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Biodata of Dr. Atsushi Yamamoto, Professor Kwang-Choon Lee, and Professor Yukio Isozaki, authors of “Lower Cretaceous Stromatolites in Far East Asia: Examples in Japan and Korea”

Dr. Atsushi Yamamoto, currently at the Department of Earth Evolution Sciences, University of Tsukuba (Japan), obtained his PhD from the University of Tokyo in 2009. His research focuses on the morphological evolution of fossil stromatolites with respect to recent cyanobacterial biomats, and on the in situ experiments of forming stromatolites from plane cyanobacterial biomats.

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Professor Yukio Isozaki of the University of Tokyo is currently studying the mass extinction and relevant environmental changes across the Paleozoic–Mesozoic boundary. He and his colleagues clarified that the famous, oldest (Early Archean) “stromatolites” from the Pilbara craton (Western Australia) actually occur in deep-sea beds deposited around an ancient mid-oceanic ridge with hydrothermal activity, denying the long-believed photosynthetic cyanobacterial origin in shallow marine settings.

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Abstract  The morphology, structure, and mode of occurrence of the Early Cretaceous nonmarine stromatolites from the Kanmon Group in northern Kyushu (SW Japan) and from the Gyeongsang Supergroup in South Korea are reviewed. These stromatolites were formed likely in intertidal–supratidal settings of a large intracontinental lake (the Kanmon–Gyeongsang Basin) that were occasionally exposed to arid condition. Seven macrostructures of stromatolite are recognized. In particular, three of them are dominant, i.e., flat type, columnar type, and domal type. The thickness of clastic layers of the stromatolites and the associated sedimentary facies suggest that the flux of terrigenous clastics into the depositional site may have controlled the morphological diversity of the stromatolites, i.e., the flat type occurred in very shallow nearshore (supratidal), while the domal type in relatively deeper, offshore (intertidal).

Keywords  Lower Cretaceous • Japan • Korea • Lacustrine • Paleoenvironment • Stromatolite • Nonmarine • Intertidal

1. Introduction

With respect to the Precambrian world, stromatolites are relatively rare in the Phanerozoic except some specific intervals such as the Cretaceous (Awramik and Sprinkle, 1999; Riding, 2006). The occurrences of Cretaceous stromatolite were reported mainly from coral/sponge reefs in the circum-Atlantic regions, such as Spain (e.g., Neuweiler et al., 1999) and Mexico (e.g., Beraldi-Campesi et al., 2004). Most of them are commonly associated with other calcareous biota, thus do not form stromatolite-dominant reefs like the Precambrian examples (Leinfelder and Schmid, 2000). The Cretaceous stromatolites from Japan and Korea are unique in this regard, because they provide rare examples of monotonously stromatolite-dominant units within terrigenous clastic packages. Such a pure stromatolite reef might form only in
nonmarine settings. Dominant reef builders of Early Cretaceous, such as corals and rudists, could not inhabit nonmarine environments. These Cretaceous stromatolites in East Asia are analog to the Precambrian stromatolites in morphology and probably also in ecology.

The occurrences of Lower Cretaceous stromatolites in East Asia were recorded already in the early twentieth century: first from the Jinju area in South Korea (Kodaira, 1922) and then from northern Kyushu in Japan (Kobayashi, 1936). Later, Ishijima (1977) and Seo et al. (1994) added descriptions of the stromatolites from northern Kyushu and discussed their fresh-water origin. Also in S. Korea, many stromatolite beds were described from the vicinity of Daegu by Lee et al. (1991), whose finding was followed up by later studies focused on morphology, internal structure, and carbon and oxygen isotopic ratios of the stromatolites (e.g., Woo et al., 2002, 2004; Nehza and Woo, 2006; Nehza et al., 2009). Recently, Yamamoto et al. (2009) clarified detailed mode of occurrence of the stromatolite from northern Kyushu, with special attention to their close association with evaporitic sedimentary features and to their branching pattern. By analyzing carbon/oxygen isotopic ratios in a lamina by lamina manner for the S. Korean specimens, Nehza et al. (2009) speculated that seasonal return of arid condition formed the rhythmic alternation of the stromatolites. In this short article, fundamental characteristics of these unique Cretaceous stromatolites in Japan and S. Korea are reviewed, and their geological implications are briefly discussed.

2. Stromatolite-Bearing Lower Cretaceous Strata

The Lower Cretaceous stromatolites occur in nonmarine strata in both N. Kyushu and S. Korea (Fig. 1). The Lower Cretaceous rocks in N. Kyushu and western Honshu (main island of Japan) are called the Kanmon Group (Matsumoto et al., 1982), while that in S. Korea the Gyeongsang Supergroup (Chang et al., 2003). The nonmarine Cretaceous strata of N. Kyushu and S. Korea, currently separated by the Tsushima strait, were likely deposited in the same large fresh-water basin (e.g., Kobayashi, 1941; Chough et al., 2000), which is tentatively called the Kanmon-Gyeongsang Basin in this article. The Cretaceous rocks in the two areas are correlated with each other on the basis of the lithologic similarity and molluscan fossils (Hase, 1960; Ota, 1960).

The Kanmon Group consists of two subgroups: the Wakino Subgroup (lower) and the Shimonoseki Subgroup (upper) (Fig. 2). The Kanmon Group overlies unconformably the basement composed of the Carboniferous high-P/T metamorphic rocks (Nishimura and Shibata, 1989), and is in turn covered unconformably by the mid-Cretaceous Yahata Formation (Ota and Yabumoto, 1998). The Wakino Subgroup is composed mainly of well-bedded shale, sandstone, and conglomerate (e.g., Ota, 1953). The Shimonoseki Subgroup is composed of sandstone, tuff, and andesite lava (e.g., Hase, 1960; Ota and Yabumoto, 1998). The depositional setting of the Kanmon Group was regarded as a mid-latitude,
intracontinental lacustrine environment under arid to semiarid climate (e.g., Ota and Yabumoto, 1998). The stromatolites occur in the Sengoku, Lower Wakamiya, and Upper Wakamiya formations of the Wakino Subgroup (Fig. 2; Ishijima, 1977; Yamamoto et al., 2009).
The Gyeongsang Supergroup in S. Korea is composed of the Sindong, Hayang, and Yucheon groups in ascending order (Fig. 2; e.g., Chang, 1975; Choi, 1985; Huh and Hayashi, 2001). The Sindong Group is composed of shale, sandstone, and conglomerate (Chang, 1975). The Hayang Group is composed mainly of shale, sandstone, and conglomerate, with minor amount of volcanic rocks that range from mafic to felsic in composition (Chang, 1975; Choi, 1985; Huh and Hayashi, 2001). The Yucheon Group is composed mainly of felsic lava and tuff with subordinate sedimentary rocks (Chang, 1975). The Gyeongsang Supergroup was regarded as a lacustrine sedimentary unit deposited in an intracontinental basin (e.g., Chough et al., 2000; Nehza et al., 2009) like the Kanmon Group in Japan. The stromatolites occur in the Jinju Formation of the Sindong Group (Lee and Woo, 1996), and also in the Banyawol, Hwasan, and Sinyangdong Formations of the Hayang Group (Fig. 2; Lee and Woo, 1996).

The Kanmon Group and the Gyeongsang Supergroup are mutually correlated (Fig. 2) on the basis of their lithologic similarity and molluscan fossils, such as Trigonioididae bivalves (Hase, 1960; Ota, 1960). The Early Cretaceous charophyte, Clypeator jiuquanensis (the Hauterivian to Early Barremian), from the Nakdong Formation and the radiometric ages of intrusive rocks (120–82 Ma) constrain that the Kanmon Group and the Gyeongsang Supergroup were deposited probably during the Hauterivian to Albian (Early Cretaceous) age (Chang, 1997; Chang et al., 1997; Matsumoto et al., 1982; Ota and Yabumoto, 1998). The Jinju Formation in S. Korea is correlated with the stromatolite-bearing Lower Wakamiya Formation in Kyushu.

3. Morphotypes of Stromatolites

3.1. STROMATOLITES FROM THE KANMON GROUP

All the Cretaceous stromatolites from N. Kyushu occur in the black shale (e.g., Fig. 4c). The stromatolite-bearing beds are intercalated in the conglomerate-dominant sections (Fig. 3a). The Lower Wakamiya Formation yields stromatolites in four horizons (Fig. 3a). Stromatolites of the Lower Wakamiya Formation have three macrostructures (Table 1): i.e., flat type (Fig. 4a), columnar type (Fig. 4b), and nodular type (Fig. 4c). In particular, the former two types are abundant. The flat-type stromatolite is composed of horizontal laminae of about 0.1 mm thick in average. The columnar-type stromatolite consists of composite columns of ca. 10 cm height. The nodular-type stromatolite is composed of composite spherical structures oriented randomly. The laminae of both columnar and nodular types are about 0.1 mm thick. Among the three, the columnar-type stromatolite is the biggest in size that reaches about 30 cm in height. The flat-type stromatolite consists of alternating clastic layers and micritic layers. The flat type is unique in
Figure 3. Columnar sections of typical stromatolite-bearing strata: (a) the Lower Wakamiya Formation [Japan, modified from Yamamoto et al. (2009)], (b) the Sinyangdong Formation [Korea, modified from Nehza and Woo (2006)].
Table 1. Seven macrostructures of the Kanmon and Gyeongsang stromatolites. Flat- and columnar-type stromatolites in Japan and domal type in S. Korea are dominant.

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<th>Secondary structure</th>
<th>Alternation</th>
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<td>Fibrous-calcite/micrite</td>
<td>Common</td>
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<tr>
<td></td>
<td>Rod type</td>
<td>Column/smooth lamina</td>
<td>Fibrous-calcite/organic carbon</td>
<td>Rare</td>
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Figure 4. Morphological variation of Kanmon stromatolites: (a) flat type, (b) columnar type. A white square indicates the illustrated area of (d, c) nodular type born from the black shale, (d) branching observed in columnar type. Arrows show branching points.
intercalating occasionally siliciclastic laminae of over 0.3 mm thick, whereas the
columnar- and nodular-type stromatolites lack the clastic layers. The internal
laminations of the rest two types consist of alternating siliciclastic-rich micrite
lamina and organic carbon-rich micrite lamina. On the basis of the random
distribution of the internal spheres and the types of alternation, the nodu-
lar-type stromatolites are regarded as broken forms of the columnar type.
The micritic laminae of all three types likely correspond to primary biomats
(Yamamoto et al., 2009).

3.2. STROMATOLITES FROM THE GYEONGSANG SUPERGROUP

The stromatolites from the Gyeongsang Supergroup occur in the black shale
just like those from the Kanmon Group in Japan (Fig. 3b; e.g., Lee et al.,
1991). Nonetheless, in contrast to those of the Kanmon Group, the stromato-
lite-bearing shales of the Gyeongsang Supergroup are commonly associated
with fine-grained sandstone, and never occur with coarse-grained sandstone
or conglomerates (e.g., Lee et al., 1991). The stromatolites of the Gyeongsang
Supergroup have four macrostructures (Table 1), i.e., domal type (Fig. 5a, b,
e), stratiform type, oncölite type (Fig. 5c), and rod type (Fig. 5d). The Hayang
Group of the Middle Gyeongsang Supergroup yields three of the four types:
domal type, oncölite type, and stratiform type. The domal type is abundant and
includes domes with smooth laminae (Fig. 5a) and/or domes with columnar
laminae (Fig. 5b). The maximum diameter of stromatolites from the Hayang
Group reaches 1 m or more (Fig. 5e).

All the stromatolites from the Hayang Group are composed of alternating
micritic lamina and fibrous-calcite lamina (Woo et al., 2004; Nehza and
Woo, 2006). The thickness of each micritic/fibrous-calcite couplet is about
2–5 mm (Nehza and Woo, 2006). The micrite laminae may have microbial
origin, whereas the fibrous-calcite laminae might have been chemically pre-
cipitated (Woo et al., 2002). This common character in the alternation sug-
gests that three types of the Hayang stromatolites were formed under almost
the same environment. The stromatolites from the Hayang Group are com-
posed of both micrite and fibrous-calcite laminae that include a minor amount
of terrigenous clastics; however, clastic-dominant laminae that are common
in the Kanmon Group are absent (Nehza et al., 2009; Nehza and Woo, 2006;
Woo et al., 2002).

The stromatolites from the Jinju Formation (the Sindong Group) are of the
rod type (Fig. 5d) and unique in having a cavity in the center (Lee and Woo,
1996). This cavity may have derived from a wood trunk around which the stroma-
lite columns/laminae grew, and the putative wood itself may have decayed out
later to leave a central cavity (Lee and Woo, 1996). The internal columns/laminae
of the rod-type stromatolites are very similar to the secondary columns/laminae of
the columnar type of the Japanese stromatolites.
Figure 5. Morphological variation of Gyeongsang stromatolites: (a) domal stromatolites with smooth laminae (Hwasan Formation), (b) domal stromatolites with many columns (Sinyangdong Formation), (c) oncolitic stromatolite (Hwasan Formation), (d) rod-shaped Jinju stromatolites (overlook view), (e) huge domal stromatolites (Banyawol Formation).

4. Discussion

4.1. STROMATOLITE-FORMING ENVIRONMENTS

As discussed above, the Lower Cretaceous stromatolites from N. Kyushu and S. Korea have several similarities and dissimilarities. Despite the slight difference in age, all these stromatolites occur in black shales with mud cracks/gypsum pseudomorphs (e.g., Lee et al., 1991; Yamamoto et al., 2009). These sedimentary features indicate that the stromatolites have formed in a very shallow-water environment, such as
The occurrence of apparent laminae composed dominantly by terrigenous clastics characterizes the stromatolites of the Kanmon Group, whereas those of the Gyeongsang Supergroup completely lack them (see Sect. 3). Among the three dominant types of the Kanmon and Gyeongsang stromatolites (Table 1), the flat type has thicker clastic laminae (sometimes >0.3 mm) than the columnar type, and the domal type lacks them. These differences in clastic content among the studied stromatolites suggest that morphological variations were controlled by the physical distance from the source of terrigenous clastics. The flat-type stromatolites likely formed in the nearest environment to the source with the highest clastic flux. The domal-type stromatolite probably formed in relatively offshore environments away from the source, because the clastic content is quite small. Thus, the successive form change in stromatolites, from the flat type to the columnar type and then to the domal type, probably represents a lateral transition of sedimentary facies from nearshore (supratidal) to offshore (intertidal) (Fig. 6). Accordingly, as to the stromatolite-bearing beds, the Kanmon Group was deposited in a proximal setting, whereas the Gyeongsang sections in distal setting with respect to the provenance of terrigenous clastics. The intimate association of the stromatolite-bearing shales and conglomerates in the Kanmon Group (Yamamoto et al., 2009) supports the above interpretation.

Previous studies (e.g., Hoffman, 1976) suggest that sedimentation rate and location within coastal settings are likely two major controlling factors that affect the morphology of modern stromatolites. The domal-type stromatolite commonly occurs in relatively offshore environments, whereas the flat-type stromatolites in nearshore environments in Shark Bay (Logan, 1961). The distribution of the columnar-type stromatolite is restricted between those of the domal type and the flat type. According to such relationships among morphology, formed environment and sedimentation rate recognized in modern stromatolites, the flat-type

![Figure 6. Estimated environment of abundant Kanmon and Gyeongsang stromatolites. The stromatolites formed in supratidal to intertidal environments. Gyeongsang stromatolites were formed more offshore than Kanmon stromatolites. Morphological change of the both stromatolites was probably suited to that of modern examples.](image-url)
stromatolites of the Kanmon Group likely formed in a nearshore environment with higher sedimentation rate, whereas the domal-type stromatolites from the Gyeongsang Supergroup in an offshore environment with lower sedimentation rate (Fig. 6).

4.2. TRANSITION OF STROMATOLITE-FORMING AREA

In Early Cretaceous East Asia, the Kanmon Group in N. Kyushu and the Gyeongsang Supergroup in S. Korea likely formed in the southeastern and northwestern parts of the large nonmarine intracontinental Kanmon–Gyeongsang Basin, respectively (e.g., Chough et al., 2000). According to the paleogeographic reconstruction of Cretaceous East Asia (Fig. 7a; Chough et al., 2000; Maruyama et al., 1997), the Kanmon Group was deposited in the southeastern coast of the Kanmon–Gyeongsang Basin, whereas the Gyeongsang Supergroup in the northwestern coast. During the Wakino–Sindong time (Fig. 2), stromatolites formed probably all around the basin (Fig. 7b) including N. Kyushu and S. Korea. On the other hand, during the Shimonoseki–Hayang time (Fig. 2), stromatolites occurred only in S. Korea, particularly along the northwestern coast of the Kanmon–Gyeongsang Basin (Fig. 7c). This fact may indicate that the preexisting, stromatolite-forming stable environments have been modified considerably in the beginning of the Shimonoseki–Hayang time (ca. 100 Ma).

In the Early Cretaceous, a large-scale subduction-related magmatism occurred in East Asia to form the Ryoke granite batholith belt in SW Japan arc, as a result of the subduction of the Izanagi–Pacific mid-oceanic ridge beneath Asia (Isozaki and Maruyama, 1991; Isozaki, 1996; Maruyama et al., 1997). In N. Kyushu, the Early Cretaceous arc-related volcanic rocks (Kitahikoshima Formation)

Figure 7. Change of stromatolite-forming area in the Kanmon–Gyeongsang Basin. Stromatolites were formed (a) the Kanmon–Gyeongsang Basin in the Early Cretaceous East Asia. The shaded square indicates the area shown in (b and c). (b) Wakino–Sindong time. Stromatolites were formed all around the basin, (c) Shimonoseki–Hayang time. Stromatolites were formed only in the west side of the basin because of volcanic activities. Dashed lines show previous position of Japanese islands and Korean Peninsula [modified from Chough et al. (2000) and Maruyama et al. (1997)].
formed during the Shimonoseki time (Ota and Yabumoto, 1998). This intensive volcanism and associated uplift of the arc complex likely increased the sedimentary flux into the Kanmon–Gyeongsang Basin, in particular to its southeastern margin, to change the basin geometry. During the shrinkage of the basin on its eastern side (Fig. 7c), the stromatolite-forming environments were destroyed or migrated to the west.

5. Summary

1. The Early Cretaceous stromatolites of the Kanmon Group (SW Japan) and the Gyeongsang Supergroup (S. Korea) were formed in intertidal–supratidal environments, occasionally exposed to arid conditions, along the large-scale intracontinental lake margin in East Asia.

2. Three abundant types of stromatolites are recognized, i.e., flat type, columnar type, and domal type. The thickness of clastic layers of the stromatolites and the associated sedimentary facies suggest that the flux of terrigenous clastics into the depositional site may have controlled this morphological diversity of the Early Cretaceous nonmarine stromatolites. The flat type occurred in very shallow proximal settings, while the domal type in relatively deeper, distal ones.

6. Acknowledgments

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7. References


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