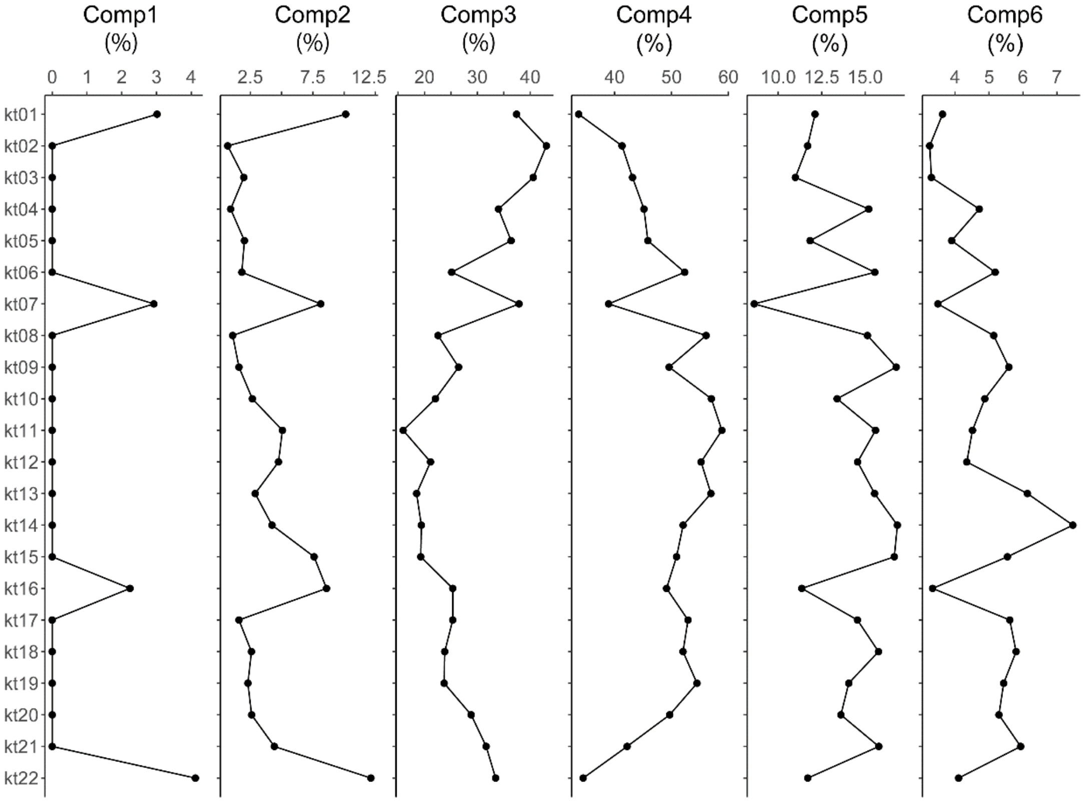

Fig. 3-9. Spatial variation of separated components of surface sediments in Lake Kitaura

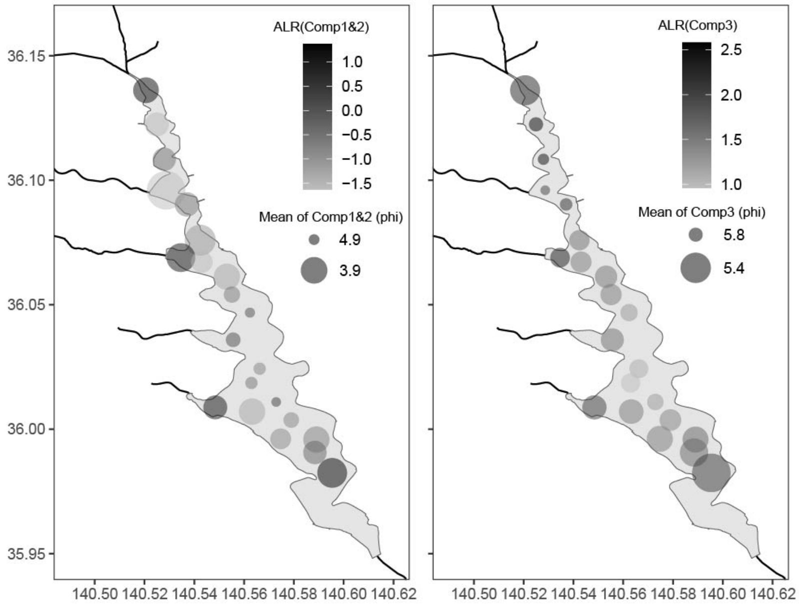

Fig. 3-10. Spatial variation of ALR(Comp1&2), ALR(Comp3), and median grain size of Comp1&2 and Comp3 in Lake Kitaura. Size of the circles show the mean grain size of Comp1&2 and Comp3.

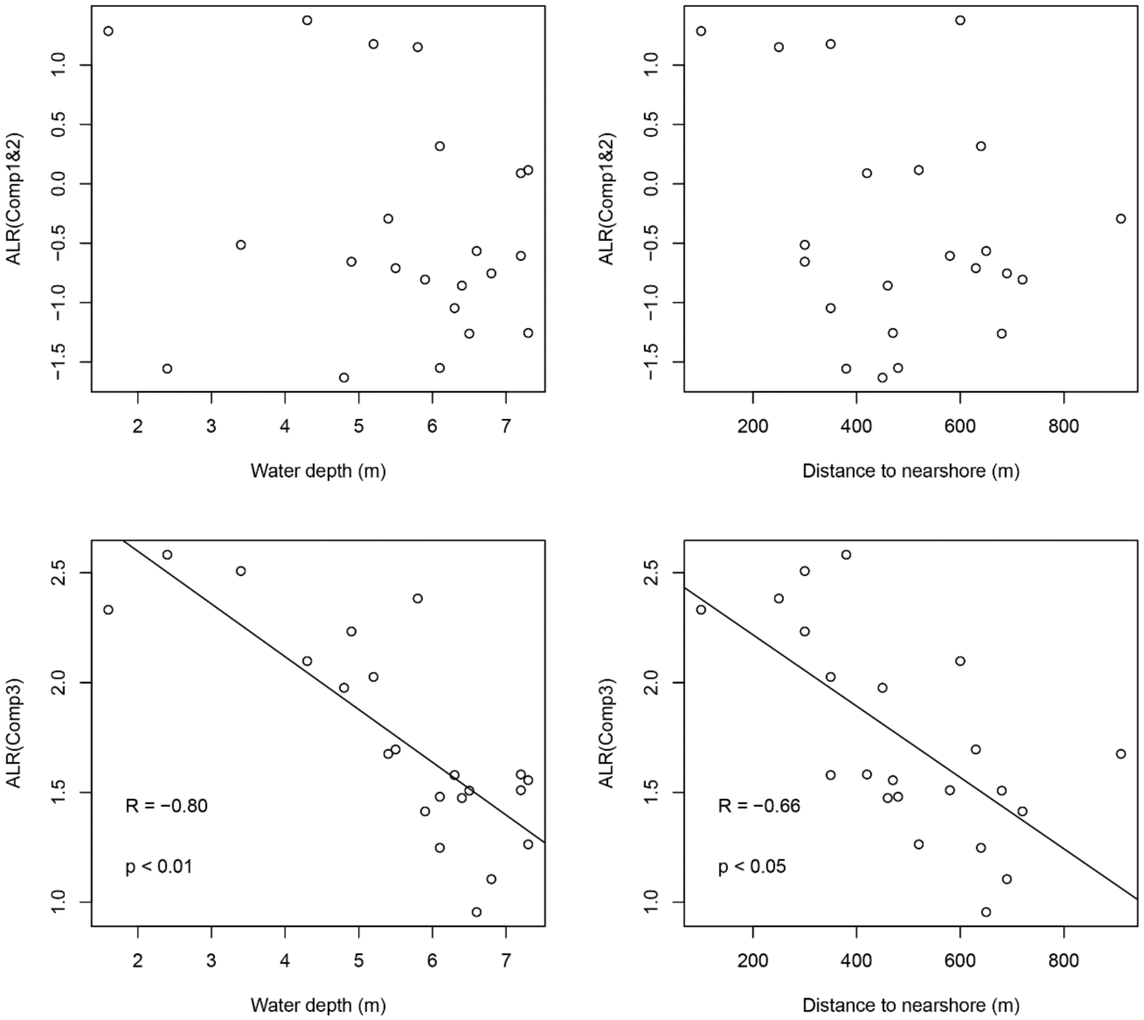

Fig. 3-11. Correlation of environmental settings (water depth and distance to nearshore) and log-ratio values of Comp1&2 and Comp3

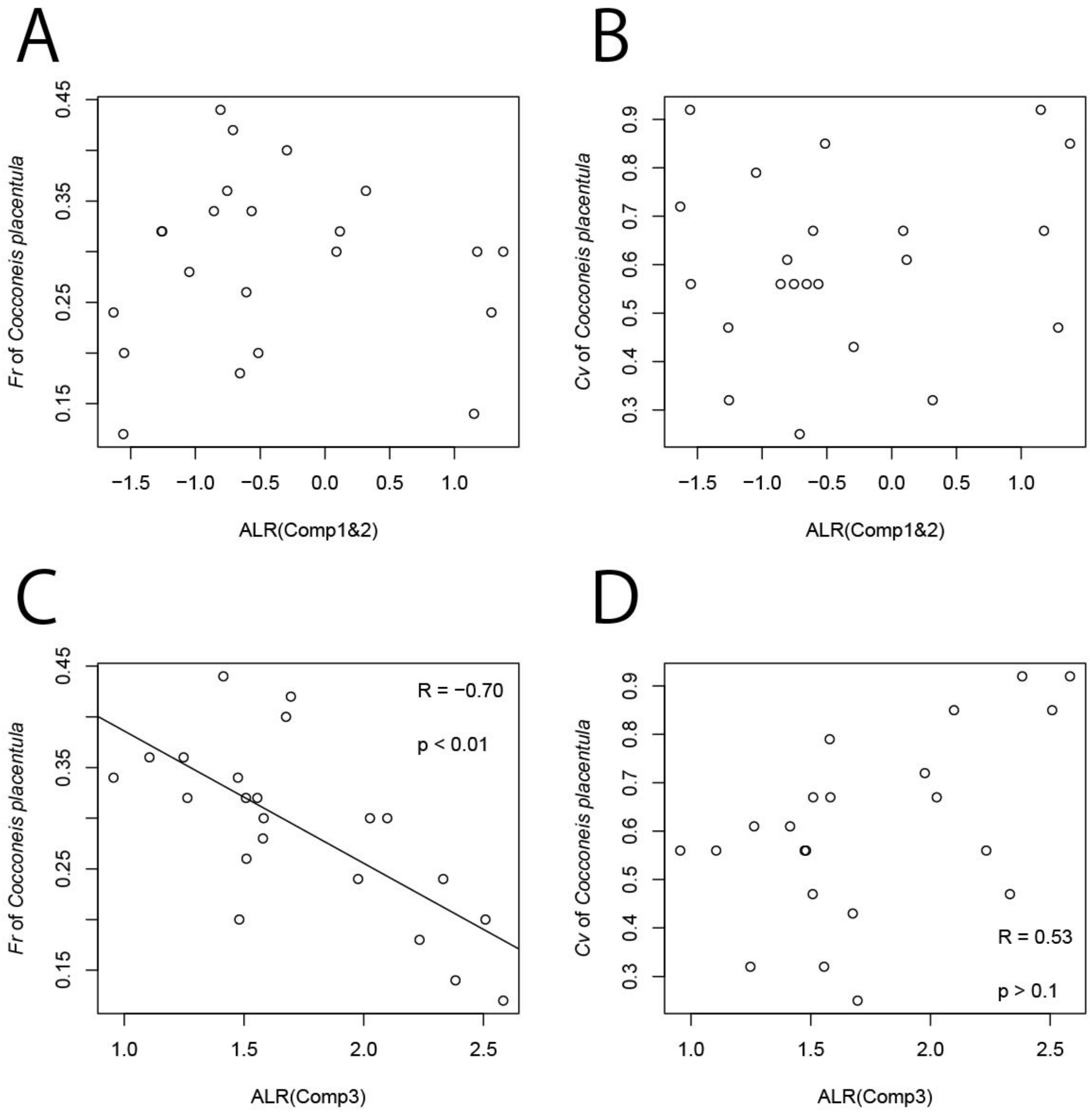

Fig. 3-12. Correlation of *Fr* and *Cv* of *Cocconeis placentula* and log-ratio values of Comp1&2 and Comp3.

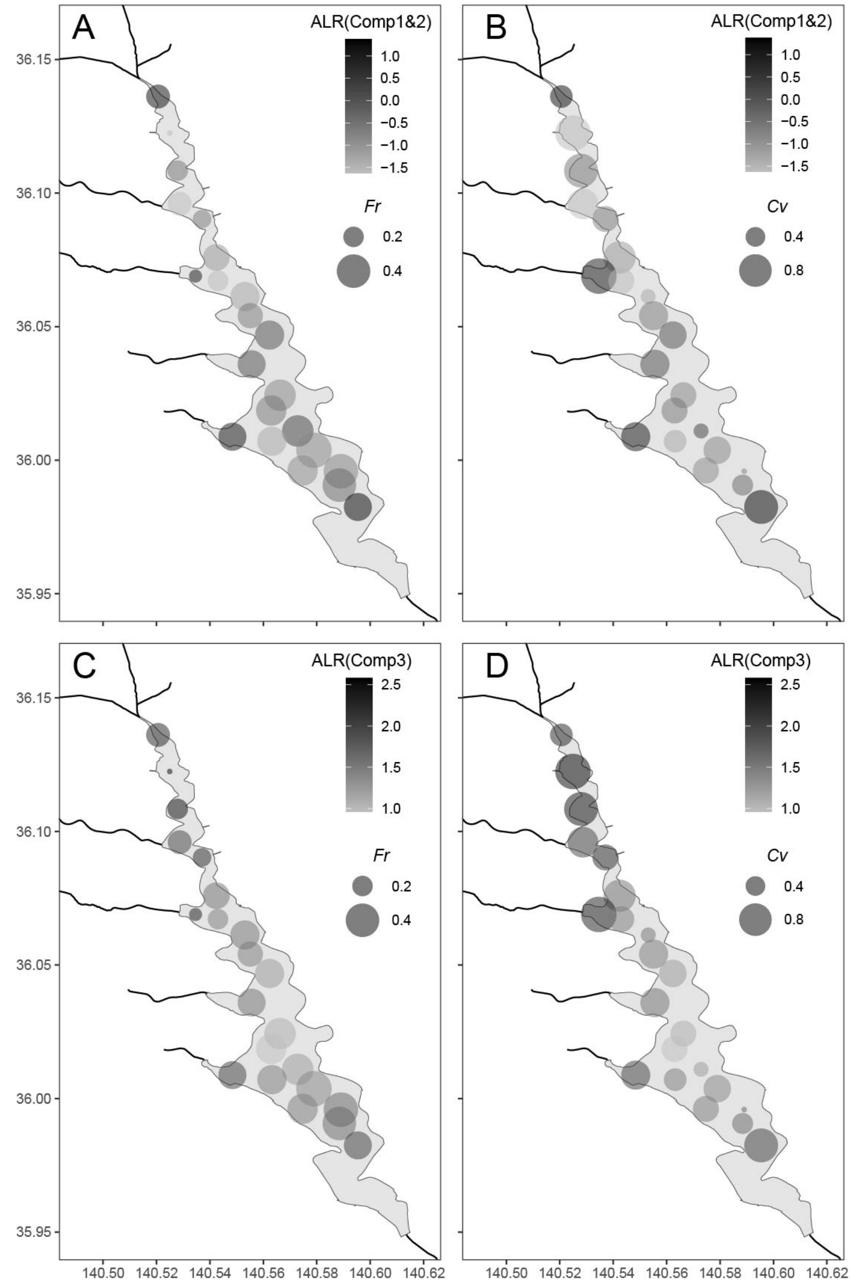

Fig.3-13. Spatial distribution of *Fr* and *Cv* values of *Cocconeis placentula* and grain-size components of Comp1&2 and Comp3: (A) *Fr* values and log-ratio of Comp1&2, (B) *Cv* values and log-ratio of Comp1&2, (C) *Fr* values and log-ratio of Comp3, and (D) *Cv* values and log-ratio of Comp3. Size of the circles show the *Fr* and *Cv* values.

CHAPTER 4

Conclusions

The diatom valve fragmentation and frustule separation in lake surface sediments in Lake Kitaura were studied to understand the transportation and deposition process in a shallow lake. The diatom valve fragmentation (*Fr*) and frustule separation (*Cv*) of the benthic diatom, *Cocconeis placentula*, reflected transportation effects such as waves and turbidity flows from inflow rivers. The *Fr* of *C. placentula* was correlated to the distance to the nearshore and could indicate diatom transport from littoral areas. Benthic diatom taxa for which both valves coexist in river mouths and lakeshore areas are autochthonous. The raphid valves of *C. placentula* were restricted to nearshore with aquatic vegetation. In contrast, the araphid valves of *C. placentula* were spread offshore. The lifeform and habitat of the benthic diatoms caused both valves to behave differently and separate. The *Cv* values can indicate the transport of diatoms from their life habitat. The diatom fragmentation and frustule separation reflect the transportation of benthic diatom valves, indicating the autochthonous diatoms from inflowing rivers and their habitat.

The sedimentological study demonstrates that the transportation of clastic sediments was mainly controlled by sediment supply and wave disturbance in Lake Kitaura. The separation of grain size distribution suggested different sedimentary processes, such as transport from inflow rivers and transport by wave disturbances. The clastic components with coarse and medium silty sizes (Comp1&2 and Comp3, respectively) corresponded to the valve size of *C. placentula*, and thus these components can be compared. The correlation with *Fr* and log-ratio of Comp3, which reflects the difference between the northern and southern sedimentary processes, suggests that the diatom fragmentation of benthic diatoms results from the sediment supply from inflowing rivers and littoral areas and high frequency of sediment resuspension in shallow lakes. In contrast, *Cv* was not correlated with Comp1&2 and Com3 despite the increasing trend at adjacent sites to inflow rivers and littoral areas. The inflows of sediment from the river and the shore coincided with the increase in *Cv*, implying that the inflow from the habitat directly affected the results. The wave disturbance may not affect the frustule separation, unlike the valve fragmentation.

Diatom taphonomy in freshwater has been overlooked in previous studies. The diatom taphonomic studies were mainly conducted in coastal or marine settings, controlled by tidal action, dissolution, and biological activity; however, this study demonstrated that diatom transportation in the shallow lake also occurred with diatom valve fragmentation and frustule separation in a relatively calm environment with littler water movement. This study contributes to the diatom valve transportation and the discrimination of autochthonous or allochthonous diatoms in shallow lakes. The diatom valve fragmentation and frustule separation provide insight into the multiple sources of benthic diatoms. These results also contributed to interpreting fossil diatom assemblages in sediment cores. Paleoenvironmental reconstructions can be precise in excluding allochthonous diatoms from fossil diatom assemblages. In addition, incorporating allochthonous diatoms may help interpret the transportation and sedimentary processes of sedimentary particles.

The diatom valve fragmentation and frustule separation explain the diatom transportation and provenance. The multiple sources of benthic diatoms can have individual productivity, suggesting that the valve abundance supplied from each source varies. Further investigations are required to assess the relationship between the diatom taphonomic signatures and diatom valve abundance in lake surface sediments. Moreover, this study demonstrates the diatom taphonomic signatures were consistent with the sedimentary processes of clastic sediments. This study suggested that the other properties, such as grain size distributions, should be considered for the diatom taphonomy. The multi-proxy approach will emphasize the reliability of diatom taphonomy. The established diatom taphonomy can be applied to multidisciplinary studies, such as forensic science.

APPENDIX A. Sampling locations and settings. "Distance" means the distance from the nearest lakeshore. Each site was assigned to cluster I, cluster II.

Sample site	Location		Water depth (m)	Distance to nearshore (m)	Distance to vegetation (m)	Environmental setting
	Latitude (°N)	Longitude (°E)				
kt01	36.1361	140.521	1.6	100	114	Cluster I
kt02	36.1224	140.525	2.4	380	384	Cluster I
kt03	36.1084	140.528	3.4	300	298	Cluster I
kt04	36.096	140.529	4.8	450	533	Cluster II
kt05	36.0903	140.537	4.9	300	1375	Cluster II
kt06	36.0759	140.542	6.3	350	665	Cluster II
kt07	36.0689	140.535	5.8	250	256	Cluster II
kt08	36.0672	140.543	6.1	480	963	Cluster II
kt09	36.0613	140.553	7.3	470	456	Cluster II
kt10	36.0541	140.555	7.2	580	640	Cluster II
kt11	36.0468	140.562	7.3	520	790	Cluster II
kt12	36.0359	140.556	7.2	420	681	Cluster II
kt13	36.0243	140.566	6.8	690	1081	Cluster II
kt14	36.0186	140.563	6.6	650	1500	Cluster II
kt15	36.0109	140.573	6.1	640	688	Cluster II
kt16	36.0088	140.548	5.2	350	705	Cluster II
kt17	36.0071	140.563	6.5	680	1623	Cluster II
kt18	36.0037	140.579	5.9	720	719	Cluster II
kt19	35.9961	140.575	6.4	460	975	Cluster II
kt20	35.9959	140.589	5.5	630	1207	Cluster II
kt21	35.9907	140.588	5.4	910	988	Cluster II
kt22	35.9825	140.595	4.3	600	686	Cluster II

APPENDIX B. Diatom taxa identified in lake surface sediments in Lake Kitaura and their ecolgy

Diatom taxa	Lifeform
Achnanthidium minutissimum (Kützing) Czarnecki	Benthic
Achnanthidium pusillum (Grunow) Czarnecki	Benthic
Actinocyclus normanii f. *subsalsa* (Juhl. -Dannf) Hustedt	Planktonic
Amphora spp.	Benthic
Aulacoseira ambigua (Grunow) Simonsen	Planktonic
Aulacoseira granulata (Ehrenberg) Simonsen	Planktonic
Aulacoseira pusilla (Meister) Tuji & Houki	Planktonic
Aulacoseira spp.	Planktonic
Bacillaria spp.	Benthic
Cocconeis diminuta Pantocsek	Benthic
Cocconeis placentula Ehrenberg	Benthic
Cyclostephanos dubius (Fricke) Round	Planktonic
Cyclostephanos spp.	Planktonic
Cyclotella atomus Hustedt	Planktonic
Cyclotella meneghiniana Kützing	Planktonic
Cyclotella ocellata Pantocsek	Planktonic
Cyclotella spp.	Planktonic
Cymbella spp.	Benthic
Diploneis spp.	Benthic
Discostella asterocostata (Lin, Xie &. Cai) Houk & Klee	Planktonic
Encyonema spp.	Benthic
Epithemia spp.	Benthic
Eunotia spp.	Benthic
Fragilaria spp.	Tychoplanktonic
Fragilariforma spp.	Tychoplanktonic
Gomphoneis spp.	Benthic
Gomphonema spp.	Benthic
Gyrosigma spp.	Benthic
Hantzschia spp.	Benthic
Melosira spp.	Benthic
Meridion spp.	Benthic
Navicula spp.	Benthic
Nitzschia amphibia Grunow	Benthic
Nitzschia spp.	Benthic
Pinnularia spp.	Benthic
Planothidium lanceolatum (Brébisson ex Kützing) Lange-Bertalot	Benthic
Planothidium rostratum (Østrup) Lange-Bertalot	Benthic
Psammothidium subatomoides (Hustedt) Bukhtiyarova & Round	Benthic
Pseudostaurosira spp.	Tychoplanktonic
Rhoicosphenia spp.	Benthic
Rhopalodia spp.	Benthic
Sellaphora laevissima (Kützing) Mann	Benthic
Staurosira construens Ehrenberg	Tychoplanktonic
Staurosira construens var. *exigua* (Smith) Krammer & Lange-	Tychoplanktonic
Staurosira venter (Ehrenberg) Cleve & Möller	Tychoplanktonic
Staurosirella spp.	Tychoplanktonic
Stephanodiscus hantzschii f. *tenuis* (Hustedt) Håkansson &	Planktonic
Stephanodiscus minutulus (Kützing) Round	Planktonic
Stephanodiscus vestibulis Håkansson, Theriot & Stoermer	Planktonic
Surirella spp.	Benthic
Synedra spp.	Tychoplanktonic
Tabellaria flocculosa (Roth) Kützing	Benthic
Thalassiosira lacustris (Grunow) Hasle	Planktonic
Tryblionella spp.	Benthic

APPENDIX C. Relative abundance of diatom taxa and lifeform in lake surface sediments in Lake Kitaura

Diatom taxa	kt01	kt02	kt03	kt04	kt05	kt06	kt07	kt08	kt09	kt10	kt11
Planktonic	12.3	32.0	50.2	72.0	83.3	88.7	81.3	91.3	90.3	91.7	84.7
Tychoplanktonic	30.0	24.7	30.4	17.3	11.7	5.0	7.0	5.3	6.0	4.7	10.7
Benthic	57.7	43.3	19.4	10.7	5.0	6.3	11.7	3.3	3.7	3.7	4.7
Actinocyclus normanii	1.0	1.0	0.3	2.0	2.0	3.0	3.0	2.7	1.7	6.0	4.0
Amphora spp.	1.3	0.7	0.3	0.3	1.0	0.7	0.0	0.3	0.0	0.0	0.0
Aulacoseira ambigua	5.0	5.7	12.0	21.7	19.7	27.0	25.0	23.7	18.3	19.7	21.0
Aulacoseira granulata	0.0	5.3	10.7	12.3	25.0	23.3	19.0	28.0	32.0	32.3	15.3
Aulacoseira pusilla	2.0	0.7	4.3	4.7	6.7	5.3	2.7	8.7	6.0	4.0	4.0
Aulacoseira spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
Bacilaria spp.	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cocconeis placentula	2.7	7.3	1.3	1.3	0.0	0.0	1.7	0.3	0.0	1.0	0.7
Cyclostephanos dublis	0.3	4.0	6.4	11.3	10.3	16.0	13.0	11.7	15.0	13.3	19.7
Cyclotella atomus	0.0	1.3	2.7	0.3	1.3	0.3	2.3	0.0	0.3	0.0	0.3
Cyclotella meneginiana	2.0	4.7	8.4	2.7	4.3	4.0	1.3	6.3	6.7	6.0	5.0
Cyclotella ocellata	0.0	0.0	0.0	1.3	0.0	1.0	4.3	2.0	2.3	2.0	2.7
Cyclotella spp.	0.0	1.3	0.7	1.7	0.7	0.0	1.3	0.0	0.0	2.0	0.0
Cymbella spp.	0.0	1.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0
Diploneis spp.	0.7	1.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Discostella asterocostata	0.0	0.3	0.3	0.0	1.7	1.7	1.3	2.7	1.7	1.3	2.7
Encyonema spp.	1.0	2.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
Epithemia spp.	0.7	2.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0
Eunotia spp.	0.3	0.7	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fragilaria spp.	3.0	1.7	4.0	0.3	1.0	1.7	0.3	1.0	1.3	0.7	2.3
Fragilariforma spp.	0.3	1.0	2.0	0.0	1.7	0.0	0.7	0.0	0.0	0.0	0.0
Gomphoneis spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gomphonema spp.	1.3	6.0	2.3	0.0	1.3	0.0	0.3	0.0	0.0	0.7	0.7
Gyrosigma spp.	0.3	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0
Hantzschia spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Melosira spp.	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meridion spp.	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
Navicula spp.	15.0	6.0	3.3	4.3	0.7	1.7	3.7	1.0	2.0	0.0	1.0
Nitzschia amphibia	3.3	1.0	0.3	0.0	0.0	0.7	0.3	0.7	0.3	0.7	0.0
Nitzshia spp.	5.7	0.3	1.0	1.3	3.0	1.7	2.0	1.3	0.7	1.0	5.0
Pinnularia spp.	2.3	2.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Planothidium lanceolatum/rostratum, Achnanthidium minutissimum/pusillum., and *Psammothidium subatomoides*	25.0	4.3	3.3	1.0	0.7	1.7	2.0	0.0	0.0	0.3	1.0
Pseudostaurosira spp.	2.0	7.0	4.3	1.3	1.0	0.7	2.7	0.7	0.7	0.0	1.0

APPENDIX C. Continued

Diatom taxa	kt12	kt13	kt14	kt15	kt16	kt17	kt18	kt19	kt20	kt21	kt22
Planktonic	90.7	89.3	88.3	89.3	72.0	88.3	85.4	82.3	85.0	72.9	84.7
Tychoplanktonic	6.0	5.7	9.7	6.0	19.0	8.0	11.0	9.3	8.3	19.1	8.7
Benthic	3.3	5.0	2.0	4.7	9.0	3.7	3.7	8.3	6.7	8.0	6.7
Actinocyclus normanii	4.3	2.7	4.0	6.0	2.3	2.0	3.3	4.0	5.3	2.3	2.0
Amphora spp.	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.3
Aulacoseira ambigua	20.3	22.7	27.0	18.0	19.7	23.7	21.9	23.7	16.7	19.4	22.0
Aulacoseira granulata	26.7	27.3	21.3	28.0	21.0	20.0	22.3	19.7	22.7	19.1	30.7
Aulacoseira pusilla	9.3	4.7	2.0	4.0	5.3	6.0	7.0	3.0	7.3	4.0	4.0
Aulacoseira spp.	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7
Bacilaria spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cocconeis placentula	0.7	0.3	0.3	0.0	1.7	0.7	1.3	1.3	0.3	0.7	2.0
Cyclostephanos dublis	14.0	17.0	19.3	11.3	11.3	14.3	13.0	15.7	18.3	13.0	9.7
Cyclotella atomus	0.0	0.7	0.3	1.7	0.3	1.3	1.3	0.7	1.7	1.3	1.3
Cyclotella meneginiana	3.3	5.0	5.7	9.3	3.0	8.3	6.3	4.0	5.3	4.3	5.0
Cyclotella ocellata	2.7	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cyclotella spp.	0.3	1.0	0.0	0.7	0.7	0.7	2.0	0.0	0.7	0.0	0.0
Cymbella spp.	0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.3	0.0
Diploneis spp.	0.0	0.7	0.0	0.0	1.0	0.3	0.0	0.7	0.0	0.3	0.7
Discostella asterocostata	2.0	2.7	1.0	3.7	3.0	1.7	1.3	4.0	1.3	2.3	2.0
Encyonema spp.	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.3	0.0
Epithemia spp.	0.0	0.3	0.0	0.0	0.0	0.0	1.0	0.0	0.3	0.0	0.7
Eunotia spp.	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fragilaria spp.	1.0	1.0	1.0	0.7	1.0	1.7	1.0	1.0	1.0	1.7	0.7
Fragilariforma spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gomphoneis spp.	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gomphonema spp.	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0
Gyrosigma spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.0
Hantzschia spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
Melosira spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meridion spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Navicula spp.	0.3	0.7	0.7	0.7	0.7	1.0	0.0	0.7	0.3	0.3	1.7
Nitzschia amphibia	0.0	0.0	0.3	0.7	0.3	0.3	0.0	0.0	0.0	1.3	0.0
Nitzshia spp.	1.7	0.7	2.0	1.7	1.7	1.3	1.0	2.3	1.7	2.7	1.0
Pinnularia spp.	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0
Planothidium lanceolatum/rostratum, Achnanthidium minutissimum/pusillum., and *Psammothidium subatomoides*	0.0	0.7	0.3	0.3	2.0	0.7	0.7	2.3	2.7	1.7	0.0
Pseudostaurosira spp.	1.7	1.7	0.0	1.7	1.7	0.3	0.3	3.0	2.7	2.0	1.3

APPENDIX C. Continued

Diatom taxa	kt01	kt02	kt03	kt04	kt05	kt06	kt07	kt08	kt09	kt10	kt11
Roicosphenia spp.	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ropalodia spp.	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0
Sellaphora laevissima	0.3	0.7	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Staurosira construence var. *exigua*	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0
Staurosira construens var. *construens*	2.7	3.7	3.0	2.0	0.7	0.0	0.0	0.0	0.0	1.3	0.3
Staurosira venter	16.0	17.3	19.4	12.7	4.3	1.3	3.3	2.7	3.7	1.7	2.3
Staurosirella spp.	2.0	0.3	1.0	0.3	0.0	0.3	0.7	0.3	0.0	0.0	0.7
Stephanodiscus hantzschii	1.0	6.0	2.7	11.7	9.3	3.7	3.0	2.3	2.0	1.3	3.7
Stephanodiscus minutulau	0.0	0.3	0.7	0.0	1.3	1.7	0.0	0.3	0.3	0.0	0.7
Stephanodiscus vestibulis	1.0	1.0	0.3	2.3	0.7	1.3	3.7	3.0	3.0	2.3	4.0
Surirella spp.	0.0	0.3	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0
Synedra spp.	0.3	0.3	0.0	0.3	1.0	0.0	0.0	0.0	0.0	0.0	0.0
Tabellaria flocculosa	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thalassiosira lacustris	0.0	0.3	0.7	0.0	0.3	0.3	1.3	0.0	0.0	1.3	1.7
Tryblionella spp.	0.0	0.7	0.3	0.7	0.0	0.0	0.3	0.0	0.3	0.3	0.0

APPENDIX C. Continued

Diatom taxa	kt12	kt13	kt14	kt15	kt16	kt17	kt18	kt19	kt20	kt21	kt22
Roicosphenia spp.	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ropalodia spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sellaphora laevissima	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Staurosira construence var. *exigua*	0.3	0.3	0.0	0.0	1.0	0.0	0.3	0.7	0.0	0.0	0.0
Staurosira construens var. *construens*	1.0	0.0	0.3	0.0	2.3	0.0	2.7	0.3	0.7	1.3	0.0
Staurosira venter	2.0	1.3	5.0	2.3	11.3	3.7	5.6	3.7	3.0	8.0	5.3
Staurosirella spp.	0.0	2.0	1.3	1.0	1.3	1.3	0.0	1.3	1.7	5.4	1.7
Stephanodiscus hantzschii	3.3	2.3	4.0	2.0	2.0	6.0	2.3	4.3	3.3	3.7	3.3
Stephanodiscus minutulau	1.0	0.0	0.0	1.0	0.0	0.3	0.0	0.3	0.3	0.3	0.0
Stephanodiscus vestibulis	2.3	1.0	2.3	1.7	1.7	3.7	2.7	2.3	1.7	2.7	3.0
Surirella spp.	0.3	0.0	0.0	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0
Synedra spp.	0.0	0.3	0.0	0.3	0.3	0.0	0.3	0.0	0.3	0.0	0.0
Tabellaria flocculosa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thalassiosira lacustris	1.0	0.0	0.3	2.0	1.7	0.3	2.0	0.7	0.3	0.3	1.0
Tryblionella spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX D. *Fr* of *Aulacoseira ambigua* and *Aulacoseira granulata,* and *Cv* values of *Cocconeis placentula* and *Planothidium lanceolatum*

Diatom taxa	kt01	kt02	kt03	kt04	kt05	kt06	kt07	kt08	kt09	kt10	kt11	kt12	kt13
Aulacoseira ambigua	0.07	0.18	0.17	0.11	0.03	0.11	0.08	0.10	0.09	0.20	0.16	0.11	0.04
Aulacoseira granulata	N/A	0.19	0.06	0.22	0.09	0.10	0.12	0.06	0.06	0.08	0.07	0.04	0.05
Cocconeis placentula	0.50	0.58	1.00	0.50	N/A	N/A	0.00	N/A	N/A	0.00	N/A	0.00	N/A
Planothidium lanceolatum	0.85	0.00	0.00	0.00	N/A	0.00	0.50	N/A	N/A	N/A	0.00	N/A	N/A

APPENDIX D. Continued

Diatom taxa	kt14	kt15	kt16	kt17	kt18	kt19	kt20	kt21	kt22
Aulacoseira ambigua	0.07	0.04	0.15	0.06	0.03	0.04	0.14	0.10	0.09
Aulacoseira granulata	0.05	0.00	0.13	0.03	0.01	0.03	0.10	0.02	0.07
Cocconeis placentula	0.00	N/A	0.00	N/A	0.00	0.00	N/A	0.00	0.50
Planothidium lanceolatum	N/A	N/A	0.00	1.00	N/A	0.00	0.50	N/A	N/A

APPENDIX E. *Fr* and *Cv* values for *Cocconeis placentula* obtained by counting 50 valves in each sample

	kt01	kt02	kt03	kt04	kt05	kt06	kt07	kt08	kt09	kt10	kt11	kt12	kt13	kt14
Fr of *Cocconeis placentula*	0.24	0.12	0.20	0.24	0.18	0.28	0.14	0.20	0.32	0.26	0.32	0.30	0.36	0.34
Cv of *Cocconeis placentula*	0.47	0.92	0.85	0.72	0.56	0.79	0.92	0.56	0.32	0.67	0.61	0.67	0.56	0.56
Fr of araphid valve	0.12	0.15	0.19	0.14	0.19	0.25	0.08	0.22	0.21	0.33	0.32	0.27	0.44	0.31
Fr of raphid valve	0.31	0.08	0.22	0.38	0.17	0.32	0.21	0.17	0.67	0.15	0.32	0.35	0.22	0.39

APPENDIX E. Continued

	kt15	kt16	kt17	kt18	kt19	kt20	kt21	kt22
Fr of *Cocconeis placentula*	0.36	0.30	0.32	0.44	0.34	0.42	0.40	0.30
Cv of *Cocconeis placentula*	0.32	0.67	0.47	0.61	0.56	0.25	0.43	0.85
Fr of araphid valve	0.39	0.37	0.24	0.39	0.41	0.38	0.43	0.37
Fr of raphid valve	0.25	0.20	0.50	0.53	0.22	0.60	0.33	0.22

Appendix F. Grain size data of each sample in Lake Kitaura

Sample name	1.25 phi (%)	1.42 phi (%)	1.6 phi (%)	1.77 phi (%)	1.94 phi (%)	2.11 phi (%)	2.28 phi (%)	2.45 phi (%)	2.63 phi (%)	2.8 phi (%)	2.97 phi (%)
kt01	0	0	0	0	0	0	0	0	0.023	0.072	0.206
kt02	0	0	0	0	0	0	0	0	0	0	0
kt03	0	0	0	0	0	0	0	0	0	0	0
kt04	0	0	0	0	0	0	0	0	0	0	0.002
kt05	0	0	0	0	0	0	0	0	0	0	0
kt06	0	0	0	0	0	0	0	0	0	0	0.006
kt07	0	0	0	0	0	0	0	0	0.019	0.071	0.216
kt08	0	0	0	0	0	0	0	0	0	0	0
kt09	0	0	0	0	0	0	0	0	0	0	0.004
kt10	0	0	0	0	0	0	0	0	0	0	0
kt11	0	0	0	0	0	0	0	0	0	0	0
kt12	0	0	0	0	0	0	0	0	0	0	0
kt13	0	0	0	0	0	0	0	0	0	0	0
kt14	0	0	0	0	0	0	0	0	0	0	0
kt15	0	0	0	0	0	0	0	0	0	0	0
kt16	0	0	0	0	0	0	0	0	0.001	0	0.041
kt17	0	0	0	0	0	0	0	0	0	0.003	0.022
kt18	0	0	0	0	0	0	0	0	0	0	0
kt19	0	0	0	0	0	0	0	0	0	0	0.001
kt20	0	0	0	0	0	0	0	0	0	0	0.026
kt21	0	0	0	0	0	0	0	0	0	0	0.012
kt22	0	0	0	0	0	0	0	0	0.041	0.127	0.352

Appendix F. Continued

Sample name	3.14 phi (%)	3.31 phi (%)	3.48 phi (%)	3.66 phi (%)	3.83 phi (%)	4 phi (%)	4.17 phi (%)	4.34 phi (%)	4.51 phi (%)	4.69 phi (%)	4.86 phi (%)
kt01	0.424	0.674	0.992	1.29	1.599	1.89	2.17	2.437	2.687	2.934	3.18
kt02	0	0.002	0.018	0.075	0.18	0.28	0.371	0.531	0.709	1.03	1.474
kt03	0	0.004	0.04	0.145	0.354	0.482	0.563	0.639	0.641	0.816	1.097
kt04	0.021	0.072	0.177	0.235	0.259	0.292	0.294	0.369	0.483	0.673	0.937
kt05	0	0.005	0.053	0.172	0.42	0.535	0.55	0.59	0.551	0.725	1.049
kt06	0.042	0.126	0.286	0.393	0.477	0.551	0.585	0.684	0.814	1	1.246
kt07	0.462	0.712	1.024	1.266	1.47	1.631	1.733	1.849	1.937	2.09	2.282
kt08	0	0.003	0.019	0.078	0.187	0.296	0.412	0.554	0.7	0.915	1.193
kt09	0.022	0.079	0.178	0.276	0.389	0.508	0.623	0.778	0.956	1.176	1.442
kt10	0	0.002	0.005	0.056	0.131	0.269	0.47	0.681	0.919	1.169	1.435
kt11	0	0	0	0	0	0.004	0.023	0.176	0.437	0.786	1.295
kt12	0	0	0	0.019	0.069	0.236	0.528	0.833	1.209	1.533	1.839
kt13	0	0	0	0.002	0.008	0.072	0.173	0.341	0.576	0.851	1.189
kt14	0	0	0	0.003	0.009	0.092	0.221	0.443	0.775	1.102	1.473
kt15	0	0	0	0	0	0.008	0.038	0.235	0.57	1.02	1.681
kt16	0.13	0.335	0.684	0.99	1.333	1.574	1.737	1.87	1.935	2.026	2.113
kt17	0.05	0.108	0.193	0.291	0.406	0.533	0.673	0.838	1.024	1.236	1.482
kt18	0	0.002	0.007	0.056	0.13	0.263	0.453	0.673	0.936	1.223	1.554
kt19	0.004	0.038	0.088	0.187	0.335	0.496	0.681	0.88	1.094	1.329	1.596
kt20	0.061	0.146	0.286	0.426	0.588	0.748	0.903	1.086	1.284	1.511	1.777
kt21	0.046	0.151	0.328	0.523	0.772	0.994	1.206	1.429	1.65	1.901	2.186
kt22	0.727	1.108	1.588	1.948	2.248	2.464	2.581	2.683	2.729	2.802	2.88

Appendix F. Continued

Sample name	5.03 phi (%)	5.2 phi (%)	5.37 phi (%)	5.54 phi (%)	5.72 phi (%)	5.89 phi (%)	6.06 phi (%)	6.23 phi (%)	6.4 phi (%)	6.57 phi (%)	6.75 phi (%)
kt01	3.398	3.627	3.74	3.783	3.695	3.437	3.217	2.927	2.789	2.766	2.777
kt02	1.989	2.646	3.221	3.831	4.232	4.477	4.597	4.523	4.509	4.476	4.493
kt03	1.512	2.112	2.676	3.33	3.791	4.138	4.346	4.366	4.426	4.448	4.525
kt04	1.252	1.653	2.022	2.415	2.72	2.948	3.169	3.327	3.579	3.893	4.238
kt05	1.472	2.065	2.592	3.163	3.567	3.845	4.042	4.095	4.216	4.343	4.507
kt06	1.501	1.809	2.041	2.246	2.363	2.363	2.416	2.425	2.599	2.893	3.266
kt07	2.531	2.874	3.158	3.467	3.626	3.658	3.651	3.532	3.51	3.539	3.599
kt08	1.485	1.839	2.111	2.357	2.502	2.524	2.585	2.592	2.763	3.057	3.421
kt09	1.713	2.031	2.263	2.46	2.555	2.519	2.529	2.489	2.609	2.851	3.16
kt10	1.71	2.022	2.27	2.496	2.636	2.666	2.745	2.785	2.98	3.302	3.671
kt11	1.701	2.091	2.368	2.553	2.655	2.618	2.651	2.649	2.825	3.149	3.527
kt12	2.117	2.381	2.589	2.759	2.864	2.876	2.932	2.957	3.117	3.385	3.697
kt13	1.521	1.899	2.185	2.425	2.564	2.567	2.632	2.655	2.857	3.208	3.609
kt14	1.802	2.135	2.38	2.571	2.662	2.62	2.626	2.578	2.704	2.961	3.291
kt15	2.187	2.67	2.973	3.131	3.167	3.011	2.916	2.755	2.785	2.956	3.21
kt16	2.231	2.385	2.518	2.654	2.742	2.767	2.831	2.875	3.026	3.27	3.535
kt17	1.719	1.982	2.177	2.333	2.425	2.42	2.474	2.504	2.686	2.991	3.357
kt18	1.867	2.212	2.452	2.635	2.71	2.643	2.626	2.557	2.661	2.898	3.206
kt19	1.852	2.13	2.326	2.47	2.538	2.491	2.519	2.526	2.706	3.035	3.419
kt20	2.028	2.304	2.496	2.636	2.698	2.644	2.649	2.62	2.748	2.997	3.307
kt21	2.458	2.757	2.958	3.101	3.137	3.032	2.96	2.826	2.833	2.945	3.115
kt22	2.968	3.096	3.143	3.157	3.065	2.837	2.663	2.445	2.386	2.463	2.571

Appendix F. Continued

Sample name	6.92 phi (%)	7.09 phi (%)	7.26 phi (%)	7.43 phi (%)	7.6 phi (%)	7.78 phi (%)	7.95 phi (%)	8.12 phi (%)	8.29 phi (%)	8.46 phi (%)	8.63 phi (%)
kt01	2.868	2.944	3.048	3.105	3.162	3.106	2.898	2.804	2.795	2.717	2.635
kt02	4.565	4.6	4.661	4.583	4.414	4.117	3.582	3.281	3.17	2.947	2.707
kt03	4.659	4.753	4.883	4.847	4.706	4.427	3.908	3.588	3.417	3.155	2.879
kt04	4.666	4.995	5.33	5.432	5.347	5.128	4.652	4.365	4.223	3.954	3.634
kt05	4.733	4.886	5.049	5.031	4.884	4.6	4.071	3.733	3.534	3.253	2.965
kt06	3.777	4.227	4.73	5.04	5.243	5.238	4.958	4.779	4.633	4.418	4.184
kt07	3.719	3.8	3.902	3.882	3.785	3.572	3.153	2.918	2.827	2.651	2.469
kt08	3.921	4.352	4.82	5.115	5.327	5.32	5.037	4.841	4.659	4.418	4.156
kt09	3.592	3.976	4.399	4.683	4.9	4.933	4.728	4.606	4.503	4.346	4.183
kt10	4.161	4.558	4.966	5.181	5.272	5.162	4.764	4.501	4.294	4.04	3.785
kt11	4.036	4.465	4.917	5.192	5.38	5.332	4.982	4.758	4.58	4.346	4.109
kt12	4.117	4.454	4.804	4.971	5.018	4.888	4.501	4.239	4.034	3.78	3.522
kt13	4.142	4.578	5.02	5.282	5.446	5.381	5.014	4.77	4.567	4.311	4.054
kt14	3.76	4.17	4.616	4.917	5.156	5.178	4.941	4.769	4.585	4.363	4.133
kt15	3.612	3.962	4.361	4.616	4.807	4.814	4.58	4.446	4.355	4.202	4.047
kt16	3.882	4.141	4.391	4.484	4.456	4.302	3.946	3.685	3.461	3.207	2.95
kt17	3.847	4.268	4.72	5.007	5.211	5.197	4.915	4.695	4.457	4.19	3.911
kt18	3.651	4.042	4.471	4.771	5.026	5.065	4.856	4.698	4.518	4.3	4.07
kt19	3.935	4.367	4.822	5.092	5.262	5.209	4.873	4.62	4.367	4.081	3.785
kt20	3.742	4.106	4.499	4.723	4.843	4.789	4.499	4.296	4.111	3.888	3.663
kt21	3.401	3.63	3.88	4.011	4.064	4.026	3.845	3.748	3.706	3.61	3.513
kt22	2.765	2.924	3.096	3.212	3.326	3.307	3.13	3.027	2.958	2.843	2.721

Appendix F. Continued

Sample name	8.81 phi (%)	8.98 phi (%)	9.15 phi (%)	9.32 phi (%)	9.49 phi (%)	9.66 phi (%)	9.84 phi (%)	10.01 phi (%)	10.18 phi (%)	10.35 phi (%)	10.52 phi (%)
kt01	2.442	2.118	1.852	1.626	1.314	0.893	0.569	0.261	0.082	0.027	0
kt02	2.372	1.872	1.559	1.427	1.142	0.721	0.424	0.165	0.023	0.004	0
kt03	2.523	2.031	1.696	1.518	1.198	0.742	0.426	0.167	0.022	0.004	0
kt04	3.223	2.652	2.23	1.955	1.523	0.92	0.513	0.201	0.022	0.005	0
kt05	2.604	2.118	1.774	1.577	1.24	0.762	0.433	0.17	0.022	0.004	0
kt06	3.834	3.345	2.895	2.481	1.929	1.172	0.66	0.271	0.043	0.011	0
kt07	2.196	1.786	1.506	1.339	1.08	0.743	0.474	0.212	0.062	0.017	0
kt08	3.794	3.311	2.867	2.478	1.927	1.146	0.63	0.251	0.03	0.007	0
kt09	3.896	3.487	3.069	2.653	2.084	1.269	0.722	0.297	0.051	0.013	0
kt10	3.435	2.968	2.565	2.241	1.756	1.06	0.595	0.237	0.032	0.007	0
kt11	3.757	3.27	2.842	2.497	1.957	1.158	0.635	0.248	0.025	0.006	0
kt12	3.182	2.735	2.356	2.052	1.608	0.98	0.554	0.224	0.033	0.008	0
kt13	3.693	3.208	2.786	2.45	1.923	1.139	0.626	0.245	0.025	0.006	0
kt14	3.809	3.385	2.97	2.59	2.029	1.207	0.667	0.266	0.033	0.008	0
kt15	3.764	3.352	2.951	2.578	2.027	1.216	0.679	0.272	0.037	0.009	0
kt16	2.642	2.267	1.941	1.671	1.315	0.849	0.511	0.223	0.056	0.017	0
kt17	3.559	3.121	2.71	2.348	1.839	1.123	0.639	0.262	0.043	0.011	0
kt18	3.748	3.33	2.921	2.548	2.004	1.21	0.681	0.275	0.041	0.01	0
kt19	3.42	2.964	2.557	2.217	1.734	1.059	0.601	0.245	0.039	0.01	0
kt20	3.355	2.957	2.575	2.218	1.739	1.078	0.623	0.262	0.051	0.014	0
kt21	3.307	3.002	2.662	2.293	1.809	1.134	0.666	0.288	0.065	0.02	0
kt22	2.513	2.206	1.935	1.7	1.372	0.925	0.587	0.269	0.084	0.028	0

Appendix G. Conventional parameters of grain size distribution and separeted grain-size components in the present study.

Sample name	Median grain size (φ)	Mode grain size (φ)	Mean grain size (φ)	Standard deviation	Coefficinet of variation	Skewness	Kurtosis
kt01	6.50	5.72	6.59	1.68	0.25	-0.24	2.02
kt02	7.01	7.43	7.04	1.29	0.18	-0.31	2.33
kt03	7.12	7.43	7.11	1.29	0.18	-0.45	2.52
kt04	7.43	7.43	7.35	1.28	0.17	-0.69	2.86
kt05	7.18	7.43	7.15	1.29	0.18	-0.50	2.59
kt06	7.61	7.78	7.42	1.41	0.19	-0.86	2.93
kt07	6.73	7.43	6.68	1.59	0.23	-0.42	2.33
kt08	7.61	7.78	7.47	1.33	0.18	-0.76	2.70
kt09	7.59	7.78	7.41	1.43	0.19	-0.77	2.68
kt10	7.49	7.78	7.37	1.34	0.18	-0.67	2.56
kt11	7.60	7.78	7.49	1.28	0.17	-0.65	2.44
kt12	7.38	7.78	7.26	1.37	0.19	-0.58	2.38
kt13	7.59	7.78	7.48	1.28	0.17	-0.68	2.55
kt14	7.61	7.78	7.46	1.34	0.18	-0.68	2.46
kt15	7.53	7.78	7.40	1.35	0.18	-0.56	2.20
kt16	7.11	7.43	6.92	1.57	0.22	-0.58	2.36
kt17	7.54	7.78	7.36	1.41	0.19	-0.79	2.78
kt18	7.58	7.78	7.41	1.38	0.18	-0.69	2.48
kt19	7.50	7.78	7.33	1.39	0.19	-0.73	2.64
kt20	7.42	7.78	7.23	1.48	0.20	-0.70	2.56
kt21	7.24	7.78	7.09	1.56	0.22	-0.54	2.24
kt22	6.57	7.78	6.55	1.78	0.27	-0.30	1.95

Appendix G. Continued

Sample name	Proportion (%)						Mean grain size (φ)					
	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
kt01	3.0%	10.1%	37.4%	33.7%	12.1%	3.6%	3.4	4.2	5.4	7.4	8.6	9.4
kt02	-	0.7%	43.1%	41.3%	11.7%	3.3%	-	4.0	5.8	7.3	8.6	9.4
kt03	-	2.0%	40.6%	43.1%	11.0%	3.3%	-	4.0	5.9	7.4	8.6	9.4
kt04	-	0.9%	34.0%	45.2%	15.2%	4.7%	-	3.7	6.0	7.5	8.6	9.3
kt05	-	2.0%	36.4%	45.9%	11.8%	3.9%	-	4.0	5.9	7.4	8.6	9.4
kt06	-	1.8%	25.1%	52.3%	15.6%	5.2%	-	3.8	5.6	7.5	8.7	9.4
kt07	2.9%	8.1%	37.9%	39.0%	8.6%	3.5%	3.4	4.1	5.6	7.4	8.6	9.4
kt08	-	1.1%	22.6%	56.1%	15.1%	5.1%	-	4.1	5.6	7.5	8.7	9.3
kt09	-	1.6%	26.5%	49.6%	16.8%	5.6%	-	3.9	5.5	7.5	8.7	9.3
kt10	-	2.7%	22.1%	57.0%	13.4%	4.9%	-	4.5	5.6	7.4	8.7	9.3
kt11	-	5.1%	16.0%	58.9%	15.6%	4.5%	-	5.0	5.7	7.4	8.7	9.4
kt12	-	4.7%	21.1%	55.2%	14.6%	4.3%	-	4.6	5.5	7.3	8.6	9.3
kt13	-	2.9%	18.5%	56.9%	15.5%	6.1%	-	4.8	5.6	7.4	8.6	9.3
kt14	-	4.2%	19.4%	52.0%	16.9%	7.5%	-	4.8	5.6	7.4	8.5	9.3
kt15	-	7.6%	19.3%	50.9%	16.7%	5.5%	-	5.0	5.7	7.4	8.7	9.3
kt16	2.2%	8.6%	25.3%	49.1%	11.4%	3.3%	3.6	4.2	5.5	7.4	8.7	9.4
kt17	-	1.6%	25.3%	52.9%	14.6%	5.6%	-	3.9	5.5	7.5	8.6	9.3
kt18	-	2.6%	23.8%	52.0%	15.8%	5.8%	-	4.5	5.6	7.5	8.6	9.3
kt19	-	2.3%	23.7%	54.5%	14.1%	5.4%	-	4.2	5.5	7.4	8.6	9.3
kt20	-	2.6%	28.8%	49.7%	13.6%	5.3%	-	3.9	5.5	7.5	8.6	9.3
kt21	-	4.4%	31.7%	42.2%	15.8%	5.9%	-	4.0	5.4	7.4	8.6	9.3
kt22	4.1%	12.1%	33.5%	34.5%	11.7%	4.1%	3.4	4.1	5.3	7.4	8.6	9.4

Appendix G. Continued

Sample name	Re-synthesized component of Comp1 and Comp2 (Comp1&2)		Log-ratio of proportion relative to Comp6			
	Proportion (%)	Mean grain size (φ)	ALR(Comp1&2)	ALR(Comp3)	ALR(Comp4)	ALR(Comp5)
kt01	13.1	3.9	1.29	2.33	2.23	1.20
kt02	0.7	4.0	-1.56	2.58	2.54	1.28
kt03	2.0	4.0	-0.51	2.51	2.57	1.20
kt04	1.0	3.7	-1.63	1.98	2.26	1.17
kt05	2.1	4.0	-0.66	2.23	2.46	1.11
kt06	1.9	3.8	-1.05	1.58	2.31	1.10
kt07	11.0	3.8	1.15	2.38	2.41	0.90
kt08	1.1	4.1	-1.55	1.48	2.39	1.08
kt09	1.6	3.9	-1.26	1.56	2.18	1.10
kt10	2.7	4.5	-0.61	1.51	2.46	1.01
kt11	5.1	5.0	0.12	1.26	2.57	1.24
kt12	4.8	4.6	0.09	1.58	2.54	1.21
kt13	2.9	4.8	-0.75	1.11	2.23	0.93
kt14	4.3	4.8	-0.57	0.96	1.94	0.81
kt15	7.6	5.0	0.32	1.25	2.22	1.10
kt16	10.8	4.0	1.18	2.03	2.69	1.22
kt17	1.6	3.9	-1.26	1.51	2.24	0.95
kt18	2.6	4.5	-0.81	1.41	2.19	1.00
kt19	2.4	4.2	-0.86	1.47	2.31	0.95
kt20	2.6	3.9	-0.71	1.70	2.24	0.94
kt21	4.5	4.0	-0.29	1.68	1.96	0.98
kt22	16.3	3.8	1.38	2.10	2.13	1.05

Appendix H. Major elemental composition data of prepared samples in Lake Kitaura

sample	mass percentage (%)								Log-ratio of proportions relative to Al_2O_3						
name	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O_3	ALR(Na_2O)	ALR(MgO)	ALR(SiO_2)	ALR(K_2O)	ALR(CaO)	ALR(TiO_2)	ALR(Fe_2O_3)
kt01	4.13	0.98	22.02	56.28	1.61	0.97	1.63	12.14	-1.67	-3.11	0.94	-2.62	-3.13	-2.60	-0.60
kt02	4.31	0.82	20.76	53.11	1.07	0.55	1.15	17.84	-1.57	-3.24	0.94	-2.96	-3.63	-2.89	-0.15
kt03	3.76	0.91	20.29	53.10	1.10	0.59	1.42	18.44	-1.69	-3.11	0.96	-2.92	-3.54	-2.66	-0.10
kt04	3.30	0.97	20.41	54.16	1.38	0.66	1.29	17.23	-1.82	-3.04	0.98	-2.70	-3.43	-2.76	-0.17
kt05	3.66	1.10	21.53	54.80	1.11	0.55	1.13	15.55	-1.77	-2.97	0.93	-2.96	-3.66	-2.95	-0.33
kt06	3.03	1.05	21.63	56.16	1.35	0.75	1.19	14.40	-1.97	-3.02	0.95	-2.78	-3.37	-2.90	-0.41
kt07	3.43	1.06	19.10	56.46	1.40	1.80	1.26	15.04	-1.72	-2.89	1.08	-2.61	-2.36	-2.72	-0.24
kt08	3.83	0.80	22.26	56.00	1.26	0.69	0.96	13.75	-1.76	-3.33	0.92	-2.87	-3.48	-3.14	-0.48
kt09	4.13	1.27	20.32	56.68	1.54	1.08	1.02	13.52	-1.59	-2.77	1.03	-2.58	-2.93	-2.99	-0.41
kt10	3.40	1.21	19.51	58.41	1.74	1.58	1.03	12.69	-1.75	-2.78	1.10	-2.42	-2.51	-2.94	-0.43
kt11	3.86	1.30	20.53	57.87	1.60	1.15	0.82	12.47	-1.67	-2.76	1.04	-2.55	-2.88	-3.22	-0.50
kt12	3.09	1.12	20.62	56.81	1.53	1.66	1.09	13.72	-1.90	-2.92	1.01	-2.60	-2.52	-2.94	-0.41
kt13	3.79	1.41	19.91	57.91	1.81	1.27	1.25	12.18	-1.66	-2.65	1.07	-2.40	-2.75	-2.77	-0.49
kt14	2.91	1.18	20.57	57.76	1.53	1.26	1.09	13.23	-1.96	-2.86	1.03	-2.60	-2.80	-2.94	-0.44
kt15	3.69	1.45	19.59	58.61	1.81	1.54	0.87	11.98	-1.67	-2.60	1.10	-2.38	-2.54	-3.11	-0.49
kt16	3.41	1.51	19.45	57.38	1.78	2.70	1.00	12.46	-1.74	-2.55	1.08	-2.39	-1.97	-2.97	-0.45
kt17	2.64	1.50	18.61	59.16	1.92	1.58	1.37	12.78	-1.95	-2.52	1.16	-2.27	-2.46	-2.61	-0.38
kt18	2.91	1.26	18.35	60.65	2.01	1.83	0.90	11.69	-1.84	-2.68	1.20	-2.21	-2.31	-3.01	-0.45
kt19	3.38	1.48	19.08	58.99	1.80	1.85	1.18	11.79	-1.73	-2.56	1.13	-2.36	-2.33	-2.78	-0.48
kt20	3.60	1.31	18.44	59.54	1.98	1.82	0.97	11.79	-1.63	-2.65	1.17	-2.23	-2.31	-2.94	-0.45
kt21	3.55	1.38	19.45	58.83	2.10	1.80	0.96	11.55	-1.70	-2.64	1.11	-2.23	-2.38	-3.01	-0.52
kt22	2.70	1.61	18.71	59.90	2.19	2.06	1.00	11.52	-1.93	-2.45	1.16	-2.15	-2.21	-2.93	-0.49

APPENDIX I. Count data of diatom taxa in lake surface sediments in Lake Kitaura

Diatom taxa	valve condition	kt01	kt02	kt03	kt04	kt05	kt06	kt07	kt08	kt09	kt10	kt11
Achnanthidium minutissimum	*Cmplete araphid*	3	3	0	0	0	0	0	0	0	0	0
	Fragmented araphid	0	0	0	0	0	0	0	0	0	0	0
	Complete raphid	5	3	2	0	0	0	0	0	0	0	0
	Fragmentad raphid	0	0	0	0	0	0	0	0	0	0	0
Achnanthidium pusillum	*Cmplete araphid*	13	1	1	0	0	1	0	0	0	0	1
	Fragmented araphid	0	0	0	0	1	0	0	0	0	0	0
	Complete raphid	13	1	4	0	1	0	0	0	0	0	1
	Fragmentad raphid	1	0	0	0	0	0	0	0	0	0	0
Actinocyclus normanii	*Complete*	2	3	1	4	5	6	4	4	3	8	5
	Fragment	1	0	0	2	1	3	5	4	2	10	7
Amphora spp.	*Complete*	4	2	1	1	3	2	0	1	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Aulacoseira ambigua	*Complete*	14	14	30	58	57	72	69	64	50	47	53
	Fragment	1	3	6	7	2	9	6	7	5	12	10
Aulacoseira granulata	*Complete*	0	13	30	29	68	63	50	79	90	89	43
	Fragment	0	3	2	8	7	7	7	5	6	8	3
Aulacoseira pusilla	*Complete*	5	2	11	14	19	16	8	25	17	12	12
	Fragment	1	0	2	0	1	0	0	1	1	0	0
Aulacoseira spp.	*Complete*	0	0	0	0	0	0	0	0	3	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Bacilaria spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	1	0	0	0	0	0	0	0	0	0	0
Cocconeis placentula	*Cmplete araphid*	3	11	2	3	0	0	3	0	0	1	2
	Fragmented araphid	0	4	0	0	0	0	0	2	0	2	0
	Complete raphid	5	4	2	0	0	0	1	0	0	0	0
	Fragmentad raphid	0	3	0	1	0	0	1	0	0	0	0
Cyclostephanos dublis	*Complete*	1	10	14	26	24	38	29	25	38	32	47
	Fragment	0	2	5	8	7	10	10	10	7	8	12
Cyclotella atomus	*Complete*	0	4	7	1	4	0	7	0	1	0	1
	Fragment	0	0	1	0	0	1	0	0	0	0	0
Cyclotella meneginiana	*Complete*	6	10	17	7	10	10	4	15	15	17	11
	Fragment	0	4	8	1	3	2	0	4	5	1	4
Cyclotella ocellata	*Complete*	0	0	0	4	0	3	8	4	6	6	7
	Fragment	0	0	0	0	0	0	5	2	1	0	1
Cyclotella spp.	*Complete*	0	4	1	5	2	0	4	0	0	6	0
	Fragment	0	0	1	0	0	0	0	0	0	0	0
Cymbella spp.	*Complete*	0	2	0	0	0	0	0	0	1	0	0
	Fragment	0	1	0	1	0	0	0	0	0	0	0
Diploneis spp.	*Complete*	1	3	0	0	0	0	0	0	0	0	0
	Fragment	1	0	0	0	1	0	0	0	0	0	0
Discostella asterocostata	*Complete*	0	0	1	0	4	2	2	5	4	1	7
	Fragment	0	1	0	0	1	3	2	3	1	3	1
Encyonema spp.	*Complete*	3	6	4	0	0	0	0	0	0	0	0
	Fragment	0	1	0	0	0	0	0	0	0	1	0
Epithemia spp.	*Complete*	2	5	0	0	0	0	2	0	0	0	0
	Fragment	0	1	0	0	0	0	0	0	0	0	0

APPENDIX I. Continued

Diatom taxa	valve condition	kt12	kt13	kt14	kt15	kt16	kt17	kt18	kt19	kt20	kt21	kt22
Achnanthidium minutissimum	*Cmplete araphid*	0	0	1	0	1	0	0	0	0	1	0
	Fragmented araphid	0	0	0	0	0	0	0	1	0	0	0
	Complete raphid	0	1	0	1	1	0	0	1	1	1	0
	Fragmentad raphid	0	0	0	0	0	0	0	0	0	0	0
Achnanthidium pusillum	*Cmplete araphid*	0	0	0	0	0	0	0	0	0	0	0
	Fragmented araphid	0	0	0	0	0	0	0	0	0	0	0
	Complete raphid	0	0	0	0	0	0	0	1	0	0	0
	Fragmentad raphid	0	0	0	0	0	0	0	0	0	0	0
Actinocyclus normanii	*Complete*	11	5	10	9	3	3	6	5	10	4	5
	Fragment	2	3	2	9	4	3	4	7	6	3	1
Amphora spp.	*Complete*	0	0	0	1	0	0	0	0	0	0	1
	Fragment	0	0	0	0	1	0	0	0	0	0	0
Aulacoseira ambigua	*Complete*	54	65	75	52	50	67	64	68	43	52	60
	Fragment	7	3	6	2	9	4	2	3	7	6	6
Aulacoseira granulata	*Complete*	77	78	61	84	55	58	66	57	61	56	86
	Fragment	3	4	3	0	8	2	1	2	7	1	6
Aulacoseira pusilla	*Complete*	28	14	6	10	16	17	20	8	22	12	12
	Fragment	0	0	0	2	0	1	1	1	0	0	0
Aulacoseira spp.	*Complete*	0	0	3	0	0	0	0	0	0	0	2
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Bacilaria spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Cocconeis placentula	*Cmplete araphid*	1	1	0	0	3	0	2	4	0	1	2
	Fragmented araphid	1	0	1	0	2	1	2	0	1	1	2
	Complete raphid	0	0	0	0	0	0	0	0	0	0	1
	Fragmentad raphid	0	0	0	0	0	1	0	0	0	0	1
Cyclostephanos dublis	*Complete*	30	35	46	26	22	34	30	36	47	24	25
	Fragment	12	16	12	8	12	9	9	11	8	15	4
Cyclotella atomus	*Complete*	0	2	1	5	1	4	4	2	5	4	4
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Cyclotella meneginiana	*Complete*	9	8	11	18	7	21	14	8	10	10	11
	Fragment	1	7	6	10	2	4	5	4	6	3	4
Cyclotella ocellata	*Complete*	7	6	0	0	0	0	0	0	0	0	0
	Fragment	1	1	0	0	0	0	0	0	0	0	0
Cyclotella spp.	*Complete*	1	3	0	2	2	2	6	0	1	0	0
	Fragment	0	0	0	0	0	0	0	0	1	0	0
Cymbella spp.	*Complete*	0	0	1	0	1	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	1	0
Diploneis spp.	*Complete*	0	1	0	0	3	0	0	0	0	0	2
	Fragment	0	1	0	0	0	1	0	2	0	1	0
Discostella asterocostata	*Complete*	4	2	3	4	6	2	3	8	2	3	5
	Fragment	2	6	0	7	3	3	1	4	2	4	1
Encyonema spp.	*Complete*	0	0	0	0	0	0	1	0	0	1	0
	Fragment	0	0	0	0	1	0	0	0	0	0	0
Epithemia spp.	*Complete*	0	1	0	0	0	0	2	0	1	0	2
	Fragment	0	0	0	0	0	0	1	0	0	0	0

APPENDIX I. Continued

Diatom taxa	valve condition	kt01	kt02	kt03	kt04	kt05	kt06	kt07	kt08	kt09	kt10	kt11
Eunotia spp.	*Complete*	1	0	0	1	0	0	0	0	0	0	0
	Fragment	0	2	0	0	0	0	0	0	0	0	0
Fragilaria spp.	*Complete*	8	4	9	1	2	3	0	2	2	2	3
	Fragment	1	1	3	0	1	2	1	1	2	0	4
Fragilariforma spp.	*Complete*	1	3	6	0	5	0	2	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Gomphoneis spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Gomphonema spp.	*Complete*	4	17	4	0	2	0	0	0	0	2	2
	Fragment	0	1	3	0	2	0	1	0	0	0	0
Gyrosigma spp.	*Complete*	1	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	2	0	0	0	0	0
Hantzschia spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Melosira spp.	*Complete*	1	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Meridion spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	1
	Fragment	1	0	0	0	0	0	0	0	0	0	0
Navicula spp.	*Complete*	41	13	6	5	1	3	7	2	4	0	3
	Fragment	4	5	4	8	1	0	4	1	2	0	0
Nitzschia amphibia	*Complete*	9	2	0	0	0	2	0	2	1	2	0
	Fragment	1	1	1	0	0	0	1	0	0	0	0
Nitzshia spp.	*Complete*	14	0	2	4	8	4	5	3	2	3	13
	Fragment	3	1	1	0	1	1	1	1	0	0	2
Pinnularia spp.	*Complete*	6	4	0	1	0	0	0	0	0	0	0
	Fragment	1	2	1	0	0	0	0	0	0	0	0
Planothidium lanceolatum	*Cmplete araphid*	13	0	0	2	0	1	1	0	0	0	1
	Fragmented araphid	0	0	0	0	0	1	1	0	0	0	0
	Complete raphid	11	1	1	0	0	0	1	0	0	0	0
	Fragmentad raphid	0	0	0	0	0	0	0	0	0	0	0
Planothidium rostratum	*Cmplete araphid*	6	1	2	1	0	2	1	0	0	0	0
	Fragmented araphid	0	0	0	0	0	0	0	0	0	0	0
	Complete raphid	6	0	1	0	0	0	0	0	0	1	0
	Fragmentad raphid	0	0	0	0	0	0	0	0	0	0	0
Psammothidium subatomoides	*Cmplete araphid*	5	0	0	0	0	0	0	0	0	0	0
	Fragmented araphid	0	0	0	0	0	0	0	0	0	0	0
	Complete raphid	2	3	0	0	0	0	1	0	0	0	0
	Fragmentad raphid	0	0	0	0	0	0	0	0	0	0	0
Pseudostaurosira spp.	*Complete*	6	18	11	3	3	2	7	2	2	0	3
	Fragment	0	3	2	1	0	0	1	0	0	0	0
Roicosphenia spp.	*Complete*	0	0	0	2	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Ropalodia spp.	*Complete*	0	1	0	0	0	0	0	0	0	0	0
	Fragment	0	0	1	0	0	0	0	1	0	0	0
Sellaphora laevissima	*Complete*	1	1	2	0	0	1	0	0	0	0	0
	Fragment	0	1	2	0	0	1	0	0	0	0	0

APPENDIX I. Continued

Diatom taxa	valve condition	kt12	kt13	kt14	kt15	kt16	kt17	kt18	kt19	kt20	kt21	kt22
Eunotia spp.	*Complete*	0	0	0	1	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Fragilaria spp.	*Complete*	1	2	1	1	1	3	2	3	1	1	0
	Fragment	2	1	2	1	2	2	1	0	2	4	2
Fragilariforma spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Gomphoneis spp.	*Complete*	1	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Gomphonema spp.	*Complete*	0	1	0	0	0	0	0	0	0	1	0
	Fragment	0	0	0	0	0	1	0	0	0	0	0
Gyrosigma spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	1	0	1	0
Hantzschia spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	1	0
Melosira spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Meridion spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Navicula spp.	*Complete*	1	1	0	1	2	2	0	0	1	0	3
	Fragment	0	1	2	1	0	1	0	2	0	1	2
Nitzschia amphibia	*Complete*	0	0	1	2	0	1	0	0	0	3	0
	Fragment	0	0	0	0	1	0	0	0	0	1	0
Nitzshia spp.	*Complete*	4	1	3	3	3	3	3	6	4	5	3
	Fragment	1	1	3	2	2	1	0	1	1	3	0
Pinnularia spp.	*Complete*	0	0	0	1	0	0	0	0	1	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Planothidium lanceolatum	*Cmplete araphid*	0	0	0	0	0	1	0	0	2	0	0
	Fragmented araphid	0	0	0	0	0	0	0	0	0	0	0
	Complete raphid	0	0	0	0	1	1	0	1	1	0	0
	Fragmentad raphid	0	0	0	0	0	0	0	0	0	0	0
Planothidium rostratum	*Cmplete araphid*	0	0	0	0	1	0	0	1	0	0	0
	Fragmented araphid	0	0	0	0	0	0	0	0	2	0	0
	Complete raphid	0	0	0	0	0	0	0	1	0	1	0
	Fragmentad raphid	0	0	0	0	0	0	0	0	0	0	0
Psammothidium subatomoides	*Cmplete araphid*	0	0	0	0	1	0	0	0	0	1	0
	Fragmented araphid	0	0	0	0	0	0	0	0	0	0	0
	Complete raphid	0	1	0	0	1	0	1	1	2	1	0
	Fragmentad raphid	0	0	0	0	0	0	0	0	0	0	0
Pseudostaurosira spp.	*Complete*	4	5	0	5	5	1	1	9	5	5	4
	Fragment	1	0	0	0	0	0	0	0	3	1	0
Roicosphenia spp.	*Complete*	0	1	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Ropalodia spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Sellaphora laevissima	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0

APPENDIX I. Continued

Diatom taxa	valve condition	kt01	kt02	kt03	kt04	kt05	kt06	kt07	kt08	kt09	kt10	kt11
Staurosira construence var. *exigua*	*Complete*	0	0	0	1	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	1	0	0
Staurosira construens var. *construens*	*Complete*	6	6	7	4	0	0	0	0	0	4	0
	Fragment	2	5	2	2	2	0	0	0	0	0	1
Staurosira venter	*Complete*	48	49	56	35	11	1	10	8	11	5	7
	Fragment	0	3	2	3	2	3	0	0	0	0	0
Staurosirella spp.	*Complete*	6	1	3	0	0	1	1	1	0	0	2
	Fragment	0	0	0	1	0	0	1	0	0	0	0
Stephanodiscus hantzschii	*Complete*	3	18	7	31	27	9	9	7	6	4	11
	Fragment	0	0	1	4	1	2	0	0	0	0	0
Stephanodiscus minutulau	*Complete*	0	1	2	0	4	5	0	1	1	0	1
	Fragment	0	0	0	0	0	0	0	0	0	0	1
Stephanodiscus vestibulis	*Complete*	3	3	1	7	2	3	9	8	9	7	12
	Fragment	0	0	0	0	0	1	2	1	0	0	0
Surirella spp.	*Complete*	0	0	1	0	0	1	0	0	0	1	0
	Fragment	0	1	0	0	0	0	0	0	0	0	0
Synedra spp.	*Complete*	0	0	0	0	1	0	0	0	0	0	0
	Fragment	1	1	0	1	2	0	0	0	0	0	0
Tabellaria flocculosa	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	1	0	0	0	0	0	0	0	0	0	0
Thalassiosira lacustris	*Complete*	0	1	2	0	1	1	3	0	0	1	2
	Fragment	0	0	0	0	0	0	1	0	0	3	3
Tryblionella spp.	*Complete*	0	2	0	2	0	0	1	0	1	1	0
	Fragment	0	0	1	0	0	0	0	0	0	0	0

APPENDIX I. Continued

Diatom taxa	valve condition	kt12	kt13	kt14	kt15	kt16	kt17	kt18	kt19	kt20	kt21	kt22
Staurosira construence var. *exigua*	*Complete*	1	1	0	0	3	0	1	2	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Staurosira construens var. *construens*	*Complete*	3	0	1	0	6	0	8	1	2	3	0
	Fragment	0	0	0	0	1	0	0	0	0	1	0
Staurosira venter	*Complete*	4	4	14	6	32	11	16	9	9	23	16
	Fragment	2	0	1	1	2	0	1	2	0	1	0
Staurosirella spp.	*Complete*	0	5	3	3	3	3	0	4	5	16	5
	Fragment	0	1	1	0	1	1	0	0	0	0	0
Stephanodiscus hantzschii	*Complete*	10	7	12	6	5	15	6	12	7	10	10
	Fragment	0	0	0	0	1	3	1	1	3	1	0
Stephanodiscus minutulau	*Complete*	3	0	0	3	0	1	0	1	1	1	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Stephanodiscus vestibulis	*Complete*	7	3	7	5	5	9	8	6	5	5	8
	Fragment	0	0	0	0	0	2	0	1	0	3	1
Surirella spp.	*Complete*	1	0	0	1	1	0	0	0	0	0	0
	Fragment	0	0	0	0	1	0	0	0	0	0	0
Synedra spp.	*Complete*	0	0	0	0	0	0	1	0	1	0	0
	Fragment	0	1	0	1	1	0	0	0	0	0	0
Tabellaria flocculosa	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira lacustris	*Complete*	2	0	1	4	3	0	5	2	1	1	3
	Fragment	1	0	0	2	2	1	1	0	0	0	0
Tryblionella spp.	*Complete*	0	0	0	0	0	0	0	0	0	0	0
	Fragment	0	0	0	0	0	0	0	0	0	0	0