VARVED LACUSTRINE SEDIMENTS OF LAKE TOUGOU-IKE, WESTERN JAPAN WITH REFERENCE TO HOLOCENE SEA-LEVEL CHANGES IN JAPAN

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Abstract Holocene laminated sequence consisting of alternations of light- and dark-colored laminae was recognized in the sediment core taken from Lake Tougou-ike in 1992 by our research group. Biochemical and mineral compositions, micro-sedimentary structures and AMS ^{14}C dating of organic remains in this laminated sequence support the laminated sediments are identified as non-glacial varves, which were formed mainly by seasonal changes of diatom productivities. Varve counting and ^{14}C dating provided Holocene detailed chronology, from annual to decadal for reconstructing paleoenvironments from the sediment core with high time resolution. Based on this chronology Holocene relative sea-level changes at Lake Tougou-ike were estimated from authogenic iron mineral contents of the sediments. The relative sea-level changes show abrupt rises at about 8,900, 7,700, 5,600, 4,000, 3,600 and 2,700 calendar years BP. with gradual falling between the interval periods. These relative sea-level changes are suggested to have synchronous relationships with ice sheet discharge events detected in the North Atlantic. Abrupt environmental changes having centurial to millennial periodicity could occur even in the Holocene as well as the last glaciation.

Key words: varve, lacustrine sediment, sea-level change, Holocene, Bond cycle

1. Introduction

Abrupt climatic and environmental oscillations with centurial to millennial scales occurred during the last glacial and evidences for these changes have been recognized in worldwide (Dansgaard *et al.* 1993 ; Porter and An 1995 ; Bhel and Kennet 1996 ; Tada 1997 ; Fukusawa 1998, 1999). These abrupt climatic changes with centurial to millennial periodicities since the last glacial were recognized at first in oxygen isotope records of Greenland ice cores (Johnsen *et al.* 1992), and they showed characteristic modes with gradational cooling after abrupt warming (Dansgaard *et al.* 1993). These climatic changes during the last glacial were named Dansgaard-Oeschger Cycle by Taylor *et al.* (1993). During cool periods just before the warmest periods in Dansgaard-Oeschger Cycle, ice rafts

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** Tono GeoScience Center, Japan Nuclear Cycle Development Institute discharged from the Greenland ice sheet to the North Atlantic (Lehman 1993) and ice-rafted debris deposited on sea floor of the North Atlantic (Heinrich 1988). These discharge events of ice rafts were so called Heinrich Events (Heinrich 1988), and occurred also in Younger Dryas period. The simultaneous climatic changes with Dansgaard-Oeschger Cycle and Heinrich Events were reported from loess-paleosol sequences of Chinese Loess Plateau (Poter and An 1995), deep sea sediments of the Santa Barbara Basin, offshore California (Behl and Kennet 1996), the Sea of Japan (Tada 1997) and varved lacustrine sediments of Japan (Fukusawa 1998, 1999). Abrupt climatic changes with centurial to millennial scales have not only occurred in the last glacial, but also in the Holocnene (Alley *et al.* 1997 ; Bond *et al.* 1997).

One of the purposes of our research is to reconstruct the centurial- to millenial-scaled environmental changes such as climatic and sea-level changes of Japan with annual to decadal time-resolution. As one of these archives, we chose a sediment core taken in Lake Tougou-ike with fine laminations by our research group. First, we confirmed that the laminated sediments are non-glacial varves for reconstructing Holocene sea-level changes with detailed chronology. Then we reconstructed continuous relative sea-level records from Lake Tougou-ike and compared with abrupt global climatic changes detected from marine sediments of the North Atlantic (Bond *et al.* 1997) discussing abrupt global environmental changes with centurial to millennial scale during the Holocene. This research will provide important information for identifying the source area where the global climatic changes started and understanding the mechanisms of the global climate changes.

2. Varved Lacustrine Sediments of Lake Tougou-Ike in Western Japan as Archives of Annual Paleoenvironmental Changes in the Holocene

Generally lake sediments consist of biochemical particles originating from biological productions, terrigeneous particles inflowing from the catchment areas through rivers, and atmospheric particles such as eolian dusts and aerosols (Beer and Strum 1995). Varved lacustirne sediments are useful as seasonal and annual archives to reconstruct biologic productions controlled by precipitations around lakes (Fukusawa 1995). Varved lacustirne sediment cores were taken in Lake Suigetsu (Fukusawa 1995), Lake Tougou-ike (Fukusawa *et al.* 1999) and Lake Ogawara (Ikeda *et al.* 1998), which are coastal brackish lakes in Japan, by our research group during the last 5 years. Coastal brackish lakes in Japan have been originated from bays or inlets extended landward in the early Holocene at the time of sea-level rise of the last deglaciation (Hirai 1989). Accordingly, sediments of these brackish lakes response sensitively to sea-level changes which control the invasion of seawater into the lakes. Brackish water lakes are commonly meromictic lakes which have no overturns in general as the heavier seawater invades under fresh water mass. Low contents of dissolved oxygen in the bottom water promote sulfate reduction, producing H_2S gas, and authogenic formation of iron sulfides such as pyrite (FeS_2) and marcasite (FeS). On the other hand, no invasion of seawater promotes authogenic formation of iron carbonate such as siderite ($FeCO_3$). Changes of iron mineral compositions in lacustrine sediments are useful proxies for indicating past water mass conditions of lakes. Fukusawa *et al.* (1995) analyzed sediment cores from Lake Suigetsu and demonstrated the past water condition by using autochthonous iron minerals. Shirakami (1985) showed total sulfur (TS) contents of the sediments mutually relate with pyrite contents of them well and are effective to distinguish marine sediments. In case of sediments from coastal lakes. brackish condition supposed from high TS contents associated with high pyrite contents and low siderite contents must have resulted from marine water invasion with relative high sea level. On the contrary. fresh conditions inferred from high siderite contents and low TS contents can suggest influence from river water when relative sea level is low. Therefore. we adopted TS and siderite contents as proxies of past water conditions accompanied with sea-level changes in this study.

Lake Tougou-ike is a coastal brackish lake. located at the central part of Tottori Prefecture. western Japan (Fig. 1). Water of Lake Tougou-ike discharges from its northwestern part into the Sea of Japan through the Hashizu River and seawater invades easily through it into the lake (Fig. 1). Although the lake is small (4.1 km^2 in area) and shallow (2 m in the mean depth and 5 m in the maximum) at present. geomorphologic studies suggest the lake area extended widely and there was larger and deeper water during high stands of sea level in the early Holocene (Onishi and Kondo 1961). A continuous sediment core of 39.97 m long was taken from Lake Tougou-ike by thin wall-type piston coring in 1992. The coring site was located at 35° 28' 58" N. 133° 55' 23" E and in 2.0 m-deep of the lake (Fig. 1). The upper part of the sediment core above 25.68 m deep was successfully taken.

Laminated sequence intercalating grayish clay and tephra layers were clearly observed in upper part of this sediment core (Fig. 2). Laminated sediments are mainly composed of light- and dark-colored laminae (Fig. 3). A series of these rhythmic alternations of laminae is

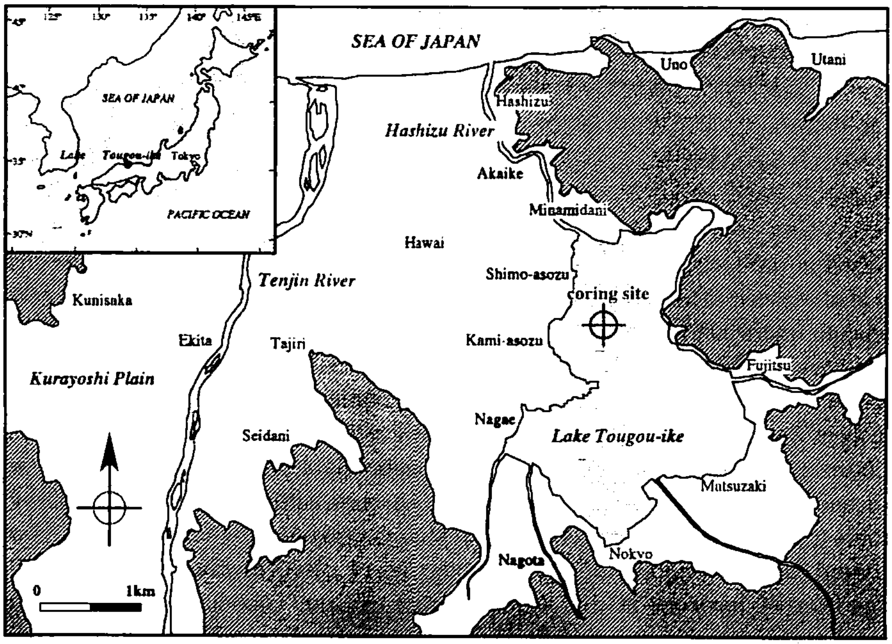

Fig. 1 Index map of Lake Tougou-ike. western Japan. including of the coring site. The striped areas show hills and mountains.

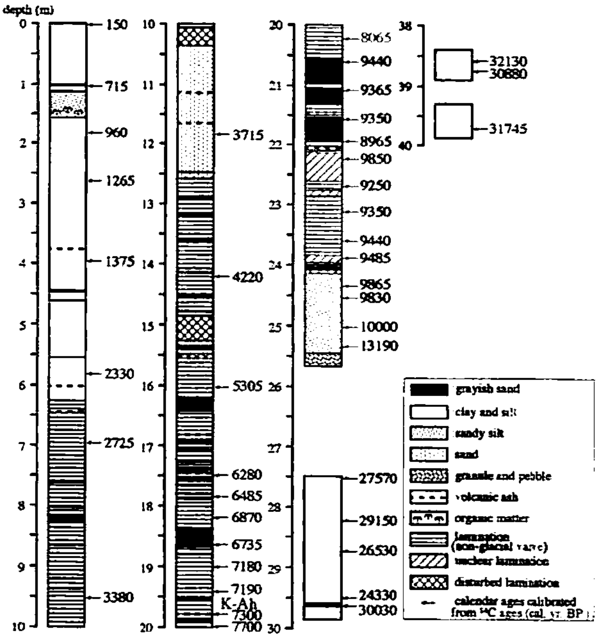

Fig. 2 Schematic columnar sections of the 39 m-long sediment core, taken in Lake Tougou-ike by our research group, with 40 calendar ages calibrated from AMS ^{14}C ages and tephra layer of K-Ah indicating 7,300 cal. BP.

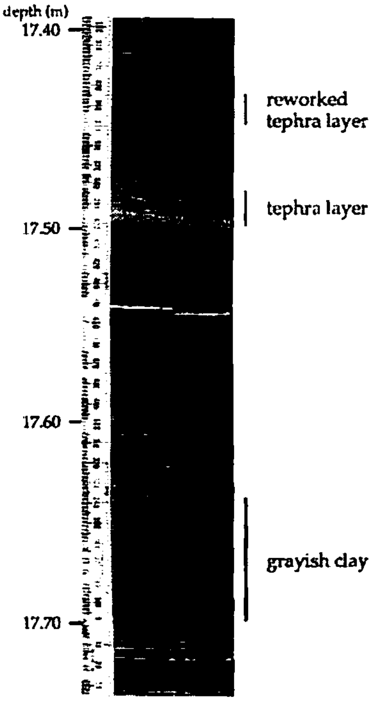

Fig. 3 Photograph showing the laminated sequence and intercalated grayish clay layer and unidentified tephra layers in the sediment core of Lake Tougou-ike. The laminations are clearly observed at this section.

recognized in the core from 6.2 m to 24.1 m in depth. Particles in these laminae consist of grains of clay to silt in size including terrigenous grains, diatom frustules, organic fragments and opaque materials by optical microscopic observations. The opaque materials were identified as authogenic iron minerals such as siderite or framboidal pyrite by X-ray diffraction analyses and optical microscopic observations. Core sediments from 10.0 m to 12.5 m deep were composed of slightly sandy silt-sized laminae which were thicker than the other horizons. A 2 cm-thick yellow-brown volcanic glass layer was found at the depth of 19.75 m and was identified as Kikai-Akahoya (K-Ah) tephra (Machida and Arai 1992) by Dr. K. Takemura (personal communication). K-Ah tephra is regarded as a wide-distributed volcanic ash around Japan falling about 7,300 calendar years BP. (Kitagawa *et al.* 1995). Organic remains from 40 horizons in this sediment core of Lake Tougou-ike were collected and measured radiocarbon ages by AMS at the University of Kiel. The AMS ^{14}C dates were calibrated into calendar ages based on the calibration curve of Kitagawa and van der Plicht (1998) (Table 1).

Table 1 AMS radiocarbon dating ages of organic remains in the sediment core of Lake Tougou-ike and calibrated calendar ages

sample No.	depth (m)			facies	^{14}C age (^{14}C yr. BP.) with 1 sigma uncertainties			calendar age (cal. yr. BP.) with 1 sigma uncertainties		
TG14C-1	1.050	~	1.080	grayish caly	820	±	70	715 .	+75	-45
TG14C-2	3.925	~	3.955	clay-silt	1510	±	50	1375 .	+35	-65
TG14C-3	5.845	~	5.875	clay-silt	2300	±	80	2330 .	+20	-170
TG14C-4	7.945	~	7.975	laminated	2530	±	50	2725 .	+15	-325
TG14C-5	9.515	~	9.545	laminated	3180	±	50	3380 .	+70	-30
TG14C-6	11.855	~	11.885	sand	3490	±	50	3715 .	+115	-75
TG14C-7	14.235	~	14.265	laminated	3820	±	60	4220 .	+130	-200
TG14C-8	15.995	~	16.025	laminated	4600	±	50	5305 .	+145	-205
TG14C-9	17.505	~	17.535	laminated	5450	±	90	6280 .	+110	-160
TG14C-10	17.830	~	17.860	laminated	5710	±	70	6485 .	+145	-75
TG14C-11	18.270	~	18.300	laminated	6020	±	80	6870 .	+100	-120
TG14C-12	18.630	~	18.660	grayish caly	5900	±	60	6735 .	+105	-95
TG14C-13	19.020	~	19.050	laminated	6250	±	50	7180 .	+30	-150
TG14C-14	19.405	~	19.435	laminated	6270	±	70	7190 .	+40	-170
TG14C-15	19.955	~	19.985	laminated	6940	±	60	7700 .	+210	-50
TG14C-16	20.220	~	20.250	laminated	7280	±	60	8065 .	+765	-125
TG14C-17	20.620	~	20.650	grayish caly	8440	±	60	9440 .	+20	-20
TG14C-18	21.085	~	21.115	grayish caly	8330	±	60	9365 .	+65	-35
TG14C-19	21.485	~	21.515	grayish caly	8310	±	60	9350 .	+70	-30
TG14C-20	21.885	~	21.915	grayish caly	8040	±	60	8965 .	+75	-10
TG14C-21	22.285	~	22.315	laminated	8780	±	60	9850 .	+320	-230
TG14C-22	22.685	~	22.715	laminated	8280	±	70	9250 .	+170	-70
TG14C-23	23.085	~	23.115	laminated	8310	±	90	9350 .	+80	-80
TG14C-24	23.565	~	23.595	laminated	8440	±	70	9440 .	+40	-40
TG14C-25	23.885	~	23.915	laminated	8530	±	60	9485 .	+25	-25
TG14C-26	24.325	~	24.355	sand	8800	±	80	9865 .	+335	-245
TG14C-27	24.535	~	24.565	sand	8750	±	70	9830 .	+350	-230
TG14C-28	25.015	~	25.045	sand	9040	±	90	10000 .	+255	-265
TG14C-29	25.335	~	25.365	sand	11350	±	80	13190 .	+90	-290
TG14C-30	27.905	~	27.935	clay-silt	25160	±	320	27570 .	+2580	-180
TG14C-31	28.235	~	28.265	clay-silt	26680	±	310	29150 .	+2100	-1850
TG14C-32	28.705	~	28.735	clay-silt	24160	±	250	26530 .	+420	-80
TG14C-33	29.505	~	29.535	clay-silt	22050	±	210	24330 .	+970	-720
TG14C-34	29.625	~	29.655	grayish caly	27520	±	330	30030 .	+1320	-1220
TG14C-35	38.605	~	38.635	clay-silt	29540	±	480	32130 .	+130	-170
TG14C-36	38.725	~	38.755	clay-silt	28340	±	350	30880 .	+1070	-620
TG14C-37	39.965	~	39.395	clay-silt	29170	±	380	31745 .	+460	-260
TG14C-38	0.005	~	0.035	clay-silt	170	±	50	150 .	–	
TG14C-39	1.855	~	1.885	clay-silt	1070	±	70	960 .	+90	-30
TG14C-40	2.625	~	2.655	clay-silt	1320	±	40	1265 .	+25	-85

3. Varves of Lake Tougou-Ike — Sedimentary Micro-Structures of Varve —

We investigated the laminated sediments by observing biochemical sedimentary structures, counting numbers of the laminae and measuring thickness of them in thin sections under optical microscopic analysis (Table 2) in order to clarify origin and sedimentary mechanism of the sediments taken in Lake Tougou-ike. Thin sections of laminated sediments were made of about 3 cm-thick horizons cut out from the sediment core and replaced the pore water with a kind of resin. Stratigraphical observation (Fig. 4) shows a couple of light-colored lamina and superimposed dark-colored lamina representing a cyclic unit in their components and microstructures. The light-colored laminae mostly consist of diatom frustules, which are small size and near-monospecific. Its components vary gradually

Table 2 Sequential changes of sedimentary features. biofacies and thickness of the varve in sediment core from Lake Tougou-ike. by observing the thin sections under optical microscope

sample no.	depth (m)	number of the layer				average thickness of the layer (mm)		remarks
		the pair of light- and dark-colored lamina	tephra	grayish clay	resting spores of *Chaetoceros* spp.	light-colored lamina	dark-colored lamina	
TG-1	17.255 ~ 17.287	26	0	0	6	0.42	0.79	
TG-2	17.435 ~ 17.467	16	0	2	0	0.48	0.82	
TG-3	17.600 ~ 17.632	23	0	2	0	0.21	0.52	
TG-4	17.710 ~ 17.742	28	0	0	0	0.31	0.78	
TG-5	17.798 ~ 17.830	19	0	1	0	0.24	0.67	upward thining of the laminae
TG-6	17.900 ~ 17.932	19	2	1	0	0.18	0.66	
TG-7	18.160 ~ 18.192	19	0	0	0	0.33	0.68	
TG-8	18.220 ~ 18.252	14	0	2	0	0.68	1.10	
TG-9	18.328 ~ 18.360	18	0	0	0	0.23	0.66	
TG-10	18.410 ~ 18.442	—	—	1	—	—	—	flood layer
TG-11	18.830 ~ 18.862	22	0	0	3	0.45	0.79	
TG-12	18.950 ~ 18.982	21	0	1	0	0.34	0.68	
TG-13	19.050 ~ 19.082	29	0	0	7	0.36	0.58	
TG-14	19.130 ~ 19.162	24	0	1	4	0.22	0.72	
TG-15	19.450 ~ 19.482	55	0	0	0	0.14	0.32	
TG-16	19.610 ~ 19.642	30	1	0	9	0.33	0.65	
TG-17	19.650 ~ 19.682	31	0	1	8	0.33	0.57	
TG-18	19.780 ~ 19.812	38	0	0	3	0.32	0.55	
TG-19	19.900 ~ 19.932	24	1	1	0	0.21	0.57	
TG-20	19.990 ~ 20.022	31	0	0	6	0.33	0.63	
TG-21	20.270 ~ 20.302	12	0	0	0	0.35	1.49	
TG-22	20.360 ~ 20.392	30	0	0	5	0.31	0.61	
TG-23	20.420 ~ 20.452	27	0	0	6	0.27	0.60	
TG-24	21.270 ~ 21.302	29	0	0	0	0.18	0.78	
TG-25	21.350 ~ 21.382	9	0	2	0	0.42	0.98	
TG-26	22.000 ~ 22.032	23	0	0	1	0.25	0.92	
TG-27	23.150 ~ 23.182	14	0	0	0	0.67	1.03	
TG-28	23.460 ~ 23.492	21	0	0	0	0.69	0.70	
TG-29	16.820 ~ 16.852	21	1	1	0	0.19	0.92	
TG-30	15.400 ~ 15.432	28	0	1	6	0.09	0.69	
TOG96-5-1	23.550 ~ 23.560	7	0	0	0	0.56	0.80	no lamination in the deeper part
TOG96-5-2	23.780 ~ 23.800	—	—	1	—	—	—	flood layer
TOG96-5-3	23.660 ~ 23.680	6	1	0	0	0.59	0.69	
TOG96-5-4	23.620 ~ 23.630	13	0	0	0	0.41	0.58	
TOG96-5-5	8.710 ~ 8.730	—	1	1	—	—	—	flood and tephra layers
TOG96-5-6	8.600 ~ 8.630	18	0	0	0	0.51	0.80	
TOG96-5-7	8.800 ~ 8.830	4	0	3	2	0.37	1.23	
TOG96-5-8	10.450 ~ 10.480	—	1	1	—	—	—	flood and tephra layers
TOG96-5-9	14.270 ~ 14.290	11	0	0	0	0.28	1.12	
TOG96-5-10	14.290 ~ 14.310	14	0	0	0	0.42	0.80	

upward into larger diatom frustules of mixed assemblage with terrigeneous deposits such as clay minerals, quartz and feldspar into the superimposed dark-colored lamina. Opaque authogenic iron minerals were observed in the dark-colored laminae and are the densest in the central horizons of them. There are many intercalations of organic fragments such as leaves at the uppermost parts of dark-colored lamina. Layers composed of resting spores of *Chaetoceros* spp. were recognized on the sheet-like organic remains of some dark-colored laminae.

These observations under the microscope provided the following interpretation for origin and sedimentary mechanism of the laminated sediments. The depositions of the sediments were probably operated by seasonal changes of the lake itself and the surroundings. The sharp boundaries between the dark-colored laminae and the each superimposed light-colored one show that light-colored laminae began to deposit suddenly with some hiatus after the dark-colored laminae deposition. In early spring, overturn of the lake water commonly caused diatom's abrupt blooms and numerous diatom frustules may probably have accumulated as a light-colored lamina inferred from its components without terrigenous deposits and the near-monospecific diatom assemblage. After this deposition,

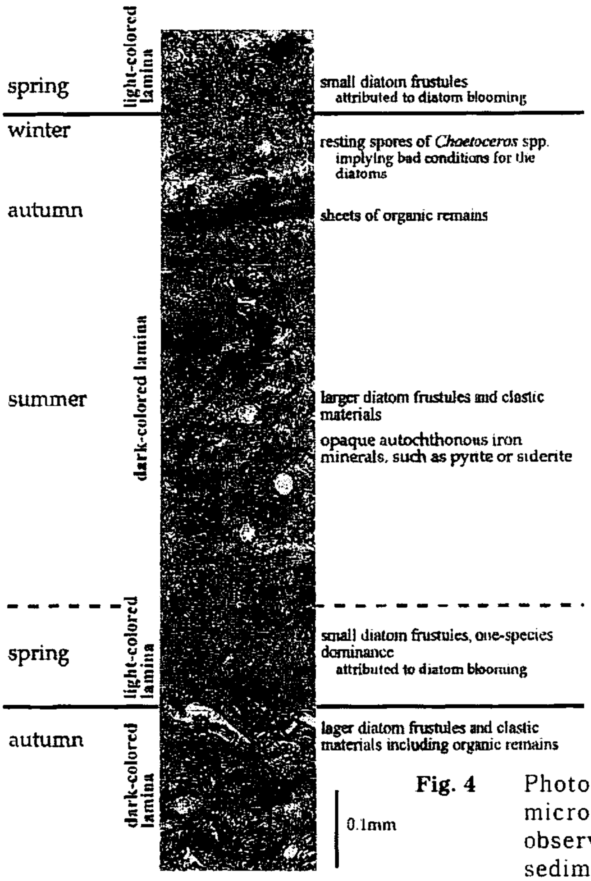

Fig. 4 Photograph showing typical sedimentary microstructures of laminated sequence observed under optical microscope of the sediment core from Lake Tougou-ike. The sequence is 1mm thick (19.6255-19.6265 m) in the sediment core.

larger diatom frustules and terrigenous materials deposited from late spring to summer on the layer of diatom bloom. In summer, opaque authogenic iron minerals possibly have formed in anoxic bottom water because the lake often stratifies. The superimposed sheet-like organic remains supposed to be fallen leaves carried from the surroundings into the lake during autumn. The resting spores of *Chaetoceros* spp. may have formed in bad conditions for the diatoms (Kuwata 1989). The stratigraphical location of the resting spores shows winter bad condition including lack of nutrients (NO_3^- *etc.*) or coldness. Thus, one couple of light- and superimposed dark-colored lamina showing the cyclic unit was assumed to have deposited in one year, from spring to autumn or winter. The alternations of these laminae are suggested to have annually deposited and well preserved with no disturbance such as bioturbation.

Besides these observations, we considered ages of each horizon in the laminated sediments. Forty calendar ages of the sediments were obtained from calibrated AMS ^{14}C ages. The bottom part of the sediment core is estimated to have deposited about 32,000 cal.

yrs. BP (calendar years before 1950) and the sediments deposited continuously since at least 10,000 cal. yrs. BP (about 25 m in depth). The sequence of lamination also supports the continuous depositing with no disturbance in the sediments, so that undisturbed detailed Holocene environmental records would be obtained from the sediment core of Lake Tougou-ike. We presumed that the couplets of light- and dark- colored lamina were annually accumulated, and could calculate calendar ages of laminated sequences by lamina counting, using core photographs. According to AMS ^{14}C dating and varve counting in Late Pleistocene - Holocene sediment of Lake Suigetsu, central Japan, the K-Ah tephra deposited about 7,300 calendar yrs. BP (Kitagawa *et al.*, 1995). Based on estimated age of the K- Ah tephra, Fig. 5 shows relationships among core depth (m), varve counting ages (cal. yrs. BP) and calibration ages (cal. yrs. BP), transfered from AMS ^{14}C dating age in varved lacustrine sediments of Lake Tougou-ike. Sequential changes of AMS ^{14}C dating ages show constant accumulation rate without a break in Lake Tougou-ike since the last glacial (Fig. 5). However, we can show that calendar ages by varve counting were not always equal to ages by AMS ^{14}C dating (Fig. 5). This fact suggests that all of these couplets of light-dark lamina were not always non-glacial varves. The reason of inconsistency between both calendar ages seems to be physical and observational errors (De Geer 1940). In varved sediments of Lake Tougou-ike, we investigated physical and observational errors of varved chronology by optical microscopic analysis and showed possible errors as follows ; 1) extra-marginal river and or littoral erosion, causing thick flood layers, 2) existence of deceptive bands, simulating winter layers, 3) existence of extra thin varves. We cannot confirm the cause of these errors in varved

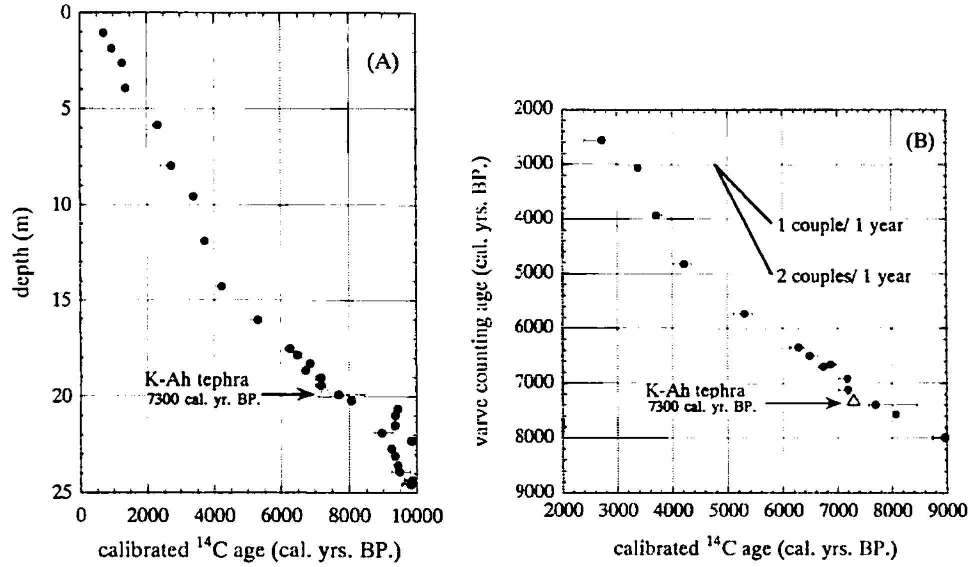

Fig. 5 (A) Diagram showing relationships between core depth (m) and calendar ages (cal. yrs. BP) calibrated from AMS ^{14}C ages with 1 sigma uncertainties. (B) Diagram showing relationships between calendar ages from calibrated AMS ^{14}C datings and those from counting the couplets of laminae. Each triangle in (A) and (B) shows the depth and the age of K-Ah that was the control point of the estimated ages from counting the laminae.

chronology and want to wait for future research and technical development.

These evidences support the alternations observed in the sediment core of Lake Tougou-ike can be identified as non-glacial varved lacustrine sediments and they deposited from about 9,000 to 2,000 cal. yrs. BP. These are recognized as biogenic varves defined in Fukusawa (1995) since the major mecanism of the varve deposition depended on seasonal changes of the diatom productivity including annual blooming cycle. The varves provide calendar ages of the sediments during most part of the Holocene, so that we employed these varve-counting calendar ages as chronology of the sediments. The ages of the horizons without varves are determined by extrapolation of the calendar ages obtained from calculating the ^{14}C ages.

4. Holocene Sea-Level Changes Reconstructed by Pyrite and Siderite Contents in Varved Lacustrine Sediments of Lake Tougou-Ike

In order to clarify sea-level changes from varved lacustrine sediments of Lake Tougou-ike, we investigated total sulfur contents relating to pyrite concentrations and siderite contents.

Methods

The sediment core taken from Lake Tougou-ike was continuously sampled with plastic cubes holding 7 cc in volume. Exceptionally the sediments of 0-4.80 m and 19.50-20.95 m were cut by 5 mm thick because only a little sediments were available in this horizon. We measured siderite contents and total sulfur of the samples after 48 hour drying in the oven at 110 ℃ and then powdered into the 200 mesh of the particle size. Total sulfur contents were measured with a TOX-10 Σ automatic sulfur determinator. Approximately 2 mg of each powdered sample was fully oxidized at 1100 ℃ for 5 minutes and emitted SO_2 gas was electrometrically titrated to measure TS content. The analyzing intervals are about 10 cm of the depth and they correspond to 10-70 years of the estimated calendar ages. Siderite contents of the each sample were measured by X-ray diffract analysis using JDX3536 autoanalyzing system. The powdered samples were mounted on a non-steel holder and X-rayed from 60° to 2° 2 θ with Cu K α radiation. Measurements were made at 35 kV and 20 mA with a slit system of 1° : 0.2 mm : 1°, scanning interval of 0.020° and time constant of 0.50 s. We used the peak area (cps : count per second) from the analysis result as the quantitative mineral content (wt.% : weight percent). There is a high positive linear correlation (r^2=0.99) between the peak areas of siderite (112) and the siderite contents (wt.%). According to the varve counting and the sedimentation rate, each sample represents the mean siderite content of the sediments deposited approximately in 10-20 years.

Results

On the varve-counting chronology, results of the analyses of TS and siderite contents are shown in Fig. 6. TS and siderite contents have negative relationship with each other for last 10,000 cal. years and change synchronously as the siderite contents (solid bars) are plotted on a reversed axis. Changes of both TS and siderite contents on the diagram show saw-toothed shape. Abrupt TS increases with abrupt siderite decreases are recognized about 8.900, 7,700, 5,600, 4,000, 3,600 and 2,700 cal. yrs. BP. Then after the abrupt change, TS contents tend to decrease and siderite contents are increasing gradually till next change.

Reconstruction of Holocene relative sea-level changes at Lake Tougou-ike

Inferred from these results of siderite and TS associated with pyrite, we attempted to reconstruct the Holocene relative sea-level changes at Lake Tougou-ike. The fact of abrupt TS increase at 8,900 cal. yrs. BP may demonstrate that seawater flowed into the coring site at that time and there was an embayment over Lake Tougou-ike caused by the sea-level rise during the last deglaciation. This is also supported by the facies change, sandy silt to laminated clay beds, exhibited in Fig. 2. Changes of TS and siderite contents following after 8,900 cal. yrs. BP, imply abrupt relative sea-level rises during the Holocene may have occurred at about 7,700, 5,600, 4,000, 3,600 and 2,700 cal. yrs. BP. (Fig. 6). The relative sea levels at Lake Tougou-ike are supposed to have gradually fallen down during the intervals lasting a few thousands years between individual sea-level rises. Although these relative sea-level falls can be considered as eustatic sea-level falls, they may influenced by geomorphic evolutions around the lake such as progradation of Tenjin River delta toward the coring site.

On the other hand, tectonic stability around the lake cannot have produced the relative sea-level rises at centurial or millenia intervals. Nakada and Lambec (1988) pointed out the importance of mantle rheology affecting on the Holocene subtle sea-level changes. In the

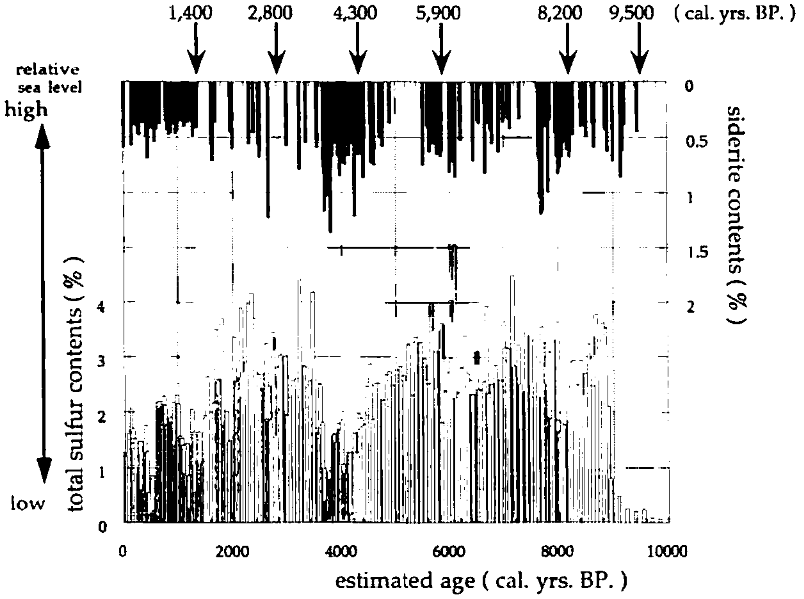

Fig. 6 Holocene abrupt sea-level changes estimated from total sulfur (lower open bars) and siderite contents (upper solid bars) in varved lacustrine sediments of Lake Tougou-ike. Arrows with calendar ages indicating discharged events of melt water in North Atlantic (Bond *et al.* 1997).

Japanese Islands, the mantle rheology can be regarded as hydro-isostasy in "far-field" sites from the late Pleistocene ice sheets proposed by Pirazzoli (1996). However, the tectonic rebounds of the hydro-isostasy were too smooth to have brought about such sea-level rises at intervals of a few thousand cal. years long. Therefore the abrupt rises and gradual falls of relative sea level inferred from the lacustrine sediments of Lake Tougou-ike can indicate abrupt eustatic sea-level rises due to increases of global seawater volume, and almost stable or gradually fallings of eustatic sea level after the sea-level rises. Such cycles of sea-level changes may have occurred repeatedly in millennial-scale during the Holocene.

Eustatic sea-level changes during the Holocene have been believed to rise continuously and smoothly toward present sea level (*e.g.*, Pirazzoli 1996 ; Saito 1997). However, some Japanese studies on the Holocene show several high or low stands of sea levels with smooth rising and falling as was summarized in Ota *et al.* (1990). Researches on tropical corals indicated evidence of abrupt sea-level rises at intervals since the last glaciation. From Barbados corals, Fairbanks (1989) reconstructed 2 abrupt sea-level rises, 12,000 and 9,500 ^{14}C yrs. BP., during the last deglaciation related to abrupt and rapid melting of ice sheets. Bard *et al.* (1996) discussed the timing of these 2 pulse-like meltwater discharges inferred from a sea-level record from Tahiti corals and the relationships between the meltwater pulses and global coolings. The abrupt sea-level rises detected from the sediment core of Lake Tougou-ike might have occurred by the similar meltwater pulses. The scale of these Holocene meltwater pulses could be smaller than those occurred in the last deglaciation because few large ice sheets were remained on the earth during this interglacial.

Relationships between abrupt sea-level rises at Lake Tougou-ike and ice discharge events in the North Atlantic

Numerous sediment cores obtained from the North Atlantic have revealed that cold meltwater or ice rafts from ice sheets around the Arctic discharged repeatedly into the North Atlantic Ocean accompanied with Dansgaard-Oeschgar Cycle (Dansgaard *et al.* 1993) during the last glacial period. Especially large discharges from ice sheets are called Heinrich Events (Bond and Lotti 1995). Broecker (1994) proposed that the melting events of the ice sheets into the North Atlantic are the trigger of global climatic coolings and spread by changing of ocean thermohaline circulation so called the conveyer belt. Bond *et al.* (1997) investigated the North Atlantic marine sediments and found evidence of such discharges from northern ice sheets even in the Holocene and scales of the discharges varied as Bond cycle. Bond *et al.* (1997) estimated that the ages of these ice discharge events were 9,500, 8,200, 5,900, 4,300, 2,800 and 1400 cal. yrs. BP. Figure 6 shows the comparison between the ages of the North Atlantic events and our research. Distinct synchronous changes are repeatedly observed through the Holocene. Relative sea level was falling at Lake Tougou-ike when the discharge event seems to have occurred in the North Atlantic, and relative sea level abruptly rose within a few hundred cal. years after the individual event. Therefore, a hypothesis is proposed as follows : an abrupt melting of ice sheets encouraged increasing of global seawater mass for a few hundred cal. years, which caused an abrupt eustatic sea-revel rise. Then, ice sheets kept stable or slightly expanded and eustatic sea level remained stable or tended to fall slightly, when the river progradations and relative sea level falling occurred at Lake Tougou-ike for about 400-1,000 cal. years. Although only a few researches have reported Holocene abrupt changes of global climate or that of eustatic sea level yet, millennial sea-level changes might have successively reconstructed by analyzing the lacustrine varved sediments that have more ability for continuous and high-resolution detecting of paleoenvironments.

5. Conclusions

In this study, we can point out three important information to reconstruct the paleoenvironments as follows:

1) Based on lamina counting and AMS ^{14}C dating, a couple of light-colored lamina and dark-colored lamina in laminated sequence of core sediment from Lake Tougou-ike represented varve deposited in one year. Alternations of thin light- and dark-colored laminae were sequentially observed in the Holocene sediments. Biochemical and mineral compositions of them observed under the microscope suggest that these varves were formed by seasonal changes of diatom bloomings. Calendar ages estimated from varve countings were consistent with dating of 40 stratigraphic horizons calibrated from ^{14}C ages of the sediments.

2) Relative sea-level changes were reconstructed from iron mineral compositions of varved sediemnts of Lake Tougou-ike, and there are abrupt sea-level rises with millennial periodicities during the Holocene. The varve-counting ages of the abrupt risings are 8,900, 7,700, 5,600, 4,000, 3,600 and 2,700 cal. yrs. BP., respectively. These facts suggest that pulse-like sea-level rising which occurred in the last glacial (Fairbanks 1989) may have also occurred during the Holocene.

3) By comparing with the ages of the climatic warming events occurred in the North Atlantic (Bond *et al.* 1997), abrupt rising of sea-level at Lake Tougou-ike occurred a few hundred years after the discharge of ice melt water into the North Atlantic. These facts show that the relative sea-level changes detected at Lake Tougou-ike have related closely to global environmental changes.

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