(Original Paper)

Latest Pleistocene Freshwater Microplankton from Paleo-Lake Sediments of Cheju Island, Korea with Reference to its Depositional Environment

Kazumi MATSUOKA

Laboratory of Coastal Environmental Sciences, Faculty of Fisheries, Nagasaki University, 1 - 14, Bunkyo-machi, Nagasaki, 852-8521, Japan

(Receivede Sep. 11, 2001, Accepted Nov. 12, 2001)

Abundant well preserved palynomorphs consisting of freshwater dinoflagellate cysts including one new species, three types of *Spirogyra* zygospores, four species of *Pediastrum* coenobia and one species of *Botryococcus* clusters of green algae are described from the latest Pleistocene paleo-lake deposit in Cheju Island of Korea. The combination of the aquatic palynomorph assemblage suggests that this lake was shallow with a large amount of standing water at the latest Pleistocene.

Key Words : Freshwater microplankton, dinoflagellate cyst, lake sediment, Cheju Island, Pleistocene

Introduction

In paleo-lake deposit, sometimes various aquatic palynomorphs consisting of freshwater dinoflagellate cysts, zygospores, coenobia and clusters of Chlorophyceae, and spores of Crysophyceae are preserved in good condition. More than fifteen species in modern freshwater dinoflagellates are known so far to have a sexual life cycle and then some of them can produce resting cysts (= hypnozygotes)[1]. However, their morphological features have not fully described yet in comparison with marine dinoflagellate cysts. On the other hand, in the Pleistocene to Holocene freshwater sediment, dinoflagellate cysts have been reported from several places in the world. Most of them were recorded in North America[2, 3, 4] and Australia[5, 6]. In a paleoenvironmental study, these fossilized aquatic palynomorphs are well known to be good biomakers for the depositional environment like standing water condition[7].

In this paper I describe several freshwater microplankton species ; one new freshwater dinoflagellate cyst, zygospores and coenobia and clusters of green algae found in the latest Pleistocene sediments. And based on their modern inhabitants I also discuss on the latest Pleistocene depositional environment of the maar located on the southern part of the Cheju Island of Korea.

Material and Method

Cheju Island of Korea located in the northern part of the East China Sea mainly consists of the late Neogene and Quaternary volcanic rocks of basalt and andesite accompanied with sedimentary rock[8]. Many maars in various size and geologic age were formed in the volcanic activities. In the western part of Sogwipo, there is the large maar with approximately 750m in diameter and 40m in depth (Fig. 1). This maar was formed at the latest Pleistocene in geologic age, because most parts of the maar have been buried by mainly peaty mud (more than 9.5m in thickness). The core contains a volcanish ash layer identified as the AT (-3.8m depth) which originated from the southern Kyushu of Japan, and with several thin sandy layers[9]. Now in this maar, agriculture of rice and fruits farming are developing. The total of 9.5m sediments was collected with a peat sampler on

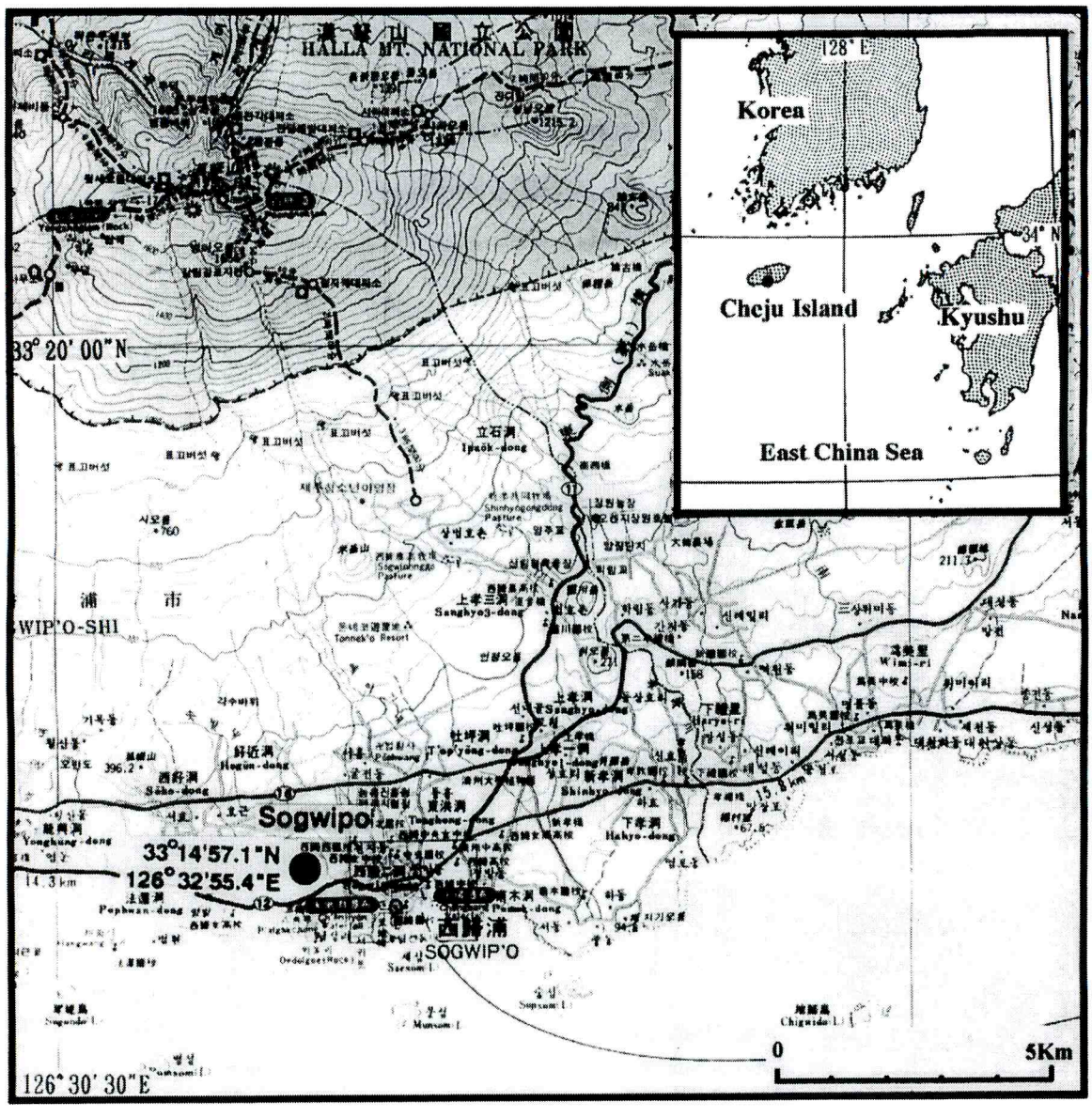


Figure 1 Sampling location in the Cheju Island, Korea

October of 1993 and October of 1994. At three horizons, ^{14}C ages were measured by Radiocarbon Dating Laboratory, University of Waikato (Wk) and Teledyne Brown Engineering Environmental Services (I) ; 8,730 ± 70yBP. (Wk-3242) at -0.9 to 1m depth, 13,630 ± 160yBP. (Wk-3243) at -2.9 to 3m depth and 26,700 ± 150yBP. (I-17648) [9] at -4.9 to 5m depth. Base on the sedimentation rate calibrated from ^{14}C dating, a subsample of -2.48 to -2.49m depth of the core provided for this study is the latest Pleistocene (approximately 11,000 yBP.) in age.

Abundant pollen and spores occurred through the sediment. Dinoflagellate cysts and other algal remains were extracted from the sample of -2.48 to -2.49m depth of the core. A subsample, about 5g was processes by a normal palynological method. For removing calcium carbonate and silicate minerals, 10% HCl and 47% HF were used under a cold condition respectively. The slides containing the type specimens are kept in the Laboratory of Coastal Environmental Sciences, Faculty of Fisheries, Nagasaki University.

All palynomorphs recovered from the sample were mounted on a slide with glycerin jelly and sealed with 24mm × 18mm cover slips. Observation

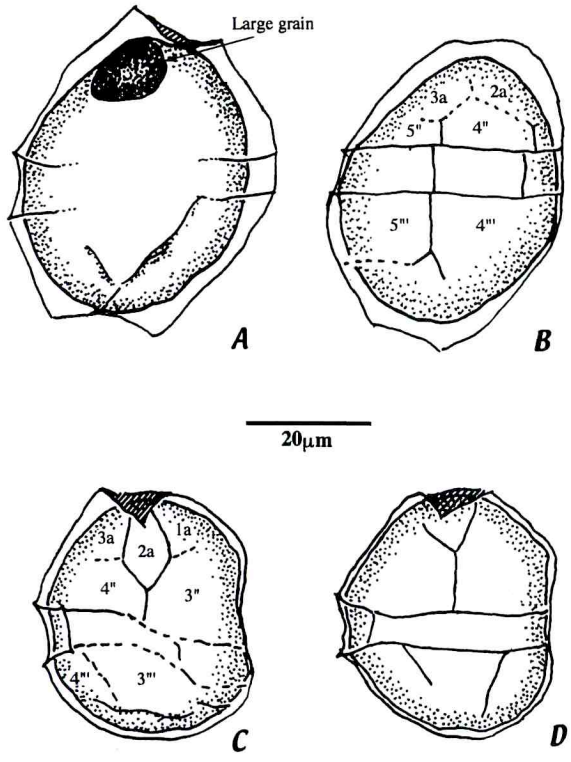


Figure 2 Schematic illustration of *Saeptodinium ovatum* sp. nov.

was carried out under normal and interference optics equipped on a Ziss Akisiophoto microscope. Fluorescent optics with U-V filter was also employed for the observation.

Results

The palynomorph assemgalge in this sample included several different freshwater algal taxa. These microfossils were mainly attributable to Dinophyceae and Chlorophyceae (mainly *Pediastrum*, *Spirogera* and *Botryococcus*). In the pollen and fern spore assemblage, harbaceous pollen taxa mainly composed of Gramineae, Cyperaceae, *Artemisia*, Cichorioideae and Carduiodeae were extremly dominated and occupied more than 70% of the total assemblage. On the other hand, tree pollen occupied ca. 17% of the total assemblage. The tree pollen assemblage consisted mainly of deciduous broad-leaved taxa ; *Betula*, *Quercus* (*Lepidobalanus*), *Ulmus-Zelkova*, *Alnus*, and *Fagus* and coniferous *Abies*, *Pinus* and Taxodiaceae, probably *Cryptomeria japonica*. Dinoflagellate cysts occupying approximately 4.6% of the total palynomorphs were followed by *Pediastrum* (4%), *Spinogyra* (3.5%), and *Botryococcus* (0.5%). The relative abundance of *Botryococcus* and *Pediastrum* was based on the numbers of cluster or ceanobia, not a single cell number.

Systematic description

Class Dinophyceae Pascher 1941

Order Peridiniales Haeckel 1894

Family Peridiniaceae Ehrenberg 1831

Genus *Saeptodinium* Harris 1974

Remarks : *Saeptodinium*, a genus for fossilized dinoflagellate cysts, differs from *Geiselodinium* in having two antapical horns, and transapical arhceopyle.

Saeptodinium ovatum Matsuoka sp. nov.(Plate 1, figs. 1-6)

Diagnosis : Circumcavate cysts of ovoidal to rounded peridinioid, and slightly compressed dorso-ventrally, with a broadly rounded epicyst, and with or without two small antapical bosses. Paracingulum wide. Periphragm thin, and endophragm relatively thick and psilate. Incomplete paratublation developed. Archeopyle theropylic and transapical.

Holotype : Plate 1, fig. 1. Slide Cheju-Sogwipo (248-249)-3 (O47/1).

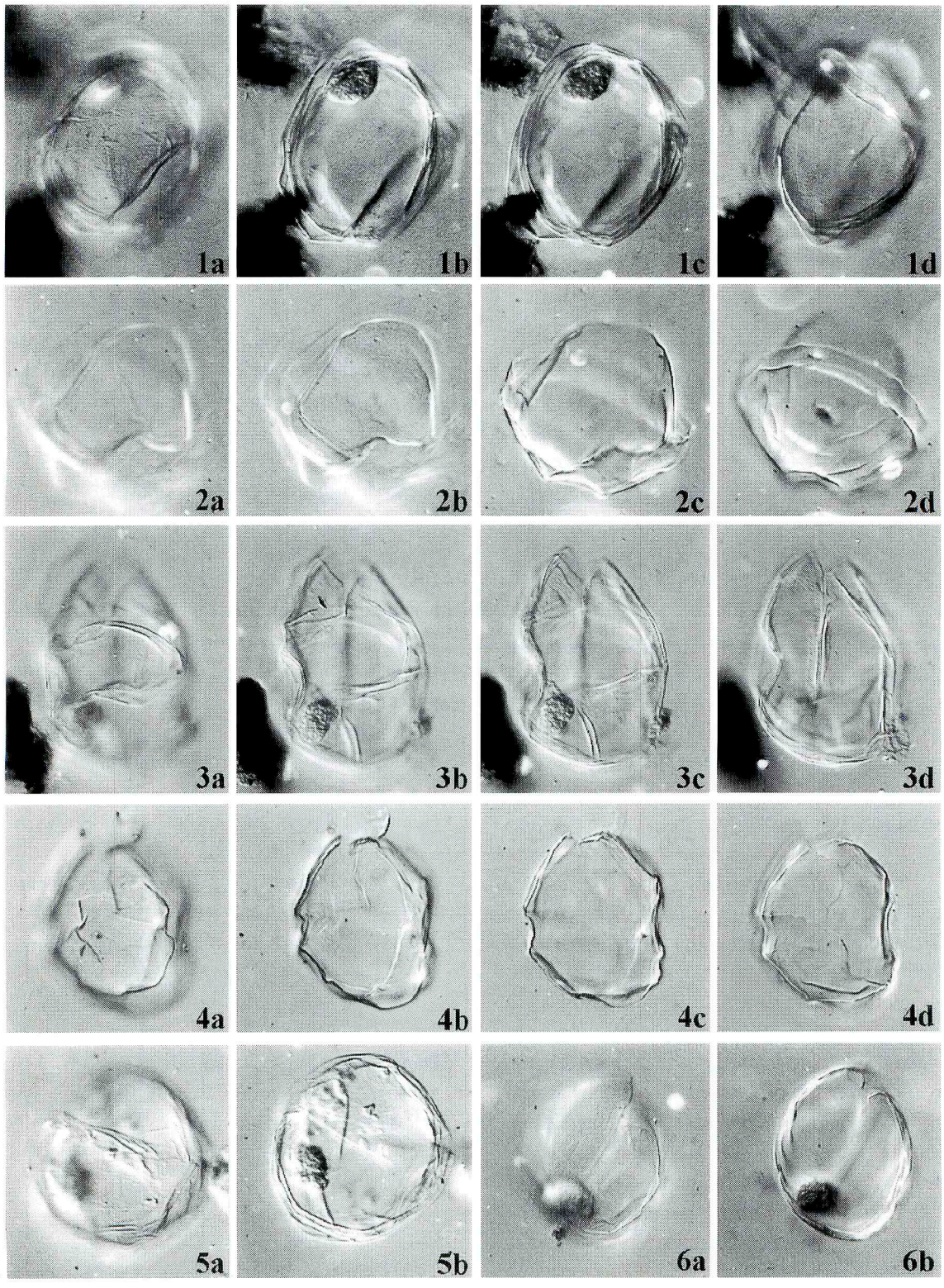
Paratype : Plate 1, fig. 2 Slide Cheju-Sogwipo (248-249)-2(G44/1).
Plate 1, fig. 3 Slide Cheju-Sogwipo (248-249)-4(H44/4).
Plate 1, fig. 4 Slide Cheju-Sogwipo (248-249)-4(J29/3).

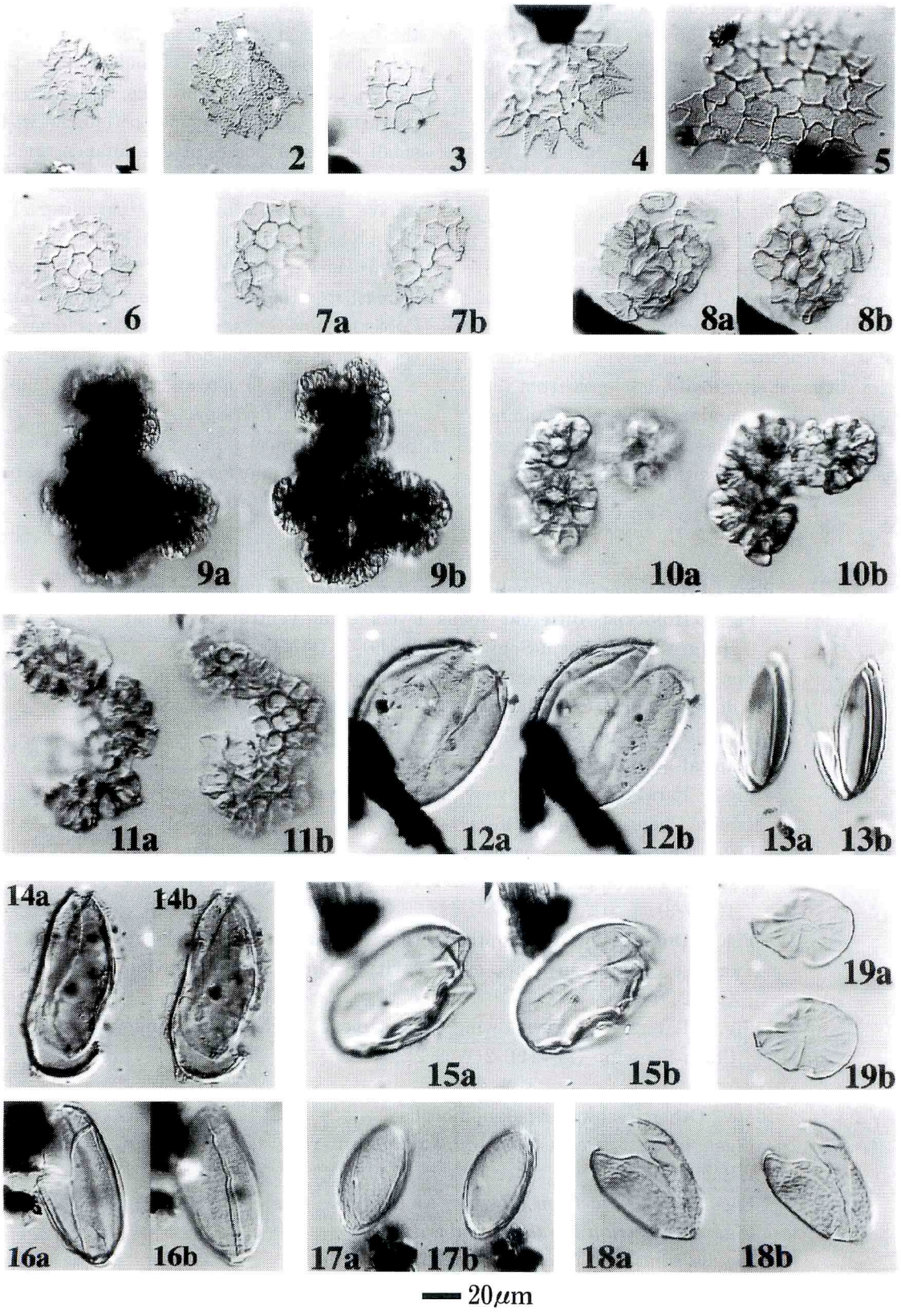
Dimensions : Pericyst ; length 38.4-62μm (53.3μm), width 34.4-51.8μm (46.7μm), Endocyst ; length 34.4-47.6μm (46.7μm), width 29.6-49μm (36.7μm) ; width of paracingulum 4.8-10μm (9.2μm)

Number of specimens measured : 10.

Type locality and geologic age : Old lake deposit at the western part of Sogwipo in Cheju Island, Korea (33°14'57.1"N, 126°32'55.4"E) ; Latest Pleistocene.

Description : Cyst wall consisted of two layers ; endophragm is subspherical to ovoidal, thin, pale brown and finely granular, and periphragm is


1a
1b
1c
1d
2a
2b
2c
2d
3a
3b
3c
3d
4a
4b
4c
4d
5a
5b
6a
6b
20μm


1
2
3
4
5
6
7a
7b
8a
8b
9a
9b
10a
10b
11a
11b
12a
12b
13a
13b
14a
14b
15a
15b
19a
19b
16a
16b
17a
17b
18a
18b
20μm

rounded pentagonal thin, colorless and sometimes with two small antapical bosses. Paraplates are reflected by parasutures incompletely developed on the periphragm. Paratabulation is partly reflected by parasutures ; possibly x', 3a, 7", 6c?, 5'", 2"", xs. Paracingulum is represented by fold of the periphragm, and wide ; approximately one-sixth of the cell length, displaced with half of its own width, and located near the equatorial zone. Parasulcus is wide, and reaches at the center of the hypocyst, and invades into one-third of the epicyst. One scar of the flagellar pore is rarely observed in the parasulcus. Archeopyle is therophylic and transapical ; a slit is longitudinally developed from the apical to the paracingulum, possibly running between 2"+ 3"+ 4'? and 3a+ 5"+ 6". A large orange grain is usually observed within the cyst cavity.

Remarks : This new species is probably identical to the Type C cyst of Norris and McAndrews[2] found from the post-glacial lake mud of Minnesota in U.S.A. Both species share the following similar characters ; ovoid to rounded peridinioid with two small bulges or bosses at the antapex, smooth to psilate periphragm, incomplete paratabulation fairly indicated by low parasutures, and theropylic-transapical archeopyle.

This new species differs from *Saeptodinium gravattense* Harris, *S. eurypylum* (Manum and Cookson), and *S. tasmaniensis* Harris in having not conspicuous antapical horns, and also differs from *S. tiandongense* in having the paracingulum and the transapical archeopyle.

Biological affinity : This cyst species is probably belonging to extant *Peridinium bipes* Stein, because the epicyst has three anterior intercaraly para-

Plate 1 Freshwater dinoflagellate cyst ; ***Saeptodinium ovatum*** sp. nov.

Fig. 1. Holotype, different focus levels from ventral to dorsal surfaces, Slide Cheju-Sogwipo (248-249)-3 (O47/1).

Fig. 2. Paratype, different focus levels from the optical section to dorsal surfaces, showing two antapical bosses. Slide Cheju-Sogwipo (248-249)-2(G44/1) ; specimen slightly deformed apical-antapically.

Fig.3. Paratype, lateral view, showing transapical archeopyle, Slide Cheju-Sogwipo (248-249)-4(H44/4).

Fig. 4. Different focus level from dorsal to ventral surfaces, 4d showing incomplete parasutures, Slide Cheju-Sogwipo (248-249)-4(J29/3).

Fig. 5. Dorsal view and optical cross section showing a large orange grain in the cyst cavity, Slide Cheju-Sogwipo (248-249)-1(D24/2).

Fig. 6. Lateral view showing transapical archeopyle, Slide Cheju-Sogwipo (248-249)-2(W29/2).

Plate 2 Other freshwater palynomorphs

Figs. 1, 4, 5 *Pediastrum duplex* Meyen var. ***subgranulatum*** Raciborski

Figs. 2, 6, 7 *Pediastrum integrum* Nagel

Fig. 3 *Pediastrum tetras* (Ehrenberg) Ralfs

Fig. 8 *Pediastrum integrum?* Nageli

Figs. 9-11 *Botryococcus braunii* Kutzing

Figs. 12, 14, 15 *Spirogyra* sp. A

Figs. 13, 16 *Spirogyra* sp. B

Figs. 17, 18 *Spirogyra* sp. C (foveolate/fossulate-type)

Fig. 19 Unknown algal spore

plates. Norris and McAndrews[3] suggested that their Type C cyst was similar to the cyst of *P. bipes* shown by Huber-Pestalozzi[10] based on the general shape and overall size. However, the cyst form of *P. bipes* reported by Sako[11] is different in being simply large spherical in shape (60-65 μm) with thick wall.

Class Chlorophyceae Kutzing 1843
Order Chlorococcales Pascher 1915
Family Hydrodictyaceae (Gray) Dumortier 1829

Genus *Pediastrum* Meyen 1829

Remarks : The oldest fossil *Pediastrum* is recovered from the Lower Cretaceous and thereafter its fossil comes up to the Holocene[7]. *Pediastrum* remains have been frequently observed from various coastal marine sediments[12], however all extant species of this genus are freshwater plankton.

Pediastrum duplex Meyen var. *subgranulatum* Raciborski 1889 (Pl. 2, figs. 1, 4, 5)
Description : Outline of coenobium circular and consisting of 8 to 32 cells. Cell surface coarsely granulate. Among the cells narrow slits well developed. Outer cells bearing two conspicuous horns with a broad base.

Prdiastrum tetras (Ehrenberg) Ralfs 1844 (Pl. 2, fig. 3)
Description : Outline of coenobium small, roundly polygonal and consisting of 4 to 8 cells. Among the cells no slits developed. The central cell heptagonal. Cell surface psilate. Outer cells bearing two short horns.

Pediastrum integrum Nageli 1849 (Pl. 2, figs. 2, 6, 7)
Description : Outline of coenobium circular and variable in cell number. Cell surface granulate. Among the cells no slit developed. Outer cells bearing two very short horns.

Pediastrum integrum? Nageli 1849 (Pl. 2, fig. 8)
Description : Outline of coenobium probably circular. Cell surface granulate. No slits developed. Outer cells bearing no horns. This species is only different from *P. integrum* in having no projection on the outer cells.

Family Botryococcaceae Wille 1909
Genus *Botryococcus* Kutzing 1849

Remarks : The genus *Botryococcus* was previously considered to be a member of the class Xanthophyceae, although now it is commonly accepted that this genus should be classified into the Chlorophyceae[7, 13]. Although its fossil record is possibly back to the Precambrian, the occurrence from the Ordovician is more reliable[14]. In the genus *Botryococcus*, only *B. braunii* is extant, and cosmopolitan in freshwater lakes and ponds as plankton.

Botryococcus braunii Kutzing 1849 (Pl. 2, figs. 9, 10, 11)
Description : Colony consisting of clustered laminated empty cups, irregular in shape. Cells contained in the cups ovoidal to subspherical, 3 × 6μm - 6 × 10μm in size, and variable in number.

Order Zygnematales Borg in Pascher 1913
Family Zygnemataceae Meneghini 1838
Genus *Spirogyra* Link 1820

Remarks : Fossil genus *Ovoidites* is a junior synonym of *Spirogyra*[15]. *Ovoidites* was first found from the European Tertiray freshwater sediment with a brief description under the genus *Pollenites*[16]. This palynomorph was newly named as the genus *Ovoidites* by Potonie[16] and sometimes classified into the Group Acritarch by paleo-palynologists. These acritarchs are sexual spores (zygospores) or aplanospores of the genus *Spinogyra* of freshwater Zygnematacean algae (Chlorophyceae) on the basis of morphological features[17, 18]. These spores are diploid, thick-walled and contains sporo-pollenin components. Most *Spirogera* species are plankton in small lakes and pools or in the littoral zone of larger lakes, and prefer shallow, stagnant, clean, and oxygen-rich waters[17]. Several different morphotypes have been described in the fossil *Spirogyra* ; psilate, reticulate, and foveolate/fossulate zygospores or aplanospores.

In the sample, three morphotypes are recognized ; *Spirogyra* sp. A, *Spirogyra* sp. B, and *Spirogyra* sp. C

Spirogyra sp. A (Pl. 2, figs. 12, 14, 15)

Description : Spore large (length 121-81 μm, width 81-58.5 μm), ovoidal to ellipsoidal with rounded ends. Wall consisting of two layers ; thin and fibrous outer layer, and thick and psilate inner layer. The outer layer usually removed. A longitudinal long slit encircling the spore.

Spirogyra sp. B (Pl. 2, figs. 13, 16)
Description : Spore intermediate (length 108-94.5 μm, width 54-49.5 μm), more or less ellipsoidal with pointed ends. Wall consisting of two layers adpressed ; thin outer layer, and thick and psilate inner layer. A longitudinal long slit encircling the spore.

Remarks : This species resembles *Spirogyra* species (Type I) of van Geel and Hamman [17] in being ellipsoidal rather than ovoidal with a smooth to psilate wall.

Spirogyra sp. C (foveolate/fossulate-type) (Pl. 2, figs. 17, 18)
Description : Spore small (length 85.5-76.5 μm, width 49.5-40.5 μm), ovoidal to ellipsoidal with rounded ends. Wall consisting of two layers ; thin and fibrous outer layer, and thick and foveolate/fossulate inner layer. The outer layer usually removed. A longitudinal long slit encircling the spore.

Remarks : This species resembles a fossil zygospore or aplanospore of *Spirogyra* species illustrated by van Geel and Grenfell [15] in possessing foveolate/fossulate inner layer.

Discussion

The palynomorph assemblage in this sample consists of pollen, fern spores, dinoflagellate cysts, coenobia of *Pediastrum*, zygospores and clusters of green algae, and others. *Peridinium bipes* that is probably the motile form of the fossil *Saeptodinium ovatum* is a typical planktonic freshwater dinoflagellate and widely distributing in temperate regions of the world [11] . Modern *Botryococcus braunii* is also globally dispersed in temperate to tropical freshwater lakes and ponds where it sometimes makes a dense cluster on water surface [13] . *Pediastrum* spp. are also known as phytoplankton in freshwater lakes and ponds. It is very difficult to identify the species of *Spirogyra* spp. found in this sample, because zygospores of *Spirogyra* morphologically resemble on each other. However, most of the modern *Spirogyra* are flowering in standing freshwater such as small lakes, ponds and in the littoral zone of larger lakes [17] .

According to the fossil palynomorph evidence obtaining from the sample, this old maar was a small lake (approximately 700m in diameter) with considerable amount of standing freshwater at the latest Pleistocene, although this area is now dried up.

Acknowledgement

I thank to Professor Moon Hon Kim, and Professor Joon Baek Lee of Cheju National University, Dr. K. Takemura of Kyoto University, and Dr. S. Nagaoka of Nagasaki University for their kind help to collect the sample. Also I am indebted to Professor H. Fukusawa of Tokyo Metropolitan University and Dr. H. Kitagawa of Nagoya University for their useful discussion on the depositional environment of this maar. Thanks are given two anonymous referees for their constructive suggestions and comments. This study was supported by Grant-in-Aid for Science of Japan Society for the Promotion of Science (11695080).

Reference

(1) Matsuoka, K. and Fukuyo, Y. Technical Guide for Modern Dinoflagellate Cyst Study, v+29pp., WESTPAC-HAB/WESTPAC/IOC, Japan Society for the Promotion of Sceince (2000).

(2) Evitt, W.R. and Wall, D. Dinoflagellate studies, 4. Theca and cyst of Recent freshwaer *Peridinium limbatum* (Stokes) LEMMERMANN. Stanford University Publication, University Series of Geological Science, **10**, 1-15 (1968).

(3) Norris, G. and McAndrews, J.H. Dinoflagellate cysts from post-glacial lake muds, Minnesota (U.S.A.). *Review of Palaeobotany and Palynology*, **10**, 131-156 (1970).

(4) Hunt, C.O., Andrews M.V. and Gilbertson,

D.D. Late Quaternary freshwater dinoflagellate cysts from the British Isles. *Jounal of Micropalaeontology*, **4**, 101-109 (1985).

(5) Churchill, D.M. and Sarjeant, W.A.S. Freshwaer microplankton from Flandrian (Holocene) peats of southwestern Australia. *Grana Palynologica*, **3**, 29-53 (1963).

(6) Harland, R. and Sarjeant, W.A.S. Fossil freshwater microplankton (Dinoflagellates and acritarchs) from Flandrian (Holocene) sediments of Victoria and Western Australia. *Proceedings of the Royal Society of Victoria*, **83**, 211-234 (1970).

(7) Zippi, P.A. Freshwater algae from the Mattagami Formation (Albian), Ontario : Paleoecology, botanical affinities, and systematic taxonomy. *Micropaleontology*, **44**, Supl. No. 1, pp. 1-78 (1998).

(8) Yoon, S.-H. and Chough, S.-K. Field Excursion Guide ; The Soguipo Formation, Cheju Island (Korea), 42pp., The Hallim Publishers, Seoul (1990).

(9) Matsuoka, K., Kim, M.-H., Takemura, K., Nagaoka, S., and Lee, J.B. Geologic age and facies of the boring core sediments from Cheju Island, Korea. *Bulletin of Faculty of Liberal Arts, Nagasaki University, Natural Science*, **35**, 135-145 (1995).

(10) Huber-Pestalozzi, G. Pyrrophyta. *In* : Die Binnengewasser. Das Phytoplankton des Susswassers, 16(3), Cryptophyceen, Chloromonadadinen, Peridinineen, p. 1-310 (1950).

(11) Sako, Y. *Peridinium bipes* Stein. *In* An Illustrated Atlas of the Life History of Algae. Hori. T (ed.), Volum **3**, p.44-45, Uchida Rokakuho Publishing Co. Ltd. Tokyo (1993).

(12) Matsuoka, K. and Hase, K. Fossil *Pediastrum* from the Pleistocene Hamamatsu Formation around Lake Hamana, central Japan. *Transaction and Proceedings of the Palaeontological Society of Japan*, NS. **104**, 432-441 (1977).

(13) Batten, D. J. and Grenfell, H. R. Chapter 7D. *Botryococcus* ; Spores of Zygnemataceae ; *In* : Jansonius, J. & McGregor, D.C. (ed.), Palynology : Princeple and applications ; American Association of Stratigraphic Palynologysts Foundation, vol. 1, p. 205-214 (1996).

(14) Traverse, A. Paleopalynology. xxiii+600pp. Allen & Unwin Inc., Winchester, U.S.A (1988).

(15) van Geel, B. and Grenfell, H. R. 1996 Chapter 7A. Spores of Zygnemataceae ; *In* : Jansonius, J. & McGregor, D.C. (ed.), Palynology : Princeple and applications ; American Association of Stratigraphic Palynologysts Foundation, vol. 1, p. 173-179 (1996).

(16) Potonie, R. Revision stratigraphisch wichtiger Sporomorphen des mittel-europaischen Tertiars. *Palaeontographica*, Abt. A, **91**, 131-151 (1951).

(17) van Geel and T. van der Hammen Zygnemataceae in Quaternary Colombian sediments. *Review of Palaeobotany and Palynology*, **25** ; 377-392 (1978).

(18) van Geel, B. Fossil spores of Zygnemataceae in diches of a prehistoric settlement in Hoogkaspel (The Netherlands). *Review of Palaeobotany and Palynology*, **22**, 337-344 (1976).

韓国・済州島の旧湖成堆積物から得た最後期更新世の淡水性マイクロプランクトンとその堆積環境

松岡　數充

長崎大学水産学部沿岸環境学研究室　〒852-8521　長崎市文教町 1 - 14

韓国・済州島南部にある現在は乾陸化している旧火口底には厚さ 9.5m に達する泥質堆積物が存在する．その堆積物の深さ 2.48m ～ 2.49m の最後期更新世試料から多様な淡水性パリノモルフが良好な保存状態で検出された．その群集は渦鞭毛藻シストの 1 新種（*Saeotodinium ovatum* sp. nov），緑藻類に属する浮遊性植物プランクトン *Pediastrum* 4 種，*Botryococcus* 1 種，*Spirogyra* 接合胞子 3 形態型から構成されていた．これらパリノモルフ群集組成の特徴から，最後期更新世の旧火口は現在とは異なり，淡水が湛えられていた環境であったと推察した．