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Paleoenvironmental Reconstruction from Calcareous Fossils

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=국문요약=

패류화석을 이용한 고환경 복원

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패류화석은 지구를 이루는 퇴적암 중 석회암을 이루고 있는 주요 구성원 중의 하나이다. 지난 20여년 간 지질학자 및 해양학자들은 주로 심해에 쌓여 있는 퇴적물 중의 미화석(microfossil)을 이용하여 과거의 기후 및 해양의 조건을 규명하기 위하여 많은 노력을 하여 왔다. 그 결과로서 지질학적 시대 중 중생대 이후로부터 신생대에 이르기까지 지구 전반에 영향을 주었던 고기후에 대한 많은 정보가 얻어졌다. 또한 일부 학자들에 의하여 천해에 서식하였던 여러 화석들의 생태와 지화학적 분석(geochemical analysis)을 통하여 지엽적인 고기후(paleoclimate) 및 고해양학적 (paleoceanographic) 이해도 증진되어 온 것이 사실이다.

천해에 서식하고 있는 석회질 골격(calcareous skeleton)을 만드는 생물종들은 주로 생화학적인 작용을 통하여 아라고나이트와 방해석이라는 탄산염 광물을 침전시킨다. 특히 이 중에서 아라고나이트라는 광물은 불안정하여 속성작용(퇴적물이 쌓인 후 거치는 물리, 화학적 작용)동안에 방해석으로 변하게 된다. 따라서 특이한 속성환경의 조건에 의해 아라고나이트로 보존되어 있는 패류를 제외하고는 주로 방해석으로 이루어진 화석의 분석을 통하여 고환경 복원을 위한 여러 정보를 얻을 수 있다. 이를 근거로 하여 분석 대상이 주로 된 것은 완족류나 방해석으로 이루어진 이매패류(e.g., 굴 등)이었다.

우리 나라에서는 최근에 이르러서야 패류 화석의 지화학적 분석을 통하여 고해양학적 연구가 수행되기 시작하였다. 신생대 제 3기 마이오세에 해당하는 포항 부근에서 발견되는 연체동물 화석들은 변질이 안된 상태로서 우리에게 매우 귀중한 고해양학적 정보를 제공한다. 과거에 생물이 자랐던 성장 온도는 산소 동위원소의 비를 측정하여 구할 수 있는데 그 결과에 의하면 해수의 온도가 현재보다 약간 높았음을 지시한다. 제주도 내의 서귀포 부근에서는 현재 천연기념물로 지정되어 있는 서귀포층내에서 많은 화석들이 산출되고 있다. 이 시대는 빙하기와 간빙기가 교호하던 시대로서, 분석 결과에 의하면 서귀포층이 쌓일 당시에 우리 나라는 빙하기의 영향을 받았던 것으로 생각된다.

INTRODUCTION

Global environmental change of the earth has been one of the interesting issues to scientists past tens of years. It is well understood that the surface condition of the earth, especially atmospheric conditions, can be easily manipulated by oceanographic changes. Recently, burning fossil fuels has increased in atmospheric pCO_2, which has caused a global warming. Even though many scientists has warned that global warming will threaten the fate of human activities, we simply do not understand thoroughly about the paleoclimatic and paleoceanographic conditions of the Earth, thus, it is quite hard to predict the environmental conditions of the Earth in the future. Throughout the geologic history, anormalously higher atmospheric pCO_2 content has been reported (e.g., Arthur *et al.*, 1985). Therefore, it is significantly important to understand paleoceanographic as well as paleoclimatic conditions, that is, paleoenvironmental conditions of the past to predict the global change of the Earth environment in the future.

In this respect, the stable isotopes of oxygen and carbon have been widely used to infer paleoceanographic conditions such as paleotemperature, paleoproductivity, paleosalinity, *etc.* (e.g., Woo *et al.*, 1992). Even though numerous studies (e.g., DSDP results) have been reported based on the oxygen isotopic compositions from microfossils such as planktonic and benthic foraminifers (e.g., Douglas and Savin, 1975; Savin *et al.*, 1985; *etc.*), relatively few studies have been carried using macrofossils (e.g., Brand, 1986; Popp *et al.*, 1986). This was mainly because macrofossils were mostly deposited in shallow marine environments and most of them were composed of diagenetically unstable aragonite and high Mg-calcite, thus, these fossils were likely to be altered diagenetically. Thus, we have to have a fairly good control in handling the fossil specimen for the right to determination of the preservational state of calcareous fossils.

It has been widely accepted that Recent marine mollusks secret their shells in isotopic equilibrium with ambient seawater, since Epstein *et al.* (1953) found out the excellent agreement between temperature and isotopic fractionation of carbonate minerals in mollusks from experiment. However, Woo *et al.* (1993) recently suggested that some extinct mollusks such as Cretaceous rudists may have had a vital effect, thus, their oxygen isotopic ratio may not represent the oxygen isotopic equilibrium.

Paleoceanographic studies in Korea have been relatively few. Woo (1989) analyzed the stable isotopic compositions of cultured pearls, and stated that the oxygen isotopic composition of the pearl layer reflects the growth temperature during summer. Paik *et al.* (1992) analyzed the oxygen isotopic contents of the mollusks from the Songjeon Formation (Eoil Basin), and reported the anomalously high temperature range for shallow seawater. Woo *et al.* (1994, 1995a) reported paleoceanographic result based on the oxygen isotopic compositions of the ostracodes and mollusk fossils from the Chunbuk Conglomerate near Pohang area. Recently, Woo *et al.* (1995b) investigated the paleoceanographic at which the calcareous fossils of the Seoguipo Formation lived (Cheju Island).

The objectives of this paper are to summarize how to use calcareous fossils to delineate paleoenvironmental reconstruction and to report the paleoceanographic results based on the geochemical analyses of the Miocene and Pleistocene calcareous fossils in Korea.

STATE OF PRESERVATION

1. Mineralogy

Recent carbonate skeletons make their shells by secreting calcium carbonate minerals such as aragonite, high Mg-calcite (HMC; > 4 mole% $MgCO_3$), and low Mg-calcite (LMC; < 4 mole% $MgCO_3$). Aragonitic and calcite are so called "polymorphs" which means that both minerals have the same chemical composition($CaCO_3$), but different crystal structure. Carbonate mineralogy of an organism is mainly dependent upon the type of a taxon. Certain types of an organism can secrete only one type of mineral (Table 1), for example, an echinoid is always composed of HMC. Some

Table 1. Original carbonate mineralogy of the major groups of carbonate-secreting organ (After Scholle, 1978).

Taxon	Aragonite	Calcite mol% $MgCO_3$ 0	10	20	30	Aragonite + Calcite
Calcareous algae						
Red algae	X		X	----------	X	
Green algae	X					
Coccoliths		X				
Foraminiferas						
Benthonic	0	X	----------	X		
Planktonic	0					
Sponges		0		X	---------- X	
Coelenterates						
Stromatoporoid*	X	X?				
Milleporoid	X					
Rugose*		X				
Tabulate*		X				
Scleractinian	X					
Alcyonarian	0		X	----------	X	
Bryozoans		0	X	----------	X	0
Brachiopods	0	X	X			
Molluscs						
Chitons	X					
Bivalves	X	X	--------- X			X
Gastropods	X	X	--------- X			X
Scaphopods	X					
Cephalopods	X					
Belemnoids*		X				
Annelids (serpulids)		X	X	----------	X	X
Arthropods						
Decapoda			X	----------	X	
Ostracods		X	--------- X			
Barnacles		X	--------- X			
Trilobites*		X				
Echinoderms			X	----------	X	

X = Common 0 = Rare *Not based on modern forms

organisms can secrete their shells with more than one mineral, for example, some mollusks are composed of both aragonite and LMC. It appears that the mineralogy of skeletons are controlled by physiological effect of an organism, not by the physicochemical conditions of the aquatic environment in which organism dwells. Since the carbonate minerals are very susceptible to post-depositional alteration, it is very important to investigate the present mineralogy of the fossils and to determine the state of preservation before using the skeletons for paleoenvironmental reconstruction. Generally, aragonite and HMC can be easily transformed into LMC upon the attack by meteoric water. Thus, the skeletons, composed of LMC, are relatively more stable than those of aragonite or HMC. This means that the LMC skeletons can be a good candidate for paleoceanographic investigation. However, if aragonitic and HMC skeletons are preserved after burial, they could also be used for geological interpretation.

2. Microstructure

Calcareous shells, regardless of the original mineralogy, exhibit their own spatial arrangement of carbonate minerals, which is called as a microstructure (or ultrastructure). Common types of microstructure are homogeneous prismatic, granular, normal prismatic, foliated, nacreous, single crystal, crossed-lamellar, complex crossed-lamellar, spherulitic-fascicular microstructures. Different taxons show their own characteristic microstructure, however, it appears that the same microstructure is shared by the same family level. Since all the calcareous shells own their original microstructure, it is expected to observe the same microstructure from the fossil specimen unless they have been altered diagenetically. This means that disrupted microstructure can be detected through careful textural examination of fossils via petrographic microscope. Only the shells which retain their original microstructure as well as original mineralogy can be used for paleoenvironmental reconstruction.

STABLE ISOTOPES

Stable isotopes of carbon (^{13}C) and oxygen (^{18}O) have been widely used for the interpretation of paleoenvironmental reconstruction past a few decades. Since the absolute abundance of a minor isotope (*i.e.*, ^{18}O concentration) or the absolute value of an isotopic ratio ($^{18}O/^{16}O$) is difficult to determine with sufficient accuracy for geological applications, the analysis has been made to determine the difference in absolute isotopic ratios between two substances. It has been widely accepted to use international standards (e.g., SMOW, PDB, *etc.*) for this purpose. To report isotopic values, the common notation is called the "δ-value" and is defined as:

$$\delta(x) = \frac{R_x - R_{std}}{R_{std}} \times 10^3$$

where R_x is the isotopic ratio of the sample ($^{18}O/^{16}O$ and $^{13}C/^{12}C$) and Rstd is the corresponding ratio of a standard. The δ-value is the relative difference in the isotopic ratio between the sample and the standard, in parts per thousand or permil (‰).

Carbon isotopic value has been generally used to trace the source of carbon from which carbonate shell was incorporated. Also, paleoproductivity as well as pCO_2 levels of atmosphere and ocean in the past could be inferred.

Oxygen isotopes is a very useful parameter to determine the paleotemperature at which calcareous shells formed, that is, the organisms with calcareous shells lived. Urey (1947) predicted that the temperature of $CaCO_3$ precipitation would lead to measurable variations in the $^{18}O/^{16}O$ ratio of the calcium carbonate. Epstein *et al.* (1953) suggested that mollusks precipitate $CaCO_3$ at oxygen isotopic equilibrium with ambient waters. Lowenstam (1961) reported that brachiopods are in isotopic equilibrium with the waters from which they were collected. It is usually accepted that belemnites were precipitated at isotopic equilibrium (Stevens and Clayton, 1971). Planktonic foraminifers secrete their tests at, or close to, isotopic equilibrium, although there is evidence for significant departures in some cases (Shackleton, 1974). Several important calcareous marine organisms exhibit large deviations form predicted oxygen isotopic equilibrium. The most thoroughly documented examples are the echinoderms (Weber, 1968) and the corals (Weber and Woodhead, 1972). Red algae also showed marked deviations from equilibrium (Keith and Weber, 1965). Some benthic foraminifers show departures from equilibrium (Shackleton, 1973; Woodruff *et al.*, 1980). Coccolithophorids grown in culture exhibit distinct nonequilibrium fractionations (Dudley *et al.*, 1980). Thus, among calcareous shells to be analyzed, it is required to select the specimen which secreted the shell in oxygen isotopic equilibrium for paleoenvironmental investigation.

Another consideration to make before interpreting oxygen isotopic data is post-depositional diagenetic effect on shells. It is previously mentioned that diagenetic stabilization of carbonate constituents involved mineral transformation and textural change. Also, diagenetic processes can significantly modify the isotopic signature of calcareous shells. Generally, oxygen isotopic composition tends to be depleted during diagenesis (Fig. 1).

If we are to understand the paleotemperature

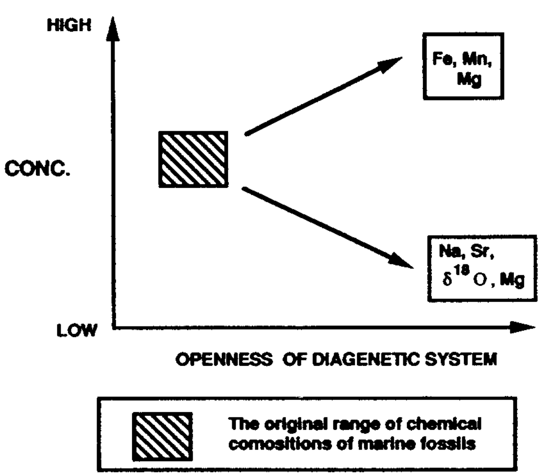

Fig. 1. Evolutionary trend of Sr, $\delta^{18}O$, Na, Mg, Fe, and Mn compositions of mollusk fossils during diagenetic alteration. Mg can either increase or decrease depending upon the original mineralogy.

variations from the fossils, it is necessary to know the oxygen isotopic composition of the ambient water in which organisms lived. It is because the $\delta^{18}O$ composition of a mineral depends upon the $\delta^{18}O$ composition of the ambient water and the temperature of growth. The oxygen isotopic composition of the present seawater is close to 0‰ (relative to SMOW), thus, it is fairly straightforward to calculate the growth temperature range for the Recent organisms. However, it is generally accepted that the oxygen isotopic composition of paleo-seawater has not been the same as that of the present seawater due to glaciation as well as other complicated factors. Therefore, it is always required to set the boundary condition to assume the oxygen isotopic composition of paleo-seawater.

TRACE AND MINOR ELEMENTS

The chemical composition of calcareous shells is also governed by the chemical composition of ambient water in which the organisms live and the partition coefficient (=distribution coefficient) for each chemical species. The equilibrium distribution of a trace and minor element between a carbonate mineral and water is described by the following equation:

$$(M_t/M_c)_s = K(M_t/M_c)_w$$

where M_t and M_c are the molar concentrations of a trace and minor element and major element (Ca for calcareous shell). K is the partition coefficient, s is the carbonate mineral, and w is ambient water. When the partition coefficient for a particular element is greater than 1 (Mn and Fe for example), the element is preferentially concentrated in the solid. When the partition coefficient is less than 1 (Sr and Mg), the element is preferentially concentrated in the solution.

Many workers have indicated that some phyla precipitate skeletons in rough inorganic equilibrium with the ambient water, however, others do not (Masuda and Hirano, 1980; Milliman, 1973). This biogenic fractionation, mostly due to the metabolitic effects of organisms, may lead to reduction, and in some cases enhancement, of element concentrations in the $CaCO_3$. The best examples of this biogenic discrimination are known for Mg and Sr. This intracellular discrimination against Mg enables precipitation of LMC shells in the marine environment, although inorganically only HMC should be the equilibrium phase. A biogenic discrimination against Sr is particularly significant in the case of mollusks (Veizer, 1983).

The present seawater is characterized by relatively high contents of Sr and Mg and low concentrations of Mn and Fe, compared to freshwater. Thus, marine organisms usually show high Na and Sr and low Fe and Mn compositions with a few exceptions. This means that Na and Sr contents tend to be depleted and Mn and Fe contents are enriched after diagenetic alteration by freshwater (Fig. 1). Thus, trace and minor elemental compositions can provide a rough idea to determine the preservational state of the fossils to be analyzed.

PALEOENVIRONMENTAL RECONSTRUCTION

1. Chunbuk Formation near Pohang Area

The Pohang Basin, the largest sedimentary basin along the southeastern coast of the Korean Peninsula, includes the Miocene sedimentary rocks(about 15 million years BP) which are up to 10 km thick (Chough, 1983). The sedimentary rocks are composed of two units: the lower unit, mainly derived by mass flow deposits forming Gilbert-type fan delta, alluvial fan, and steep-faced slope systems (Chough *et al.,* 1993), and the upper unit, composed of hemipelagic to pelagic sediments. The stratigraphic division of the sequence is conventionally divided into several formations, which is still debatable (Um *et al.,* 1964; Kim, 1965; Yoon, 1975; Yun, 1985; Choe and Chough, 1988). The sampling localities (Seocheongri, Songhacdong, Danguri, Gyeongju, and Mulcheonri areas) consist of gravelstones interbedded with massive sandstones (Fig. 2). The Seocheongri section shows gravelstones interbedded with massive fine to medium sandstones. Within the sandstone units, carbonate concretions are present and numerous fossils such as pectenids, oysters, gastropods, and other bivalves can be observed. This section was suggested to have been deposited in the topset of the fan delta system (Chough *et al.,* 1993). The Songhacdong section is characterized by thick crudely stratified gravelstone with a few intercalations of massive fine to pebbly sandstones (Huh, 1991). The gravelstone unit is occasionally cemented, and this cemented unit contains oysters, bivalves, and corals as well as ostracodes in the matrix. This section appears to have been deposited at the bottomset of the fan delta system (Chough *et al.,* 1993). Despite the fact that this section was deposited in fairly deep setting (ca 500 m deep?), the fossil assemblage including shallow marine ostracodes, corals and oyster fragments indicates that the shells were transported from the shallow marine environment nearby. The Mulcheonri and Gyeongju sections are mostly composed of massive fine to coarse sandstones with a few beds of mudstones and gravelstones. Carbonate concretions contain numerous fossils such as bivalves and gastropods. Detailed sedimentological information is lacking in these sections, however, the fossil assemblage (ostracodes, bivalves including oysters, and gastropods) suggests that these sections were probably deposited in shallow marine environment. The Danguri section is characterized by massive and crudely stratified breccias, massive and stratified conglomerates, and massive sandstones. This section belongs to the topset of the Doumsan fan delta system (Chough *et al.,* 1993), and contains carbonate concretions. Mollusks fossils are present within the concretions.

Williams (1977) suggested the relationship between salinity and $\delta^{18}O$ of surface seawater used

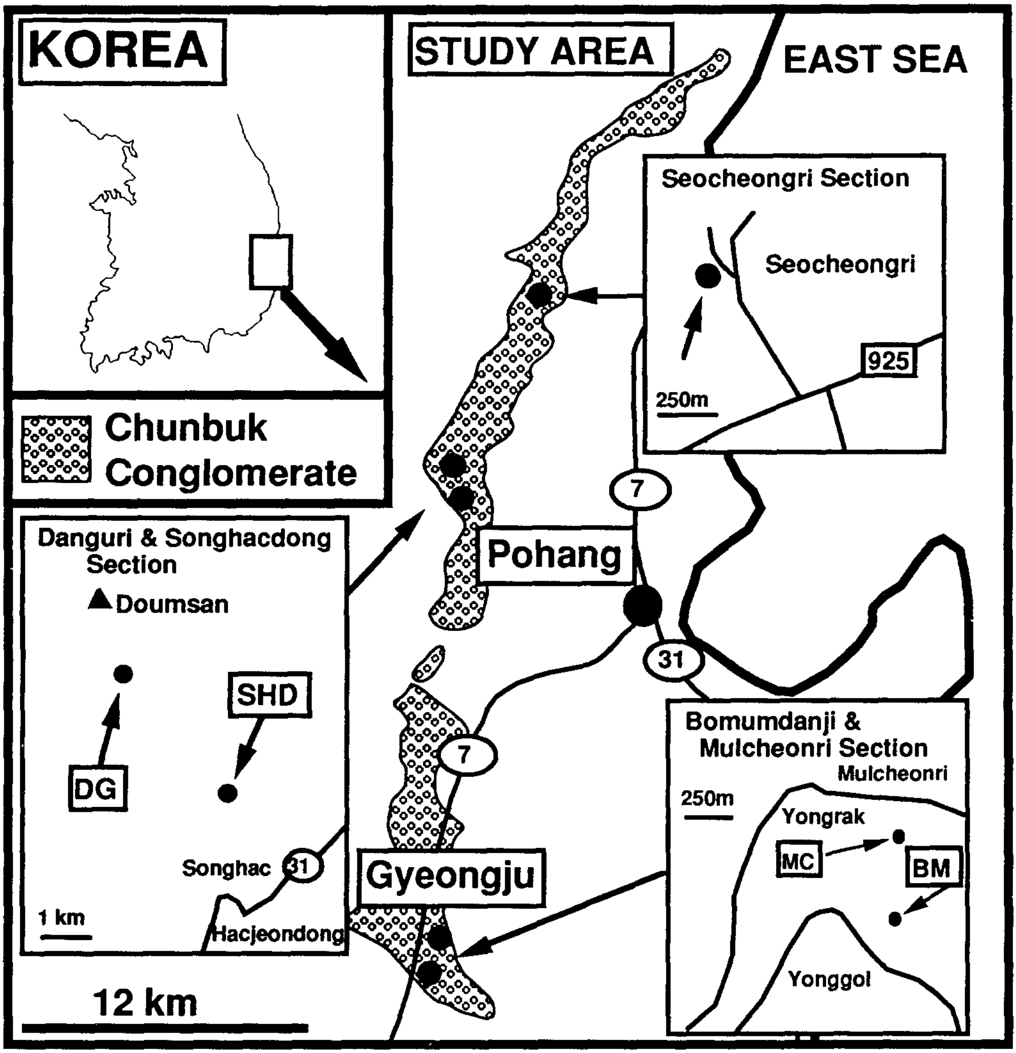

Fig. 2. Geographic locations of the sampling localities and the distribution map showing the Chunbuk Formation near Pohang area. MC=Mulcheonri, SHD=Songhacdong, DG=Danguri, BM=Gyeongju Bomundanji, and SC=Seocheongri.

in calculations of equilibrium $\delta^{18}O$ values of marine carbonates. $\delta^{18}O$ of coeval seawater (vs. SMOW) was calculated by the following equation:

$\delta^{18}O_{water}$ = 0.553 x salinity − 19.35. Since averaged annual salinity value near Pohang area is 34.3‰ (Fisheries Research and Development Agency, 1986), $\delta^{18}O$ value of surface seawater during the Middle Miocene would have been −0.38‰(vs. SMOW) assuming that the paleosalinity of surface seawater during the Middle Miocene was the same as that of the present-day seawater. The analyzed $\delta^{18}O$ values are well within the predicted range of equilibrium precipitates during the Late Miocene time (−2.87 to −0.48‰ PDB; Savin *et al.*, 1985). Also similar results have been reported from the ostracodes recently (Woo *et al.*, 1994). Assuming the $\delta^{18}O$ composition of coeval seawater to be ca -0.38‰ (vs. SMOW) and using the calcite-water and aragonite-water fractionation values according to temperature (Epstein *et al.*, 1953; Grossman and Ku, 1986), $\delta^{18}O$ values of the gastropods and aragonitic bivalves from Gyeongju (1.8 to -0.5‰ and -0.8 to 0.1‰ indicate that their corresponding paleotemperature ranges from ca 21 to 27℃ (average=24℃) and 19 to 23℃ (average=21℃), respectively (Fig. 3). $\delta^{18}O$ values of the calcitic bivalves (pectenids) and aragonitic bivalves from Seocheongri area range from -2.5 to 1.3‰ and from -2.4 to 1.1‰, and their corresponding paleotemperature ranges from ca 10 to 26℃ (average=19℃) and 14 to 30℃ (average=23℃), respectively. $\delta^{18}O$ value of the aragonitic gastropod from Mulcheonri area is -1.8‰ and their corresponding paleotemperature was ca 27℃. $\delta^{18}O$ values of the aragonitic mollusks (mixture of bivalves and gastropods) from Songhacdong area range from -0.9 to -0.7‰, and their corresponding paleotemperature ranges from ca 23 to 24℃ (average=23℃). The paleotemperatures of the Seocheongri, Songhacdong and Mulcheonri areas are similar to those based on the oxygen isotopic compositions of the ostracodes (Woo *et al.*, 1994). $\delta^{18}O$ values of the aragonitic bivalves from Danguri area range from -2.4 to -1.1‰, and their corresponding paleotemperature ranges from ca 25 to 31℃ (average=29℃). The higher temperature values of the Dang ri area may reflect different hydrograhic conditions, and these data are consistent with the other paleoceanographic information from ostracodes (Huh, 1994).

From the direct measurement of shallow seawater temperature to the water depth of ca 30 m (Fisheries Research Development Agency, 1986), the warmest temperature range of the year (August and October) is ca 13 to 20℃ with average values of 16℃, 14℃, and 13℃. These data suggest that the paleotemperatures of the shallow seawater of the Pohang Basin may have been even higher than the warmest present-day shallow seawater temperature near Pohang area.

2. Seoguipo Formation in Cheju Island

The Seoguipo Formation is located in the

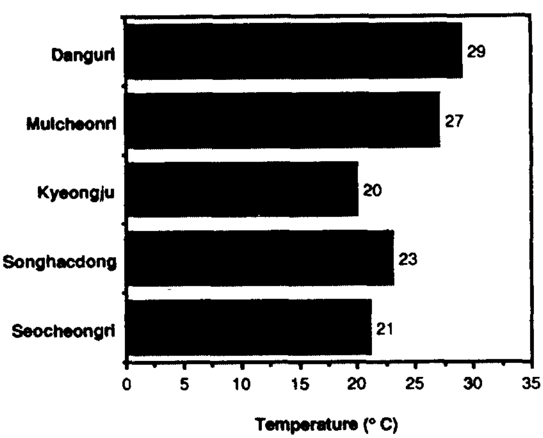

Fig. 3. Paleotemperatures calculated from oxygen isotopic compositions of the Middle Miocene well preserved mollusk fossils of the Chunbuk Formation according to the sampling localities near Pohang area.

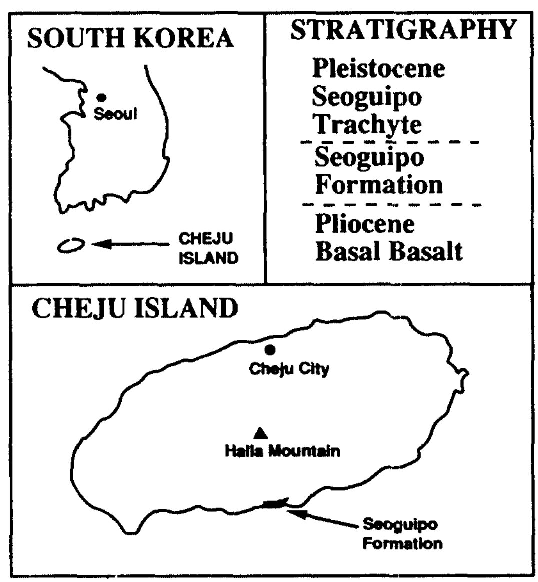

Fig. 4. Geographic location of the Seoguipo Formation in Cheju Island.

southern part of the Cheju Island, which is in the Korean Strait to the south of the Korean peninsula (Fig. 4). The Cheju Island consists of voluminous basalt and minor hawaiite and trachyte, forming a continuous series of alkali basalt-trachyte association, with some sedimentary rocks of late Neogene to Pleistocene (Won, 1976). The geologic history of the Cheju Island has been widely investigated by many geologists (Kim, 1969, 1972; Yoon, 1970; Won, 1975; Lee, 1982, Paik and Lee, 1984, 1986; Sohn and Chough, 1989; Yoon and Chough, 1990; Lee *et al.*, 1994; Lee *et al.*, 1994). The southern part of the Cheju Island is mostly composed of alkaline volcanic rock series of lava, basalt, andesite, trachyte, and trachytic andesite. The ages of these volcanic rocks range 0.9 Ma to 0.03 Ma by K-Ar radiometric datings (Lee *et al.*, 1994). The island was initially emerged by successive central eruptions during the late Pliocene to early Pleistocene, and the final eruptions were recorded in 1002 and 1007 A.D. (Won, 1976; Lee, 1982).

The Seoguipo Formation is composed of about 60 m-thick siliciclastic, bioclastic, and volcaniclastic sequence which is underlain by Pliocene basal basalt and overlain by Pleistocene trachyte. The Formation consists of shell-rich, light-gray, fine to coarse sandstones, pebbly sandstones, sandy mudstones, and agglomerates, showing a fining-upward trend. Various sedimentary structures such as wavy, flaser, and lenticular beddings, planar cross-beddings, ripple marks, and thin laminations, can be observed. Main components of coarse clasts in sandstones are basalt fragments and shell debris, and other finer components are quartz, feldspar, olivine, and pyroxene (Yoon and Chough, 1990). The formation is composed of two parts: 1) the lower part of the formation consists of alternated fossiliferous strata and non-fossiliferous siliciclastic strata, which are subdivided into eight fossiliferous units and five non-fossiliferous units (Lee *et al.*, 1994); and 2) the upper part of the formation comprises volcanic ash and agglomerate beds. The lower I, II, III units in the lower part represent storm deposits accumulated on nearshore banks or spits and subsequently reworked by tidal currents and waves above the fair weather wave base. The unit IV of thick bioturbated sandstone is a relict sediment winnowed by strong waves and currents on nearshore sand bank, foreshore, and shoreface. The middle V, VI units are composed of fine-grained sediments offshore of bank and bay below the fairweather wave base and in shelf. The upper VII, VIII, IX, X, XI, XII, XIII units are interpreted to be nearshore storm surge deposits, and shoreface tidal sand and mud deposits above the fair weather wave base (Lee *et al.*, 1994). The overall sedimentary facies show a deepening-upward trend up to the unit V and a consequent shallowing-upward trend in upper units. Yoon (1995) interpreted that two trends are associated with a relative sea-level rise and a successive sea-level fall, respectively. The lower unit includes six fossiliferous strata, which contain various bivalves including pectenids, gastropods, scaphopods, brachiopods, echinoids, barnacles, corals, bryozoans, fish teeth, and numerous other microfossils such as foraminifers, ostracodes, nannofossils, *etc.*.

The geologic age of the formation is still controversial, and has been suggested to be late Pliocene based on mollusk fauna (Yoon, 1988), Pliocene based on planktonic and benthic foraminifers (Kim, 1972), Pleistocene based on ostracodes (Lee, 1990), and Plio-Pleistocene based on nannofossils (You *et al.*, 1986). From the paleomagnetic data, the Gauss normal epoch (late Pliocene) was suggested by Min *et al.* (1986), and the Brunhes normal epoch (middle Pleistocene) was suggested by Lee *et al.* (1987). Recently, Lee *et al.* (1994) suggested that the Seoguipo Formation was deposited during the late Pleistocene transgressive period of 0.73 Ma to 0.41 Ma.

Emiliani (1955, 1966) has shown that isotopic variations in foraminiferal tests undergo quasi-periodic changes corresponding to glacial and interglacial periods, and that the changes were due entirely to temperature changes. He estimated that ca 70% of the maximum isotopic change in $\delta^{18}O$ of calcite was due to changes in temperature (*i.e.*, 5-6 ℃), the other 30% resulting from changes in the isotopic composition of ocean water (to +0.5‰ during maximum glaciations). However, Dansgaard and Tauber (1969) argued that the present isotopic composition of precipitation in the world, and the measured isotopic composition of glacial-age precipitation in ice cores, point to much lower ^{18}O concentrations in continental and polar ice sheets. Thus, they estimated that the isotopic composition of seawater during maximum glaciation was +1.2‰ accounting for ca 70% of the observed isotopic change in foraminiferal carbonate at that time.

Carbon isotopic compositions of aragonitic bivalves, a gastropod, brachiopods, and pectenids of the Seoguipo Formation range from +0.5 to +2.2‰ (Fig. 5), which reflects marine carbonate carbon values (Anderson and Arthur, 1983). Oxygen isotopic contents are from +0.6 to +2.1‰. This is a reasonable range for shallow water carbonates deposited in shallow temperate region (Anderson and Arthur, 1983). There is no significant discrepancy of the $\delta^{18}O$ values between aragonitic

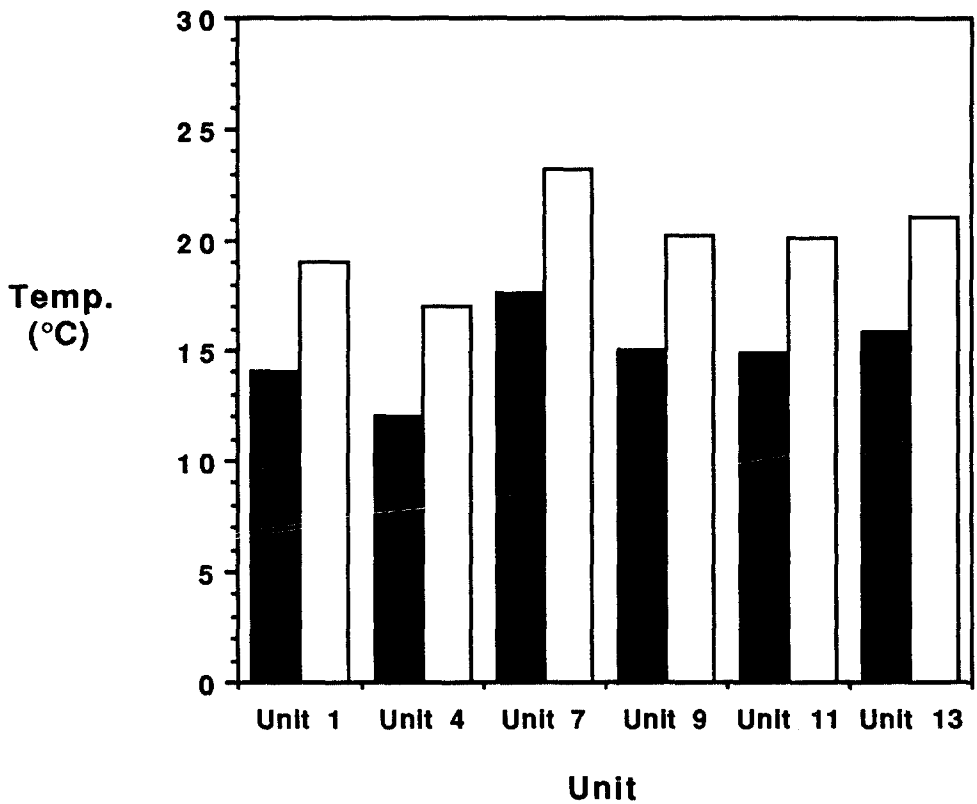

Fig. 5. Averaged paleotemperatures calculated from oxygen isotopic compositions of the well preserved mollusk fossils according to the sampling units of the Seoguipo Formation in the study area. Open bars represent the paleotemperatures when $\delta^{18}O$seawater is 0‰ (SMOW), and filled bars represent the paleotemperatures when $\delta^{18}O$seawater is +1.2‰ (SMOW).

and calcitic shells. All the units show similar oxygen isotopic ranges except for the pectenids in Unit 4 which show relatively higher values (Fig. 5). These higher values of Unit 4 may indicate the deeper water conditions (thus, lower temperature) where the pectenids lived. This result coincides well with the depositional interpretation by Yoon (1995). Possible diagenetic alteration by meteoric water can be easily excluded by the state of textural preservation, high Na and Sr contents and relatively low Mn and Fe compositions as well as heavy oxygen isotopic contents of the shells examined in this study.

Figure 5 shows the possible range of the paleotemperature calculated from the oxygen isotopic compositions at which the fossils of the Seoguipo Formation may have lived. Dashed areas are shown by the assumption that the oxygen isotopic composition of the contemporaneous seawater could vary from maximum glacial condition (+1.2‰ SMOW) to present-day interglacial condition (0‰ SMOW). If we assume that the Seoguipo Formation was deposited during Pleistocene epoch (Lee *et al.*, 1994) when glaciers were present around polar regions, the actual oxygen isotopic composition of seawater during the deposition of the Seoguipo Formation should have been between 0 to +1.2‰ (SMOW). If the $\delta^{18}O$ value of ambient seawater was +1.2‰ the paleotemperature of the calcitic shells ranges from 12.9 to 21.6℃ with an average of 18.6 and that of the aragonitic shells ranges from 19.5 to 26.5℃ with an average of 23.2℃. Also, if the $\delta^{18}O$ value of ambient seawater was the same as that of the present-day seawater (*i.e.*, 0‰, the paleotemperature of the calcitic shells ranges from 8.5 to 16.5℃ with an average of 13.7℃ and that of the aragonitic shells ranges from 13.9 to 21.3℃ with an average of 17.6℃. The present-day temperature of shallow seawater near Cheju Island ranges from 20 - 27℃ during summer (Fisheries Research and Development Agency, 1986), and it is well known that most of the shell growth occur during the warm period of the year. Therefore, this result clearly indicate that, during the deposition of the Seoguipo Formation, the paleotemperature of the shallow seawater was lower than that of the present seawater, or $\delta^{18}O$ of composition of paleoseawater was heavier due to the increase in ice volume. This means that the Seoguipo Formation was deposited probably during the glacial period.

From the Unit 1 to Unit 13, the overall temperature trend does not vary much. Assuming that the oxygen isotopic composition of paleo-seawater is 0‰ (+1.2‰ (SMOW), fossils of the Unit 1, Unit 9, Unit 11, and Unit 13 shows the paleo-temperature range of 14 - 17℃ (19 - 21℃). Unit 4 shows a little lower paleotemperature of ca 13℃ (18 ℃), and Unit 7 shows higher paleotemperature of ca 18℃ (24℃). As mentioned above, the lower temperature of Unit 4 probably reflects the different paleoecologic conditions of large pectenids (Table 1). Thus, the paleotemperature change during the deposition of the Seoguipo Formation may have been more or less uniform except the Unit 7.

SUMMARY

The applicability of stable isotopes is summarized. Oxygen isotopic analysis of calcareous fossil in sedimentary rocks has been used as a powerful tool to reconstruct a paleoenvironment. The $\delta^{18}O$ values of all the well preserved mollusks and their corresponding paleotemperature suggest that the paleotemperature of the Middle Miocene shallow seawater in Pohang Basin was higher than the present-day annual shallow seawater temperature (ca 11 to 20℃) near Pohang area. Also, the oxygen isotopic compositions of the calcareous fossils from the Seoguipo Formation indicate that the formation was deposited during glacial period.

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