

Paleoenvironmental and Paleoclimate change from lagoon sediments in Korea and Japan during the Holocene

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Paleoenvironmental and Paleoclimate change
from lagoon sediments in Korea and Japan
during the Holocene

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Paleoenvironmental and Paleoclimate change from lagoon sediments in Korea and Japan during the Holocene

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in partial fulfillment of the requirements for the
Doctor of Philosophy

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ABSTRACT

Korea and Japan are an essential place to understand environmental change induced by sea level change and climate change in East Asia. Even though both Korea and Japan close to each other, climate change and sea level change have worked differently. Therefore, the environmental change also reacts differently depending on relative sea level (RSL) and monsoon. Lagoon sediment offers critical information for paleoenvironment and climate change. Therefore, reconstruction of the environment during the Holocene is necessary to understand paleoclimate change and sea level fluctuation. The paleoenvironmental change was reconstructed by using diatom assemblage, sedimentary characteristics, grain analysis, chemical analysis and chronology by optical luminescence age, radiocarbon age, ^{137}Cs dates in Hwajinpo lagoon in Korea and Lakes Hamana, Ryuuoo and Kawahara in Japan.

Chapter 1 is a concise introduction about the lagoon, relative sea level change in East Asian, East Asian monsoon and El Niño/Southern Oscillation (ENSO). The objective and importance of my researches are also introduced.

Paleoenvironment, climate change, and the history of Hwajinpo lagoon were studied in Chapter 2. Centennial to millennial-scale sea-level fluctuation and paleoclimate changes strongly influenced the coastal ecosystem and human civilization. Hwajinpo lagoon is the largest lagoon in Korea and is located along the east coast of the country. Even though many lagoons including Hwajinpo were developed along the east coast of Korea during the Holocene, there were a few publications about the Holocene sea-level and precipitation change. Here, we studied the evolution of Hwajinpo lagoon to reconstruct the Holocene climate and sea-level changes using grain-size and diatom assemblage. Lagoonal Holocene sediments provide an important record of past climate change. We investigated an 11.0-m core named HJ02, which was obtained at the mouth of a small river that drains into the lagoon. Core chronology was established with accelerator mass spectrometry (AMS) ^{14}C and optically stimulated luminescence (OSL) dates. Diatom assemblages and grain size analysis revealed that estuarine conditions in the inner lagoon area transitioned to an open embayment ca. 8 ka as a result of sea-level rise. Around 7.8 ka, the open bay became a semi-closed bay as a consequence of the development of a sand barrier. After the bay was semi-closed, marine water inflow was generally restricted as the sand barrier development, and the semi-closed bay became a completely enclosed, low-salinity, brackish lagoon around 6 ka. There was an erosional hiatus between 5.5 and 1.7 ka (7.0 m depth), likely

caused by river flooding and a switch in the location of drainage along the delta. The lagoon became oligohaline around 1.6 ka, likely because of increasing precipitation associated with an intensified Asian summer monsoon. This increase in precipitation resulted in an expansion of the sand bar by sediment inflow, driven by agricultural development in the area. About 1 ka, the diatom assemblage was similar to the modern assemblage, suggesting the lagoon's current geomorphic conditions had been established.

In Chapter 3, the environmental change depended on coastal deformation associated with great earthquake along the Nankai Trough from Lakes Hamana, Ryuuoo, and Kawahara in the subduction zone. The environmental change was reconstructed from three lakes using sedimentary record and diatom assemblage. The environmental change of these three lakes occurred almost the same time as a consequence of great earthquakes which are recorded from the historical document. Approximately AD 600 to 700, the environments changed to freshwater lake from Oligohaline lake in Lake Hamana, from a brackish lagoon to a freshwater lake in Lake Ryuuoo, and from the lagoon, which was affected by sea water to the brackish lagoon in Lake Kawahara. These environment changes in three lakes suggest less marine water as a result of falling RSL. Therefore, these environment change of three lakes might be related to falling RSL as the ground recovered after subsidence by Tenmu earthquake in AD 684. Around AD 1100, three lakes indicate lake level decreased at the same time. It might be assumed that the environmental change was resulted by Kowa and Eicō earthquakes in AD 1099 and 1096, respectively. The last environment change happened in approximately AD 1700. The environment changed from oligohaline pond to the oligohaline lake in Lake Kawahara. Also, The environment of Lake Ryuuoo changed to freshwater lake from a freshwater pond in AD 1750. This environmental change of both lakes indicates that the level of the lake increased. The environmental change was might because of Hoei earthquake in AD 1707 as the ground of lakes have not recovered yet after subsidence by the earthquake. Therefore, the environmental change from Lake Hamana, Ryuuoo and Kawahara were strongly influenced by great earthquakes during the common era.

In Chapter 4, paleoenvironment and paleoclimate changes during the Little Ice Age (LIA) were investigated using sediments from Lake Hamana. This lagoon in central Japan is under a complicated climate system influenced by the East Asian summer monsoon (EASM), East Asian winter monsoon (EAWM), and strong typhoon events. Diatom assemblages and chemical

components of a 1.3 m sediment core suggest historical events of rapid salination and cyclical ecosystem shifts accompanied by monsoon condition changes. Most research has indicated that Lake Hamana changed from a freshwater lake to a brackish lagoon because of the Meio earthquake in AD 1498. However, based on results from the diatom assemblage and chemical components, this salination occurred because of changes in the Hamana paleoriver flow, and this change happened before the earthquake, around the mid-15th century. Furthermore, it is clear that Lake Hamana was an oligohaline lagoon before salination. The lithology of the lake sediments and the diatom assemblage changed during the LIA; sand, water, and total diatom contents decreased. However, the relative abundance of marine diatom taxa increased during the LIA. These changes were introduced by a weakening EASM coupled with low precipitation under low solar activity during the LIA. Several flood events represented by freshwater diatom taxa and magnetic susceptibility peaks co-occurred with strong El Niño events during the LIA. It is inferred that this strong El Niño during the LIA induced frequent typhoons causing floods in central Japan.

In Chapter 5, the main results and conclusions of my works in each chapter are summarized. Future directions about the research in Korea and Japan are also suggested in this chapter.

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Chapter 1. Introduction

The coastal lagoon is defined as shallow brackish or marine water separated from the ocean by a barrier island or sand bar, and connected restricted inlet (Phleger, 1969; Colombo, 1977; Gonenc and Wolfin, 2004) Normally, the lagoon is oriented parallel to the coastal line (Phleger, 1969). Coastal lagoons are normally developed as a result of sea level rising and formation of barrier island (Fig. 1-1) (Roy et al., 1994). Coastal lagoons account for 13% of coastal areas in the world and are often influenced by natural and anthropogenic effect (Mee, 1978; Sikora and Kjerfve, 1985). Coastal lagoons are generally sensitive to climate change, sea level rise, droughts, typhoon, and other storms effect (Kennish and Paerl 2010).

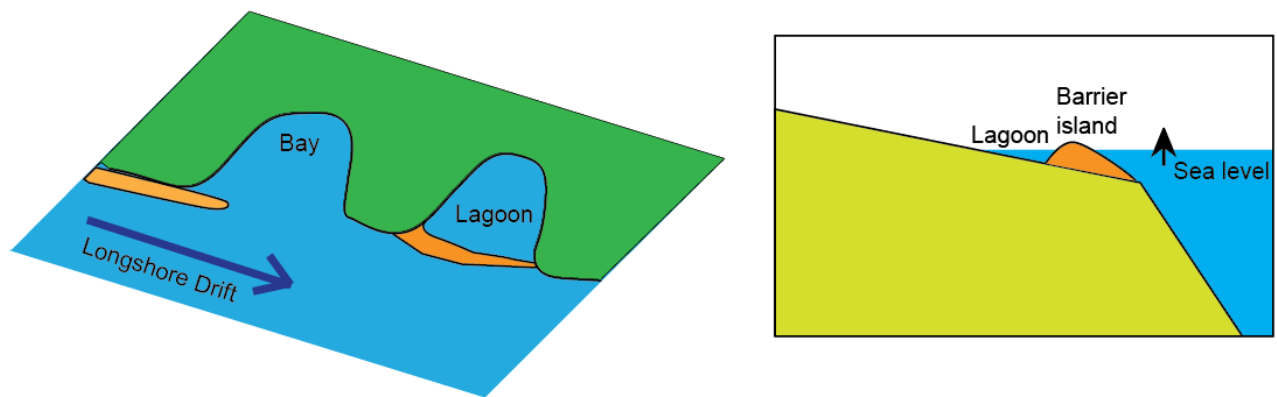


Figure 1-1. Lagoon formation

Lagoon sediment offers valuable records of barrier island formation, and paleoenvironment and paleoclimate changes (Pernetta and Milliman, 1995). Lagoon sediment is useful to understand the sea level change because lagoon environment is sensitive to even a small variation of sea level (Howell et al., 1988; Carter et al., 1989; Kirk and Lauder, 2000; Li et al., 2001). The research about sea level change has been studied in East Asia (Ota et al. 1990;

Yum et al., 2003, 2004). Depending on local climatic conditions, lagoons exhibit salinities range from completely freshwater to hypersaline (Moore and Slinn, 1984; Kjerfve, 1986; Knoppers et al., 1991). The paleoclimate change was reconstructed by lagoon sediment especially as East Asian monsoon (e.g. Yamada et al., 2016; Cho et al., 2019) Paleo typhoon deposit was also studied from lagoon sediment (Woodruff et al., 2009, 2015; Katsuki et al., 2016, 2017).

Even though several types of research about paleoenvironmental and climate change have been reconstructed from the lagoon sediments in Korea and Japan, it had been unclear. The age data were insufficient to understand climate change and environmental change during the Holocene. To clarify paleoenvironmental and climate change during the Holocene and common era, the detailed age data is necessary because those are changed with either decadal or centennial scale.

The diatom is microalgal and phytoplankton, which photosynthesize in the water where sunlight reaches. The diatom can inhabit from freshwater to marine water. The diatom reacts sensitively to changes such as water temperature, salinity, pH, nutrient transfer, geomorphology (Smol and Soermer, 2010). The diatom is deposited with sediments and leave the valve. That is why we can reconstruct environment, ecology, climate change as identifying the diatom species. Therefore, diatom is a useful proxy for the reconstruction of paleoenvironmental and climate changes (Kashima, 1985, 1986; Ryu et al., 2003).

1.1. Sea level change during Holocene in Korea and Japan

The eustatic sea level has been stable for approximately the last 4000 years (Fig. 1-2) (Yokoyama et al., 2012; Lambeck et al., 2014). During the Holocene, RSL change is influenced by eustatic factors, regional glacio-hydro isostatic adjustment, ocean dynamics, tectonic

movements such as uplift or subsidence and local factors which generate complex patterns of RSL (Clark et al., 1978; Mitrovica and Milne, 2002; Peltier, 2004). These regional patterns of RSL change have affected the coastal environments which provide stratigraphy and ecology records of Holocene RSL (Sato et al., 2001; Kato et al., 2003). The RSL showed a declining trend after approximately 6000 years ago in Asia (Bradley et al., 2016). Furthermore, previous research about RSL in East Asia suggests RSL kept rising until a highstand between 7000 and 600 years ago (Park et al., 1996). In contrary to Korea, Japan lies a complex geological setting. Especially west-south coast of Japan is located along the Nankai Trough which is a subduction zone of moving Philippine Sea Plate below the Eurasian Plate. The Nankai Trough generates great earthquakes, and it resulted in coastal deformation at coast area along the Nankai Trough. Therefore, the RSL has been influenced by the earthquake associated with coastal deformation along the Nankai Trough.

The RSL kept decreasing because of upheaval during the last 6000 years until the present on the coast of Kobe which is located in western Japan (Sato et al., 2001). In the Shimokita Peninsula which lies on Tsugaru Strait between Honshu and Hokkaido, the highstand occurred approximately 4000 years ago, and then the RSL has decreased until the present (Yokoyama et al., 2012). Furthermore, the RSL started to decrease since approximately 6000 years ago in Kyushu island of southern Japan due to the record of diatom assemblage (Yokoyama, 1996). Along the east coast of Japan, the RSL had been a falling trend since mid of Holocene. Although, the eustatic sea level has been stable after 2000 years ago (Yokoyama et al., 2012; Lambeck et al., 2014), the RSL has been changed regionally in Japan because of coastal deformation induced by the tectonic

movement (Sato et al., 2001; Chiba et al., 2016). Several studies for RSL change induced by the tectonic deformation were targetted during whole Holocene (Sato etl., 2001; Yokoyama et al., 2012; Chiba et al., 2016; Dura et al., 2016).

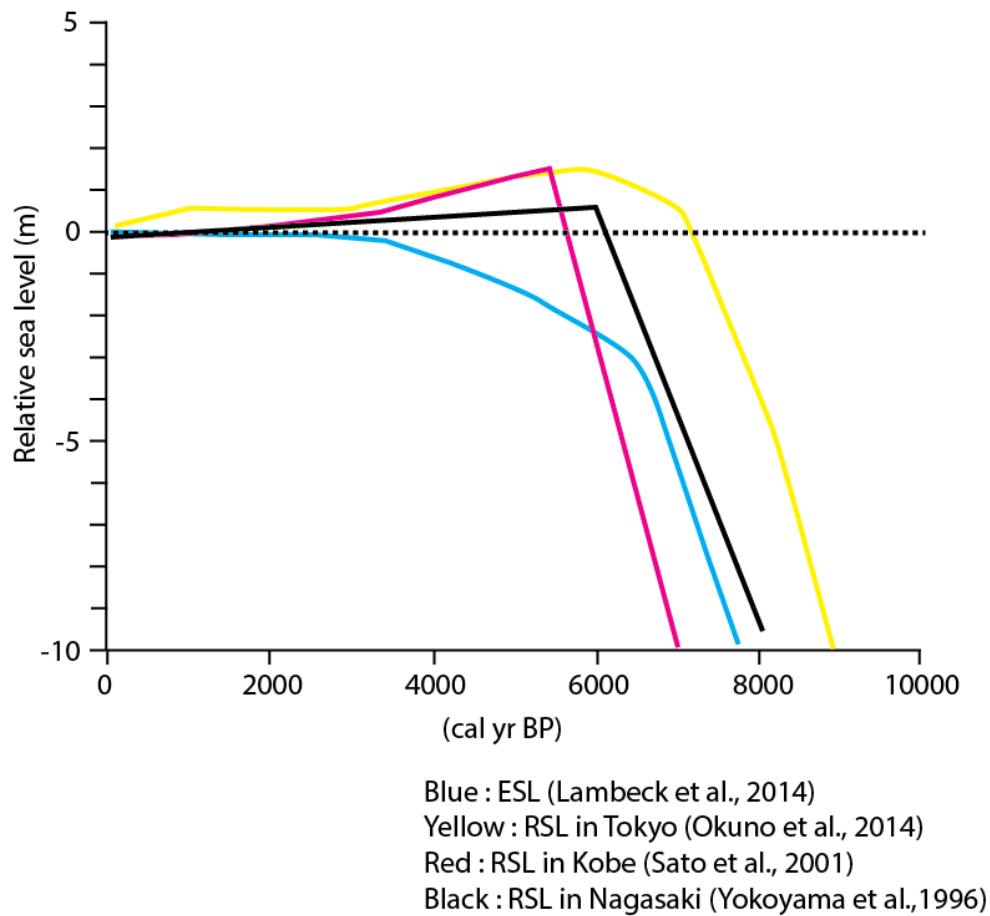


Figure 1-2. The reconstruction of eustatic sea level change and relative sea level change in Japan

1.2. East Asian monsoon

The Asian monsoon system is a significant factor of atmospheric circulation, and the system roles an important function in the global hydrological cycle. Over the past millennium, significant civilization has been developed, and this progress is strongly related to climate change (Yancheva et al., 2007). The monsoon intensity read the rise and fall in China (Yancheva et al., 2007). Monsoon influences direct effects on human society and natural ecology in the world. Generally said when it comes to the East Asian monsoon, continental Siberian high bring dry and cold atmosphere to Japan and Korea during winter. On the other hands, the Pacific high bring moisture and hot atmosphere to Japan and Korea in the summer (Fig. 1-3). Both the East Asain summer monsoon (EASM) and East Asian winter monsoon (EAWM) have anticorrelated effects on lake sediments, and the balance of the monsoon force is dependent on the location of the intertropical convergence zone (ITCZ) (Yancheva et al., 2007). Monsoonal climate variability has occurred from centennial to millennial-scale cycles since the late Holocene in East Asia (Gupta et al., 2003), which are primarily related to solar radiation (Gupta et al., 2003; Wang et al., 2005). Previous studies agree that the EASM is anticorrelated with the EAWM and its strength depends on the movement of the ITCZ (Yancheva et al., 2007).

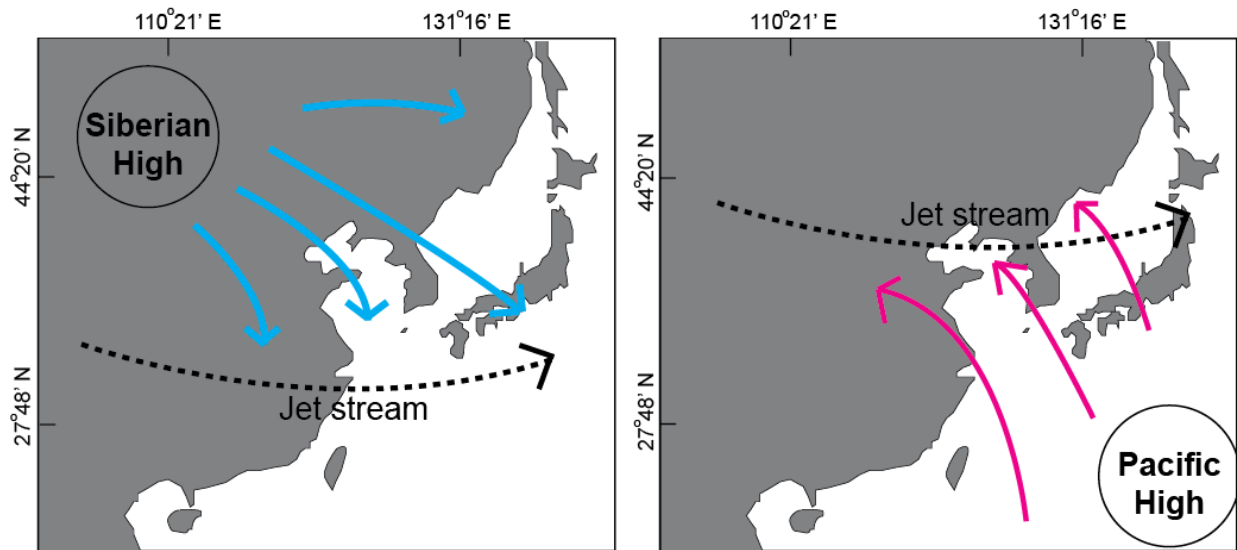


Figure 1-3. East Asian monsoon depending on the seasonal change

1.3. Typhoon associated with El Niño/Southern Oscillation (ENSO)

The typhoon generates significant casualties and financial damage in Korea and Japan. Heavy rainfall has been produced by typhoons in the Asian region (Fumin et al., 2002; Kim et al., 2006). Generally, the typhoon track is closely influenced by ENSO variation. For example, the typhoons tend to recurve to Japan, Korea, and northern China during El Niño year. On the other hand, the typhoons toward Philippine and south China during La Niña year (Fig. 1-4) (Elsner and Liu, 2003). ENSO is the largest annual climate signal induced by the interaction of the dynamics of both ocean and atmosphere. ENSO is strongly controlled by sea surface temperature (SST) in the Pacific Ocean (Schwing et al., 2002; Marchitto et al., 2010). Furthermore, this SST is influenced by solar activity. According to Marchitto et al, 2010, El Niño is related to solar irradiance to show SST record on Mg/Ca ratio correlated with the generation of cosmogenic ^{14}C and ^{10}Be .

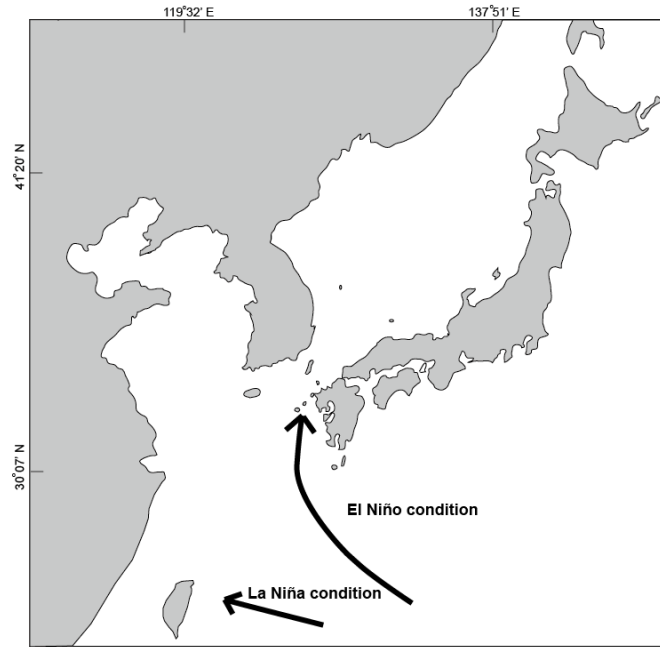


Figure 1-4. Typhoon track depending on El Niño and La Niña condition

1.4. Objective

My objective is to clarify paleoenvironmental and paleoclimate change by reconstructing paleoenvironmental, and paleoclimate change during the Holocene with centennial to decadal scale by Korean and Japanese lagoon sediments using not only diatom assemblage but also several proxies such as grain size analysis, chemical analysis, and chronology. In this study, the unclear environmental change because of insufficient age data will make clear and suggest new insight into monsoonal change using diatom assemblage and other proxies. Even though both Korean and Japan lie in East Asia and close each other, the factors which influence environmental change such as monsoon and relative sea level change have worked differently depending on each region. Therefore, the purpose of this research is to compare both results to understand how the environment has been changed, and the monsoon system has been worked differently between Korea and Japan.

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Chapter 2. Holocene environmental and climatic changes inferred from diatom assemblage in Hwajinpo coastal lagoon, Korea

2.1. Introduction

Coastal lagoons are commonly formed as a result of slowly changing sea-level and the formation of stable coastal barriers (Roy et al. 1994). These lagoonal systems are commonly defined by a coastal barrier between land and marine environments, with their sediments containing valuable records of barrier beach formation, stability and paleoenvironment and paleoclimate changes (Pernetta and Milliman 1995). In addition, these sediments can provide a record of sea-level change during the Holocene because lagoonal barriers can be sensitive to fluctuations in sea-level (Kraft et al. 1981; Howell et al. 1988; Selivanov 1996; Morton et al. 2000). Lowland lagoonal sediments also commonly have a high temporal resolution because of their relatively high rates of sedimentation relative to that commonly observed off-shore in marine environments.

There are currently a number of reconstructions of Holocene sea-level changes in East Asia (Ota et al. 1990; Selivanov 1996; Yum et al. 2002, 2003, 2004). However, few sea-level records are available from the eastern Korean Peninsula (Yum et al. 2003, 2004, 2015), where stable basement conditions in this area provide suitable conditions for understanding regional sea-level change. Hwajinpo lagoon is located on the eastern coast of the Korean Peninsula and is the largest lagoon in Korea. This lagoon is partitioned into an inner and outer lake (Fig. 2-1). Unlike the sediments of other lagoons in Korea, bottom sediments in Hwajinpo lagoon are well preserved, up until modern disruptive industrial activities (Yum 1996). Recent studies on Hwajinpo sediments include sedimentary facies modeling, chemical components analysis, accelerator mass spectrometry (AMS) ¹⁴C age dating, and analyses of diatom and mollusca assemblages (Yum et al. 2002, 2003, 2004,

2015; Go et al. 2013). Additionally, evidence for changes in Holocene sea-level has been suggested by Yum et al. (2003, 2004, 2015) based on an analysis of Hwajinpo sediments. However, sea-level changes around this lagoon are still somewhat ambiguous because of the short core depths and/or limited age control points in previous studies, particularly for the inner lake. For example, previously only two dates have been available between 5 and 9.5 m sediment depth in the inner lake (Yum et al. 2003; Go et al. 2014)

Commonly, research for paleoclimate change in lagoonal environments is limited. However, recently many studies for reconstructing paleoclimate change using microfossils have been performed in lagoonal systems because they provide valuable information of natural climate change at a variety of temporal and spatial scales (Woodward et al. 2014; Abu-Zied and Bantan 2015; Peros et al. 2015). Diatoms are microalgal paleoenvironmental indicators and vital primary producers capable of photosynthesis in all waters where sunlight is available. They are very sensitive to environmental changes, such as water temperature, salinity concentration, water depth, and geographical position (Smol and Stoermer, 2010). Thus, changes in any one of these ecological factors greatly impact the biological form, growth, colony formation, and geographical distribution of diatom assemblages. Furthermore, the valves of diatoms are preserved after death and sediment burial. Thus, diatom valves in the sediment provide preserved information about the paleoenvironment, paleoclimate, and paleoceanographic settings and changes. Additionally, diatoms are a good indicator for reconstructing the geomorphic evolution of a lagoon, including the timing and conditions present during its formation and development (Kashima 1985, 1986; Vos and Wolf 1993; Yasui and Kobayashi 2001; Ryu et al. 2003; Sylvestre et al. 2004).

No previous diatom research had been conducted on Hwajinpo lagoon's modern environment and ecosystem with the exception of a report documenting a sudden red-tide algal

bloom event (Kim et al. 2012). Therefore, modern diatom assemblage in surface sediment was required in order to investigate and compare to changes in fossil diatom assemblage within deeper sediments. In this paper we provide a new sedimentary reconstruction of changing ecosystem and environmental conditions in Hwajinpo lagoon. We compare our sediments core from the inner lake to the modern diatom assemblage and a previous sediment core obtained from the outer lake (Yum et al. 2004). Results provide new information on lagoonal development and changing climatic and environmental conditions on the eastern Korean Peninsula during the Holocene.

2.2. Study area

Hwajinpo lagoon is made up of an inner and outer lake, both with brackish water linked with a small and shallow channel (Fig. 2-1). The lagoon has a surficial area of 2.4 km² with a maximum depth of 4.6 m. The Hwajinpo lagoon has two main streams, which drain to the inner lake and its catchment area is approximately ten times larger than the lagoon's total area. The outer lake of the Hwajinpo lagoon has a small ephemeral outlet to the sea that bisects the approximately 200 m wide sand beach. This outlet is currently opened temporarily during the summer rainy season (the monsoon season) to lower the lake level for flood prevention. Seawater also enters the lagoon through this outlet along with periodic groundwater seepage during high storm wave activity. As a result, Hwajinpo lagoon is hyposaline with a prominent halocline (Yum et al. 2003, 2004). As the distance departs from the outlet, the salinity decreased in both surface and bottom layers. The lake salinity is highly fluctuated per season and year, particularly in surface layer between 0.2 and 33 psu. Mean salinity of the outer lake is around 11-15 psu in surface, and 25-33 psu in bottom. In the inner lake, mean surface salinity is around 11 psu, and mean bottom salinity is about 11-15 psu (Heo et al. 2004; Bhattarai et al. 2017). The annual mean temperature of Hwajinpo lagoon is around

11°C (Yum et al. 2002). Mean values of total nitrogen (TN) and phosphorus (TP) in surface between A.D. 1998 and 2015 were 0.06-0.09 and 0.82-1.24 mg L⁻¹, respectively. The basement rock of Hwajinpo lagoon is composed of the Gyeonggi Gneiss Complex intruded by the Jurassic Daebo granites (Cho et al. 1998).

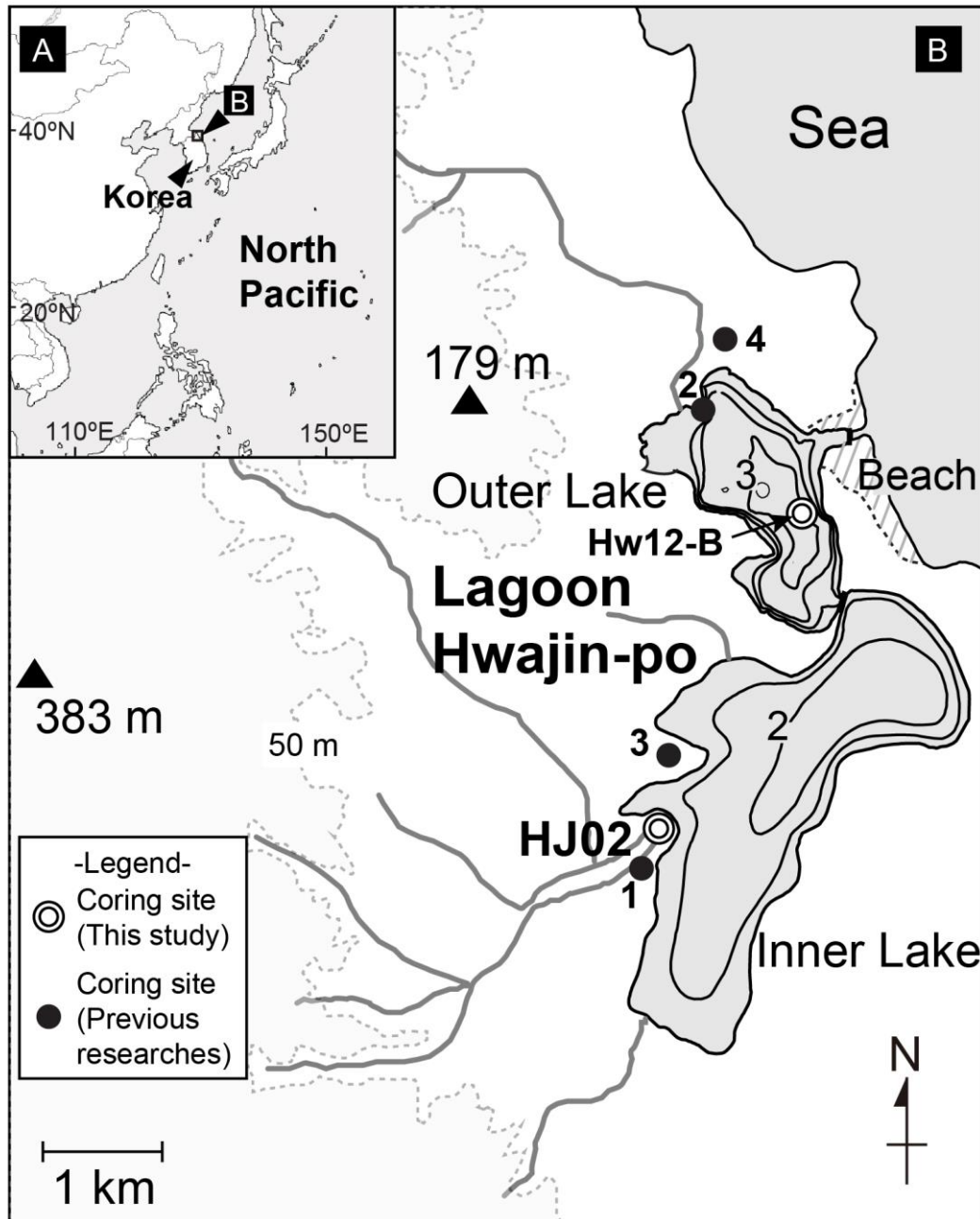


Figure 2-1. Maps of (A) East Asia and (B) Hwajinpo lagoon area, including core sites Double circles are HJ02 and Hw12-B cores, and black circles are coring sites of previous papers: 1. Nameless core (Yum et al. 2003), 2. HJ99 (Yum et al. 2004), and 3-4: HJP01 and HJP02 (Go et al. 2013)

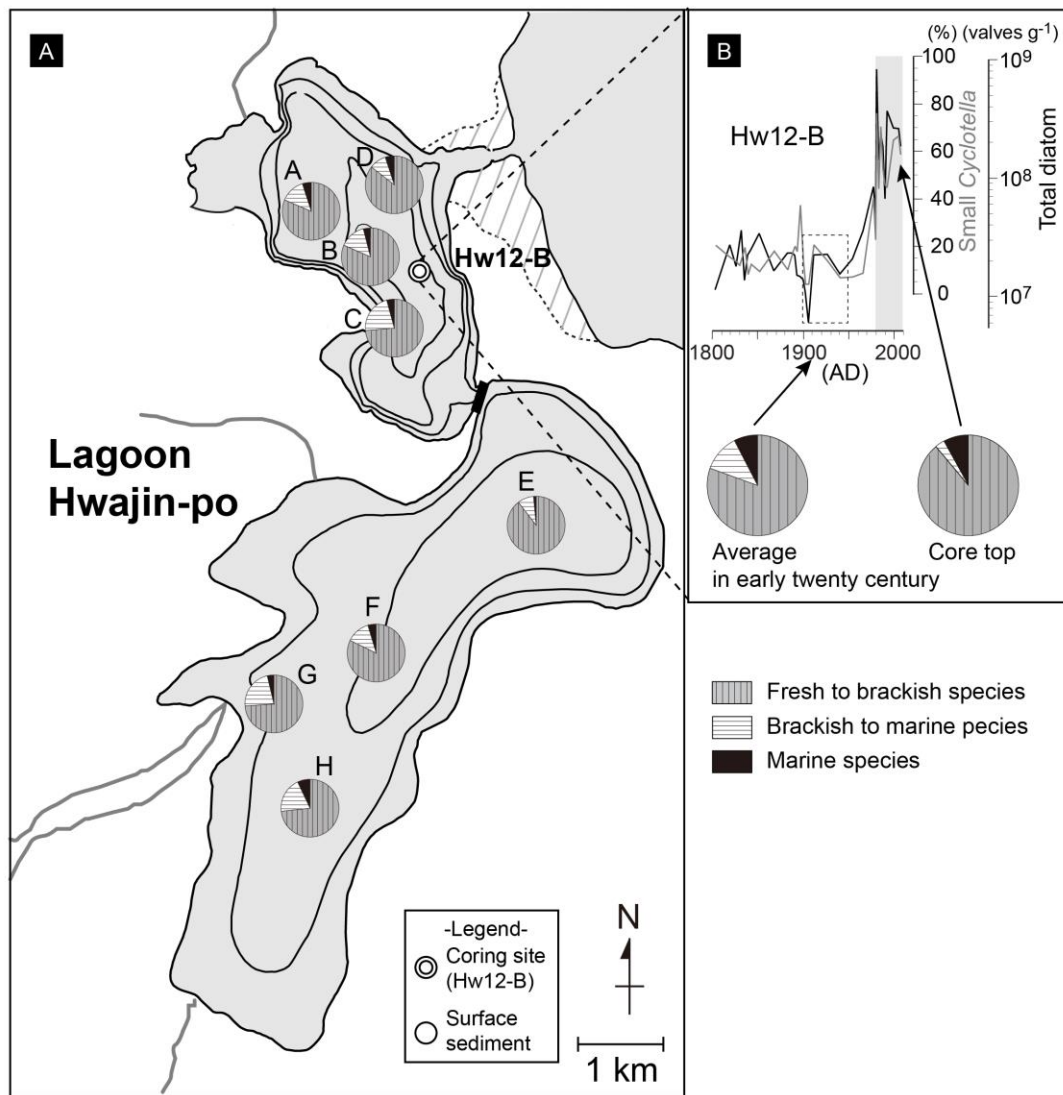


Figure 2-2. (A) Location of eight surface samples and core Hw12-B. Pie chart from A to D are for the outer lake surface samples and pie chart from E to H are for the inner lake samples. Pie charts show the relative abundances of fresh to brackish, brackish to marine and marine diatom taxa. (B) Temporal variation of the total diatom numbers and relative abundance of small diatom numbers and relative abundance of small *Cyclotella* since A.D. 1800 in core Hw12-B. Pie charts show the relative abundance of diatom groups in the core top and average in the early twentieth century

2.3. Materials and methods

In June of 2012, eight surface sediment samples were collected from Hwajinpo lagoon by an Ekman-barge core sampler (4 samples from the inner lake and 4 other samples from the outer lake; Fig. 2-2). During the same field campaign Core Hw12-B with a length of 1.66 m was obtained by a manual piston push corer from the outer/seaward lake of the Hwajinpo lagoon. In May of 2014 a longer vibro core (Core HJ02), with a length of 11.0 m and diameter 7.6 cm was also collected from the front of reclaimed land around the inner/landward lake of the Hwajinpo lagoon (Fig. 2-1). Both Core Hw12-B and drilling core HJ02 were sealed in the field site, and then transported to the Korea Institute of Geoscience and Mineral Resources (KIGAM). Once in the laboratory, the sediments were described, photographed, and analyzed with the methods described below.

2.3.1. Age dating of core Hw12-B

An age model for core Hw12 was constructed based on ^{210}Pb , ^{137}Cs , and ^{14}C dating. ^{210}Pb and ^{137}Cs were measured using a Gamma-ray Spectrometry System 8000 (Princeton Gamma Tech, USA). The ^{137}Cs peak and ^{210}Pb activities were used to calculate the sedimentation rate and sediment age at depths of 5–50 cm in core Hw12-B assuming a constant initial concentration (CIC) model for ^{210}Pb and a 1954 onset and 1963 peak in ^{137}Cs . To exclude the effects of core-top sediment disturbance and terrestrial sediment inflow, the upper 5 cm and extremely low data values of ^{210}Pb were excluded from calculation of the age-depth model. ^{14}C ages were measured by accelerator mass spectrometry at the KIGAM (details in Hong et al. 2010a, b). A more detailed description of the age model and associated methods are provided in Katsuki et al. (2016).

2.3.2. Core HJ02

2.3.2.1. Accelerator mass spectrometry ^{14}C dating

To establish a stratigraphically consistent chronology for the HJ02 core during the Holocene Epoch, we measured eleven ^{14}C ages using AMS dating on material that includes five plants, two bivalves (Order Arcoida), and four snails (*Batillaria multiformis* and *Batillaria* spp.), (Fig. 2-3, Table 2-1). These samples were washed repeatedly using an ultrasonic cleaner and then cleaned chemically using acid-alkali-acid or just acid treatments to remove secondary contamination. Samples of radiocarbon free wood were treated using the same procedure to serve as blanks. The carbonate samples (NIST OxII, IAEA C-7, and C-8) were milled and combusted using an elemental analyzer. CO_2 gases were purified cryogenically in a high-vacuum automatic preparation system (Hong et al. 2010a) and then converted to graphite via reduction on Fe powder with hydrogen gas in a quartz tube. The ^{14}C ages of the samples were measured using standard methods at the AMS facility at the KIGAM (Hong et al. 2010a, b). Carbon isotopic fractionations were corrected using $\delta^{13}\text{C}$ values measured at the AMS facility. The ^{14}C ages were calculated and converted to calendar dates using IntCal13 (Reimer et al. 2013) and CALIB 7.0 (Stuiver and Reimer 1993).

2.3.2.2. Optically stimulated luminescence age dating

Three samples were collected for Optically Stimulated Luminescence (OSL) dating because error of radiocarbon dating was very high just above 7 m depth (Fig. 2-3, Table1). For dating the fine grained samples, chemically purified quartz grains 4-11 μm in diameter were extracted using sodium pyrophosphate ($\text{Na}_4\text{P}_2\text{O}_7 \cdot 10\text{H}_2\text{O}$) to remove any clay, and hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2) to remove any carbonates and organic matter respectively. Settling occurred according to Stokes' Law over a depth of 20 cm in a 0.01 M sodium oxalate ($\text{Na}_2\text{C}_2\text{O}_4$)

solution. Finally, samples were etched in hydrofluorosilicic acid (H_2SiF_6) for 14 days to chemically remove feldspar. Heavy liquid separation in sodium polytungstate ($\text{Na}_6[\text{H}_2\text{W}_{12}\text{O}_{40}]$) (2.62 g cm^{-3}) was used to obtain quartz rich extracts. Concentrated hydrofluoric acid (HF) was applied to remove any remaining feldspar grains and to etch away the outer $10 \text{ }\mu\text{m}$ of the quartz grains. Luminescence signals were measured with a TL/OSL-DA-20 Luminescence Reader (Risø DTU, Denmark) equipped with a blue light emitting diode ($470 \pm 20 \text{ nm}$) stimulation source. The single aliquot regenerative dose (SAR) procedure (Murray and Wintle, 2000) was applied to chemically purified quartz grains of 4-11 and 90-212 μm in diameter. All samples for dating were dated at the OSL laboratory and the luminescence dating laboratory of the KIGAM.

Radiocarbon age data		
Sample	Depth(cm)	¹⁴C age(cal yr BP)
Wood	95	modern
Wood	238	145±115
Wood	284	modern
Wood	380	155±155
Wood	736	5470±140
Snail (Batillaria spp.)	766	7295±125
Shell (Arcoida)	835	6915±185
Shell (Arcoida)	880	7365±125
Snail (Batillaria spp.)	927	8035±135
Snail (Batillaria spp.)	962	7705±155
Snail (Batillaria spp.)	1051	7385±145
OSL age data		
Sample	Depth(cm)	OSL age (ka)
Fine grain	558-562	0.7±0.053
Fine grain	620-627	1.6±0.1
Fine grain	680-687	1.66±0.1

Table 2-1. Radiocarbon and OSL age dating data. Wood and snails were used in radiocarbon dating and were calculated and converted to calendar dates by IntCal13 (Reimer et al. 2013) and CALIB 7.0 (Stuiver and Reimer 1993). Only fine grain was performed by Risø DTU in OSL dating

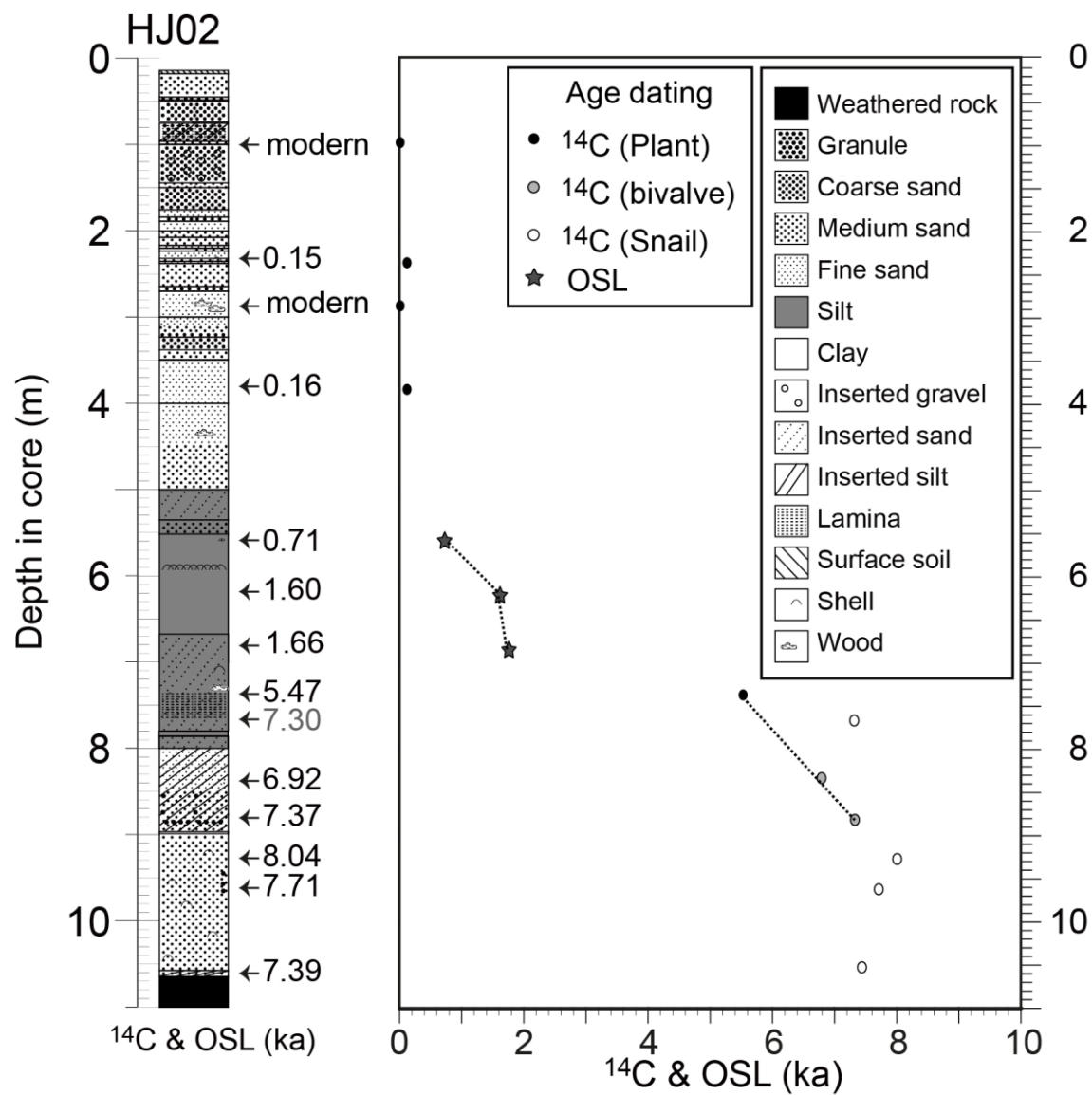


Figure 2-3. Lithology descriptions and age-depth plots of HJ02 core. The age data on line plot for chronology and unused age is written in gray word

2.3.2.3. Grain size analysis

Grain size analysis of the core sediments was performed at an interval of 10 cm between 5 and 6 m, every 2 cm between 6 and 8 m, and every 4cm interval between 8 and 9 m depth. The sample was treated with 35% H₂O₂ to reduce organic matter and boiled in 1 N HCl for one hour to remove carbonates and iron oxides. After washing with distilled water, the samples were shaken by an ultrasonic vibrator for 15 min to keep them in suspension and to facilitate dispersion. Grain size analysis was performed on a sample of about 300mg using a Mastersizer 3000 laser diffraction particle size analyzer, which automatically offers the percentage of clay, silt and sand. Mean grain size was calculated using the method of moments as described by Folk and Ward (1957).

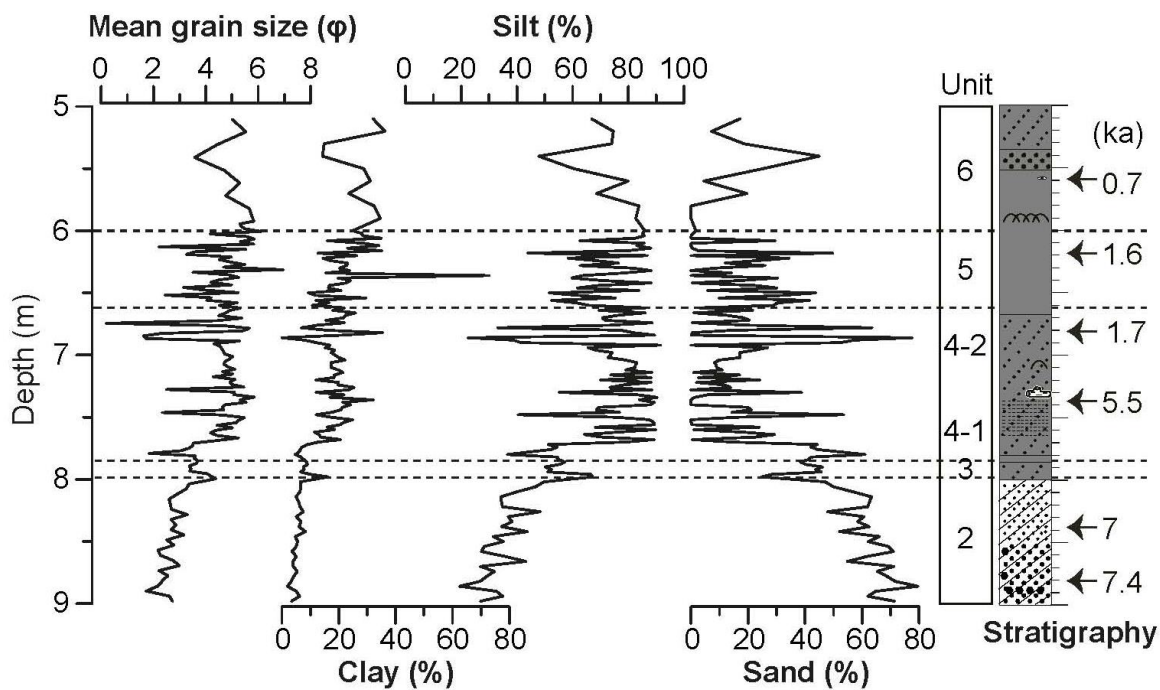


Figure 2-4. Stratigraphy, depth profiles of mean grain size, and percent of clay, silt, and sand contents in core HJ02

2.3.2.4. Diatom analysis

Diatom assemblages were analyzed in the eight surface sediment samples from Hwajinpo lagoon and in 131 samples from the HJ02 core between 5.00 and 9.00 m depth using the same sampling interval as grain size. For the diatom analysis 0.05 to 7 g of dry sediment were placed into a 200 ml beaker with 5 ml of 30% H₂O₂ and 2 ml of 3 % HCl to eliminate organic matter and calcareous material from the sediment. After boiling for one hour, 200 ml of distilled water was poured into each beaker and soaked for 4 hours. Clean water at the top of the beaker was replaced twice with new distilled water, and additional distilled water was added three times to separate substances with a density greater than that of the diatoms. Remaining bottom solutions of 0.2 to 0.6 ml after decantation were pipetted onto a cover slip using a micropipette and mounted in Pleurax. At least 300 diatom valves were counted on each slide under a 2000× magnification light microscope, with the exception of some samples with poor preservation or lower abundance of diatom valves on 5.7-6.0 m and 8.0-8.5 m depths. The number of total diatom valve is calculated by using equation below:

$$\begin{aligned} & \text{Total diatom valves per 1 dry sediment gram [No. g}^{-1}\text{]} \\ &= \text{Counted valve on slide [No.]} \times \text{Observation area (slide area [mm}^{-2}\text{]} / \text{counted area [mm}^{-2}\text{])} \\ &\times \text{Using liquid volume (beaker liquid volume [ml]} / \text{micropipette volume [\mu l]} \times 1000) \times \\ &\text{sediment}^{-1} \text{ [g}^{-1}\text{]} \end{aligned}$$

2.4. Results

Diatom assemblages in the surface sediments and core Hw12B sediments in the early twenty century

Eight surface samples were collected from bottom of the Hwajinpo lagoon. A to D samples were taken from the outer lake and E to H samples were collected from the inner lake (Fig. 2-2). Species composition of these samples was nearly the same. The most dominant diatom taxon was small ($< 10 \mu\text{m}$) *Cyclotella* (60-70 %) and the second dominant diatom taxon was *Navicula* spp. (0.2-9 %). Small *Cyclotella* is assumed *Cyclotella atomus*, *Cyclotella atomus* var. *gracilis*, and other variations. *Cyclotella atomus* is a freshwater to brackish taxa and indicator of eutrophication (Joh 2010; Kobayashi et al. 2006). And, *C. atomus* var. *gracilis* is an euryhaline species which prefers the salinity condition higher than *C. atomus* (Genkal and Kiss 1993). More specifically from site A to G the individual fractions of diatom taxa for: fresh to brackish taxa including small *Cyclotella* were 81, 81, 73, 85, 89, 82, 73, and 73 %, respectively; for brackish to marine taxa were 13, 14, 22, 9, 8, 13, 22, and 19 %; and for marine taxa were 6, 5, 5, 6, 3, 5, 5, and 8 %. The top sample of core Hw12-B also showed similar species composition as the A-G surficial samples. Relative fractional abundance of small *Cyclotella*, fresh to brackish taxa, brackish to marine taxa, and marine taxa were 56, 88, 4, and 8 %, respectively (Fig. 2-2b). According to Katsuki et al. (2016), the abundance of diatoms suddenly increased in 1970 due to an influx of fertilizer from abundant agriculture. The average species composition in the early twenty century in core Hw12-B of small *Cyclotella*, fresh to brackish taxa, brackish to marine taxa, and marine taxa were 37, 80, 12, and 8 %, respectively (Fig. 2-2b).

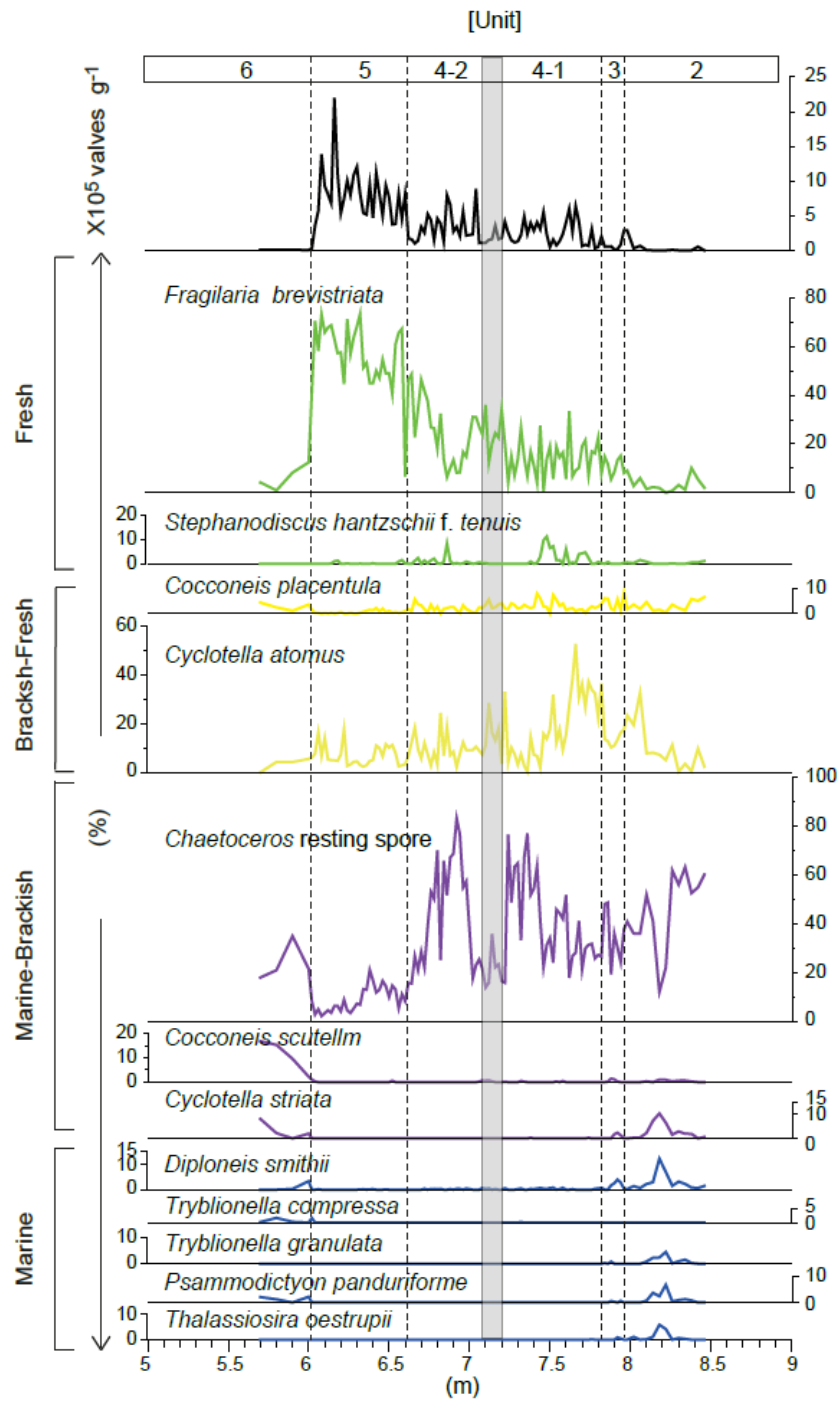


Figure 2-5. Depth profiles of the fossil diatom assemblages in core HJ02. On the basis of the ecological group, diatoms were categorized into four groups, such as marine, marine-brackish, brackish-freshwater, and freshwater, and were divided into six divisions namely Unit 1 to 6. Gray zone indicates the hiatus layer

2.4.1. Sediment lithology of core HJ02

The 11.0 m long Core HJ02 contained a weathered basement rock below 10.64 m. From 10.64 to 9.00 m sediments were composed of light gray, fine to coarse sand with snails, shell fragments, silt, and angular granules. Sand grains were upward fining in this section. From 8.0 to 9.0 m the sediments were composed of dark gray silt with fine to coarse sand including shell fragments and angular granule. Between 8.00 and 7.00 m sediments were composed of silt and sandy silt and wood fragments, with a unit of well developed lamina between 7.37 to 7.66 m. Sediments from 7.00 to 6.00 m contained dark gray silt with shell fragments. Between 6.00 and 5.50 m sediment was composed of silt with some fine sand and a lot of shell fragments, particularly in an especially pronounced shell layer at 5.8 m. At the interval between 5.50 to 5.30 m, sediments consisted of coarse sandy silt. The final upper 5.30 m of sediments were composed of alternating coarse and fine sands with granule (Fig. 2-3).

2.4.2. Grain size distribution of core HJ02

The same samples used for the diatom assemblage (between 5 and 9 m of depth) were used for the mean grain size analysis of the core HJ02. This data exhibits a gradual upward decrease in grain size between 9.00 and 8.00 m varying from 2 to 3.8 ϕ . This decreasing grain size trend continued from 8.00 and 7.80 m in depth. Mean grain size between 7.80 and 6.60 m varied widely between 0.5 to 5 ϕ , and there were several peaks in the upper and lower parts of this section of the core. The mean grain size between 6.60 and 6.00 m depth also exhibited a decreasing trend, with a range of 2 ϕ to 5 ϕ . From 6.00 to 5.50 m of depth, the mean grain size increased from 6 ϕ to 4 ϕ (Fig. 2-4).

In addition to mean grain size we analyzed changes in the fractional composition of clay, silt, and sand with depth. From 9.00 to 7.80 m in depth, the sediments were composed of silt and sand,

and the sand percent decreased until 7.80 m to about 35%. From 7.80 and 6.60 m, silt and sand fractions varied widely, from 20 to 80 % in silt and from 0 to 80 % in sand. Sediments between 6.60 and 6.00 m exhibited a more stable trend with percent clay increasing to around 35% except spike at 6.4 m depth. From 6.60 to 5.50 m, percent silt decreased and percent sand increased upward up to 50% (Fig. 2-4).

2.4.3. Diatom assemblage in core HJ02

The diatom fossils were well preserved in the HJ02 core and composed of forty-two genera and two hundred and seven species identified in total (Fig. 2-5). Twelve taxa were dominant and accounted for more than 90% in the HJ02 core. The taxa reaching more than 10% relative abundance were *Stephanodiscus hantzschii* f. *tenuis*, *Chaetoceros* spp. resting spore, *Cocconeis scutellum* var. *parva*, *Cyclotella atomus*, *Cyclotella striata*, *Diploneis smithii*, and *Fragilaria brevistriata*. The subappearance taxa (less than 10%) were *Cocconeis plancentula*, *Psammodictyon panduriforme*, *Tryblionella compressa*, *Tryblionella granulata*, and *Thalassiosira oestrupii*. In the lower part (9.00-8.00 m), *Chaetoceros* spp. resting spores, *C. striata*, *D. smithii*, *P. panduriforme*, *T. granulata*, and *T. oestrupii* occurred predominantly. *Cocconeis plancentula*, *C. atomus* and *Chaetoceros* spp. resting spores occurred between 8.00 to 7.80 m. The interval between 7.80 to 6.60 m depth was mainly composed of *Chaetoceros* spp. resting spore, *C. atomus*, *Fragilaria brevistriata*, *S. hantzschii* f. *tenuis* and *C. plancentula* var. *lineata*. Between 6.60 and 6.00 m depth, *C. atomus*, and *F. brevistriata* were dominant. *Chaetoceros* spp. resting spores, *C. scutellum* var. *para*, *C. striata*, *C. plancentula* occurred, and *T. compressa* became dominant in the upper part (6.00-5.00 m) of the core. On the basis of the ecological spectra, these diatoms were categorized into four ecological groups, namely marine, marine-brackish, brackish-freshwater, and freshwater.

Marine species were represented by *D. smithii*, *P. panduriforme*, *T. compressa*, *T. granulata*, and *T. oestrupii*. Marine–brackish species were represented by *Chaetoceros* ssp. resting spores, *C. scutellum* var. *parva*, and *C. striata*. The main brackish–freshwater species were *C. atomus* and *C. plancentula*. Freshwater species were represented by *S. hantzschii* f. *tenuis*, and *F. brevistriata*. The taxa in genus *Navicula*, which is common in the surface sediment of Hwajinpo lagoon, hardly appeared less than 1 % throughout core HJ02.

2.5. Discussion

2.5.1. Sediment chronology of core HJ02

Fig. 2-3 and Table 1 show the results of AMS ^{14}C and OSL ages in core HJ02. According to the AMS ^{14}C dating, preserved sediments at site HJ02 begin around 8.0 ka or at a sediment depth of 10.64 m, beginning with sandy sedimentation above basal material between 7.4 and 8.0 ka (10.64–9.00 m of depth). The silt and sandy silt sediments continued until 5.50 m (Fig. 2-3). Although there was no clear sediment boundary in this lower unit, there was a large age gap around 7.00 m in depth extending between 5.5 and 1.7 ka that likely represents either an erosional or depositional hiatus. Shell fragments were scattered within the upper 7.00 m of sediment, however, there was no plant matter or complete shell material on which AMS ^{14}C dating could be performed. According to OSL age dating, sediment layers between 7.00 and 5.00 m date to period of roughly 1.7 to 0.7 ka. The top 5.00 m of sediment in HJ02 of alternating gravely sand and silt layers were probably deposited within the last 150 years based on AMS ^{14}C dating results. Plant material AMS ^{14}C ages in this uppermost unit indicated and age range between Present and 150 years ago (Fig. 2-3 and Table 1).

The human population of Korea experienced a marked increase around A.D. 1,900 (National Geographic Information Institute, 2006). This population growth was particularly high in the

Gangwon Province, including the boundary close to the Hwajinpo lagoon. During 1900-1930, the population growth was over fourfold, leading to an increase in the number of farmers during that time. Beginning in 1900 topsoil outflow from surrounding agricultural land development likely caused high sediment inflow into the Hwajinpo lagoon. In fact, the lagoon shrank by approximately 10% during 1918-1960 due to terrestrial sediment input, similar to other lagoons throughout Gangwon Province (Yoon et al. 2008). Furthermore, a map from 1918 indicated that site HJ02 was underwater at that time (Yoon et al. 2008). Thus, the facies of alternating gravely sand and silt layers within the upper 5 m unit of HJ02 likely formed in the last 100 years due to increased sediment inflow as a result of agricultural activities in the region.

2.5.2. Holocene paleoenvironmental history of the Hwajinpo lagoon

Core HJ02 can be divided into the following six units based on the cores obtained chronologies, lithology, grain size distributions, and diatom cluster analyses (Figs. 2-3,2-4,2-5,2-6).

Unit 1 (10.64 - 9.00 m): estuarine tidal flat environment

This unit is composed primarily of middle to coarse sand with some silt, angular gravels, shell fragments, and snails (Fig. 2-3). There are no diatoms in this unit. The snails were the *Batillaria multiformis* and *Batillaria* spp., which live in brackish condition consistent with estuarine conditions (Okutani 2001). Similar ^{14}C ages throughout this unit suggest that the sediment in this unit was well mixed due to high-energy condition. Our interpretation is that this lower unit represents estuarine environment based on snails and core lithology and suggests that the first marine transgression at the site started about 7.4 ka.

Unit 2 (9.00 ~ 8.00 m): open bay

Unit 2 was deposited during 7.4-6.5 ka and is composed primarily of silt containing some sand. There are no diatoms in the lower 50 cm of this unit, and the upper 50 cm of this unit

consisted of fine sand with abundant marine and marine to brackish taxa, *Chaetoceros* spp. resting spores, *C. striata*, *D. smithii*, *T. granulata*, and *T. oestrupii* (Figs. 2-4, 2-5). *Chaetoceros* spp. resting spore are common in marine to brackish areas. *Cyclotella striata* is a marine to brackish species, and is indicative of an inner bay environment (Kosugi 1988). *Diploneis smithii*, *P. panduriforme*, *T. granulata*, and *T. oestrupii* are marine species (Hendey 1964). In particular, *D. smithii* and *T. oestrupii* are indicators of an outer bay environment (Kosugi 1988). The abundance of marine and marine to brackish taxa were greatest within the core, and the abundance of freshwater taxa were lower than in other units (Fig. 2-6). It is reasonable to consider that water depth in this unit had become deeper than in Unit 1, and this site was under the sea water effect in Unit 2.

Silt composition increased gradually in this unit. According to Yum et al. (2004), the mean grain size is closely related with sea-level and coastal lake level changes. For example, coarse grain can be deposited under the low sea and coastal lake levels. The observed fining in this unit is consistent with increasing water depths at the site as a result of rising sea-level (Yum et al. 2003; 2004) (Fig. 2-4). Previous sea-level studies in East Asia reported a rise until a highstand between 6 and 7 ka (Park et al. 1996), which is consistent with rising sea-level during the deposition of Unit 2 between 7.4-6.5 ka. It means that volume of sea water inflow increased gradually belonging to the rising sea level.

Diatomic environment indicators in Unit 2 are of inner bay taxa like *C. striata*, outer bay taxa like *D. smithii* and *T. oestrupii*, and marine species (Fig. 2-5). Additionally, *T. granulata* which lives on sandy shores appeared frequently in this zone (Kumano et al. 1990). It is inferred that there was active circulation between sampling site HJ02 and the sea during the deposition of Unit 2. and the coastal sand barrier had not yet developed. The high sand content with prominence of sandy shore and marine diatom taxa in Unit 2 indicated the active transport of sand to the site from the

beach zone between 7.4-6.5 ka. Taken together, the inner lake of Hwajinpo lagoon including this coring site was open bay in Unit 2. There was high sea-water exchange due to the rising sea level and undeveloped coastal sand barrier.

Unit 3 (8.00 - 7.80 m): semi-closed bay

Unit 3 was deposited during 6.5-6.0 ka, and this unit was defined by sand inserted silt layer between fine sand layer as Unit 2 and laminated silt layer as lower part of Unit 4-1. *Cyclotella atomus* and *Chaetoceros* spp. resting spores dominated the assemblage in Unit 3 (Fig. 2-5). *Cyclotella atomus* is a freshwater to brackish taxa under eutrophication as introduced above. *Cyclotella striata*, *D. smithii*, *T. granulata* and *T. oestrupii* abruptly decreased in this unit. Although marine diatom taxa abruptly decreased in Unit 3, other dominant diatom taxa were similar to Unit 2 (Fig. 2-5). This assemblage shift suggests that the site was beginning to separate from the sea, yet still partially connected. The sudden drop of sand percentage and *C. atomus* were caused by getting far away from inflow stream and land side (Figs. 2-4, 2-5). The sand bar between the lagoon and the sea is considered to have formed in this unit under sea-level highstand condition (Pirazzoli 1991; Matsubara 2000). The sea-level highstand along the east Korean coast dates to around 6 ka (Jo 1980; Yum et al. 2015), and is consistent with the timing of Unit 3's deposition under semi-enclosed bay conditions.

Unit 4-1 (7.80 -7.00 m): lagoon isolated from sea

Unit 4 (1 and 2) was deposited from 6 to 1.7 ka. In Unit 4-1 *Chaetoceros* spp. resting spores became the dominant taxon, together with *C. atomus*, *Fragilaria brevistriata*, *S. hantzschii* f. *tenuis*, and *C. plancentula* (Fig. 2-5). *Cocconeis plancentula* is a freshwater to brackish species and a benthic diatom in streams (Joh 2012). *Stephanodiscus hantzschii* f. *tenuis* is a low temperature diatom that lives in water temperatures below 12° C. *Fragilaria brevistriata* is an epipelagic

euryhaline species, and mainly appears in shallow fresh water lakes (Bradbury 1989; Colombaroli et al. 2007). These diatom taxa indicate that the salinity at the site Unit 4-1 decreased compared with the previous units. In addition, the salinity of Unit 4-1 is likely to lower than present based on rare marine taxa, although there were marine diatom taxa at present and in early 20 century (Figs. 2-2, 2-6). Sediments in this unit also consisted of silt with fine sand including shell and wood fragments (Fig. 2-3). Sand content suddenly decreased in this unit while silt and clay fractions clearly increased (Fig. 2-4). These changes suggest that the site during the deposition of Unit 4-1 was isolated from the sea. It is likely that the Hwajinpo lagoon formed at this time. In this unit, laminated layers are also well developed (Fig. 2-3). This lamina structure also supports lagoonal conditions at the site. Stratified lagoons with well developed haloclines often develop lamina deposits as a result of reduced bioturbation. Yum et al. (2003) mentioned that the laminated layer in the inner lake of Hwajinpo could be explained by the runoff stagnation model of Howell et al. (1988). The development of low oxygen condition and lamina development was formed by the reduction of surface water salinity due to river water inflow and restricted sea water inflow, and resultant anoxic conditions at the bottom of the lagoon. Large vertical density gradients restrict the vertical mixing and oxygen supply to bottom waters of the basin. Laminated layers are also observed in sediments collected from the outer lake of Hwajinpo lagoon in the Core HJ99 (Yum et al., 2004) (Fig. 2-8). The starting time of the lamina deposition in core HJ99 was about 5.5 ka, which is similar to a 6.0 ka onset of lamina in core HJ02 (Fig. 2-7). This means that not only the inner lake but also the outer lake was isolated from the sea during this time. On the other hand, HJ02 core has only a 0.40 m laminated layer, compared to a 1.50 m laminated layer in Core HJ99 core that extends to 2.8 ka (Yum et al., 2004). The shorter laminated layer in the HJ02 core, which was deposited until 5.5 ka, suggests either an erosional or depositional hiatus in HJ02 between 5.5

ka and 2.8 ka (shaded area in Fig. 2-5) which is consistent with a step function change in the age model at the top of Unit 4-1 (Fig.2-3).

Unit 4-2 (7.00 - 6.60 m): lagoon isolated from sea

The diatom assemblage and lithology of Unit 4-2 was almost the same as in Unit 4-1 (Figs. 2-4, 2-5), meaning that the site was also an isolated lagoon during the deposition of this unit. As explained above, there was a hiatus between units 4-1 (about 5.5 ka) and 4-2 (about 1.7 ka) at an approximate sediment depth of 7.30 m. This hiatus is not likely the result of sea-level rising because the Hwajinpo lagoon was isolated by a sand bar during this time, and marine taxa did not exist in this unit. It is also unlikely that the lake level decreased significantly to subaerial condition because no oxidized sediment was observed in Unit 4. In the bottom part of Unit 4-2, fresh water diatom taxa was correlated with a sand peak (Figs. 2-4, 2-6) while the total number of diatoms decreased. A flood event is one possible explanation for this depositional signal. At present, coring site HJ02 is located on the front of river delta (Fig. 2-1). Even if the paleo river mouth in Unit 4-2 was somewhat retrogressed compared to the present, the coring site should be subject to river flow. An extreme flood could potentially have eroded bottom sediments and explain the erosional unconformity observed in the cores age model. This would be followed with the abrupt deposition of flood-derived sediments. However, it is difficult to explain the observed hiatus with just a single flooding event. Other flood events therefore could have occurred despite delineating evidence of multiple floods within the core.

Unit 5 (6.60 - 6.00 m): oligohaline lagoon

Unit 5, which was deposited around 1.6 ka, is mainly composed of silt (Fig. 2-3). Dominating diatoms in Unit 5 are brackish to freshwater taxa of *Cyclotella atomus* and freshwater taxa of *F. brevistriata* (Fig. 2-5). Freshwater taxa and benthic taxa abundance in this unit was the

highest in the core, and the marine and marine to brackish taxa were rare. This suggests that the inner lake of Hwajinpo lagoon was further isolated from the sea during this period. Results presented by Yum et al. (2004) and Go et al. (2013) also showed that the outer lake of Hwajinpo lagoon became a freshwater lake around 1.7 ka (Fig. 2-7). On the other hand, the lithology of all cores is different. Sand is included in deposition in HJP01, HJP02 and HJ99 because those core sites are close to stream rather than core of HJ02 and Yum et al. (2003) (Fig. 2-7). The diatom assemblage of Unit 5 suggests a similar transition to fresh water taxa around 1.6 ka. Therefore, it is reasonable to consider that seawater exchange throughout the sand beach was minimal during this period. As a result, the condition of Hwajinpo lagoon shifted to a oligohaline lagoon around 1.6 ka. High sedimentation rates of silt accompanied by the dominance of freshwater diatom taxa suggests that this environmental change to an oligohaline lagoon was related with climate change (Figs. 2-3, 2-5, 2-6). A more detailed justification for this interpretation is provided in Section 5.4.

Unit 6 (6.00 - 5.00 m): lagoon similar to modern conditions.

Unit 6 was deposited after 1.2 ka, and diatom rarely occurred from 5.5 m. The primary diatom species in Unit 6 were *Chaetoceros* spp. resting spores, *C. scutellum* var. *parva*, *C. striata*, *C. plancentula*, and *T. compressa* (Fig. 2-5). *Cocconeis scutellum* var. *parva* is a benthic species in seaweed, and is indicative of shallow water depths (Joh, 2012). This diatom assemblage indicated that salinity of the inner lake during the deposition of Unit 6 likely increased. There are two ways to change from isolated lagoon to condition of Unit 6 like suddenly increasing marine and marine-brackish species. First possibility is sea level rising. If sea level rose, the grain size and lithology should be showed fining upward such as transgression. However, it showed coarsening upward from 6 to 5.5 m depth and fining upward from 5.5 to 5 m depth (Fig. 2-4). Besides, Yum et al (2004) suggested that coring site of HJ99 was prograding river system since 1.2 ka. Therefore, sea level

rising after 1.2 ka considered difficult to occur. As second possibility, marine water inflow and salinity increasing was introduced by opening inlet similar to modern lagoon conditions. At case of present lagoon, lagoonal inlet on sand barrier often opened under incidental natural extreme freshwater runoff event (Elwany et al., 1998). In core HJ02, the mean grain size increased upward from fine to medium sandy silt from 5 to 5.5 m depth (Fig. 2-4). River associated freshwater taxa like *C. placentula* also increased in this unit (Fig. 2-5). This grain size coarsening and freshwater taxa increasing suggests that the coring site might have been closer to the river due to delta progradation with freshwater runoff event. Besides, the ecology of Unit 6 is closely similar to early twenty century (Fig. 2-6). According to Yoon et al.,(2008), Hwajinpo lagoon have had an inlet from the early twenty century. Even though there is no citation about the development of inlet before AD 1900, this consequently might cause an inlet opening in this unit.

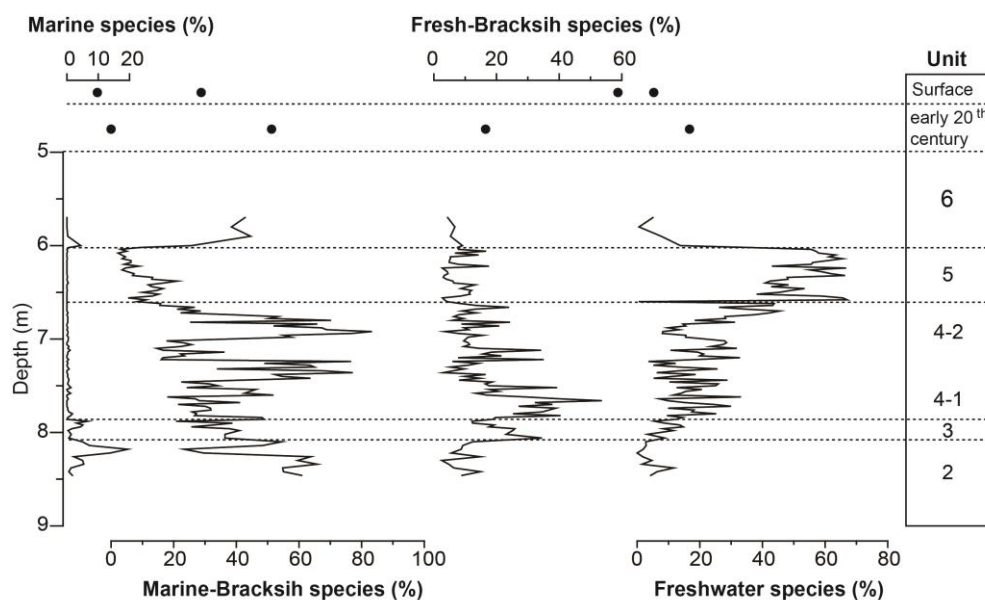


Figure 2-6. The relative abundances of total marine, marine-brackish, freshwater-brackish and freshwater species of HJ02 core and core top and early twenty century of Hw12-B core

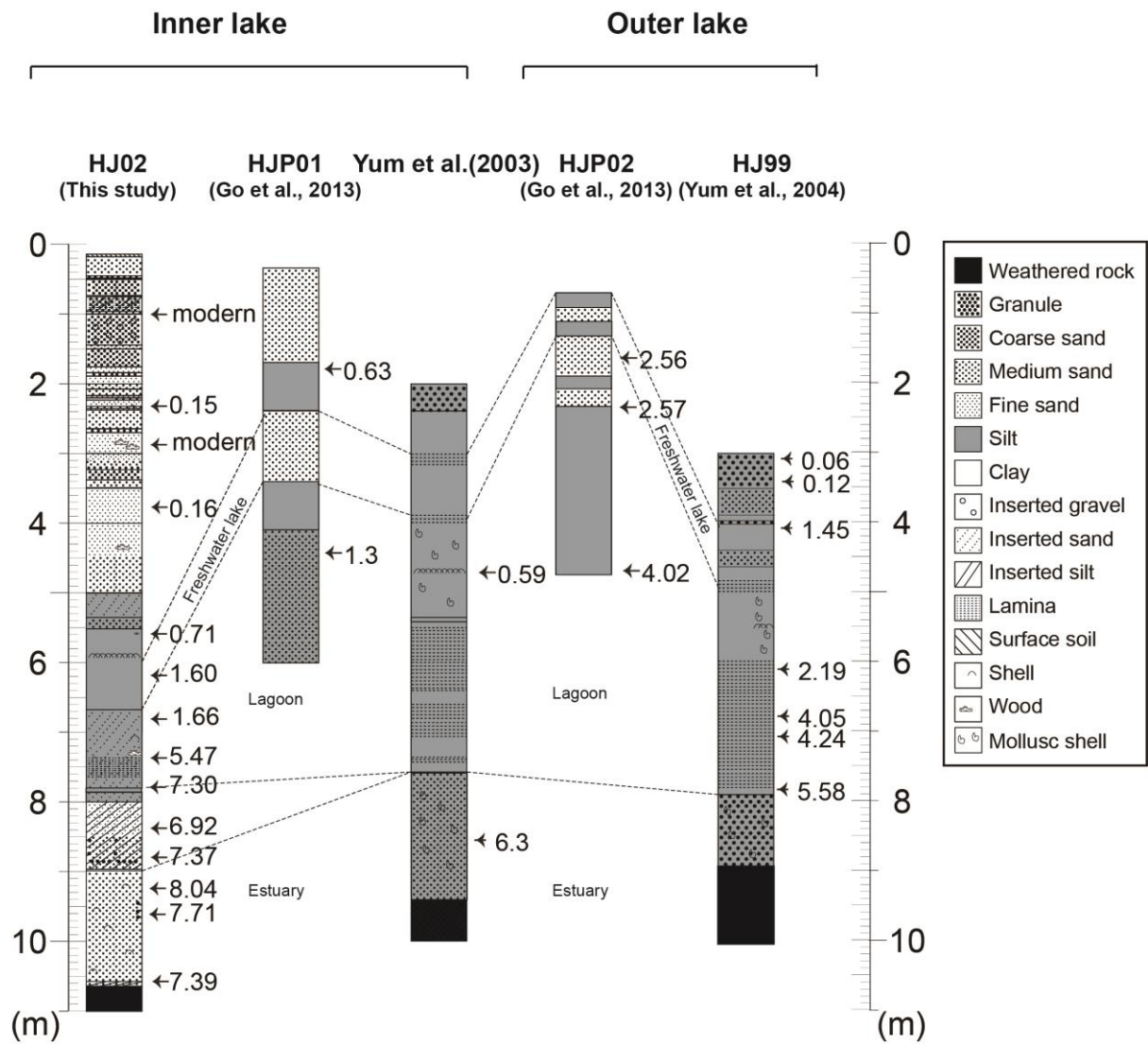


Figure 2-7. Lithological descriptions and age data of the nameless core (Yum et al. 2003), HJ99 (Yum et al. 2004), HJP01 and HJP02 (Go et al. 2013) compared with HJ02 core. Lithological symbols in previous researches are revised to coincident with the lithological figure of HJ02 core

2.5.3. Lagoon evolution and barrier beach formation during the Holocene

The evolution of the Hwajinpo lagoon is tied closely to the development of the site's sand barrier. As discussed, the sand barrier of the Hwajinpo lagoon likely developed in Unit 3, and the boundary of Units 3 and 4 at approximately 6.0 ka likely represents complete barrier separation of the lagoon from the sea. The transition from open bay, to semi-enclosed bay, and finally to lagoonal conditions is therefore evident in Unit 3 and the boundary between Unit 3 and Unit 4. Although there is no direct evidence of complete sand barrier development, it can be inferred by the different diatom assemblage in Unit 4 and the surface sediments showing the modern environmental setting where the barrier inlet is presently (Figs. 2-2, 2-5). At present, the Hwajinpo lagoon is separated from the sea by a 200m wide sandy barrier (Fig. 2-1). In spite of the existence of this sand barrier, seawater enters the lagoon via seepage and storm waves (Heo et al. 2004). Consequently, 5-8 % of marine diatom taxa appeared in the surficial sediments of the Hwajinpo lagoon (Fig. 2-2). Present day diatom assemblages of surface sediments showed almost the same components in both the outer and inner lakes (Fig. 2-2). This indicates that the circulation of sea water between outer and inner lakes is strong. On the other hand, present Hwajinpo lagoon has experience eutrophication due to high nutrient input by human activity since the 1970s (Katsuki et al. 2016). According to Katsuki et al. (2016), the small *Cyclotella* became the dominant taxon (> 55 %) following 1970 due to this high nutrient input by using chemical fertilizer. Before chemical fertilizer became popular in the early twentieth century, this small *Cyclotella* was only at 10 % relative abundance, and total marine diatom taxa was also about 10 % relative abundance (Fig. 2-2). The relative abundance of marine diatom taxa in Unit 4-1 in core HJ02 was lower than that both surface and early twentieth century sediments (Figs. 2-2, 2-5, 2-6), meaning the introduction of seawater to the lagoon during Unit 4-1 deposition was limited. Previous research on sea-level in East Asia suggested a highstand around

6.0 ka with mean sea-level similar to or higher than present during this time (Jo 1980; Yum et al. 2015). Therefore, low marine diatom relative abundance in Unit 4-1 indicates that the sand barrier was completely developed after Unit 4-1, and it was probably broader at that time relative to present. According to diatom assemblages in Units 4-2 and 5 of HJ02 core, the sand barrier was also broad, and sea-level was likely lower than during the deposition of Unit 4-1. This broad sand barrier had probably become narrow from the beginning of Unit 6, which allowed for the opening of a barrier similar to present conditions and around 1.2 ka in Unit 6.

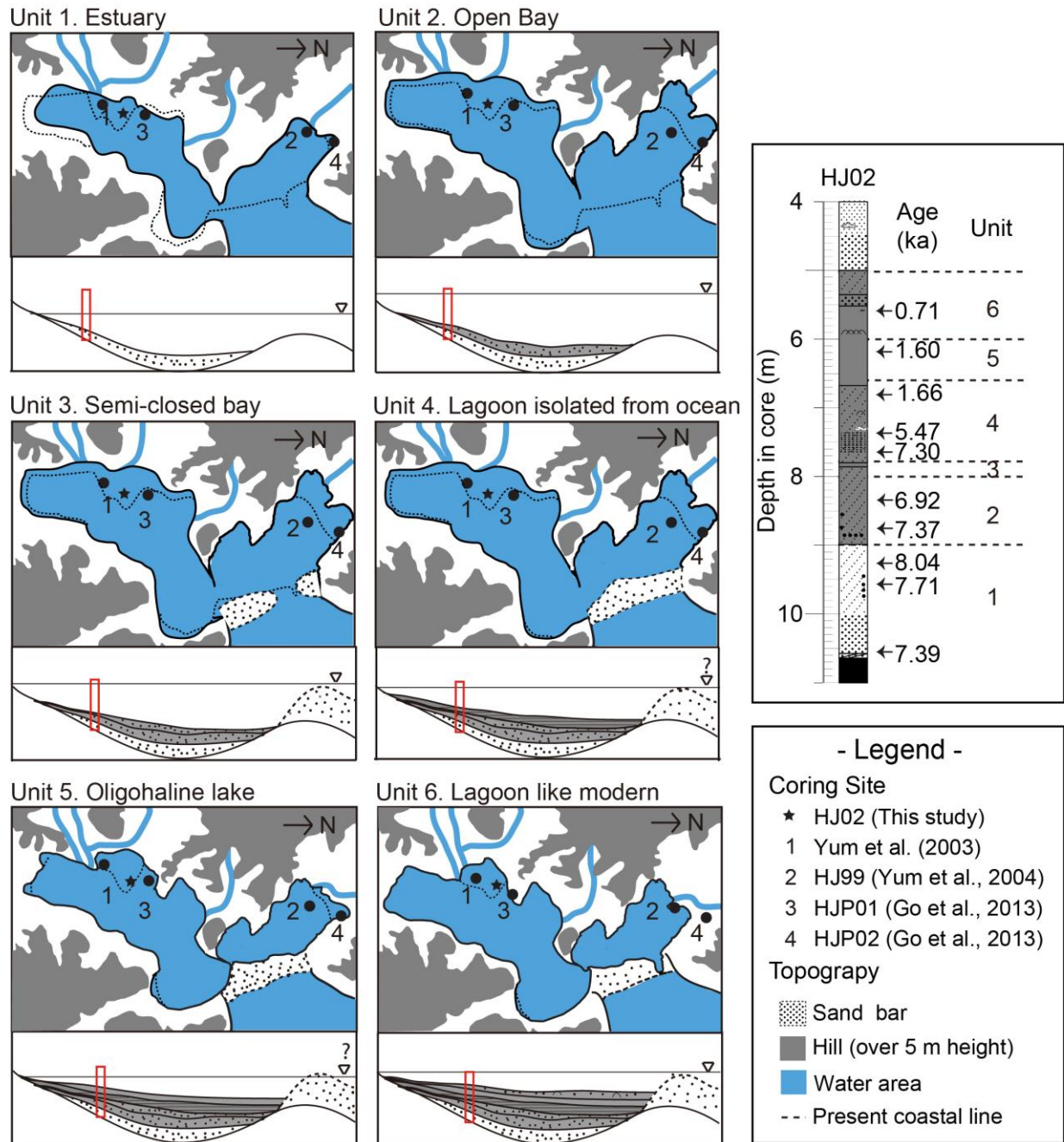


Figure 2-8. Illustrations depicting the lagoon evolution of the Hwajinpo lagoon from Unit 1 to Unit

2.5.4. Paleoenvironmental change during the late Holocene

Our diatom data showed desalination of the Hwajinpo lagoon from 1.6 ka. This agrees roughly with preceded core data, although there are some time gaps due to poor age model and halocline depth. Previous investigations suggested that the ecosystem and environment of Hwajinpo lagoon changed to a closed freshwater lake after about 1.7-1.5 ka (Yum et al 2004; Go et al. 2013). Results from core HJP02 from the outer lake by Go et al. (2013) suggest that Hwajinpo was a bog around 1.5 ka. Furthermore, results from delta core HJ99 (Fig. 2-1) by Yum et al. (2004) suggest that the lagoon changed to a freshwater lake in 1.7 ka. The diatom assemblage presented here from Core HJ02 also showed quite low salinity or fresh water condition since 1.6 ka with over 60 % freshwater to brackish taxa (Fig. 2-6). According to Go et al. (2013), the brackish to marine diatoms dominated until 1.3 ka. Timing of the ecological shift from brackish to an oligohaline lagoon based on the results from Core HJP01 are slightly different than results from Core HJ02 and other cores along the outer Lake, although Core HJP01 is only 200 m away from Core HJ02. This discrepancy might be due to differences in the paleo-depth at the core HJ02 and HJP01 core sites, because there is a halocline in the Hwajinpo lagoon and a 5-10 ppt difference in salinity at the different depths of these two core sites. However, age discrepancies between the two cores might also be associated with uncertainty in the two core's age models with the HJP01 core only having 2 age controls and derived using bulk organic matter that generally has a large error range.

Why was the Hwajinpo Lagoon changed to freshwater lake? Previous studies of the Hwajinpo lagoon addressed the issues of sea-level fall. Before 1.6 ka, the outer lake was an oxic brackish lagoon with a direct connection to the sea (Yum et al. 2004). It has been hypothesized that this was followed by the lake transitioning to a freshwater system in response to a fall in sea-level. However, the abrupt doubling of the total diatom valves in Unit 5 of core HJ02 implies that

abundant nutrients were available after 1.6 ka (Fig. 2-5). Furthermore, peaks in sand content abundant in fresh water diatom taxa indicated that these nutrients were provided by a river system (Figs. 2-5, 2-6). Previous results also suggested that terrestrial vegetation on the Korean Peninsula also shifted around 1.7 ka (Yi et al. 2008; Park et al. 2012). A minor warming period can be implied by pollen records throughout the Korean Peninsula. Evidence for this warming extends to the inner part of China including an alkenone based temperature record from Lake Qinghai (Chu et al. 2005). According to Lim et al. (2012), such vegetation changes mainly have evolved in response to increasing summer monsoon intensity. Therefore, it is reasonable to suppose that the observed freshening and high nutrient supply in Hwajinpo lagoon around 1.6 ka was the result of increased precipitation rather than sea-level change. However, observed vegetation changes on Korean Peninsula around 1.7 ka are thought to have been influenced by human disturbance rather than climate change. In fact, a rice pollen record in Lake Hyangho, located 60 km south of the Hwajinpo lagoon showed a sharp rise in charcoal content during this period (Park et al. 2012), implying that rice agriculture developed along the east coast of the Korean Peninsula at that time. Therefore, it is also possible that the development of agricultural cultivation induced the high nutrient and terrigenous sediment supply into the Hwajinpo lagoon, and it was this sediment that resulted in the isolation of the lagoon due to the expansion of the lagoon's sand barrier. Either or both climate change and human activity therefore might be responsible for the isolation of Hwajinpo lagoon around 1.6 ka.

2.6. Conclusions

Diatom analysis in core HJ02 from the Hwajinpo lagoon provides a record of the environmental changes and lagoon formation in response to relative sea-level change during the Holocene as well as climatic variations in precipitation and human induced land use change. The Hwajinpo lagoon was initially influenced by marine water under estuarine conditions around 8.0 ka. This estuarine environment then transitioned to a semi-enclosed bay by 6.0 ka due to rising sea-level and the resulting formation of a sand bar. The Hwajinpo lagoon was isolated from ocean after about 6.0 ka based on a comparison with modern data (Hw12-B). Until 5.5 ka, the coring site was a lagoon. There was a hiatus between 5.5 ka and 1.7 ka potentially due to fresh water flood events. After 1.6 ka, oligohaline conditions were established in lake due either to climatic increases in precipitation or the onset of agricultural activities in the region. Conditions similar to present were established in Hwajinpo lagoon after around 1.2 ka.

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Chapter 3. The environmental change from lagoon sediments along the Nankai Trough in Japan during the past 2000 years

3.1. Introduction

Barrier island tends to move inland when sea level rises by marine processes (e.g., Swift, 1975; Zhang et al., 2004; Masetti et al., 2008; Moore et al., 2010). Therefore, the lagoons were mostly developed as a consequence of a slowly rising sea level during Holocene (Kjerfve et al., 1994). Lagoon sediment offers critical information for sea level change because lagoon reacts sensitively with a small fluctuation of sea level (Howell et al., 1988; Morton et al., 2000; Yum et al., 2004; Cho et al., 2018). In other words, the environmental change in coastal lagoon depends on sea level fluctuation. In certain cases these relative sea level fluctuation result in salinity changes preserved as shifts in the chemical make-up of lagoonal sediment (Kato et al., 2003), which also offer additional proxies of paleoclimate change and typhoon impacts (Yum et al., 2004; Katsuki et al., 2016; Sato et al., 2016; Woodruff et al., 2009, 2015; Cho et al., 2018).

During the Holocene, relative sea level (RSL) change is influenced by eustatic factors, regional glacio-hydro isostatic adjustment, ocean dynamics, tectonic movements such as uplift or subsidence and local factors which generate complex patterns of RSL (Clark et al., 1978; Mitrovica and Milne 2002; Peltier 2004). These regional patterns of RSL change have affected the coastal environments, which are provided by stratigraphy and ecology records of Holocene RSL (Sato et al., 2001; Kato et al., 2003). The research areas are located along the Nankai Trough, which is a subduction zone. The Nankai Trough has generated large earthquakes that have resulted both in

tsunamis and coastal deformation (Garrett et al., 2016). Therefore, coastal RSL in the region has been affected by uplift and subsidence induced by earthquakes associated with the Nankai Trough (e.g. Baranes et al., 2016 and Baranes et al., 2018).

Twelve earthquakes, which were recorded in historical documents, have been generated from the Nankai Trough during the common era. These earthquakes deformed coastal areas such as ground uplift or subsidence, depending on the segment (Garrett et al., 2016). One of the recent Hoei earthquakes in AD 1707 generated subsidence approximately 1-2 m from Kyushu to central Honshu island (Furumura et al., 2011; Baranes et al., 2018). Even though the RSL has fallen less than 1 m during the last 2000 years from south Kyushu island to Tokyo, which is located in the Pacific side of Japan (Yokoyama et al., 1996; Okuno et al., 2014), the vegetation in coastal area has changed as a consequence of coastal deformation induced by earthquakes (Fujiwara et al., 2016). In Ukishimagahara lowland, which is located at the northeast end of the Nankai Trough, the vegetation was sharply transferred because the water level was altered by subsidence and uplift by earthquakes (Fujiwara et al., 2016). Therefore, environmental changes such as the transition of vegetation and ecology in the coastal area are directly influenced by earthquakes associated with coastal deformation.

Here we provide reconstructions of paleoenvironmental change over the past 2000 yrs using a network of lagoonal sites both directly facing the Nankai Trough (Lake Hamana, Ryuuoo) and away from the trough (Lake Kawahara) and focused on assessing impacts associated with tectonically induced uplift and subsidence for the region. Our objective is to reconstruction resultant paleoenvironmental changes within our lagoonal sites associated with primary earthquakes recorded within the historical record and as evident as sedimentological shifts in diatom assemblages observed at each site.

3.2. Study sites

3.2.1. Nankai Trough

The Nankai Trough extends from southern Kyushu to western Honshu island, and is comprised of the subduction zone of the Philippine Sea Plate below the Eurasian Plate at an approximate convergence rate of 5 cm year^{-1} (Fig. 3-1) (Seno et al., 1993). The Nankai Trough is located just off shore of a densely populated and industrialized coasts along the Pacific side of Japan. The strain has accumulated because the plate interface is strongly coupled historically resulting in earthquake's that have potentially reached as high as 9 in magnitude (Sagiya, 1999; Ozawa et al., 1999; Mazzotti et al., 2000; Aoki and Scholz 2003; Baranes et al., 2018). Many of these earthquakes have been tsunamigenic, with a rough return period of every 100 to 200 years (Ishibashi, 1999). Along the Nankai Trough, the ruptured segments are divided (Ando, 1975; Ishibashi, 2004). Earthquakes and tsunamis have been recorded by historical documents since the 7th century, AD 684 (Ando 1975; Ishibashi, 1999, 2004). Twelve subsequent earthquakes are generally accepted, as those earthquakes were generated from the Nankai Trough with magnitudes of greater than eight as a part of the plate boundary rupturing in AD 684, 887, 1096, 1361, 1498, 1605, 1707, 1854 (twice), 1944 and 1946.

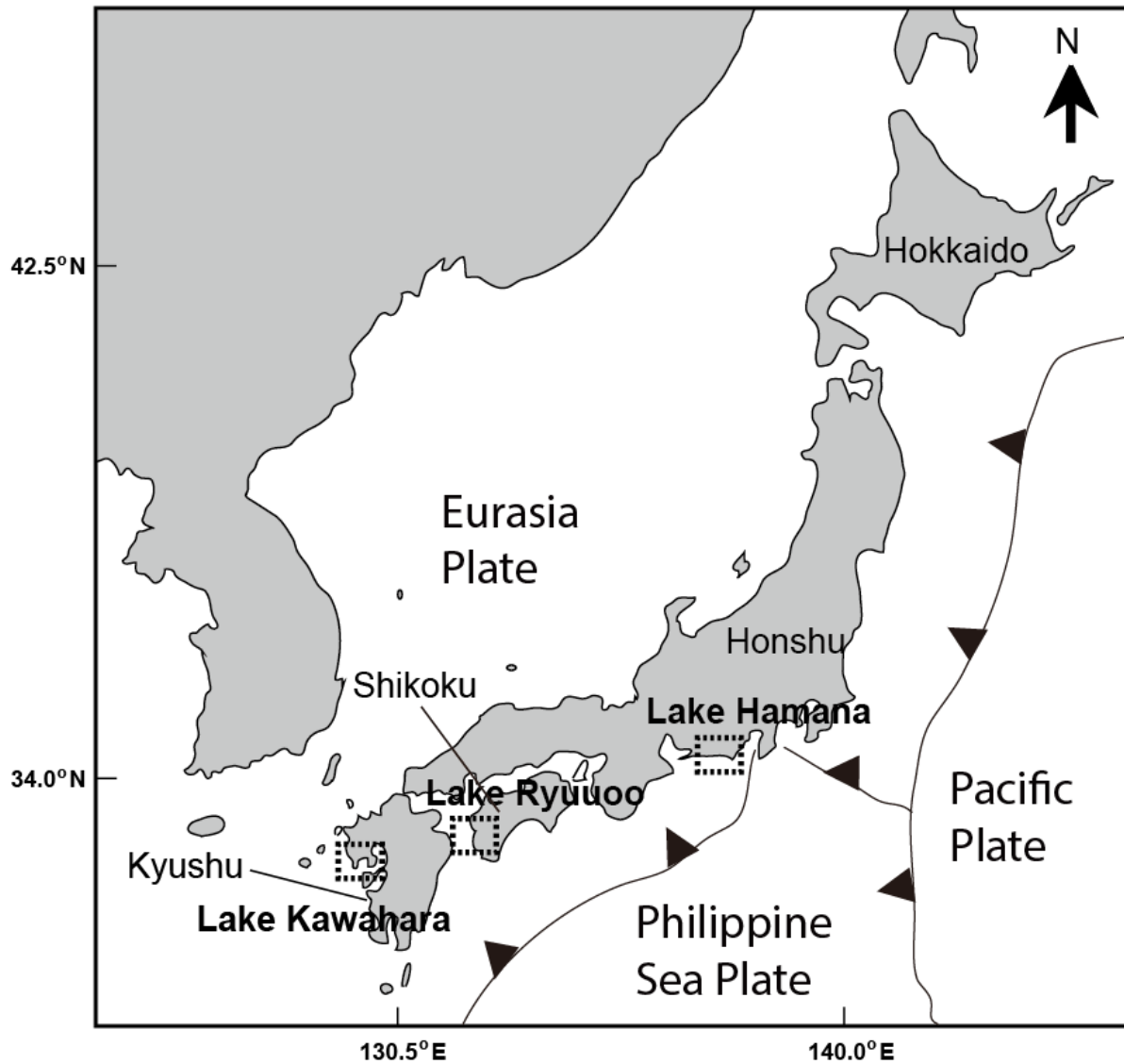


Figure 3-1. Map of Japan and study site location. The square boxes are a research area.

3.2.2. Lake Hamana

Lake Hamana lies on the southward-facing Enshu-nada coast in Shizuoka Prefecture (Fig. 3-1 and 3-2). The lake is presently connected to the Pacific Ocean by way of Imakari Inlet and currently results in brackish condition at the site (Fig. 3-2). The area of Lake Hamana is 65 km², and has an average water depth of 4.8 m (Fig. 3-2). Water depths in the lake increase towards the northern part where they reach between 10-12 m, compared to generally shallower bathymetry in the southern section of the lake where depths are between 2-3 m (Sato et al., 2016). Lake Hamana is seasonally stratified in the summer and more well mixed in the winter season (Mazda, 1999). The regional tidal range for the tide gauge closest to the site in Maisaka in Shizuoka Prefecture is roughly 1.4 m (Japan Meteorological Agency, 2018).

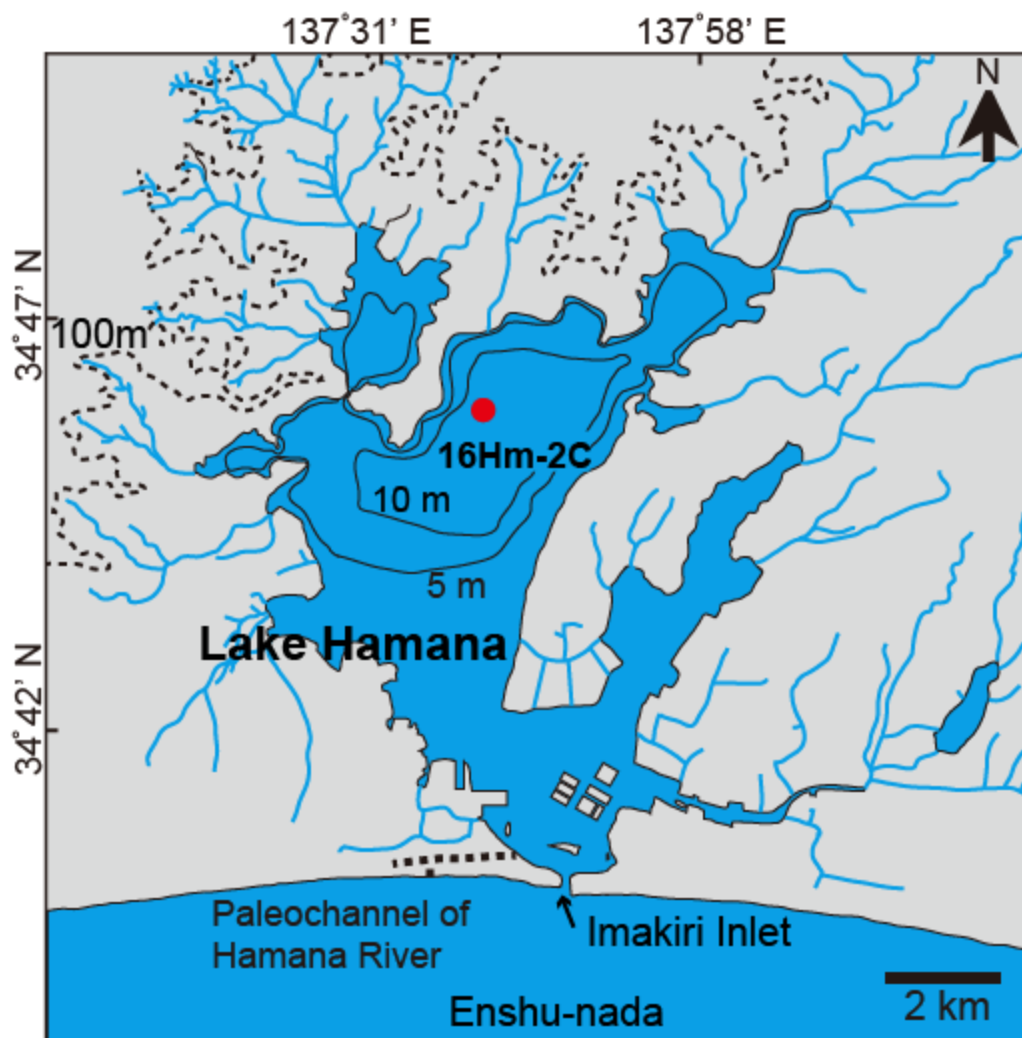


Figure 3-2. Core site (16Hm-1C and 16Hm-2C) in the Lake Hamana.

3.2.3. Lake Ryuuoo

Lake Ryuuoo lies on a small island on the off the northeast Pacific facing shore of the Bungo Channel which separates the mainland islands of Shikoku and Kyushu (Figs. 3-1 and 3-3). Lake Ryuuoo is a drowned value separated from the sea by a cobble and sandy barrier beach. The ~200 m barrier beach is 3-4 meters high relative to mean sea level and ~40 m wide. Lake Ryuuoo is relatively shallow reaching a maximum of 2 m depth in its central part (Fig. 3-3). The regional tidal range is approximately 2.3 m with an average high tide is 105 cm, and low tide of -126.4 cm at the nearest tide gauge at Uwajima in Shikoku Island (Japan Meteorological Agency, 2018).

Estimates for background rates of sea level rise over the last 6000 years range from 9.7 mm/yr to 0.2 mm/yr with the highest rates in the earliest part of this record when rates of glacio-isostatic rebound was at its greatest (Nakada et al., 1991). However, land-elevation can be easily changed with the rapid rate from subsidence associated with Nankai Trough earthquakes at the coring site (Baranes et al., 2016 and 2018).

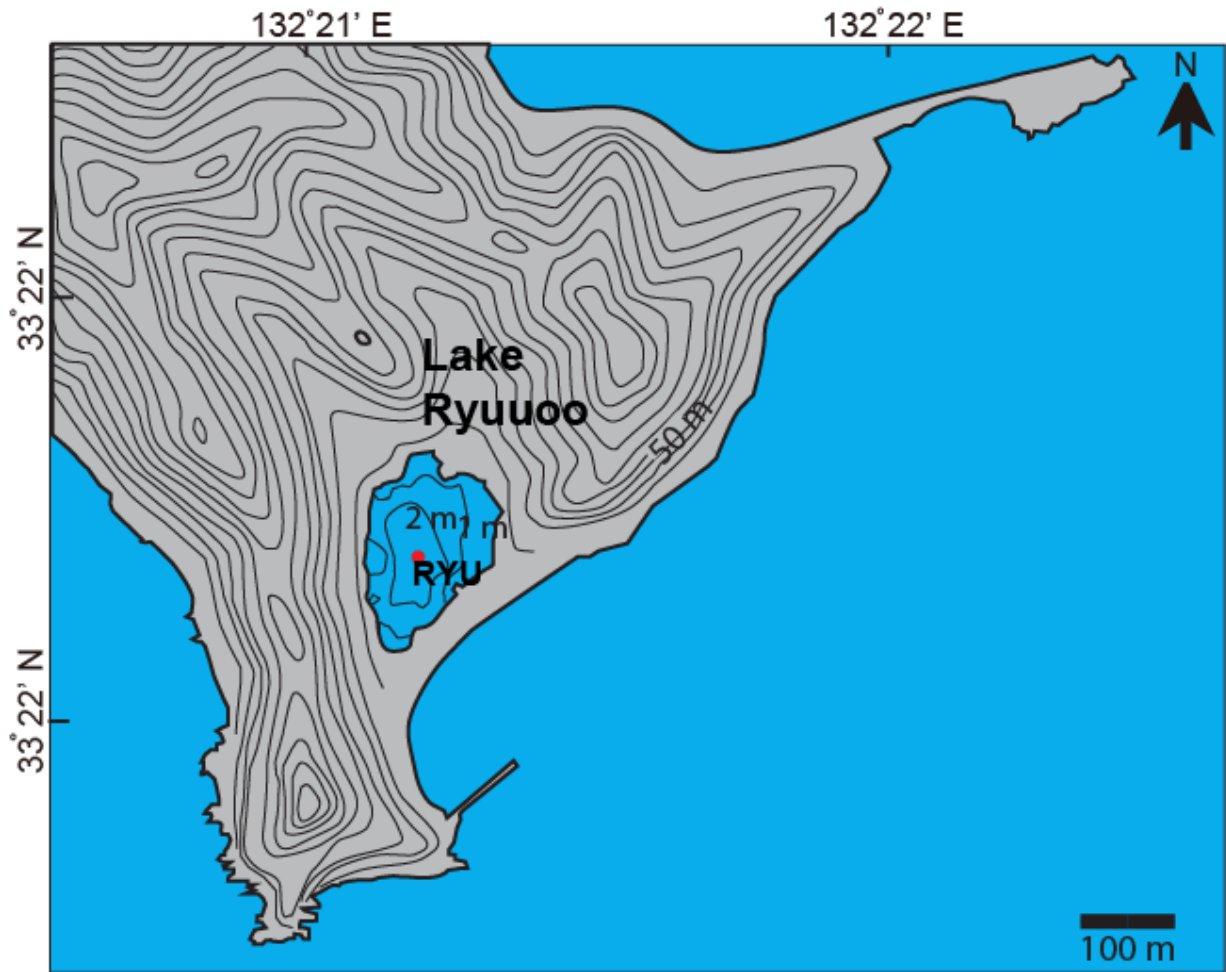


Figure 3-3. Core site (RYU) at Lake Ryuuoo

3.2.4. Lake Kawahara

Lake Kawahara is located on Nagasaki Peninsula located along the southwester coast of Japan. The small lake has an area of 0.127 km² and a maximum depth of 9 m (Figs. 3-4) (Azuma, 1992; Hossain et al., 2013). A 250 m long barrier beach separates Lake Kawahara from the sea and consists of coarse to fine sand with gravel, with a approximate height of 3 m and a with of 130 m. The regional tidal range is roughly 3.0 m, with an average high tide elevation of 137.3 cm, and a low tide elevation of -162.6 cm for the nearest tidal gauge at Fukue on the Nagasaki Peninsula in 2017 (Japan Meteorological Agency, 2018). A small tributary with a watershed of 1.74 km² drained into the southwestern back side of the lake. At present the lake is fresh with eutrophic conditions and a prominent seasonal thermocline that developes between February and October (Furumoto et al., 1999). However, Lake Kawahara was historically been brackish before a sluice gate was constructed across an ocean inlet through the barrier and salt water was pumped out from the lake in 1979 (Azuma, 1992; Hossain et al., 2013).

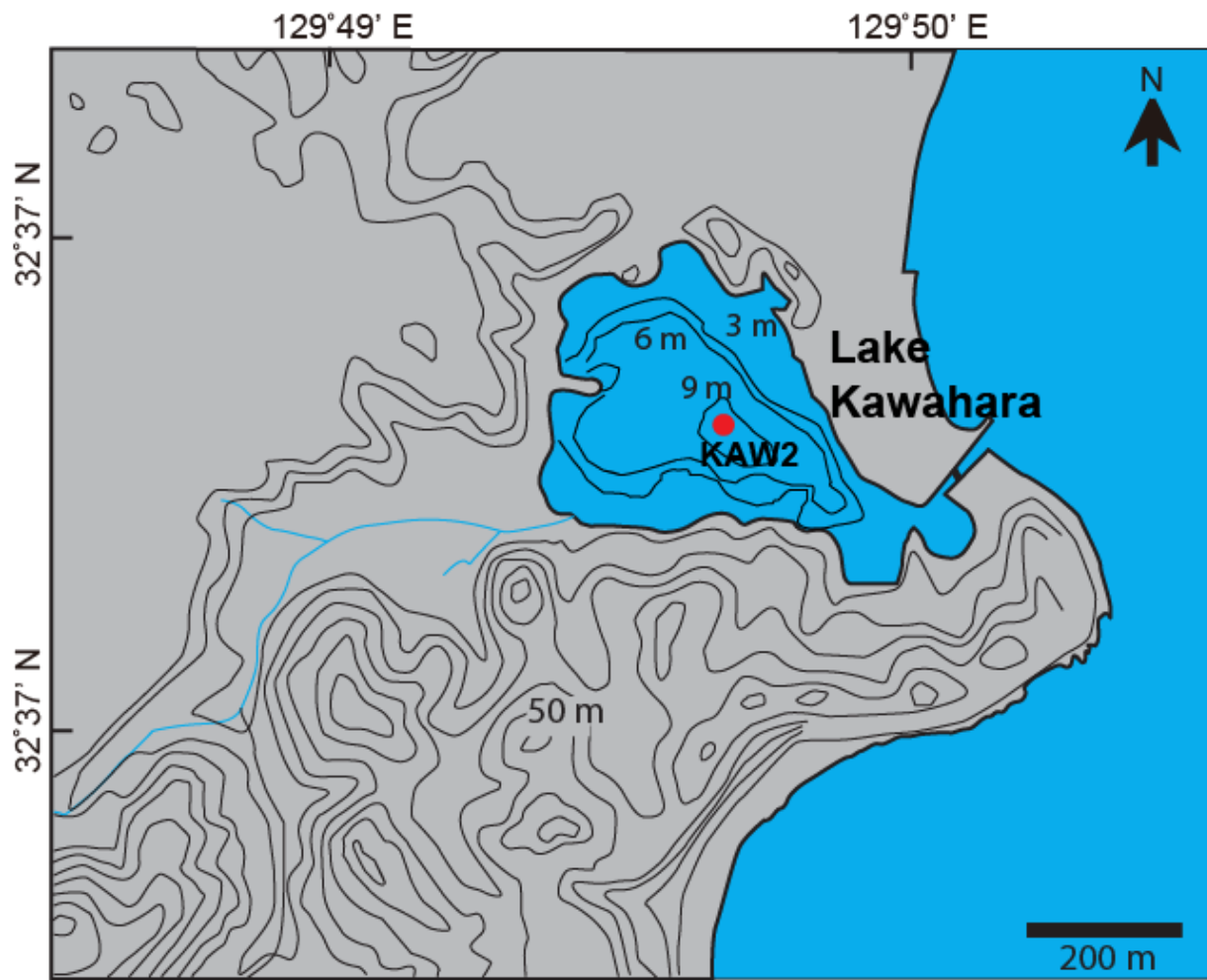


Figure 3-4. Core site (KAW2) at Lake Kawahara

3.3. Material and methods

Cores 16Hm-1C and duplicate core 16 Hm-2C were taken from the north part of Lake Hamana by a pneumatic piston corer. Both the KAW and RYU cores were collected by Vohnout-Colinvaux piston corer (Woodruff et al., 2009, 2015). A detailed description of collection methods and initial core analyse for the Lake Kawahara KAW2 is provided by Ladlow et al. (in review) and for the RYU cores from Lake Ryuuoo by Baranes et al., (2016) and Baranes et al. (2018).

One shell, one possible seagrass, and five plants from 16Hm-1C and 16 Hm-2C, five small organic macros from KAW2, and six organic macrofossils from RYU were analyzed to obtain ^{14}C derived ages by accelerator mass spectrometry (AMS) (Linick et al., 1989). The ^{14}C ages were calculated and converted to calendar dates using IntCal13 (Reimer et al., 2013) and CALIB 7.1 (Stuiver and Reimer, 1993).

For the KAW2 and RYU cores the onset and subsequent peak of ^{137}Cs were identified by a Canberra GL2020R low-energy germanium detector to mark the C.E 1954 beginning and C.E 1963 peak in atmospheric nuclear testing, respectively (Pennington et al., 1973). Radio-carbon and Cs-137 derived ages were combined to derive Bayesian depth to age models for KAW2 and RYU cores by the Bchronology function in the Bchron R package (Haslett and Parnell 2008; Parnell et al., 2008; Baranes et al., 2016; Ladlow et al., in review).

3.3.1. Diatom analysis

Diatom assemblage were analyzed in 190 samples from Hm16-1C and Hm16-2C cores at a sampling resolution of every 1 cm from 25 to 108 cm, every 2 cm from 108 to 188 cm depth, every 4 cm from 188 to 300 cm depth, and every 2 cm from 300 to 376 cm depth (with the except

of a lost sample at 374 cm). The assemblage from KAW2 core was analyzed in 102 samples from 5 to 525 cm depth at a sampling interval of every 5 cm. The assemblage from RYU core was analyzed in 20 samples every 10 cm from 0 to 200 cm depth, in 80 samples from 200 to 600 cm depth every 5 cm, in 10 samples from 600 to 700 cm depth, and in 37 samples from 700 to 900 cm depth. To analyze diatom, 0.01 to 0.05 g of dry sediments were initially placed into a 200 ml beaker with 10 ml of 15% H₂O₂ to remove organic matter. The solution was boiled for one hour, and then each beaker was filled and diluted with distilled water. After settling, water in each beaker was decanted, and remaining sediment diluted again with distilled water three times. Following the final deantation, the remaining bottom sediment solution was pipetted onto a coverslip, dried and mounted by Pleurax or Hyrax. Over 300 diatom valves were counted in each sample at 1000x magnification under a light microscope.

3.4. Results

3.4.1. Lake Hamana

16Hm-1C is 385 cm long core and contains bioturbided clays at its base along with smaller laminated clay units and flood layers (Fig. 3-5). The core begins with bioturbided clays from 385 to 370 cm depth, followed by a laminated layer from 370 to 288 cm depth interbedded with bioturbided clays from 329 to 322 cm depth and from 312 to 298 cm depth. Another large bioturbided clay layer exists between 298 cm to 107 cm depth that is interbedded with a laminated layer between 279 and 272 cm depth.

Twelve taxa were account for more than 90% of the total in Hm16-1C and 2C cores (Fig.3-6). The most prevalant taxa at over 10% are *Achnantheidium minutissimum*, *Aulacoseira ambigua*, *Aulacoseira granulata*, *Fragilaria capucian*, *Pseudostaurosira brevisitriata*, *Pseudostaurosira*

spp., *Ulnaria delicatissima*, *Cyclotella atomus*, *Cyclotella atomus* var. *gracilis*, *Cyclotella* spp., *Thalassiosira lineata*. *Diploneis smith* account for lower than 10%. *Pseudostaurusira brsvistriata*, *Pseudostaurusira* spp., *C. atomus*, *C. atomus* var. *gracilis* and *Cyclotella* spp. appeared under 300 cm depth. *Achnanthes minutissimum*, *A. ambigua*, *A. granulata*, *P. brevisistriata*, *Pseudostaurusira* spp., *U. delicatissima* and *Cyclotella* spp. appeared from 300 to 225 cm depth. However, *A. ambigua* appeared above 270 cm depth. The main taxa between 225 and 160 cm depth are *A. ambigua*, *A. granulata*, *F. capunica* and *U. delicatissima*. From 160 to 110 cm depth, *A. granulata*, *P. brevisistriata* and *Pseudostaurusira* spp. occurred. *A. ambigua* suddenly increased from 125 to 100 cm depth. After 110 cm depth, taxa were mainly comprised of *C. atomus*, *C. atomus* var. *gracilis*, *Cyclotella* spp., *D. smithii* and *T. lineata*.

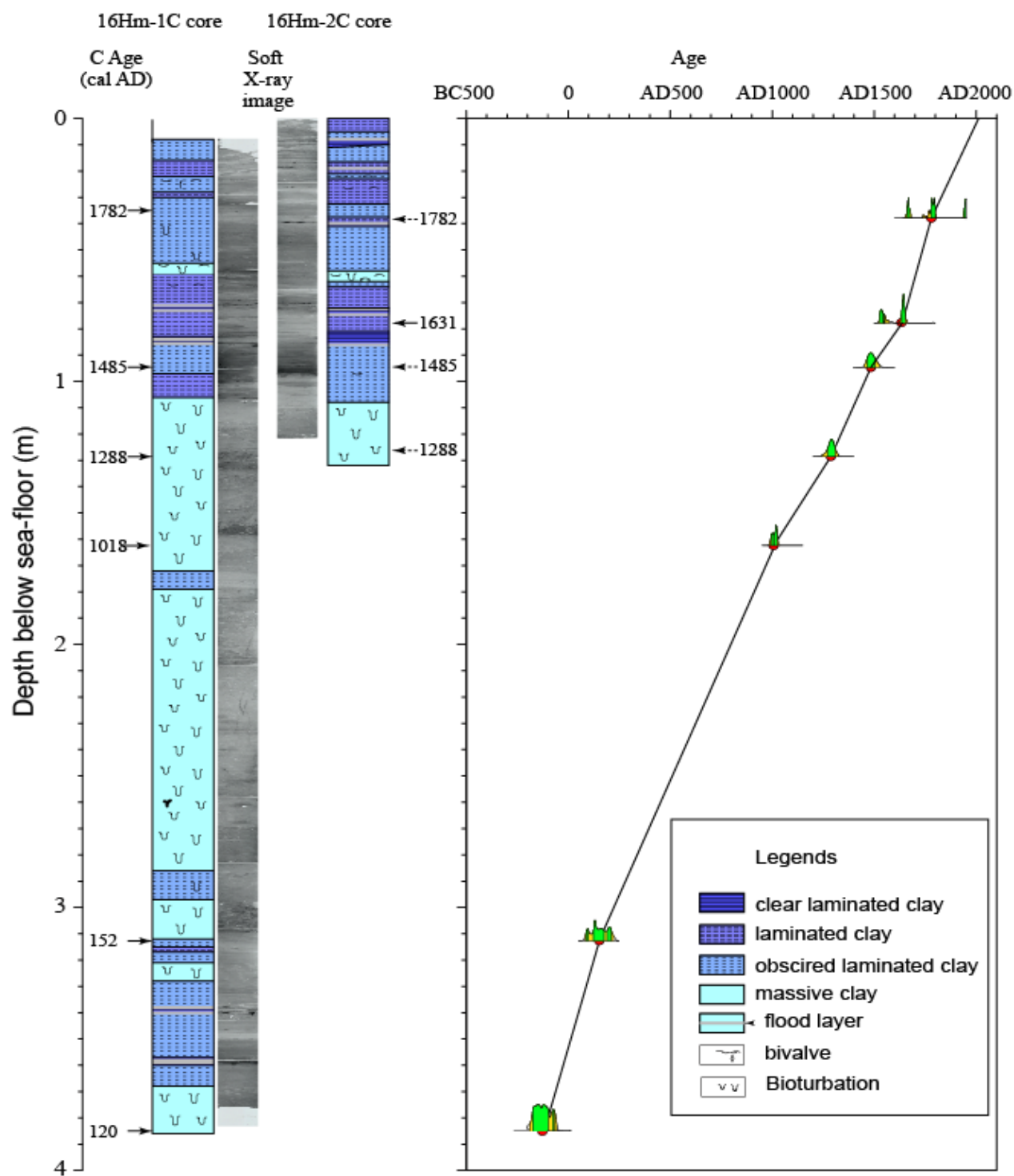


Figure 3-5. Lithology description and age-depth plot for cores 16Hm-1C and 16Hm-2C.

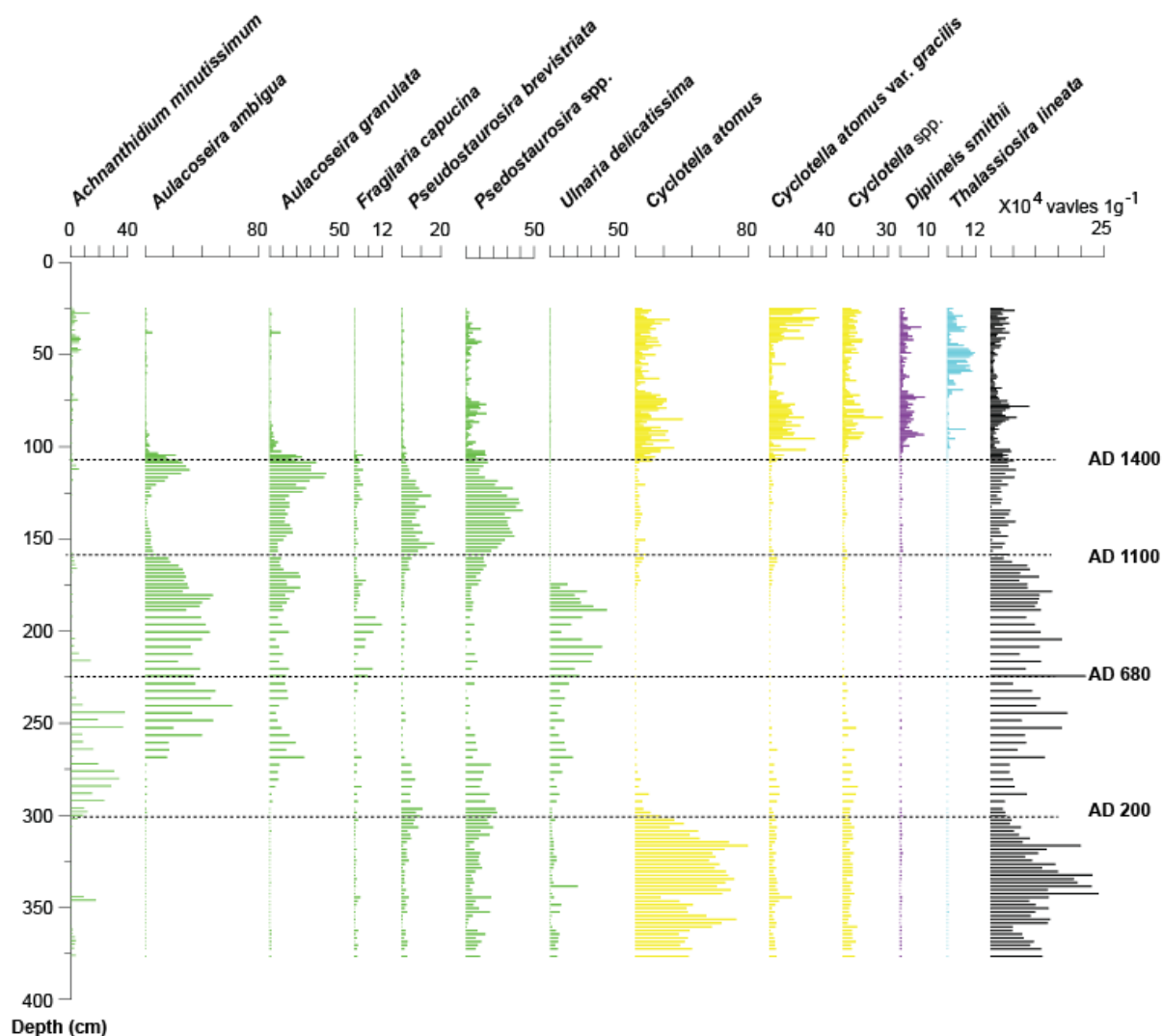


Figure 3-6. Depth distribution of the fossil diatom relative abundance by taxa from cores 16Hm-1C and 16Hm-2C. Green is a freshwater species. Yellow is freshwater to brackish species. Violet is brackish to marine species. Blue is a marine species.

3.4.2. Lake Ryuuoo

The sediments are composed of an organic-rich clay with the laminated layers from 934 to 595 cm depth, and a sand layer inserted around 701 cm depth. From 600 cm depth, the core lithology abruptly changes to from laminated clays to gyttja and is interbedded with sand and clay layers. In total nine coarse sand layers were observed between 595 to 100 cm (Fig. 3-7).

In the RYU core, ten diatom taxa account for over 90% of the assemblages (Fig. 3-8). The taxa reaching more than 10% relative abundance were *Aulacoseira granulata*, *Hantzschia amphioxys*, *Humidophila contenta*, *Navicula radiosa*, *Pseudostauriosira* spp., *Ulnaria ulna*, *Cyclotella meneghiniana*, *Cylotella* spp., and *Cylotella caspia*. *Gomphonema* spp appeared less than 10% from RYU core. *Psudostaurosira* spp., *U. ulna*, *C. meneghiniana* and *C. caspia* occurred from 900 to 700 cm depth. *Cyclotella caspia* suddenly disappeared from 700 cm depth and reached its peak at 140 cm depth. *Gomphonema* spp., *H. amphoxys*, *H. contenta*, *N. radiosa*, *Pseudostaurosira* spp., *U. ulna*, *C. meneghiniana*, *Cyclotella* spp. were dominant between 600 and 200 cm depth. *Aulacoseira granulata*, *Pseudostaurosira* spp., *C. meneghiniana* and *Cyclotella* spp. appeared from 2.00 m depth on top of the RYU core.

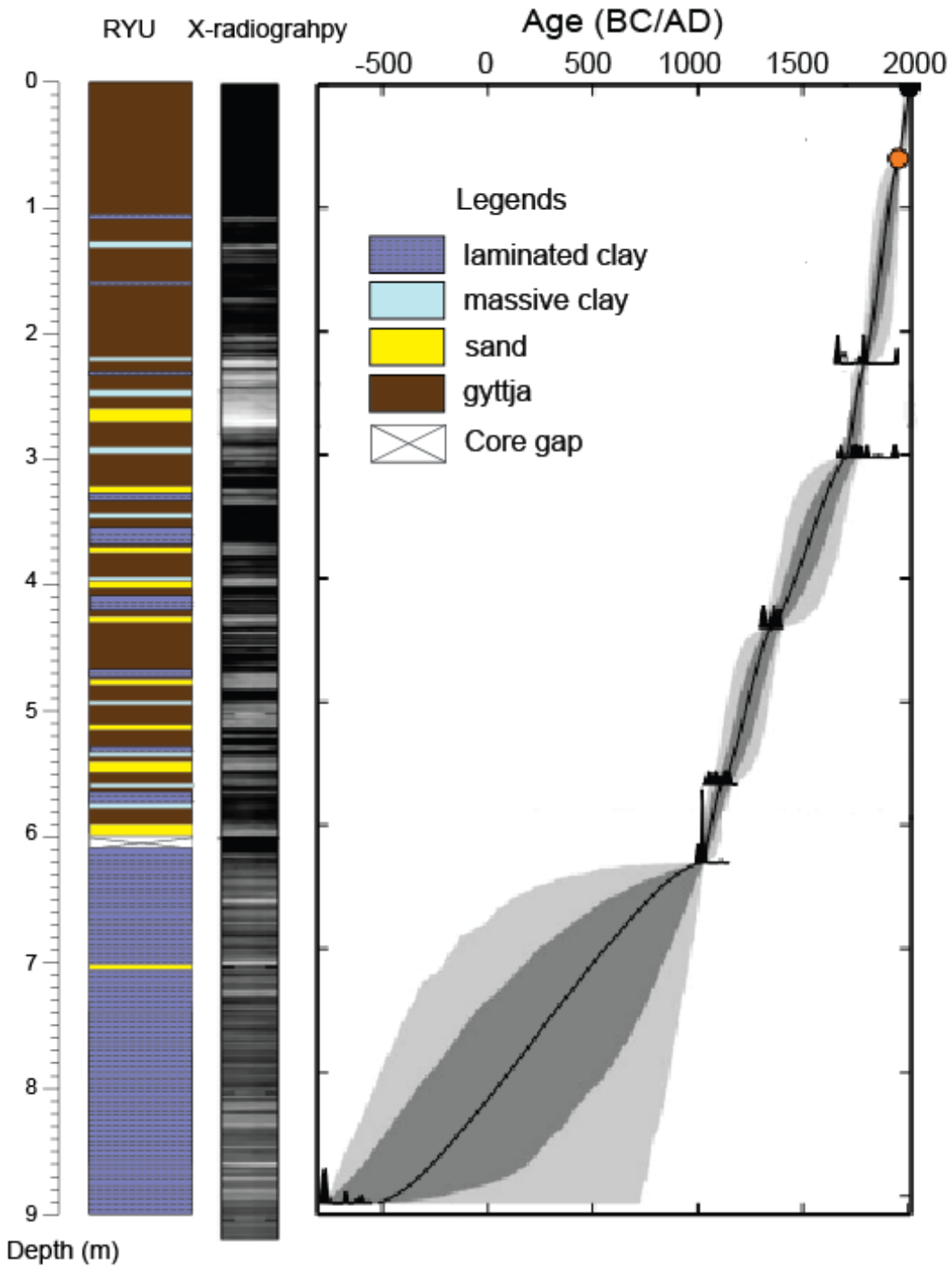


Figure 3-7. Lithology and age model for core RYU modified from Baranes et al., 2016. Bayesian-derived age, and 68 and 95 % high-density regions of the posterior age distributions (light and dark gray shaded regions, respectively).

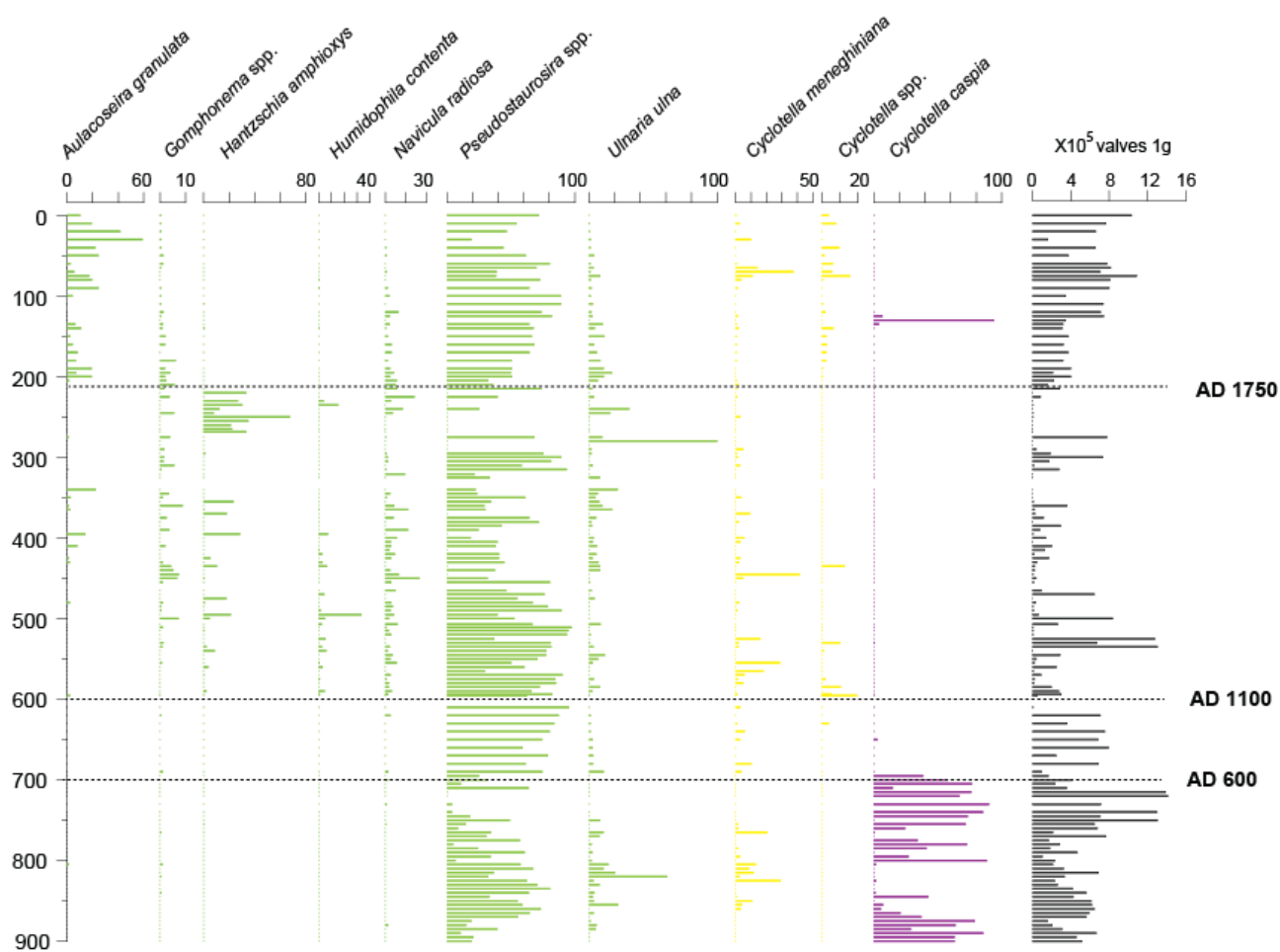


Figure 3-8. Depth distribution of the fossil diatom relative abundance by taxa from core RYU. Green is a freshwater species. Yellow is freshwater to brackish species. Violet is brackish to marine species.

3.4.3. Lake Kawahara

KAW2 is a 540 cm long core and composed of fine mud and laminated layer (Fig. 3-9). An initial unit of brown-grey mud is found between 540 and 285 cm depth inserted with light grey clay layers from 440 to 430 cm depth, a laminated layer from 435 to 425 cm depth and black-grey mud from 425 to 385 cm depth. Another larger laminated unit exists between 285 to 155 cm, with a light grey clay inserted between 214 and 211 cm depth. Above this a black-grey mud unit is found between 155 to 60 cm, followed by a another laminated unit between 60 to 30 cm depth. The top 30 cm of the core consist of black gyttja.

Fifteen taxa accounted for more than 90% of the total in KAW2 core (Fig. 3-10). *Pseudostaurosira* taxa appeared over whole KAW2 core. *Cyclotella atomus*, *C. atomus* var *gracilis*, *Diploneis smithii*, *Palaria sulcata*, *Thalassionema nitzschioides* and *Thalassiosira lineata* occurred between 525 and 250 cm depth. *Pseudostaurosira* spp. increased and *Cyclotella* spp. decreased above 330 cm depth. From 250 m to 130 cm depth, *Fragilaria tenera*, *P. brevisiriata*, *Pseudostaurosira* spp, *Staurosirella lapponica* were mainly composed. *Achnanthyidum minutissimum*, *Aulacoseira ambigua*, *Aulacoseira granulata*, *Discostella stelligera*, and *Pseudostaurosira* spp. appeared from 130 to 0 m of the KAW2 core.

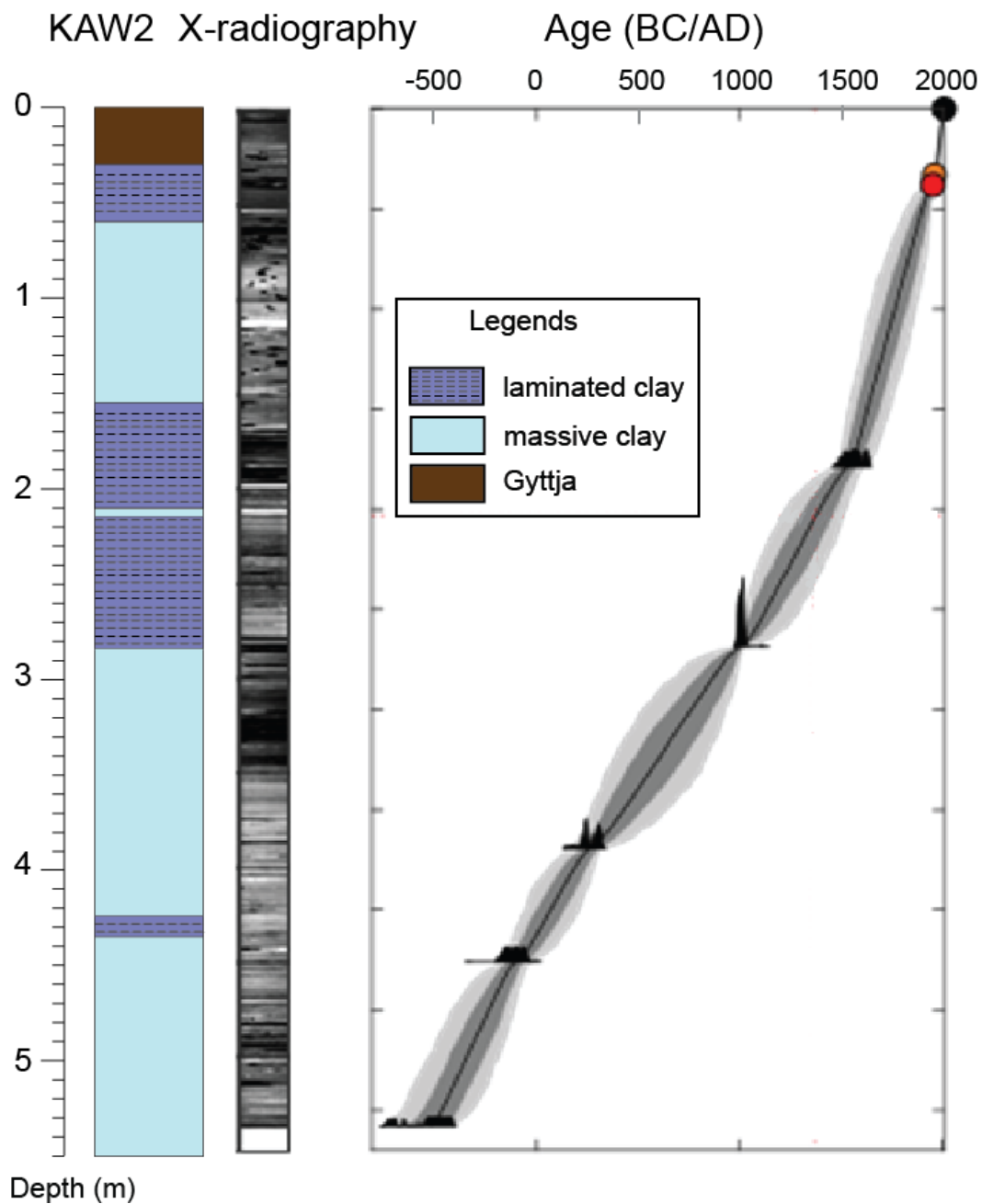


Figure 3-9. Lithology and age model for core KAW2 modified from Ladlow et al., in review. Bayesian-derived age, and 68 and 95 % high-density regions of the posterior age distributions provided (light and dark gray shaded regions, respectively).

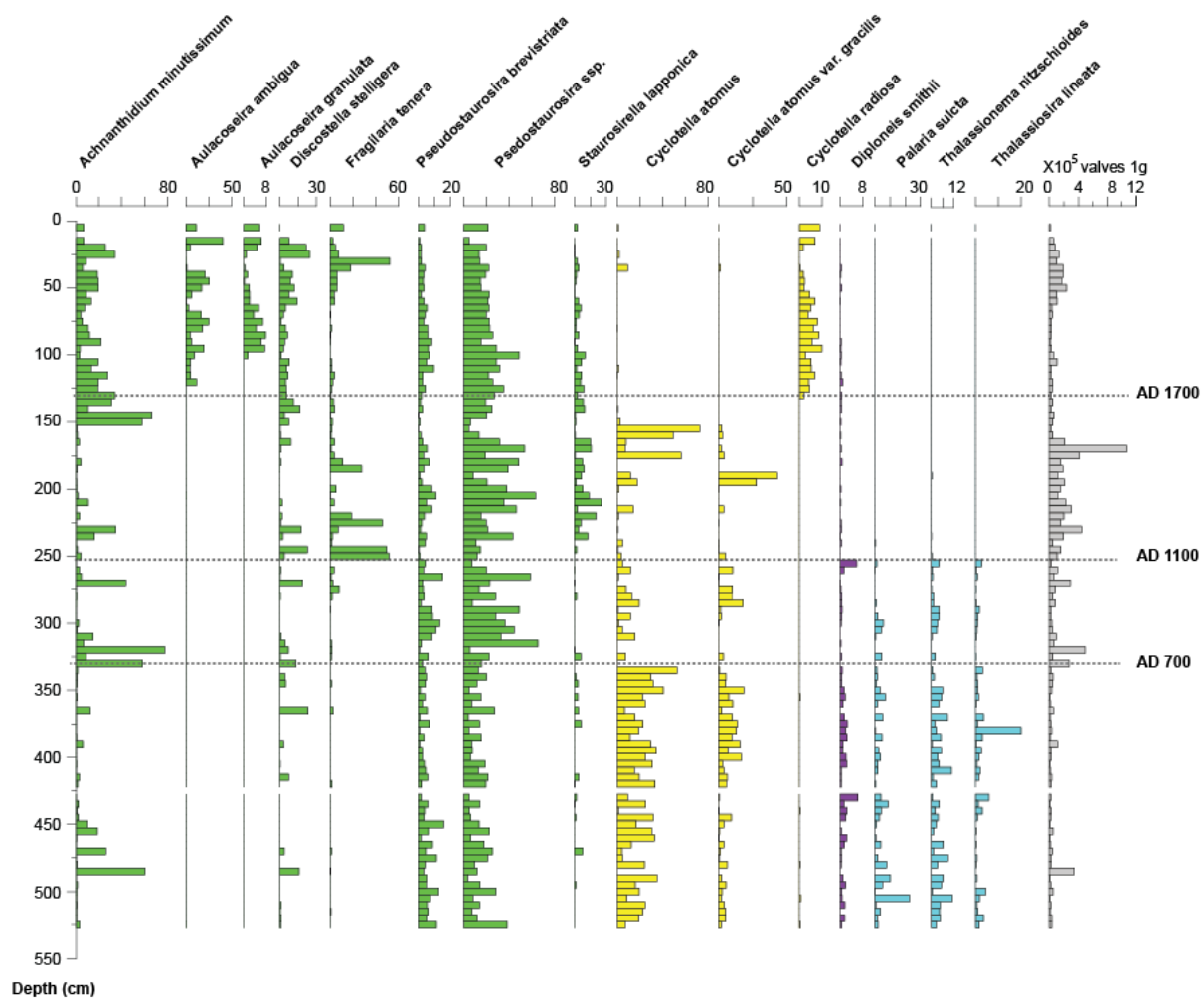


Figure 3-10. Depth distribution of the fossil diatom relative abundance by taxa from core KAW2. Green is a freshwater species. Yellow is freshwater to brackish species. Violet is brackish to marine species. Blue is a marine species.

3.5. Discussion

The paleoenvironmental change was interpreted from diatom assemblage in Lakes Hamana, Ryuuoo, and Kawahara. The lake environment in each age was divided based on ecology by diatom assemblage and chronology.

3.5.1. Lake Hamana

The environment of Lake Hamana abruptly changed from a freshwater lake to a brackish lagoon in the early 15th century likely due to the sudden direct connection to the Pacific via the paleo-channel shown in Fig. 3-2, and potentially as consequences a consequence of the Nankai Trough derived Meio earthquake in AD 1498 (Cho et al., 2019; Fujiwara et al., 2013). Before the early 15th century, Lake Hamana had less of a direct connection to the Pacific Ocean because the sand barrier beach was more developed and continuous, thus restricting the inflow of seawater. This is evident by the disappearance of the marine taxa prior to approximately AD 1400 (Fig. 3-6). According to the diatom assemblage in 16Hm-1C and 2C cores, the environment of Lake Hamana could be separated into 5 zones during the last two millenniums. Zone 1 is between 368 and 300 cm depth of 16Hm-1Cm (Fig. 3-5). This zone is mostly composed of laminated layer inserted massive clay 368 to 370 cm and 312 to 300 cm depth (Fig. 3-5). Zone 1 was dominant with *Cyclotella* taxa, which is planktonic diatom such as *C. atomus*, *C. atomus* var. *gracilis* and *Cyclotella* spp.. *Cyclotella atomus* inhabit fresh to brackish water (Fig. 3-6) (Joh, 2010). *Cyclotella atomus* var. *gracilis* prefer hypersaline conditions (Genkal and Kiss, 1993). *Cyclotella* spp. is assumed by either *C. atomus* or *C. atomus* var. *gracilis* because those species were usually observed from girdle view under the light microscope. Therefore, Zone 1 is interpreted to reflect a deep hypersaline lagoon. In Zone 2 from 300 to 225 cm depth, freshwater species as *A.*

minutissimum, *A. ambigua*, *A. granulata*, *P. brevisrisata*, and *Pseudostaurosira* spp. were dominant, and are accompanied by a change in lithology from laminated to bioturbation sediments (Figs 3-5 and 3-6). *Achnantheidium minutissimum* is reported as a benthic freshwater species and has been found at 5-20 m water depths of the water with limited sunlight (Joh, 2012). *Aulacoseira ambigua* and *A. granulata* prefer vertical water circulation because they are tychoplanktonic diatom (Petrova 1986; Joh, 2010). Therefore, bioturbation likely developed well due to increased water circulation and a resulting increase in oxygenic bottom water conditions. Besides, *Cylotella* taxa suddenly decreased but, still occurred shortly after AD 200 (Fig. 3-6). The water condition of this lake changed to an oligohaline condition in Zone 1. In Zone 3 from 225 to 160 cm depth, only freshwater species of *A. ambigua*, *A. granulata*, *F. capucian*, and *U. delicatissima* were evident (Fig. 3-6). *Fragilaria capunina* is epiphytic freshwater species (Winter and Duthie 2000; Joh et al., 2010). *Ulnaria delicatissima* is a planktonic freshwater species (Fukumoto et al., 2015). In addition, *Cylotella* taxa disappeared from Zone 3 (Fig. 6). Therefore, the environment of Zone 3 is interpreted as a freshwater lake. In Zone 4 from 160 to 110 cm depth, after AD 1100, *P. brevisstriata* and *Pseudostaurosira* spp., which are benthic freshwater species, were dominant (Fig. 3-6) (Joh et al., 2010). *Pseudostaurosira* spp. is assumed by *Pseudostaurosira brevisstriata* or *P. brevisstriata* var. *minor* because it was generally observed by girdle view under the light microscope. The increase in benthic freshwater species in Zone 4 suggests a decrease in lake level. Prior work by Fujiwara et al. (2013) indicates that at approximately AD 1400, a paleo-river existed that connected Lake Hamana directly to the ocean (Fujiwara et al., 2013). It is interpreted that the Meio earthquake in AD 1498 redirected a paleo-river at the site and resulted in an inlet forming a direct connection between the ocean and Lake Hamana (Fujiwara et al., 2013). This interpretation is supported by the transition from freshwater to brackish and brackish-marine

and marine species at approximately AD 1400 (Fig. 3-6). Furthermore, a laminated layer is evident in zone 5 likely reflecting similar brackish conditions as the laminated sediments in Zone 1 (Fig. 3-5), and suggests that laminated sediments in the lake are formed during vertically stratified conditions induced due to changes in salinity and temperature in surface and bottom waters.

3.5.2. Lake Ryuuoo

Pseudostaurosira spp. and *Cyclotella meneghiniana*, which are freshwater and freshwater to brackish water taxa respectively, appeared in the whole core of RYU (Fig. 3-8). This core was divided into four zones by diatom assemblage. Zone 1, between 900 and 700 cm depth, was dominated by *Pseudostaurosira* spp. and *C. caspia* (Fig. 3-8). *Cyclotella caspia* is a planktonic brackish to marine species (Hustedt, 1930; Katsuki et al., 2008). Zone 1 before AD 600 was brackish lagoon based on dominant diatom taxa (Fig. 3-8). The critical change of diatom assemblage happened at 700 cm depth because *C. caspia* abruptly disappeared and *Pseudostaurosira* spp., and *C. meneghiniana* dominated (Fig. 3-8). According to diatom assemblage, Zone 2 is interpreted as a freshwater lake. However, there was no change in lithology between Zone 1 and Zone 2. Zone 2 was deposited with a laminated layer, and this suggests water stratification existed. In the present, Lake Ryuuoo has a maximum of 2 m of water depth. That is not enough water depth to develop the water stratification in the lake. This might imply that the lake in Zone 1 and 2 was deeper than present and sufficient for the development of salinity and temperature induced vertical stratification. Above 6 m the RYU lithology suddenly changed to gyttja interbedded with several sand and clay layers. Even though the dominant taxa in Zone 3 are similar to Zone 2 including an abundance of *Pseudostaurosira* spp., Zone 3 also contained benthic taxa of *Navicula radiosa*, *Humidophila contenta*, *Hantzschia amphioxys* and *Gomphonema* spp.

(Fig. 3-8). *Navicula radiosa* usually inhabit lakes as an epipelagic species (Round, 1964). *Humidophlia contenta* is a freshwater periphytic species (Douglas and Smol, 1995), and *Hantzschia amphioxys* is a soil and terrestrial diatom (Bradbury et al., 2004). *Gomphonema* taxa are normally freshwater haptobenthos (Round et al., 1990). *Gomphonema* spp. was observed in girdle view, however, it was interpreted as *Gomphonema angustum*, *Gomphonema clevei* and *Gomphonema truncatum* under a light microscope. The gyttja lithology in Zone 3 is common to a eutrophic lake (Fig. 3-7) (Hansen, 1959). Water depths during the deposition of Zone 3 are interpreted to be shallower than present because only benthic species were present in this zone. Zone 4 from 200 to 0 cm was deposited following approximately AD 1750. *A. granulata* suddenly appeared in these surface sediments (Fig. 3-8). Tychoplanktonic species such as *A. granulata* increase in Zone 4 while benthic taxa generally decrease (Fig. 3-8) (Joh, 2010). Water depths are therefore interpreted to have increased in Zone 4 and reflect a transition from a shallow water pond in Zone 3 to a deeper freshwater lake in Zone 4 due to an increase in lake level.

3.5.3. Lake Kawahara

Pseudosaturiosira brevistriata and *Pseudosaturiosira* spp. appeared in whole KAW2 core (Fig. 8). This core is also divided into 4 zones by diatom assemblage. Zone 1 from 540 to 340 cm depth was deposited with massive clay before approximately AD 700 (Fig. 4). *Cyclotella atomus* and *cylotella atomus* var. *gracilis*, which are freshwater to brackish taxa were dominated in Zone 1 (Fig. 3-10) (Genkal and Kiss 1993; Joh, 2010). Besides, *Diploneis smithii*, which inhabit brackish to marine taxa was dominant in zone 1 (Fig. 3-10) (Hendey, 1964). Especially, *Palaria sulcata*, *Thalassionema nitzschioides*, and *T. lineata*, which indicate the marine environment dominated in zone 1 (Fig. 3-10). *Palaria sulcata* is found in littoral sediments (Witkowski et al., 2000). The

lagoon along the coast of the Nomozaki Peninsula in Nagasaki prefecture was developed as the barrier island, and beach ridges emerged approximately 3000 years ago as result of Yayoi regression (Matsubara, 2000; 2015). It is suggested that the RSL might be same as the barrier island because the diatom assemblage appeared from freshwater to marine taxa. Therefore, zone 1 is interpreted by the lagoon, which was affected by sea water. After around AD 700, in zone 2, from 340 to 250 cm depth, the lake changed to the brackish lagoon as consequences of decreasing salinity. *Pseudostaurosira* spp. of freshwater taxa increased, and *Cyclotella atomus*, *C. atomus* var. *gracilis* of freshwater to brackish taxa and other marine taxa decreased in zone 2 (Fig. 3-10). *Psdeuostaruosira* spp. is assumed by *P. brevisitriata* or *P. brevestriata* var. *minor*. Therefore, it is suggested that *Psdeuostaruosira* spp. is freshwater taxa. *Cyclotella atomus* and *C. atomus* var. *gracilis*, which are halophilic taxa appeared off and on but generally decreased in zone 2 (Genkal and Kiss 1993; Joh 2010). This can indicate the salinity of zone 2 was lesser than zone 1 as the RSL might decrease. The brackish to marine and marine taxa disappeared in AD 1100 (Fig. 3-10). In zone 3 from 250 to 130 cm depth, *Fragilaria tenera*, *Psdeuostaruosira* spp., and *S. lapponica* were dominated (Fig. 3-10). *Staurosirella lapponica* is freshwater benthic diatom (Watanabe et al., 2005). The RSL decreased than in barrier island, and it resulted in the disappearance of marine taxa and increasing freshwater benthic species. Therefore, the lake changed to freshwater pond from brackish lagoon due to decreasing RSL. After approximately AD 1700, which was in zone 4 from 130 cm depth to top of the core, *Achnantheidium minutissimum*, *A. ambigua*, *A. granulata*, *D. stelligera* and *Cyclotella radiosa* dominated (Fig. 3-10). *Discostella stelligera* is generally found in deep lake (Joh, 2010). *Cyclotella radiosa* rarely is found as a benthic freshwater species and from the brackish area. However, *C. radiosa* is generally observed from a deep freshwater lake

(Joh, 2010). It means that the lake changed to a deep freshwater lake from a pond. Therefore, zone 4 is interpreted as a freshwater lake deeper than before.

	Lake Hamana	Lake Kawahara	Lake Ryuuoo	Recorded earthquake	Lake level and RSL from environments
AD 2000					
	Brackish Lagoon	Freshwater Lake	Freshwater Lake		Increased
AD 1500				← Hoei AD1707	
	Freshwater Lake	Pond	Pond	← Meio AD1498	inlet created
AD 1000				← Kowa AD 1099	Decreased
	Freshwater Lake	Brackish Lagoon	Freshwater Lake	Eicho AD 1096	
AD 500				← Tenmu AD 684	Decreased
	Oligohaline Lake				
AD 0		Marine- brackish Lagoon			Decreased
	Hypersaline Lake		Brackish Lagoon		
BC 500					

Figure 3-11. The environment change from Lake Hamana, Kawahara, and Ryuuoo by the recorded earthquake.

3.5.4. The environmental change related to coastal deformation

Japan is located on the boundary of the plate and has a complex geological structure. Especially, these study areas are located on along the Nankai Trough (Fig. 3-1). This Nankai Trough generates great earthquakes accompanied by a tsunami. As mentioned in the introduction, an earthquake generates coastal deformation such as subsidence or uplift along the coast of the Pacific side in Japan. Depending on the seismic segment, the coastal deformation occurred differently (Garrett et al., 2016). Hoei earthquake generates subsidence and uplift on the coast of the Pacific side from Shizuoka to Kyushu island (Furumura et al., 2011). Based on earthquake

source model, large ground subsidence happened on the coast where is located on the Nankai Trough even on Kyushu island by Hoei earthquake in AD1707 (Furumura et al., 2011). Besides, there was subsidence, which was related in Shohei earthquake in 1361 in Ukishima-ga-Hara where is located the most northern end of the Nankai Trough (Fujiwara et al., 2016) Therefore, these huge earthquakes influenced the coastal deformation and RSL. RSL has reacted sensitively by coastal deformation because the earthquake resulted in subsidence and uplift with several meters (Dura et al., 2016). The environmental change in coastal lagoon depends on RSL change because ESL has been stable during the past 2000 years until the present (Lambeck et al., 2014; Yokoyama et al., 2012).

Previous research suggests five rapid submergence event in a marsh on the north coast of Suruga Bay, central Japan along the Nankai Trough during the last 1500 years (Fujiwara et al., 2016). This result was inferred from diatom and pollen analysis in marsh sediments. The subsidence was assumed by the recovery of marshland after subsidence induced by great earthquake using water level change. Furthermore, the subsidence was estimated at approximately 60 cm in Lake Ryujin, which is located on Kyushu island by Hoei earthquake in AD 1707 (Frumura et al., 2011). During the past ten years, the vertical ground upheaval has occurred by 2 mm/year derived from GEONET along the east coast of Japan. The ground upheaval areas are related to Hoei earthquake to the recovery of ground subsidence because of earthquakes. This research estimated the upheaval around 60 cm during the past 300 years after Hoei earthquake (Furumura et al., 2011). That is how estimated the subsidence rate in Lake Ryujin, which is located on Kyushu island. The coastal deformation happened rapidly as a result of the earthquake, in contrast, the recovery of coastal deformation took a long time.

The environmental change from three coastal lagoons, Lake Hamana, Lake Kawahara and Lake Ryuuoo, occurred almost the same time (Figs. 3-6, 3-8, 3-10, 3-11). The sea level changes influence directly to an environmental change in the lagoon because the lagoon has border on a barrier island or with the inlet. The first environmental change occurred around AD 200 in Lake Hamana from a hypersaline lagoon to an oligohaline lake (Fig. 3-6). On the other hand, the other lakes from Lake Kawahara and Lake Ryuuoo did not change at that time. The magnitude of deformation induced by an earthquake depends on the location (Furumura et al., 2011). This suggests the RSL change, which is influenced by coastal deformation, could be different along the Pacific side coast of Japan. Besides, the rupture area induced by an earthquake is different in each location even though the earthquake was generated by Nankai Trough (Furumura et al., 2011). Lake Hamana is quite far from both Lake Ryuuoo and Kawahara. Therefore, the RLS change might work differently in Lake Hamana and the environment was changed only Lake Hamana in AD 200.

Between AD 600 and AD 700, the environment changed to freshwater lake from an oligohaline lake in Lake Hamana, from a brackish lagoon to a freshwater lake in Lake Ryuu and from the lagoon, which was affected by sea water to the brackish lagoon in Lake Kawahara (Figs. 3-6, 3-8, 3-10). Those environment changes in three lakes suggest less marine water as a result of falling RSL. The oldest record of the earthquake in the historical documents is Tenmu earthquake in AD 684. Tenmu earthquake ruptured the western coast of Japan, with possible evidence for subsidence of Ukishima-ga-hara lowlands that is located in the most north part of the Nankai Trough (Fujiwara et al., 2016). Even though there is no data for Tenmu earthquake to affect on Kyushu island, the range of rupture was quite huge from Shikoku to central Japan (Garrett et al., 2016). Therefore, these environment change of three lakes might be related to falling RSL as the

ground recovered after subsidence by Tenmu earthquake. Although the environmental change seems to be generated after Tenmu earthquake in Lake Ryuuoo, the error range of radiocarbon age is over 100 years. Therefore, those environmental changes in the three lakes were caused by Tenmu earthquake.

In Lake Hamana, the ecology was transferred from freshwater lake to freshwater pond as the benthic species increased in AD 1100 (Fig. 3-6). Besides, the lagoon changed oligohaline pond from the brackish lagoon as a consequence of disappearing brackish to marine and marine taxa in Lake Kawahara in AD 1100. The environment was changed from freshwater lake to freshwater pond in Lake Ryuuoo in AD 1000. The lithology changed abruptly in not only Lake Ryuuoo but also Lakes Kamega and Amega in Shikoku island near Lake Ryuuoo (Fig. 3-8) (Baranes et al., 2016). The lithology from the laminated layer to gyttja changed in Lake Kamega. In addition, the amount of Bromine (Br) abruptly decreased in Lake Amega at the same time. Br counts indicate marine organic carbon content and salinity (e.g., Ziegler et al., 2008). The changes of three Lakes Ryuuoo, Kamega, and Amega in Shikoku island suggest less marine water effect and falling lake level. Therefore, all the data from lakes suggest that research area uplifted approximately AD 1100. According to the historical record, there was Kowa and Eicho earthquakes in AD 1099 and 1096, respectively. Kowa earthquake ruptured near Shikoku to the Kii Peninsula in Honshu although the historical documentation is insufficient (Ishibashi, 1999; 2004). The Eicho earthquake ruptured upper Honshu Island along the Nankai Trough (Ishibashi, 1999; 2004). Although the data is insufficient for coastal deformation about both Kowa and Eicho earthquakes, it might be assumed that the earthquake resulted in the environmental change.

The interesting environmental change happened approximately in AD 1700. The Hoei earthquake was generated in along the Nankai Trough in 1707. The subsidence occurred a

maximum of 1-2 m from Kyushu island to central Japan along the east coast of Japan (Furumura et al., 2011). The environment changed from a freshwater pond to a lake for the Lake Kawahara (Fig. 3-10). In addition, the environment of Lake Ryuuoo changed to freshwater lake from a freshwater pond in AD 1750 (Figs. 3-8). This environmental change from both lakes indicates the lake level increased after approximately AD 1700. In Lake Kawahara, before developing the sluice gate, the lake was a brackish condition, and the lake changed to a freshwater lake at AD 1979 (Azuma, 2002; Hossain et al., 2013). However, the diatom assemblage did not change at that time (Fig. 3-10). Even though we could not know when the sluice gate was created from the age curve of Lake Kawahara exactly, the diatom assemblage suggested the ecology did not change before and after in AD 1979. It might be because the lake level is adjusted with RSL through the barrier island. Therefore, the lake level might be strongly influenced by RSL change even though the barrier island separates the lagoon and the sea. According to RSL history along the western coast of Japan, the RSL has decreased continuously during Holocene in Nagasaki Peninsula where is located on the southern part of Japan and Kobe where is located in central Japan (Yokoyama et al., 1996; Sato et al., 2001). However, the environmental change of both lakes suggests that the water level has been increased after the Hoei earthquake in AD 1707.

Furthermore, it was already mentioned before that the ground upheaval has occurred since Hoei earthquake AD 1707 (Furumura et al., 2011). The uplift in the coastal area indicates the declining water level in lakes and RSL. Therefore, it can be interpreted that both lakes have not recovered yet after subsidence by Hoei earthquake in AD 1707. It can be suggested that the environment in Lake Ryuuoo and Lake Kawahara is still deeper than earlier's environments. On the other hand, the great happening in Lake Hamana is Imakari inlet created by Meio earthquake in AD 1498. Even though the inlet was developed in AD 1498, the lake environment changed

brackish lagoon, which is connected to the Pacific Ocean before Meio earthquake. The environmental change in Lake Hamana is because of the activity of paleo-river early of the 15th century (Cho et al., 2019). Approximately AD 1400, the environment has not changed in Lake Hamana. After AD 1400, the total diatom was changed four times, and it depended on nutrient change induced by precipitation. Furthermore, the diatom assemblage changed 70 cm depth of core, and it happened in AD 1640 before Hoei earthquake in AD 1707. Besides, the error range is less than 35 years, between 78 cm and 38.3 cm. Lake Hamana is affected by seawater directly through the inlet after creating Imakari inlet. This means that the lagoon is quite close to coastal ecology. That is why Lake Hamana reacts much sensitively with precipitation change than the insertion of sea water. Therefore, the environment had not changed as much as before after the inlet was created.

3.6. Conclusion

Along the Nankai Trough, the great earthquakes with tsunami were generated. These earthquakes generated coastal deformation and changed RSL. Therefore, the environment along the Nankai Trough was changed by coastal deformation and RSL changed by the earthquake. First environment change happened in Lake Hamana in AD 200. Approximately AD 700, the environment suggested falling RSL associated with uplift by Tenmu earthquake as a result of salinity decrease from Lakes Hamana, Ryuuoo, and Kawahara. Furthermore, the environment of three lakes changed like a pond as consequences of declining lake level. It might be related to the Kowa and Eicho earthquake around AD 1100. However, the environment of Lake Ryuuoo and Kawahara changed to lake from the pond as lake level increased after Hoei earthquake. In contrast, the environment indicated that the lake level increased after AD 1700. It might be because the

ground has not recovered yet until today. That is why the lakes have been deeper than before the Hoei earthquake.

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Chapter 4. Climate Change during the Little Ice Age from the Lake Hamana Sediment Record

4. 1. Introduction

Japan has a complicated climate system influenced by the East Asian summer monsoon (EASM), East Asian winter monsoon (EAWM), and strong typhoon events. In summer, climate in central and southern Japan is controlled by the Pacific High, which leads to high rainfall and small seasonal temperature variations. In contrast, the continental Siberian High brings dry and large seasonal temperature variations in winter. Both the EASM and EAWM have anticorrelated effects on lake sediments, and the balance of the monsoon forcing is dependent on the location of the intertropical convergence zone (ITCZ) (Yancheva et al., 2007). Japan is also moderately affected by typhoons, which have generated heavy rainfall events averaging three times per year for the past ten years (Japan Meteorological Agency, 2018). From June to October, typhoons crossed Shizuoka prefecture, in central Japan, once or twice per year for the last five years (Fig. 4-1) (Japan Meteorological Agency, 2018).

Paleoclimate change research in lagoonal systems can be difficult because lagoons are easily affected by sea level change. Recently, however, many studies reconstructing paleoclimate based on microfossils have been performed in lagoonal systems because they provide valuable information on environmental changes at a variety of temporal and spatial scales (Woodward et al., 2014; Peros et al., 2015). Furthermore, ample evidence for ancient typhoons has been obtained by chemical analysis of lagoon sediments (Woodruff et al., 2009, 2015; Katsuki et al., 2016, 2017). Paleoenvironmental change research has been performed on sediments from Lake

Hamana examining its salinity and ecology change (Kashima 1988; Morita et al., 1988; Sato et al., 2016). In addition historical documents state that the inlet of Lake Hamana was modified by a large earthquake (Yata, 2005). A detailed record of environmental change in recent centuries is still unclear due to poor age control of the Lake Hamana sediment deposits, and the record of the impact of the Meio earthquake in AD 1498 is also unclear. Climate change research in Lake Hamana is also rare for the same reason.

Diatoms are microalgal paleoenvironmental indicators and vital primary producers capable of photosynthesis in all waters where sunlight is available. They are very sensitive to environmental change, such as variation in water temperature, pH, and nutrients. Climate can control catchment processes, which affect nutrients, pH, and temperature (Anderson, 2000). Thus, changes to any one of these ecological factors significantly impact the biological form, growth, colony formation, and geographical distribution of diatom assemblages. The diatoms leave their valves in the sediment, and diatoms preserve a record of climate change. Therefore, diatoms are useful for reconstruction of paleoenvironmental and climate changes (Kashima, 1985, 1986; Ryu et al., 2003). In this work, we examine how the EASM and EAWM modify the climate in both eastern Japan and western Japan inferred from chemical components, diatom assemblage and diatom abundance in Lake Hamana sediments, which are controlled by precipitation and nutrients. Furthermore, flood layers, which were observed in the sediment cores and recorded in historical documents suggest a relationship between typhoons and El Niño/Southern Oscillation (ENSO) during the Little Ice Age (LIA).

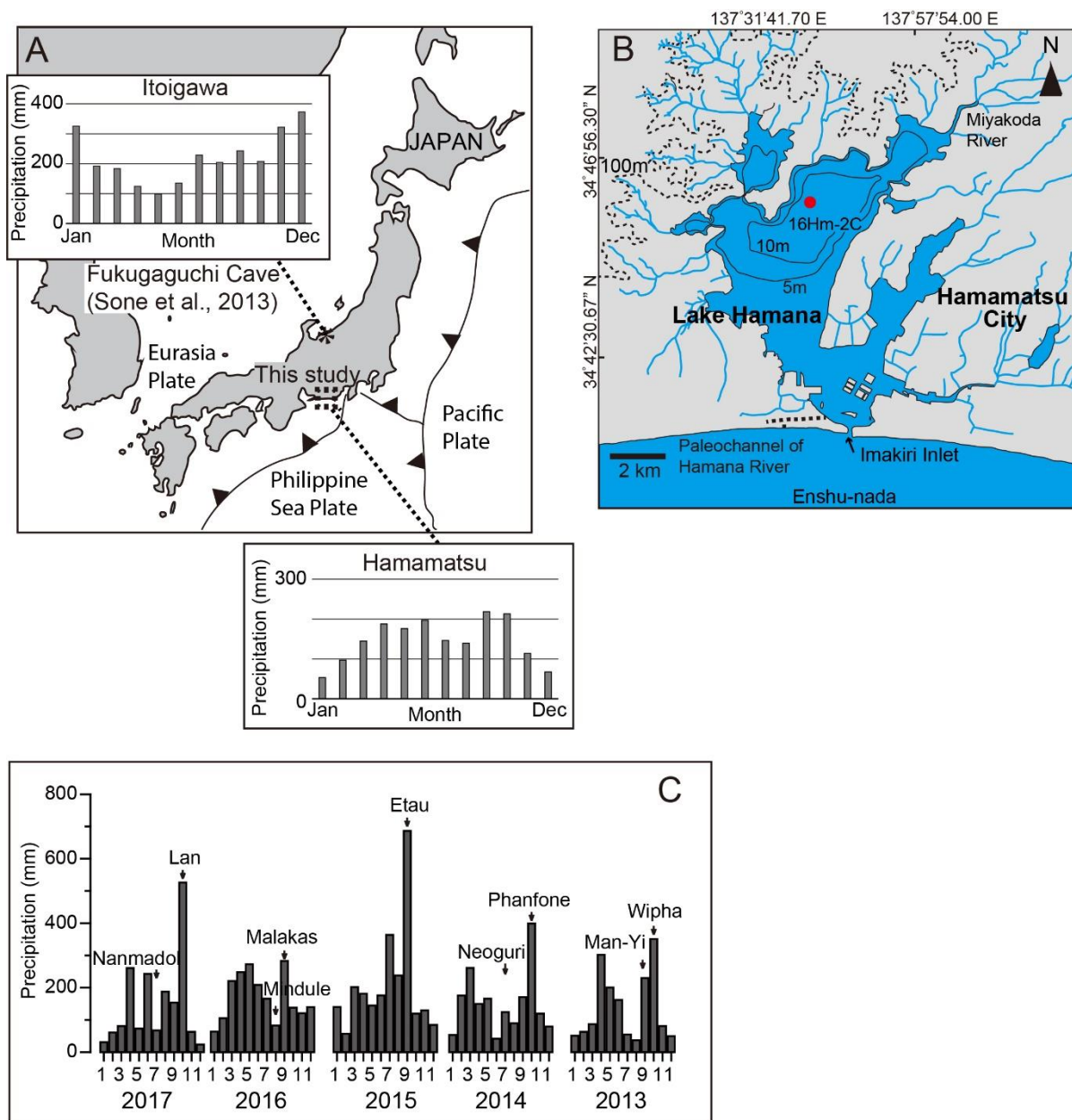


Figure 4-1. Location of the study area and monthly average precipitation: (A) map of Japan and study site location. Monthly average precipitation of Hamamatsu and Itoigawa from 2008 to 2017. (B) Core site (16Hm-2C) at Lake Hamana. (C) Hamamatsu monthly average precipitation

from 2013 to 2017, showing heavy rainfall due to typhoons (Lan, Malakas, Etau, Phanfone, Man-Yi, and Wipha).

4. 2. Study area

Lake Hamana, located in Shizuoka Prefecture in central Japan, is a coastal lagoon with a surface area of approximately 65 km² and an average depth of 4.8 m (Fig. 4-1). The average water depth of the northern part of Lake Hamana is 10–12 m and 2–3 m in the southern region (Sato et al., 2016). Lake Hamana contains brackish water today because the lake is connected to the Pacific Ocean. The average tidal range in 2017 was 240 cm, and high tide and low tide were 360 and 145 cm respectively (Japan Meteorological Agency, 2017). There is a gradient in surface salinity across the lake; salinity was 19–21 psu near inflowing streams, and salinity increased up to 29 psu near the coast in the summer season. The salinity of the bottom water is 29 psu (Taguchi and Nakata, 1998).

Lake Hamana is surrounded by mountains, hills, and terraces. Three terraces, the Tenpakubara, Kamoe, and Mikatagahara terraces, were developed during the middle to late Pleistocene, and are distributed along its eastern and western shores (Isomi and Inoue, 1972; Muto, 1987; Sugiyama, 1991, Nakashima et al., 2008). Six coastal sand barriers are located along the Enshu-nada coast (Matsubara, 2001, 2007) (Fig. 4-1).

4. 2.1. Tectonic movement

The Nankai Trough is located close to the Enshu-nada coastal plain. Along the Nakai Trough, the Phillippine Sea plate moves beneath the Eurasian plate (Fig.4-1). This Nankai Trough is the locus of recent earthquakes associated with tsunami (Fujiwara et al., 2013).

According to historical documents, large earthquakes which generated severe damage have occurred along the Nankai Trough (Yata, 2009). It is reported that the lake has been a brackish lagoon since the Meio earthquake in 1498, when the sand dune barrier was broken and a marine inlet opened (Fujiwara et al., 2006, 2013). Tsunami deposits caused by Meio earthquake have been found in the nearby coastal plain, although not in the lake sediments.

4. 3. Materials and methods

Water quality at the coring site was measured when the cores were taken (Fig. 4-2). Measurements of water depth, water temperature, salinity, chlorophyll, and turbidity were taken at 1-second intervals with an AAQ-RINKO system (Alec Electronics, Japan). The depth precision of the AAQ-RINKO is 0.3%. The 16Hm-1C and 16Hm-2C cores were obtained from the northern part of Lake Hamana (E137°34.995', N34°45.912') at a water depth of 11.56 m on 30th June 2016 using a pneumatic piston corer and hand push piston corer, respectively (Fig. 4-1). The 16Hm-2C core was collected because the upper part of the 16Hm-1C core was lost; the 16Hm-1C core was used only for core chronology. The 1.3 m long core 16Hm-2C is 6.2 cm in diameter. Diatom assemblage, chemical components, magnetic susceptibility, sand content, and water content in the 16Hm-2C core were analyzed from 25 cm to 130 cm at a 1 cm interval. A soft X-ray image was taken using a 25 cm length case. To analyze the water content, the weight of each sample was compared before and after freeze drying. A portion of the dried samples were sieved at 63- μ m mesh. After picking out the calcareous material from the sieved samples, the weight of the remaining coarse sample was used to calculate sand content.

4.3.1. Chronology of core 16Hm-2C

The age model was constructed by ^{14}C dating obtained from two cores: 16Hm-1C and 2C, both from the same location. The lithology of the two sediment cores was compared and correlated using physical properties, such as density and magnetic susceptibility (Fig. 4-3). The ^{14}C ages of two plant fragments, one shell, and one possible seagrass samples were measured using accelerator mass spectrometry (AMS) dating (Linick et al., 1989). These samples were washed repeatedly using an ultrasonic cleaner, and then chemically cleaned using acid-alkali-acid treatments to remove secondary contamination. Samples of radiocarbon-free wood were treated using the same procedure to serve as blanks. These samples and standard samples (NIST OxII, IAEA C-7, and IAEA C-8) were combusted using an elemental analyzer. CO_2 gases were purified cryogenically in a high-vacuum automatic preparation system and then converted to graphite via reduction on Fe-powder with hydrogen gas in a quartz tube. The ^{14}C ages of the samples were measured at the AMS facility in Paleo Labo Co., Ltd in Gunma Prefecture of Japan. Carbon isotopic fractionations were corrected using $\delta^{13}\text{C}$ values measured at the AMS facility. The ^{14}C ages were calculated and converted to calendar dates using IntCal13 (Reimer et al., 2013) and CALIB 7.1 (Stuiver and Reimer, 1993). The two samples at 95 and 129 cm depths were calibrated by the marine 13 data-set and the local marine reservoir effect should be considered. However, the ΔR values have not yet been documented in Lake Hamana. The lake is located on the Pacific Side of central Japan and the Kuroshio current flows near the inlet of Lake Hamana. ΔR values in regions belonging to the Kuroshio Current system have been reported: 73 ± 17 years in Taiwan, 29 ± 18 years in the Ryukyu Islands, and -22 ± 18 years in the Ogasawara Islands (Yoneda et al., 2007). Also, ΔR values reported from the Miura Peninsula were 82 ± 33 yr and 77 ± 32 yr (Shishikura et al., 2007). The range of ΔR value might be from -22 to 82 years.

However, ΔR values in brackish lakes are generally smaller than coastal marine regions because of the freshwater input. Therefore, here, we estimate the ΔR value at close to zero in the 16Hm-1C and 16Hm-2C cores.

Depth below sea floor (cm)	C ¹³ /C ¹² Ratio (‰)	Conventional		Calibrated C ¹⁴ Age					Lab.No.	Sample No.	Material
		C ¹⁴ Age (yr BP)	std. (yr)	1 sigma (Cal AD)							
				Median Probability	Range	Probability					
38.3	-30.83	202	17	intcal13	AD	1782	(1662-1673) (1778- 1799) (1942- 1950)*	0.239 0.548 0.213	PLD-33242	16Hm-1C-27	plant
78	-30.31	279	19	intcal13	AD	1631	(1528- 1544) (1549- 1550) (1634- 1652)	0.351 0.033 0.616	PLD-35544	16Hm-2C-78	plant
95	-0.32	821	17	marine13	AD	1485	(1465- 1504)	1.000	PLD-33240	16Hm-1C-86.5	shell
129	-11.77	1104	19	marine13	AD	1288	(1273- 1308)	1.000	PLD-35545	16Hm-1C-120.5	seagrass?

* This standard deviation (error) includes a lab error multiplier.

Table 4-1. Radiocarbon age data from core 16Hm-1C and 16Hm-2C, Lake Hamana. Radiocarbon dates were calculated and converted to calendar dates with IntCal13 (Reimer et al., 2013) and CALIB 7.0 (Stuiver and Reimer 1993).

4.3.2. Chemical component analysis

Samples of the 16Hm-2C core were prepared by freeze-drying and grinding. After drying, 1N HCl solution was added to a 10 mg sample in a silver container to remove inorganic carbon and then heated on a hot plate for 4 hours. Dried samples were then loaded into tin capsules. Total organic carbon (TOC), total nitrogen (TN), and total sulfur (TS) were determined by a CHNS material analyzer, Thermo ELECTRON CORPORATION, model Flash EA 1112. The ratios of C/N and C/S were calculated from the TOC, TN, and TS values. The accuracy of the procedure was controlled by standard BBOT (2,5-Bis-(5-tert.-butyl-benzoxazole-2-yl)-thiophene), which was measured after every ten sediment samples.

4.3.3. Diatom analysis

Diatom assemblages were analyzed from 25 cm to 130 cm in the 16Hm-2C core at 1 cm intervals, using 0.01 g of dry sediment. Dry sediments were placed into a 200 ml beaker with 10 ml of 30% H₂O₂ to eliminate organic matter. After boiling for 1 hour, 200 ml of distilled water was added to each beaker and samples were soaked for 4 hours. Water was decanted and replaced twice with new distilled water, and additional distilled water was added three times to separate higher density substances from diatoms. The remaining bottom solutions of 0.2 to 0.8 ml after decantation were pipetted onto a coverslip using a micropipette and mounted with Pleurax. At least 300 diatom valves were counted on each slide under 2000× magnification by light microscope. Diatoms were classified based on classification schemes used in previous studies (Hendey 1964; Round et al. 1990; Takano 1990; Kojima et al. 1995; Hasle and Syvertsen 1996; Watanabe 2005; Kobayashi et al. 2006). The following equation calculated the total diatom valves and Diatom Accumulation rate (DAR):

$$\begin{aligned} \text{Total diatom valves per 1g dry sediment [No. g}^{-1}\text{]} &= \text{Counted valves on slide [No.]} \\ &\times \text{Observation area (slide area [mm}^{-2}\text{] / counted area [mm}^{-2}\text{])} \times \text{Liquid volume used} \\ &\text{(beaker liquid volume [ml])/ micropipette volume[}\mu\text{L])} \times 1000 \times \text{sediment}^{-1}\text{[g}^{-1}\text{]}. \end{aligned}$$

$$\begin{aligned} \text{Diatom Accumulation Rate (DAR) [No. valves cm}^{-2}\text{ kyr}^{-1}\text{]} &= (\text{No. valves g}^{-1}\text{ dry} \\ &\text{sediment) [No. g}^{-1}\text{]} \times (\text{dry bulk density) [g cm}^{-3}\text{]} \times (\text{sedimentation rate) [cm kyr}^{-1}\text{]}. \end{aligned}$$

4.4. Results

4.4.1. Water stratification at the coring site

Vertical water quality measurements at the coring site were carried out just before obtaining the sediment cores. The surface temperature on 30 June 2016 was 25°C and 21°C at

the bottom of Lake Hamana (Fig. 4-2). The salinity was around 24 psu; however, it suddenly increased to 34 psu below a depth of 1.8 m (Fig. 4-2). Similarly, chlorophyll and dissolved oxygen (DO) dropped drastically at the 1.8 m depth, with chlorophyll increasing again between 4.2 and 7.7 m. Turbidity was low down to 8 m and increased strongly up to 7 (FTU) at 11.9 m.

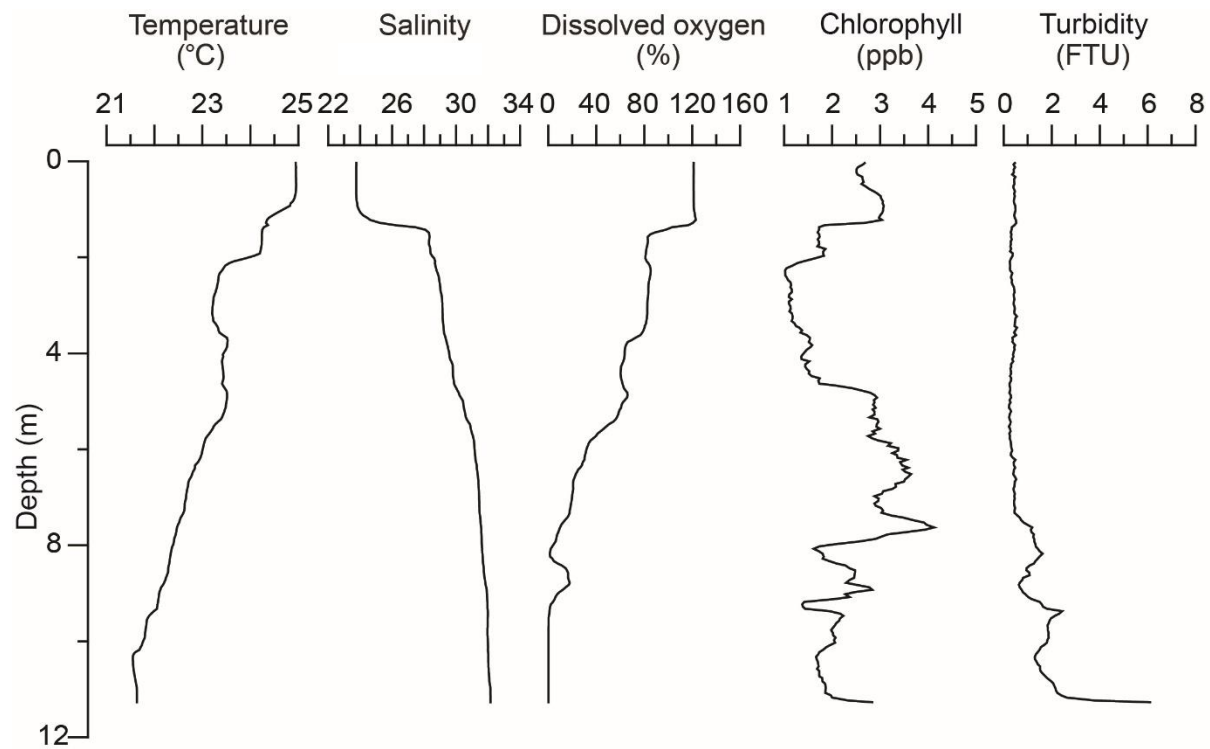


Figure 4-2. Variations in temperature, salinity, dissolved oxygen, chlorophyll and turbidity against water depth at the coring site, June 2016.

4.4.2. 16Hm-2C core

The sediment of the 16Hm-2C core was dominated by laminated clay with disarticulated bivalves to the 109 cm depth, while bioturbation was observed below 109 cm (Fig. 4-3). High-density layers including sand were deposited at 40.5, 72.0, 74.0, and 87.0 cm depths (Fig. 4-3). To avoid core top disturbance, we began our study at a depth of 25-cm. High-density layers represented by dark colors on the soft X-ray image appear several times (Fig. 4-3). The range of magnetic susceptibility is from 1 to 6×10^{-5} SI (Fig. 4-3). TOC, C/N and C/S ratios are 1.5 to 4.5 (%), 8.8 to 11.2 and 0.4 to 2.4, respectively (Fig. 4-4). Sand and water content showed similar tendencies and fluctuated from 0.5 to 4.6% and from 55.7 to 75.2%, respectively (Fig. 4-4).

Twelve diatom taxa were dominant in the 16Hm-2C core. The taxa reaching more than 10% relative abundance were *Aulacoseira ambigua*, *Aulacoseira granulata*, *Pseudostaurosira brevistriata*, *Cyclotella atomus*, *Cyclotella atomus* var. *gracilis*, *Cocconeis scutellum*, *Thalassionema nitzschioides*, and *Thalassiosira lineata* (Fig. 4-5). The taxa with relative abundances below 10% were *Diploneis smithii*, *Fallacia nyella*, *Podosira stelligera*, and *Thalassiosira nano-lineata*. *Aulacoseira ambigua* and *A. granulata* dominated, and *P. brevistriata* start increasing before AD 1440. After AD 1440, *C. atomus*, *C. atomus* var. *gracilis*, *C. scutellum*, *D. smithii*, *F. nyella*, *P. stelligera*, *T. nitzschioides*, *T. lineata*, and *T. nano-lineata* showed high percentages. The abundance of *Achnantheidium minutissimum* has several peaks (Fig. 4-3). The total diatom valve indicates the number of valves in 1g dry sample and diatom accumulation rate (DAR) is the annual diatom accumulation. These two graphs have a very similar pattern (Fig. 4-5).

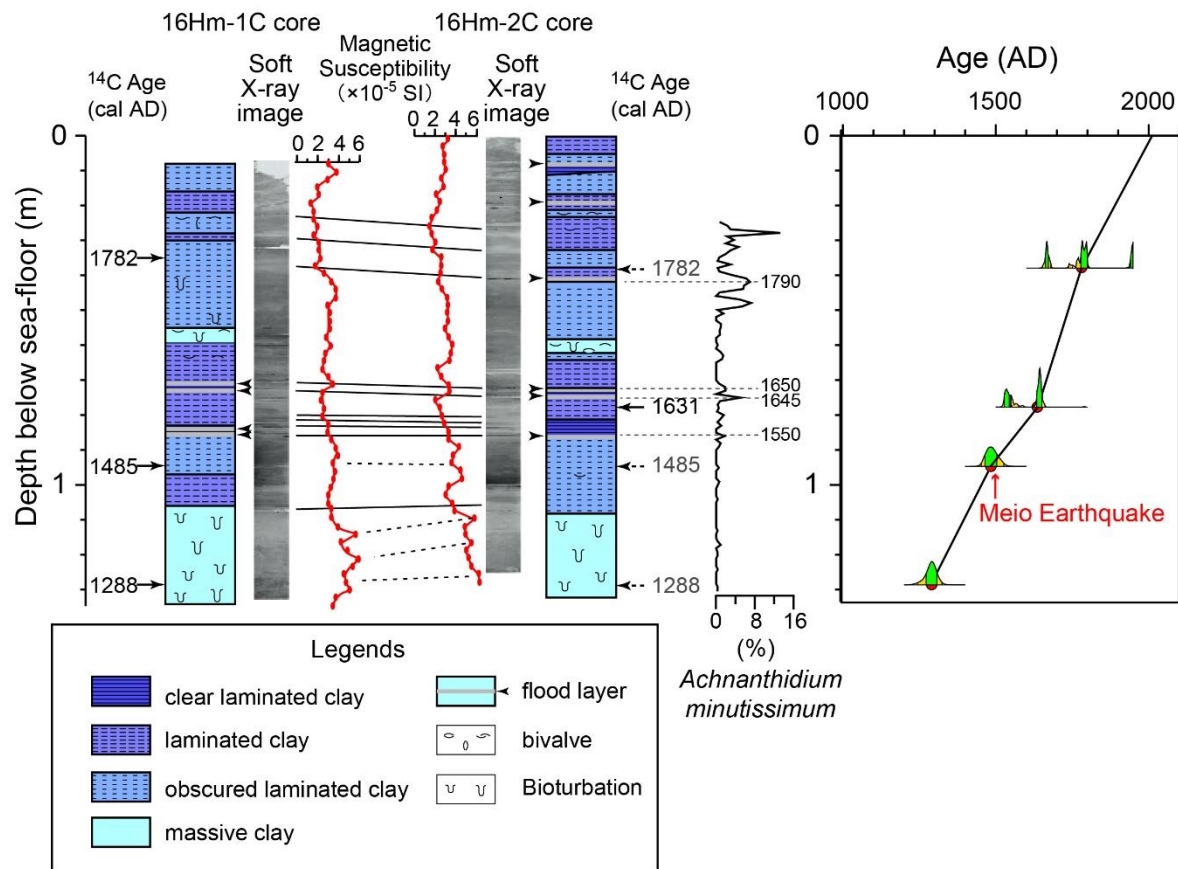


Figure 4-3. Lithology description, soft X-ray image, magnetic susceptibility, and age-depth plot for cores 16Hm-1C and 16Hm-2C. Yellow and green ranges in age-depth plot are the age range of 1 and 2 sigma, relatively. The abundance of *Achnantheidium minutissimum* in 16Hm-2C is also shown. The obscured lamina can hardly be seen with the naked eye, however indistinct layers can be confirmed in soft-X ray image.

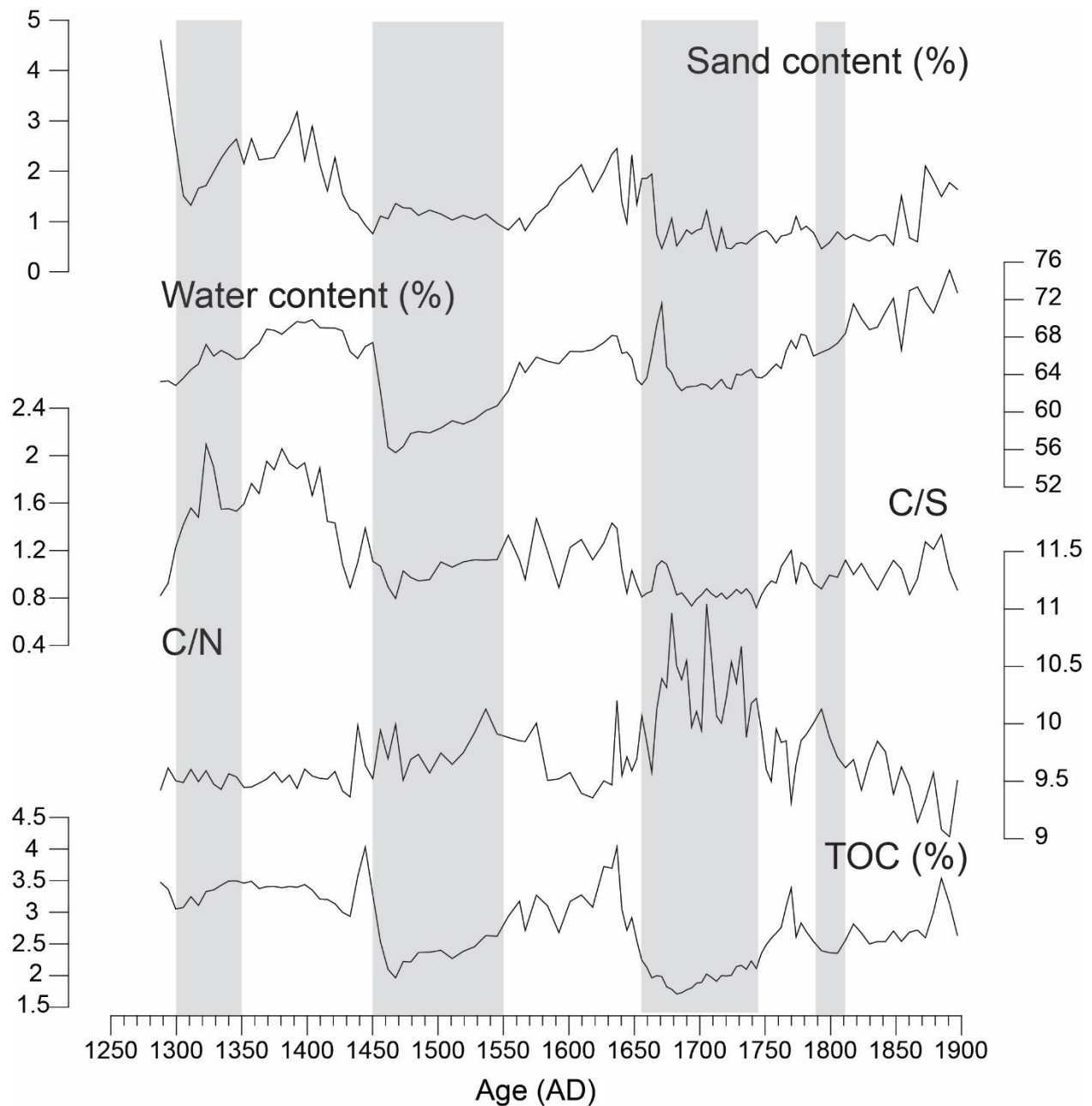


Figure 4-4. Sand content, water content, C/S, C/N ratio and TOC in core 16Hm-2C. Gray zones represent intervals of climate change based on the chemical components and diatom assemblage.

5. Discussion

5.1. Environmental changes before and after the Meio earthquake AD 1498.

The Meio earthquake in AD 1498 generated a tsunami that is documented in the written record (Watanabe, 1998). Previous studies suggested that the Imakari inlet (Fig. 4-1) between Lake Hamana and the North Pacific Ocean was formed and that the opening of this inlet led to the lake transitioning from freshwater to brackish lagoon following the Meio earthquake. One study indicates that Lake Hamana was previously connected to the Pacific Ocean via the Hamana river, a short tributary that was lost after the earthquake (Fujiwara et al., 2013). Tsunami deposits have been identified as thick sand beds on the floodplain of the Hamana River (Fujiwara et al., 2013). However, in the lake a dramatic change of the diatom assemblage probably occurred in the mid-15th century, well before the Meio earthquake (Fig. 4-5). Marine diatoms appeared, and *A. ambigua* and *A. granulata*, which are freshwater species (Joh, 2010), suddenly disappeared at AD 1440 in the 16Hm-2C core (Fig. 4-5). The lithology also changed from clay with bioturbation to laminated clay and the halophilic species *C. atomus* increased significantly (Joh, 2010) around the 109 cm depth, at approximately AD 1400, in the 16Hm1C and 16Hm2C cores (Figs. 4-3, 4-5). *Aulacoseira granulata* prefers conditions of vertically active water and is vulnerable to standing water (Joh, 2010). These results imply that there was active lake water circulation before the 15th century, leading to high DO in the bottom layer of Lake Hamana, shown by the core's bioturbated sediment. Based on historical documents, the Hamana River connected an enclosed embayment (the present-day Lake Hamana) to the Pacific Ocean during the 14 and 15th centuries (Ebara, 2008; Yata, 2009). In addition, geological data supports a Hamana paleoriver channel that flowed to the Pacific until at least AD 1340-1400 (Fujiwara et al., 2013). In the southwestern floodplain next to Lake Hamana, an estuarine environment was

terminated by the development of coastal sand dunes and beach-ridge plains in the 13-15th centuries, and a brackish-freshwater marsh environment was present in this area (Fujiwara et al., 2006, 2013). Freshwater diatom taxa were dominant in Lake Hamana before the mid-15th century represented by this floodplain development, suggesting that seawater inflow was prevented by the expanded coastal beach. However, the diatom assemblage data from the 16Hm-2C core suggests that seawater exchange with the Pacific Ocean through the Hamana paleoriver increased at about the mid 15th century, well before the Meio earthquake. Furthermore, the brackish-freshwater species, *Cyclotella atomus* started to increase around AD 1415 (Fig 4-5). After the Meio earthquake, the Hamana paleoriver was lost, and the present inlet was created. The water exchange rate with the Pacific Ocean throughout this new inlet was higher than the exchange in the mid-15 century. Note that some uncertainty remains in the core chronology, although the delta-R values are most likely close to zero, if an uncertainty of ± 30 years is incorporated into the calibrated marine 14C dates in the core, a very small chance exists that the diatom transition level (1.06 m) dates to ~1500 and the Meio earthquake. We should emphasize, however, that this is unlikely.

Some previous reports have suggested that Lake Hamana was a freshwater lake before the Meio earthquake (Morita et al., 1998; Sato et al., 2016). Although freshwater diatom taxa are dominant before the Meio earthquake, the lake was not completely freshwater based on the C/S ratio. The range in C/S ratio is 0.7–2.1 through the 16Hm-2C core. Prior to AD 1440, the C/S ratio increased to 2 (Fig. 4-4). This value strongly suggests that the lake was affected by marine water (Berner and Raiswell, 1984). This difference between the diatom assemblage and C/S ratio indicates that Lake Hamana had seasonal stratification before the earthquake. The salinity of the bottom water was higher than surface water due to the inflow of seawater through the sand bar of

the Hamana paleoriver. Therefore, the lake was not a freshwater lake but was an oligohaline lake before the Meio earthquake.

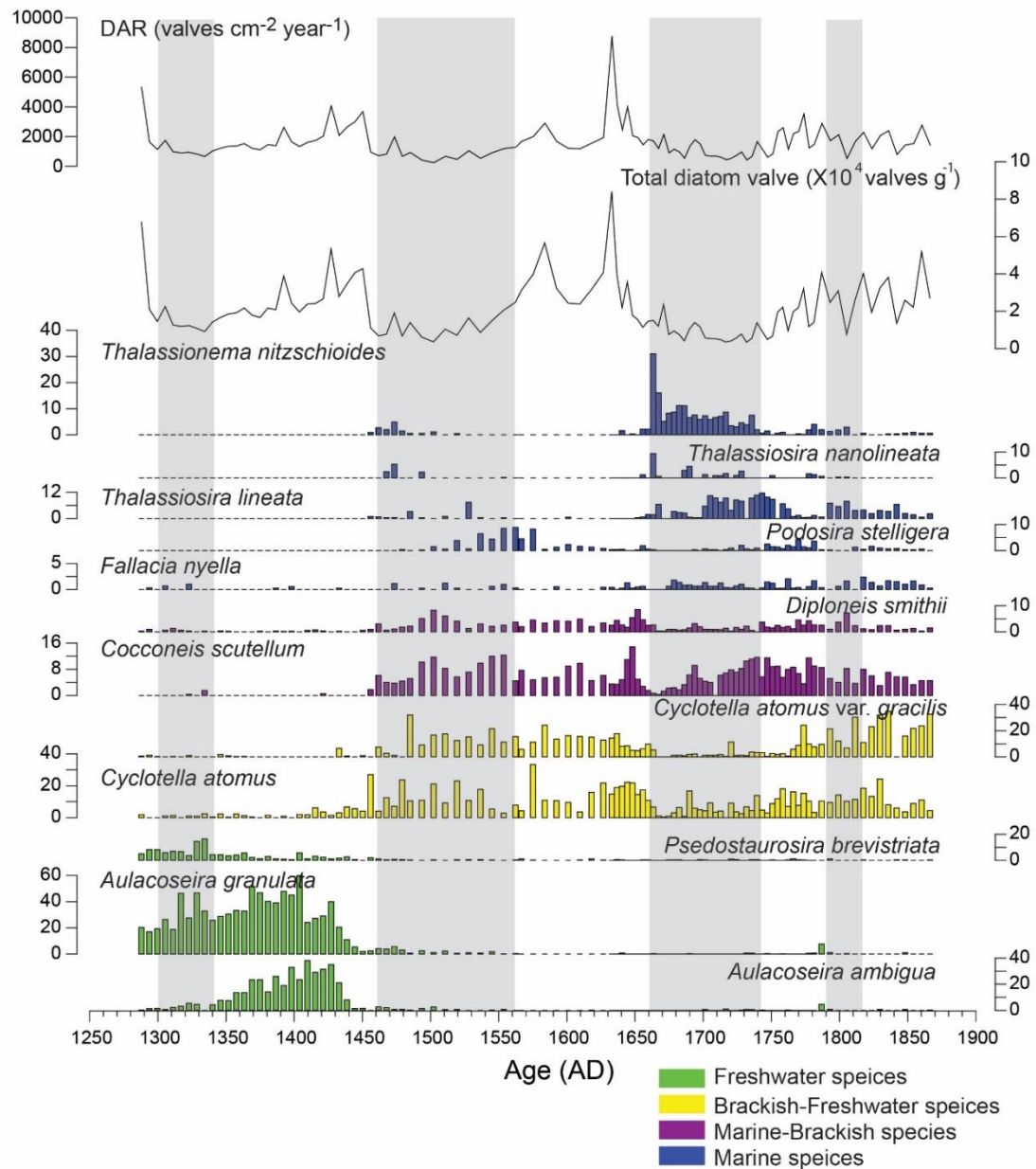


Figure 4-5. Age distribution of diatom relative abundance by taxa, DAR and total diatom valves in core 16Hm-2C are categorized as freshwater, brackish-freshwater, marine-brackish, and marine species.

4.5.2. Climate change related to EASM and EAWM

As mentioned above, seasonal change in Japan is tied to the EASM and EAWM. In East Asia, monsoonal climate variability occurs in centennial to millennial-scale cycles since the late Holocene (Gupta et al., 2003), which are primarily related to solar radiation (Gupta et al., 2003; Wang et al., 2005). Previous studies agree that the EASM is anticorrelated with the EAWM and its strength depends on the movement of the ITCZ (Yancheva et al., 2007). Average surface air temperature and precipitation, reconstructed across the East Asian monsoon region during the past 1000 years, document the strength of EASM during Little Ice age and Medieval Warm period (Zhou et al., 2011) (Fig. 4-6). According to Sone et al. (2013), the EAWM brings moisture and generates frequent snowfall or rainfall when it crosses the warm oceanic waters of sea between Korea and Japan. The stalagmite $\delta^{18}\text{O}$ record of Fufugaguchi Cave suggests that the EAWM has brought variable amounts of moisture to western Japan over the past 10,000 years (Fig. 4-6). In fact, for Itoigawa city, in northwest Japan, the average monthly precipitation was over 300 mm from November to January during the past ten years (Fig. 4-1). In contrast, the Pacific side of Japan is much drier, with average monthly rainfall less than 120 mm November to February and 50 to 70 mm from December to January during the past ten years in Hamamatsu city, Shizuoka Prefecture (Fig. 4-1). The impact of the EAWM is very different depending on location, with a strong contrast between northwest Japan and the Pacific side of Japan (Fig. 4-1).

The diatom abundance and composition are controlled by nutrients. The nutrient input and transfer to Lake Hamana will depend on rainfall (Anderson, 2010). A strong winter monsoon leads to low precipitation and cold temperatures on the Pacific side of Japan. On the other hand, the summer monsoon results in high precipitation and warm temperatures in Lake Hamana (Fig. 4-1). The salinity change in this lagoon has probably been dependant on precipitation. Although

there is no record of centennial scale sea-level and tidal prism history in central Japan before the 19th century, sea-level was generally lower during the Little Ice Age (e.g., Akasofu, 2010). Contrary to what we would expect from a lower sea-level, marine taxa in Lake Hamana increased during the Little Ice Age (Fig. 4-5). This suggests that rainfall had a stronger impact on lake salinity than sea-level change. Therefore, it appears that indicators of primary production, such as TOC, diatom amounts (total diatom valve and DAR), and the composition of the diatom assemblage were strongly influenced by precipitation and its impact on nutrient input and lake salinity. Overall the precipitation amounts are tied to the competing strengths of the EASM and EAWM.

4.5.3. Relationship with EASM

In the 16Hm-2C core of Lake Hamana, the total number of diatom valves generally correlates with a strong EASM and an increased number of sunspots (Fig. 4-6). Additionally, sand and water content increased when the EASM and sunspot frequency intensified (Fig. 4-4 and 4-6). Sand at the core site was probably delivered by the river and with increased sand in the core the water content increases because porosity increases. *Cyclotella atomus* var. *gracilis* lives in euryhaline conditions, which is an indicator of a eutrophic setting (Genkal and Kiss, 1993). This taxon also appeared when the summer monsoon intensified after Lake Hamana became a brackish lagoon. These results suggest that diatom abundance increased in times of high solar activity and Lake Hamana became eutrophic. This is because a strong EASM triggers high precipitation for central Japan, and heavy precipitation drives terrestrial nutrients into the lake along with coarse sand. After AD 1750, sand content did not increase to earlier levels because the seagrass *Zostera marina* interrupted input of sand. This *Z. marina* increased following the

increase in solar activity after AD 1750 (Fig. 4-6). When Lake Hamana was an oligohaline lake, *A. ambigua* and *A. granulata* were dominant, in the interval AD 1350-1440 (Fig. 4-5). High levels of these *Aulacoseira* taxa appeared during periods of a strong EASM. *Aulacoseira ambigua* and *A. granulata* usually inhabit mesotrophic and eutrophic environments (Joh, 2010). Under oligohaline lake conditions, a strong EASM also produced significant diatom productivity and lake eutrophication.

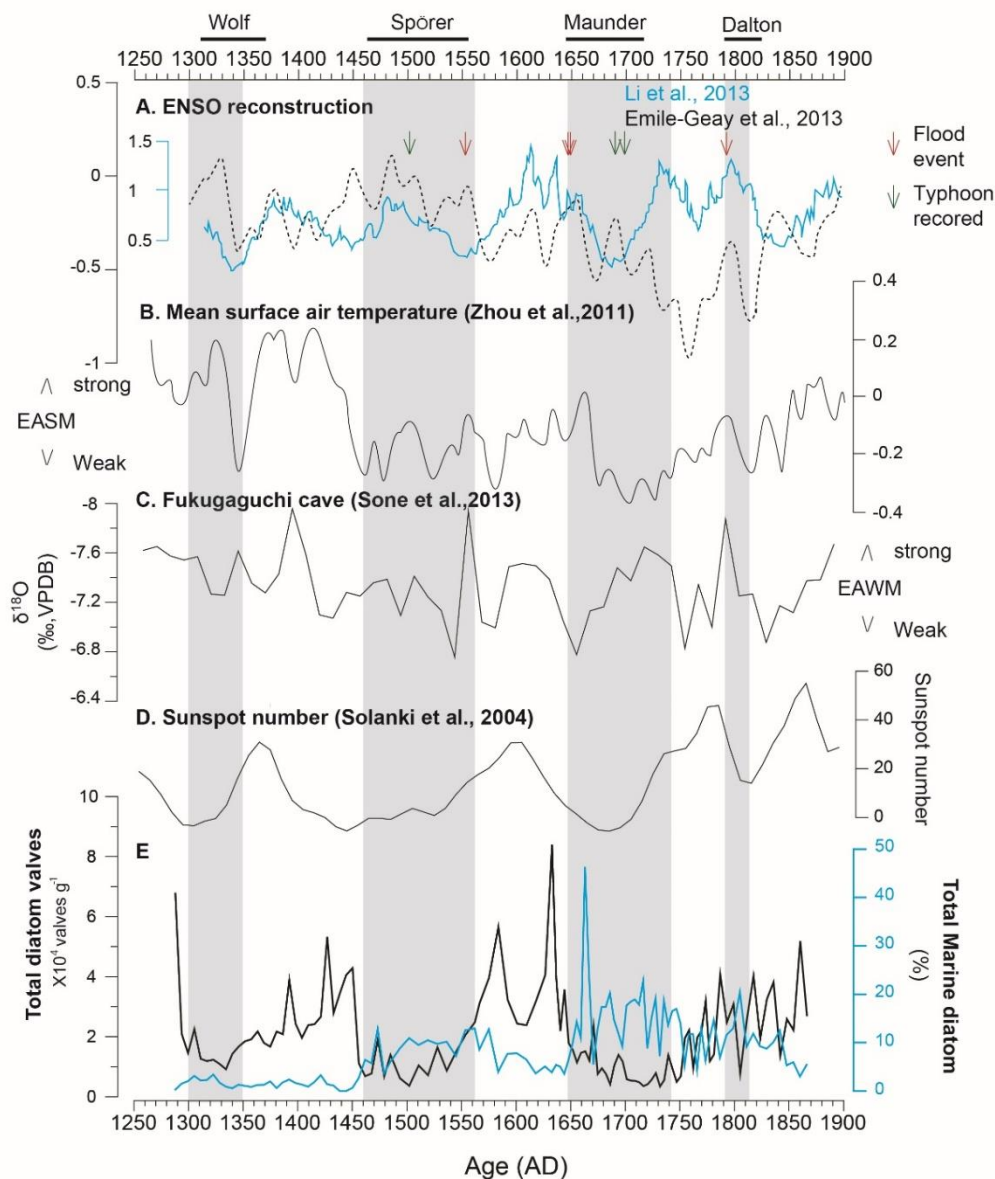


Figure 4-6. Time comparisons: (A) ENSO reconstruction. Blue line is modified from Li et al., 2013. Dotted line is modified from Emile-Geay et al., 2013. (B) Mean surface air temperature over the East Asia monsoon region is modified from Zhou et al., 2011. (C) EAWM intensity of stalagmites from Fukugaguchi Cave (Sone et al., 2013). (D) Sunspot number based on dendrochronologically dated radiocarbon concentrations (Solanki et al., 2004). (E) Total diatoms and total marine diatoms in core 16Hm-2C. Wolf, Spörer, Maunder, and Dalton are regarded as a minimum solar event.

4.5.4. Climate change during LIA

From AD 1645 to 1740, the total number of diatom valves decreased and *T. nitzschioides*, which inhabits the neritic zone (Hallegraeff, 1986), became dominant, rising to 38% of the assemblage (Fig. 4-5). These results can be attributed to decreased precipitation and increased salinity. In addition, the C/N ratio shows the highest value during this period (Fig. 4-4). A high C/N ratio usually indicates an input of terrestrial material because the land plants contain high amounts of nitrogen-depleted lignin and cellulose unlike aquatic plankton (Lamb et al., 20016). The seagrass *Zostera marina* is distributed in the shallows and inlet of Lake Hamana (Sato et al., 2016). Seagrasses also have a high C/N ratio, and it is common to see the reefs of *Z. marina* in Lake Hamana. This seagrass is transported into the lake by the tides at present. Therefore, a high C/N ratio may be explained by significant sea-water inflow. In the lagoon, the salinity is primarily controlled by rainfall because sea level has been mostly stable for the last 1000 years (Umitsu, 1991). During AD 1460-1560, total marine taxa increased to greater than 10% and *T. nitzschioides* also showed an increase (Figs. 4-5, 4-6). Between AD 1790 and 1810, the total number of diatom valves decreased and marine diatoms suddenly increased. Total diatom valve number and marine taxa abundance showed similar patterns during AD 1460-1560 and AD 1790-1810 (Figs. 4-5, 4-6). On the other hand, when Lake Hamana was an oligohaline lake, an increase of marine taxa did not occur. However, a dramatic change of dominant taxa still happened. *Aulacoseira ambigua* suddenly dropped to low abundances, while *P. brevistriata* increased. These changes happened against the backdrop of a decrease in the total number of diatom valves during AD 1300-1350 (Figs. 4-5, 4-6). *Aulacoseira ambigua* prefers high temperatures and high light intensities compared to other species (Shear et al., 1976). *Pseudostaurosira brevistriata* is a benthic freshwater species and inhabits oligotrophic lakes (Joh

et al., 2010). Low precipitation in the catchment must have resulted in lower sediment and nutrient input. Therefore, *P. brevistriata* increased during AD 1300-1350 when sunlight reached the bottom of the lake, indicative of a change to an oligotrophic lake. However, in the early LIA, AD 1320 to 1350, the EASM increased, and EAWM decreased, in a trend counter to solar irradiance changes (Fig. 4-6). Total diatom numbers were still low even though there was a small increase at the beginning of 14th century (Fig. 4-6). The reason why might be a reduction in solar irradiance and its impact on photosynthesis. Also, TOC decreased during these periods (AD 1300-1350, 1460-1560, 1645-1740 and 1790-1810), well synchronized with low counts of total number of diatom valves (Figs 4-4, 4-5). The small change of TOC from AD 1300 to 1350 is because Lake Hamana was an oligohaline lake at that time. The EASM and sunspot number show a trend very similar to diatom and chemical data. Therefore, these periods (AD 1300-1350, 1460-1560, 1645-1740 and 1790-1810) fall within the climate interval defined as the LIA (Fig. 4-6). These diatom results suggest that the amount of precipitation decreased during the LIA due to the weak monsoon in these periods.

In contrast, before AD 1650 the EAWM is not in a strongly anti-correlated relationship with the EASM and sun spot record, based on our data (Fig. 4-6). One of the most likely reasons for this is because of the low resolution of the long stalagmite record, which is used as the basis of the EAWM proxy that covers the last 10,000 years. In it the last 500 years is represented by less than 50 data points (Sone et al., 2013). In addition, the EAWM climate of the Sea of Japan side and the Pacific side of Japan is very different today and is likely to have been different in the past.

4.5.5. Flood events related to ENSO during the Little Ice Age

In the Asian monsoon area, significant amounts of extreme precipitation are induced by typhoons (Fumin et al., 2002; Kim et al., 2006; Ge et al., 2010; Lee et al., 2010). This typhoon pattern is strongly affected by ENSO, and typhoons tend to recurve to Japan, South Korea, and Northern China during El Niño events (Elsner and Liu, 2003). The typhoons occur from July to October and lead to very heavy rainfall when they occur in September and October (Fig. 4-1). However, when typhoons do not occur during the fall season the monthly precipitation tends to be low (Fig. 4-1).

Evidence for typhoons, for example sand deposits, were found as overwash deposits from the Lake Hamana barrier beach (Komatsubara et al., 2008). Woodruff et al. (2009) used strontium (Sr), which was derived from a lagoon barrier beach to identify storm deposits. However, there are no sand deposits in the 16Hm-2C core because the coring site is too far away from the sandbar and inflowing streams. Based on tide direction, the sediments are transported from the Miyakoda River to the coring site (Fig. 4-1) (Taguchi and Nakata, 1998). In addition, the seagrass *Zostera marina* is distributed in shallow parts of Lake Hamana (Sato et al., 2016). Therefore, sand, which is transported as bed load, is blocked by *Zostera marina* beds.

High-density layers in the soft X-ray images were present at AD 1550, 1645, 1650, and 1790 (Fig. 4-3). These layers are well correlated with peaks of *Achanathidium minutissimum* (Fig. 4-3). *Achanathidium minutissimum* is a benthic freshwater species (Joh, 2012), and can be an indicator of terrestrial input accompanied by inflow of river water in the lagoon. In addition, magnetic susceptibility is controlled by pedogenesis and deposition of dust that are both dependent on precipitation (An et al., 1991). Magnetic susceptibility also increased during those periods (Fig. 4-3). Ample rainfall might have induced flooding that resulted in the deposition of

A. minutissimum, which inhabits only freshwater environments such as streams or lakes. Therefore, these high-density layers are used as proxies of flood layers, which might be deposited after heavy rain events in the Lake Hamana catchment. Several typhoon events in Shizuoka Prefecture have been recorded in historical documents. A storm which occurred in AD 1509 destroyed the bridge at the mouth of Lake Hamana. Other storms in AD 1680 and 1699 washed away houses in Shizuoka Prefecture (Komatsubara et al., 2008).

The possibility that one of these flooding event layers was caused by the tsunami associated with the Meio earthquake is very low. These flood events are more likely associated with high amounts of precipitation induced by the intensity of EASM and typhoons accompanied by heavy rainfall. It is hard to distinguish these event layers whether typhoon or tsunami deposit based on lithological condition because these layers are so thin. An important feature that argues against a tsunami deposit is that there was no marine diatom in these layers, although the marine diatoms are common in tsunami deposits because the tsunami brings offshore marine water and sediment far inland. For example, a large amount of marine diatoms were deposited in the tsunami deposit generated by the 2004 Indian Ocean tsunami at Phra Thong Island, Thailand (Sawai et al., 2009). Furthermore, these event layers are not synchronous with the Meio earthquake, which occurred in AD 1498. These layers, therefore, were probably not formed by tsunami events. The diatom assemblages and lithology suggest these flood sediments were deposited when the EASM was weak, not strong. This suggests that these flood event layers were not formed by a high amount of precipitation under an intensified EASM. Therefore, the event layers are most strongly related to typhoons accompanied by very heavy rainfall.

An ENSO record has been reconstructed based on 2,222 tree-ring chronologies and by modeling over the past several centuries (Emile-Geay et al., 2013, Li et al., 2013) (Fig. 4-6). Red

arrows, marking flood events in Lake Hamana, and green arrows indicating typhoon events from historical records synchronize with some of the peaks in of the ENSO record in Figure 4-6. Some events, however, do not clearly match with both reconstructed ENSO peaks, perhaps due to disagreements in the different reconstructed ENSO records (Fig. 4-6). Including events from the historical record and our record of flood deposits (AD 1550, 1645, 1650, and 1790) flood frequency increased during the LIA (Fig. 4-6). Another study makes the same observation; typhoon frequency increased during LIA in Hwajinpo lagoon, Korea (Katsuki et al., 2016). As mentioned above, the EASM was weak during the LIA, and the amount of precipitation was lower than in other periods. ENSO is strongly related to sea surface temperature (SST) in the Pacific Ocean (Schwing et al., 2002; Marchitto et al., 2010). This SST is also affected by solar activity. Marchitto et al. (2010) showed that proxy-based SST records based on Mg/Ca ratio correlated with the generation of cosmogenic nuclides ^{14}C and ^{10}Be . Therefore low solar activity is correlated with El Niño-like conditions (Marchitto et al., 2010). Japan has a complicated climate system, but it is one that is closely related to solar insolation. The climate of Japan over the last 1000 years has undergone significant variation. The LIA was in place for about 650 years from AD 1300-1950 (Matthews and Briffa, 2005). Before the LIA, the Medieval Solar Maximum occurred from AD 1100 to 1250 (Jirikowic and Damon, 1994). During the LIA, El Niño was strong, and typhoons during El Niño years tended to recurve to the northeast (Wang and Chan, 2002), which may increase the likelihood of typhoons making landfall in Japan (Elsner and Liu, 2003). The heavy precipitation levels induced by typhoons in Japan is strongly dependent on the typhoon strength and the study area's distance from the typhoon. Therefore, even if many typhoons make landfall in central Japan, they do not always result in heavy rains on Lake Hamana. On the other hand, strong storms around Lake Hamana in historical documents,

and flood records in core 16Hm-2C, represented by flood layer deposits and peaks in *A. minutissimum* abundance, can be matched to strong ENSO events during the LIA (Figs. 4-1, 4-6). We suggest that a strong El Niño during the LIA might lead to frequent typhoon events in Japan, accompanied by significant floods.

6. Conclusion

This research documented paleoenvironmental and climate changes in eastern central Japan during the LIA by analysis of diatom assemblages and chemical components of an AMS ¹⁴C dated core of lake sediments. Lake Hamana changed from an oligohaline lake to a brackish lagoon in the mid-15th century because of changes in the flow volume of the Hamana paleoriver. This occurred before the Meio earthquake. The diatom assemblage in Lake Hamana shows a strong relationship to the strength of the EASM. When the EASM intensified, diatom abundance increased due to high rainfall and river runoff and Lake Hamana became eutrophic. Diatom productivity decreased under increasing sea water inflow when the EASM weakened during the LIA. Lake Hamana was often affected by flooding events induced by typhoons based on historical data and flood deposits in the core. During the LIA, frequent typhoons impacted central Japan because typhoons move toward Japan under El Niño-like conditions.

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Chapter 5. Conclusions

5.1. Conclusions

The paleoclimate change and RSL has played quite differently between Korea and Japan during the Holocene based on the reconstruction of environmental change. The environmental reconstruction was performed by diatom assemblage, grain size analysis, chemical components and chronology. The environment changed as a consequence of the development of sand barrier island, RSL change and climate change in Hwajinpo lagoon. Approximately 6000 cal years BP, the barrier island was completely developed, and the environment was a brackish lagoon. The environment did not identify between until the 1700 cal year BP because of hiatus. However, the environment changed oligohaline lake after 1600 years ago because the precipitation increased due to monsoon strengthens.

In contrast with Korea, Japan has much-complicated climate system and RSL history. In my research, three lakes as Lake Hamana, Lake Ryuuoo and Lake Kawakawa along the Nankai Trough were investigated. The environment of these lakes has changed continuously as a result of upheaval from the coastal area along the Nankai Trough. The Nankai Trough generates great earthquakes, and it resulted in coastal deformation such as uplift and subsidence. Furthermore, the RSL changed depending on coastal subsidence and uplift. Therefore, the environment was changed by coastal deformation and RSL change. Before AD 1700, the environment changed as a result of the uplift of the coastal area. However, the lake level rose up after the Hoei earthquake in AD 1707. It might be because the ground had not recovered yet until today.

The monsoon has played typically in Korea. On the other hands, the EASM and EAWM worked quite differently depending on the region between the western and eastern coast of Japan. The EAWM brings high precipitation to the western coast of Japan. In contrary, the Pacific side of Japan has a typical monsoon system. During LIA, the diatom assemblage and total diatom valve were correlated well with solar irradiance and EASM monsoon intensity in Lake Hamana. In contrast, the total diatom valve induced by nutrient decreased during less solar irradiance period in Lake Hamana.

5.2. Future work

The East Asian monsoon seems to be influenced by local factors in Japan than Korea. According to stalagmite data of Fukugaguchi cave, the Siberian High bring moisture when it crosses warm sea water to Japan. That is why the western coast of Japan has a high amount of precipitation during the winter season. On the other hands, the Pacific side of Japan shows typical monsoon dry winter and humid summer. There is no research on why the monsoon works differently between the western and the Pacific side of Japan. I think it might be because of the Foehn wind between western and eastern Japan when the north wind over a mountain from western to eastern Japan, the moisture in air drops before crossing a mountain. However, it is just one of hypothesis based on my results compared with EAWM result. Therefore, many results are needed to understand monsoon activity induced by local factors with many research area along the western coast of Japan.

Appendix 1. The relative percentages of diatom in core HJ02

Depth (m)	Fragilaria brevistriata	Stephanidiscus hantzschii f. tenuis	Cocconeis plancentula	cyclotella atomus	Chaetoceros resting spore	Cocconeis scutellum	Cyclotella striata	Diploneis smithii	Tryblionella compressa	Tryblionella granulata	Psammodictyon panduriforme	Thalassiosira oestrupii	Total diatom per 1 gram
5.7	4.192872117	0	4.402515723	4.26829268	18.0293501	16.77148847	7.966457023	0	0.209643606	0	2.096436059	0	721.5727563
5.8	0.914634146	0	2.43902439	4.24403183	21.03658537	15.24390244	2.134146341	0	1.829268293	0	1.219512195	0	765.9828868
5.9	8.222811671	0	1.061007958	5.52486188	35.0132626	9.549071618	0	0.265251989	0.265251989	0	0	0	885.1427498
6	12.43093923	0	3.591160221	6.18556701	21.54696133	2.209944751	1.933701657	3.314917127	0	0	2.209944751	0	402.9026801
6.02	41.58075601	0	1.374570447	7.61904762	8.24742268	1.030927835	0	0	1.718213058	0	0	0	3028.221778
6.04	70.47619048	0	0.238095238	16.4750958	2.857142857	0.238095238	0	0	0	0	0	0	35750.76609
6.06	58.23754789	0	0.191570881	6.71378092	4.980842912	0	0	0.191570881	0	0	0	0	57036.71329
6.08	73.14487633	0	0	14.0977444	2.237926973	0	0	0	0	0	0	0	138318.6706
6.1	65.78947368	0	0.187969925	5.26315789	3.383458647	0	0	0	0	0	0	0	92650.64437
6.12	67.74193548	0	0	5.04587156	4.584040747	0	0	0	0	0	0	0	81129.47658
6.14	68.69266055	0.114678899	0.229357798	4.96323529	3.555045872	0	0	0	0	0	0	0	68103.71759
6.16	63.14338235	1.011029412	0	4.73083197	6.341911765	0	0	0	0	0	0	0	219797.9798
6.18	57.2593801	1.305057096	0.163132137	7.26256983	6.362153344	0	0	0	0	0	0	0	110569.9856
6.2	57.54189944	0	0.558659218	17.6090468	4.189944134	0	0	0	0	0	0	0	53705.37054
6.22	44.58804523	0	0	2.66875981	8.885298869	0	0	0	0	0	0	0	74830.75435
6.24	71.27158556	0.156985871	0	3.24189526	4.552590267	0	0	0	0	0	0	0	100536.6162
6.26	56.85785536	0	0.249376559	4.30925222	3.49127182	0	0	0	0	0	0	0	79944.17863
6.28	63.75158428	0	0	4.52322738	5.323193916	0	0	0	0	0	0	0	108677.686
6.3	68.21515892	0	0	2.99516908	7.334963325	0	0	0	0	0	0	0	120329.5087
6.32	73.33333333	0.096618357	0.289855072	2.32172471	6.859903382	0	0	0.096618357	0	0	0	0	81676.13636
6.34	51.40961857	0	0.663349917	2.93040293	13.26699834	0	0	0.165837479	0	0	0	0	53954.90336
6.36	53.2967033	0	1.098901099	4.65393795	13.003663	0	0	0	0	0	0	0	51704.54545
6.38	44.98806683	0	1.431980907	5.06329114	21.12171838	0	0	0.119331742	0	0	0	0	95227.27273
6.4	44.93670886	0.210970464	1.265822785	10.989011	16.87763713	0	0	0.210970464	0	0	0	0	46837.94466
6.42	50	0	2.197802198	9.96483001	11.9047619	0	0	0	0	0	0	0	111793.6118
6.44	47.12778429	0	0.703399766	6.64819945	13.01289566	0	0	0	0	0	0	0	81455.3094
6.46	54.57063712	0	1.939058172	11.5693013	16.62049861	0	0	0	0	0	0	0	50027.71619
6.48	48.9117984	0	0.458190149	10.1890756	14.54753723	0	0	0.114547537	0	0	0	0	93589.19383
6.5	49.05462185	0	1.050420168	11.1926606	10.08403361	0	0	0	0	0	0	0	76724.69375
6.52	40.55045872	0	0.366972477	8	14.67889908	0.550458716	0	0	0	0	0	0	37534.43526
6.54	60.85714286	0	0.571428571	2.43161094	13.14285714	0	0	0	0	0	0	0	38243.00699
6.56	65.65349544	0.911854103	0.303951368	2.89532294	5.47112462	0	0	0	0	0	0	0	81274.70356
6.58	67.26057906	1.559020045	0.445434298	3.32541568	11.13585746	0	0	0	0	0	0	0	45556.00649
6.6	6.650831354	0.237529691	0.950118765	6.77966102	8.313539192	0	0	0	0	0	0	0	80744.15036
6.62	46.32768362	0	1.694915254	12.4610592	15.81920904	0	0	0	0	0	0	0	16761.36364
6.64	48.59813084	0	0.934579439	18.2370821	15.57632399	0	0	0	0	0	0	0	15998.80383
6.66	22.79635258	1.215805471	5.775075988	9.52380952	26.74772036	0	0	0	0	0	0	0	10131.80586
6.68	34.3537415	2.380952381	3.741496599	5.72207084	21.08843537	0	0	0	0	0	0	0	14096.66283
6.7	46.32152589	0	3.269754768	11.9205298	28.61035422	0	0	0	0	0	0	0	34184.05365
6.72	41.7218543	1.324503311	1.655629139	7.47863248	22.18543046	0	0	0.331125828	0	0	0	0	25610.58345
6.74	37.60683761	0.213675214	0.427350427	2.82352941	38.88888889	0	0	0	0	0	0	0	52139.03743
6.76	26.82352941	1.411764706	3.529411765	8.20668693	53.17647059	0	0	0.235294118	0	0	0	0	43904.95868
6.78	26.443769	2.127659574	1.215805471	3.22580645	50.45592705	0	0	0.303951368	0	0	0	0	14954.54545

Depth (m)	Fragilaria brevistriata	Stephanidiscus hantzschii f. tenuis	Cocconeis plancentula	cyclotella atomus	Chaetoceros resting spore	Cocconeis scutellum	Cyclotella striata	Diploneis smithii	Tryblionella compressa	Tryblionella granulata	Psammodictyon panduriforme	Thalassiosira oestrupii	Total diatom per 1 gram
6.8	18.11414392	0.248138958	2.729528536	24.3243243	70.22332506	0	0	0.248138958	0	0	0	0	45795.45455
6.82	32.43243243	0	0	6.93333333	25.22522523	0	0	0.3003003	0	0	0	0	38613.17254
6.84	13.6	0.8	1.866666667	18.7165775	65.86666667	0	0	0	0	0	0	0	12952.47306
6.86	6.417112299	8.288770053	2.139037433	7.10128056	51.87165775	0	0	0	0	0	0	0	79439.25234
6.88	10.12805588	1.047729919	2.561117579	8.4548105	67.28754366	0	0	0.232828871	0	0	0	0	65955.15971
6.9	13.41107872	0	2.623906706	2.20820189	68.80466472	0	0	0	0	0	0	0	27067.55051
6.92	8.201892744	0.315457413	1.261829653	7.44047619	83.2807571	0	0	0.315457413	0	0	0	0	33983.70497
6.94	8.333333333	0	0.297619048	12.293578	76.78571429	0	0	0.297619048	0	0	0	0	20750.98814
6.96	16.69724771	0.183486239	3.302752294	9.09090909	55.04587156	0	0	0	0	0	0	0	55794.43079
6.98	14.77272727	0.909090909	1.818181818	9.14396887	57.5	0	0	0.454545455	0	0	0	0	21367.52137
7.02	31.12840467	0	0.389105058	10.5022831	17.70428016	0	0	0	0	0	0	0	23178.21068
7.04	31.05022831	0.228310502	0.456621005	8.90269151	23.05936073	0	0	0	0	0	0	0	88879.87013
7.06	27.12215321	0.621118012	2.48447205	7.32484076	25.46583851	0.207039337	0	0	0	0	0	0	10636.89218
7.08	23.88535032	0.318471338	2.229299363	11.0119048	21.65605096	0.636942675	0	0.636942675	0	0	0	0	11012.90685
7.1	36.01190476	0.297619048	3.571428571	28.5359801	13.98809524	0.595238095	0	0.297619048	0	0	0	0	10785.82435
7.12	12.40694789	0	5.70719603	16.2576687	15.8808933	0.744416873	0	0.496277916	0	0	0	0	15265.15152
7.14	20.24539877	0	2.147239264	13.1868132	35.88957055	0.306748466	0	0	0	0	0	0	16248.00638
7.16	24.45054945	0	2.472527473	17.9220779	22.25274725	0	0	0.274725275	0	0	0	0	35658.30721
7.18	22.5974026	0	3.636363636	3.55029586	23.37662338	0	0	0	0	0	0	0	16203.7037
7.2	34.02368664	0	4.142011834	33.1125828	16.56804734	0	0	0	0	0	0	0	17781.98653
7.22	20.13245033	0	1.986754967	4.08163265	15.89403974	0.132450331	0	0.529801325	0	0	0	0	41247.81469
7.24	4.308390023	0	1.814058957	10.0946372	76.64399093	0	0	0	0	0	0	0	25699.3007
7.26	14.82649842	0	4.100946372	7.57180157	48.89589905	0	0	0	0	0	0	0	14643.38507
7.28	7.049608355	0	3.394255875	3.18906606	63.4464752	0	0	0	0	0	0	0	11513.94901
7.3	13.66742597	0	2.050113895	7.40740741	64.92027335	0	0	0.227790433	0	0	0	0	13065.47619
7.32	26.62037037	0	2.314814815	2.66393443	33.33333333	0.462962963	0	0.462962963	0.231481481	0	0	0	22314.04959
7.34	14.3442623	0	3.483606557	0.27173913	67.41803279	0.204918033	0	0	0	0	0	0	48644.33812
7.36	6.793478261	0	2.717391304	14.3730887	77.17391304	0	0	0	0	0	0	0	23626.09142
7.38	16.81957187	0.917431193	2.140672783	7.23562152	51.98776758	0	0.305810398	0.305810398	0	0	0	0	39530.94778
7.4	11.13172542	0	2.597402597	6.66666667	54.54545455	0	0	0.185528757	0	0	0	0	28356.48148
7.42	4.137931034	0.459770115	8.045977011	1.92307692	63.67816092	0	0	0.459770115	0	0	0	0	40517.88376
7.44	27.56410256	2.884615385	6.08974359	15.7575758	41.66666667	0	0	0.641025641	0	0	0	0	30564.26332
7.46	0.606060606	9.696969697	2.828282828	13.7767221	22.42424242	0	0	0.404040404	0	0	0	0	55147.05882
7.48	13.77672209	11.16389549	2.612826603	17.5895765	31.35391924	0	0	0.237529691	0	0	0	0	23000.43706
7.5	18.89250814	6.51465798	0	31.8766067	34.2019544	0	0	0.651465798	0	0	0	0	4886.045327
7.52	5.65526992	7.197943445	7.455012853	12.2093023	24.16452442	0	0	0.771208226	0	0	0	0	15564.98079
7.54	18.89534884	1.453488372	5.523255814	17.5824176	45.93023256	0.290697674	0	0	0	0	0	0	7361.753124
7.56	14.50549451	1.538461538	3.076923077	9.3676815	44.3956044	0	0	0.21978022	0	0	0	0	13464.72538
7.58	16.39344262	0	3.981264637	15.4929577	42.15456674	0.468384075	0	0.702576112	0	0	0	0	23440.93105
7.6	5.633802817	5.915492958	1.408450704	27.4456522	51.83098592	0	0	0	0	0	0	0	40748.39302
7.62	33.42391304	0	1.902173913	38.2045929	17.93478261	0	0	0	0	0	0	0	59954.38254
7.64	6.680584551	0.626304802	2.087682672	52.6490066	26.93110647	0	0	0.208768267	0	0	0	0	26682.26381
7.66	9.105960265	0.165562914	0.993377483	30.7692308	28.14569536	0	0	0	0	0	0	0	63552.18855

Depth (m)	Fragilaria brevistriata	Stephanidiscus hantzschii f. tenuis	Cocconeis placentula	cyclotella atomus	Chaetoceros resting spore	Cocconeis scutellum	Cyclotella striata	Diploneis smithii	Tryblionella compressa	Tryblionella granulata	Psammodictyon panduriforme	Thalassiosira oestrupii	Total diatom per 1 gram
7.68	10.17369727	3.970223325	1.488833747	36.1842105	41.191067		0	0	0	0	0	0	41632.2314
7.7	19.07894737	4.276315789	1.644736842	26.7647059	21.38157895		0	0	0	0	0	0	6190.941675
7.72	21.47058824	4.705882353	0.294117647	37.1257485	30		0	0	0	0	0	0	8308.895406
7.74	7.185628743	2.395209581	1.796407186	33.9237057	31.43712575		0	0.299401198	0	0	0	0	6487.956488
7.76	16.89373297	0	2.861035422	32.3624595	31.88010899		0	0	0	0	0	0.136239782	30665.10695
7.78	16.18122977	0	2.265372168	22.4747475	25.88996764		0	0	0.323624595	0	0	0	3048.058712
7.8	22.47474747	0.757575758	2.777777778	36.6666667	27.27272727		0	0	0.505050505	0	0	0	5136.986301
7.82	7.857142857	0.238095238	3.80952381	13.6231884	26.66666667		0	0	0.714285714	0	0	0	19803.8476
7.84	14.7826087	0	6.086956522	12.8158845	48.11594203		0	0	0	0.289855072	0	0	5632.836991
7.86	11.73285199	0.722021661	5.9566787	10.2209945	48.73646209	0.180505415		0	0	0	0	0	5427.115987
7.88	5.524861878	0	1.933701657	10.9550562	19.33701657	1.38121547		0	1.657458564	0	0.828729282	0.552486188	5847.386444
7.9	8.426966292	0	1.404494382	13.3949192	35.95505618	1.123595506	1.685393258	2.528089888		0	0	0.280898876	1440.688941
7.92	13.39491917	0	5.773672055	16.3865546	30.25404157	0.230946882	2.309468822	3.926096998		0	0	0	9.923787529
7.94	15.12605042	0	1.260504202	17.5054705	24.3697479	0	1.260504202	2.731092437		0	0	0.630252101	1851.186812
7.96	8.096280088	0.437636761	8.315098468	23.4042553	37.85557987	0	0	0.437636761		0	0	0	8464.931
7.98	9.042553191	0.531914894	1.773049645	19.4444444	40.95744681	0	0	0.177304965		0	0	0	28851.0101
8.02	2.777777778	0.277777778	3.611111111	32.6018809	36.11111111	0	0.277777778	1.388888889		0	0	0	28869.77887
8.06	5.956112853	1.567398119	1.880877743	7.8098472	36.05015674	0	0.313479624	0.626959248		0	0	0	2973.044397
8.1	1.528013582	0.848896435	4.584040747	8.06916427	51.9524618	0.339558574	2.20713073	2.20713073		0	0.848896435	0.679117148	6567.028986
8.14	2.305475504	0	1.152737752	7.2815534	41.21037464	0	7.204610951	2.88184438		0	2.305475504	3.746397695	554.9902005
8.18	1.941747573	0	1.45631068	5.06912442	12.13592233	0.970873786	10.19417476	12.13592233		0	2.427184466	2.427184466	43.89116004
8.22	0	0	0.460829493	11.2482853	22.11981567	0.921658986	6.451612903	6.912442396		0	4.608294931	6.912442396	17.89138712
8.26	0.823045267	0.137174211	3.566529492	0.31347962	62.00274348	0.274348422	1.508916324	1.508916324		0	0.137174211	0.411522634	86.10017776
8.3	3.134796238	0	2.194357367	3.48101266	56.11285266	0.626959248	2.821316614	3.134796238		0	0.940438871	0.940438871	0
8.34	1.265822785	0	1.265822785	0.53191489	63.29113924	0.632911392	1.898734177	2.215189873		0	1.582278481	1.265822785	173.2625944
8.38	10.10638298	0.531914894	5.85106383	9.72644377	52.65957447	0.265957447	1.861702128	0.79787234		0	0.265957447	0.79787234	57.09825236
8.42	5.47112462	0.607902736	5.167173252	2.31884058	55.01519757	0	0	0.607902736		0	0	0	0
8.46	2.028985507	1.15942029	6.666666667		60.28985507	0	0.579710145	1.449275362		0	0	0	173.5188139
													5265.685019
													73.69275461

Appendix 2. The relative percentages of diatom in core 16 Hm-1C and 2C

Depth (cm)	Achnanthisium minutissium	Aulacoseira ambigua	Aulacoseira granulata	Fragilaria capucina	Pseudostaurosira brevistriata	Pseudostaurosira spp.	Ulnaria delicatissima	Cyclotella atomus	Cycltella atomus var.gracilis	Cyclotella spp.	Diploneis smithii	Thalassiosira lineata	total diatom per 1 gram	
24.5	0.906344411	0.302114804	0	0	0.302114804	0	0	4.5317221	32.62839879	5.1359517	1.510574	2.114803625	27108.92711	
25.5	2.395209581	0	0	0	0	0	0	11.077844	23.65269461	10.179641	0.2994012	0.598802395	51903.6519	
26.5	2.98013245	0	0	0	0	1.986754967	0	8.9403974	21.85430464	11.92053	1.3245033	1.655629139	22140.76246	
27.5	13.24503311	0.662251656	0.99337748	0	0.331125828	0	0	3.6423841	15.89403974	7.2847682	0.9933775	2.317880795	25900.51458	
28.5	2.272727273	0	0	0	0.378787879	1.515151515	0	6.0606061		0	8.7121212	0.7575758	6.439393939	13559.32203
29.5	3.691275168	0	0	0	0	1.006711409	0	8.0536913	34.89932886	4.0268456	2.3489933	3.355704698	38156.20999	
30.5	2.02020202	0.673400673	0	0	0	1.346801347	0	24.242424	31.98653199	6.7340067	2.3569024	3.703703704	32530.12048	
31.5	4.632152589	0	0	0	0	0	0	13.351499	23.16076294	9.5367847	0.8174387	2.179836512	19397.463	
32.5	2.96735905	0	0	0	0.296735905	4.154302671	0	18.397626	10.97922849	3.5608309	1.1869436	3.857566766	40311.00478	
33.5	2.027027027	0	0	0	0	2.702702703	0	11.486486	30.40540541	7.4324324	2.3648649	3.716216216	25874.12587	
34.5	0.660066007	0	0.330033	0	0	2.640264026	0	10.231023	6.930693069	8.2508251	7.2607261	7.920792079	7651.515152	
35.5	0.309597523	0	0	0	0	10.52631579	0	14.241486	12.07430341	8.0495356	3.7151703	5.572755418	30909.09091	
36.5	2.972972973	0.810810811	1.08108108	0	1.081081081	1.351351351	0	9.4594595	21.35135135	4.0540541	1.0810811	7.027027027	24732.62032	
37.5	0.327868852	4.590163934	7.54098361	0	0	4.590163934	0	10.491803	9.508196721	9.5081967	2.6229508	0.655737705	40775.40107	
38.5	0.666666667	0	0.66666667	0	0	1.333333333	0	3.3333333	7.666666667	3.6666667	2.6666667	1.333333333	14094.4327	
39.5	3.2	0	0.53333333	0	0	0	2.4	10.4	9.866666667	7.7333333	4.2666667	0.533333333	11837.12121	
40.5	6.23501199	0	0	0	0.239808153	1.438848921	0	15.347722	24.2206235	4.0767386	2.6378897	0.479616307	31990.79402	
41.5	7.01754386	0	0	0	0.350877193	6.315789474	0	7.7192982	8.771929825	12.982456	4.5614035	1.403508772	21956.8567	
42.5	5.780346821	0	0	0	1.156069364	10.98265896	0	16.184971	5.780346821	12.427746	1.1560694	0.867052023	19782.73299	
43.5	5.604719764	0.294985251	0	0	0.294985251	8.259587021	0	7.079646	0.589970501	5.3097345	2.0648968	4.424778761	9511.784512	
44.5	0.722891566	0	0.24096386	0	0	0	0	18.072289	2.409638554	7.2289157	1.686747	6.746987952	22192.51337	
45.5	0	0	0	0	0	3.87755102	0	11.836735	1.632653061	1.6326531	2.4489796	0	19537.48006	
46.5	4.848484848	0	0	0	0.303030303	2.424242424	0	8.7878788	2.424242424	8.7878788	1.5151515	8.787878788	6802.721088	
47.5	7.220216606	0	0.36101083	0	0	1.444043321	0	2.8880866	0.36101083	5.4151625	1.8050542	9.747292419	4937.611408	
48.5	5.34591195	0.314465409	0	0	0	2.51572327	0	4.7169811	3.144654088	10.062893	3.7735849	11.63522013	9325.513196	
49.5	0.323624595	0	0	0	0.647249191	3.236245955	0	13.915858	3.236245955	0.6472492	0	10.67961165	13872.05387	
50.5	1.506024096	0.602409639	0.60240964	0	0.602409639	0	0	4.5180723	3.614457831	0.9036145	0.6024096	9.337349398	5548.128342	
51.5	0	0.638977636	0.63897764	0	0	0	0	6.7092652	0.958466454	5.4313099	2.2364217	0	3436.539306	
52.5	0	0.330033003	0	0	0	2.640264026	0	2.640264	1.320132013	3.630363	0.990099	7.920792079	7870.12987	
53.5	1.020408163	0	0	0	0.680272109	1.360544218	0	3.7414966	1.020408163	4.4217687	1.7006803	8.503401361	5698.778833	
54.5	0.943396226	0	0	0	0.943396226	0	0	9.1194969	11.32075472	2.8301887	0.3144654	3.773584906	4153.605016	
55.5	0.722021661	1.083032491	0	0	0	0	0	0	0.36101083	2.8880866	1.4440433	9.386281588	3546.734955	
56.5	0.829875519	0	0	0	0	1.659751037	0	4.1493776	1.659751037	5.3941909	0.8298755	7.468879668	4815.184815	

Depth (cm)	Achnanthisium minutissium	Aulacoseira ambigua	Aulacoseira granulata	Fragilaria capucina	Pseudostaurosira brevistriata	Pseudostaurosira spp.	Ulnaria delicatissima	Cyclotella atomus	Cyclotella atomus var. gracilis	Cyclotella spp.	Diploneis smithii	Thalassiosira lineata	total diatom per 1 gram
57.5	0	0	0	0	0	0.630914826		0 3.4700315	1.261829653	3.1545741	0.9463722	9.463722397	5297.459893
58.5	0	0	0	0	0	0		0 9.2307692	1.230769231	1.2307692	0.9230769	10.46153846	5371.900826
59.5	0.333333333	0.666666667	0	0	0.333333333	0		0 4.3333333	1.333333333	2	1	5.666666667	5815.080442
60.5	0	0	0	0	0.655737705	0.655737705		0 4.9180328		0 3.9344262	1.9672131	0.327868852	11748.84438
61.5	0.949367089	0	0	0	0	0		0 6.0126582	2.215189873	1.2658228	3.164557	0.316455696	13945.27802
62.5	1.492537313	0	0.29850746	0	0	3.582089552		0 16.716418	1.791044776	4.1791045	1.4925373	0.597014925	10501.5674
63.5	1.239669421	0	0	0	0	1.652892562		0 0.8264463	0.826446281	8.677686	0.8264463	2.479338843	4150.943396
64.5	0	0	0	0	0.340136054	0		0 6.462585	1.360544218	1.0204082	0.6802721	2.721088435	7560.756076
65.5	0	0	0	0	0.3003003	1.801801802		0 3.003003	1.201201201	1.2012012	0.9009009	3.303303303	9475.03201
66.5	0	0	0	0	0.317460317	0		0 0.952381		0 1.5873016	0.952381	0	7575.757576
67.5	0	0	0	0	0	0		0 0.3205128		0 0.9615385	0.3205128	0	23636.36364
68.5	0	0	0	0	0	0		0 1.0238908		0 2.3890785	0.3412969	6.484641638	11998.362
69.5	0	0	0.333333333	0	0	0		0 6.6666667	5.333333333	3.6666667	2.6666667	1.666666667	15151.51515
70.5	0.607902736	0	0	0	0.303951368	0.607902736		0 10.942249	9.726443769	4.5592705	2.4316109	1.823708207	14661.31907
71.5	1.869158879	0	0	0	0.31152648	0		0 17.445483	6.230529595	10.903427	4.6728972	0.62305296	11399.14773
72.5	1.97044335	0	0	0	0	1.477832512		0 14.53202	4.679802956	6.4039409	8.6206897	0.246305419	15573.45608
73.5	0	0	0	0	0	3.03030303		0 21.818182	4.848484848	1.8181818	5.4545455	0	17857.14286
74.5	5.089058524	0	0	0	0	3.307888041		0 22.137405	8.396946565	7.1246819	1.7811705	0	35727.27273
75.5	0.79787234	0	0.79787234	0	0.265957447	9.574468085		0 19.680851	7.978723404	7.4468085	2.6595745	0	21911.42191
76.5	0.336700337	0	0	0	0.673400673	14.47811448		0 18.855219	17.84511785	11.111111	4.3771044	0	39705.88235
77.5	0.550458716	0	0	0	0	9.174311927		0 14.862385	14.31192661	0	2.5688073	0	83975.34669
78.5	0.203665988	0	0	0	0.203665988	10.38696538		0 21.792261	12.83095723	1.4256619	3.4623218	0	40578.5124
79.5	1.590909091	0.227272727	0	0	1.136363636	2.272727273		0 15.909091		15 13.636364	2.0454545	0	31746.03175
80.5	0.977198697	0	0	0	0.325732899	7.817589577		0 3.5830619	15.63517915	13.029316	4.8859935	0	23853.92385
81.5	0.289017341	0	0	0	0	14.73988439		0 9.5375723	16.1849711	2.3121387	4.0462428	0.578034682	24383.36857
82.5	1.063829787	0	0	0	0	6.914893617		0 10.638298	13.56382979	13.829787	4.2553191	0	32246.99828
83.5	0	0	0	0	0	1.690140845		0 10.985915	24.22535211	26.197183	3.3802817	0	56618.81978
84.5	0	0	0	0	0.216450216	0		0 33.333333	11.25541126	0.4329004	4.5454545	0	39622.64151
85.5	1.714285714	0	0	0	1.142857143	5.428571429	0.285714286	4.2857143	5.714285714	6.2857143	2	0	31194.2959
86	0	0	0.31545741	0	0.315457413	9.463722397		0 7.8864353	15.45741325	0.9463722	3.785489	0	24843.26019
87	0.947867299	0.710900474	0.23696682	0	0	2.606635071		0 2.8436019	11.37440758	9.7156398	2.6066351	0.236966825	20625.61095
88	0.598802395	0.299401198	1.79640719	0	0.299401198	4.191616766		0 5.3892216	21.55688623	7.7844311	2.0958084	0	15031.50315
89	0	0	0.68027211	0	0.680272109	3.741496599		0 17.687075	9.183673469	1.7006803	3.0612245	0.340136054	8677.68595

Depth (cm)	Achnanthisidium minutissium	Aulacoseira ambigua	Aulacoseira granulata	Fragilaria capucina	Pseudostaurosira brevistriata	Pseudostaurosira spp.	Ulnaria delicatissima	Cyclotella atomus	Cycltella atomus var.gracilis	Cyclotella spp.	Diploneis smithii	Thalassiosira lineata	total diatom per 1 gram	
90		0	0	0.97402597	0	0.649350649	1.948051948	0	10.714286	15.25974026	8.4415584	1.2987013	7.467532468	16470.58824
91		0	0.769230769	0.51282051	0	0.512820513	0	0	23.076923	12.56410256	5.1282051	4.1025641	0	7162.534435
92		0	0.613496933	2.14723926	0	0	1.226993865	0	9.202454	17.48466258	13.803681	6.1349693	0.920245399	10435.33931
93		0	2.641509434	1.13207547	0	0.377358491	3.018867925	0	21.132075	16.60377358	3.0188679	8.3018868	0	3650.137741
94	0.566572238	1.416430595	2.54957507	0	0	1.133144476	0	11.048159	9.065155807	12.181303	5.0991501	0.283286119	6171.328671	
95		0	0.285714286	0.57142857	0	0.285714286	0.571428571	0	10.571429	32	10.857143	2.2857143	3.142857143	13955.3429
96		0	0.729927007	2.91970803	0	0.729927007	0	0	23.722628	0	1.459854	1.8248175	0	6732.186732
97		0	0.754716981	5.66037736	0	0.754716981	6.79245283	0	7.1698113	1.132075472	3.0188679	1.1320755	0.377358491	19119.76912
98	0.675675676	2.027027027	3.71621622	0	0.337837838	4.391891892	0	12.5	2.702702703	1.6891892	0.6756757	0.337837838	7732.497388	
99	0.338983051	2.711864407	4.06779661	0	1.016949153	1.355932203	0	4.0677966	7.457627119	3.3898305	3.0508475	0.677966102	6841.372913	
100		0	0	2.38095238	0	2.083333333	0	0	27.083333	0	1.7857143	0.8928571	0.892857143	11107.43802
101		0	1.612903226	1.84331797	0	0	4.147465438	0	17.281106	25.57603687	1.1520737	0.921659	0	41775.40107
102	0.230946882	2.309468822	8.08314088	0.692841	0	0	13.85681293	0	17.551963	0	0.9237875	0.9237875	0	44284.09091
103		0	8.55704698	0	0.167785	2.348993289	13.75838926	0	10.402685	2.181208054	0	0.1677852	0	25665.07177
104	1.049868766	21.25984252	19.160105	3.412073	1.312335958	14.43569554	0	6.0367454	9.711286089	3.6745407	0	0	0	37110.38961
105	0.634920635	13.96825397	23.1746032	0.952381	1.904761905	6.984126984	0	13.650794	3.492063492	0	0.3174603	0	0	26033.05785
106	0.526315789	15.26315789	15	1.315789	1.578947368	12.89473684	0	10.526316	8.421052632	2.3684211	0	0	0	38383.83838
107	1.654846336	23.1678487	18.6761229	1.891253	0.472813239	5.910165485	0	11.583924	4.491725768	3.3096927	0.2364066	0	0	50158.10277
108	1.591511936	25.99469496	33.9522546	2.122016	2.122015915	15.64986737	0	2.3872679	0.795755968	1.061008	0	0	0	37163.19825
110	3.801169591	28.65497076	30.1169591	1.169591	2.923976608	12.28070175	0	0.5847953	1.461988304	0.877193	0.2923977	0	0	38331.25778
112	5.607476636	31.07476636	30.1401869	3.504673	3.738317757	9.579439252	0	2.3364486	0.934579439	0.7009346	0.2336449	0	0	54715.90909
114	0.699300699	24.82517483	41.2587413	1.398601	4.195804196	9.090909091	0	0.6993007	0.34965035	1.048951	0.6993007	0	0	30789.47368
116	0.197628458	15.81027668	39.7233202	1.976285	3.359683794	13.43873518	0	1.1857708	0.790513834	2.3715415	0.3952569	0	0	51750
118	1.528384279	13.5371179	29.0393013	2.401747	7.205240175	23.1441048	0	2.1834061	1.746724891	2.4017467	0	0	0	23716.916
120	0.299401198	7.185628743	19.1616766	3.592814	6.886227545	20.95808383	0	6.5868263	2.694610778	0.5988024	0.2994012	0	0	37434.62017
122		0	3.827751196	26.3157895	0.717703	8.612440191	34.21052632	0	0.9569378	0.717703349	1.4354067	0.4784689	0	20357.14286
124	0.242718447	2.669902913	23.7864078	1.699029	10.19417476	25.72815534	0	1.6990291	1.45631068	2.184466	0.4854369	0	0	22776.41278
126	0.673400673	4.04040404	13.8047138	2.020202	14.81481481	29.96632997	0	2.6936027	0.336700337	1.3468013	0	0	0	13278.68852
128		0	0.984251969	11.023622	3.149606	8.464566929	38.58267717	0	1.7716535	1.377952756	0.984252	0.7874016	0	23090.90909
130		0	1.420959147	14.0319716	1.420959	6.927175844	39.07637655	0	1.7761989	2.309058615	0.8880995	0.1776199	0	21935.06494
132	0.242718447	0.242718447	14.0776699	0.970874	12.13592233	36.65048544	0	2.9126214	0	0.7281553	0.2427184	0	0	1546.288574
134		0	0.495049505	11.0561056	0.330033	8.580858086	41.41914191	0	2.8052805	1.155115512	1.650165	0	0	42742.94671
136	0.205761317	0.205761317	12.7572016	0.205761	6.995884774	28.18930041	0	4.7325103	0.205761317	2.6748971	0	0	0	39763.63636

Depth (cm)	Achnanthisidium minutissium	Aulacoseira ambigua	Aulacoseira granulata	Fragilaria capucina	Pseudostaurosira brevistriata	Pseudostaurosira spp.	Ulnaria delicatissima	Cyclotella atomus	Cyclotella atomus var. gracilis	Cyclotella spp.	Diploneis smithii	Thalassiosira lineata	total diatom per 1 gram
138	0	0.574712644	11.1111111	0.574713	7.088122605	32.37547893	0	3.256705	0.383141762	1.532567	0.3831418	0	30506.49351
140	0	0.980392157	10.4575163	0.980392	5.065359477	30.06535948	0	3.4313725	0.816993464	0.9803922	0	0	53841.64223
142	0	1.268115942	14.673913	0.905797	9.239130435	30.61594203	0	2.3550725	0.362318841	0.5434783	0.7246377	0	37636.36364
144	0	2.421307506	15.9806295	1.452785	6.053268765	31.96125908	0	1.4527845	1.210653753	0	0.4842615	0	17784.689
146	0	3.405572755	16.7182663	0.309598	10.52631579	33.74613003	0	0	0	0	0.3095975	0	20646.30682
148	0	3.84	11.52	0.32	6.88	35.36	0	0.32	0.16	0.48	0.16	0	37055.33597
150	0	3.715170279	9.59752322	0.619195	8.66873065	28.48297214	0	6.8111455	0.92879257	0	0.3095975	0	2493.138937
152	0	3.206412826	5.41082164	1.402806	16.43286573	25.65130261	0	2.004008	0	0.8016032	0.6012024	0	30468.11398
154	0	4.282655246	5.56745182	0.428266	12.63383298	23.12633833	0	1.7130621	1.070663812	0.856531	0.6423983	0	25472.72727
156	0.279329609	5.027932961	5.58659218	0	8.100558659	18.15642458	0	1.9553073	2.51396648	2.2346369	0.8379888	0	2789.61039
158	1.232032854	6.981519507	3.08008214	0	7.802874743	14.16837782	0	7.8028747	4.722792608	2.4640657	0	0	40658.62709
160	1.893287435	16.00688468	7.91738382	1.032702	4.819277108	12.73666093	0	5.6798623	5.163511188	2.7538726	0.172117	0	27319.74922
162	2.419354839	17.20430108	6.72043011	0.537634	3.225806452	12.90322581	0	4.0322581	5.107526882	0.8064516	0.2688172	0	46115.70248
164	3.270440252	23.39622642	7.42138365	0.503145	3.270440252	14.71698113	0	2.1383648	3.270440252	1.3836478	0.1257862	0	80303.0303
166	4.18079096	26.32768362	9.60451977	0.451977	3.95480226	12.20338983	0	0.4519774	2.146892655	1.2429379	0	0	86201.2987
168	0.992063492	27.18253968	20.8333333	0.595238	1.587301587	10.11904762	0	1.5873016	0.992063492	0.1984127	0.1984127	0	64431.81818
170	0.243902439	28.65853659	22.3170732	1.341463	0.975609756	7.195121951	0	2.4390244	0.975609756	0.2439024	0	0	106493.5065
172	0.178890877	26.83363148	11.4490161	4.651163	1.431127013	10.55456172	0	3.2200358	1.788908766	0.3577818	0.3577818	0	62652.55293
174	0.127226463	29.77099237	12.3409669	3.180662	1.526717557	8.651399491	12.46819338	1.5267176	1.272264631	0.2544529	0	0	80386.36364
176	0.301659125	30.31674208	22.0211161	1.659125	1.508295626	3.619909502	6.938159879	0.1508296	0.150829563	1.5082956	0.1508296	0	80963.36499
178	0.444049734	26.19893428	17.6731794	1.953819	0.79928952	3.108348135	26.55417407	0.2664298	0.26642984	0.6216696	0	0	135481.2834
180	1.090188305	47.57185332	11.0009911	2.180377	0.594648167	2.874132805	17.44301288	0	0.198216056	0.4955401	0.099108	0	107213.6954
182	0.648648649	45.18918919	13.9459459	1.189189	0.540540541	3.243243243	21.18918919	0	0	0.5405405	0	0	106594.1101
184	1.132404181	39.80836237	12.0209059	1.219512	1.219512195	5.052264808	22.12543554	0	0.087108014	0	0	0	103216.7832
186	0.092592593	37.96296296	8.7962963	0.462963	1.203703704	4.166666667	31.2962963	0	0	0.462963	0.0925926	0	97102.8971
188	0.505050505	28.78787879	9.5959596	0.841751	0.336700337	4.208754209	41.41414141	0	0	0.6734007	0	0	110454.5455
192	1.111111111	39.16666667	5.55555556	8.888889	1.111111111	2.222222222	23.05555556	0	0	1.1111111	0.2777778	0	77511.96172
196	0.3125	42.5	8.4375	11.5625	2.1875	5.625	15	0	0	0.9375	0	0	96969.69697
200	0.729927007	45.25547445	13.5766423	7.883212	1.02189781	2.335766423	7.591240876	0	0	0.729927	0	0.145985401	109893.0481
204	3.052064632	39.85637343	3.9497307	4.667864	1.436265709	3.590664273	22.98025135	0	0	0.5385996	0	0	157147.3354
208	1.986754967	31.78807947	6.62251656	4.304636	0.993377483	0	37.74834437	0	0	0	0	0	107430.83
212	5.660377358	33.15363881	9.16442049	1.347709	0.539083558	6.199460916	31.53638814	0	0	0	0	0	63238.63636
216	14.08934708	22.68041237	6.52920962	0.343643	0.687285223	7.903780069	29.89690722	0	0	0	0	0	110739.9577

Depth (cm)	Achnanthisidium minutissimum	Aulacoseira ambigua	Aulacoseira granulata	Fragilaria capucina	Pseudostaurosira brevistriata	Pseudostaurosira spp.	Ulnaria delicatissima	Cyclotella atomus	Cyclotella atomus var. gracilis	Cyclotella spp.	Diploneis smithii	Thalassiosira lineata	total diatom per 1 gram
220	0.215982721	38.44492441	13.6069114	7.559395	1.079913607	3.887688985	17.49460043	0	0	0.4319654	0	0	76528.92562
224	0.558659218	33.89199255	11.5456238	5.586592	0.186219739	0	21.04283054	0	0	0.3724395	0.1862197	0	209220.7792
228	1.066666667	35.2	10.9333333	1.333333	0.533333333	5.866666667	13.33333333	0.2666667	0	1.8666667	0	0	48701.2987
232	0.947867299	49.52606635	12.5592417	1.184834	0.236966825	0	6.63507109	0.2369668	0.236966825	2.8436019	0	0	90861.24402
236	3.812824957	46.10051993	12.9982669	0.17331	0.866551127	1.213171577	10.22530329	0	0.173310225	1.559792	0.1733102	0	108526.6458
240	8.287292818	61.32596685	6.07734807	0	0.552486188	2.209944751	7.458563536	0	0.276243094	1.3812155	0	0	100400.6163
244	38.2566586	32.92978208	3.99515738	0	1.694915254	1.089588378	4.963680387	0	0	1.8159806	0	0	168954.5455
248	18.94736842	47.71929825	5.26315789	0	1.754385965	0	9.824561404	0	0	3.1578947	0.3508772	0	67588.93281
252	36.85674548	19.47148818	8.20584145	0	0.417246175	2.64255911	2.781641168	0	1.390820584	8.6230876	0.4172462	0	156872.7273
256	8.053691275	39.82102908	14.0939597	0.447427	0.447427293	6.263982103	5.81655481	0	0.894854586	3.1319911	0	0	74638.21892
260	8.653846154	15.96153846	18.6538462	0.576923	0.384615385	6.923076923	10	0.1923077	1.153846154	0	0	0	77355.3719
264	15.82089552	16.71641791	11.641791	0.597015	0.597014925	7.76119403	11.04477612	0.8955224	5.074626866	7.1641791	0	0	58317.2147
268	1.937406855	15.05216095	25.0372578	2.831595	1.490312966	4.470938897	16.24441133	0	0	1.7883756	0.1490313	0	119347.8261
272	19.33471933	0.623700624	6.86070686	1.039501	4.781704782	17.87941788	6.652806653	0.6237006	3.118503119	5.4054054	0.4158004	0	40994.31818
276	30.57324841	0	5.52016985	0.849257	4.883227176	12.7388535	8.280254777	1.2738854	2.123142251	6.1571125	0	0	40779.22078
280	34.15384615	0.615384615	5.84615385	0	6.769230769	11.38461538	2.461538462	3.3846154	4.615384615	4.6153846	0	0	49242.42424
284	28.5106383	0.638297872	3.40425532	2.978723	5.106382979	9.787234043	4.255319149	1.9148936	6.382978723	9.5744681	0.212766	0	52319.10946
288	15.04424779	0.589970501	0.88495575	0.884956	4.12979351	16.81415929	6.194690265	9.1445428	6.784660767	8.5545723	0	0	79246.75325
292	23.66666667	0.333333333	1.33333333	1.333333	4.333333333	14	4	4.6666667	5	6.6666667	0.3333333	0	29933.48115
296	9.268292683	0.487804878	0	0	10.48780488	21.46341463	0.487804878	5.3658537	1.219512195	4.6341463	0.2439024	0	26004.22833
298	11.83098592	0.563380282	0	0.84507	7.042253521	22.53521127	0.563380282	10.422535	2.253521127	4.2253521	0.2816901	0	31231.67155
300	8.653846154	0	0	0.320513	9.294871795	18.58974359	0.961538462	17.628205	3.525641026	4.1666667	0.6410256	0	34036.36364
302	4.794520548	0.342465753	0	1.369863	6.506849315	15.4109589	3.082191781	27.39726	4.109589041	4.4520548	0	0	45506.49351
304	0	0	0	0.222717	5.79064588	16.48106904	0.222717149	34.075724	1.113585746	5.1224944	0.4454343	0	41276.81307
306	0.705882353	0	0	0.470588	8.470588235	19.76470588	0.470588235	24	5.176470588	7.2941176	0.2352941	0	66233.76623
308	0.198019802	0	0.59405941	0.19802	2.97029703	10.2970297	0.792079208	44.158416	3.366336634	5.1485149	0.3960396	0	50082.64463
310	0.568181818	0	0	0.284091	4.261363636	17.04545455	0.568181818	38.352273	4.545454545	5.9659091	0.5681818	0	61276.59574
312	0.15503876	0	0	0	4.651162791	8.992248062	1.395348837	45.271318	4.651162791	6.5116279	0.4651163	0	85809.31264
314	0	0	0	0	2.444987775	5.378973105	1.95599022	66.01467	3.422982885	3.6674817	0	0	69715.90909
316	0.196078431	0	0	0	0.588235294	1.960784314	1.960784314	79.607843	1.568627451	1.7647059	0.1960784	0	198701.2987
318	0	0	0	0.591716	2.366863905	5.621301775	2.366863905	63.017751	1.775147929	4.4378698	0.295858	0	122909.0909
320	0	0	0.26525199	0	2.387267905	10.0795756	1.591511936	54.376658	4.24403183	6.8965517	0.795756	0	104560.8629
322	0	0	0	0.232558	2.325581395	9.302325581	3.953488372	56.744186	2.093023256	4.6511628	0.2325581	0	74854.9323

Depth (cm)	Achnanthyidium minutissimum	Aulacoseira ambigua	Aulacoseira granulata	Fragilaria capucina	Pseudotaurosira brevistriata	Pseudotaurosira spp.	Ulnaria delicatissima	Cyclotella atomus	Cyclotella atomus var. gracilis	Cyclotella spp.	Diploneis smithii	Thalassiosira lineata	total diatom per 1 gram
324	0	0	0	0.628931	3.5639413	8.595387841	4.192872117	51.991614	3.354297694	4.6121593	0.4192872	0	90761.09937
326	0	0	0	0.45045	1.576576577	9.684684685	2.477477477	59.459459	1.801801802	6.0810811	0.2252252	0	142459.893
328	0.361663653	0.180831826	0	0.180832	0.542495479	11.57323689	1.446654611	55.877034	4.159132007	5.9674503	0	0	113113.6364
330	0.209643606	0	0	0.209644	1.467505241	6.603773585	0.104821803	64.046122	2.51572327	6.0796646	0.3144654	0	148675.3247
332	0.173611111	0	0	0.347222	1.388888889	3.645833333	1.041666667	65.625	3.472222222	6.0763889	0.3472222	0	224415.5844
334	0	0	0	0.759013	1.328273245	4.743833017	0.569259962	69.829222	4.554079696	2.0872865	0.1897533	0	183481.6248
336	0.457317073	0	0.15243902	0.304878	1.524390244	5.640243902	1.829268293	63.567073	5.182926829	6.25	0	0	191688.3117
338	0	0	0	0.440529	0.440528634	2.202643172	19.82378855	57.709251	3.964757709	4.5521292	0	0	222872.7273
340	0.265957447	0	0	0	2.127659574	4.255319149	0	67.553191	5.319148936	5.0531915	0	0	125565.8627
342	0.249376559	0	0	0.124688	1.122194514	3.740648379	0.748129676	61.346633	6.483790524	7.2319202	0	0	238611.5702
344	9.10623946	0	0	2.360877	3.541315346	18.21247892	2.360876897	17.706577	15.5143339	4.2158516	0.5059022	0	127679.4258
346	17.71929825	0	0	1.22807	1.754385965	6.666666667	0	31.052632	6.315789474	5.2631579	0.5263158	0	84793.38843
348	0.580270793	0	0	0.580271	2.321083172	5.02901354	7.543520309	40.618956	3.868471954	4.8355899	0.1934236	0.193423598	98372.09302
350	0.299401198	0	0	0	1.497005988	9.281437126	0	36.077844	1.646706587	3.742515	0.1497006	0	127103.5941
352	0	0	0	0.26178	2.617801047	17.27748691	6.544502618	36.910995	3.403141361	3.6649215	0	0.261780105	97670.45455
354	0.23923445	0	0	0	0.4784689	4.545454545	0.4784689	50.239234	1.913875598	5.2631579	0.2392344	0	87692.30769
356	0	0	0	0.362319	0.543478261	1.630434783	0	71.195652	2.898550725	3.2608696	0	0	130909.0909
358	0	0	0	0	0	0.867678959	0	60.954447	4.555314534	2.8199566	0	0	125727.2727
360	0.289017341	0	0	0	0	0.289017341	1.156069364	54.046243	4.046242775	9.2485549	0.2890173	0	48391.60839
362	1.428571429	0	0.57142857	1.428571	1.714285714	8	3.714285714	38.285714	0.285714286	5.7142857	0.2857143	0	46944.85842
364	1.038575668	0	0.74183976	0.445104	1.928783383	13.94658754	6.379821958	30.563798	2.077151335	5.9347181	0.148368	0	68931.81818
366	2.982107356	0.198807157	0.39761431	0.994036	0.994035785	6.75944334	5.367793241	36.978131	2.982107356	5.9642147	0.3976143	0	72200.95694
368	3.504043127	0	0.53908356	0	2.964959569	10.78167116	5.39083558	34.770889	3.773584906	8.3557951	0.2695418	0	94857.95455
370	2.952755906	0	0.39370079	1.377953	2.755905512	8.267716535	3.346456693	31.496063	3.74015748	5.1181102	0.3937008	0	86590.90909
372	2.337228715	0	0.66777963	1.001669	1.335559265	6.844741235	5.008347245	39.899833	4.340567613	5.6761269	0.3338898	0	111384.2975
376	3.527815468	0.13568521	0.27137042	1.085482	2.849389417	9.905020353	4.613297151	37.449118	4.748982361	7.5983718	0.2713704	0	113773.5849

Appendix 3. The relative percentages of diatom in core RYU

	Aulacoseira	Gomphonema	Hantzschia	Humidophila	Navicula	Pseudotaurosira	Ulnaria	Cyclotella	Cyclotella	Cyclotella	total diatom	
Depth (cm)	granulata	spp.	amphioxys	contenta	radiosa	spp.	ulne	meneghiniana	spp.	caspia	per 1 gram	
0	10.1744186	0.290697674		0	0	0	71.80232558	0	0.290697674	3.779069767	0	10320000
10	19.21568627	0.392156863		0	0	0	54.11764706	0.3921569	2.352941176	7.843137255	0	7650000
20	41.55251142	0.456621005		0	0	0	46.57534247	0.456621	0	0	0	6570000
30	58.93536122	0.380228137		0	0	0	19.01140684	1.1406844	9.885931559	0	0	1578000
40	22.01834862	0.458715596		0	0	0.4587156	44.03669725	0.9174312	0	9.633027523	0	6540000
50	24.3902439	1.219512195		0	0	0.81300813	61.38211382	3.6585366	0	1.219512195	0	3690000
60	2.702702703	1.158301158		0	0	0	80.30888031	0.7722008	0.386100386	6.177606178	0	7770000
65	0	0.36900369		0	0	0	69.74169742	3.3210332	14.02214022	0	0	8130000
70	5.531914894	0		0	0	0.85106383	38.72340426	0.8510638	37.44680851	5.531914894	0	7050000
75	17.17451524	0		0	0	0	38.22714681	8.5872576	10.8033241	15.51246537	0	10830000
80	19.33085502	0		0	0.371747212	0	72.49070632	1.1152416	3.345724907	0.371747212	0	8070000
90	24.43609023	0.37593985		0	0.751879699	1.5037594	64.28571429	1.8796992	1.127819549	0	0	7980000
100	4.166666667	0.347222222		0	0	2.777777778	88.88888889	1.0416667	0	0	0	3456000
110	0	0.408163265	0.408163265		0	0	88.97959184	2.8571429	0	0.408163265	0	7350000
120	0	1.271186441		0	0	9.3220339	73.72881356	1.6949153	0	1.694915254	0	7080000
125	0	0.4048583		0	0	3.2388664	81.78137652	2.4291498	1.214574899	0	6.477732794	7410000
130	0	0		0	0	0	0	0	0	0	93.88646288	3435000
135	6.41509434	1.132075472		0	0	3.01886792	64.1509434	10.566038	0.377358491	0	3.773584906	3180000
140	10.9375	0.78125	0.78125	0.390625	0.390625		67.578125	4.296875	1.5625	6.25	0	3072000
150	2.43902439	2.032520325		0	0	1.62601626	66.2601626	11.788618	0.406504065	2.43902439	0	3690000
160	4.135338346	1.879699248		0	0	4.5112782	68.04511278	3.7593985	0.37593985	2.631578947	0	3192000
170	8.097165992	0		0	0	4.4534413	64.37246964	6.0728745	0.4048583	2.429149798	0	3705000
180	6.818181818	6.060606061		0	0	1.51515152	50.37878788	8.7121212	0.378787879	2.272727273	0	3168000
190	19.24528302	1.886792453		0	0	3.39622642	50.56603774	11.320755	0	0.377358491	0	3975000
195	7.117437722	3.914590747		0	0	6.04982206	49.82206406	17.793594	0	0	0	2107500
200	19.24528302	1.886792453		0	0	3.39622642	50.56603774	11.320755	0	0.377358491	0	3975000
205	1.556420233	2.33463035		0	0	8.17120623	31.90661479	6.614786	0.389105058	0	0	2202857.143
210	0	5.447470817		0	0	7.39299611	35.79766537	0.3891051	1.556420233	0	0	1542000
215	0	1.70212766		0	0	8.5106383	73.61702128	2.1276596	0.425531915	0	0	2820000
220	0	0	33.33333333		0	0	0	0	0	0	0	4500
225	0	3.649635036		0	0	21.1678832	39.41605839	3.649635	0.729927007	0	0	822000

Depth (cm)	Aulacoseira granulata	Gomphonema spp.	Hantzschia amphioxys	Humidophila contenta	Navicula radiosa	Pseudostaurosira spp.	Ulnaria ulne	Cyclotella meneghiniana	Cyclotella spp.	Cyclotella caspia	total diatom per 1 gram
230	0	0	26.92307692	3.846153846	3.84615385	0	0	0	0	0	26000
235	0	0	30.3030303	15.15151515	0	0	0	0	0	0	39600
240	0	0	12.5	0	12.5	25	31.25	0	0	0	19200
245	0	5.405405405	8.108108108	0	5.40540541	0	16.216216	0	0	0	55500
250	0	0	67.64705882	0	0	0	0	2.941176471	0	0	40800
255	0	0	35	0	0	0	0	0	0	0	24000
260	0	0	21.42857143	0	0	0	0	0	0	0	33600
265	0	0	22.22222222	0	0	0	0	0	0	0	10800
268.5	0	0	33.33333333	0	0	0	0	0	0	0	18000
275	1.162790698	3.875968992	0	0	0.3875969	68.21705426	10.077519	0	0	0	7740000
280	0	0	0	0	0	0	100	0	0	0	1200
285	0	0	0	0	0	0	0	0	0	0	1200
290	0	1.587301587	0	0	0	0	1.5873016	4.761904762	0	0	378000
295	0	0	1.224489796	0	0.81632653	75.10204082	1.6326531	0.408163265	0	0	1837500
300	0	1.639344262	0	0	1.63934426	89.3442623	0	1.229508197	0	0	7320000
305	0	1.304347826	0	0	1.73913043	81.30434783	0	0	0	0	1725000
310	0	5.454545455	0	0	0	58.18181818	2.7272727	2.727272727	0	0	132000
315	0.436681223	0.436681223	0	0	0.43668122	93.44978166	0	0	0	0	2748000
321	0	0	0	0	14.2857143	21.42857143	0	0	0	0	16800
325	0	0	0	0	0	33.33333333	8.3333333	0	0	0	14400
340	22.22222222	0	0	0	0	22.22222222	22.222222	0	0	0	10800
345	0	3.333333333	0	0	3.33333333	23.33333333	6.6666667	0	0	0	90000
350	2.684563758	1.006711409	0	0	1.00671141	61.0738255	4.6979866	3.355704698	0	0	3576000
355	0	0	23.4375	0	0	34.375	7.8125	0	0	0	192000
360	1.265822785	8.860759494	0	0	6.32911392	29.11392405	10.126582	0	0	0	237000
365	2.577319588	0	0.515463918	0.515463918	16.4948454	29.89690722	18.041237	0	0	0	1164000
370	0	0	18.18181818	0	0	0	0	9.090909091	0	0	16500
375	0	2.469135802	0	0	5.76131687	64.19753086	5.3497942	0	0	0	2916000
380	0	0	0	0	0	71.77419355	1.6129032	1.612903226	0	0	744000
385	0	0	0	0	0	42.55319149	2.1276596	0	0	0	70500
390	0	3.47826087	0	0	16.5217391	24.34782609	0	0	0	0	1380000

	Aulacoseira	Gomphonema	Hantzschia	Humidophila	Navicula	Pseudostaurosira	Ulnaria	Cyclotella	Cyclotella	Cyclotella	total diatom	
Depth (cm)	granulata	spp.	amphioxys	contenta	radiosa	spp.	ulne	meneghiniana	spp.	caspia	per 1 gram	
395	14.28571429		0	28.57142857	7.142857143	0	0	0	0	0	21000	
400		0	0	0	0	8.33333333	18.45238095	3.5714286	5.357142857	0	2016000	
405		0	0	0	0	3.84615385	39.42307692	2.8846154	2.884615385	0	1248000	
410		8	2	0	0	4	38	6	0	0	150000	
415		0	0	0	0.704225352	2.81690141	0	0	0	0	1704000	
420		0	0	0	2.702702703	6.75675676	40.54054054	5.4054054	0	0	444000	
425	1.351351351		0	5.405405405	0	4.05405405	40.54054054	2.7027027	2.702702703	0	222000	
430	2.02020202	1.01010101		0	3.03030303	0	44.44444444	7.0707071	2.02020202	0	198000	
435		0	4.255319149	10.63829787	6.382978723	0	0	8.5106383	0	12.76595745	0	70500
440		0	5.084745763	0	0	3.38983051	37.28813559	8.4745763	0	0	0	354000
445		0	7.317073171	0	0	9.75609756	0	0	41.46341463	0	0	123000
450		0	6.578947368	0.657894737	0	25	31.57894737	0	4.605263158	0	0	912000
455		0	0.930232558	0	0	4.18604651	80.46511628	0.4651163	0	0	0	6450000
465		0	0	0	0	7.40740741	46.2962963	1.8518519	0	0	0	324000
470		0	0	0	4.347826087	0	76.08695652	0	0	0	0	69000
475		0	0	17.80821918	0	0	54.79452055	4.109589	0	0	0	109500
480	2.06185567	1.030927835	1.030927835		0	4.12371134	67.01030928	0	2.06185567	0	0	582000
485		0	0.35971223	0	0	5.39568345	78.77697842	0	0	0	0	8340000
490		0	0.456621005	0	1.369863014	3.65296804	89.49771689	0	0.913242009	0	0	2628000
495		0	0	21.21212121	33.33333333	6.06060606	39.39393939	0	0	0	0	49500
500		0	7.142857143	4.761904762	4.761904762	2.38095238	52.38095238	0	0	0	0	63000
507		0	0	0	2.222222222	8.88888889	66.66666667	8.8888889	0	0	0	67500
511		0	0.943396226	0	0	0.47169811	97.16981132	0	0	0	0	12720000
515		0	0	0.446428571	0	2.23214286	94.64285714	0	0	0	0	6720000
520		0	0	0	0	4.14746544	93.5483871	0.921659	0	0	0	13020000
525		0	0	0	5.263157895	0	36.84210526	0	15.78947368	0	0	19000
530		0	1.260504202	0	0	0	80.67226891	0.4201681	1.680672269	10.08403361	0.420168067	2856000
535		0	0.806451613	2.419354839	2.419354839	3.22580645	81.4516129	3.2258065	1.612903226	0	0	372000
540		0	0	8.695652174	5.797101449	1.44927536	77.53623188	0	0	0.724637681	0	207000
545		0	0	0	0	5.33980583	77.18446602	12.135922	0	0	0	2472000
550		0	0	0	0	3.44827586	70.68965517	6.8965517	0	0	0	87000

Depth (cm)	Aulacoseira granulata	Gomphonema spp.	Hantzschia amphioxys	Humidophila contenta	Navicula radiosa	Pseudostaurosira spp.	Ulnaria ulne	Cyclotella meneghiniana	Cyclotella spp.	Cyclotella caspia	total diatom per 1 gram
555	0	0.684931507	0	0.684931507	8.21917808	50	2.739726	28.76712329	0	0	876000
560	0	0	3.731343284	2.985074627	0	60.44776119	0	0	0	0	201000
565	0	0	0	0	0	29.48717949	0	17.94871795	0	0	117000
570	0	0	0.383141762	0	3.44827586	90.03831418	0	5.363984674	0	0	1957500
575	0	0	0	0.877192982	0.87719298	84.64912281	3.5087719	1.315789474	1.754385965	0	2736000
580	0	0	0	0	2.41935484	85.08064516	0	4.838709677	0	0	2976000
585	0	0	0	0	2.45398773	72.39263804	8.5889571	0	10.42944785	0	489000
590	0	0	2.272727273	4.545454545	4.54545455	65.90909091	2.2727273	0	0	0	66000
594	0	0	0	0.85106383	1.70212766	82.12765957	0	0.85106383	5.106382979	0	7050000
595.5	2.083333333	0	0	0	0	62.5	0	0	19.58333333	0	3600000
610	0	0	0	0	0	95.21912351	0	2.788844622	0	0	7530000
620	0	0.440528634	0	0	3.52422907	87.2246696	0.8810573	0	0	0	6810000
630	0	0	0	0	0	83.71212121	0.7575758	0.75757578	3.787878788	0	7920000
640	0	0	0	0	0	80.2955665	0.9852217	5.911330049	0	0	2436000
650	0	0	0	0	0	74.23580786	2.6200873	2.620087336	0	2.620087336	6870000
660	0	0	0	0	0	58.97435897	2.5641026	0	0	0	936000
670	0	0	0	0	0	78.83211679	2.919708	0	0	0	1644000
680	0	0	0	0	0	61.45454545	2.9090909	10.18181818	0	0	4125000
690	0	1.020408163	0	0	2.04081633	74.48979592	11.22449	3.571428571	0	0	2352000
695	0	0	0	0	0	24.89451477	0	0	0	38.39662447	3555000
700	0	0	0	0	1.73160173	31.6017316	0	0	0	57.57575758	13860000
705	0	0	0	0	0	10.63829787	0	0	0	76.59574468	14100000
710	0	0	0	0	0	63.71308017	0	0	0	14.76793249	7110000
715	0	0	0	0	0	0	0	0	0	75.92592593	12960000
720	0	0	0	0	0	0	0	0	0	66.80851064	7050000
730	0	0	0	0	0.92165899	3.686635945	0	0	0	89.86175115	13020000
740	0	0	0	0	0	3.720930233	0	0	0	85.11627907	6450000
745	0	0	0	0	0	17.77777778	0	0	0	73.33333333	6750000
750	0	0	0	0	0	48.86363636	8.5227273	0	0	0	2112000
755	0	0	0.393700787	0	0.39370079	14.56692913	0	1.181102362	0	71.65354331	7620000
760	0	0	0	0	0	8.571428571	0	1.428571429	0	24.28571429	1680000

Depth (cm)	Aulacoseira granulata	Gomphonema spp.	Hantzschia amphioxys	Humidophila contenta	Navicula radiosa	Pseudostaurosira spp.	Ulnaria ulne	Cyclotella meneghiniana	Cyclotella spp.	Cyclotella caspia	total diatom per 1 gram
765	0	0.427350427	0	0	0	34.18803419	11.111111	20.51282051	0	0.427350427	2808000
770	0	0	0	0	0	30.66666667	8	0	0	0	1800000
775	0	0	0	0	0	56.89655172	0	0	0	34.05172414	4640000
780	0	0	0	0	0	4.761904762	1.7857143	0	0	72.61904762	1008000
785	0	0	0	0	0	24.02597403	0	1.298701299	0	40.90909091	2310000
790	0	0	0	0	0	60.57142857	2.2857143	0	0	0	2100000
795	0	0	0	0	0	34.07407407	0	2.592592593	0	27.03703704	3240000
800	0	0	0	0	0	6.578947368	1.754386	0	0	88.15789474	6840000
805	1.351351351	0.900900901	0	0	0	57.20720721	14.864865	13.06306306	0	1.351351351	3330000
810	0	0	0	0	0	67.32026144	11.111111	8.496732026	0	0	2295000
815	0	0	0	0	0	36.41618497	20.231214	11.56069364	0	0	2595000
820	0	0.4784689	0	0	0	32.05741627	60.76555	2.392344498	0	0	4180000
825	0	0	0	0	0	62.3655914	3.2258065	29.03225806	0	1.612903226	5580000
830	0	0	0	0	0	70.28301887	8.0188679	0	0	0	4240000
835	0	0	0	0	0	80.39215686	0	0	0	0	6120000
840	0	0.487804878	0	0	0	63.90243902	3.902439	0	0	0.975609756	6150000
845	0	0	0	0	0	33.02325581	2.7906977	0.465116279	0	42.3255814	6450000
850	0	0	0	0	0	55.10204082	3.5714286	10.71428571	0	0	5880000
855	0	0	0	0	0	58.60215054	22.580645	3.76344086	0	6.989247312	5580000
860	0	0	0	0	0	73.07692308	0	3.076923077	0	5.384615385	1560000
865	0	0	0	0	0	64.5320197	3.4482759	0	0	20.68965517	2030000
870	0	0	0	0	0	55.51181102	0	0	0	37.00787402	3048000
875	0	0	0	0	0	19.00452489	0.9049774	0	0	78.73303167	6630000
880	0	0	0	0	1.74672489	14.84716157	5.6768559	0	0	63.75545852	4580000
885	0	0	0	0	0	39.29961089	5.0583658	0	0	28.79377432	5140000
890	0	0	0	0	0	10.41666667	0	0	0	85.41666667	7200000
895	0	0	0	0	0	20.53571429	0	0	0	62.94642857	6720000
900	0	0	0	0	0	19.31330472	0	0	0	63.09012876	3495000

Appendix 4. The relative percentages of diatom in core KAW2

Depth (cm)	Achnanthisium minutissimum	Aulacoseira ambigua	Aulacoseira granulata	Discotella stelligera	Fragillaria tenera	Pseudostaurisira brevistriata	Pseudostaurisira spp.	Staurisirella lapponica	Cyclotella atomus	Cyclotella var. gracilis	Cyclotella radiosa	Diploneis smithii	Palaria sulcata	Thalassionema nitzschoides	Thalassiosira lineata	total diatom per 1 gram
5	6.930693069	11.55115512	5.610561056	0	11.55115512	3.96039604	21.45214521	0.99009901	0.66006601	0	8.91089109	0	0	0	0	17707.79221
15	6.872852234	40.54982818	6.18556701	7.560137457	2.405498282	1.030927835	4.810996564	0.687285223	0	0	6.87285223	0	0	0	0	59522.72727
20	25.76028623	4.472271914	4.651162791	21.64579606	4.472271914	1.967799642	19.8568873	0.357781753	0	0	1.78890877	0	0	0	0	84696.9697
25	34.12698413	0	0.793650794	24.6031746	7.407407407	1.587301587	13.49206349	0.793650794	1.58730159	0	0	0	0	0	0	128863.6364
30	8.647450111	0.22172949	0	0.44345898	52.32815965	1.99556541	13.96895787	2.2172949	0	0	0	0	0	0	0	99729.72973
35	5.89254766	1.039861352	0.346620451	3.466204506	17.85095321	4.159445407	21.83708839	0.346620451	9.01213172	1.386481802	0.34662045	0.3466205	0	0	0	188836.3636
40	18.69328494	21.23411978	1.270417423	10.34482759	5.989110708	3.448275862	19.23774955	0.362976407	0	0	1.81488203	0.1814882	0	0	0	187840.9091
45	19.45812808	25.73891626	0.246305419	8.620689655	6.157635468	3.201970443	14.65517241	0.123152709	0	0	2.33990148	0	0	0	0	166090.9091
50	19.70149254	17.46268657	1.940298507	11.79104478	5.970149254	3.582089552	15.07462687	1.044776119	0	0	2.08955224	0.4477612	0	0	0	238339.9209
55	9.181636727	6.387225549	1.996007984	7.385229541	3.393213573	1.796407186	22.35528942	0.598802395	0	0	4.59081836	0	0	0	0	97597.4026
60	13.21695761	0.374064838	1.995012469	14.21446384	3.865336658	3.6159601	21.32169576	0.249376559	0	0	6.85785536	0.1246883	0	0	0	105835.7771
65	7.284768212	2.98013245	5.298013245	4.635761589	0	5.629139073	22.18543046	1.324503311	0	0	4.96688742	0	0	0	0	35810.27668
70	4.010025063	17.04260652	3.50877193	2.756892231	0.501253133	4.260651629	19.54887218	0.501253133	0	0	3.7593985	0	0	0	0	42954.54545
75	5.769230769	25	6.730769231	0.961538462	0	3.525641026	22.43589744	0.961538462	0	0	8.01282051	0	0	0	0	31909.09091
80	10.46511628	18.31395349	4.360465116	4.651162791	1.162790698	5.813953488	22.6744186	0	0.29069767	0	6.10465116	0	0	0	0	31272.72727
85	11.83431953	4.733727811	7.692307692	6.213017751	0.591715976	5.917159763	25.44378698	0.591715976	0	0	8.57988166	0	0	0	0	27654.54545
90	21.92982456	6.140350877	6.140350877	3.801169591	0.292397661	8.479532164	14.9122807	2.339181287	0	0	5.55555556	0.2923977	0	0	0	17272.72727
95	3.541666667	20	7.291666667	2.916666667	0	6.458333333	28.54166667	0.833333333	0	0	10	0.2083333	0	0	0	31168.83117
100	3.313253012	9.337349398	1.506024096	1.204819277	0	6.927710843	48.4939759	1.807228916	0	0	2.71084337	0.3012048	0	0	0	56590.90909
105	19.43231441	5.021834061	0	7.860262009	1.091703057	5.240174672	28.60262009	1.091703057	0	0	5.24017467	0.2183406	0	0	0	107064.9351
110	13.15789474	4.276315789	0	5.592105263	1.315789474	9.868421053	31.57894737	0.657894737	1.31578947	0	5.26315789	0	0	0	0	29610.38961
115	27.77777778	5.263157895	0	6.725146199	3.801169591	2.923976608	21.6374269	0.877192982	0.29239766	0	6.7251462	0.2923977	0	0	0	23318.18182
120	19.57831325	11.74698795	0	4.819277108	2.108433735	2.710843373	25.30120482	1.204819277	0	0	4.21686747	0.9036145	0	0	0	48506.49351
125	19.09385113	0	0	5.177993528	1.294498382	4.530744337	34.95145631	0.323624595	0	0	4.53074434	0	0	0	0	36640.31621
130	34.06326034	0	0	5.596107056	0.729927007	2.189781022	26.76399027	1.216545012	0	0	1.94647202	0.486618	0	0	0	27339.24612
135	31.19266055	0	0	11.31498471	3.058103976	1.529051988	19.26605505	0.611620795	0	0	0	0.3058104	0	0	0	50480.27444
140	10.58823529	0	0	16.47058824	3.921568627	2.745098039	24.70588235	1.568627451	0.39215686	0	0	0.3921569	0	0	0	25757.57576
145	66.4921466	0	0	3.664921466	0.261780105	0.523560209	20.15706806	0.523560209	0	0	0	0	0	0	0	67944.66403
150	57.90754258	0	0	7.299270073	1.946472019	1.216545012	5.839416058	0.486618005	2.43309002	0	0	0.243309	0	0	0	50950.41322
155	0.573065903	0	0	0.286532951	1.432664756	0.286532951	4.297994269	0.573065903	72.2063037	2.29226361	0	0	0	0	0	26439.39394
160	1.12	0	0	0.64	0.8	1.6	13.28	0.48	48.8	2.72	0	0.16	0	0	0	48701.2987
165	2.818991098	0	0	9.050445104	3.857566766	2.96735905	31.30563798	1.632047478	7.56676558	0	0	0	0	0	0	212097.9021
170	0	0	0	0.835654596	0.835654596	5.571030641	53.34261838	1.671309192	6.82451253	1.949860724	0	0.2785515	0	0	0	1068099.174
175	0	0	0	0.234741784	3.521126761	3.286384977	19.01408451	0.234741784	55.8685446	3.990610329	0	0	0	0	0	410053.4759
180	4.192872117	0	0	0.838574423	11.11111111	6.918238994	48.21802935	2.51572327	0	0	0	0.6289308	0	0	0	150104.8951
185	0.879120879	0	0	0.21978022	27.69230769	3.516483516	38.9010989	2.417582418	0	0	0	0	0	0	0	186136.3636
190	0	0	0	0	0	1.136363636	8.238636364	1.704545455	11.3636364	42.89772727	0	0	0	0.284090909	0	110769.2308
195	0.328947368	0	0	0	0	2.302631579	20.39473684	0.328947368	17.4342105	27.63157895	0	0	0	0	0	207272.7273
200	0.425531915	0	0	0	5.319148936	8.510638298	37.65957447	4.255319149	1.4893617	0.212765957	0	0.212766	0	0	0	147902.0979
205	1.386748844	0.154083205	0	0	0.154083205	11.24807396	62.86594761	2.157164869	0	0	0	0	0	0	0	110625
210	10.72555205	0	0	1.735015773	3.312302839	5.047318612	35.33123028	1.577287066	0	0	0	0.1577287	0	0	0	225533.5968
215	0.134770889	0	0	0	0	8.625336927	46.22641509	0.943396226	14.0161725	3.773584906	0	0	0	0	0	303545.4545
220	3.105590062	0	0	1.614906832	18.50931677	3.97515528	15.1552795	1.739130435	0.99378882	0	0	0	0	0	0	199586.7769
225	0	0	0	0.643500644	45.68854569	2.187902188	19.43371943	0.386100386	0	0.128700129	0	0.2574003	0	0	0	151363.6364
230	34.95798319	0	0	17.4789916	6.890756303	1.512605042	20.84033613	0.336134454	0.50420168	0	0	0.3361345	0	0	0	442561.9835
235	16.28595276	0	0	2.443438914	1.990950226	4.977375566	42.8959276	1.266968326	0	0	0	0.0904977	0	0.090497738	0	196541.502
240	0.191204589	0	0	0	1.338432122	4.206500956	10.51625239	0	4.58891013	0.191204589	0	0.3824092	0.38241	0	0	45281.38528
245	1.209677419	0	0	22.58064516	49.39516129	0.60483871	14.71774194	0	0.40322581	0.201612903	0	0	0	0	0	156083.9161

Depth (cm)	Achnanthisdium minutissimum	Aulacoseira ambigua	Aulacoseira granulata	Discotella stelligera	Fragillaria tenera	Pseudostaurisira brevistriata	Pseudostaurisira spp.	Staurisirella lapponica	Cyclotella atomus	C. atomus var. gracilis	Cyclotella radiosa	Diploneis smithii	Palaria sulcata	Thalassionema nitzschoides	Thalassiosira lineata	total diatom per 1 gram
250	4.407713499	0	0	3.581267218	51.51515152	1.101928375	11.84573003	0	3.58126722	4.958677686	0	0	0	0.275482094	0	108000
255	0	0	0	0	0	4.436860068	7.167235495	0	4.43686007	0	0	5.8020478	1.36519	4.09556314	2.730375427	31543.0622
260	2.84463895	0	0	0.656455142	3.282275711	3.282275711	19.69365427	0.218818381	11.5973742	10.50328228	0	1.3129103	0.21882	0.656455142	0.437636761	109973.262
265	4.722222222	0	0	0.277777778	0.833333333	15.55555556	58.33333333	0.277777778	1.11111111	0.277777778	0	0	0	0.833333333	0.833333333	61363.63636
270	43.62477231	0	0	0.1867030965	2.367941712	2.823315118	22.76867031	0.091074681	0	0.182149362	0	0.0910747	0	0	0	289794.7214
275	0	0	0	0.225733634	7.900677201	3.16027088	13.54401806	0	7.67494357	10.15801354	0	0.2257336	0	0.225733634	0.225733634	86298.7013
280	0.477326969	0	0.477326969	1.909307876	3.818615752	27.92362768	0.477326969	12.4105012	10.02386635	0	0.477327	0	0	1.193317422	0	45709.09091
285	0.183823529	0	0	0	0	1.654411765	7.536764706	0	19.1176471	18.01470588	0	0.5514706	0.91912	1.102941176	0.367647059	87272.72727
290	0	0	0	0	0.303951368	8.814589666	48.63221884	0.303951368	0.60790274	1.519756839	0	0.6079027	0	3.951367781	1.823708207	19939.39394
295	0	0	0	0	0	9.00243309	27.98053528	1.216545012	11.4355231	1.946472019	0	0.486618	1.94647	4.136253041	0.97323601	20016.23377
300	2.402402402	0	0	0	0	13.51351351	36.03603604	1.501501502	1.5015015	0.3003003	0	0.3003003	5.70571	3.303303303	0.900909091	35849.2823
305	0.980392157	0	0	0	0	11.11111111	44.11764706	0.326797386	4.24836601	0	0	0	4.24837	2.941176471	0.653594771	37933.8843
310	15.07936508	0	0	1.058201058	0	8.73015873	32.53968254	1.851851852	15.6084656	0	0	0	0.5291	0.264550265	0.529100529	93719.00826
315	6.744186047	0	0	4.186046512	1.162790698	2.093023256	65.11627907	0	0	0	0	0.2325581	0	0	0	61722.48804
320	77.9047619	0	0	7.047619048	1.523809524	0.761904762	5.333333333	0	0	0	0	0	0	0	0	490909.0909
325	8.737864078	0	0	0.485436893	0.970873786	6.310679612	22.33009709	1.699029126	7.2815534	3.640776699	0	0.4854369	4.61165	2.184466019	0.242718447	49572.19251
330	58.48056537	0	0	13.25088339	0	2.650176678	15.72438163	0.176678445	0	0	0	0	0	0	0	272406.4171
335	1.374570447	0	0	0	0	4.12371134	12.71477663	0.343642612	52.233677	0.687285223	0	0.6872852	1.37457	0.687285223	3.092783505	22461.40652
340	0.902934537	0	0	4.063205418	0	5.191873589	19.86455982	0.451467269	29.3453725	5.417607223	0	0.4514673	1.58014	1.58013544	0.677200903	52529.64427
345	0.950118765	0	0	4.750593824	1.187648456	4.513064133	11.40142518	1.187648456	31.3539192	5.225653207	0	0.4750594	0.95012	0	0.950118765	43327.61578
350	0	0	0	0	0	1.393728223	4.87804878	0	40.4181185	18.46689895	0	1.3937282	3.48432	5.923344948	1.045296167	33545.45455
355	1.030927835	0	0	0	0	4.12371134	15.12027491	0.343642612	21.9931271	7.560137457	0.34364261	1.7182131	6.87285	5.498281787	1.374570447	8016.528926
360	0	0	0	0	0	2.605863192	6.840390879	0	24.4299674	10.42345277	0	0.9771987	1.62866	3.908794788	0.325732899	16101.3986
365	12.5	0	0	23.09782609	2.717391304	5.706521739	26.90217391	0.27173913	6.52173913	2.445652174	0	0	0	0	0	56809.60549
370	0	0	0	0	0	1.219512195	3.963414634	1.219512195	15.5487805	10.06097561	0	1.5243902	5.18293	8.536585366	3.658536585	14124.40191
375	0	0	0	0	0	7.210031348	13.79310345	1.880877743	22.5705329	13.79310345	0	2.507837	0	1.880877743	0.940438871	20714.28571
380	0	0	0	0	0	1	4.571428571	1.428571429	18.5714286	13	0	1.8571429	0.42857	2.714285714	20	33492.82297
385	0.301204819	0	0	0	0	3.614457831	15.36144578	0.301204819	11.1445783	9.638554217	0	2.4096386	4.81928	5.120481928	3.012048193	15090.90909
390	6.042296073	0	0	3.021148036	0	0.906344411	6.948640483	0	29.305136	15.70996979	0	0.9063444	0	0.302114804	0.302114804	112840.9091
395	0	0	0	0	0	2.526315789	7.578947368	0	34.3157895	6.947368421	0	0.8421053	2.52632	5.263157895	2.526315789	23697.33925
400	0	0	0	0	0	2.557544757	5.882352941	0	24.8081841	16.62404092	0	2.0460358	3.83632	3.58056266	1.534526854	26659.09091
405	0.323624595	0	0	0.323624595	0	3.883495146	18.77022654	0	30.7443366	2.912621359	0	2.2653722	1.94175	4.207119741	0.647249191	13167.61364
410	0	0	0	0	0	4.733727811	12.72189349	0.887573964	14.7928994	3.846153846	0	0.295858	2.07101	10.65088757	2.071005917	17070.70707
415	2.949852507	0	0	7.079646018	0	5.899705015	21.23893805	1.179941003	19.1740413	6.489675516	0	0.2949853	0	0.884955752	1.474926254	32251.58562
420	1.347708895	0	0	0	1.617250674	2.156334232	19.40700809	0.539083558	33.1536388	5.660377358	0	0.2695418	0.53908	2.69541779	0	26981.81818
430	0	0	0	0	0	1.857585139	4.643962848	0.309597523	8.97832817	0.619195046	0	6.1919505	4.02477	0.619195046	5.882352941	22022.72727
435	2.229299363	0	0	0	0	6.050955414	14.01273885	0.955414013	24.8407643	0	0	1.2738854	8.59873	4.140127389	1.27388535	10194.80519
440	1.016949153	0	0	0	0	4.06779661	5.084745763	0	1.01694915	0.338983051	0.33898305	2.3728814	4.0678	2.033898305	3.050847458	26235.17787
445	1.955307263	0	0	0	0	3.631284916	6.145251397	1.117318436	31.5642458	9.497206704	0	1.9553073	3.07263	3.631284916	0.837988827	19791.15479
450	10.28938907	0	0	0	0	16.07717042	13.50482315	0.964630225	16.7202572	3.8585209	0	0	0.96463	2.572347267	0	7440.191388
455	18.77133106	0	0	0	0	6.484641638	22.52559727	0	30.0341297	0.682593857	0	0.3412969	0	1.365187713	0.341296928	52687.31269
460	0.324675325	0	0	0	0	1.623376623	6.168831169	0.649350649	32.4675325	0.324675325	0	2.2727273	0.64935	0	0	10000
465	0	0	0	0	0	9.009009009	17.71771772	0	12.3123123	3.903903904	0	1.5015015	3.9039	6.306306306	0.3003003	17924.64115
470	26.03878116	0	0	3.601108033	1.108033241	4.709141274	25.20775623	0.831024931	4.15512465	1.385041551	0	0.2770083	0	1.108033241	0	39381.81818
475	0	0	0	0	0	11.50627615	20.92050209	0	4.39330544	0.627615063	0	0.41841	1.88285	8.786610879	0.627615063	23559.69332
480	0.925925926	0	0	0	0	4.320987654	9.567901235	0.308641975	24.0740741	6.481481481	0.30864198	0.308642	7.71605	3.395061728	0.308641975	24545.45455
485	60.53333333	0	0	15.73333333	0.533333333	3.466666667	11.73333333	0	0	0	0	0	0	0	0	340909.0909
490	0	0	0	0	0	5.214723926	3.374233129	0.306748466	34.6625767	2.147239264	0	0.9202454	10.1227	6.134969325	0.613496933	8890.909091

Depth (cm)	Achnanthisium minutissimum	Aulacoseira ambigua	Aulacoseira granulata	Discotella stelligera	Fragillaria tenera	Pseudostausira brevistriata	Pseudostausira spp.	Stausosirella lapponica	Cyclotella atomus	C. atomus var. gracilis	Cyclotella radiosa	Diploneis smithii	Palatia sulcata	Thalassionema nitzschioides	Thalassiosira lineata	total diatom per 1 gram
495	1.242236025	0	0	0	0	4.968944099	14.28571429	0	15.8385093	5.590062112	0	1.863354	4.96894	5.279503106	0	20188.08777
500	0.516795866	0	0	0	0	12.91989664	28.16537468	1.291989664	19.121447	2.583979328	0	0.5167959	0.2584	0.516795866	4.392764858	52772.72727
505	0.316455696	0	0	0	0	7.594936709	7.911392405	0.949367089	8.5443038	1.898734177	0.63291139	0.6329114	22.7848	11.07594937	1.898734177	8079.545455
510	0.657894737	0	0	0.986842105	0	5.592105263	13.81578947	0	24.3421053	4.276315789	0	1.6447368	0.65789	4.605263158	0.657894737	21628.4585
515	0.371747212	0	0	0.371747212	0.743494424	6.319702602	7.063197026	0	22.3048327	5.204460967	0	0	3.71747	4.460966543	1.115241636	15390.97266
520	0.261780105	0	0	1.047120419	0	5.235602094	11.78010471	1.308900524	18.8481675	5.235602094	0	1.5706806	1.57068	4.712041885	3.664921466	35924.76489
525	3.205128205	0.213675214	0	0.854700855	0	11.53846154	38.03418803	0.427350427	6.83760684	1.923076923	0.42735043	0.4273504	2.13675	2.564102564	1.709401709	36123.49914

Appendix 5. The relative percentages of diatom in core 16Hm-2C

Age (AD)	Achnanthisidium minutissimum	Aulacoseira ambigua	Aulacoseira granulata	Pseudostaurosira brevistriata	Cyclotella atomus	C. atomus var. gracilis	Cocconeis scutellum	Diploneis smithii	Fallacia nyella	Podosira stelligera	Thalassiosira lineata	Thalassiosira nanolineata	Thalassionema nitzschoides	total diatom per 1 gram	
1866.31332	0.906344411	0.302114804	0	0	0	4.53172221	32.628399	4.53172205	1.510574	0	0	2.114803625	0	0.604229607	27108.92711
1860.20366	2.395209581	0	0	0	0	11.077844	23.652695	4.49101796	0.299401	0	0.5988024	0.598802395	0	0.598802395	51903.6519
1854.09399	2.98013245	0	0	0	0	8.9403974	21.854305	3.31125828	1.324503	0	0.3311258	1.655629139	0	0.993377483	22140.76246
1847.98433	13.24503311	0.662251656	0.9933775	0	0	3.6423841	15.89404	5.62913907	0.993377	0	0.3311258	2.317880795	0	0.662251656	25900.51458
1841.87467	2.272727273	0	0	0	0	6.0606061	0	5.68181818	0.757576	0	0.7575758	6.439393939	0	0.378787879	13559.32203
1835.76501	3.691275168	0	0	0	0	8.0536913	34.899329	7.04697987	2.348993	0	0.6711409	3.355704698	0	0.33557047	38156.20999
1829.65535	2.02020202	0.673400673	0	0	0	24.242424	31.986532	3.03030303	2.356902	0	1.010101	3.703703704	0	0	32530.12048
1823.54569	4.632152589	0	0	0	0	13.351499	23.160763	5.99455041	0.817439	0	1.6348774	2.179836512	0	0	19397.463
1817.43603	2.96735905	0	0	0	0	18.397626	10.979228	8.01186944	1.186944	0	0.5934718	3.857566766	0	0.59347181	40311.00478
1811.32637	2.027027027	0	0	0	0	11.486486	30.405405	3.71621622	2.364865	1.013514	1.3513514	3.716216216	0	0	25874.12587
1805.21671	0.660066007	0	0.330033	0	0	10.231023	6.9306931	8.25082508	7.260726	0	0	7.920792079	0.330033003	2.97029703	7651.515152
1799.10705	0.309597523	0	0	0	0	14.241486	12.074303	4.0247678	3.71517	0	0	5.572755418	0.309597523	1.857585139	30909.09091
1792.99739	2.972972973	0.810810811	1.0810811	0.27027027	9.4594595	21.351351	5.13513514	1.081081	0.540541	0.2702703	7.027027027	7.027027027	0	1.351351351	24732.62032
1786.88773	0.327868852	4.590163934	7.5409836	0	10.491803	9.5081967	8.52459016	2.622951	0	0.3278689	0.655737705	0.655737705	1.967213115	40775.40107	
1781.23929	0.666666667	0	0.6666667	0	3.3333333	7.6666667	9	2.666667	0	3.6666667	1.333333333	1.333333333	4	14094.4327	
1777.43577	3.2	0	0.5333333	0	10.4	9.8666667	11.4666667	4.266667	0	1.0666667	0.533333333	1.6	1.866666667	11837.12121	
1773.63224	6.23501199	0	0	0.239808153	15.347722	24.220624	3.5971223	2.63789	0	1.4388489	0.479616307	0	0.239808153	31990.79402	
1769.82872	7.01754386	0	0	0	7.7192982	8.7719298	6.6666667	4.561404	0	4.2105263	1.403508772	0	0.350877193	21956.8567	
1766.02519	5.780346821	0	0	0	16.184971	5.7803468	8.67052023	1.156069	0	1.4450867	0.867052023	0	0	19782.73299	
1762.22166	5.604719764	0.294985251	0	0	7.079646	0.5899705	7.96460177	2.064897	0	2.0648968	4.424778761	0	0	9511.784512	
1758.41814	0.722891566	0	0.2409639	0	18.072289	2.4096386	5.54216867	1.686747	0	0.7228916	6.746987952	0	0.963855422	22192.51337	
1754.61461	0	0	0	0	11.836735	1.6326531	8.97959184	2.44898	0	1.4285714	0	0	0.612244898	19537.48006	
1750.81108	4.848484848	0	0	0	8.7878788	2.4242424	8.78787879	1.515152	0	1.5151515	8.787878788	0.909090909	0	6802.721088	
1747.00756	7.220216606	0	0.3610108	0	2.8880866	0.3610108	11.5523466	1.805054	0	2.5270758	9.747292419	0	1.444043321	4937.611408	
1743.20403	5.34591195	0.314465409	0	0	4.7169811	3.1446541	5.66037736	3.773585	0	0	11.63522013	0	0.628930818	9325.513196	
1739.4005	0.323624595	0	0	0.647249191	13.915858	3.236246	11.6504854	0	0	0.9708738	10.67961165	0	1.941747573	13872.05387	
1735.59698	1.506024096	0.602409639	0.6024096	0	4.5180723	3.6144578	11.1445783	0.60241	0	0.3012048	9.337349398	0	7.530120482	5548.128342	
1731.79345	0	0.638977636	0.6389776	0	6.7092652	0.9584665	10.543131	2.236422	0	0.6389776	0	0	3.833865815	3436.539306	
1727.98992	0	0.330033003	0	0	2.640264	1.320132	8.25082508	0.990099	0	1.980198	7.920792079	2.640264026	4.620462046	7870.12987	
1724.1864	1.020408163	0	0	0.340136054	3.7414966	1.0204082	7.14285714	1.70068	0	0	8.503401361	1.020408163	3.06122449	5698.778833	
1720.38287	0.943396226	0	0	0.314465409	9.1194969	11.320755	7.86163522	0.314465	0	0.9433962	3.773584906	0	3.459119497	4153.605016	
1716.57935	0.722021661	1.083032491	0	0	0	0.3610108	6.85920578	1.444043	0	0.3610108	9.386281588	1.805054152	8.664259928	3546.734955	
1712.77582	0.829875519	0	0	0	4.1493776	1.659751	6.22406639	0.829876	0	0	7.468879668	0.829875519	7.053941909	4815.184815	
1708.97229	0	0	0	0	3.4700315	1.2618297	0	0.946372	0	0.3154574	9.463722397	0.94637224	6.624605678	5297.459893	
1705.16877	0	0	0	0	9.2307692	1.2307692	4	0.923077	0	0.3076923	10.46153846	0	5.846153846	5371.900826	
1701.36524	0.333333333	0.666666667	0	0	4.3333333	1.3333333	4.3333333	1	0	0.6666667	5.666666667	1.333333333	7.333333333	5815.080442	
1697.56171	0	0	0	0.327868852	4.9180328	0	5.24590164	1.967213	0	0	0.327868852	0	5.901639344	11748.84438	
1693.75819	0.949367089	0	0	0	6.0126582	2.2151899	9.17721519	3.164557	0	0.3164557	0.316455696	0	7.594936709	13945.27802	
1689.95466	1.492537313	0	0.2985075	0	16.716418	1.7910448	6.26865672	1.492537	0	0	0.597014925	4.47761194	6.567164179	10501.5674	
1686.15113	1.239669421	0	0	0	0	0.8264463	0.8264463	3.30578512	0.826446	0	2.479338843	2.892561983	11.15702479	4150.943396	
1682.34761	0	0	0	0.340136054	6.462585	1.3605442	1.70068027	0.680272	0	0	2.721088435	0	11.2244898	7560.756076	
1678.54408	0	0	0	0.3003003	3.003003	1.2012012	2.4024024	0.900901	0	0	3.303303303	0	8.708708709	9475.03201	

Age (AD)	Achnanthidium minutissimum	Aulacoseira ambigua	Aulacoseira granulata	Pseudostaurosira brevistriata	Cyclotella atomus	C. atomus var. gracilis	Cocconeis scutellum	Diploneis smithii	Fallacia nyella	Podosira stelligera	Thalassiosira lineata	Thalassiosira nanolineata	Thalassionema nitzschoides	total diatom per 1 gram
1674.74055	0	0	0	0.317460317	0.952381	0	2.22222222	0.952381	0	0	0	0	8.253968254	7575.757576
1670.93703	0	0	0	0	0.3205128	0	1.28205128	0.320513	0	0	0	0	5.128205128	23636.36364
1667.1335	0	0	0	0	1.0238908	0	0.34129693	0.341297	0	0	6.484641638	0.682593857	16.04095563	11998.362
1663.32997	0	0	0.3333333	0	6.6666667	5.3333333	0.66666667	2.666667	0	0.3333333	1.666666667	9.333333333	31	15151.51515
1659.52645	0.607902736	0	0	0	10.942249	9.7264438	1.51975684	2.431611	0	0.6079027	1.823708207	0	2.127659574	14661.31907
1655.72292	1.869158879	0	0	0	17.445483	6.2305296	2.80373832	4.672897	0	1.8691589	0.62305296	1.246105919	2.180685358	11399.14773
1651.9194	1.97044335	0	0	0	14.53202	4.679803	4.92610837	8.62069	0	0.2463054	0.246305419	0	0	15573.45608
1648.11587	0	0	0	0	21.818182	4.8484848	14.8484848	5.454545	0	0	0	0	0.303030303	17857.14286
1644.31234	5.089058524	0	0	0	22.137405	8.3969466	10.9414758	1.78117	0	0	0	0	0	35727.27273
1640.50882	0.79787234	0	0.7978723	0	19.680851	7.9787234	4.78723404	2.659574	0	0.5319149	0	0	1.595744681	21911.42191
1636.70529	0.336700337	0	0	0	18.855219	17.845118	3.36700337	4.377104	0	0.3367003	0	0	0	39705.88235
1632.90176	0.550458716	0	0	0	14.862385	14.311927	3.48623853	2.568807	0	0.3669725	0	0	0	83975.34669
1626.70588	0.203665988	0	0	0	21.792261	12.830957	6.10997963	3.462322	0	0.814664	0	0	0	40578.5124
1618.11765	1.590909091	0.227272727	0	0	15.909091	15	4.54545455	2.045455	0	1.3636364	0	0	0	31746.03175
1609.52941	0.977198697	0	0	0	3.5830619	15.635179	9.77198697	4.885993	0	1.6286645	0	0	0	23853.92385
1600.94118	0.289017341	0	0	0	9.5375723	16.184971	8.95953757	4.046243	0	2.3121387	0.578034682	0	0	24383.36857
1592.35294	1.063829787	0	0	0	10.638298	13.56383	5.58510638	4.255319	0	1.3297872	0	0	0	32246.99828
1583.76471	0	0	0	0	10.985915	24.225352	5.35211268	3.380282	0	0.5633803	0	0	0	56618.81978
1575.17647	0	0	0	0	33.333333	11.255411	4.76190476	4.545455	0	8.2251082	0	0	0	39622.64151
1566.58824	1.714285714	0	0	0	4.2857143	5.7142857	7.71428571	2	0	4.5714286	0	0	0	31194.2959
1562.29412	0	0	0.3154574	0.315457413	7.8864353	15.457413	4.41640379	3.785489	0	8.8328076	0	0	0	24843.26019
1553.70588	0.947867299	0.710900474	0.2369668	0	2.8436019	11.374408	12.3222749	2.606635	0	8.5308057	0.236966825	0.236966825	0	20625.61095
1545.11765	0.598802395	0.299401198	1.7964072	0	5.3892216	21.556886	11.9760479	2.095808	0	4.491018	0	0	0	15031.50315
1536.52941	0	0	0.6802721	0.340136054	17.687075	9.1836735	9.86394558	3.061224	0	6.462585	0.340136054	0	0	8677.68595
1527.94118	0	0	0.974026	0.324675325	10.714286	15.25974	7.14285714	1.298701	0	0.6493506	7.467532468	0	0	16470.58824
1519.35294	0	0.769230769	0.5128205	0	23.076923	12.564103	5.64102564	4.102564	0	3.8461538	0	0	0.512820513	7162.534435
1510.76471	0	0.613496933	2.1472393	0	9.202454	17.484663	8.28220859	6.134969	0	0.6134969	0.920245399	0	0	10435.33931
1502.17647	0	2.641509434	1.1320755	0	21.132075	16.603774	11.6981132	8.301887	0	1.509434	0	0	1.132075472	3650.137741
1493.58824	0.566572238	1.416430595	2.5495751	0	11.048159	9.0651558	10.1983003	5.09915	0	0.2832861	0.283286119	2.266288952	0.566572238	6171.328671
1485	0	0.285714286	0.5714286	0	10.571429	32	5.14285714	2.285714	0	0	3.142857143	0	0.571428571	13955.3429
1479.20588	0	0.729927007	2.919708	0.364963504	23.722628	0	4.37956204	1.824818	0	0.3649635	0	0	1.459854015	6732.186732
1473.41176	0	0.754716981	5.6603774	0	7.1698113	1.1320755	3.77358491	1.132075	0	0	0.377358491	5.283018868	4.905660377	19119.76912
1467.61765	0.675675676	2.027027027	3.7162162	0.337837838	12.5	2.7027027	4.05405405	0.675676	0	0	0.337837838	2.364864865	2.027027027	7732.497388
1461.82353	0.338983051	2.711864407	4.0677966	0	4.0677966	7.4576271	6.10169492	3.050847	0	0	0.677966102	0	2.711864407	6841.372913
1456.02941	0	0	2.3809524	1.785714286	27.083333	0	1.78571429	0.892857	0	0	0.892857143	0	0.892857143	11107.43802
1450.23529	0	1.582278481	1.8987342	0	4.1139241	0.9493671	0	0.632911	0	0	0	0	0	42876.52646
1444.44118	0	1.337792642	5.3511706	0.334448161	5.6856187	0	0	0	0	0	0	0	0	40569.87788
1438.64706	0.333333333	8	11	1.666666667	6.6666667	0.6666667	0	0	0	0	0	0	0	34522.43959
1432.85294	0	21.06741573	20.505618	0.561797753	3.0898876	6.4606742	0	0.280899	0	0	0	0	0	27899.68652
1427.05882	0	34.94318182	40.056818	0.852272727	1.4204545	0	0	0	0	0	0	0	0	53333.33333
1421.26471	0	31.49741824	29.08778	0.860585198	3.6144578	0	0.51635112	0.344234	0	0	0	0	0	26675.8494
1415.47059	0	29.06666667	27.2	2.4	6.1333333	0	0	0.8	0	0	0	0	0	24177.94971

Age (AD)	Achnanthyidium minutissimum	Aulacoseira ambigua	Aulacoseira granulata	Pseudostaurosira brevistriata	Cyclotella atomus	C. atomus var. gracilis	Cocconeis scutellum	Diploneis smithii	Fallacia nyella	Podosira stelligera	Thalassiosira lineata	Thalassiosira nanolineata	Thalassionema nitzschoides	total diatom per 1 gram
1409.67647	0	38.06646526	24.169184	0.906344411	1.8126888	0	0	0.60423	0	0	0	0	0	23881.67388
1403.88235	0	23.56902357	59.93266	5.050505051	2.020202	0	0	0	0	0	0	0	0	19636.36364
1398.08824	0	32.86908078	45.125348	0	0	0	0	0.278552	0	0	0	0	0	24355.49525
1392.29412	0	19.04761905	48.051948	0.432900433	0.8658009	0	0	0.21645	0	0	0	0	0	38888.88889
1386.5	0.299401198	26.04790419	39.221557	0.898203593	0	0	0	0.299401	0	0	0	0	0	20797.01121
1380.70588	0	14.24242424	40.30303	1.212121212	1.5151515	0	0	0	0	0	0	0	0	21739.13043
1374.91176	0	23.38308458	46.766169	0.248756219	0	0	0	0.248756	0	0	0	0	0	16687.42217
1369.11765	0.319488818	23.32268371	51.757188	0.958466454	0.3194888	0	0	0	0	0	0	0	0	17895.94054
1363.32353	0.949367089	13.60759494	32.911392	1.265822785	1.2658228	0.3164557	0	0	0	0	0	0	0	21763.0854
1357.52941	0	13.58381503	33.236994	1.156069364	2.3121387	0.2890173	0	0	0	0	0	0	0	19150.40819
1351.73529	0.265957447	7.446808511	30.585106	1.063829787	0.2659574	0.7978723	0	0.265957	0	0	0	0	0	18476.65848
1345.94118	0.330033003	7.590759076	28.712871	1.650165017	2.310231	1.650165	0	0.330033	0	0	0	0	0	16694.21488
1340.14706	0	4.261363636	25.852273	1.420454545	0.2840909	0	0	0	0	0	0	0	0	14285.71429
1334.35294	0	0	32.831325	7.228915663	2.4096386	0	1.5060241	0.301205	0	0	0	0	0	9146.00551
1328.55882	0	4.422604423	46.683047	9.582309582	0.982801	0	0	0	0	0	0	0	0	10882.35294
1322.76471	0.341296928	5.460750853	27.645051	0.682593857	1.0238908	1.0238908	0.34129693	0.341297	0	0	0	0	0	12331.64983
1316.97059	0	3.246753247	46.428571	4.545454545	0	0	0	0.649351	0	0	0	0	0	11864.40678
1311.17647	0	2.179836512	18.80109	3.269754768	1.3623978	0.2724796	0	1.362398	0	0	0	0	0	12637.74105
1305.38235	0	0.694444444	26.388889	3.472222222	1.0416667	0	0	0.694444	0	0	0	0	0	22570.53292
1299.58824	0	1.461988304	19.298246	2.631578947	0	0.2923977	0	0	0	0	0	0	0	14545.45455
1293.79412	0.305810398	1.22324159	16.819572	1.22324159	0	1.2232416	0	0.917431	0	0	0	0	0	20971.62097
1288	0.298507463	0.298507463	20.298507	0.895522388	1.7910448	0.5970149	0	0.298507	0	0	0	0	0	67676.76768

Appendix A. Diatom catalog from SEM (scanning electron microscope)

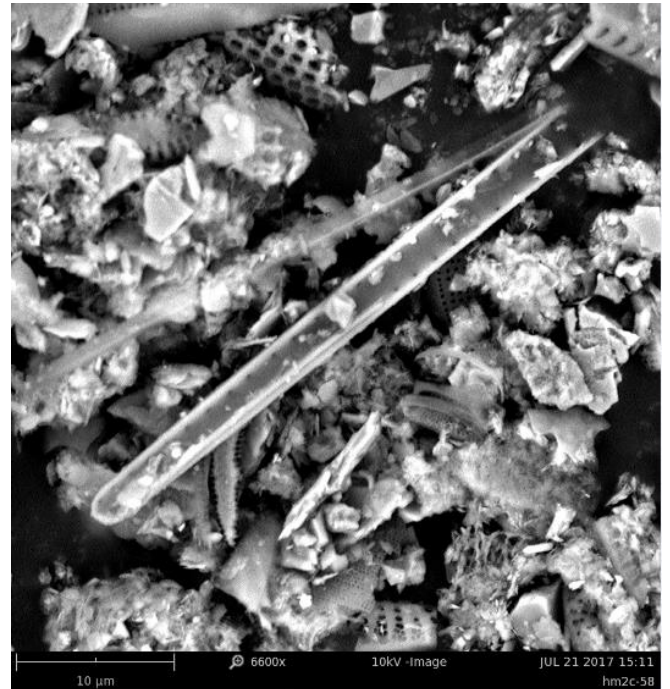


Plate 1. *Thalassionema nitzschioides*

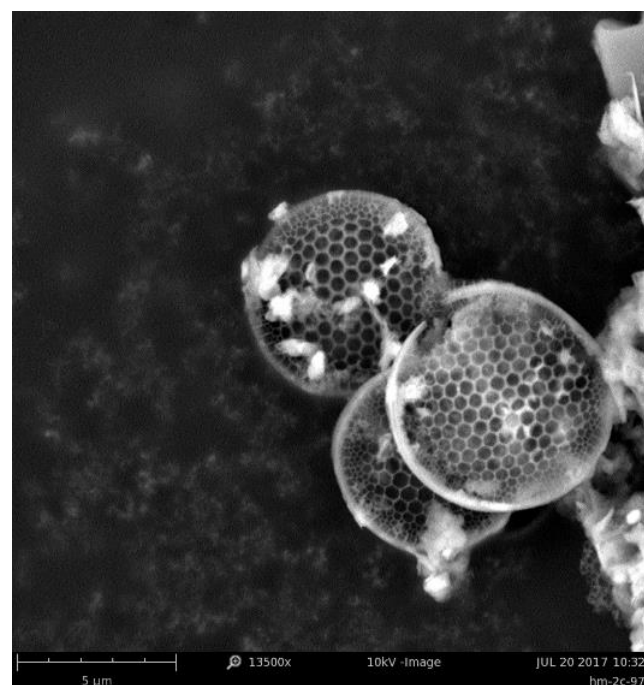
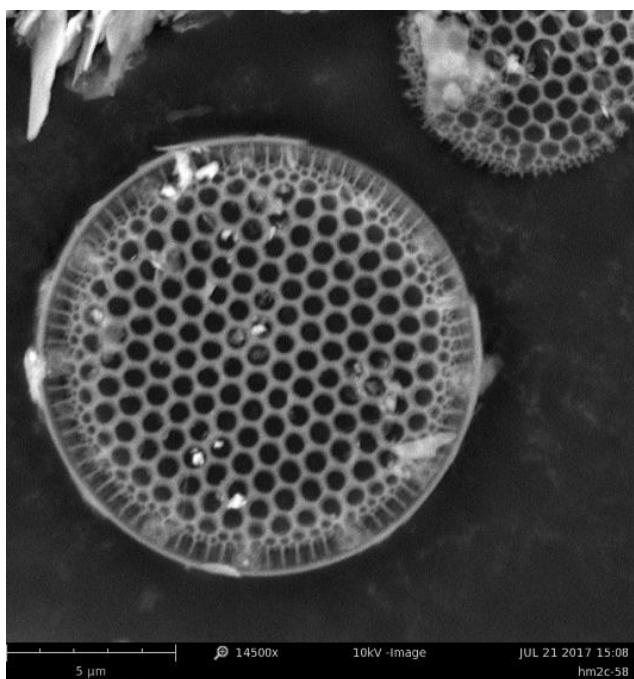
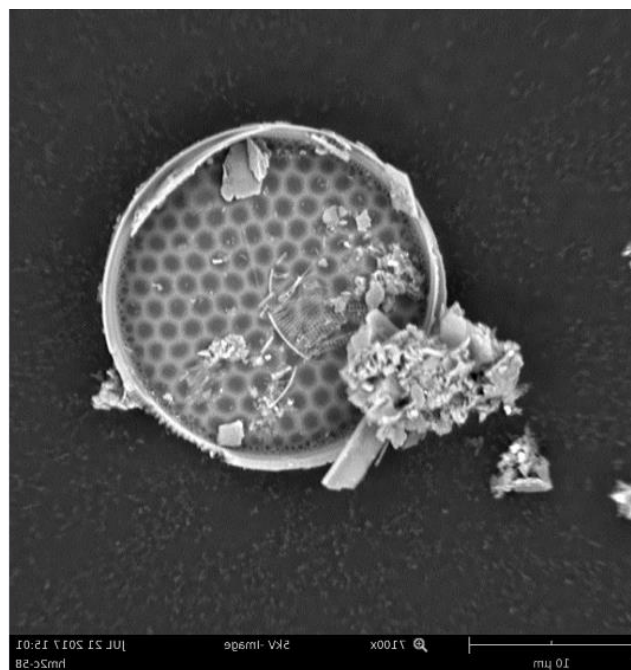
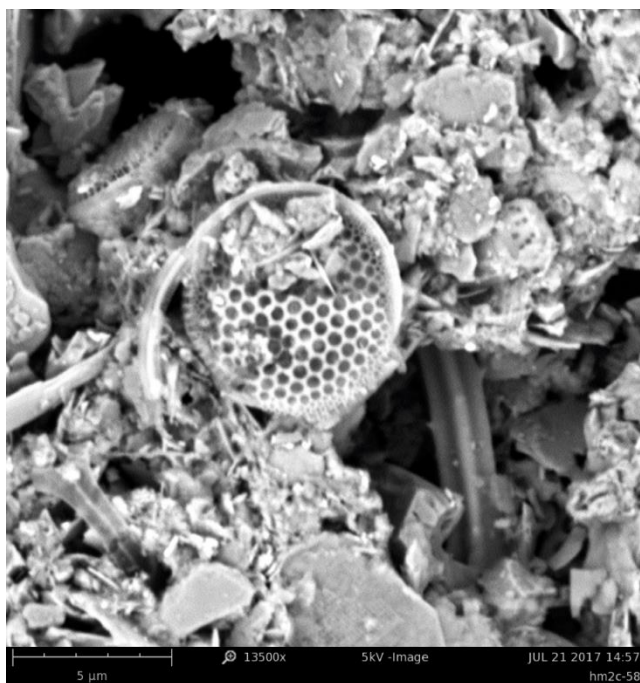


Plate 2. *Thalassiosira nanolineata*

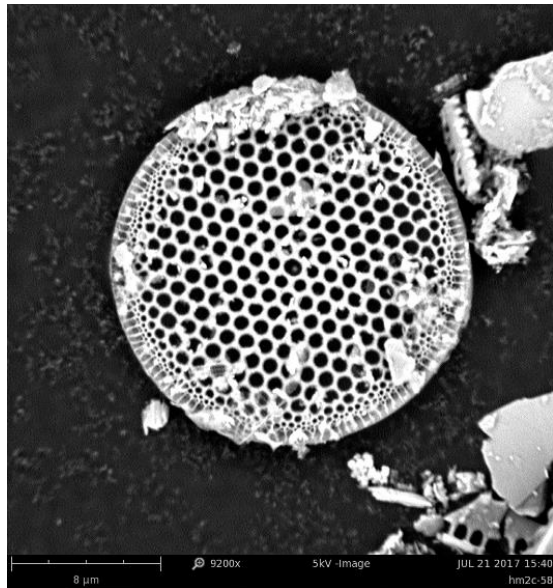
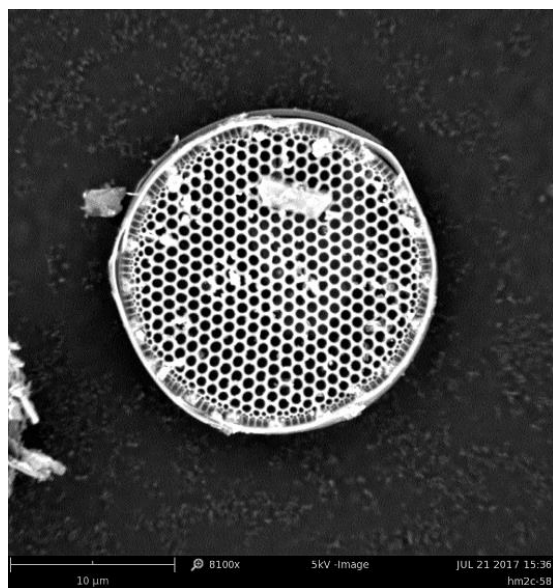
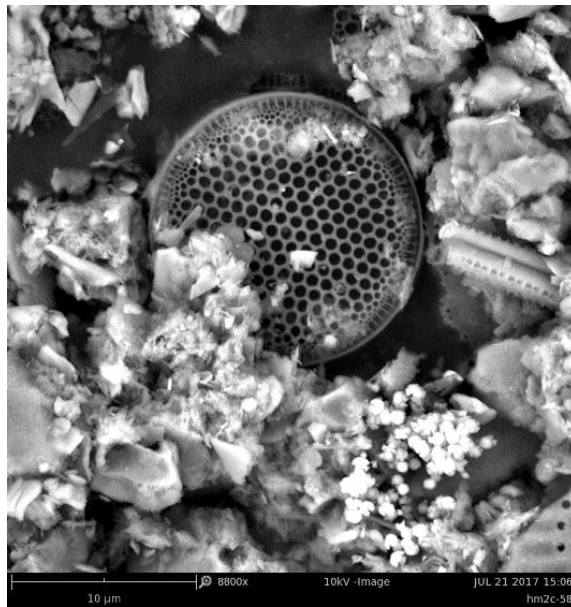
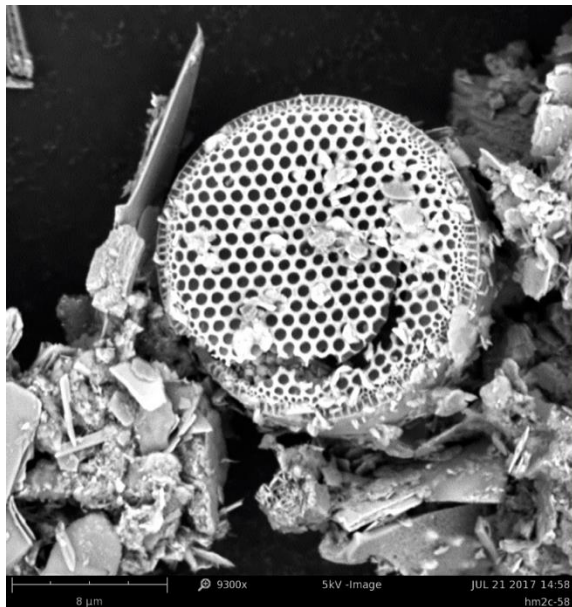


Plate 3. *Thalassiosira lineata*

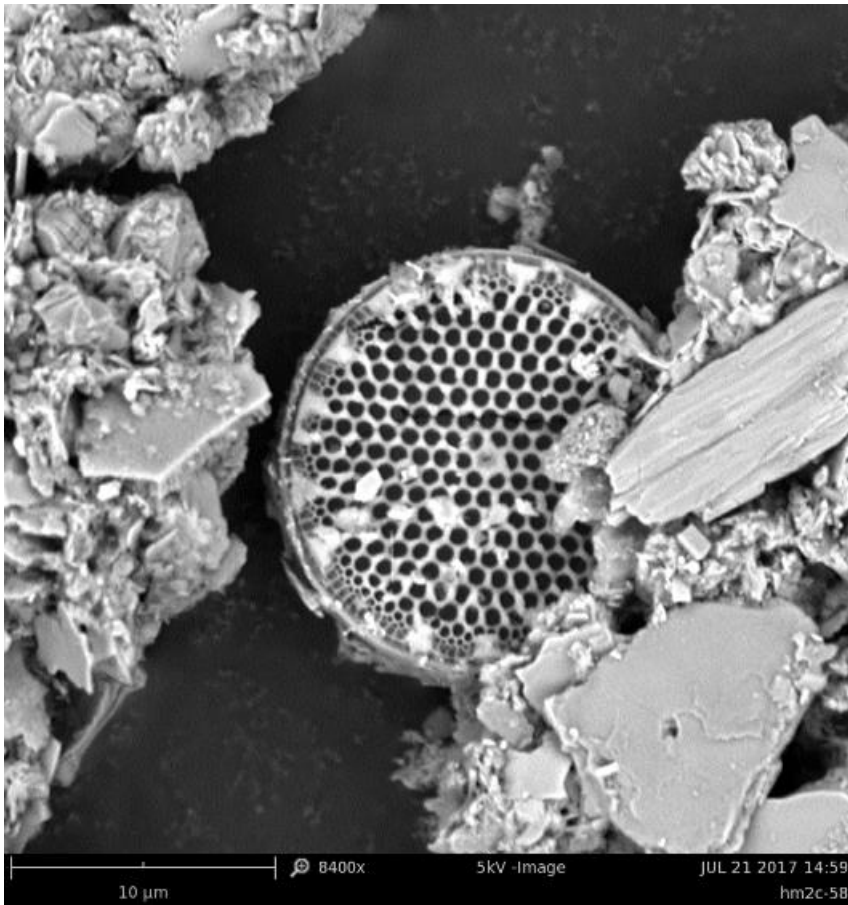


Plate 4. *Thalassiosira nodulolineata*

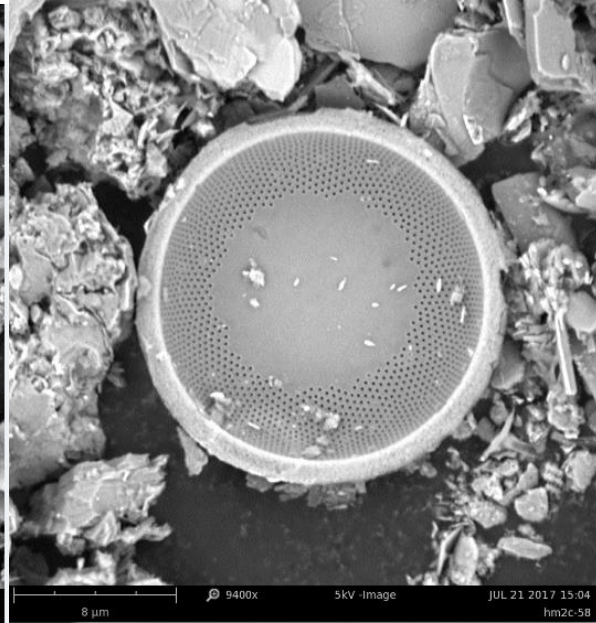


Plate 5. *Hyalodiscus scoticus*

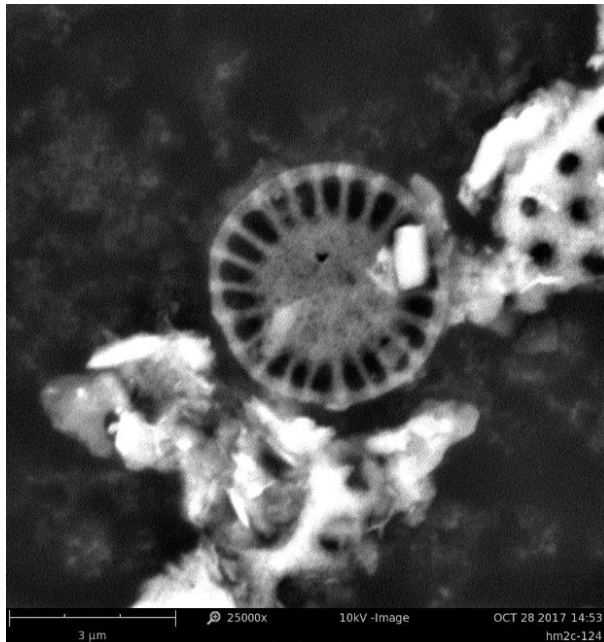
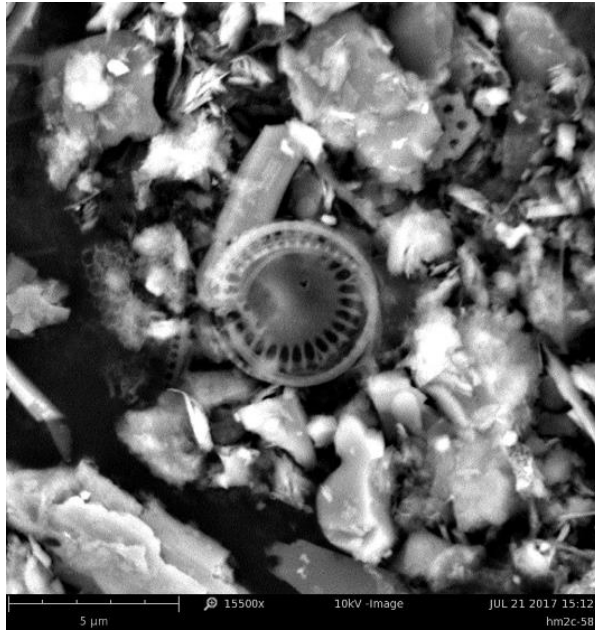


Plate 6. *Cyclotella atomus*

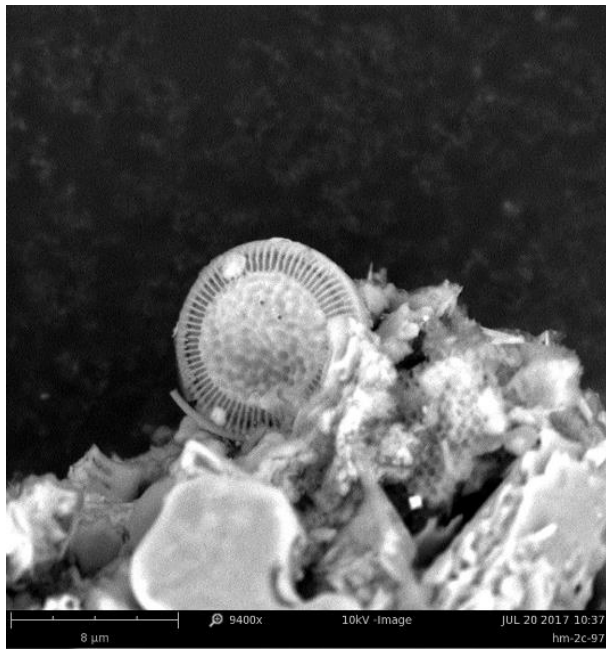


Plate 7. *Cyclotella atomus* var. *gracilis*

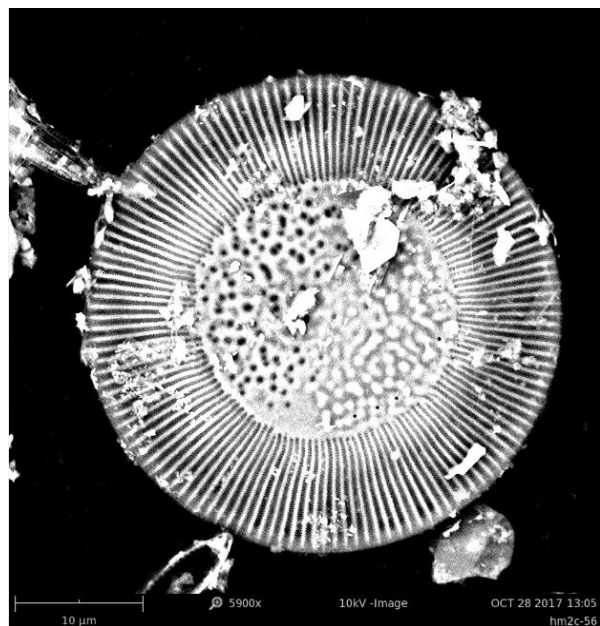
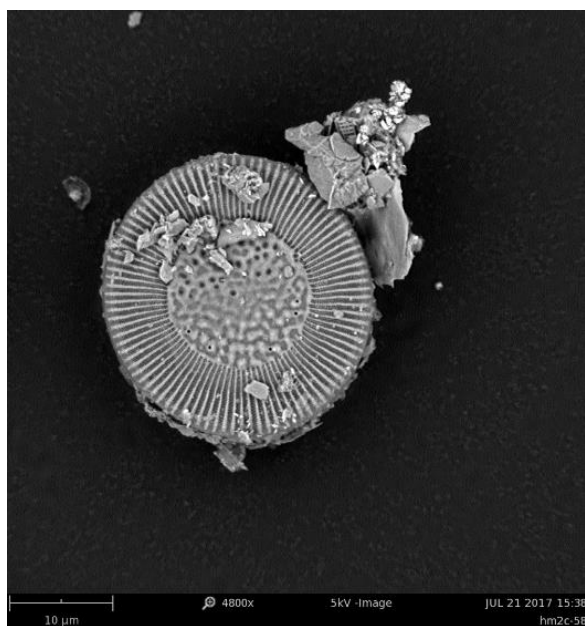


Plate 8. *Cyclotella striata*

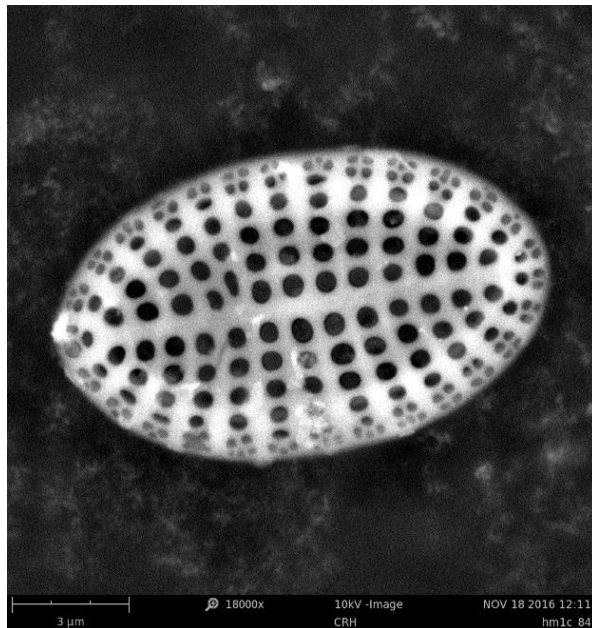
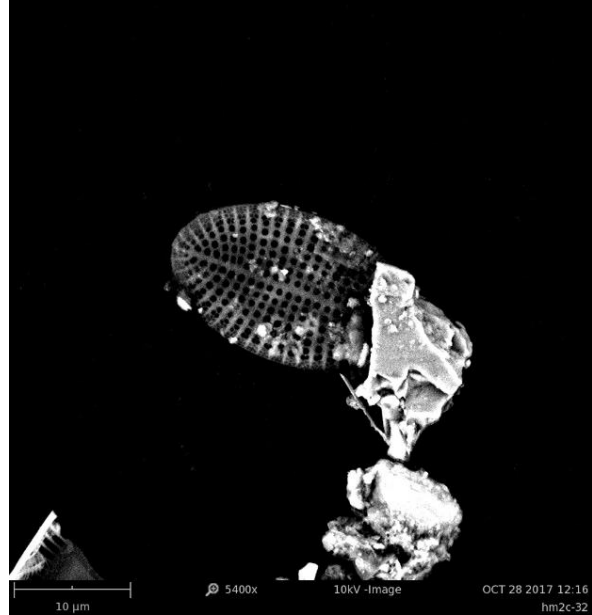
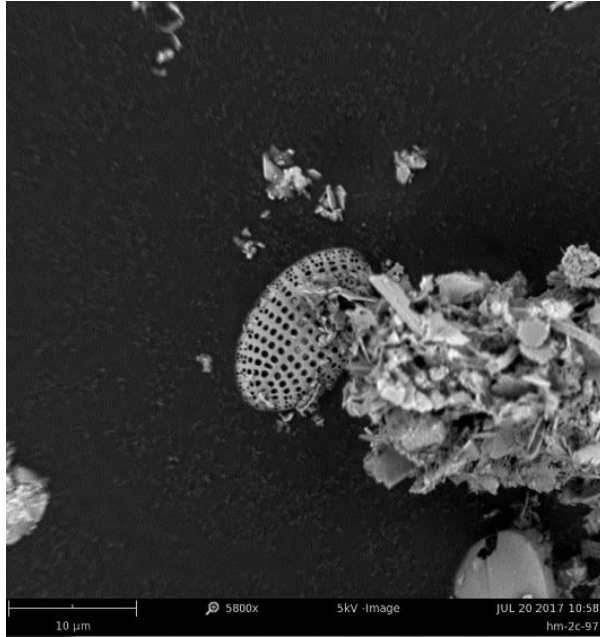


Plate 9. *Cocconeis scutellum*

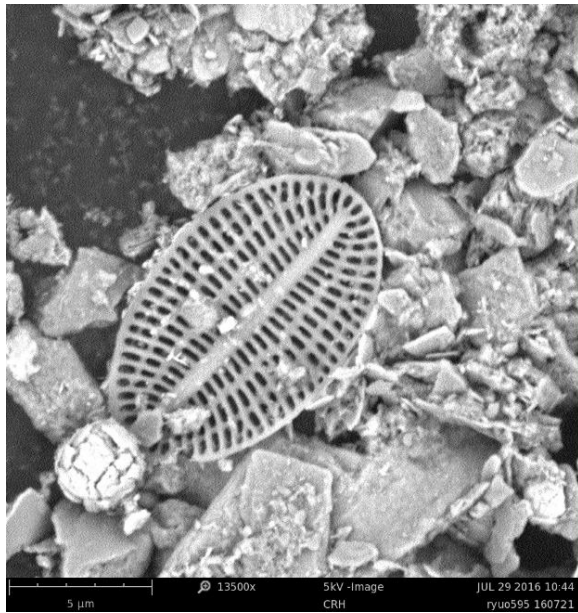
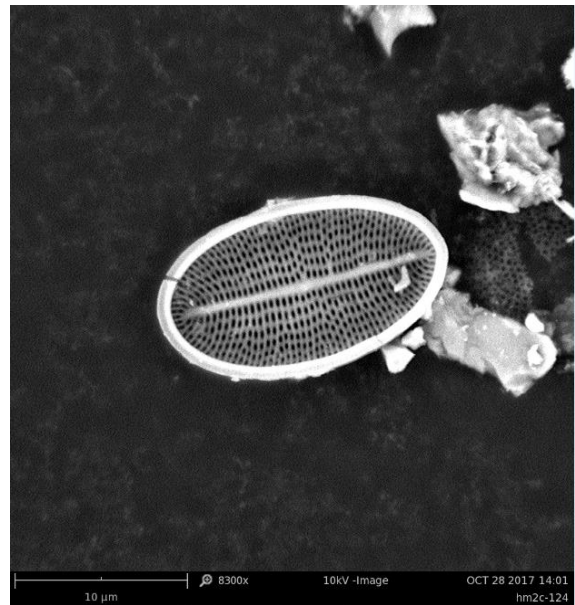
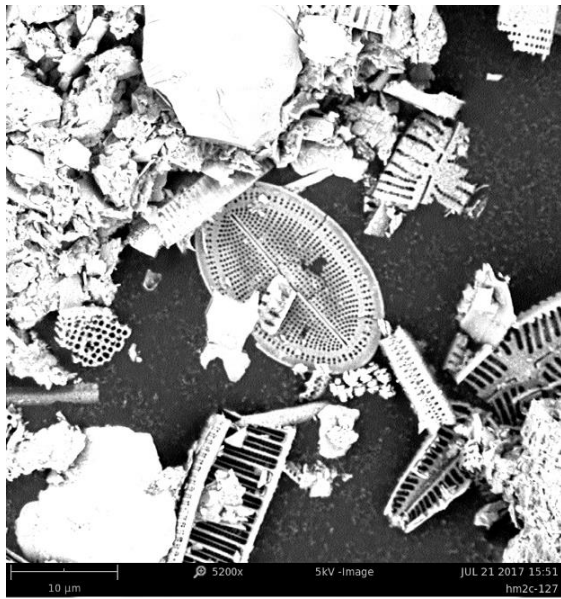


Plate 10. *Cocconeis plancetula*

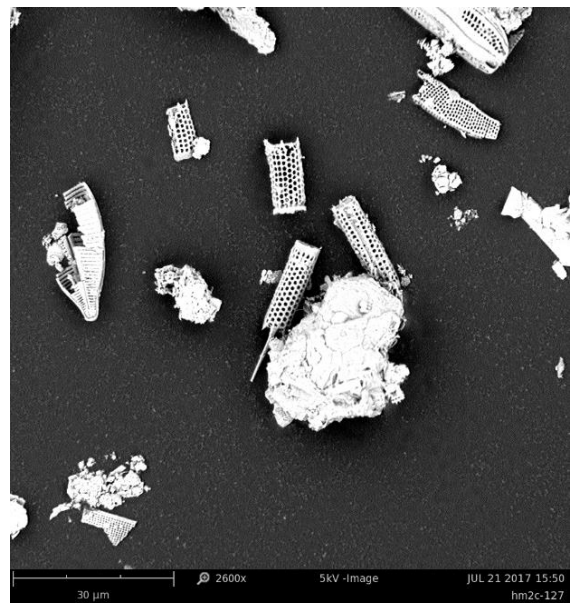
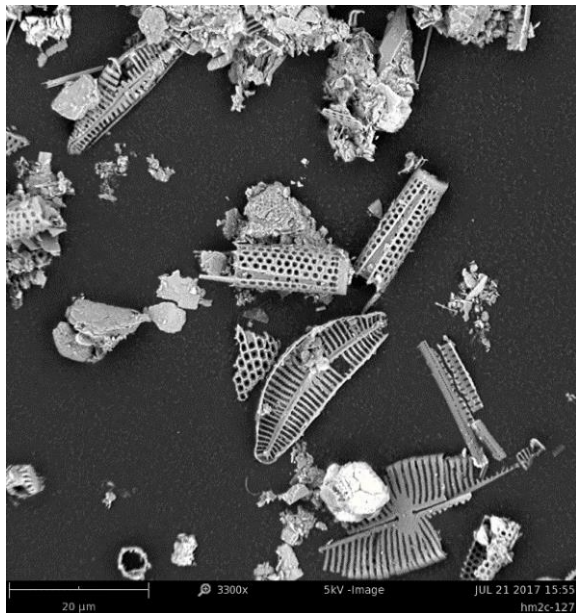


Plate 11. *Aulacoseira granulata*

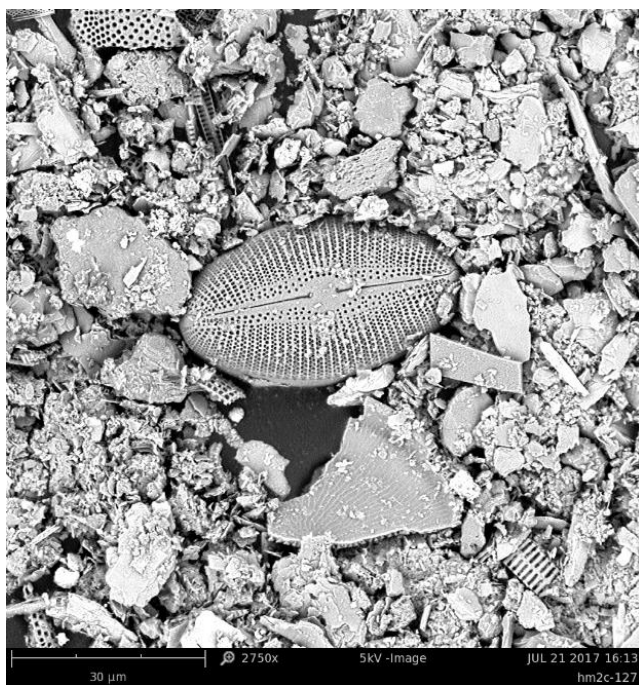
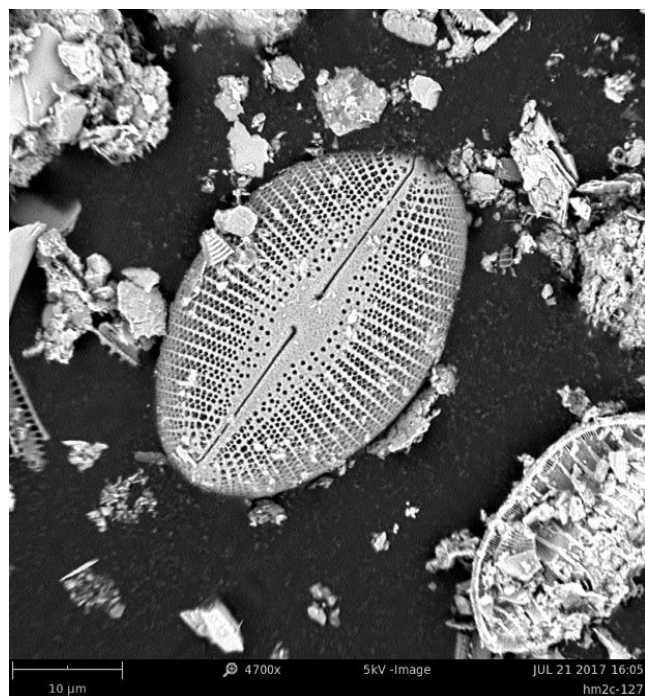
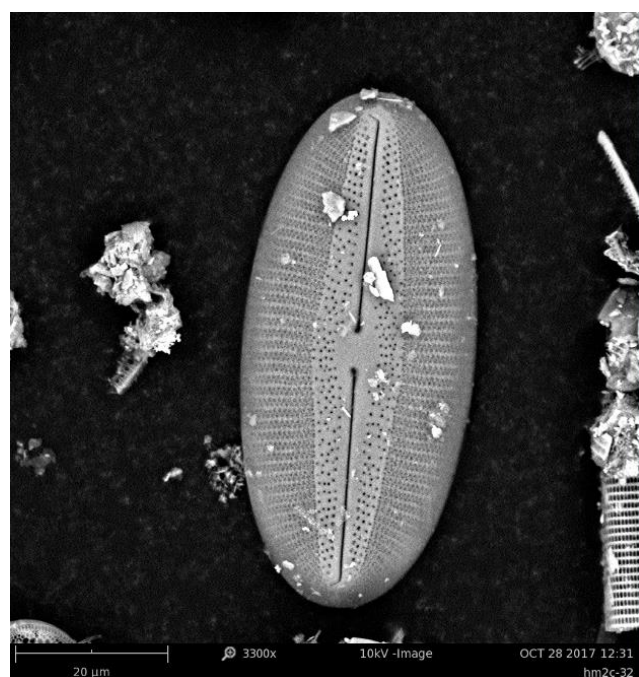
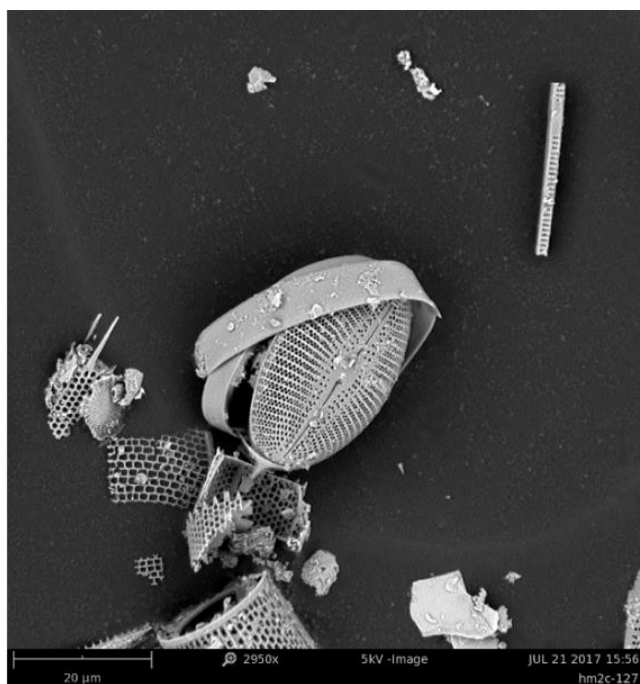


Plate 12. *Diploneis smithii*

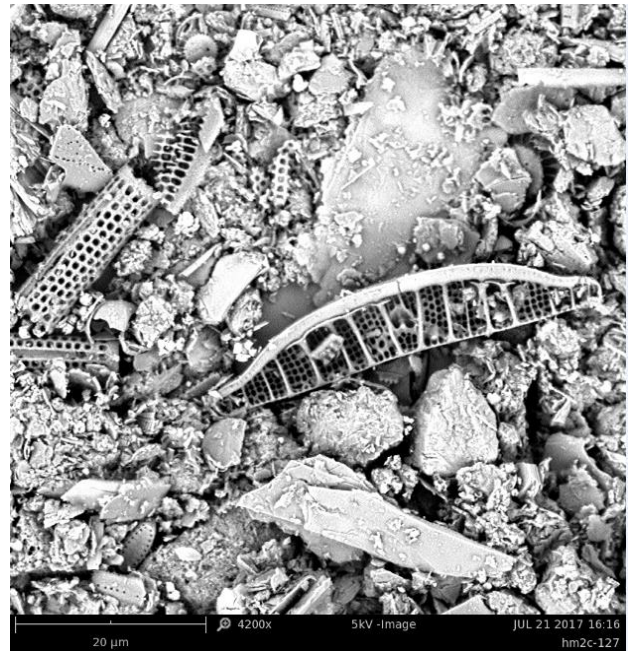
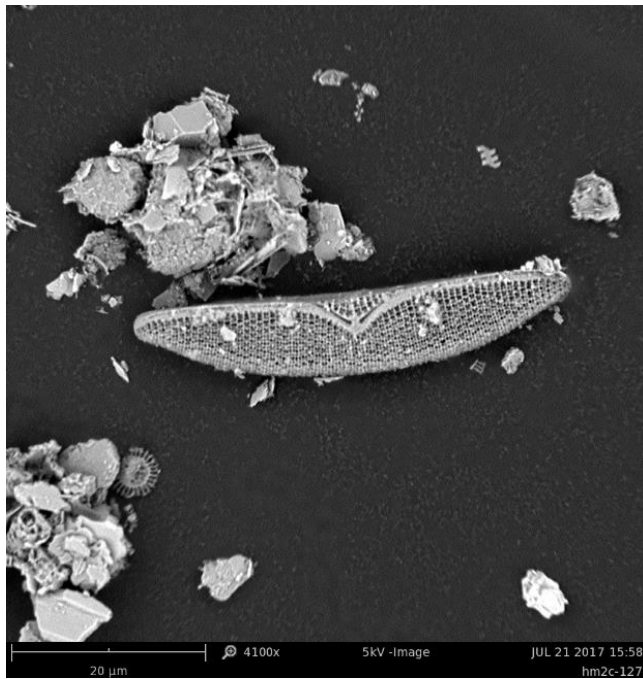


Plate 13. *Epithemia geoppertiana*

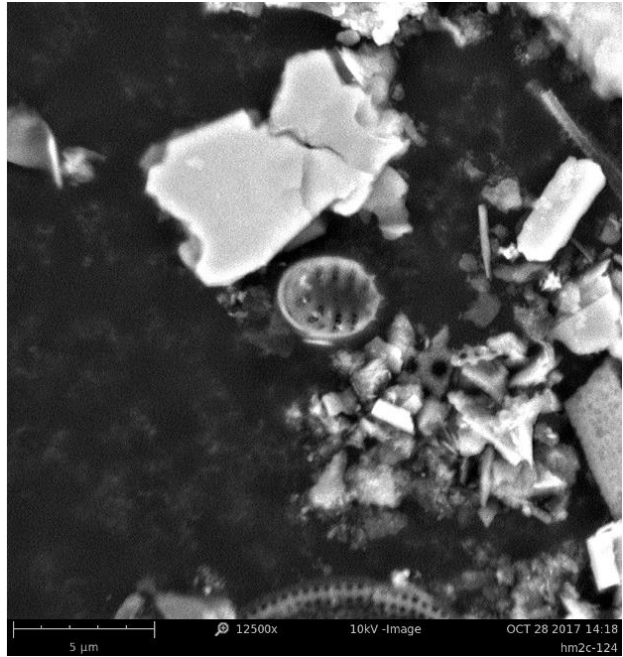


Plate 14. *Pseudostratosira brevistriata* var. *minor*

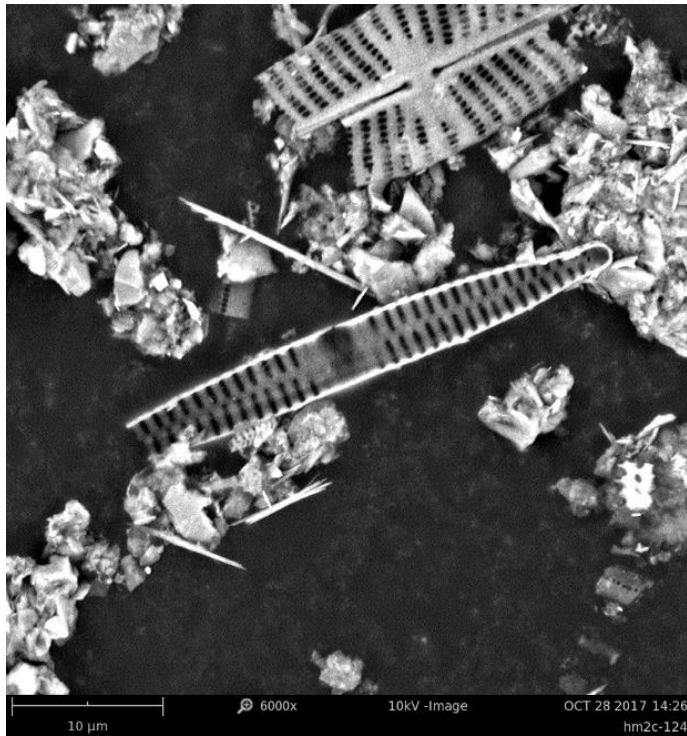


Plate 15. *Fragilaria capucina*

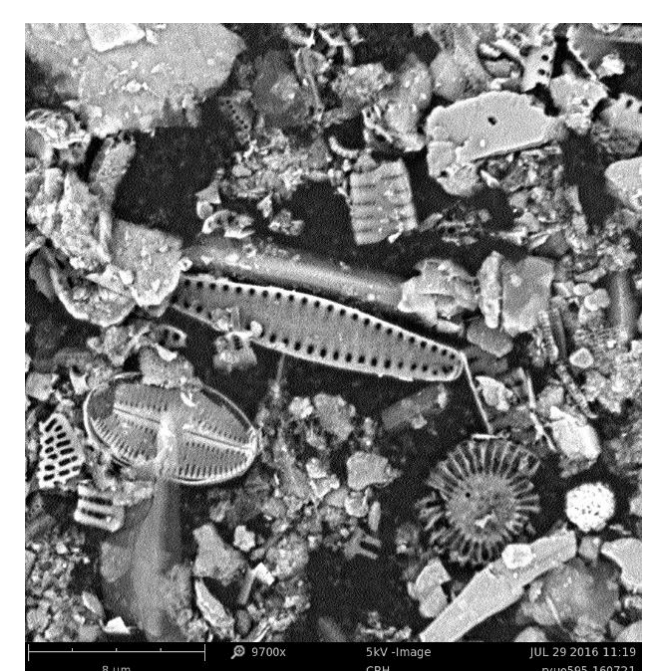
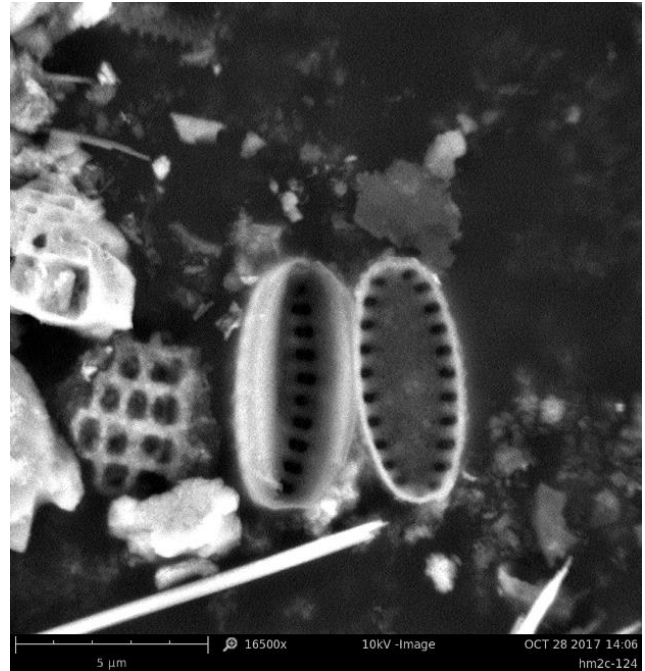


Plate 16. *Pseudostaurosira brevistriata*

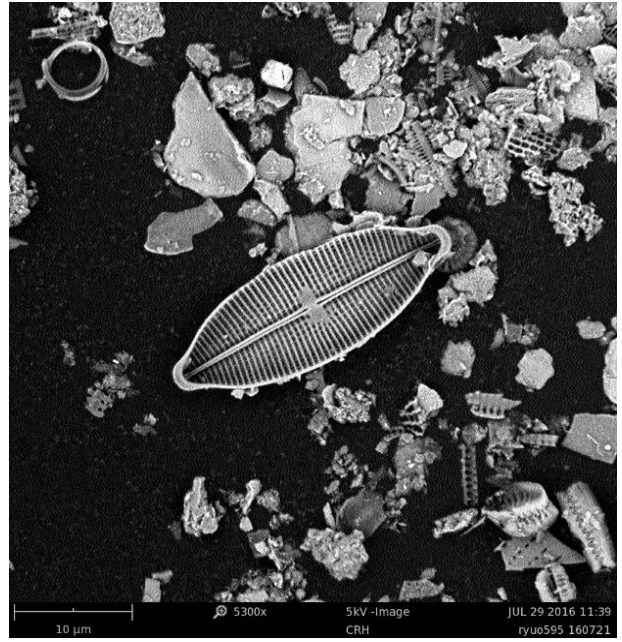
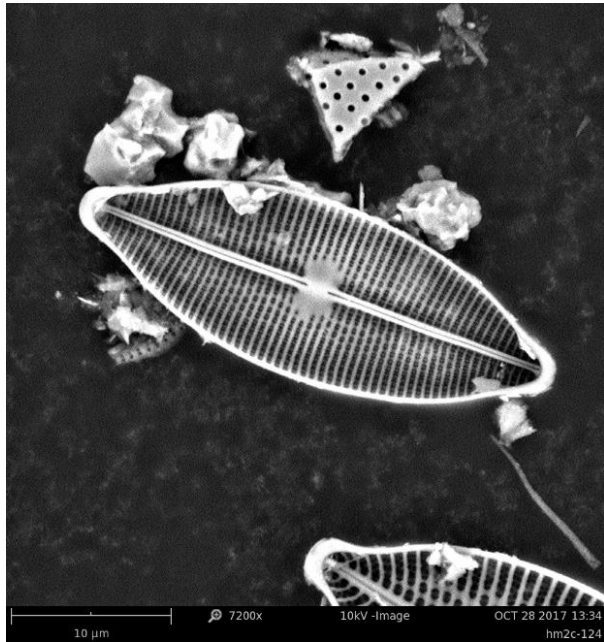


Plate 17. *Mastogloia smithii*

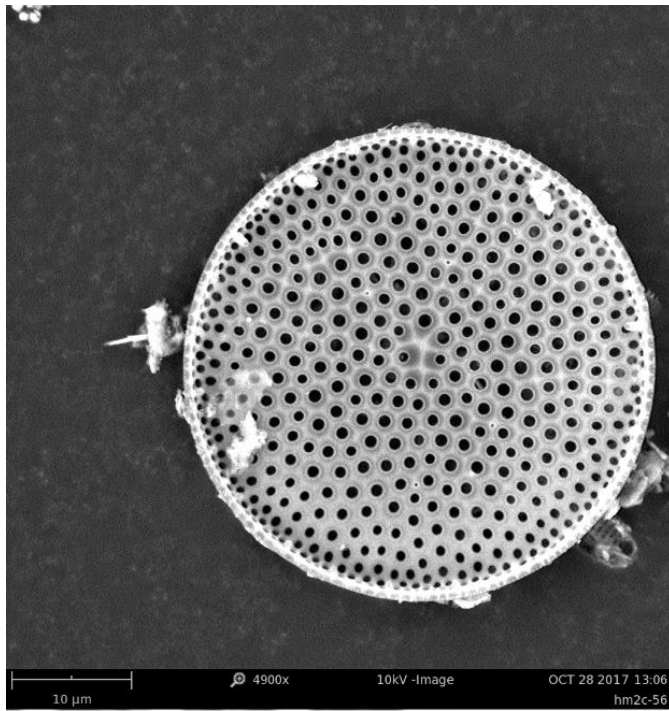


Plate 18. *Coscinodiscus radiatus*

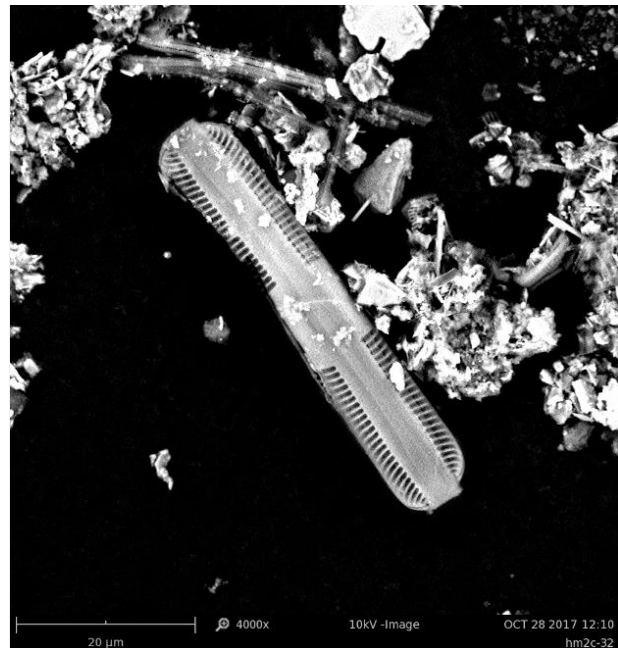
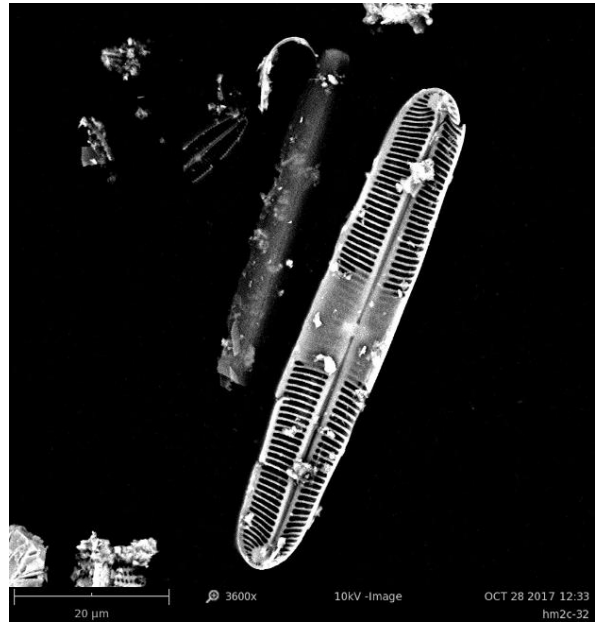
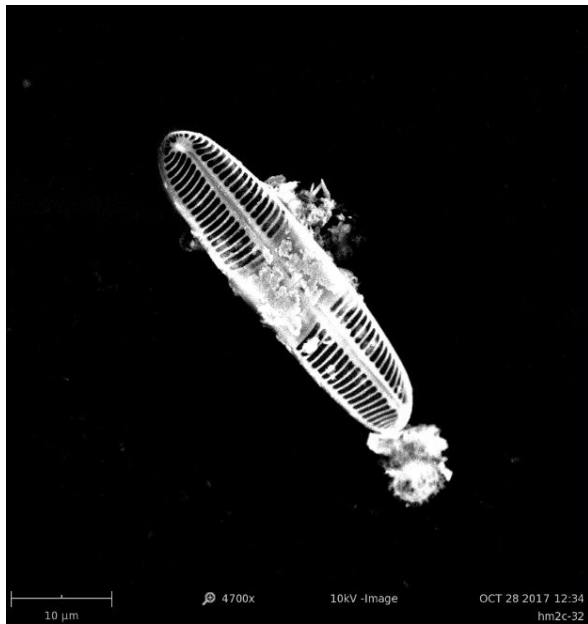


Plate 19. *Pinnularia quadratarea*

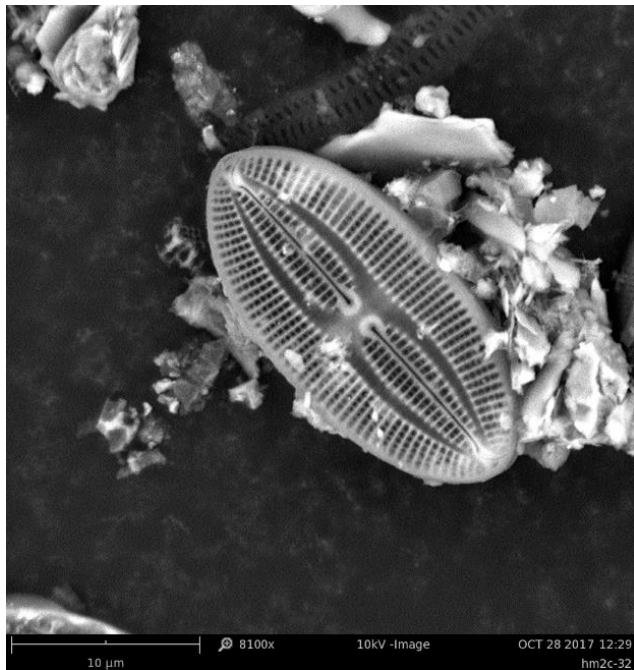


Plate 20. *Fallacia forcipata*

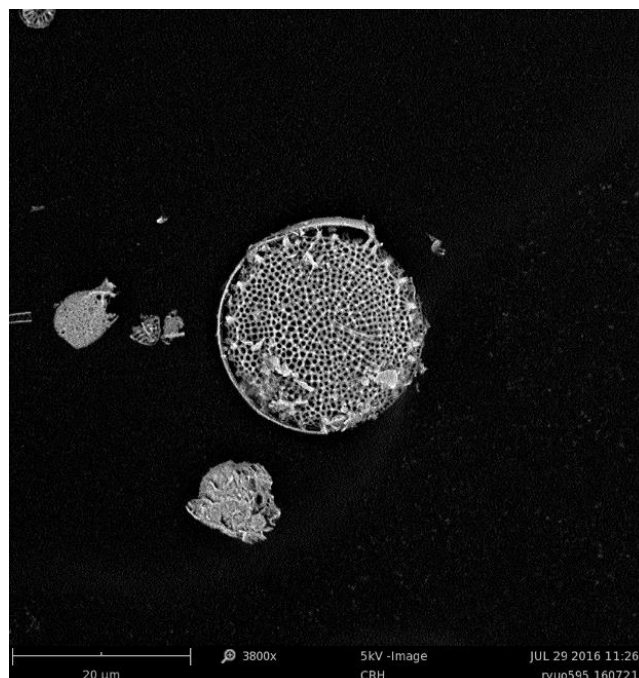
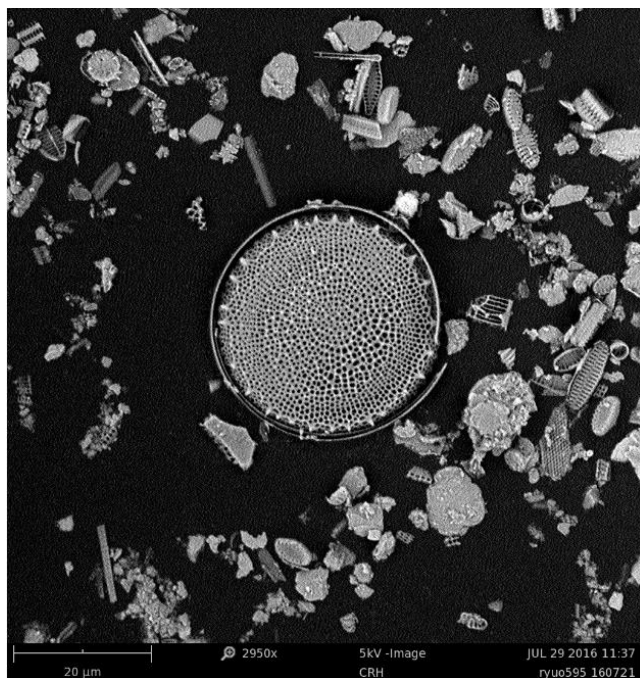


Plate 21. *Thalassiosira lacustris*

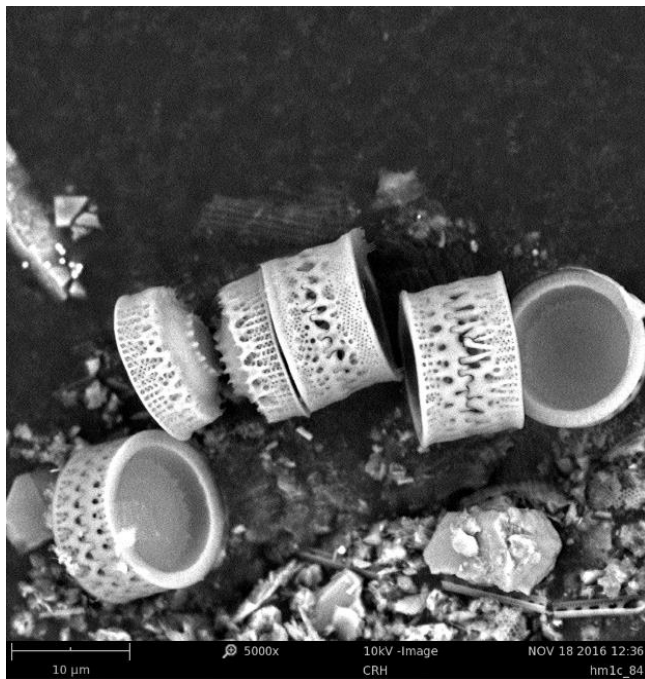
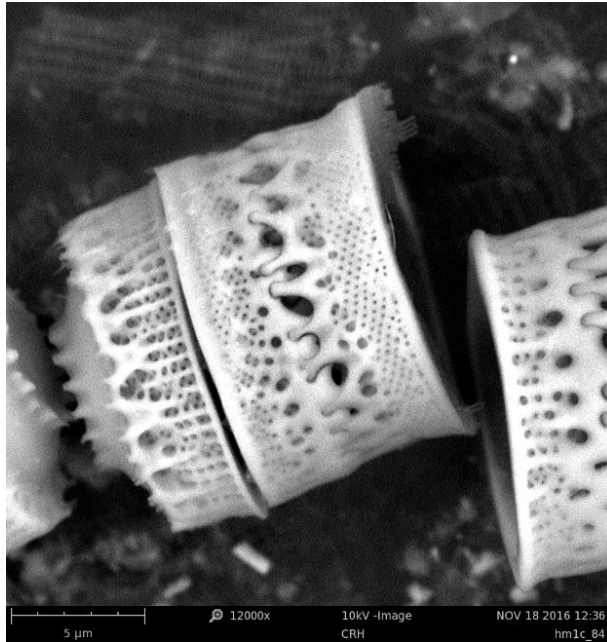


Plate 22. *Palaria sulcata*

Appendix B. Diatom catalog from LM (Light Microscope)

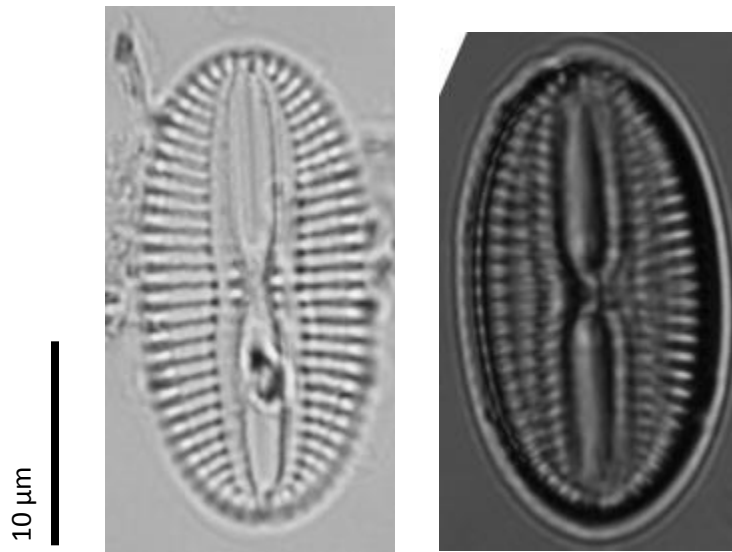


Plate 1. *Diploneis suborbicularis*

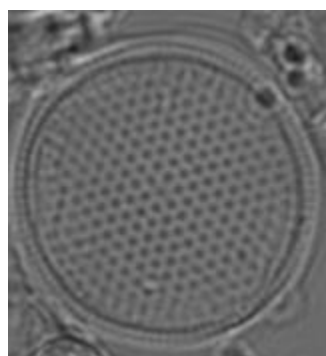
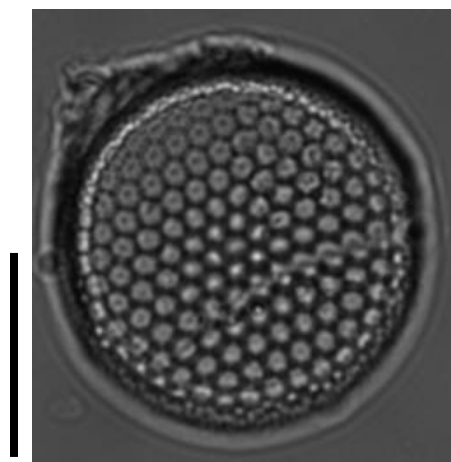
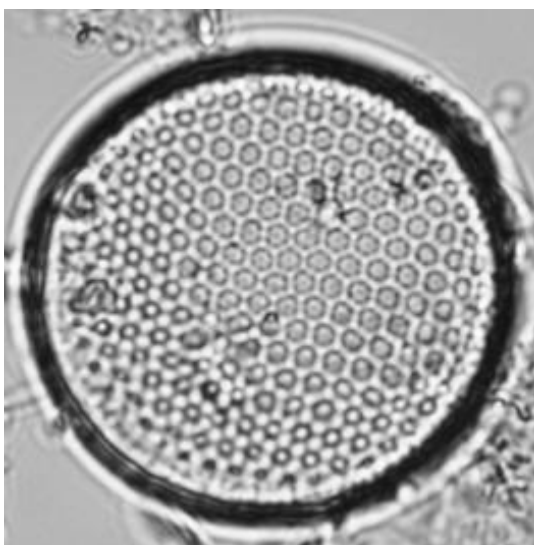
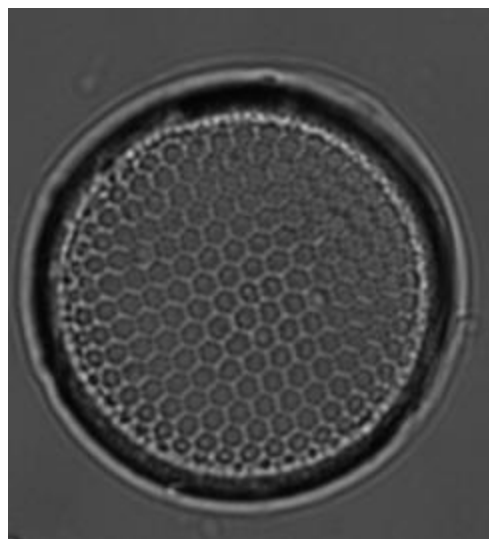
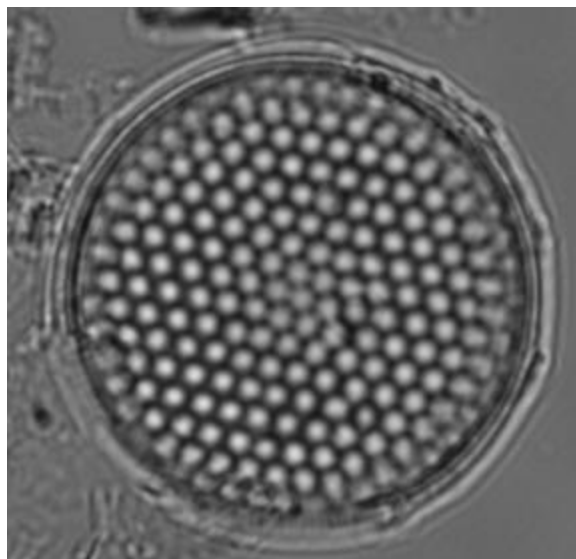
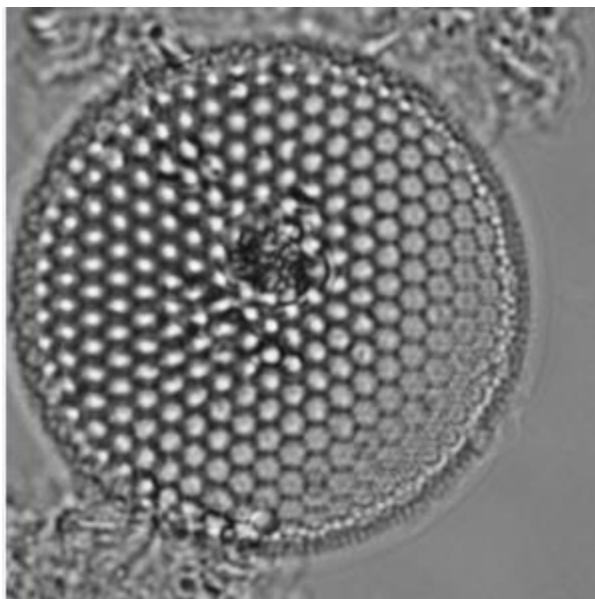


Plate 2. *Thalassiosira lineata*

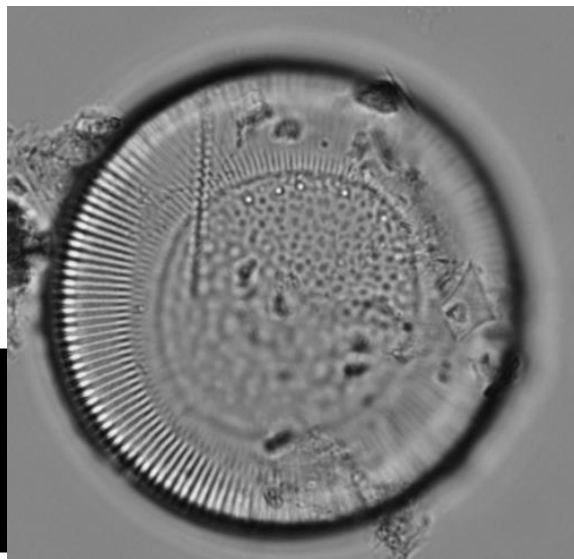


Plate 3. *Cyclotella striata*

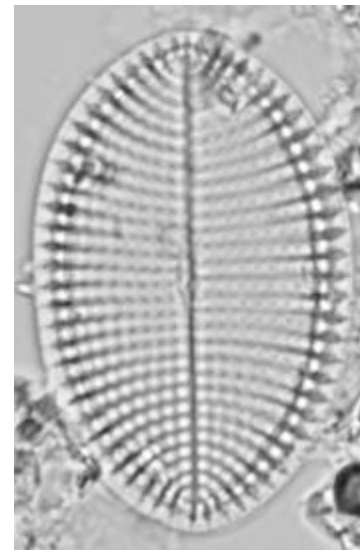
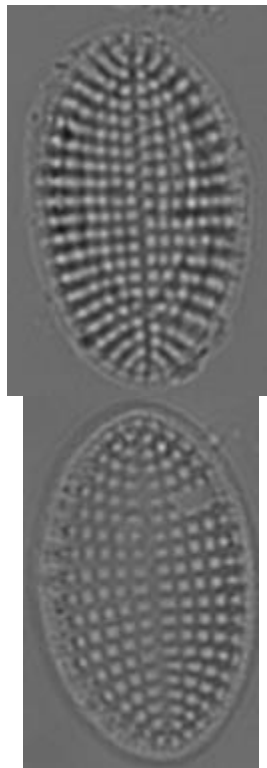
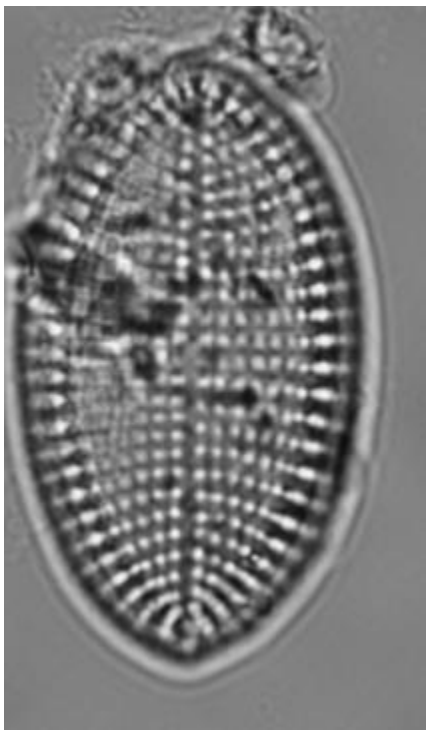


Plate 4. *Cocconeis scutellum*

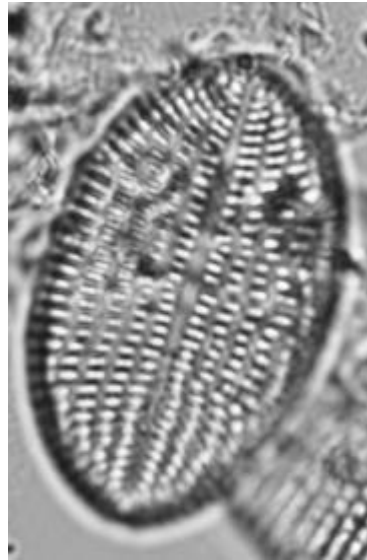


Plate 5. *Cocconeis palancentula*

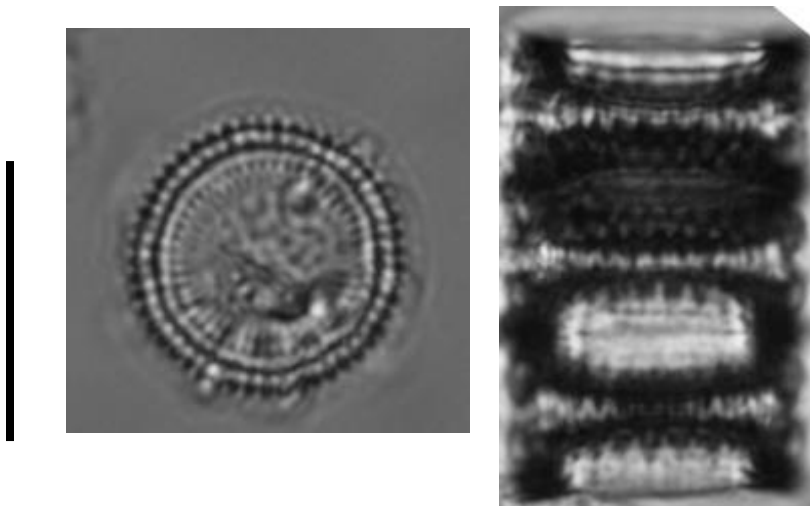


Plate 6. *Palaria sulcata*

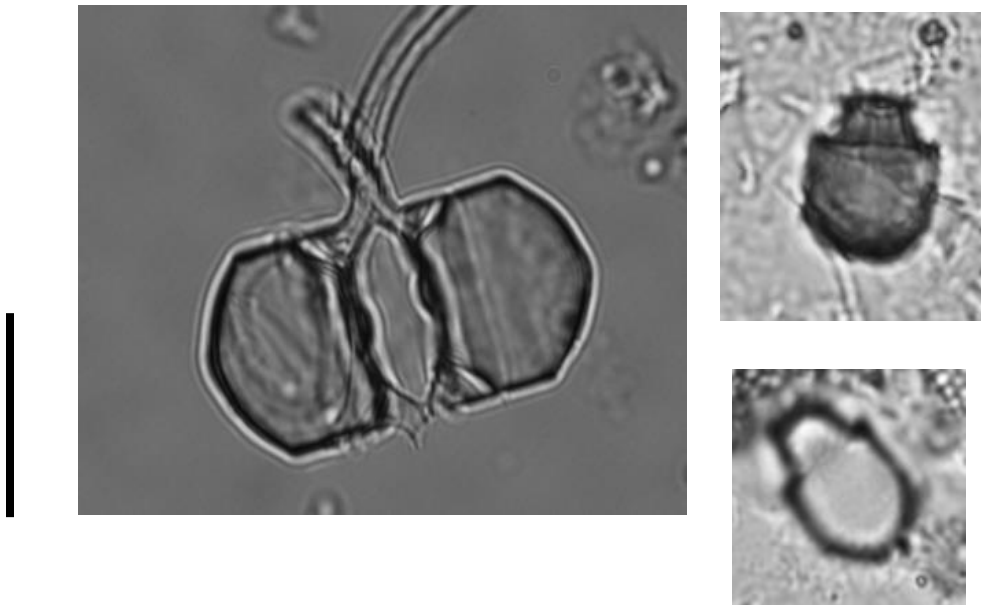


Plate 7. *Chaetoceros* resting spore

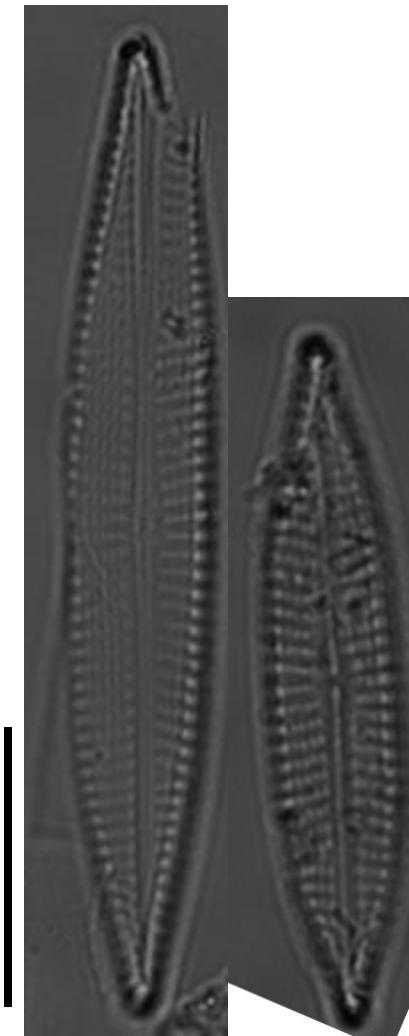


Plate 8. *Navicula* sp1.

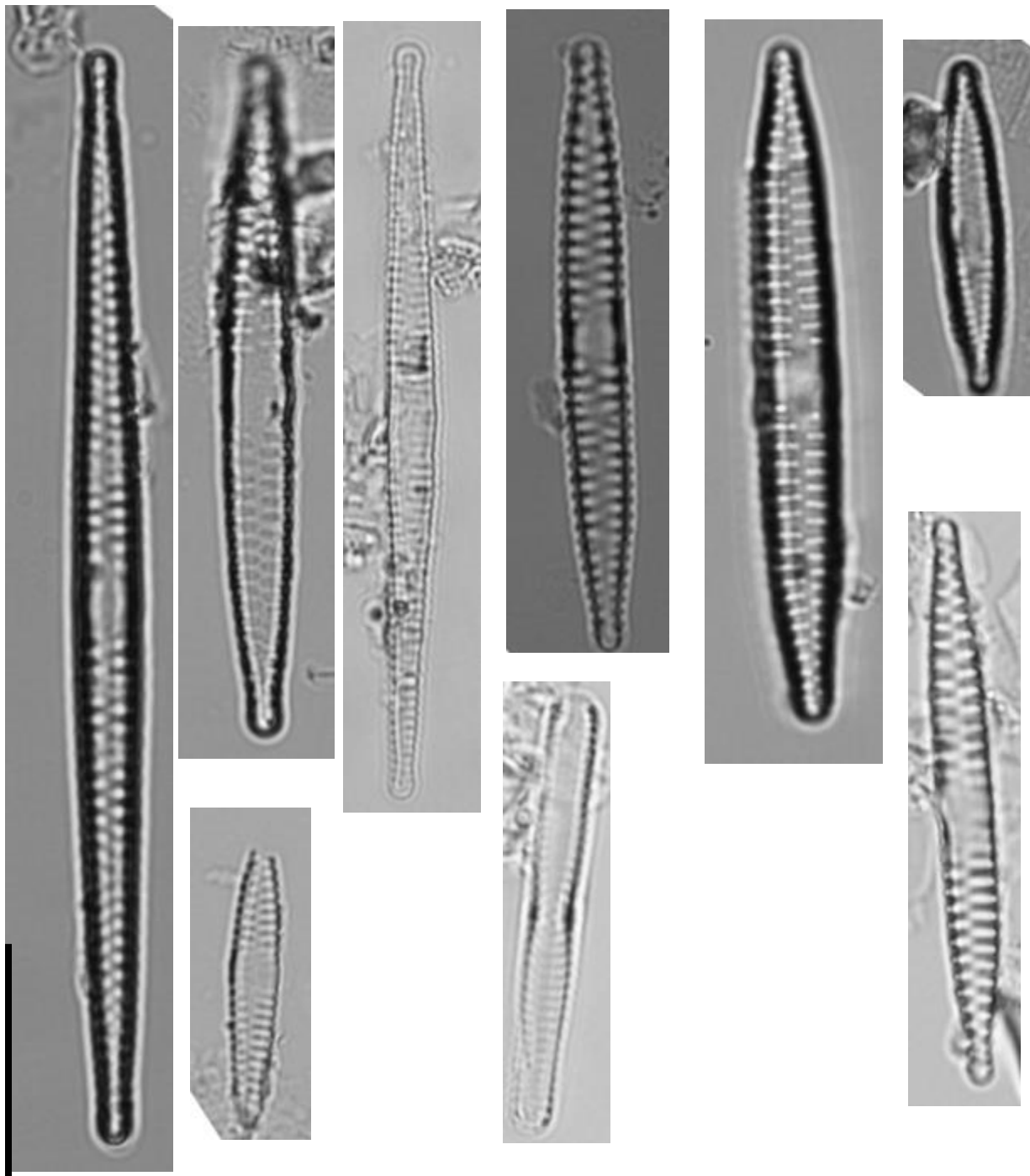


Plate 9. *Fragilaria capucina*

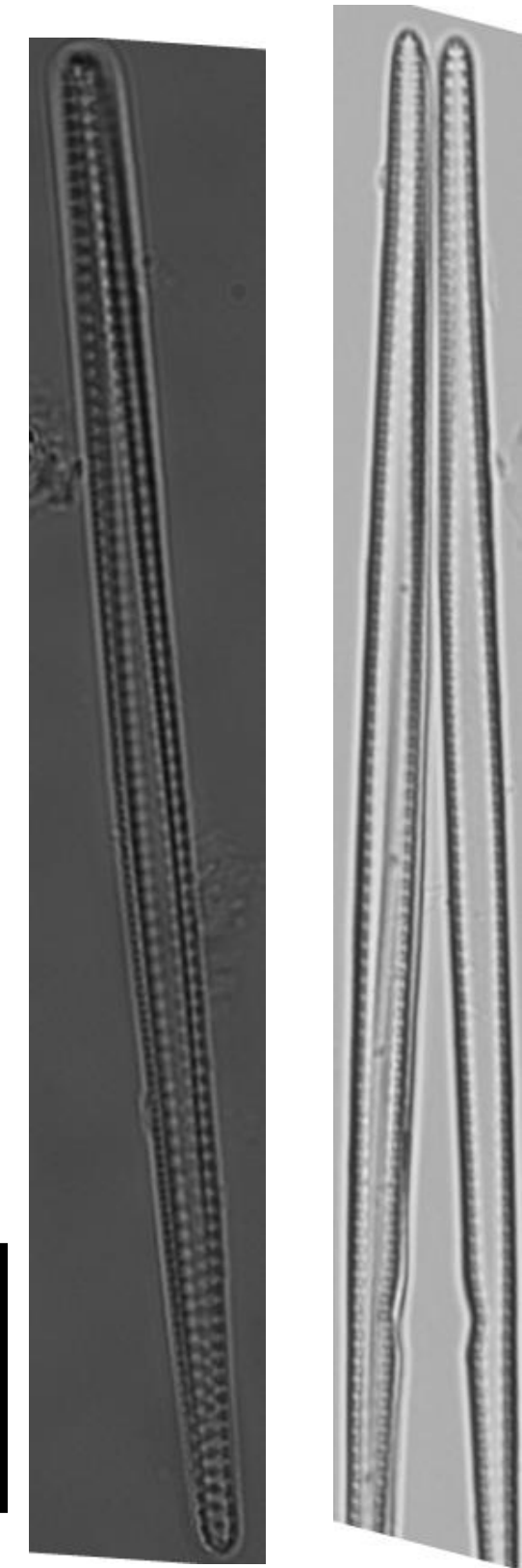


Plate 10. *Thalassionema nitzschioides*

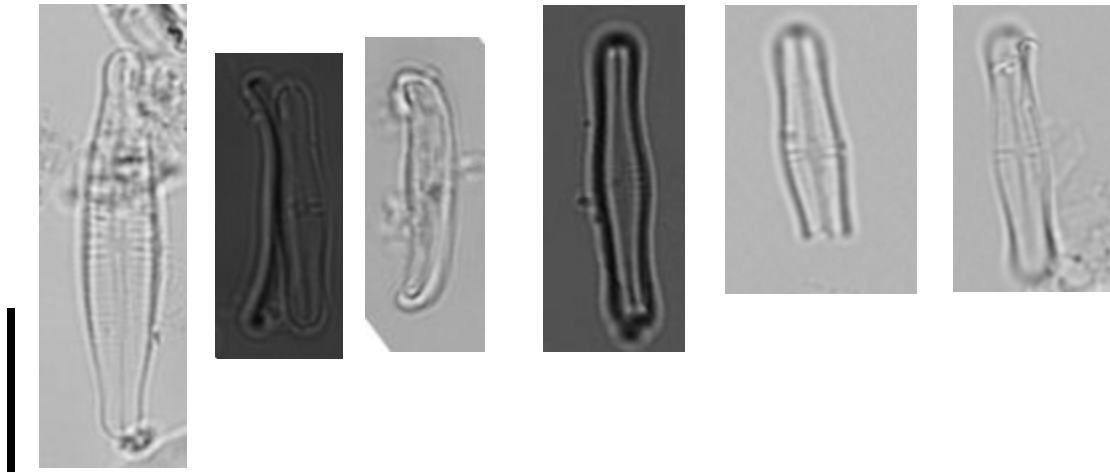


Plate 12. *Achnanthidium minutissimum*

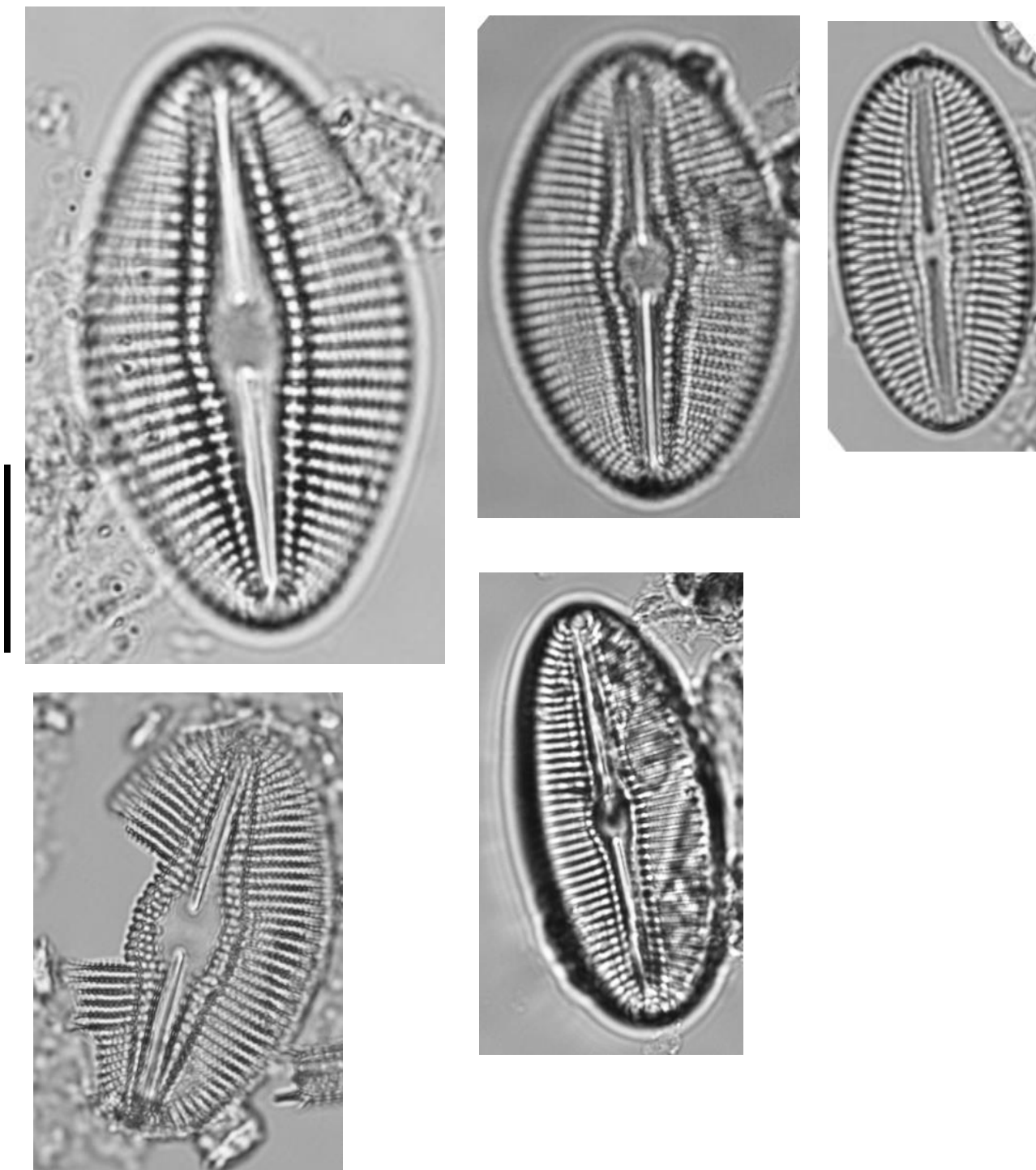


Plate 12. *Diploneis smithii*

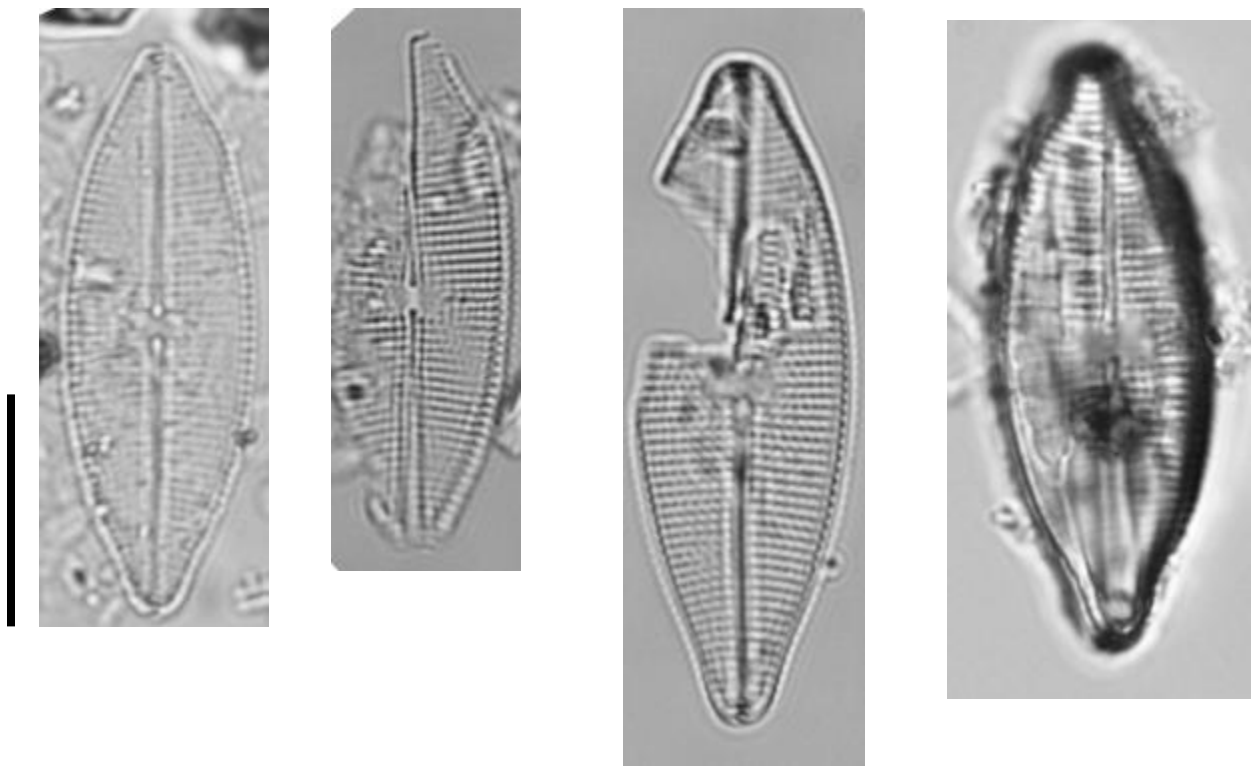


Plate 14. *Mastogloia smithii*

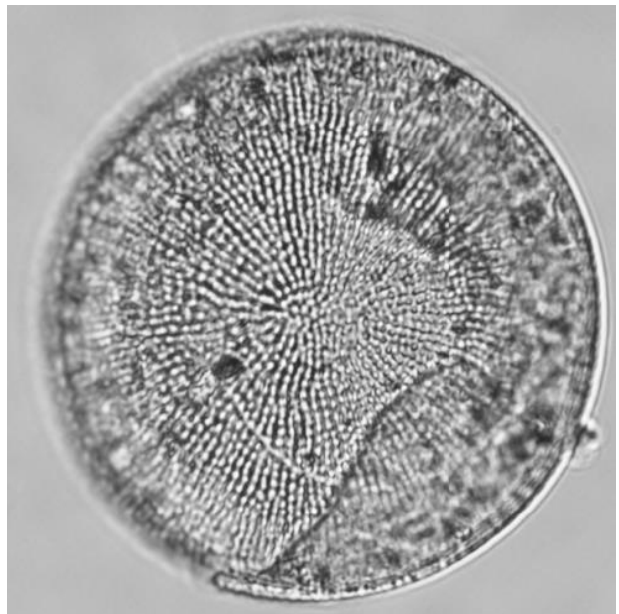
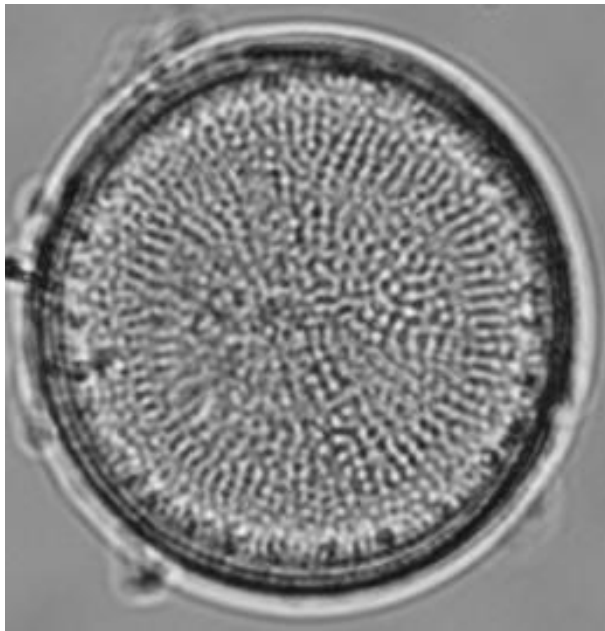
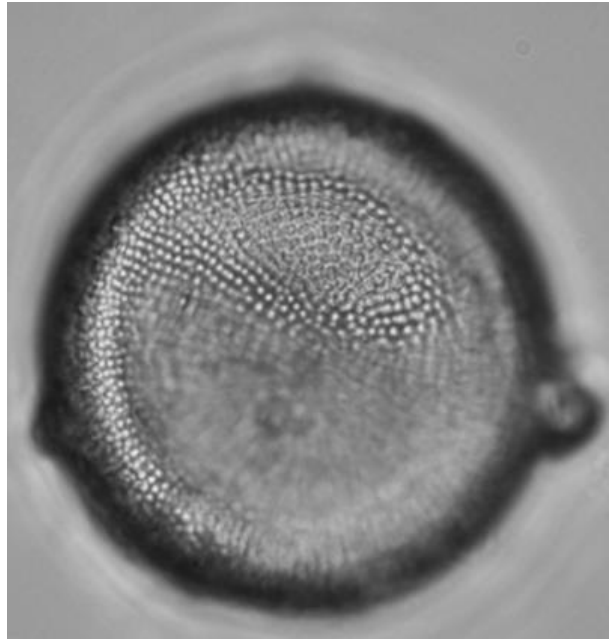
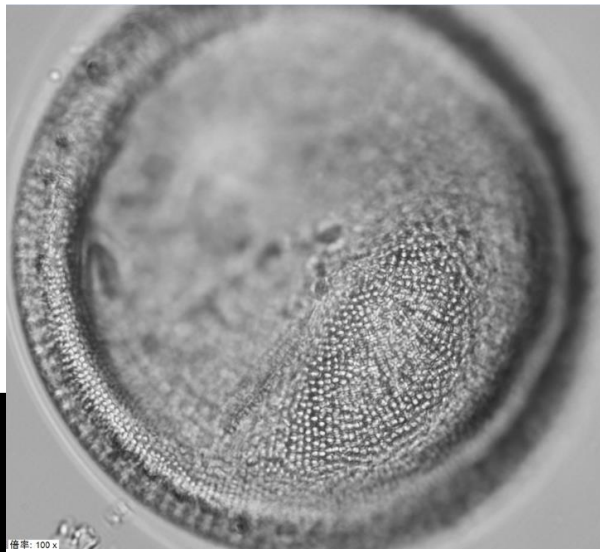


Plate 14. *Thalassiosira lacustris*

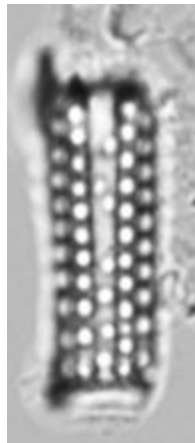
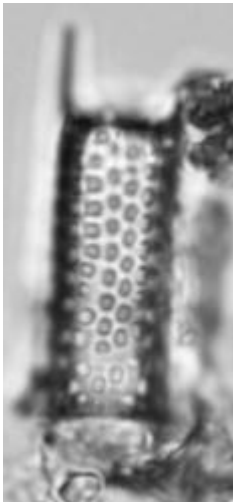
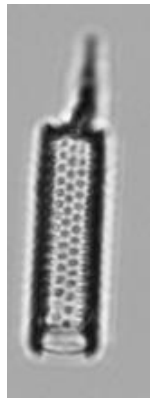
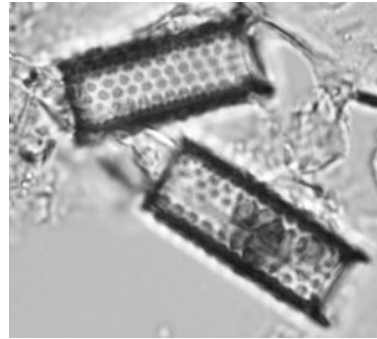
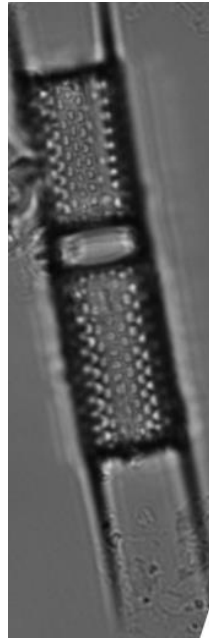
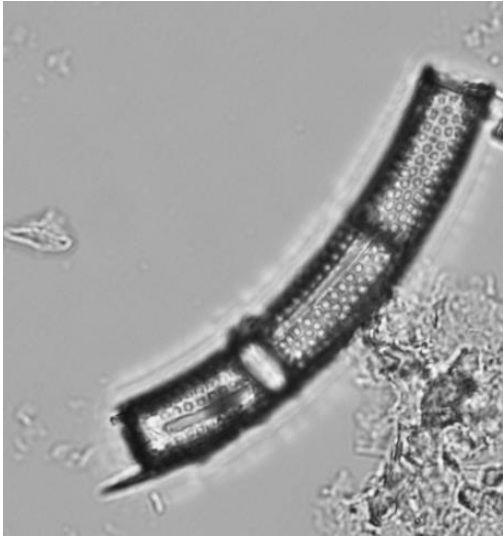


Plate 15. *Aulacoseira granulata*

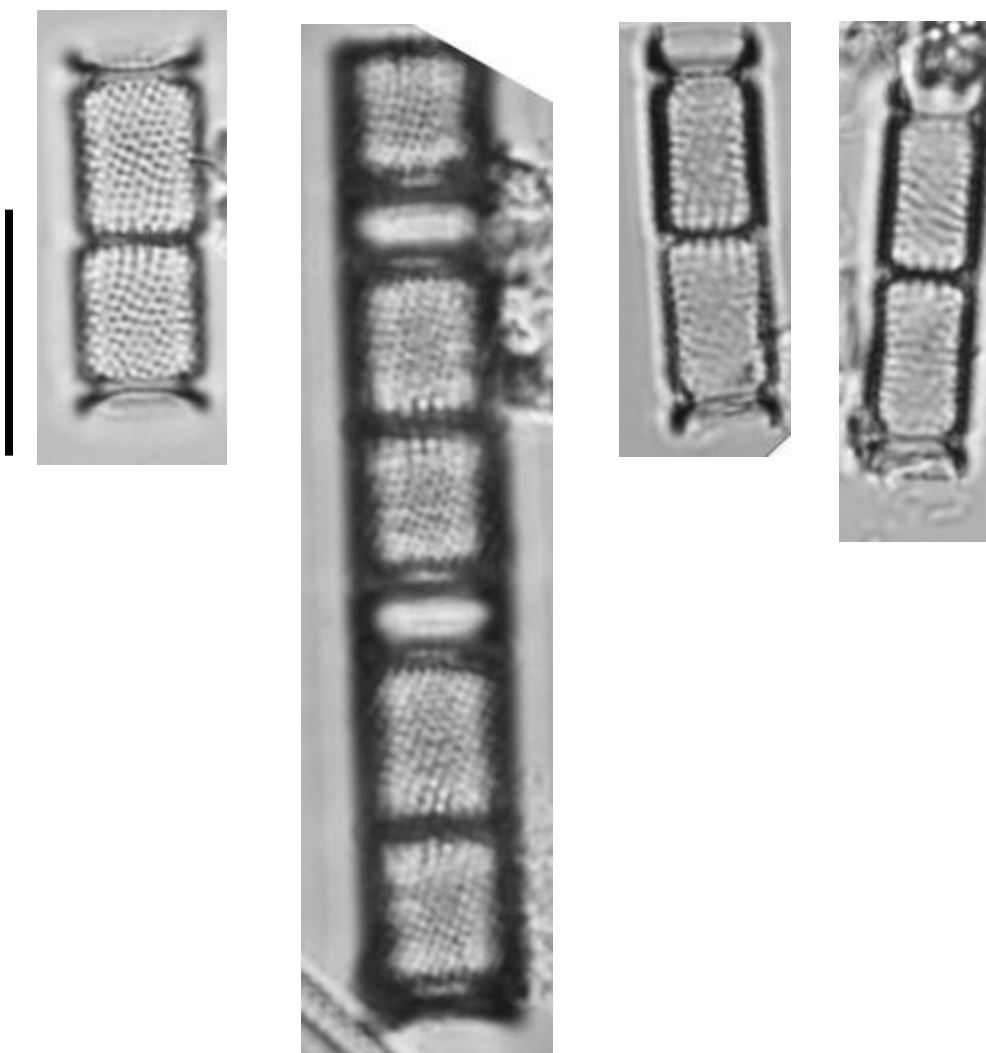


Plate 16. *Aulacoseira ambigua*

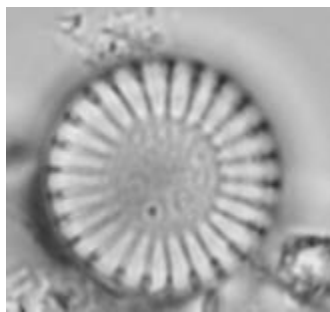
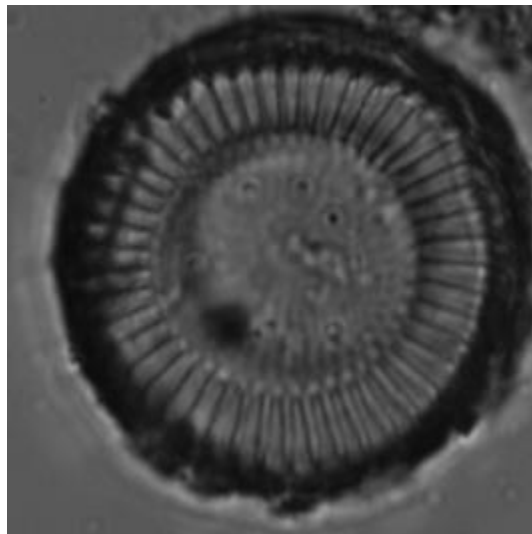
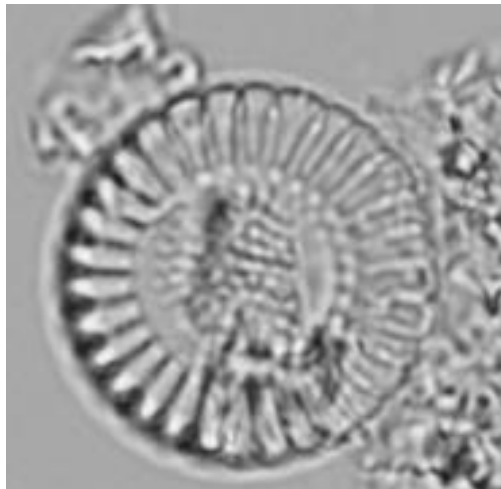
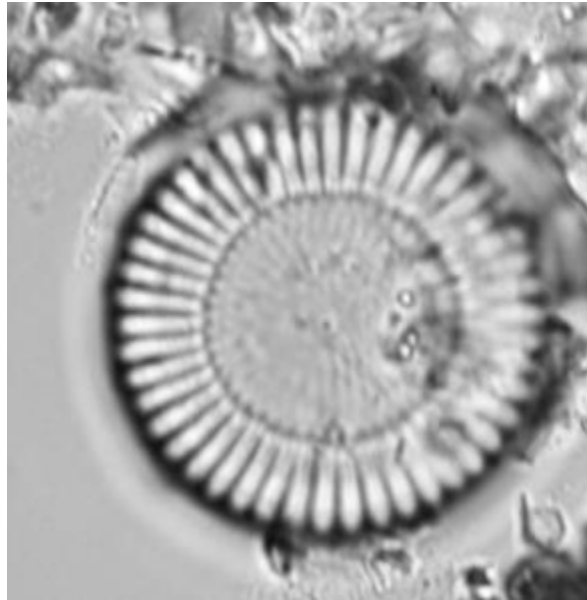
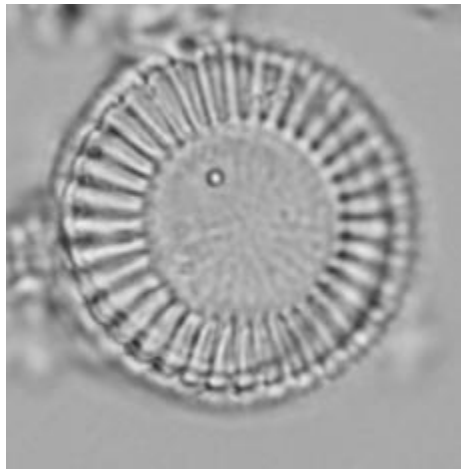


Plate 17. *Cyclotella meneghiniana*

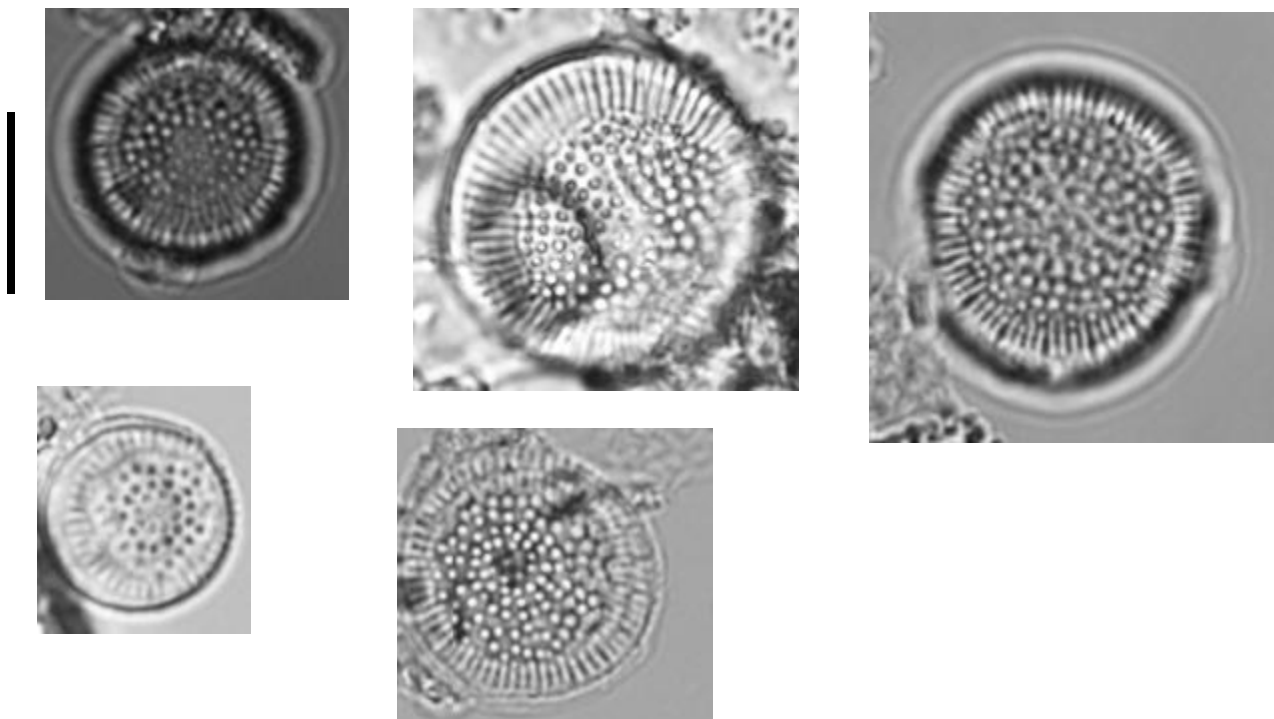


Plate 18. *Cyclotella radiosa*

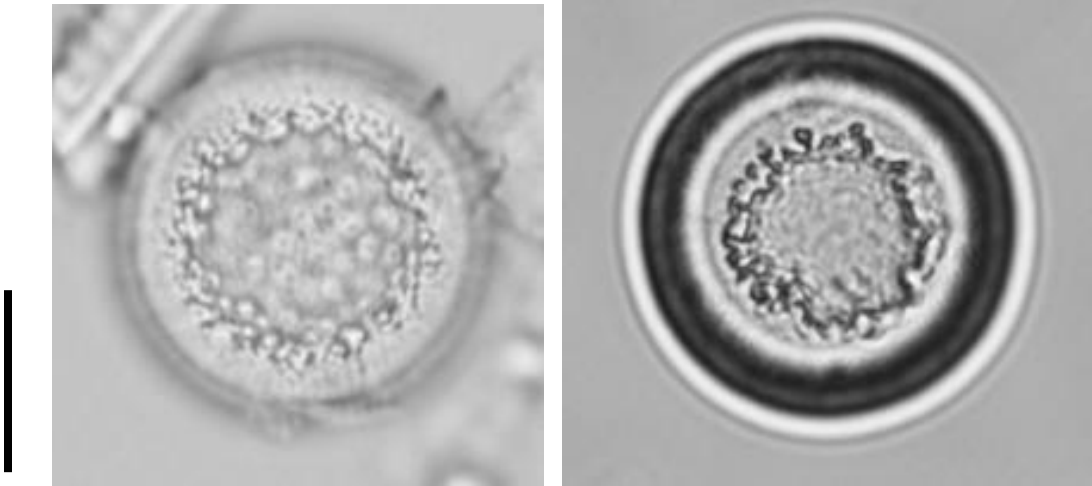


Plate 19. *Podosira stelligera*

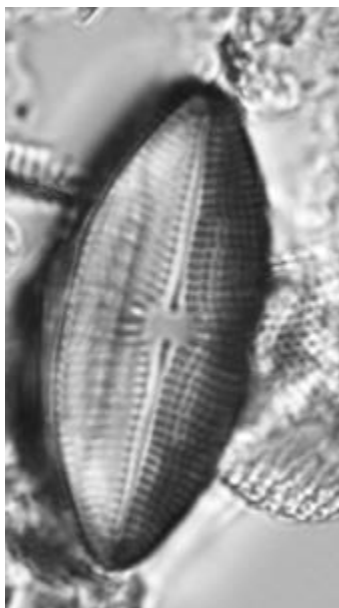


Plate 20. *Mastogloia grunowii*

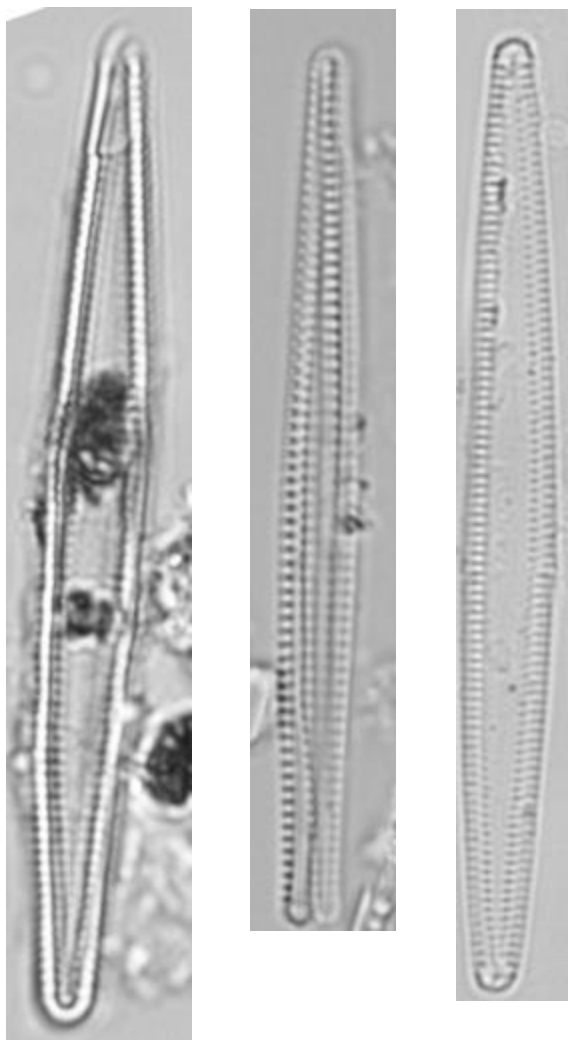


Plate 21. *Tabularia fasciculata*