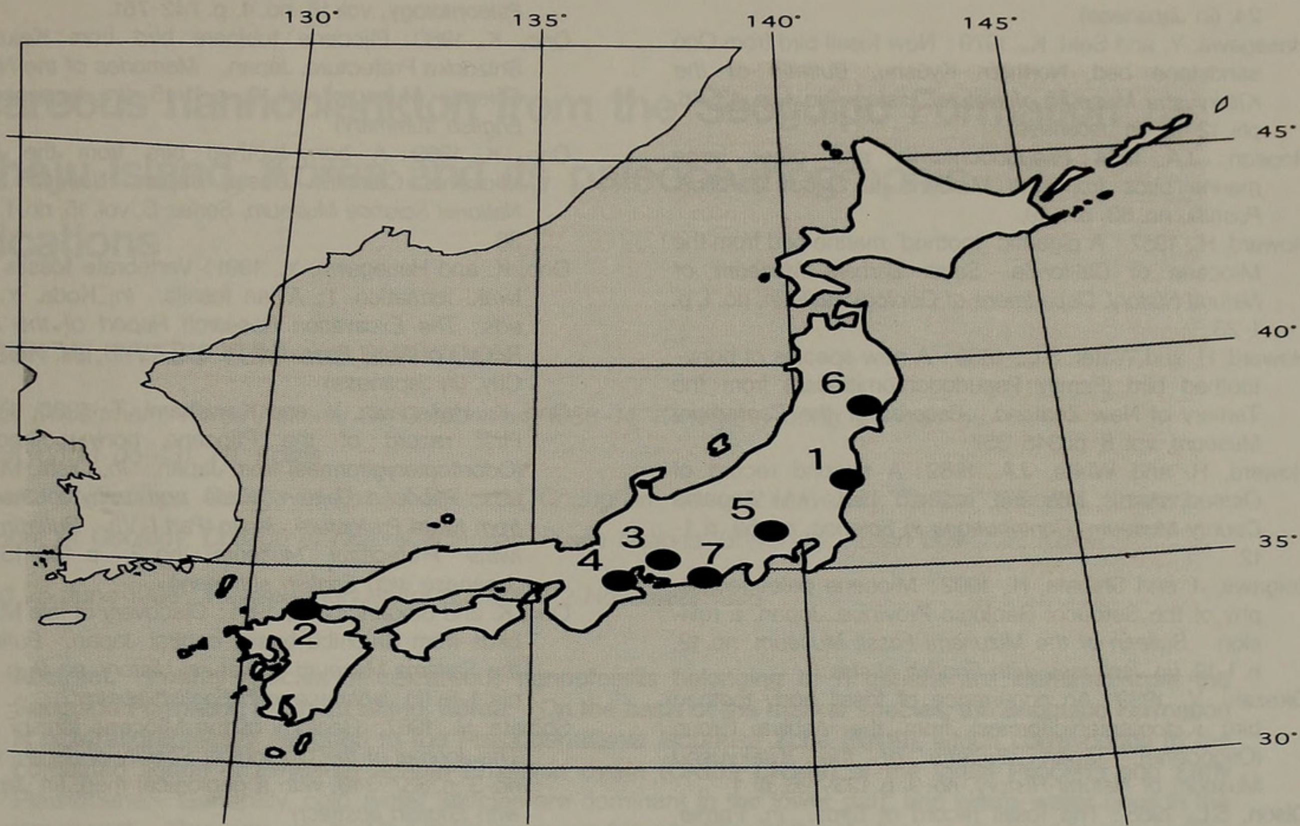

No. in map	Age	Locality	Horizon	Element	Reference
1	E. Oligocene	Ogawa-tyo, Iwaki, Fukushima.	Iwaki F., Shiramizu G.	Rostrum	Hasegawa et al., 1986 Ono and Hasegawa, 1991
2	L. Oligocene	Yoshida, Mizumaki, Fukuoka.	Yamaga F., Ashiya G.	Humerus (left)	Okazaki, 1989
3	late E. Miocene	Mizunami, Gifu.	Mizunami G.	- No report -	(Ono, 1989)
4	late E. Miocene	Sangou, Misato, Mie.	Oi F., Ichishi G.	Dentary (right)	Present report
5	early M. Miocene	Ohnohara, Chichibu, Saitama.	Nagura F., Chichibumachi G.	Quadrate (right)	Ono, 1989
6	E. Pliocene	Seibo, Maesawa, Iwate.	Yushima F. (=Tatsunokuchi F.)	Humerus (right)	Ono et al., 1985
7	L. Pliocene	Haranoya, Kakegawa, Shizuoka.	Dainichi F., Kakegawa G.	Femur (right)	Ono, 1980 Ono et al., 1985

Figure 5. Summary of pseudodontorn records of Japan. Locality numbers in above figure correspond to material listed in below in order of geological age. Abbreviations : E, Early ; M, Middle ; L, Late ; F, Formation ; G, Group.

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Calcareous nannoplankton from the Seoguipo Formation of Cheju Island, Korea and its paleoceanographic implications

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Abstract. Twenty species of calcareous nannofossils belonging to 11 genera are identified from the Seoguipo Formation in Cheju Island, Korea. On the basis of the marker species, the Seoguipo Formation is biostratigraphically assigned to the *Pseudoemiliania lacunosa* Zone (NN19), which corresponds to the combined zones of *Emiliania annula-Emiliania ovata* (CN13a-CN14a) of the latest Pliocene and Early Pleistocene. Generally, cold-water species are dominant in the lower part, and warm-water ones in the upper part. This suggests that the paleoceanographic condition of the study area changed from a cooling to a warm phase. The change in floral composition and abundance of specific species allows recognition of four ecostratigraphic zones in the Seoguipo Formation and the migration of an oceanographic frontal boundary. According to nannofossil distribution in the study area, the position of an oceanographic boundary between warmer water and cooler water appeared to have oscillated north-south over the Korea Strait and Cheju Island in response to glacial and interglacial cycles. The geologic time of the interpreted paleoceanographical changes determined by nannofossil biochronology agrees well with the results obtained from the Japan Sea (East Sea) and Japan-Sea side of Japan.

Key words: Bio- and ecostratigraphy, Cheju Island, Korea, nannoplankton, paleoceanography, Seoguipo Formation.

Introduction

Cheju Island, located 90 km off the southern coast of Korea at 33°12′-33°34′N, 126°10′-126°58′E, was formed by Late Cenozoic volcanic activity (Figure 1). The Seoguipo Formation, a highly fossiliferous marine formation, seems to have been deposited just before the onset of Quaternary volcanism, since it underlies Pleistocene volcanic rocks that cover most of the island (Table 1). The Seoguipo Formation is mainly composed of sandstone with a minor amount of interbedded conglomerate and mudstone. It is well developed at the subsurface level all over the island and is exposed only on the southern coast of the island at Seoguipo. The subsurface Seoguipo Formation is encountered in core samples of numerous bore holes drilled in the island.

Yokoyama (1923) first reported molluscan fossils from these sedimentary deposits, designating their geologic age as Upper Pliocene. Haraguchi (1931), who described diverse invertebrate faunas such as mollusks, brachiopods, echinoids, corals and fish teeth, named this fossiliferous sedimentary formation the Seikiho (Seoguipo) Formation of the Pleistocene epoch. After Haraguchi's research, numerous works including detailed field survey, paleontological, magnetostratigraphic, and sedimentological studies were carried out for determination of the geologic age, depositional environment, and stratigraphical zonation (Kim, 1972; Won, 1975; Lee, M.W., 1982a, 1982b; Kim, 1984; Nomura, 1984; Yun *et al.*, 1987; Min *et al.*, 1986; You *et al.*, 1987; Yoon, 1988; Tamanyu, 1990; Lee E.H., 1990; Yoon *et al.*, 1995; Kang, 1995). However, no consensus was achieved for the geologic age of the Seoguipo Formation which was assigned to different ages from Pliocene to Pleistocene (Table 1). Several studies analyzed paleoclimate and paleoceanographic conditions of the Seoguipo Formation based on molluscan fauna and isotope data (Yoon, 1988; Amano, 1994; Park *et al.*, 1994; Woo *et al.*, 1995). The results for the water temperature are also contradictory, reporting warm or cold glacial environment during deposition of the formation.

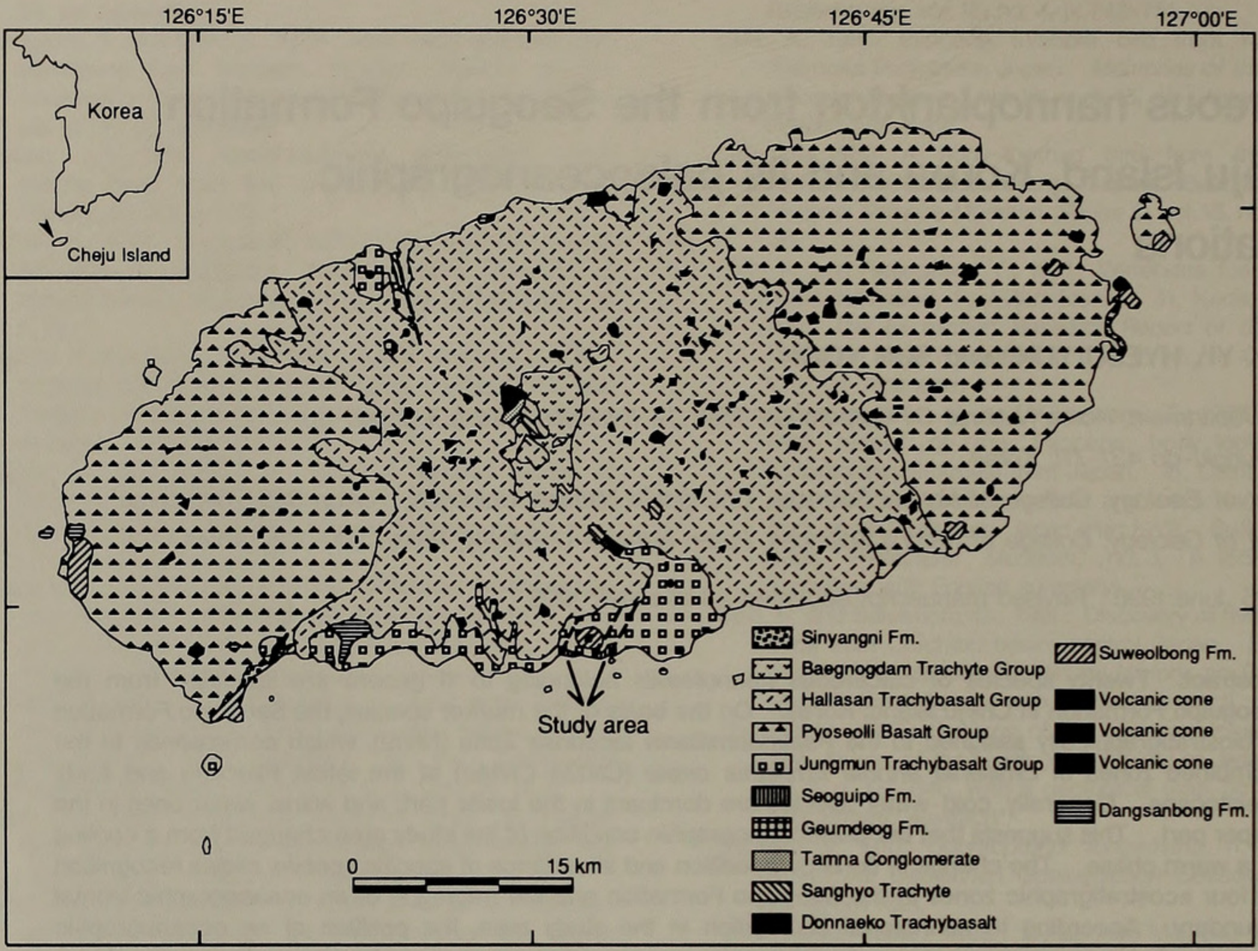

Figure 1. Geologic map of Cheju Island with sample locality (after Yoon *et al.*, 1995).

Cheju Island is located in the oceanic pathway to the Japan Sea. This area was paleoclimatologically and tectonically sensitive and often affected by small- or large-scale changes in the tectonic (Inoue, 1982) or climatological settings. The climatic or sea-level changes may cause subsidence or uplift which in turn affects the system of current and the biofacies. Therefore, a biofacies analysis may deductively provide a clue to the climatic and tectonic history of this area, which is not only important for the development of Cheju Island and the Korea Strait, but also for the evolution of the Japan Sea during the late Pliocene and Pleistocene (Muza, 1992; Rahman, 1992).

Analysis of calcareous nannofossil assemblage is the best means to resolve the debateble claims made concerning the geologic age and environment of the Seoguipo Formation, since it may enable fine zonation and reconstruction of the paleoenvironmental and geologic events. Therefore, our study primarily aims to establish a biozonation and ecostratigraphy based on nannoplankton, and to investigate the frequency and nature of paleoceanographic changes during deposition of the Seoguipo Formation. The results may help in interpretation of the paleoclimatic and tectonic history of Cheju Island and the neighboring area.

Geologic setting of the Seoguipo Formation

The Seoguipo Formation is divided into 7 distinctive lithologic units in ascending order (Lee, 1990; Figure 2). Litho-unit I of about 3.5 m thickness is composed of laminated yellowish gray siltstones in the lower part, and massive fine-grained gray sandstones with fossil shells and volcanic clasts in the upper part. Litho-unit II overlying the Litho-unit I with a diastem is about 5 m thick, and consists of alternating brownish medium-grained, parallel-stratified sandstones and thin-laminated mudstones. The upper part of this unit with a thickness of about 2 m is highly bioturbated and contains a few articulated bivalve shells. Litho-unit III with a thickness of about 15 m is relatively homogeneous. It is composed of poorly consolidated massive sandstones. The lower boundary of this unit nearly coincides with the Pliocene-Pleistocene boundary. Except for the middle part this unit is highly fossiliferous and bioturbated. Litho-unit IV with a thickness of about 2 m is composed of massive yellowish- gray fine-grained sandstones and highly bioturbated mudstones. Litho-unit V, which is about 10 m in thickness, overlies Litho-unit IV with a diastem. It is lithologically very variable showing cross-laminated shell conglomerate layers, medium- to coarse-grained sandstones intercalated with mudstones, and massive, poorly sorted gray

Table 1. Stratigraphic classifications of volcanics and sedimentary strata in Cheju Island (The sources of the radiometric ages ae indicated in brackets : a. Ahn *et al.*, 1995 ; b. Yoon *et al.*, 1995 ; c. Lee, 1994 ; d. Won *et al.*, 1986 ; e. Sameshima *et al.*, 1988).

Age	Haraguchi, K. (1931)	Won, C.K. (1975)	Lee, M.W. (1982)	Yun, S.K. *et al.* (1987)	Tamanyu, S. (1990)	Yoon, S. *et al.* (1995)
Holo.	Flood Deposits Shell-Sand Bed Wacke Bed	Shell-sand Formation Parasitic volcanic ejectas	1007, 1002 activities Groups of small basalt cones	1007, 1002 activities	1002, 1007 activities Shell and Formation Scoria vol. cones	Sinyangni Formation [4780±60 y.B.P.][e]
Pleistocene, Late	Gunzan Basalt Suikido Basalt Kanrasan Basalt Aphanitic Basalt Augite Basalt Feldspar Basalt Saishu Basalt Alkali-basalt Trachy-andesite	Baegrogdam Basalt Hanlasan Trachy-andesite Hanlasan Basalt Seongpanak Basalt Sihungri Basalt Beobjeongn Trachyte Hahyori Basalt Jeju Basalt	Sinyangri Formation Hanlasan Trachyte Hanlasan hawaiite Seonpanak hawaiite Sihungri hawaiite Beobjeongri mugearite Hahyori hawaiite Jeju hawaiite	Dongnam palaeosol Basalt flows along the flanks of Hanlasan [0.07±0.04–0.035±0.014 Ma] Sinyangri Formation	Paeknoktam Hawaiite [0.47±0.07 Ma] Hallasan Trachyte [0.07±0.01 Ma]	Baegnogdam Trachyte Group: Baegnogdam Trachyte [0.025±0.008 Ma][d]; Yeongsil Trachyte Hallasan Trachybasalt Group: Hallasan Trachybasalt; Seongpanag Trachybasalt; Cheju Trachybasalt
Pleistocene, Middle	Hornblende-bearing Trachy-andesite Gyojoseigaku Lava Kakushugan Lava Sanbosan Lava	Sinyangri Formation	Hornblende mugearite Sanbangsan Trachyte	Hanlasan trachyte Tuff-rings (Songaksan, Ilchulbong, Suwolbong) Seoguipo trachyandesite [0.41±0.01 Ma] Tuff-rings (Dansan, Dusan) **Seoguipo Formation** Pyoseonri basalt [0.63±0.03 Ma]	Pyosonri Alkali Basalt [0.31±0.04 Ma] Hallasan Hawaiite [0.52±0.03 Ma] Sogwip'o Hawaiite [0.55±0.04 Ma]	Pyoseolli Basalt Group: Siheungni Trachybasalt; Pyoseolli Basalt [0.63±0.03 Ma][c]; Seoguipo Trachybasalt
Pleistocene, Early	**Seikiho Formation**	Jungmun Trachyte: Seongsanpo Fm., Hwasun Fm. Seoqwipo Trachyte Pyoseonn Basalt	Jungmun hawaiite Seonsanpo Formation Seoguipo hawaiite Pyoseonri alkali basalt	Tuff-rings (Hwasoon, Dansan) Sanbangsan Trachyte [0.87±0.13 Ma] marine sediments basalt (olivine augite basalt) [1.20±0.05 Ma]	Sanbangsan Trachyte **Sogwip'o Formation** Basal Basalt	Jungmun Trachybasalt Group: Jungmun Trachybasalt; Sanbangsan Trachyte [0.733±0.056 Ma][d]; Gagsuam Trachyte [0.893±0.027 Ma][c]
Pliocene	Shinto Lava Johangaku Lava Gyojoseigaku Lava Kanrasan Lava Granite Blocks-bearing Volcanic Detritus Bed	**Seoqwipo Formation** Basal basalt	**Seoguipo Formation** Basal Basalt			Cheju Group: **Seoguipo Formation**; U Formation (uncemented sediment beds); Geumdeog Formation; Tamna Conglomerate Sanghyo Trachyte Donnaeko Basalt Panpo Basalt [2.22±0.16 Ma][b]
Cret. (?)-Paleogene	Granite ?		Granite ?	Granite in the northern part Tuff in the eastern and southern part	Granite ?	Granite [58.14±1.4 Ma][a] Volcanic sandstones and mudstones Welded tuffs Lapilli tuffs

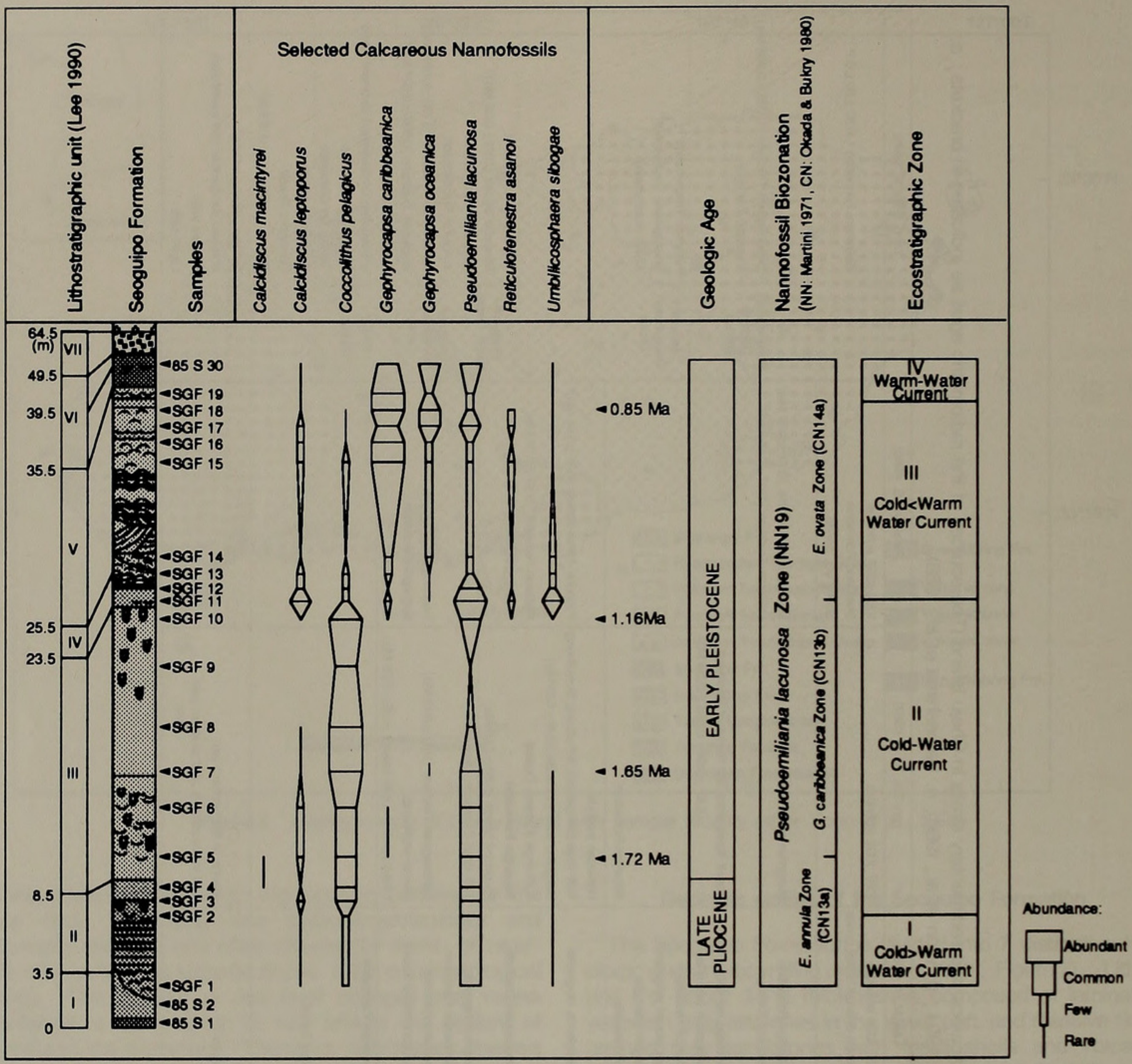

Figure 2. Biozonation and ecostratigraphic zones of the outcrop section of the Seoguipo Formation based on nannofossils.

medium to coarse sandstones. This unit is characterized by a variety of sedimentary structures such as ripple drift laminae, wavy bedding, flaser bedding, graded bedding, and convolute bedding. Litho-unit VI with a thickness of about 14 m is composed of semi-consolidated massive, light-gray siltstones and volcanic ash. Litho-unit VII of about 15 m thickness consists of volcanic conglomerate without any fossil remains. This unit is covered by a basalt flow.

Methods

Twenty-two samples were collected from the outcrop of the Seoguipo Formation (Figure 2, Table 2). Smear slides were prepared following the centrifuging method of Perch-Nielsen (1985, p. 330-331). Samples were crushed and centrifuged for 30 seconds at 2,000 r.p.m. Slides were examined with a light microscope at ×1,250 magnification and a scanning electron microscope. Preservation and abundance of nannofossils in each sample are denoted as follow: Abundant (A), 1-10 specimens/one field of view; Common (C), 1 specimen/2-10 fields of view; Few (F), 1 specimen/11-100 fields of view; Rare (R), 1 specimen/101-1,000 fields of view; Barren (B), no fossils observed; Good (G): specimens show little effects of dissolution or overgrowth; Moderate (M), specimens show some effects of dissolution or overgrowth.

Table 2. Stratigraphic occurrence of calcareous nannofossil from the Seoguipo Formation.

Geologic Age	Nannofossil zone		Ecostratigraphic Zone	Formation	Samples	Abundance	Preservation	*Braarudosphaera bigelowii*	*Calcidiscus leptoporus*	*Calcidisucs macintyrei*	*Ceratolithus cristatus*	*Coccolithus pelagicus*	*Coccolithus* sp.	*Gephyrocapsa caribbeanica* (3.5-4.0 μm)	*Gephyrocapsa oceanica* (>4.0 μm)	small *Gephyrocapsa* spp. (<3 μm)	*Helicosphaera carteri*	*Helicosphaera* sp.	*Pontosphaera japonica*	*Pontosphaera discopora*	*Pseudoemiliania lacunosa*	*Reticulofenestra asanoi*	small *Reticulofenestra* spp.	*Syracosphaera pulchra*	*Syracosphaera* sp.	*Umbilicosphaera hulburtiana*	*Umbilicosphaera sibogae*
PLEISTOCENE	*Pseudoemiliania lacunosa* Zone (NN19)	CN14a	IV	Seoguipo	85 S 30	A	G	•	R	•	•	•	•	A	C	A	R	•	R	•	C	•	C	R	•	F	R
					SGF 19	A	G	•	R	•	•	•	•	A	F	A	F	•	•	•	F	•	F	•	•	•	R
			III		SGF 18	A	G	R	R	•	R	R		A	C	A	R	•	R	•	F	F	F'	R	•	•	R
					SGF 17	C	G	R	F	•	•	R	•	C	C	A	R	R	•	•	C	F	F	•	•	•	R
					SGF 16	A	M	•	F	•	•	R	•	A	F	A	R	•	•	•	F	R	F	•	•	•	R
					SGF 15	A	G	R	F	•	•	F	•	A	F	A	R	•	•	•	F	C	C	•	•	•	R
					SGF 14	F	M	•	R	•	•	R	•	F	F	F	•	•	•	•	F	R	F	•	•	R	F
					SGF 13	A	G	•	F	•	R	F	•	F	R	A	F	•	R	•	C	R	F	•	•	•	F
					SGF 12	A	G	•	F	•	•	F	R	R	R	A	R	R	R	R	A	F	C	•	R	•	F
					SGF 11	A	G	R	C	•	R	F	•	F	R	A	C	•	R	•	A	F	C	F	•	•	C
		CN13b	II		SGF 10	A	G	R	R	•	•	A	F	R	•	C	F	•	•	•	C	F	C	•	•	•	R
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					SGF 8	A	G	R	R	•	•	A	F	•	•	•	R	•	•	•	F	•	R	•	•	•	•
					SGF 7	A	G	R	R	•	•	A	F	•	R	F	R	•	R	•	C	•	C	•	R	•	R
					SGF 6	C	M	F	F	•	•	C	R	R	•	R	F	•	•	•	C	•	F	•	•	•	R
					SGF 5	C	M	R	F	R	•	C	R	R	•	R	F	•	R	•	C	•	F	•	•	•	R
PLIOCENE		CN13a			SGF 4	C	M	•	R	R	•	C	•	•	•	•	R	•	•	•	C	•	R	•	•	•	R
					SGF 3	C	M	•	F	•	•	C	R	•	•	F	R	•	R	•	C	•	R	•	•	•	R
			I		SGF 2	C	M	•	R	•	•	F	R	•	•	C	R		R	•	C	•	•	•	•	•	R
					SGF 1	A	G	•	R	•	•	F	R			A	R	•	R	•	C	•	C	•	•	•	R
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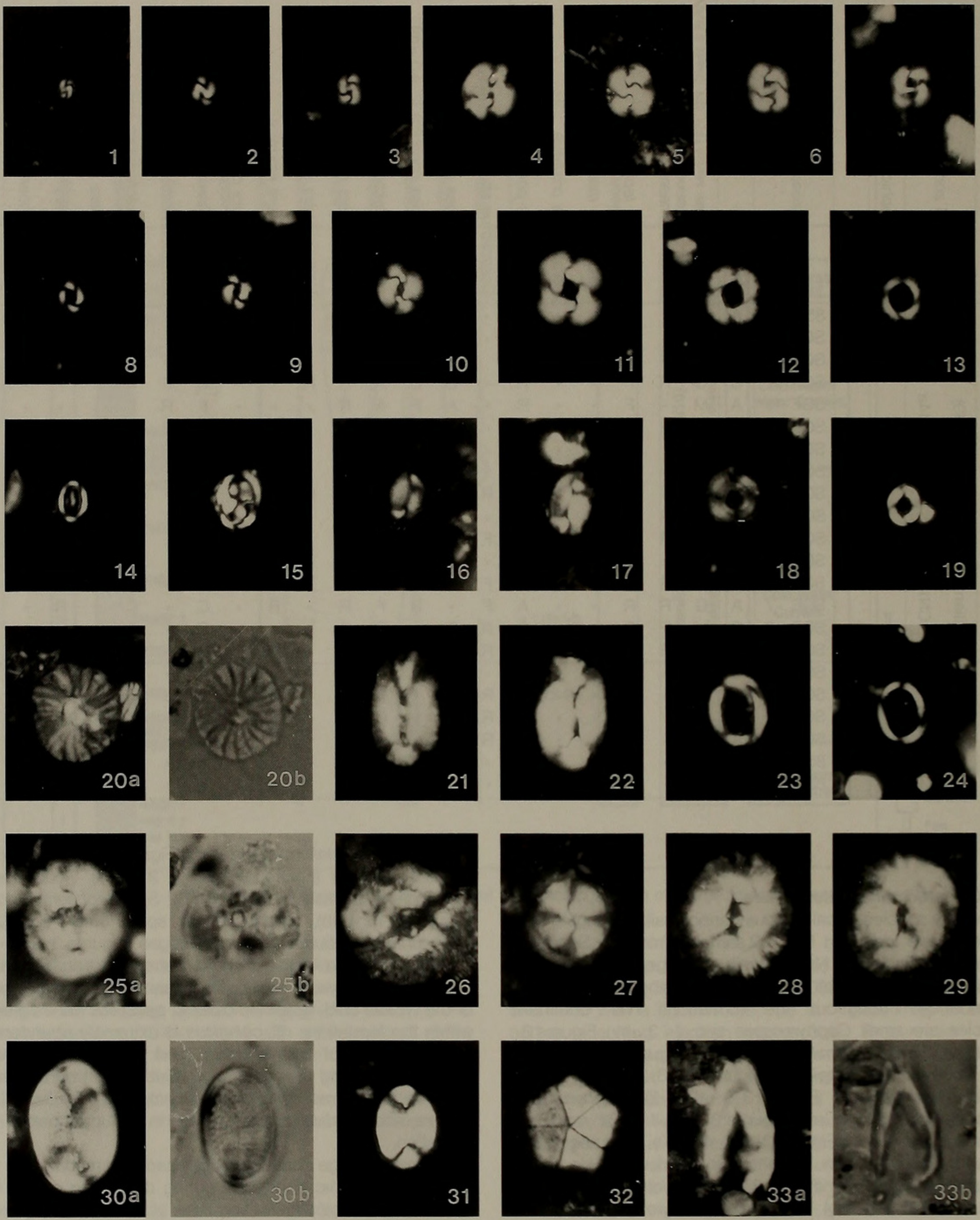
Results

1. Calcareous nannofossil flora

Twenty species of calcareous nannofossils belonging to 11 genera were identified from 22 samples from the Seoguipo Formation (Table 2). Nannofossils were generally common to abundant. However, some species changed their relative abundance throughout the formation. The dominant species are small *Gephyrocapsa* spp. (<3 μm; Figures 3-1—3, 4-1, 2), *Pseudoemiliania lacunosa* (Figures 3-12, 13, 4-4, 5), *Coccolithus pelagicus* (Figures 3-28, 29, 4-15), small *Reticulofenestra* spp. (Figures 3-8—10, 4-3), *Gephyrocapsa caribbeanica* (3.5-4 μm; Figures 3-4, 5, 4-7, 8) and *G. oceanica* (>4 μm; Figures 3-6, 7, 4-9, 10) in ascending order in the formation. The minor species include *Braarudosphaera bigelowii* (Figure 3-32), *Calcidiscus leptoporus* (Figures 3-20a, b, 27, 4-12—14), *C. macintyrei* (Figures 3-25a, b, 26), *Ceratolithus cristatus* (Figures 3-33a, b), *Coccolithus* sp. (Figures 3-19, 23, 24, 4-11), *Helicosphaera carteri* (Figures 3-21, 22, 4-16), *Helicosphaera* sp. (Figures 3-16, 17), *Pontosphaera japonica* (Figures 3-30a, b, 31, 4-17), *P. discopora*, *Reticulofenestra asanoi* (Figure 3-11), *Syracosphaera pulchra* (Figures 3-15, 4-18), *Syracosphaera* sp. (Figure 3-14), *Umbilicosphaera hulburtiana* and *U. sibogae* (Figures 3-18, 4-6).

The nannoflora in the formation shows a transition from cold subpolar to warm subtropical assemblage. Abundance of the typical cold-water indicator *C. pelagicus* varies greatly within the formation. *C. pelagicus* is extremely abundant in the lower part of the formation and gradually decreases upward, becoming few to barren. Subtropical nannofossils such as *G. oceanica* (>4 μm), *C. leptoporus*, *U. sibogae*, *S. pulchra*, and *C. cristatus* are common in the upper part of the formation.

The assemblage characteristics change in response to the paleoceanographic conditions during deposition of the formation and hence allow recognition of four ecostratigraphic zones in the outcrop section of the Seoguipo Formation (Figure 2). Zone I (SGF 1-2) contains dominant small *Ge-*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phyrocapsa spp. (<3 μm), common *P. lacunosa* and small *Reticulofenestra* spp., and few *C. pelagicus*. The flora of these strata consists of mixtures of warm and cold-water species. Zone II (SGF 3-10) is characterized by a prominent peak in abundance of the cold-water species *C. pelagicus*. Zone III (SGF 11-18) shows an abrupt decrease of *C. pelagicus* and increase of subtropical to tropical species including *G. oceanica* (>4 μm), *C. leptoporus, U. sibogae, S. pulchra*, and *C. cristatus*. The change from a cold- to warmer-water flora and increase of the oceanic species took place at SGF 11. Zone IV (SGF 19, 85S30) reveals dominance of *G. oceanica* (>4 μm), *G. caribbeanica* (>3.5-4 μm), small *Gephyrocapsa* spp. (<3 μm), and *U. hulburtiana* and was barren of *C. pelagicus*.

2. Nannofossil biochronology

The Seoguipo Formation yields Pleistocene marker species such as *G. caribbeanica* (>3.5-4 μm), *G. oceanica* (>4 μm), *P. lacunosa, C. macintyrei*, and *R. asanoi* (Table 2, Figures 2, 3). Among them, the first appearance datum of *G. caribbeanica* (FAD : 1.72 Ma ; Sato and Kameo, 1996) has been used for the determination of the Pliocene-Pleistocene boundary. This species is first recognized in sample SGF 5. *G. oceanica* (FAD : 1.65 Ma ; Sato and Kameo, 1996), another important indicator for the Pliocene-Pleistocene boundary, occurs in sample SGF 7. *C. macintyrei* with the last occurrence datum (LAD) of 1.60-1.64 Ma (Shipboard Scientific Party, 1996) was encountered in sample SGF 5, although the total occurrence of *C. macintyrei* may not have been properly detected because of its rarity in the samples, and would be expected to occur also in somewhat younger samples. Compiling all these data, the Pliocene-Pleistocene boundary can be drawn between SGF 4 and SGF 5. Consequently, the lowermost part (SGF 1-4) can be presumed to be older than 1.72 Ma and thus belongs to the latest Pliocene.

The sample SGF 11 indicates the lower boundary of Zone CN14a defined by the reoccurrence of *G. oceanica* (>4 μm ; 0.94-1.02 Ma ; Shipboard Scientific Party, 1996). The presence of *P. lacunosa* (LAD : 0.41 Ma ; Sato and Kameo, 1996) indicates that the uppermost part of the formation is older than 0.41 Ma in age. Specimens of *R. asanoi*, with FAD of 1.16 Ma (Sato and Kameo, 1996), are first found in sample SGF 10 at the end of the cooling phase. Therefore, the upper section of sample SGF 10 is younger than 1.16 Ma. This species is last recorded in sample SGF 18, near the upper boundary of the formation, suggesting that this layer is older than the LAD of *R. asanoi* (0.85 Ma ; Sato and Kameo, 1996).

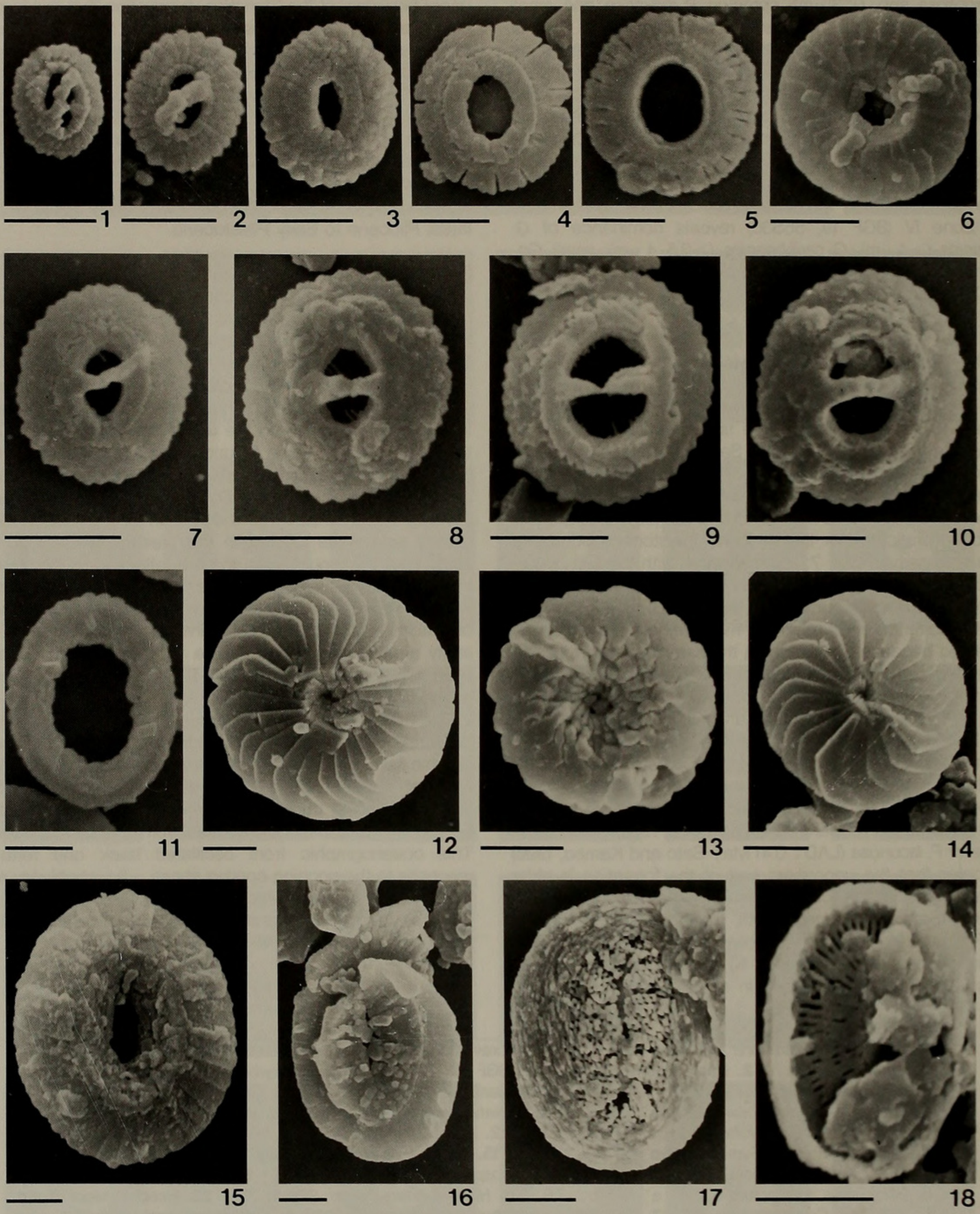
Thus, it is clear that the Seoguipo Formation comprises the latest Pliocene to Early Pleistocene nannofloras. The lower boundary is older than 1.72 Ma, while the upper one is slightly younger than 0.85 Ma. The calcareous nannofossil of this formation is assigned to the *P. lacunosa* Zone (NN19) (Martini, 1971), which corresponds to the combined zones *E. annula* to *E. ovata* (CN13a-CN14a ; Okada and Bukry, 1980) of the latest Pliocene to Early Pleistocene.

3. Paleoceanography

The four ecostratigraphic zones established on the basis of the floral composition reflect paleoceanographic conditions (Figure 2). The lowermost section, Zone I is characterized by co-existence of cold (subpolar) and warm (subtropical) water masses. The cooler-water influence increases upward reaching its peak in the middle part of the core (Zone II). It deteriorates toward the upper part (Zone III) until it is totally replaced in Zone IV under the influence of warmer water. This is interpreted as a cooling phase which began in Zone I, culminated in the Zone II, and finally faded out at the upper section (Zone III and IV). In view of the absence of any cold-water current in the present sea around the study area this would seem to be a reflection of the glacial-interglacial cycle rather than due to the local influence of a warm-water current. Comparing the cooling phase with biochronological data, it is certain that a glacial cycle in the study area started shortly before 1.72 Ma (FAD of *G. caribbeanica*) and halted around 0.94-1.02 Ma (reoccurrence of *G. oceanica*).

The distribution of calcareous nannofossils in the Seoguipo Formation also records the position of an oceanographic frontal boundary between warmer water derived from a branch of the Kuroshio Current as it entered the Japan Sea to the north and cooler water introduced into the western portion of the Japan Sea derived from the Liman Current. This oceanographic front oscillated back and forth in response to the ongoing cooling phase. It probably lay near Cheju Island during deposition of Zone I and Zone III, whereas it stood south and north of the island during formations of Zone II and Zone IV, respectively.

Figure 3. All illustrations are light micrographs. Abbreviations : XP=cross-polarized light, TR=transmitted light. Magnification=×2,000. **1, 2.** small *Gephyrocapsa* spp., SGF 12, XP. **3.** small *Gephyrocapsa* spp., SGF 11, XP. **4.** *Gephyrocapsa caribbeanica*, SGF 5, XP. **5.** *Gephyrocapsa caribbeanica*, SGF 10, XP. **6.** *Gephyrocapsa oceanica*, SGF 7, XP. **7.** *Gephyocapsa oceanica*, SGF 30, XP. **8, 9.** small *Reticulofenestra* spp., SGF 10, XP. **10.** small *Reticulofenestra* spp., SGF 11, XP. **11.** *Reticulofenestra asanoi*, SGF 15, XP. **12.** *Pseudoemiliania lacunosa*, SGF 11, XP. **13.** *Pseudoemiliania lacunosa*, SGF 5, XP. **14.** *Syracosphaera* sp., SGF 12, XP. **15.** *Syracosphaera pulchra*, SGF 18, XP. **16.** *Helicosphaera* sp., SGF 12, XP. **17.** *Helicosphaera* sp., SGF 17, XP. **18.** *Umbilicosphaera sibogae*, SGF 11, XP. **19.** *Coccolithus* sp., SGF 16, XP. **20a, b.** *Calcidiscus leptoporus*, SGF 11, a : XP., b : TR. **21.** *Helicosphaera carteri*, SGF 11, XP. **22.** *Helicosphaera carteri*, SGF 12, XP. **23.** *Coccolithus* sp., SGF 7, XP. **24.** *Coccolithus* sp., SGF 1, XP. **25a, b.** *Calcidiscus macintyrei*, SGF 4, a : XP., b : TR. **26.** *Calcidiscus macintyrei*, SGF 5, XP. **27.** *Calcidiscus leptoporus*, SGF 3, XP. **28.** *Coccolithus pelagicus*, SGF 5, XP. **29.** *Coccolithus pelagicus*, SGF 7, XP. **30a, b.** *Pontosphaera japonica*, SGF 12, a : XP., b : TR. **31.** *Pontosphaera japonica*, SGF 7, XP. **32.** *Braarudosphaera bigelowii*, SGF 5, XP. **33a, b.** *Ceratolithus cristatus*, SGF 4, a : XP., b : TR.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Discussion

1. Stratigraphy

Although the exposure of the Seoguipo Formation above sea level measures about 50 m thick in the Seoguipo area, this formation is developed in the subsurface throughout Cheju Island except for the eastern area of a line connecting Bukchon and Pyoseon. The upheavals of the Seoguipo Formation at Seoguipo City indicate a 150 m uplift of this area at least (cf. Yoon, 1988). However, it is reasonable to suspect that the Seoguipo Formation was formed at a much lower level than where it is at present, since sea level dropped 85–130 m during intense global glacial periods (Muza, 1992).

Quaternary studies on the Seoguipo Formation reported that the outcrop of the Seoguipo Formation in Seoguipo stratigraphically differs from its subsurface strata (Yun *et al.*, 1987 ; Lee *et al.*, 1987). The above-mentioned researchers considered the age of the Seoguipo Formation to be Middle Pleistocene (0.60–0.41 Ma). They further insisted that subsurface marine sediments recovered from core are Lower Pleistocene (1.2–0.87 Ma) in age (Table 1). For the age determination of sedimentary bodies they applied the paleomagnetic data and radiometric age (K-Ar) of the volcanic rocks that they believed to underlie or overlie two different sedimentary sequences. However, the FAD and LAD of index nannofossils such as *G. caribbeanica* (3.5-4 μm), *G. oceanica* (>4 μm), *C. macintyrei, R. asanoi, P. lacunosa* and the characteristic nannoflora of the four ecostratigraphic zones recognized in the outcrop section are also observed in 20 cores of Cheju Island. These facts imply that the outcrop strata are to be stratigraphically correlated to subsurface ones. The ecostratigraphic zones and their order of appearance, cold-dominant transitional, cold, warm-dominant transitional, and warm phase from bottom to top can be used as a good stratigraphic tool in Cheju Island. The subdivision of these units largely coincides with that of lithostratigraphic units.

The geologic age and stratigraphic range of the Seoguipo Formation provide a clue in determining the stratigraphic position of comparable sedimentary deposits in Cheju Island and Japan. In previous molluscan studies *Turritella saishuensis*, which occur throughout the Seoguipo Formation, is regarded as an index species for the depositional period of the Seoguipo Formation. However, the lower boundary of this formation is ambiguous due to the absence of stratigraphic marker fossils that may be caused by an influence of cold-water current. Therefore, the FAD of *Turritella saishuensis* also could not be clearly delineated. Some recent paleontological works attempted to define the age of the Seoguipo Formation by paleoceanographic conditions in the Early Pleistocene, when the cold-water mass expanded and the southward migration of the boreal species proceeded further along the Japan Sea borderland (Lee, 1990 ; Kang, 1995 ; Woo *et al.*, 1995). However, there are two different results for the age of first occurrence of *Turritella saishuensis* in the Seoguipo Formation ; Pliocene or Pleistocene. The Pliocene to Pleistocene Omma-Manganzian fauna in Honshu Island of Japan is correlated with the Seoguipo fauna based on the *Turritella saishuensis* bioseries (Ogasawara, 1981, 1986, 1996 ; Yoon, 1988). Our result confirms the lower stratigraphic range of the Seoguipo Formation and extension of the FAD of *Turritella saishuensis* to the latest Pliocene. Consequently, the formations correlated to the Seoguipo Formation might be stratigraphically placed between upper Pliocene and Pleistocene (Yoon, 1988).

The paleomagnetic normal polarities of the Seoguipo Formation have been interpreted as the Gauss Normal Polarity Epoch of late Pliocene age (Min *et al.*, 1986) or the Brunhes Normal Polarity Epoch in the middle Pleistocene (Yun *et al.*, 1987). Referring to the reverse polarity of the unconformably overlying Sanbangsan Trachyte, the Seoguipo Formation was placed in the Matuyama Reverse Polarity Epoch of the early Pleistocene (Taneda *et al.*, 1970). However, in a recent paleomagnetic study of the Seoguipo Formation two reversals were recognized in the upper part of the Seoguipo outcrop (Lee, 1998).

2. Biochronology

Previous paleontological studies on the Seoguipo Formation suggested that it was deposited during the Late Pliocene (Yokoyama, 1923 ; Kim, 1972 ; Kim, 1984 ; Yoon, 1988), Pleistocene (Haraguchi, 1931 ; Lee, 1990 ; Kang, 1995) or around the Plio-Pleistocene boundary (Paik and Lee, 1984 ; You *et al.*, 1987).

Our study suggests the age of the upper boundary of the formation is slightly younger than 0.85 Ma based on the presence of *P. lacunosa* (Last Appearance Datum : 0.41 Ma) and LAD (0.85 Ma) of *R. asanoi* (Table 2, Figure 2). It is confirmed by the reoccurrence of *G. oceanica* (>4 μm ; e.g. medium *Gephyrocapsa*) whose acme zone is known to be 0.94–1.02 Ma, in the upper part of the formation. This age of the upper boundary coincides with the results of radiometric K-Ar age of overlying basalt rocks (Table 1 ; Sanbangsan Trachyte : 0.733±0.056 Ma [Won *et al.*, 1986], 0.87±0.13 Ma [Yun *et al.*, 1987] ; Gaksuam Trachyte : 0.893±0.027 Ma [Lee, 1994]). The boundary of the Pleistocene-Pliocene determined by the FAD of *G. caribbeanica* (1.72 Ma) is regarded to lie between Sample SGF 4 and SGF 5. The two samples (SGF 3 and 4) of cold-water environment below Sample SGF 5 are provisionally assigned to the Pliocene, because they may not contain the Pleistocene index taxa for environmental reasons. However, the lowermost part of the formation (Sample SGF1 and 2) definitely belongs to the

Figure 4. All illustrations are Scanning Electron Micrographs. Scale bar equals 2 μm. **1, 2.** small *Gephyrocapsa* spp., SGF 11. **3.** small *Reticulofenestra* spp., SGF 11. **4.** *Pseudoemiliania lacunosa*, SGF 30. **5.** *Pseudoemiliania lacunosa*, SGF 11. **6.** *Umbilicosaphera sibogae*, SGF 11. **7, 8.** *Gephyrocapsa cabibbeanica*, SGF 30. **9, 10.** *Gephyrocapsa oceanica*, SGF 30. **11.** *Coccolithus* sp., SGF 1. **12.** *Calcidiscus leptoporus*, SGF 11. **13.** *Calcidiscus leptoporus*, SGF 11. **14.** *Calcidiscus leptoporus*, SGF 11. **15.** *Coccolithus pelagicus*, SGF 5. **16.** *Helicosphaera carteri*, SGF 11. **17.** *Pontosphaera japonica*, SGF 30. **18.** *Syracosphaera pulchra*, SGF 30.

Pliocene in age, since its relatively warmer environment exclude the possibility of climatic effect on distribution of index taxa. This presumption is also supported by normal polarity (Olduvai Normal Polarity Subepoch) specifically obtained from the paleomagnetic analysis of samples SGF 1-SGF 4 (Lee, 1998).

3. Paleoceanography

1). Paleotemperature.—Most paleontological studies reported that the Seoguipo floras and faunas are composed of mixtures of warm- and cold-water elements (Paik and Lee, 1984; You *et al.*, 1987; Yoon, 1988; Lee, 1990; Kang, 1995). According to our results the Seoguipo sequence is characterized by a cooling phase in the lower part and a warm phase in the upper part, and by two transitional phases (Figure 2). Ecostratigraphic Zone I is a first transitional phase in the lowermost part of the formation before beginning of cooling phase. Zone II is characterized by abundant occurrence of *C. pelagicus* is the coldest zone among the eco-zones of the Seoguipo Formation. *C. pelagicus* is presently restricted to the subarctic and transitional waters in the North Atlantic (7°-14°C: McIntyre and Bé, 1967) and North Pacific (6°-14°C: McIntyre *et al.*, 1970). This fact indicates that the paleotemperature of the surface water during deposition of this zone was below 14°C. Zone III is the second transitional phase indicating turnover to the general warming trend. The remarkable bio-event during deposition of the Seoguipo Formation is the sudden emergence of warm-water taxa in this zone. The abundance of *C. pelagicus* abruptly decreases, whereas diversity and abundance of the warm-water elements of *C. leptoporus, U. sibogae, G. oceanica,* and *S. pulchra* (the first two being oceanic elements) increase substantially. *G. oceanica* is presently distributed within a temperature range of 18°-29°C (McIntyre *et al.*, 1970; Honjo, 1977) or 19°C-31°C (Brand, 1994, p. 44). *Umbilicosphaera sibogae* prefers moderately nutrient-rich, tropical water (Roth and Coulbourn, 1982; Brand, 1994). *S. pulchra* is also a characteristic species in tropical and subtropical environments (Roth and Coulbourn, 1982). Zone IV in the uppermost part of the Seoguipo Formation contains diverse and abundant warm-water taxa. This means that the paleotemperature of the surface water of Zone III and IV was slightly warmer than the average present temperature, 19.38°C (Kwak *et al.*, 1993).

Study of ostracods also revealed similar paleoclimatic patterns to our results in six established biotopes of the formation; cooling phase in the lower part of the formation and warming trend upward (Lee, 1990). Assemblage of biotope 1 and 2 (Eco-Zones I and II: SGF 1-SGF 10) in the lower part of the formation is dominated by cold-water elements such as *Normanicythere sogwipoensis* and *Kotoracythere paiki* which are completely replaced by the warm-water elements *Cytheropteron uchioi* and *Cytheropteron abnormis* at biotope 3 (basal part of the Eco-Zone III: SGF 11-SGF 12), and in biotopes 4 and 5 (middle part of the Eco-Zone III: SGF 13 - SGF 14) the cold-water elements slightly increase again. The upper part of biotope 6 (upper part of Eco-Zone IV and higher: SGF 15-SGF 19) is characterized by a decrease in the cold-water elements and the occurrence of several warm-water elements. The warm-water ostracods found in the Seoguipo Formation are presently distributed in the South China Sea, southern part of the Yellow Sea and Korean South Sea influenced by warm Kuroshio Current (Lee, 1990).

Amano (1994) investigated the surface temperature of the Japan Sea in the Pleistocene through molluscan assemblages from coastal areas of the Japan Sea of Hokkaido to Cheju Island. He estimated the paleotemperature of the Seoguipo Formation as 20°C warmer than the average present temperature, 18.5°C (Marine Environment Map by Japanese Marine Safety Agency).

Woo *et al.*, (1995) analyzed oxygen isotopes from calcareous skeletons of Mollusca. The paleotemperature of his lithologic Unit 4 (SGF 5-SGF 10) from the Seoguipo Formation is calculated to be 13°C. He considered his lithologic Unit 4 the coldest, and the warmest temperature for the entire sequence was 18°C. Paleotemperature of other Units 1, 9, 11, 13 varies from 14 to 17°C. Based on these data, he concluded that the whole sequence of the Seoguipo Formation was deposited during glaciation. His paleoclimatic interpretation coincides with our results for the lower part of the Seoguipo Formation influenced by cold water.

2). Paleoceanographic front.—The site of the Seoguipo Formation is now located in warm surface waters south of an oceanographic front. However, in response to Pleistocene glacial episodes in the last 1.8 m.y. the cold-water front may have migrated southward over Cheju Island as global climate cooled (Momohara, 1994), the sphere of cooler-water influence expanded, and the effect of the warm-water Kuroshio Current diminished (Muza, 1992). Then the Pleistocene nannofossil association in the Seoguipo Formation could record the oscillation or migration of the oceanographic front over Cheju Island as the Japan Sea and the Korea Strait responded to glacial-interglacial cycles. If this is the case, as the oceanographic front migrated southward over Cheju Island owing to global glaciation, cooler surface water would replace warmer water during the deposition of the Seoguipo Formation. This, in turn, may have resulted in a reduced calcareous nannoplankton diversity dominated by cooler-water forms such as *C. pelagicus* as shown in the lower part of the Seoguipo Formation. A lowering of the sea level around the Cheju area in response to the early Pleistocene glaciation is also expected.

Conversely, when the Seoguipo Formation was located south of the oceanographic front in warmer water, assemblage diversity may have been higher, dominated by warmer-water forms such as *G. oceanica*. Since glacial and interglacial cycles have been the primary influence on oceanography of the Japan Sea, Korea Strait, and the vicinity of Cheju Island during the last 1.8 m.y., the changing paleoceanographic conditions of the Seoguipo Formation indicated by the nannofossil assemblages are primarily interpreted as an expression of global climatic changes.

The migration of the oceanographic front is related to the influence of local warm-water currents and global glaciation in the Pleistocene. As a function of these two factors the oceanographic front migrates southward or northward. When global glaciation set about, the cooler-water front was built first in the Oki Ridge, Ishikawa-Toyama area and migrated southwards to Cheju Island and the Okinawa Trough about 1.8 Ma (Figure 5). It retreated from the Okinawa Trough at 1.60-1.64 Ma (LAD of *C. macintyrei*), from Cheju Island at 0.94-1.02 Ma (reoccurrence of *G. oceanica*), and from the Oki Ridge and the Ishikawa-Toyama area of Japan at 0.85 Ma. The duration of the cooling phase is shortest in the Okinawa Trough and longest in the Japan Sea. Generally invasion of cooler water took place abruptly in comparison to the relatively slow retreating process. Influence of cooler water that migrated southward is well documented in the samples of Oki Ridge, Ishikawa-Toyama area, Niigata area, Seoguipo Formation and Okinawa Trough (Kobayashi, 1990 ; Muza, 1992 ; Ogasawara, 1996 ; Yi *et al, in press*). Considering the geographic location and present-day oceanography only the Niigata area provides an exceptional case, since a cooling phase in this area appeared later and disappeared earlier than expected for its geographic location. The duration of the cooling phase in the Niigata area is also different from that of the neighboring Ishikawa-Toyama area. Therefore, the influence of a warm-water current (*G. inflata* bed No. 2) in this area is considered to be stronger than global glaciation effect in the Pleistocene.

Regarding the cooling phase and cold-water influence in the Seoguipo Formation that lasted from ca. 1.8 Ma to 0.94-1.02 Ma, it would appear that the Korea Strait never closed during the first Quaternary glaciation. Hence, the cold-water current could expand through the Korea Strait into the Okinawa Trough (Yi *et al., in press*).

3). **Paleobathymetry.**—The depositional environment of the Seoguipo Formation was interpreted as a littoral zone of shallow sea based on the foraminifera (Kim, 1972), Mollusca (Yoon, 1988) and brachiopods such as *Coptothyris grayi* and *Terebratalia coreanica* that are indicative of a depth of about 50 m (Kim, 1984). Ostracod studies from the Seoguipo Formation enabled a finer subdivision of six biotopes deposited in a shallow sea ranging from bay, through near-shore, to offshore environments (Lee, 1990). An investigation of molluscan fossils suggests the Seoguipo Formation has been formed under the environment of bay to open sea (Kang, 1995).

Among the nannofossil assemblage, neritic species such as *Braarudosphaera bigelowii*, *Gephyrocapsa oceanica*, and *Syracosphaera* spp. occur consistently throughout the formation except for the upper part (Sample SGF 11), where

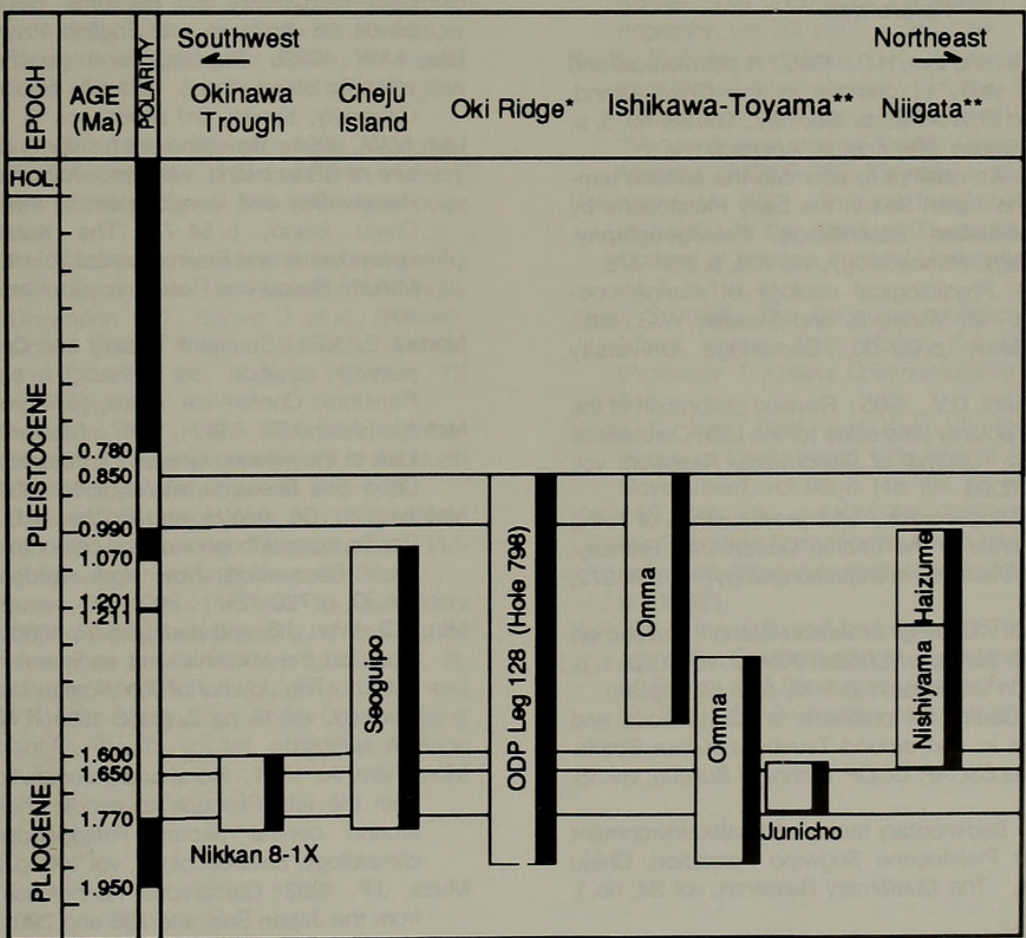

Figure 5. Correlation of Plio-Pleistocene cooling phases between the Okinawa Trough, Cheju Island, Oki Ridge, and Japan Sea (East Sea) borderland of Japan (Polarity : Cande and Kent, 1995 ; * : Muza, 1992 ; ** : Ogasawara, 1996).