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Lower Ordovician Sponge Bioherms in the Makkol Formation, Taebaeksan Basin, Mideast Korea

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KEYWORDS: SPONGE BIOHERMS – *ARCHAEOSCYPHIA* – *CALATHIUM* – ORDOVICIAN - KOREA

Summary

Isolated sponge bioherms are documented from the Lower Ordovician Makkol Formation of the Taeback Group in the Taebaeksan Basin, mideast Korea. They are formed by an association of a lithistid sponge *Archaeoscyphia*, a receptaculid *Calathium* and stromatolitic algae, and share many features with the Lower Ordovician buildups known elsewhere. These bioherms were established in an incised bottom and reached up to about 1 m in height. As the bioherms grew upward, they were more severely affected by intense wave action and frequent storms, which eventually perished the bioherms. The occurrence of *Archaeoscyphia-Calathium* association suggests a close biogeographic link between Korea and North China, supporting the paleogeographic model that the Taebaeksan Basin was connected through contiguous shallow waters to North China in the early Paleozoic.

1 INTRODUCTION

Sponges are one of the most significant reef-building organisms in the geologic records, and in particular the only reef-building organisms in the Early Ordovician (Rigby, 1971, 1987). The Early Ordovician reef-building sponges commonly occur in skeletal biohermal facies, characterized mostly by an association of *Archaeoscyphia* and *Calathium* (Church, 1974; Rigby and Toomey, 1978; Pratt and James, 1982; Webby, 1984; Cañas and Carrera, 1993; Zhu et al., 1993; Rigby et al., 1995). Carrera and Rigby (1999) have noted that the *Archaeoscyphia* and *Calathium* association was a worldwide phenomenon in the Early Ordovician with a restricted distribution in tropical or subtropical regions.

The Early Ordovician sponges are found in isolated mound-like skeletal bioherms in the Makkol Formation (Arenigian), Taeback Group, Taebaeksan Basin, mideast Korea. These bioherms mainly comprise a lithistid sponge *Archaeoscyphia*, a receptaculid *Calathium*, and stromatolitic algae. This paper presents a detailed analysis of these bioherms and associated sedimentary facies, so as to provide a better information on paleoecological conditions for the growth of lithistid sponge bioherms in the Early Ordovician and their paleogeography.

2 GEOLOGICAL SETTING AND STRATIGRAPHY

The Taebaeksan Basin occupies the mid-eastern part of the Korean peninsula and comprises mainly the lower Paleozoic Choson Supergroup and the upper Paleozoic Pyongan Supergroup (Cheong, 1969; Choi, 1998) (Fig. 1). The Choson Supergroup rests unconformably on the Precambrian granitic gneiss and metasedimentary rocks and is overlain unconformably by the Pyongan Supergroup (Fig. 1).

The lower Paleozoic sediments (Choson Supergroup) consist predominantly of carbonates and subordinately of sandstones and shales. In the Cambrian the Taebaeksan Basin was a shallow marine siliciclastic-carbonate system with progressively deeper water to the west (Chough et al., 2000). In the Ordovician, the basin was transformed to a low-relief carbonate platform, spotted with shoals, lagoons, and tidal flats (Choi et al., 2001). Marine sedimentation ceased in the Late Ordovician and the basin was emergent during the mid-Paleozoic until marine transgression resumed during the Late Carboniferous (Chough et al., 2000).

The Makkol Formation consists of a thick sequence of carbonate rocks and yields trilobites, gastropods, and cephalopods of Early to Middle Ordovician age (Kobayashi, 1966; Paik, 1987; Choi, 1998; Woo, 1999; Yun, 1999; Kwon, 2000) (Table 1). The formation is subdivided into three members (Fig. 2). The lower member (about 60 m thick) consists mainly of limestone-shale couplet, bioturbated wackestone to packstone, grainstone, pebble-grade limestone conglomerate, and sponge bioherm facies. The sponge bioherms occur in the middle and upper parts of the lower member (Fig. 2). The succeeding middle member consists of about 60-m-thick bioturbated limestone and massive dolostone facies. The upper member (about 100 m thick) contains bioturbated limestone, massive grainstone, grainstone-mudstone couplet, massive dolostone, and pebble-grade limestone conglomerate facies, characterized by stromatolitic lime-mudstone and breccia facies. A detailed description of the sponge bioherms was made at a well-exposed outcrop in the Sukgaejae section (Fig. 1).

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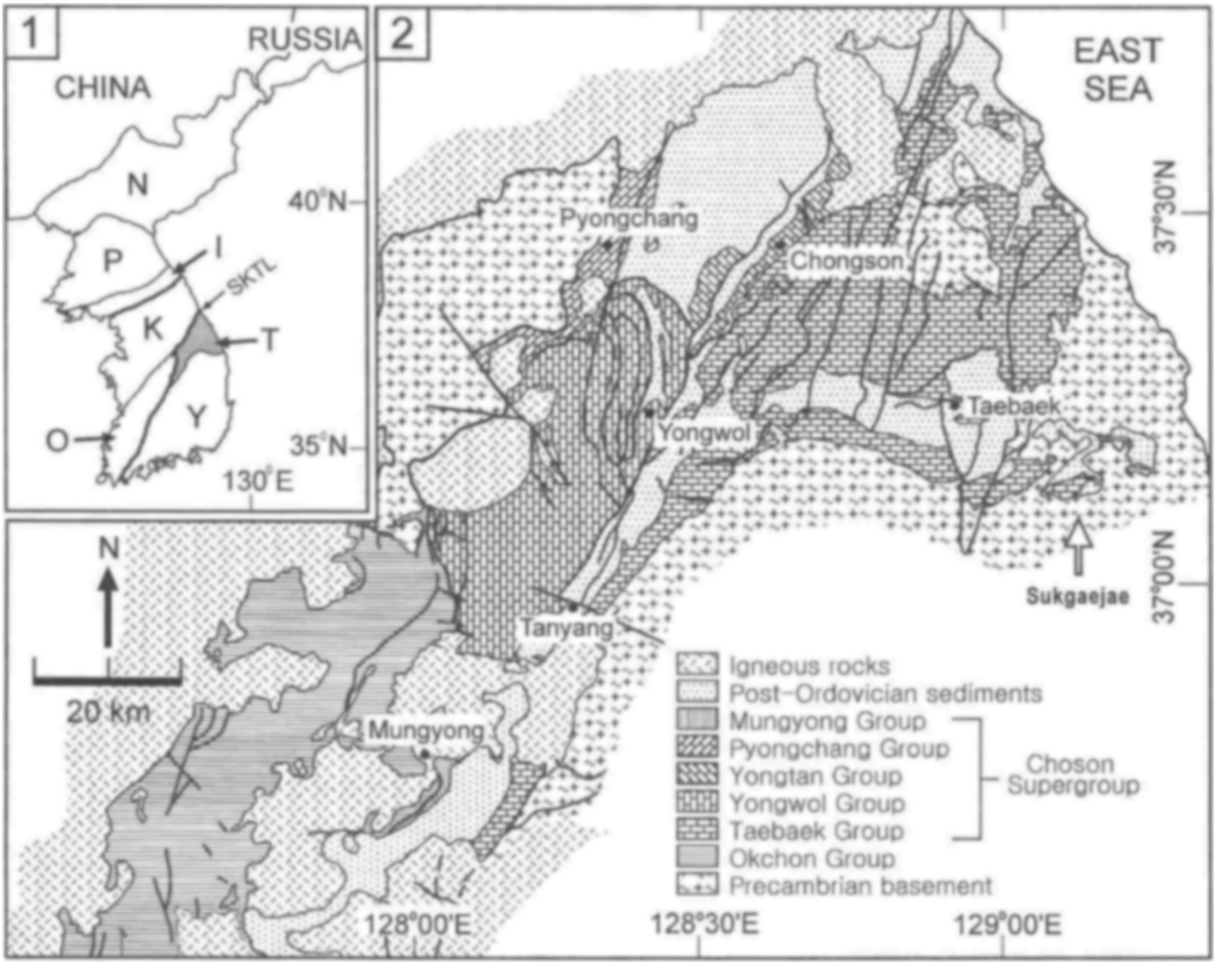


Fig. 1. Location map. (1) Tectonic division of the Korean peninsula, showing the location of the Taebaeksan Basin. (I, Imjingang Belt; K, Kyonggi Massif; N, Nangrim Massif; O, Okchon Belt; P, Pyongnam Basin; Q-D, Qinling-Dabie Belt; S, Sulu Belt; T, Taekbaeksan Basin; Y, Yongnam Massif; SKTL, South Korean Tectonic Line). (2) Simplified map of the Taekbaeksan Basin (T in Fig. 1.1). The open arrow to the right indicates the location of the measured section.

3 SEDIMENTARY FACIES

The sedimentary sequence in the upper part of the lower member of the Makkol Formation consists mainly of bioturbated wackestone/packstone (*W/Pb*), limestone-shale couplet (*L-S*), grainstone (*G*), pebble-grade limestone conglomerate (*PC*), and sponge bioherm (*SB*) facies. The sponge bioherms typically occur in an incised channel bottom of grainstone or pebble-grade limestone conglomerate, overlain by bioturbated wackestone to packstone or limestone-shale couplet (Fig. 3).

3.1 Facies W/Pb: Bioturbated Wackestone/Packstone

This facies consists mainly of wackestone and packstone, and subordinately of grainstone and pebble-grade limestone conglomerate. It is characterized by mottled texture, resulting from vertical and subhorizontal burrowing and selective dolomitization of burrows (Fig. 3). This facies commonly shows burrow-mottles of ichnofacies index-3 or index-4 (Droser and Bottjer, 1986). Bioclastic fragments of trilobites, echinoderms, and gastropods are commonly present. Each facies unit is 30 cm to more than 1 m thick. Some facies units contain hummocky cross-stratification.

This facies represents shallow subtidal deposits (e.g., Rubin and Friedman, 1977). Abundant occurrence of vertical burrows indicates intertidal to shallow subtidal deposition (Rhoads, 1967; Paik, 1987; Woo, 1999). The common presence of bioclasts such as trilobites, echinoderms, and gastropods also supports deposition in shallow subtidal zones (Heckel, 1972; Paik, 1987).

3.2 Facies L-S: Limestone-Shale Couplet

This facies consists of centimeter-thick alternations of crudely laminated, bluish gray limestone layer and thin-bedded or anastomosing, dark gray argillaceous layer (Fig. 3). The limestone layers vary in thickness from less than 1 cm to a few centimeters, whereas the argillaceous layers are relatively thin (ca. 0.5 cm in thickness) (Fig. 3). The limestone layers are composed mainly of lime-mudstone and subordinately of wackestone and packstone, occasionally ripple cross- and parallel-laminated. In some cases, the limestone layers are normally graded with peloids, intraclasts, and fossil fragments of brachiopods, trilobites,

Geologic Age		Distribution: Yongwol		Distribution: Taebaek Group		
Ordovician	Ashgill					
	Caradoc	Yongwol Group	Yonghung Fm	Taebaek Group	Sangdong Subgroup	Tuwibong Fm Chigunsan Fm Makkol Fm
	Llanvirn					
	Arenig					Tumugol Fm
	Tremadoc		Mungok Fm			Tongjom Fm
Cambrian	Late		Wagok Fm Machari Fm		Chikdong Subgroup	Hwajeol Fm Sesong Fm
	Middle		Sambangsan Fm			Taegi Fm Myobong Fm
	Early					Changsan/Myonsan Fm

Table 1. Lithostratigraphic summary and correlation of Choson Supergroup (Choi, 1998).

and echinoderms. The argillaceous layers contain clay minerals, lime-micrites, and euhedral or rhombohedral dolomites. Wispy "stylolite-like" seams and microstylolite swarms are commonly present in the slightly dolomitized argillaceous layers. Bioturbation is common in this facies. This facies has been commonly identified as alternations of (graded) limestone layer as distal storm deposits and clayey layer as background deposits (Markello and Read, 1981; Moshier, 1985; Sami and Desrochers, 1992). The facies is closely similar to 'ribbon limestone', in which the alternations probably originate from annual varves or decadal (centennial) bandings of carbonate and clay lay-

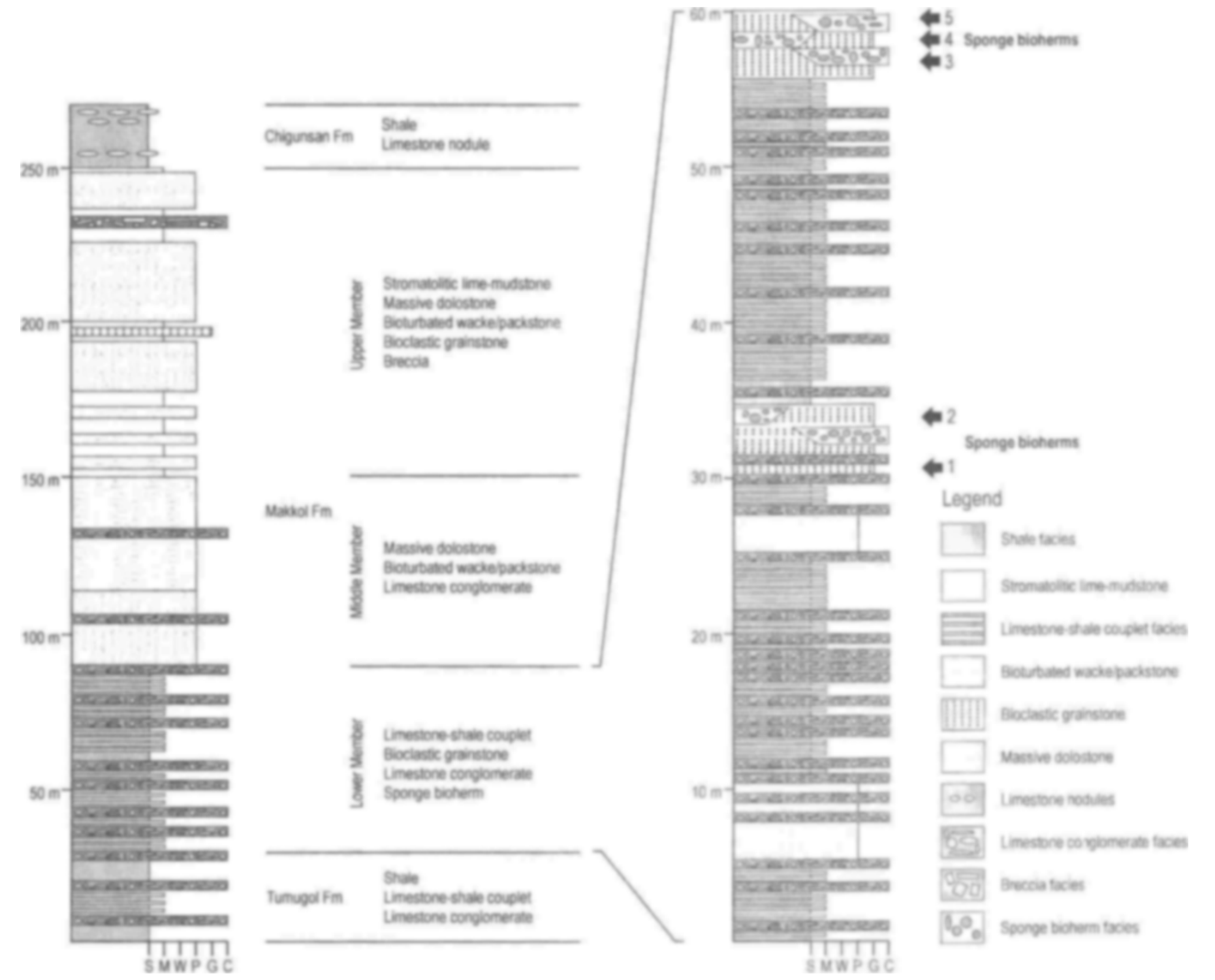


Fig. 2. Simplified columnar description of the Makkol Formation at the Sukgaejae section. Arrows indicate stratigraphic position of the sponge bioherms.

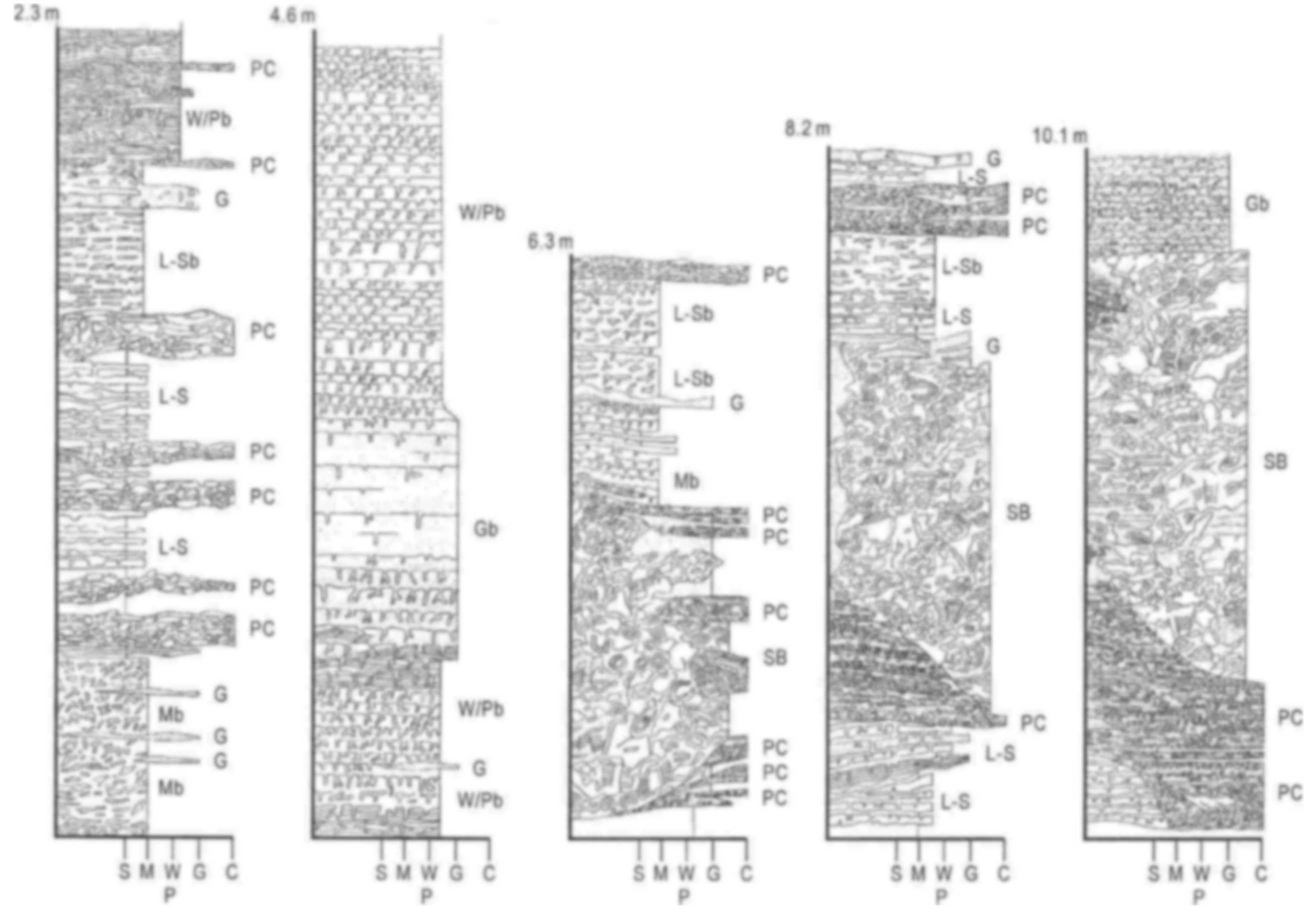


Fig. 3. Detailed columnar description of three sponge bioherms in the uppermost part of the lower member of the Makkol Formation at the Sukgaejae section. Note the stratigraphic position of sponge bioherm facies *(SB)* which overlies pebble-grade limestone conglomerate *(PC)* or grainstone*(G)*, and underlies limestone-shale couplet *(L-S)* or bioturbated wackestone/packstone *(W/Pb)*. For stratigraphic positon, see Fig. 2. Mb: bioturbated lime-mudstone, W/Pb: bioturbated wackestone/packstone, Gb: bioturbated grainstone, L-S: limestone-shale couplet, L-Sb: bioturbated limestone-shale couplet, G: grainstone, PC: pebble-grade limestone conglomerate.

ers, resulting from seasonal and/or environmental changes over decades, centuries, and millennia, characterized by diffuse or transitional boundaries between carbonate-rich and -poor layers (Anderson, 1986; Allen and Anderson, 1993; Anderson, 1996; O'Brian and Pietraszek-Mattner, 1998). This facies is interpreted as deposits of intermediate to deep subtidal environments between fair weather wave base and storm wave base (Markello and Read, 1981; Moshier, 1985; Sami and Desrochers, 1992).

3.3 Facies G: Grainstone

This facies comprises normally graded and/or crudely stratified grainstone layers (Fig. 3). The normally graded grainstone layers consist of silt or sand-sized quartz grains, intraclasts, and fossil fragments, including trilobites, gastropods, brachiopods, and echinoderms. The crudely stratified grainstone layers are made up of non-graded, pebble-bearing grainstone and in places hummocky cross stratification and weak bioturbation. Each bed is generally less than 5 cm thick with a sharp erosional base. Most beds are planar to gently undulatory with wavelengths of a few decimeters.

This facies is a deposit of storm sedimentation in intertidal to shallow subtidal zones (Allen, 1982; Kreisa and Bambach, 1982; Aigner, 1985) or of tidal channel and levees (Elliot, 1986; Cloyd et al., 1990). Storms produce intense bottom-shear conditions during the peaks, and concentrate shells of organisms on the sea floor. They also exhume previously buried shells and churn up the underlying weakly consolidated sediments to form an essentially autochthonous lag deposit (Bowen et al., 1974). Winnowing and suspension of sediments by storm turbulence result in depostion of fining-upward sequences (Kumar and Sanders, 1976). The sharp erosional base is attributable to scouring by storm surges (Kreisa, 1981; Kreisa and Bambach, 1982). Non-graded grainstone may form under relatively uniform peak storm conditions rather than under waning conditions (Allen, 1982; Jennette and Pryor, 1993).

3.4 Facies PC: Pebble-Grade Limestone Conglomerate

This facies consists mainly of rounded to subrounded, granule- to pebble-grade gravel clasts with oval or tabular shape (Fig. 3). The clasts comprise laminated wackestone to packstone and bioclastic, peloidal, or intraclastic grainstone, ranging in long diameter from a few millimeters to 3 cm. The platy clasts are mostly subparallel to bedding plane and occasionally show imbrication. Matrices are

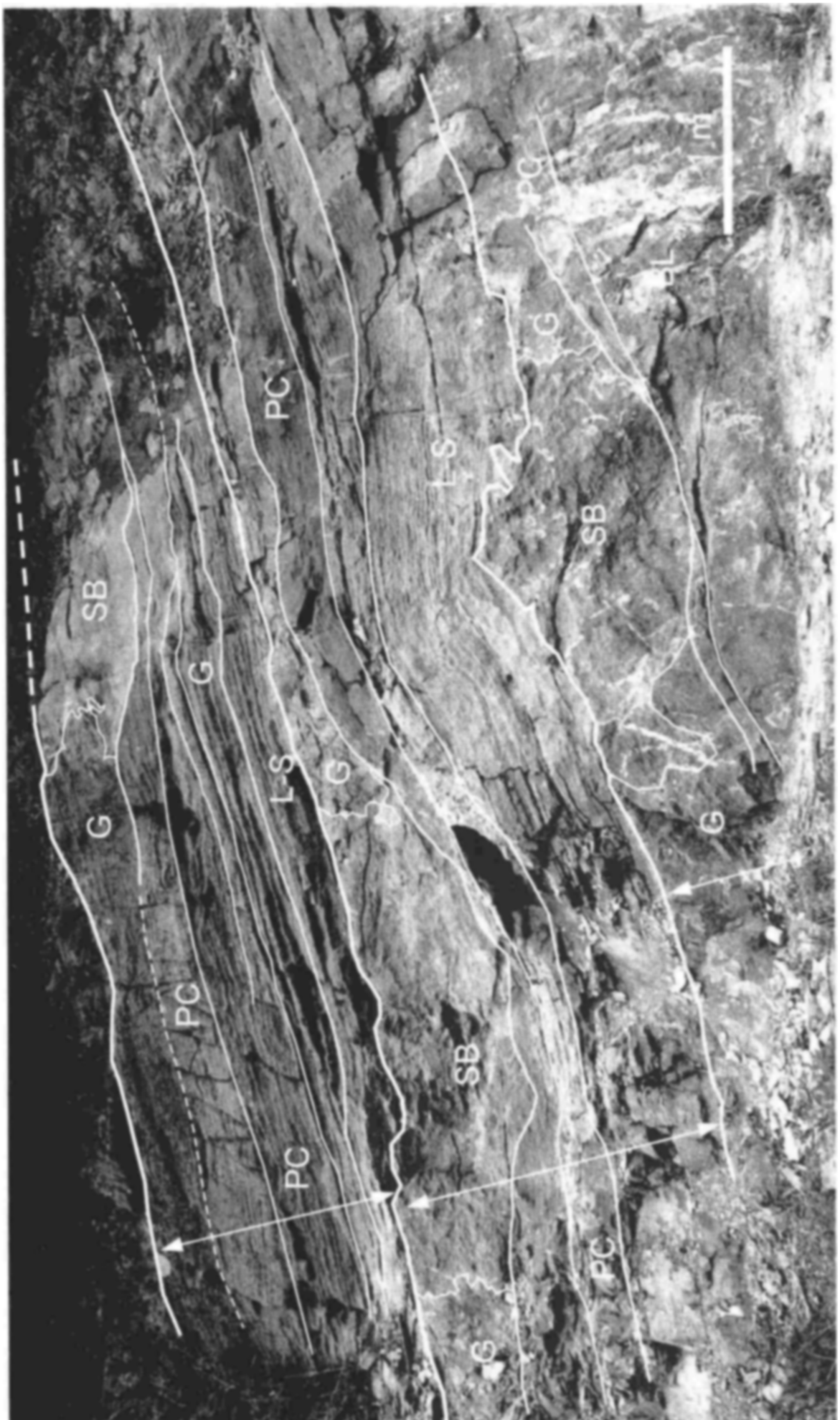


Plate 15 Photograph and line-drawing of the outcrop in the Sukgaejae section, showing sponge bioherms and the associated facies. Sponge bioherms occur at the top of meter-scale carbonate cycles, showing laterally abrupt transition to grainstone (*G*) or pebble-grade limestone conglomerate (*PC*). Sponge bioherms grew up on the incised channel bottom. For detailed photograph, see Pl. 16. *BL*: bioturbated limestone, *L-S*: limestone-shale couplet, *G*: grainstone, *PC*: pebble-grade limestone conglomerate, *SB*: sponge bioherm.

Facies	Description	Interpretation
Limestone-shale couplet (*L-S*)	Alternation of crudely laminated, bluish grey limestone (1-3 cm thick) and thin-bedded or anastomosing, dark grey shale (ca. 0.5 cm thick); in limestone layers, occasionally parallel or cross-laminated; in some cases, limestone layers are normally graded with lags of intraclasts, bioclastic fragments (trilobites, brachiopods, and echinoderms), and peloids; in shale layers, wispy stylolite seams and microstyolite swarms are common; slightly dolomitized.	Formed in subtidal environments; alternation due to tidal cycles; varves (Anderson, 1986; 1996; Allen and Anderson, 1993; O'Brian and Pietraszek-Mattner, 1998); centenial cycles; or recurring of turbidity current or storm current sedimentation and hemipelagic settling sedimentation (Choi et al., 1993)
Bioturbated wackestone/packstone (*W/Pb*)	Packstone/wackestone mainly of bioclastic fragments (trilobites, echinoderms, gastropods, and brachiopods), lime-micrites, peloids, clays, and dolomites; burrows are mainly vertical with minor horizontal, ichnofacies index 3-4 (Droser and Bottjer, 1986); occasionally intercalated with hummocky beds or pebble conglomerate layers.	Subtidal deposit with abundant bioturbation (Heckel, 1972; Paik, 1987; Woo, 1999; Kwon, 2000)
Bioturbated grainstone (*G*)	Crudely stratified or normally graded, thin-bedded grainstone (less than 5 cm thick); composed of intraclasts, quartx grains, and bioclastic fragments (trilobites, gastropods, echinoderms, and brachiopods); commonly hummocky cross-stratified; sharp erosional base.	Storm deposits in lower intertidal or subtidal flat environments (Allen, 1982; Kreisa and Bambach, 1982; Aigner, 1985) or in tidal channel and levees (Elliot, 1986; Cloyd et al., 1990); hummocky stratification is common in subtidal zones between fair weather wave base and storm wave base (Southard et al., 1990; Myrow and Southard, 1991)
Pebble-grade limestone conglomerate (*PC*)	Disorganized or slightly-imbricated, granule- to pebble-grade conglomerate; clasts of oval and tabular shape, rounded to subrounded; clasts of laminated wackestone to packstone, grainstone, and lime-mudstone; tabular clasts are mostly parallel to subparallel to bedding plane; matrices of clays, lime-micrites, quartz grains, dolomites, cement matrials, and bioclastic fragments; each unit is generally tabular and laterally continuous; lower boundary is commonly erosional and bored.	Storm (lag) deposits in intertidal or subtidal zones (Sepkoski, 1982; Sepkoski et al., 1991; Demicco and Hardie, 1994; Kwon et al., 2002).

Table 2. Sedimentary facies in the lower member of the Makkol Formation at the Sukgaejae section, Taebaeksan Basin, Korea.

composed mainly of bioclasts of brachiopods, bryozoans, echinoderms, trilobites, and other invertebrates and subordinately of lime-micrites, clays, and dolomitized cement materials. Each bed is generally tabular and laterally continuous in outcrop scale with little variations in thickness, but some thin beds (less than 1 cm thick) are occasionally amalgamated or wedged. The lower boundary of each bed is erosional and occasionally forms a submarine hardground with erosional truncation and boring.

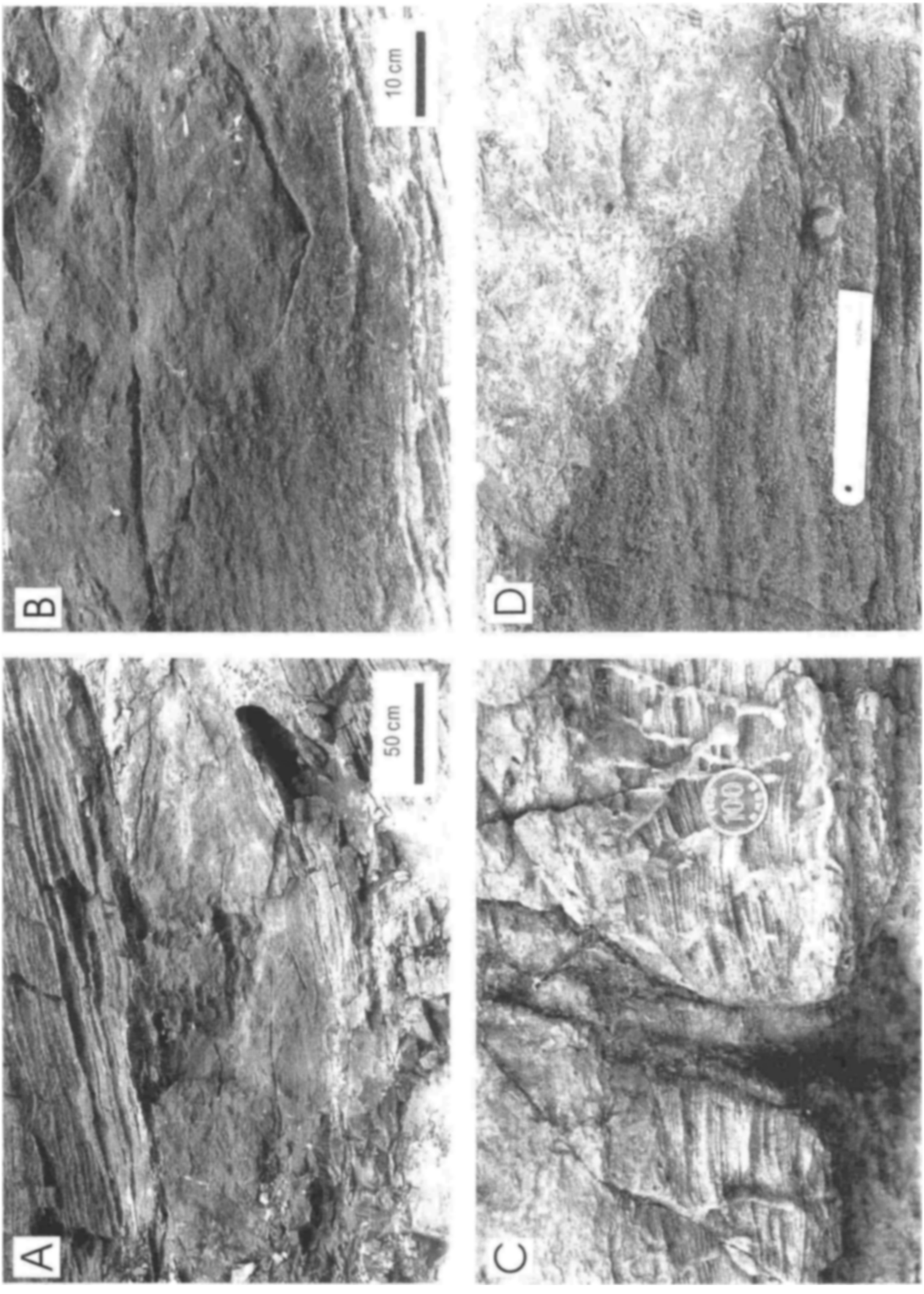
This facies is similar to subtidal limestone conglomerates which have been commonly interpreted as storm lags in subtidal settings (Sepkoski, 1982; Sepkoski et al., 1991; Demicco and Hardie, 1994; Kwon et al., 2002). The pebble-grade limestone conglomerates formed during intense storms when semiconsolidated bottom sediments are eroded. Rounded clasts indicate intense reworking or considerable lateral transport during resedimentation. Some conglomerates form channel fills (Elliot, 1986; Cloyd et al., 1990).

4 SPONGE BIOHERMS

The sponge bioherms were found from a mountain trail near Taebaek (Fig. 1: latitude 37° 04' 50"N, longitude 129° 08' 06"E), where a complete succession (ca. 1400 m thick) of the Taebaek Group is well exposed. Good exposure along the trail reveals that the Makkol Formation measures about 220 m in thickness (Fig. 2). Five bioherms were recognized at the interval of 30-40 m and 50-60 m above the base of the formation (Fig. 2). They are lenticular to ellipsoidal in outline and range in width from 1 to 4 m and in height from 0.7 to 1.2 m.

Sponge bioherms are composed of a lithistid sponge *Archaeoscyphia*, a receptaculid *Calathium*, stromatolitic algae, void-filling lime-muds, and bioclastic debris of brachiopods, trilobites, and cephalopods. The bioherms form skeletal mounds and have a concave base and a planar (or irregular) top, averaging 1 m in height and 2 m in length (Fig. 3 and Pl. 15). The top is capped by limestone-shale

Plate 16 (A) Photograph of the sponge bioherm, overlain by limestone-shale couplet facies (*L-S*). (B) Photograph of erosional scour of the underlying pebble-grade conglomerate layers and sharp lower base of the sponge bioherm. (C) Photograph of hummocky cross stratification with vertical burrows. Coin for scale is 2.2 cm in diameter. (D) Photograph of fragmentary sponges within flanking pebble-grade limestone conglomerate layers, indicative of intense storm reworking. Scale bar is 16.5 cm in length.


A
50 cm
B
10 cm
C
D

couplet facies (Pl. 16A), and the base is sharp and erosional (Pl. 16B). The bioherms were initiated on pebble-grade limestone conglomerate or grainstone layers. Some grainstone facies show hummocky cross stratification with vertical burrows (Pl. 16C). Pebble-grade limestone conglomerates comprise granule- to pebble-grade clasts of lime-mudstone, laminated wackestone and bioclastic grainstone, which are mostly flat-lying and subordinately imbricated. The bioherms show laterally abrupt facies transition to thin-bedded bioclastic grainstone, packstone, dolomitic grainstone, and pebble-grade limestone conglomerate (Pl. 15). The flanking facies commonly contain fragments of lithistid sponges and other skeletal fossils (Pl. 16D).

Lithistid sponges are abundant in the core facies, which are preserved most likely in life growth positions (Pl. 17A). They were an important contributor for the framework of the bioherms. *Calathium* is associated with sponges in the core, but forms minor constituent of the bioherms (Pl. 17B). Stromatolitic algae are common in the mound core, and would have played a significant role for the stabilization of the substrate, helping formation of a hardground for attachment of reef-building organisms (Pl. 17C). Allochtonous individuals of *Archaeoscyphia* and *Calathium* also occur in the pebble-grade limestone conglomerate beds between these bioherms and are often fragmented and abraded (Pl. 16D). Associated megafossils include trilobites, gastropods, cephalopods, brachiopods, and crinoids.

A total of eight sponge and four *Calathium* specimens, preserved by calcification, are collected from both bioherms and inter-biohermal layers. They are fragmentary and show a various degree of preservation. Sponges are represented entirely by *Archaeoscyphia*, which is the only lithistid genus reported from the Lower Ordovician reef-mound structures (Carrera and Rigby, 1999). They are cylinderical or steeply obconical in shape. Although the full height of the sponge is unknown, the largest specimen, though incomplete, measures about 100 mm high with maximum diameter of 60 mm on the crest of annulations. Spongocoels, filled with sediments, are simple, circular, and gently broadening upward, 34 mm in width (Pl. 17D). The outer wall has distinct ringlike annulations which are spaced 16-23 mm apart (Pl. 17E). The wall thickness ranges from 9-14 mm in opposite annulation ridges to 3-4.5 mm in trough between annulations. Annulations are extended abaxially to 10-13 mm from gastral surface of the walls. Trabs are well developed upward and outward from the gastral margin. These sponges are closely similar to *Archaeoscyphia chihliense* (Grabau, 1922) reported from the Lower Ordovician of North China (Grabau, 1922; Endo, 1932; Shenyang Institute of Geology and Mineral Resources, 1980; Guo 1982, 1983).

The associated receptaculitid alga *Calathium* has a double-walled conical skeleton with maximum diameter of 30 mm. Root-like structures or outgrowths in the central cavity and around the outer wall at the basal part are well developed in some specimens (Pl. 17B and F). Unfortunately, morphological details of these specimens have not been observed due to poor preservation, but the overall appearance suggests a close resemblance to *Calathium delicatus* (Guo, 1983) that was described from the Lower Ordovician of North China where the association of *Archaeoscyphia* and *Calathium* was also documented.

5 GROWTH HISTORY OF SPONGE BIOHERMS

The Lower Ordovician carbonate sponge-algal bioherms are composed of an association of lithistid sponge *Archaeoscyphia* and receptaculid *Calathium*. The lithistid sponges are solitary organisms, which obtain nutrients from suspended organic matter and bacteria, and thus have preference for nutrient-rich waters. Although many authors have pointed out low turbulence and soft substrate settings for sponge growth, the paleoecological studies on lithistid sponges in the Precordillera Basin, Argentina suggest hard substrate and high-energy conditions for sponge growth (e.g., Carrera and Cañas, 1996). The sedimentological features of the sponge-algal bioherms from the Taebaeksan Basin also suggest hard substrate and high energy conditions as suitable conditions for sponge biohermal growth.

The sponge-algal bioherms in the Makkol Formation grew up on the bottom of incised channels (Pl. 15). The channel bottom would provide hard substrate by early cementation and high-energy conditions suitable for colonization of the sponges. In addition, channel currents probably provide effectively nutrients which are essential for growth of the lithistid sponges and receptaculid *Calathium*. Consequently, the subtidal incised channels would provide most fit places for sponge bioherm growth.

The growth of reefal organisms is closely related to water depth and relative sea level changes (Bosschers and Schlager, 1992). As relative sea level rises in shallow marine subtidal setting, meter-scale shallowing-upward cycles are commonly formed (e.g., James, 1984; Osleger and Read, 1991). The shallowing-upward cycles in the lower member of the Makkol Formation consist entirely of subtidal facies, and the cycles in the uppermost part of the lower member (see Fig. 2), where sponge bioherms occur, starts with bioturbated wackestone to pacstone (*W/Pb*) or limestone-shale couplet (*L-S*) in the lower part and is topped by grainstone (*G*), pebble-grade limestone conglomerate (*PC*), or sponge bioherm (*SB*) (Pl. 15). The purely subtidal shallowing-upward cycles have been interpreted to originate from allocyclic process, in which the ultimate control may be eustasy acting in concert with autocyclic processes (e.g., Osleger, 1991). During early fast sea-level rise, relatively deep subtidal facies (L-S or W/Pb) would form on subtidal flatform. As the rate of sea level rise decreases, shallow subtidal facies (G or PC) were prevalent, forming shallowing-upward cycles. Active subtidal incision commonly forms small-scale channels, which provide suitable conditions for attachment of sponges and growth of the bioherms (Pl. 15). Subsequent sea-level falls

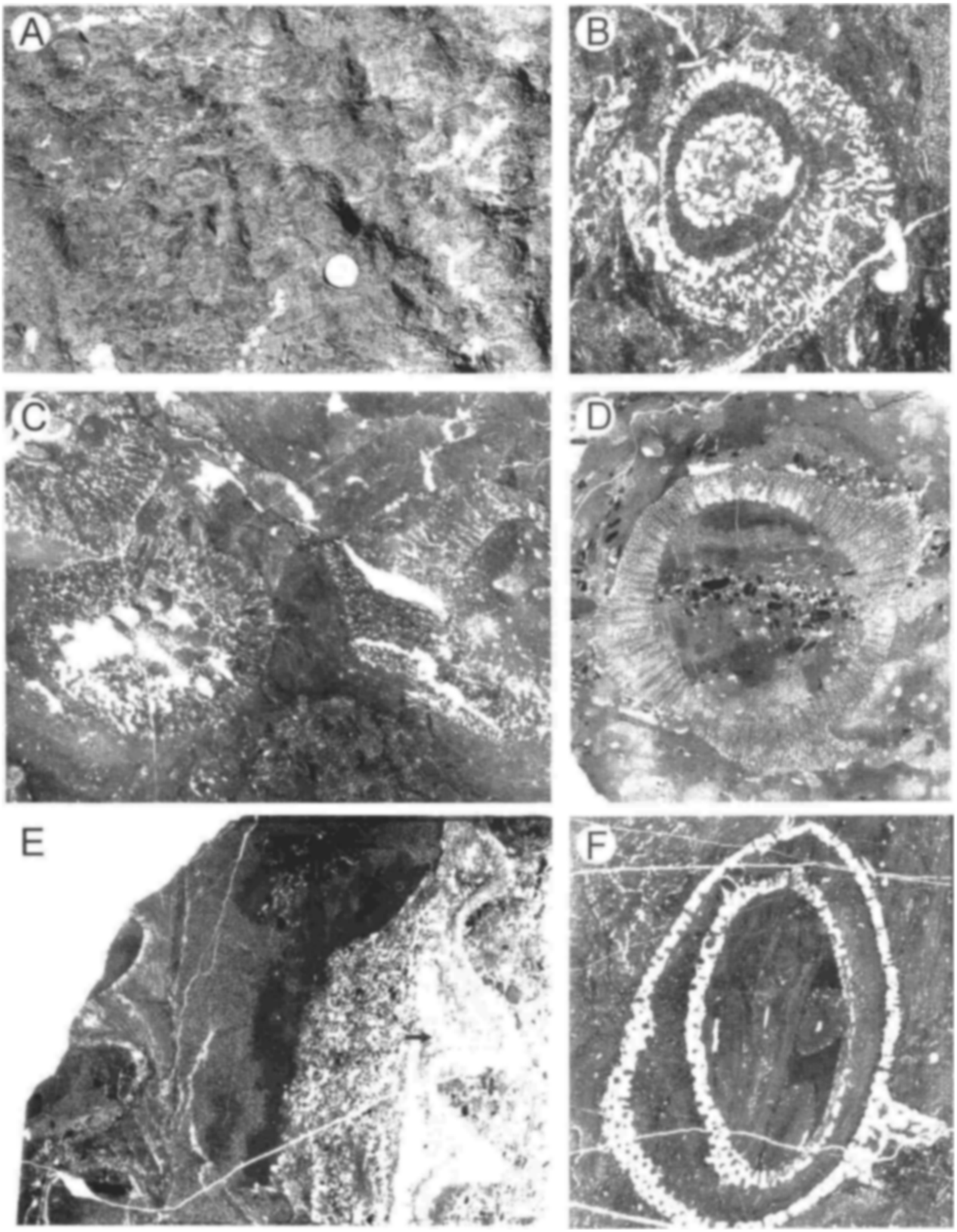


Plate 17 (A) Enlargement of part of the sponge bioherm. *Archaeoscyphia* sponges are mostly preserved in their life growth positions in mound core facies. Coin diameter = 23 mm. (B) Transverse thin section of *Calathium* (NSM30101) illustrating outgrowths in the central cavity and around the outer wall in the basal part. (x 1.4) (C) Photomicrograph of sponge fragments surrounded by stromatolitic algae. (x 1.7) (D) Transverse thin section of *Archaeoscyphia* (NSM10211) of the middle part, showing radially arranged trabs around spongocoel. (x 1.4) (E) Longitudinal thin section of *Archaeoscyphia* (NSM10212), showing annulations (indicated by arrows) and flaring trabs. (x 1.4) (F) Transverse thin section of *Calathium* (NSM30102) showing concentric double walls. (x 1.4)

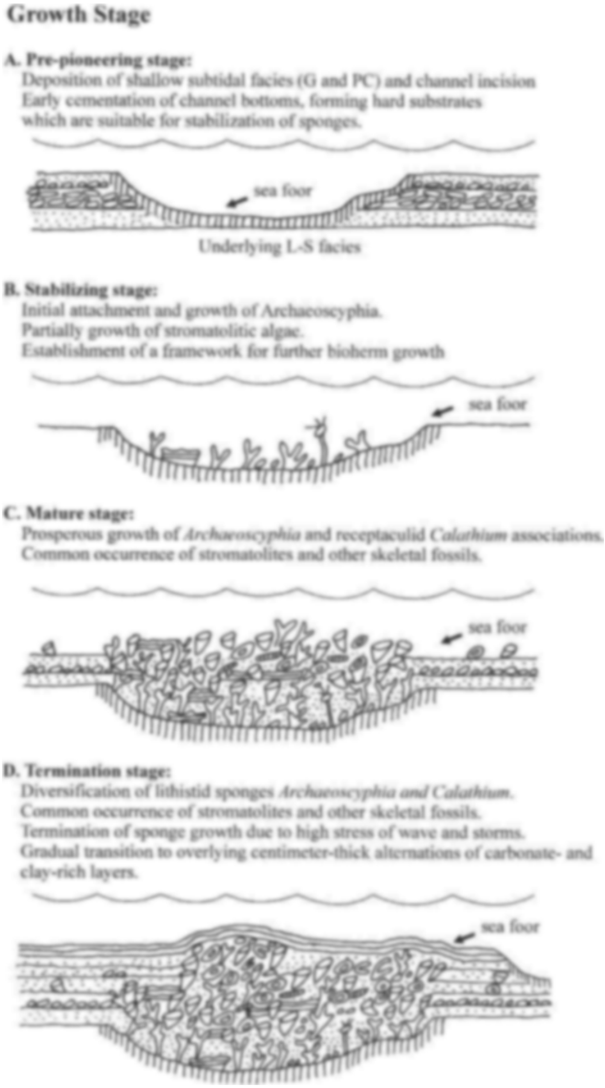


Fig.4. A schematic illustration, showing growth stages of sponge bioherms.

probably resulted in strong reworking and redistribution of the sediments by frequent storms and waves, which would provoke severe stress to sponges and other organisms, and thus would terminate the growth of sponge bioherms.

Figure 4 depicts the four-stage growth history of the sponge bioherms in the Makkol Formation: pre-pioneering, stabilizing, mature, and termination stages. Sponges are sessile and benthic suspension feeders with a delicate water circulation system. Initial settlement (attachment) of lithistid sponges requires pre-pioneering condition, such as relatively clear water and rigid substrate of incised channel bottom (Fig. 4A). At the stabilizing stage, the lithistid sponges would be successfully attached and initially act as baffles, trapping fine carbonate muds and establishing a framework for further mound growth (Fig. 4B).

As *Archaeoscyphia* grew, *Calathium* with well-developed holdfasts would colonize as a baffle, trapping increasing amounts of sediment and providing favorable conditions for the mound growth with stromatolitic algae (Fig. 4C). The association of *Calathium* and more fragmentary sponges in the middle part of the bioherms suggests a mature stage of bioherm growth (Fig. 4C). The occurrence of stromatolitic algae indicates that the bioherms grew within the depth of photic zone. Sponges and calathids acted as baffles, and trapped and/or bound loose carbonate sediments and muds winnowed from the interreef area, thereby constructing the rigid reef bioherm mass. Sponge would have grown above the channel bottom, keeping pace with interdigitating grainstone on the flanks of the bioherms (Fig. 4C). In the unchannelized flat areas, deposition of grainstone or pebble-grade limestone conglomerate took place under subtidal regime. Small-scale hummocky cross stratification in this zone indicates wave-generated oscillatory flows and/or combined flows produced by storms (Southard et al., 1990; Myrow and Southard, 1991).

When the channel was leveled with the adjacent sea floor, the growth of the bioherms was probably interrupted. At the termination stage, intense reworking and redistribution by frequent storm surges would have suffocated the sponges by influx of abundant suspended lime-mud particles and consequently terminated the growth of the bioherms (Fig. 4D).

6 PALEOGEOGRAPHIC IMPLICATIONS

The Early Ordovician was an initial stage of experiments for the Paleozoic evolutionary faunas (Sepkoski, 1981) to utilize shallow marine environments. The *Archaeoscyphia-Calathium* association was one of the pioneering groups which colonized successfully in tropical-subtropical carbonate shelves. The widespread occurrence of *Archaeoscyphia-Calathium* association in peri-Gondwana, Laurentia, and Siberia in the Early Ordovician (Carrera and Rigby, 1999) may be attributable to the disposition of these Paleozoic continents in the equatorial regions (Scotese and McKerrow, 1991), thereby allowing animals to cross the oceans via equatorial currents. The Early Ordovician sponge faunas with low diversity and less provincialism have apparently little paleogeographic significance compared with those of the Middle and Upper Ordovician (Carrera and Rigby, 1999). The occurrence of *Archaeoscyphia-Calathium* association in the Korean peninsula can be employed to test the feasibility of paleogeographic correlation of the Ordovician continents in eastern Asia.

The reconstruction of the early Paleozoic paleogeography of the Korean peninsula has mainly relied on the faunal characteristics of trilobites and cephalopods (Kobayashi, 1969; Whittington and Hughes, 1974). Although there are diverse views on the disposition of the Paleozoic continental blocks, it has been widely accepted that the Sino-Korean (or North China) and Yangtze (or South China) blocks were separated during much of the Paleozoic (Burrett, 1973; Burret and Stait, 1986; Watson et al., 1987; Scotese and McKerrow, 1991). In these paleogeographic models, the Korean peninsula was either included in the Sino-Korean block or was divided into two parts, i.e., North Korea in the

Sino-Korean block and South Korea in the Yangtze block, respectively. Recent analysis on the Ordovician trilobite assemblages (Choi et al., 2001) clearly demonstrates that the Taebaeksan Basin was connected to that of North China, suggesting that mideast Korea was part of the Sino-Korean block. The occurrence of a stromatoporoid, *Labechiella regularis* (see Lee and Yoo, 1993), which has a restricted distribution in Korea, North China, and Australia, supports the faunal links among these regions. The *Archaeoscyphia-Calathium* association in the Makkol Formation furthers the biogeographic connection between Korea and North China, as it is closely comparable to that reported from the Lower Ordovician of North China (Guo, 1983). These fauna are apparently more distantly related to those of South China (Liu et al., 1997).

7 CONCLUSION

Isolated bioherms composed of *Archaeoscyphia* and *Calathium* occur in the Lower Ordovician Makkol Formation of the Taebaek Group, Taebaeksan Basin, mideast Korea. The bioherms are associated with bioturbated wackestone/packstone, limestone-shale couplet, grainstone, and pebble-grade limestone conglomerate, and formed most likely under shallow to intermediate subtidal settings. The lithistid sponges may have favored the channel bottoms for initial settlement. As the sponge bioherms grew upwards, they were increasingly affected by intense wave action and frequent storms, which eventually perished the bioherm growth. The occurrence of bioherms with *Archaeoscyphia-Calathium* association indicates a strong biogeographic link between Korea and North China, providing a further evidence for the paleogeographic model that the Korean peninsula was part of the Sino-Korean block in the early Paleozoic.

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