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Seasonal deposition of non-glacial varved clay in the Asono Formation of the middle Pleistocene in central Kyushu, Japan

Yoshitaka Hase[1] and Yuko Ando[2]

(1 Goshoura Cretaceous Museum, 4310-5 Goshoura, Goshoura Town, Amakusa City, Kumamoto 866-0313, Japan)
(2 Yuko Nishinaka (Ando), MSc.)

Abstract

The Asono Formation is composed of a lacustrine sediment which includes non-glacial varved clay. The non-glacial varved clay is composed of light-colored and dark-colored laminae in alternating layers. The lamina includes fossil diatom and pollen. Based on the idea that strata formed in lakes record the changes in the surrounding terrestrial environment, we have so far grasped those changes mainly based on pollen analysis. We understood the changes in the lake environment from the analysis results of diatom fossils and pollen fossils for each non-glacial varve clay lamina, and demonstrated that there was a part of the non-glacial varved sediments indicating seasonal changes of the lake environment.

Keywords: non-glacial varved clay, seasonal deposition, middle Pleistocene, Asono Formation

Introduction

Lake sediments including fossils of pollen and diatom are sensitive indicators of past environmental changes such as lake conditions, surrounding land vegetation and climate. Diatom assemblages contained in fine sediments in lake beds show past aquatic conditions, while pollen from sediments indicate surrounding vegetation and climate in the area. These lake sediments are often composed of alternating light- and dark-colored laminae; thin clay layers of 1-2 mm in thickness. These alternating laminae are so-called *non-glacial varved clay*. Non-glacial varved clay is generally known to be composed of very fine grain, thin lamina formed by sediments which were deposited as light-colored clay in the summer and dark-colored clay in the winter, showing an annual sediment by a set of two laminae. Ishihara and Miyata (1999) reported that the breeding season of diatom (*Stephanodiscus* sp.), which constituted the light-colored lamina, was winter, based on the research of the Research Group for the Hiruzenbara (1975) on the lacustrine banded diatomaceous sediments of the Middle Pleistocene Hiruzenbara Formation, Okayama Prefecture. Therefore, it was thought that a dark-colored and light-colored pair represented a year. It is possible that analysis of non-glacial varved clay reveals details of environmental changes of surrounding land. It is also mentioned that oscillation of light- and dark-colored laminae demonstrates a cyclic orbital activity of intervals of 11 or 22 years (Sonett and Williams, 1985).

Diatomite, mainly composed of frustules of fossil diatoms, is part of the composition of non-glacial varved clay. Diatoms live under aquatic conditions that have pH, temperature, nutrition availability and salinity. Therefore, diatoms in sediment indicates its life condition at the time of its deposition. Pollen included in sediment indicates its parent plant and shows how luxuriant it was under existing climatic conditions of temperature, precipitation and moisture. As a result, analysis of diatom and pollen within laminae leads to the understanding of environmental changes during deposition of sediments.

The Asono Formation in the middle Pleistocene is formed by siltstone with intercalated sandstone layers at the Asono Basin of Syonai-Town, Oita Prefecture in central Kyushu (Fig. 1). Hase and Iwauchi (1985), Iwauchi and Hase (1986) and Ando (2004) described the Asono Formation with regard to its stratigraphy and environmental changes during the period of deposition based on pollen and diatom analysis.

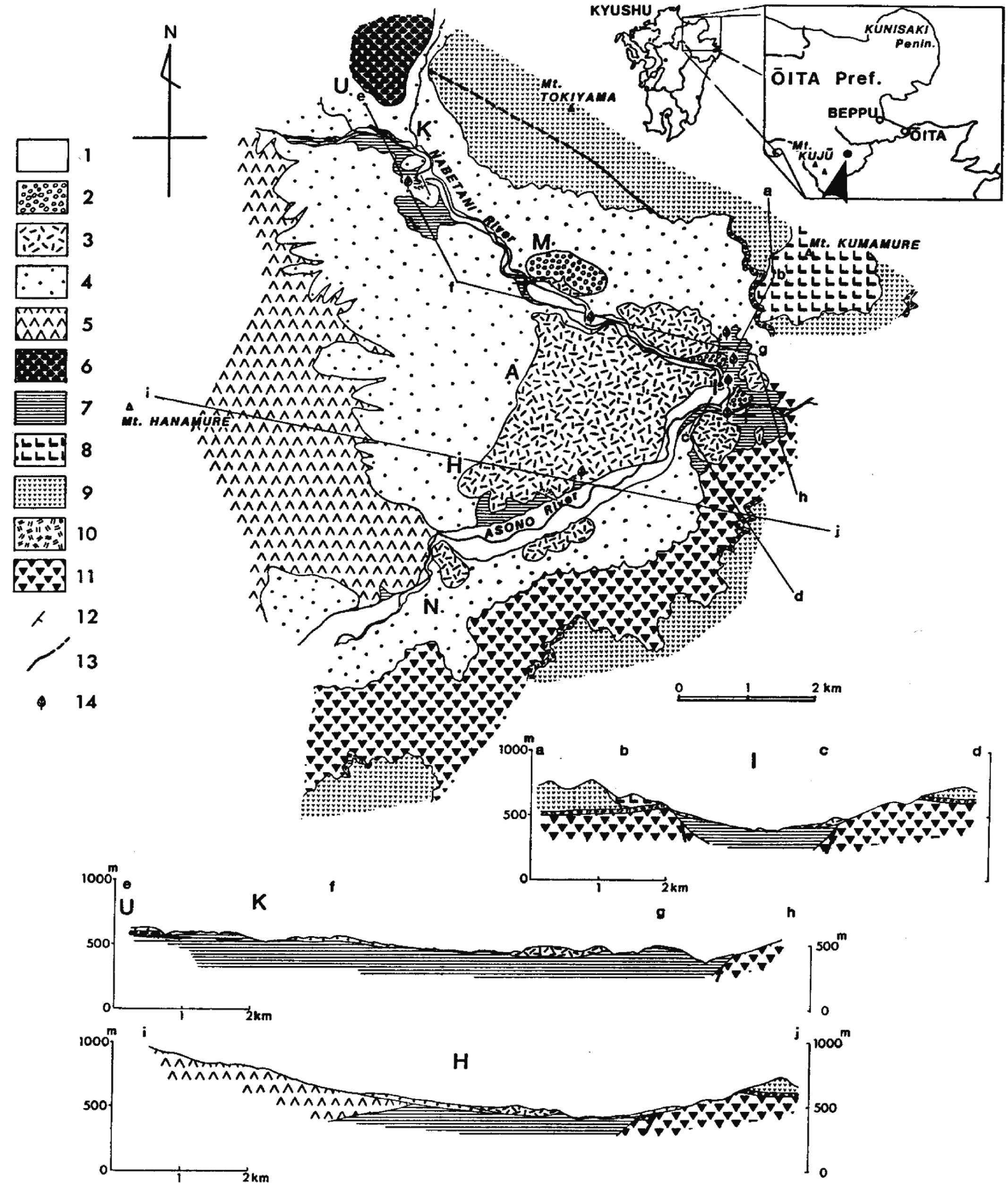

Fig. 1. Locality and geologic map of the Asono area (Hase and Iwauchi, 1985).
1: alluvium, 2: terrace deposit, 3: Serikawa Pyroclastic Flow Deposit, 4: volcanic fan deposit, piedmont deposit and ash bed, 5: Hanamureyama Volcanic Rocks, 6: Uchiyama Hornblende Andesite, 7: Asono Formation, 8: Kumamureyama Rhyolite, 9: Tokiyama Andesite, 10: Imaichi Pyroclastic Flow Deposit, 11: Kakura Andesite, 12: strike and dip, 13: fault, 14: localities of macrofossils, U: Uchiyama, K: Kozuno, M: Makinoharu, I:Iwashita, A: Ageju, H: Harunaka, N: Nagano.

We studied laminated samples from the Asono Formation and clarified that the lamina deposited under seasonal changes based on the diatom and pollen inclusion of each lamina.

Geologic setting of the Asono area

The Asono area is mainly composed of Kakura Andesite, Imaichi Pyroclastic Flow Deposit, Tokiyama Andesite, Kumamureyama Rhyolite, Asono Formation, Hanamure Volcanic Rocks, detritus and fan deposits on mountain slopes and Serikawa Pyroclastic Flow Deposit, in an ascending order (Hase and Iwauchi, 1985) (Table 1).

The Kakura Andesite and Tokiyama Andesite consist of lava and tuffbreccia of an augite hypersthene andesite, and the Imaichi Pyroclastic Flow Deposit is intercalated with these andesites and mainly composed of welded tuff of augite hypersthene andesite. The Kumamureyama Rhyolite is composed of lava and tuff breccia of biotite rhyolite.

The Asono Formation as identified by Ono (1963) is mainly composed of diatomaceous siltstone with tuffaceous sandstone and is intercalated with the Uchiyama Andesite lava at the upper part. The formation is 50-80 m in thickness and abutted against the Kumamureyama Rhyolite (Fig.2). According to radiometric aging by the fission-track method, the Kumamureyama Rhyolite is dated at 0.73±0.14 Ma and the Uchiyama Andesite is dated a 0.34±0.17 Ma (Hase and Iwauchi, 1985). Therefore, the Asono Formation was formed in the middle Pleistocene. The upper part of the Asono Formation includes very laminated clay, known as non-glacial varved clay, at a thickness of about 5 m.

The Hanamureyama Volcanic Rocks lay on the Asono Formation unconformably. The Hanamureyama Volcanic Rocks are composed of a hypersthene hornblende

Table 1. Stratigraphy of the Asono area (After Hase and Iwauchi, 1985).

Geologic Age	Stratigraphic Sequence
Holocene	Alluvium
	Loam layer
	Terrace deposits
Pleistocene	Serikawa Pyroclastic Flow Deposit
	volcanic fan deposits/piedmont deposits
	Hanamure Volcanic Rocks
	Uchiyama Holnblende Andesite
	Asono Formation
	Kumamureyama Ryolite
?	
Pliocene	Tokiyama Andesite
	Imaichi Pyroclastic Flow Deposit
	Kakura Andesite

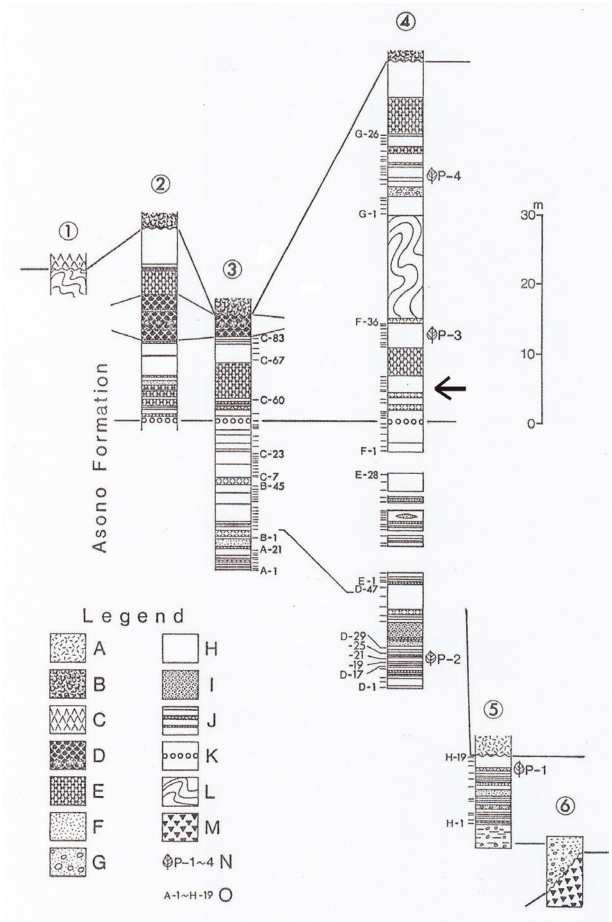

Fig. 2. Columnar sections of the Asono Formation (Hase and Iwauchi, 1985).

A: Serikawa Pyroclastic Flow Deposit, B: volcanic fan deposit, piedmont and ash bed, C: Hanamure Volcanic Rocks, D: Uchiyama Hornblende Andesite, E-L: Asono Formation (E; alternation of tuffaceous sand and silt, F; sand bed, G; sandy gravel bed, H; diatomite, I; pumice bed, J; ash bed, K; "Shiromaru band", L; slump bed), M: Kakura Andesite, N: Macrofossils of plants, O: sampling horizon for the pollen analysys.

← : Showing the sampling point of non-varved clay.

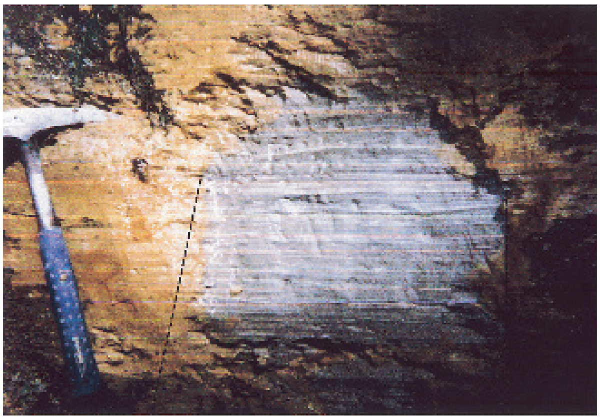

Fig. 3. Photograph of the non-glacial varved clay layers of the Asono Formation.

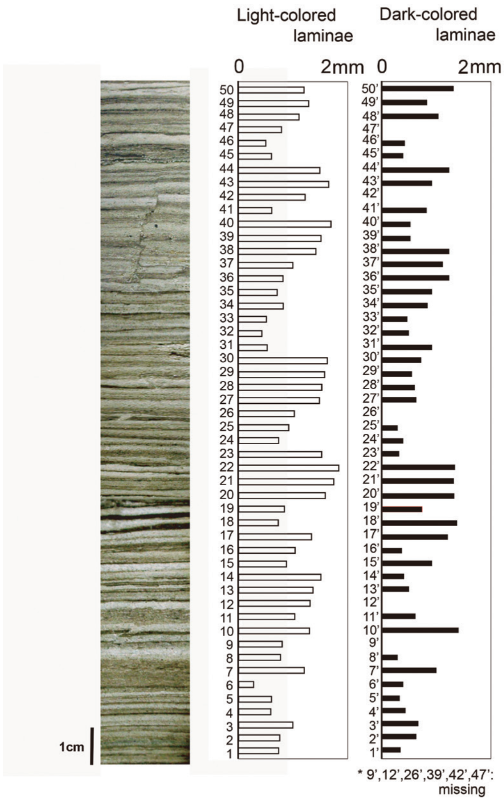

Fig. 4. Thickness of light- and dark-colored laminae. Number 1～50 and 1'～50' are shown the light-colored and the dark-colored laminae from bottom to top, respectively. Number 9', 12', 26', 39', 42' and 47' in the dark-colored laminae are missing.

andesite in the northern slope and an augite hypersthene andesite in the southern slope of Mt. Hanamureyama. These andesitic activities made tuffbreccia at the lower part and lava flows at the upper part. Detritus and fan deposits on mountain slopes are made of less sorting conglomerate with pumice and tuff derived from surrounding mountains. The Serikawa Pyroclastic Flow Deposit was correlated with the Aso-4 Pyroclasitic Flow Deposit by Ono (1963).

Material and method

A rectangular column of 10 cm wide and 50 cm long with 5 cm in thickness was taken vertically at a bedding plane of the Asono Formation (Fig. 3) from an outcrop of a cliff in a branched stream of the Nabetani River in the eastern part of the Asono Basin. After a slow drying period, the column was shaved off along its vertical plane for cleaning, then it was photographed and sketched to detail its sedimentary features.

The samples were taken from a thin lamina of the column using a knife. The thin laminae were colored light-colored as white to yellowish white, and dark-colored as black to dark gray, and they basically alternated. The column had 50 sets of light-colored and dark-colored laminae with five laminae missing (Fig. 4). All of 95 laminae were treated to measure their thicknesses and perform diatom analysis. Furthermore, the light-colored laminae were used for pollen analysis.

1) Measurement of lamina thickness

The thickest part of each lamina is directly measured by using a ruler. Each lamina colored light or dark has a common thickness from 0.5 to 1.5 mm (Fig. 4).

2) Diatom analysis

0.05 g of material was prepared for diatom analysis by cutting down a plane of lamina and preparing a smear slide with a drop of liquid and the sample and enclosing it in Mountmedia (Daiichi Yakuka Co.). Diatoms in the slides were observed under a microscope at 600x. Diatom frustules in each slide numbered more than 500 counts under microscopic observation.

3) Pollen analysis

All samples of light-colored lamina weighing 20-40 mg were analyzed by the HF and washing method because diatom frustules were mainly composed of SiO_2. This was followed by viewing on prepared slides with glycerin jelly for observation under a microscope with a magnifying power of 600x.

Results

1) Measurement of lamina thickness

Figure 4 shows the change of thickness of light- and dark-colored lamina in a 16 cm vertical thickness. Each colored lamina of light and dark is given a sequential number from 1 to 50 and 1' to 50' from the bottom to the top, respectively.

(a) Light-colored lamina: about 1 mm in thickness, some looseness, white to yellowish white in color, boundary of the lower dark-colored lamina gradually changes, but the upper dark-colored lamina change is sharper. Laminae numbered 1-6 have a 1mm thickness on average, 7-21 have from 1 to 1.5 mm, 22-26 have about 2 mm thickness consistently, and 27-35 have changes from 0.9 to 1.7 mm in thickness gradually.

(b) Dark-colored lamina: 0.5-1.5 mm in thickness is denser than light-colored lamina, gray to black in color, some dark-colored lamina have.

2) Diatom analysis

(a) Light-colored lamina (Fig. 5)

Light-colored lamina was composed of more than 95% diatom frustule. There are *Cyclotella comta* that were planktonic and oligotrophic species, and *Stephanodiscus astraea* that were planktonic and mesotrophic species. These two species combined were seen in more than 95% of frustules in each light-colored lamina, and basically these species mainly appeared in alternating slides.

By detailed observation, laminae of number 1 to 6 are alternatively composed of *Cyclotella comta* and *Synedra ulna* + *Stephanodiscus astraea* at a high rate (more than 90%). *Cyclotella comta* changes at 40-50% and *Stephanodiscus astraea* changes at 30-40% in the laminae of number 7 to 24. Above number 25 lamina, the samples have a high rate (more than 90%) of *Cyclotella comta* and *Stephanodiscus astraea*. *Synedra ulna* is dominant in rate as aquatic

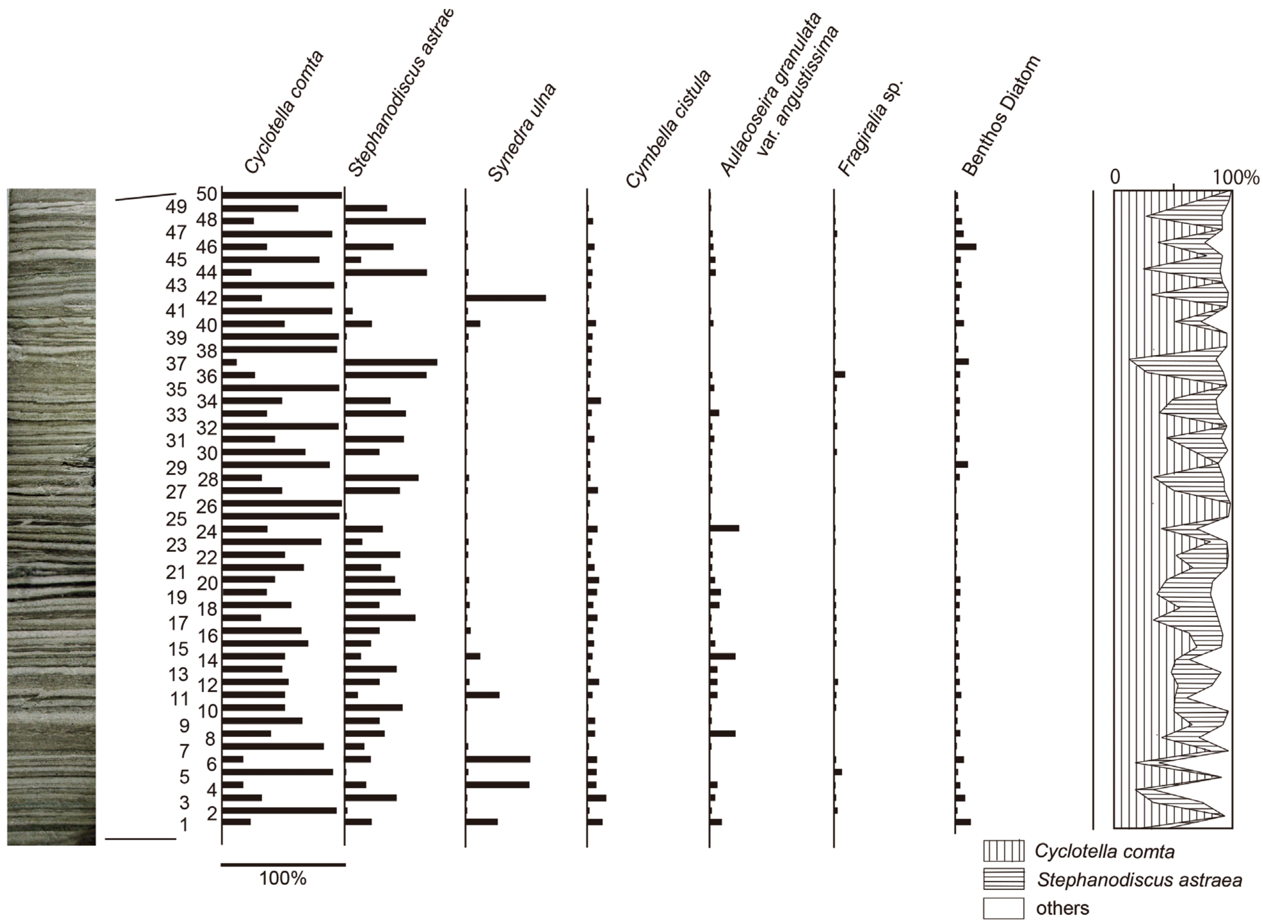

Fig. 5. Diatom diagram of the light-colored laminae.

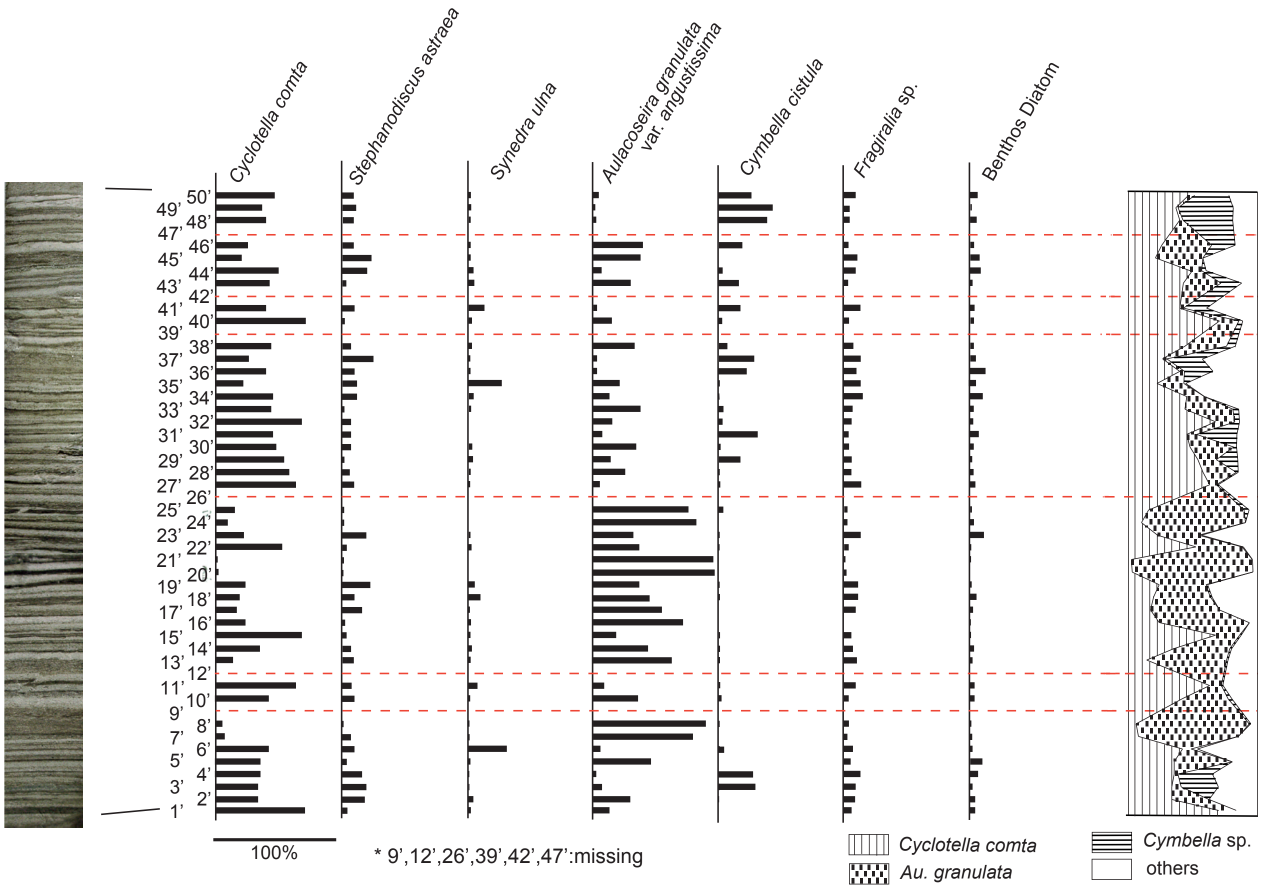

Fig. 6. Diatom diagram of the dark-colored laminae.

conditions occurred prominently in the laminae of number 4, 6 and 43.

(b) Dark-colored lamina (Fig. 6)

The dark-colored lamina was composed of diatom frustules and very fine organic materials. There are *Aulacoseira granulata* var. *angustissima* that were planktonic and eutrophic species, *Cymbella cistula* that is epiphytic and eutrophic species, and *Cyclotella comta.*

A characteristic of occurrence of diatom in the dark-colored lamina is that *Aulacoseira granulata* var. *angustissima* and *Cymbella cistula* were dominant alternately in number 1'-6' and 27'-50'. *Aulacoseira granulate* var. *angustissima* occurred varyingly at 20-90%, but *Cymbella cistula* did not occur in number 7'-25' samples. *Synedra ulna* did not occur at the same rate as in light-colored lamina except for number 6', 35'and 41' laminae.

(c) Occurrence change of diatom assemblage in the sequence of laminae

The sequence is divided into three parts: numbers 1'-6'(i), 7'-24'(ii) and 25'-50'(iii) (Fig. 6).

i) Occurrence rates of *Cyclotella comta* and *Stephanodiscus astraea* + *Synedra ulna* + others alternately change in light-colored laminae. Occurrence rates of *Cyclotella comta* and other species change gradually in dark-colored laminae.

ii) *Cyclotella comta* changed from 50-70% in light-colored laminae. *Aulacoseira granurata* var. *angustissima, Cyclotella comta* and others changed 20-30% and 70-90% alternately in dark-colored laminae.

iii) *Cyclotella comta* at 20-40% and 80-90%, and *Stephanodiscus astraea* + others at 10-20% and 50-80%, alternately changed in light-colored laminae, and *Cyclotella comta* at 60-70% and *Aulacoseira granulata* var. *angustissma* + *Cymbella cistula* + others at 30-50%, changed alternately.

3) Pollen analysis

Almost all light-colored laminae are composed of diatom frustules. Therefore, pollen in the light-colored laminae settled originally, and not from lake

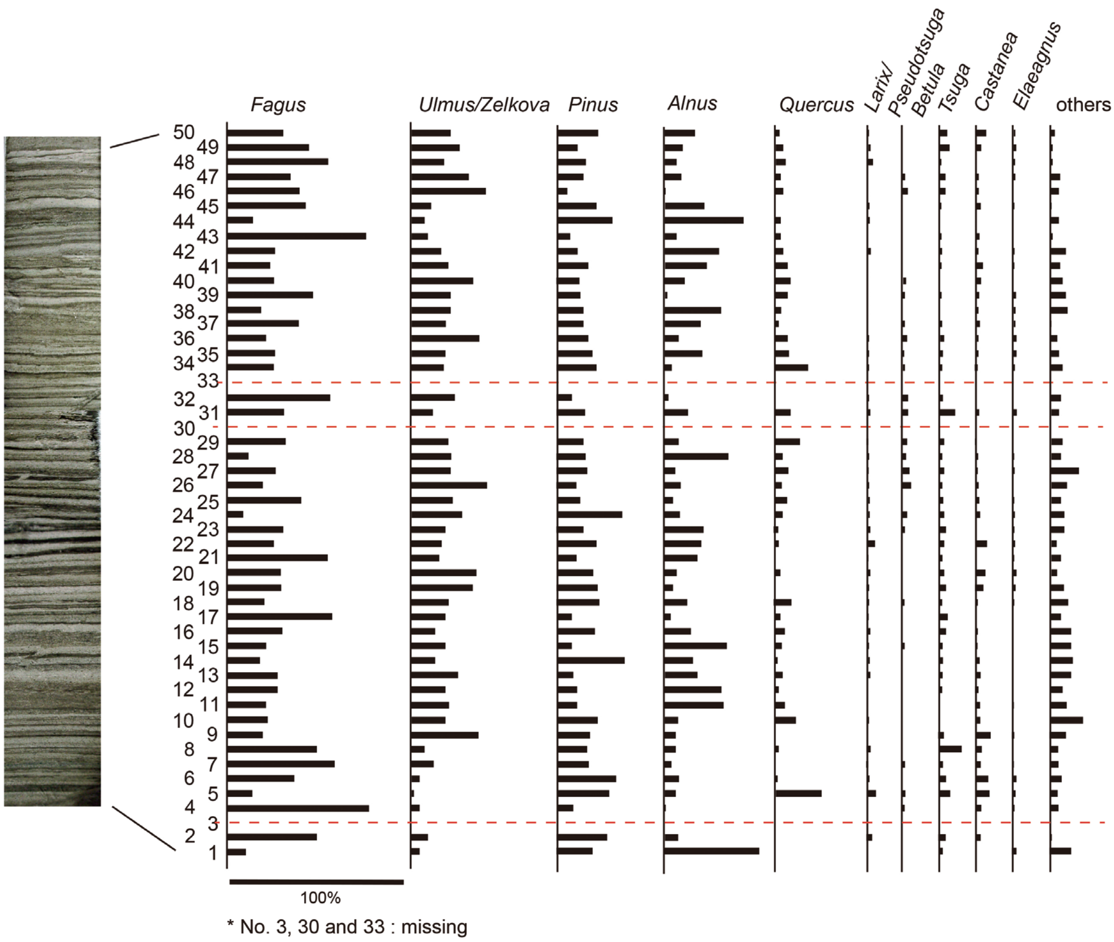

Fig. 7. Pollen diagram of the light-colored laminae

flow. Each light-colored lamina was treated for pollen analysis (Fig. 7). Pollen assemblages were mainly composed of tree species with herb species. Broad-leaf tree species consisted of *Fagus, Ulmus/Zelkova,* and *Alnus*, which are accompanied by *Quercus, Betula, Castanea/Castanopsis* and *Elaeagnus,* Conifers such as, *Pinus* were also included, accompanied by *Larix/ Pseudotsuga* and *Tsuga*.

Fagus occurred with 30-50% stably, sometimes 50-80%. *Ulmus/Zelkova* also occurred around 20% and sometimes 50%, excluding numbers 1-8 light-colored lamina which were less than 10%. Occurrence rate of *Alnus* varied from less than 5% to 50%.

Consideration to sedimentary condition

1) Light- and Dark-colored laminae

The composition of diatom frustule consisted of one or two species, while almost all in the light-colored lamina were assumed to have formed by diatom blooming in the mixture zone of a lake in spring and autumn. *Cyclotera comta* and *Stephanodiscus astraea* occupied a large percentage alternating in the light-colored lamina. It has been shown that one occurred by blooming in spring, and the other by blooming in autumn. Some research suggests that *Cyclotella comta* usually occurred in spring and autumn, but *Stephanodiscus astraea* occurred under cool temperate conditions. In this study, it is assumed that the dominant laminae of *Cyclotella comta* in the spring, and the laminae of *Stephanodiscus astrea* were constructed in the autumn.

Dark-colored laminae were composed of diatom frustules of *Cyclotella comta* and other eutrophic species such as *Aulacoseira granulata* var. *angustissima, Cymbella cistula*, and organic matter from surrounding land areas. It is assumed that the dark-colored laminae were made by diatom reacting to eutrophic conditions made by material from the land.

Aulacoseira granulata var. *angustissima* and *Cymbella cistula* are both eutrophic diatoms. In this study, they occurred dominant and alternating in the dark-colored lamina. What caused this? It is assumed that

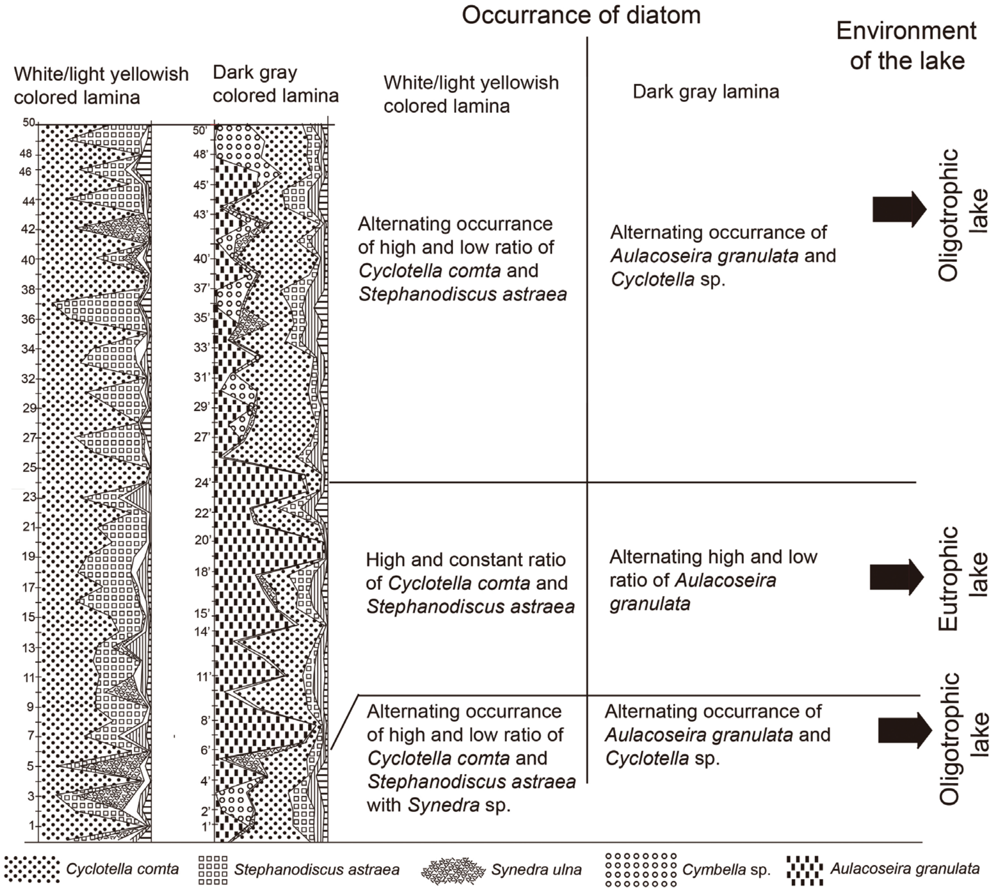

Fig. 8. Seasonal changes of the environmental conditions based on non-glacial varved clay of the Asono Formation.

Aulacoseira granulata var. *angustissima* was planktonic and bred under a highly eutrophic condition, while *Cymbella cistula* was epiphytic, and could not breed under oligotrophic conditions. Conversely, if the conditions were nutrient deficient, *Cyclotella comta* could not breed, and *Cymbella cistula* would breed under the eutrophic conditions of the benthic area in a lake.

2) Change of environmental condition in lake

According to the result of diatom analysis of both numbers 1-6 and 25-50 of light-and dark-colored laminae, it is assumed that the lake was under oligotrophic conditions. During the sedimentary interval from number 7 to 24 laminae, the lake was assumed to be eutrophic because a high percentage of *Aulacoseira granurata* var. *angustissima* and *Cymbella cistula*, occurring from much precipitation existed (Fig. 8).

3) Determination of season based on pollen analysis

The light-colored laminae mainly included pollen of *Fagus, Ulmus/Zelkova, Alnus* and *Pinus. Fagus* blossomed in May, and *Ulmus/Zelkova* from April to June. *Pinus* also blossomed in April and May. Therefore, they were blossoming in spring. Conversely, *Alnus* blossoms from autumn to winter. Figure 7 shows the changing pattern of pollen rate blooming in spring and in autumn. The diagram shows an alternating high rate of spring blooming pollen and autumn blooming pollen. It is shown that the light-colored laminae having spring blooming species deposited in spring, and the light-colored laminae having autumn blooming species deposited in autumn.

Figure 9 shows diatom species in the light-colored lamina deposited in spring and autumn respectively. It also shows that the laminae of spring blooming included *Cyclotella comta* dominantly, while the laminae of autumn blooming included *Stephanodiscus astraea* dominantly. Therefore, *Cyclotella comta* bloomed in spring, and *Stephanodiscus astraea* bloomed in autumn except for laminae number 7-24.

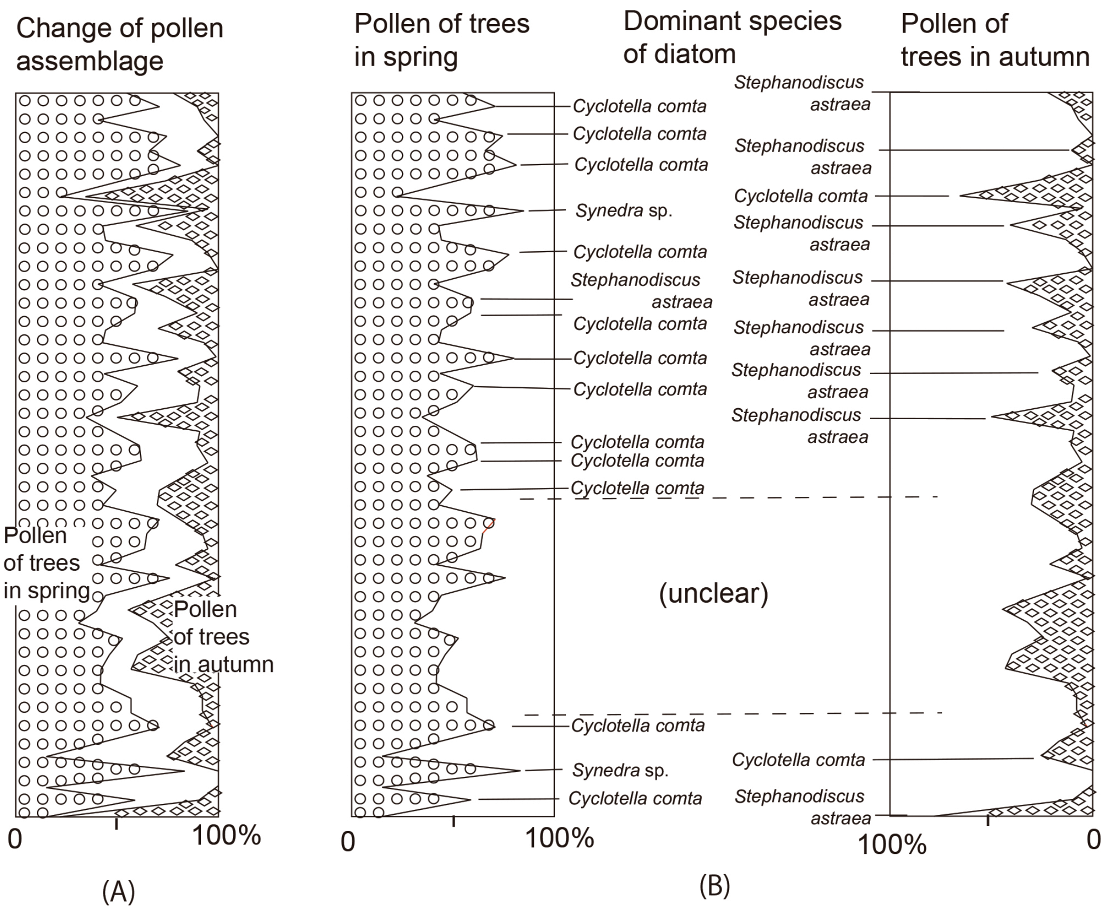

Fig. 9. Connection between pollen and dominant diatom assemblages.

According to the above consideration, it is assumed that the dark-colored lamina laid on the light-colored lamina of spring was made in summer, and the dark-colored lamina laid on the light-colored lamina of autumn was made in winter.

4) Unexpected sedimentation in lake

During the blooming of *Stephanodiscus astraea* in autumn, it sometimes happens that *Cymbella cistula* was dominant. It is assumed that while *Stephanodiscus astraea* is breeding and light-colored lamina is being created, an unexpected sedimentation occurs such as those triggered by typhoons. Dark-colored lamina is made with much material including epiphytic and flowable diatom such as *Cymbella cistula.* These dark-colored laminae were intercalated with light-colored laminae including *Stephanodiscus astraea* as a dominant feature.

Process of annual sedimentation of laminae

It is clarified according to this study that there

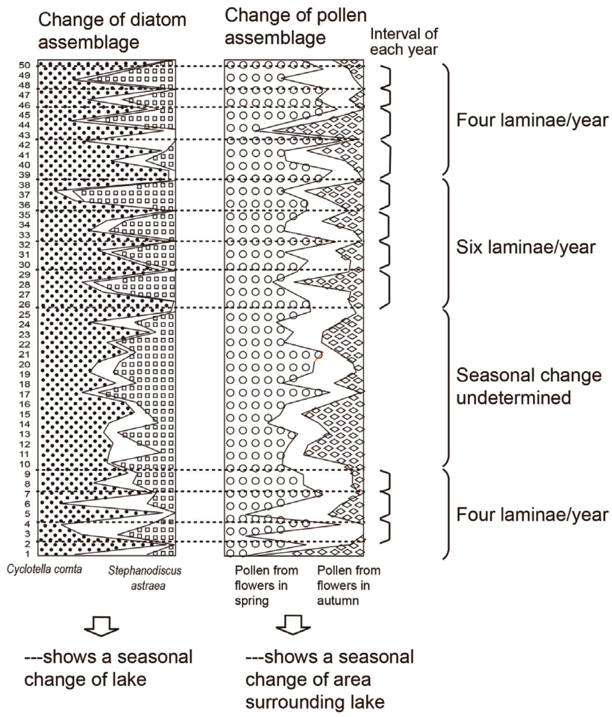

Fig. 10. Diagram showing annual interval indicated by the light-colored lamina diatom and pollen composition.

are five original patterns for depositional environment of non-glacial varved lamina in the Asono Formation.

Light-colored lamina originated during blooming of diatom in the spring and autumn. Laminae of *Cyclotella comta* and *Fagus, Ulmus/Zelkova* and other dominant forms, were created in the spring and laminae of *Stephanodiscus astraea* and *Alnus* dominant were formed in autumn (Figs. 9, 10).

Dark-colored lamina were formed with organic matter in summer and winter. Laminae dominated by the eutrophic species *Aulacoceira granulata* var. *angustissima* and *Cymbella cistula* show that the lake was in a eutrophic condition. Lamina on light-colored lamina made in spring was formed in summer and other lamina on light-colored lamina made in autumn was formed in winter. Intercalated lamina into light-colored lamina made in autumn was formed under special conditions such as during typhoons. Fig. 10 shows one year as indicated by the diatom and pollen compositions of the white laminae, although in samples 9-24 the diatom-pollen compositions do not show a clear seasonal change.

Environmental changes of lamina deposition in lake

The environmental changes in lakes during lamina formation are described as below (Fig. 11).

In spring, the temperature of the surface water (epilimnion) gradually rises causing a circulation with the hypolimnion in the lake. The eutrophic material rose from the bottom to the top of the water body, and planktonic species such as *Cyclotella comta* occurred and bloomed during the formation of light-colored lamina. Broad-leaf trees grew and produced much pollen around the lake.

In summer, the temperature of the surface water (epilimnion) in the lake rose and the thermocline stratified on the cool and heavy water (hypolimnion) in the lake. The water of the lake was stable (stagnation period in summer) except for the epilimnion. Planktonic species such as *Aulacoseira granulata* var. *angustissima* were dominant under the condition with eutrophic and organic matter in the lake. When there was much precipitation, epiphytic species such as *Cymbella cistula* were dominant and a dark-colored lamina was formed.

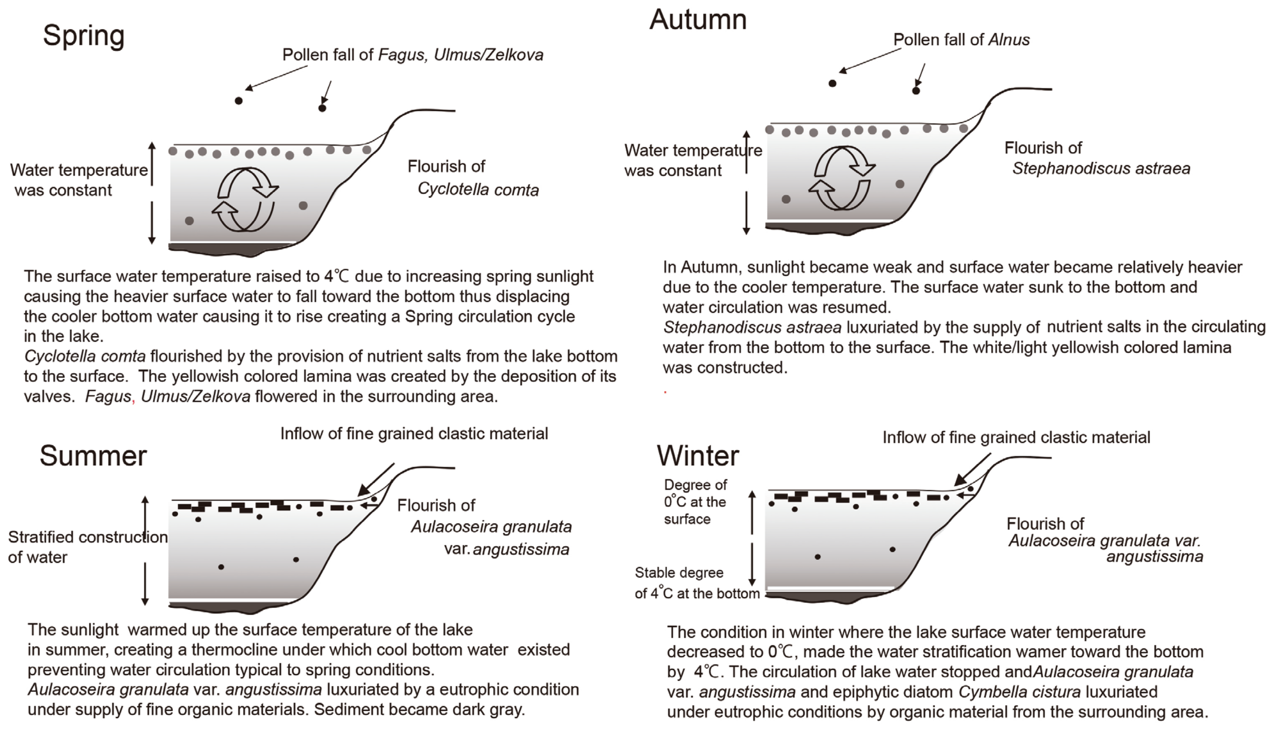

Fig. 11. Seasonal environment during deposition of the Asono Formation.

In autumn, sun energy decreased and the surface water (epilimnion) gradually moved deeper creating circular contamination making the differences between the deep water and shallow water less obvious. The planktonic species *Stephanodiscus astraea* bloomed and made a light-colored lamina. When storms came, debris entered the lake and *Cymbella cistula* became dominant forming a dark lamina. After that, *Stephanodiscus astraea* bred and made light-colored lamina. Around the lake, large amounts of *Alnus* blossomed causing that byproduct to flow into the lake.

In winter, the surface temperature fell to about 0 Celsius while bottom temperatures gradually rose up to 4 Celsius. The lake condition was stable (stagnation period in winter). Eutrophic diatom species such as planktonic *Aulacoseira granurata* var. *angustissima* or epiphytic *Cymbella cistula* bred and dark-colored lamina was made.

Conclusion and discussion

Based on the laminae that clearly formed seasonally, the annual sequence had two patterns of sedimentation. One is basically made of the light spring lamina dark summer lamina, light-colored autumn lamina and dark-colored winter lamina in an ascending order. And the other having a sequence in ascending order with unexpected sedimentation. That is, an annual sequence made of light-colored spring lamina, dark-colored summer lamina, light-colored autumn lamina within the unexpected dark-colored lamina and the dark-colored winter lamina.

Seasonal change was not clearly recognized for the annual sequence of laminae. Though the laminae must have been made under the environment of seasonal change, the area had much precipitation and a eutrophic condition of the lake, resulting in no changes of diatom association and pollen assemblage.

Fukusawa (1995) discussed the origin of the non-glacia l varved clay based on diatom assemblage and mineral conposition.

Ishihara and Miyata (1999) clarified sedimentary process of the non-glacial varved clay of the Hiruzenbaru Formation of the Middle Pleistocene as follows: the light-colored lamina made by *Stephanodiscus* sp. bloomed mainly deposited in winter while the dark-colored lamina with *Cyctella comta*, resulted in lamina made by an annual deposition. In Sasaki et al. (2019), there was a normal dark-colored layer with a light-colored layer that was about half the thickness of the normal layer in the Miyajima Formation of the Shiobara Group, and two sets of stripes were formed in one year. The “double couplet" indicates that diatom bloom peaks occurred twice a year. Also Sasaki et al. (2019) discussed event sediments in lacustrine laminated sediments.

By understanding the pollen fossil content of each light-colored lamina, we were able to incorporate information on seasonal changes into lamina formation. For this reason, the formation process of sediments showing non-glacial lacustrine varved clay cannot be generally regarded as a set of light- and dark-colored lamina representing the details of the sedimentary environment.

Based on the idea that strata formed in lakes record the changes in the surrounding terrestrial environment, we have so far understood the changes mainly based on pollen analysis. We grasped the changes in the lake environment from the analysis results of diatom fossils and pollen fossils for each non-glacial varve clay lamina, and demonstrated that there is a part of the non-glacial varved sediments indicating the seasonal changes of lake environment. In addition to the part that clearly shows seasonal changes, it was also revealed that there were parts that were formed by events such as typhoons. Considering previous studies, the formation of varved lamina does not occur under the same conditions throughout the lake. It seems that what the set of light- and dark-colored lamina have different meanings. This suggests that seasonal changes can be read in the varved sediments taken up this time in the Asono Formation.

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