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## Composition and spatial distribution of microencrusters and microbial crusts in upper Jurassic–lowermost Cretaceous reef limestone (Torinosu Limestone, southwest Japan)

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**Abstract** Tethyan microencrusters and microbial crusts, most of them previously unknown in Japanese Mesozoic biotas, are present in the uppermost Jurassic–lowermost Cretaceous Torinosu Limestone distributed in southwestern Japan. They construct reefal facies together with reef-forming metazoans. *Bacinella irregularis* and *Lithocodium aggregatum* are quantitatively most important, while subordinate constituents include *Thaumatoporella parvovesiculifera*, *Koskinobullina socialis*, *Iberopora bodewi*, *Girvanella* sp. and “*Tubiphytes*“ *morronei*. They are especially common in the shallow-water reefal facies, but appear micritic in outcrops. Microencrusters and microbial crusts can only be recognized in thin sections, and they grow around the reef building metazoans and form bindstone. Each microencruster exhibits some specific spatial distribution associated with its paleoecology. Similarities with the taxonomic composition of the upper Jurassic Tethyan microencruster association imply that the community extended geographically at least to the Tethyan gateway where the Japanese Island Arc was located.

**Keywords** Microencrusters · Microbial crusts · Reefs · Jurassic–Cretaceous · Japan

### Introduction

It has been widely recognized that microbialites are important components of Phanerozoic carbonate sediments, particularly in reefal limestone, where they play an important role in reef construction by frame-building and sediment-trapping (Webb 1996; Riding 2002). However, abundance of the microbialites has been uneven throughout the Phanerozoic, and was conspicuous in some

geologic intervals, including the Jurassic–early Cretaceous (Kiessling et al. 1999; Leinfelder and Schmid 2000; Riding 2000; Webb 2001; Leinfelder et al. 2002). Based mainly on investigations in Europe, it has been shown that microbialites, together with microencrusters (e.g. encrusting foraminifers and algae), played an important role in reef building (e.g. Leinfelder et al. 1993; Schmid 1996; Olivier et al. 2003). Microencrusters occur in a range of water energies, bathymetries, and nutrient/oxygen levels, and have been attempted using as environmental indicators (Leinfelder et al. 1993, 1996; Schmid 1996; Dupraz and Strasser 1999, 2002).

Limestone bodies of latest Jurassic–earliest Cretaceous age in southwest Japan, so-called Torinosu Limestone, are widespread and generally rich in bioclasts and ooids. Previous sedimentological studies (e.g. Kano 1988; Kano and Jiju 1995) showed that the Torinosu Limestone includes a reefal facies mainly composed of reef-builders such as corals and stromatoporoids. Unfortunately, these studies paid little attention to microencrusters and microbialites, although two genera had been observed in paleontological studies of the Torinosu Limestone (*Girvanella*; Yabe and Toyama 1928 and *Lithocodium*; Endo 1961).

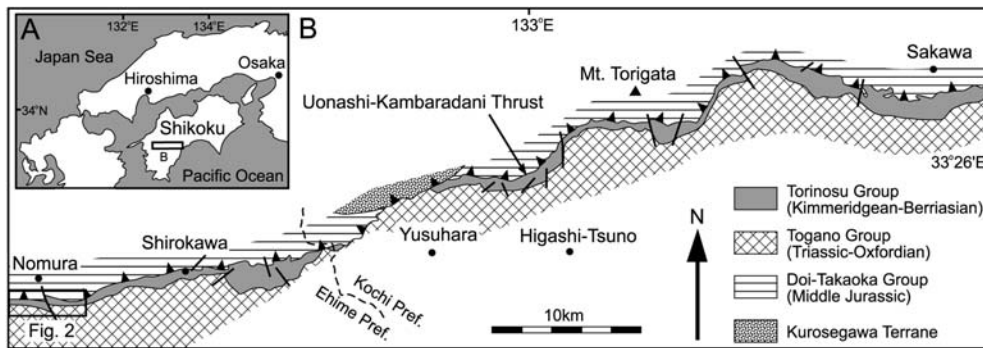
We found abundant occurrence of microencrusters and microbial crusts, in the Torinosu Limestone at Nomura Town, Ehime Prefecture, southwestern Japan (Fig. 1), and the purpose of this study is to describe them. Based on observations of large thin-sections, we also indicate the quantitative importance of microencrusters and microbial crusts in carbonate production, and discuss the paleoecology and microenvironment.

### Geological setting

General description of the Torinosu Group

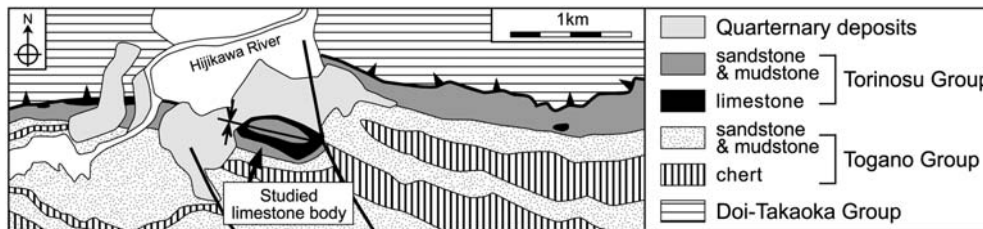
Sequences bearing the uppermost Jurassic–lowermost Cretaceous limestones are widespread in southwest Japan. Among these, the Torinosu Group has the widest distri-

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**Fig. 1** A Location of Shikoku Island and B distribution of the Torinosu Group (modified after Kano and Jiju 1995). The Torinosu Group unconformably lies upon the Triassic–upper Jurassic Togano

Group. The northern limit of the Torinosu Group is truncated by the Uonashi-Kambaradani Thrust. Geology of the study area (Fig. 2) is also shown



**Fig. 2** Geological map of the Nomura area (see inset in Fig. 1B). The distribution of the Torinosu Group is cut by NNW–SSE-trending faults. The limestone body studied is shown in the middle

bution, and forms an almost continuous belt across Shikoku Island (Fig. 1). The Torinosu Group consists of a mixture of siliciclasts and carbonates, and is thought to have been deposited in a forearc basin upon a Mesozoic accretional wedge named the Southern Chichibu Terrane (Matsuoka 1992). The Torinosu Group lies unconformably upon the Triassic–upper Jurassic Togano Group, and it is usually subdivided into the Tsukadani Formation, composed mainly of sandstone and conglomerate, and the Yatsuji Formation, composed mainly of mudstone, limestone and small amount of marlstone (Kano and Jiju 1995). Radiolaria and nannoplankton imply that the Tsukadani Formation is of Kimmeridgean–Tithonian age, and the Yatsuji Formation is of Tithonian–Berriasian age (Aita and Okada 1986). Limestones occur as many discontinuous lenticular bodies in some horizons of the Yatsuji Formation, and some of them attain a maximum lateral extent of 2 km and a maximum thickness of 120 m.

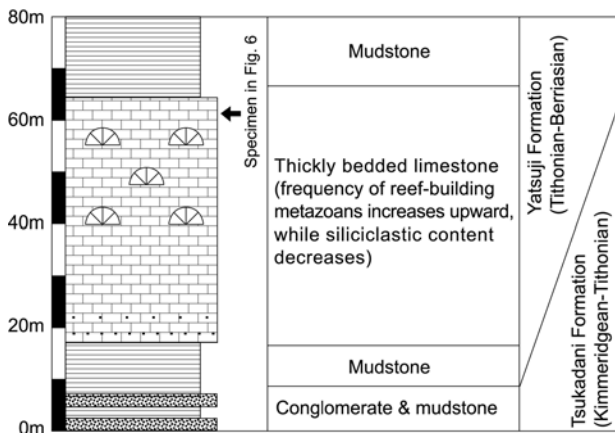
Depositional environment of the Torinosu Limestone have been described in sedimentological and petrological studies (Kano 1988; Morino 1993; Kano and Jiju 1995). These studies focused on the vertical facies change from the stratigraphically lower mudstone to the overlying limestone, and documented gradual increases in both the purity of the carbonates and the frequency of reef-building organisms (stromatoporoids and corals). Kano and Jiju (1995) inferred that the limestone was deposited as a carbonate mound rather than a reef, because of its scattered spatial distribution and its lack of a rigid framework derived from reef-building metazoans. From outcrop ob-

ervation, the reefal facies was described as a floatstone with micritic matrix, which implies low-energy conditions during mound development (Kano 1988; Kano and Jiju 1995).

#### Geology of study area

The Torinosu Group occurs as an E–W belt in the study area (Nomura Town, Ehime Prefecture, western Shikoku) with the northern limit truncated by an ENE–WSW-trending thrust (Uonashi Thrust), and is covered in place by Quaternary deposits (Fig. 2). We investigated the largest limestone bodies in the study area (Fig. 2). This body occurs as a dome with a width of 600 m situated upon a hill that occupies the axis of a WNW–ESE-trending syncline. It mainly consists of reefal facies. Outcrops on the flanks of the hill expose deposits below the limestone that are several meters thick and consist mostly of conglomerate with chert gravels. This facies is comparable to typical siliciclasts of the Tsukadani Formation. This conglomeratic section is overlain by mudstone and limestone and it corresponds to the Yatsuji Formation (Fig. 3).

The thickness of the limestone is ca. 50 m. The limestone is thickly bedded and composed mainly of bioclastic packstone–wackestone. The basal part includes a higher proportion of siliciclasts with decrease up-section. Bioclasts in the limestone include corals, stromatoporoids, microencrusters, molluscs, brachiopods and



**Fig. 3** Schematic lithological column of the Torinosu Group in the study area. Arrow indicates sampling horizon of the specimen shown in Fig. 6

echinoderm remains. Oncoids are common in some horizons. Frame-building metazoans, corals and stromatoporoids are dominant, increase in frequency upward and are mostly preserved in growth positions, but at outcrops are seldom seen to form reef frameworks by themselves. The reefal facies contains abundant microencrusters and microbial crusts that appear micritic in outcrops, and exhibit floatstone fabric without distinct reef frameworks. The limestone body is followed up-section by mudstone that crops out along the syncline axis on the hilltop, although no outcrop shows a direct contact between the two lithologies.

## Material and methods

We made thin sections from 135 rock samples from throughout the limestone body (Figs. 4, and 5), containing abundant microencrusters and microbial crusts (including calcareous microbes), which are barely recognizable in outcrops. The composition of microencruster associations in the limestone under study appears to vary in order of hand specimens to thin sections. Particularly in reefal facies, the dominant species of microencrusters vary relative to the shapes and sizes of available spaces, and to their spatial relationship with frame-builders. In order to examine the spatial distribution of microencrusters and microbial crusts, we collected a large sample from typical reefal facies containing abundant microencrusters, and made polished slabs 12×50 cm in size (top view). Since it was difficult to differentiate microencrusters and microbial crusts from micritic sediments by observing only polished surfaces, we prepared thin sections. The spatial distribution of reef organisms, sediment (allomicrite), and cement in the thin sections are shown in Fig. 6. We observed that much of the apparently micritic matrix in polished slabs consists of microencrusters and microbial crusts. The examined materials were first divided into six components (microencrusters and microbial crusts, stromatoporoid, coral, bioclasts, allomicrite and fine-grained bioclasts and cements; Fig. 6A). In the second step, the microencrusters and microbial crusts were further subdivided into six subcomponents (Fig. 6B). We designate a subcomponent *Lithocodium* and *Bacinella*, because these two taxa are closely related and in some cases are not separated by a well-defined boundary. Subordinate microencrusters (*Koskinobullina socialis*, “*Tubiphytes morronensis*, *Girvanella* sp.) are shown together with microbial crusts, as well as other microencrusters and microbial crusts, because of their scattered spatial distribution. Photographs of

the large thin sections are shown in Fig. 7, with their locations shown in Fig. 6B.

## Microencrusters of the limestone under study

All microencrusters identified in this study are comparable with Jurassic–Cretaceous forms known in Europe (e.g. Leinfelder et al. 1993, 1996; Schmid 1996; Dupraz and Strasser 1999, 2002). We will first describe the taxa found in the reef facies before we discuss their spatial distribution and paleoecology. Only *Girvanella* (Yabe and Toyama 1928) and *Lithocodium* (Endo 1961) have been reported previously from the Torinosu Group, therefore this is the first description of a Jurassic–Cretaceous microencruster association from Japan.

### *Bacinella irregularis* Radoicic 1959

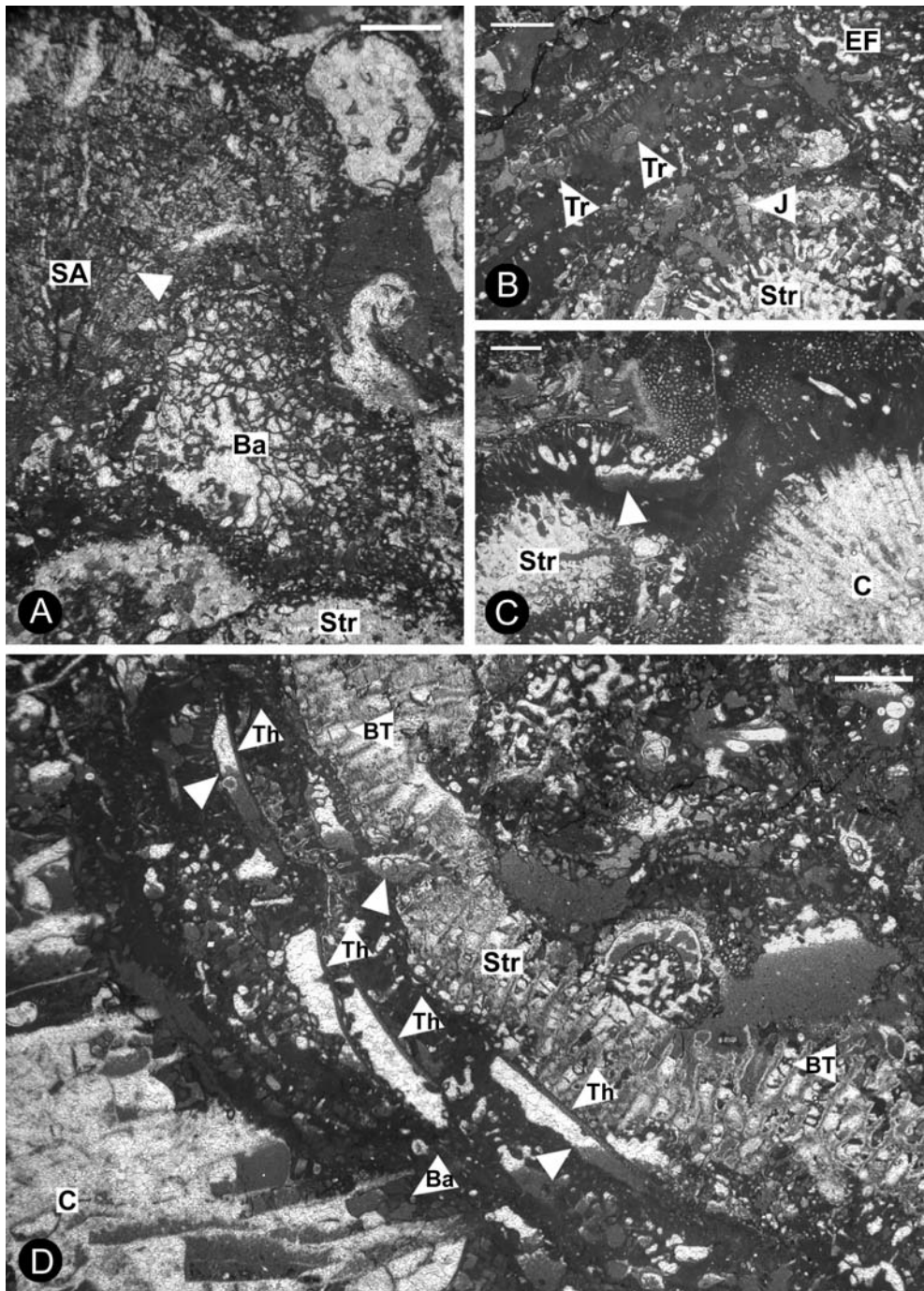
*Bacinella irregularis* is an enigmatic microencruster with an irregular micritic meshwork (thickness of threads is 15–20  $\mu\text{m}$ ; Fig. 4A) that is assumed to represent a cyanobacterial structure (e.g. Schäfer and Senowbari-Daryan 1983; Nose 1995; Schmid 1996). In the limestone body studied, where it encrusts reef organisms or bioclasts together with *Thaumatoporella parvovesiculifera*, it is a dominant microencruster, encrusting both foraminifers and *Lithocodium aggregatum*. In some cases, *B. irregularis* apparently has intruded into the skeletons of corals and stromatoporoids (Fig. 4D). It commonly occurs as thin micritic layers, which have been interpreted as being parts of a stromatoporoid skeleton (Yabe and Sugiyama 1935). The co-occurrence with solenoporacean algae is common (Fig. 4A), but the boundary between the two organisms is complex and sometimes obscure (see also e.g. Dupraz and Strasser 1999). Interspaces in the *Bacinella* meshwork are filled with both calcite spar and lime-mud (e.g. Fig. 4D).

### *Lithocodium aggregatum* Elliott 1956

and *Troglotella incrustans* Wernli and Fookes 1992

*Lithocodium aggregatum* is a microencruster, characterized by inner cavities and an aggregated outer wall with numerous alveoli about 50  $\mu\text{m}$  in diameter (Fig. 4B–D). It encrusts frame-builders (Fig. 4D) or bioclasts, together with other microencrusters. *L. aggregatum*, like *B. irregularis*, is a dominant encruster in the limestone under study.

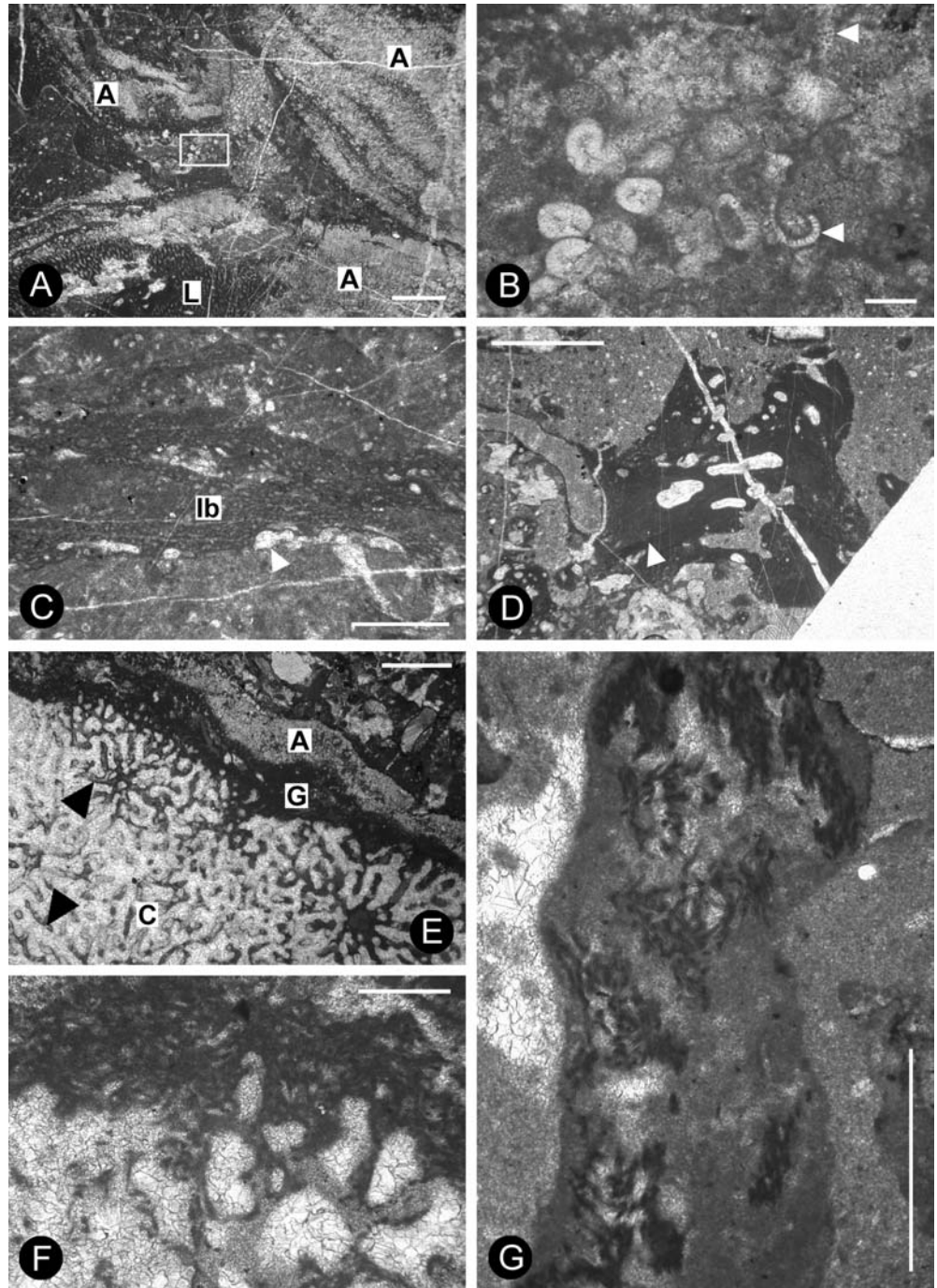
The inner cavities of *L. aggregatum* are sometimes occupied by bubble-like structures (20–50  $\mu\text{m}$  in diameter), which are inferred to be chambers of the foraminifer *Troglotella incrustans* (Schmid and Leinfelder 1996; Fig. 4B, D). The interiors of *L. aggregatum* and *T. incrustans* chambers are often filled with lime-mud (Fig. 4B–D). *L. aggregatum* was originally interpreted as a codiacean alga by Elliott (1956). Schmid and Leinfelder



**Fig. 4** Microencrusters in the uppermost Jurassic-lowermost Cretaceous Torinosu Group in the Nomura area, SW Japan. **A** Irregular meshwork of *Bacinella irregularis* (*Ba*) develops in interspaces between solenoporacean algae (*SA*) and a stromatoporoid (*Str*), and also invades algal skeletons (*arrow*). Sample N2-102. Length of bar is 1 mm. **B** *Lithocodium aggregatum* and encrusting foraminifers (*EF*) thickly encrusting the periphery of a stromatoporoid (*Str*). The inner cavities of *L. aggregatum* are occupied by *Troglotella incrustans* (*Tr*). Note that the crust is bored by juvenile *T. incrustans* (*J*). Inner spaces of *L. aggregatum* and *T. incrustans* chambers are filled by lime-mud. Sample N2-133. Length of bar is 1 mm. **C** Stromatoporoid (*Str*) and coral (*C*) encrusted by *L. aggregatum*. Note that lime-mud (*arrow*) accumulates in the inner

cavity of *L. aggregatum*, and shows a geopetal structure. Sample N2-097. Length of bar is 1 mm. **D** Encrusting microsuccession. Crevices in coral (*C*) encrusted and consequently filled by *B. irregularis* (*Ba*), and encrusted by *L. aggregatum* and *Thaumatoporella parvovesiculifera* (*Th*) association, and a thin stromatoporoid (*Str*; *Parastromatopora* sp.). Note that fine sediments accumulated in sheltered cavities beneath *T. parvovesiculifera*, and in inner cavities of *L. aggregatum* and *T. incrustans*, and form geopetal structures (*arrows*). In the galleries of the stromatoporoid, thin micritic lines (about 15  $\mu\text{m}$  in thickness; e.g. *BT*), are arranged perpendicular to pillars; these are inferred to be threads of *B. aggregatum*. Sample N2-132. Length of bar is 1 mm

**Fig. 5** Microencrusters in the uppermost Jurassic–lowermost Cretaceous Torinosu Group in the Nomura area, SW Japan. **A** *Koskinobullina socialis* inset in narrow interspaces of algae (**A**; *Neospongiostroma tosenis* Endo 1961) and *Lithocodium aggregatum* (L). This *K. socialis* colony grows to about 1 mm in height. Magnified view of the framed area is shown in Fig. 5B. Sample N2–008. Length of bar is 1 mm. **B** Enlarged detail of *K. socialis* in Fig. 5A. Fine pore structures of *K. socialis* are recognized in longitudinal section (*lower arrow*) and cross section (*upper arrow*). Length of bar is 100  $\mu$ m. **C** Crust formed by vesicles of *K. socialis* (*arrow*) and *Iberopora bodeuri* Grainer and Berthou 2002 (*Ib*). Sample N2–006. Length of bar is 500  $\mu$ m. **D** “*Tubiphytes*” *moronensis* growing on bioclasts. The outer test slightly shows growth lines (*arrow*). Sample N2–016. Length of bar is 1 mm. **E** *Girvanella* sp. (**G**) encrusting a coral (**C**), and encrusted by algae (**A**; *Neospongiostroma tosenis*). *Girvanella* sp. is also present in intraskeletal spaces of the coral (*arrows*). Magnified view of the framed area is shown in Fig. 5F. Sample N2–106. Length of bar is 1 mm. **F** Enlarged view of the framed area in Fig. 5E. *Girvanella* sp. fills the intraskeletal spaces of a coral colony. Length of bar is 250  $\mu$ m. **G** *Girvanella* sp. filaments within a microbial crust. Sample N2–122. Length of bar is 500  $\mu$ m

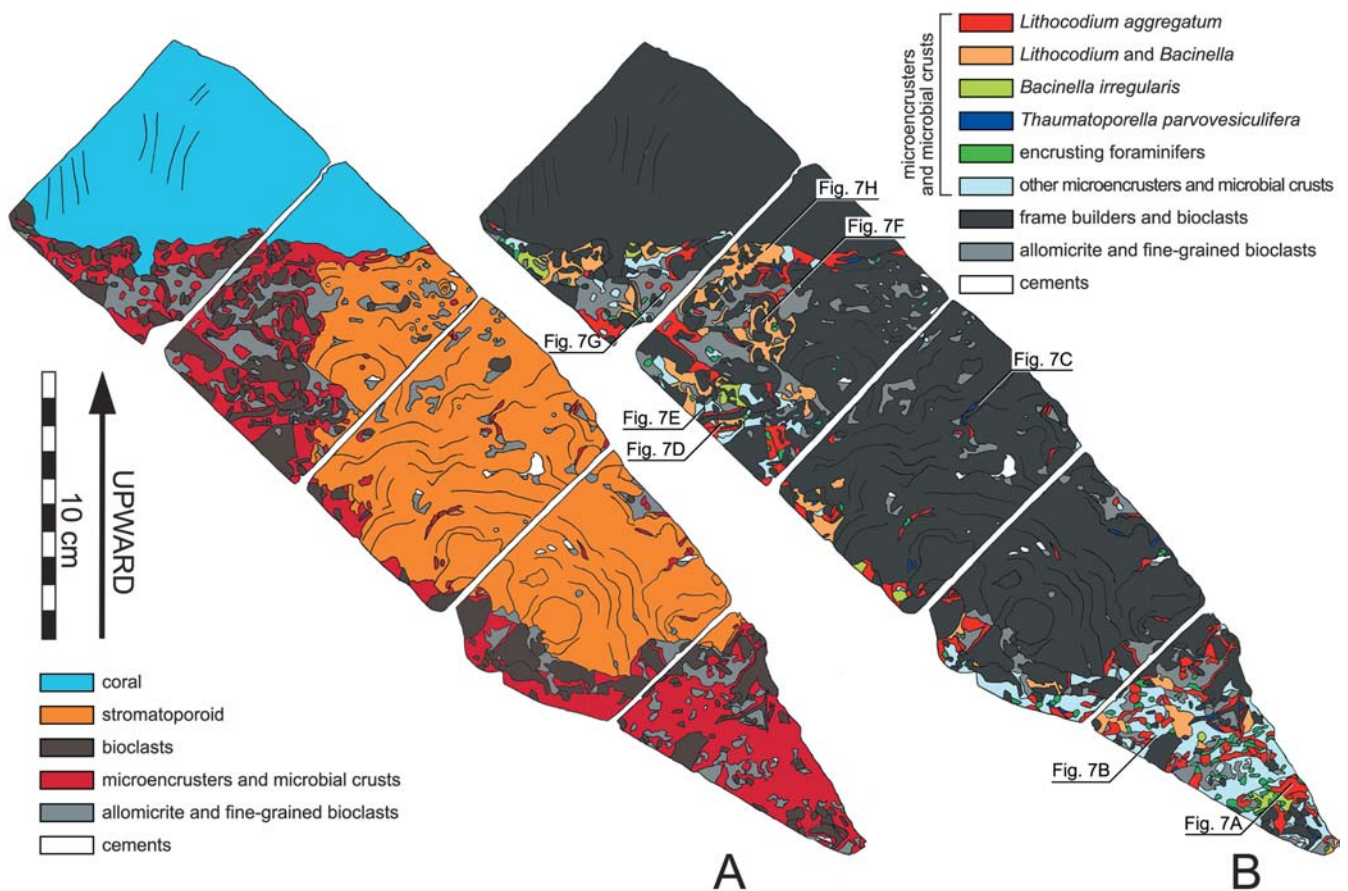


(1996) inferred that *L. aggregatum* was a foraminifer with symbiotic algae and had a commensal relationship with *T. incrustans*.

However Endo (1961) reported *L. japonicum* and *L. morikawai* from Torinosu Limestone, Schmid and Leinfelder (1996) regarded these species invalid because the proposal of these two species was mainly based on the features of *T. incrustans*. We follow their interpretation since no obvious difference exists between our Japanese forms and *L. aggregatum*.

#### *Thaumatoporella parvovesiculifera* (Raineri 1922)

*Thaumatoporella parvovesiculifera* consists of a thin wall structure (50–100  $\mu$ m thick) that rarely extends more than 3 mm laterally. This problematic genus has been interpreted as red alga (e.g. Ramalho 1971; Flügel 1979) or chlorophycean (e.g. Barattolo 1991), and it occurs commonly with *B. irregularis* and *L. aggregatum*. *T. parvovesiculifera* encrusts frame-builders or intergrows with other microencrusters such as *B. irregularis* and *L. aggregatum* (Fig. 4D). Open spaces are often present beneath the *T. parvovesiculifera* walls, and are filled with



**Fig. 6** Sketches of large thin sections from limestone of the Yatsuji Formation (Tithonian-Berriasian). **A** Spatial distribution of major components. **B** Spatial distribution of microencrusts and microbial crusts

sparitic cement and in some cases also with lime-mud (Fig. 4D). The wall structure thins toward its margins where it attaches directly to the substrate.

*Koskinobullina socialis* Cherchi and Schroeder 1979  
and *Iberopora bodeuri* Grainer and Berthou 2002

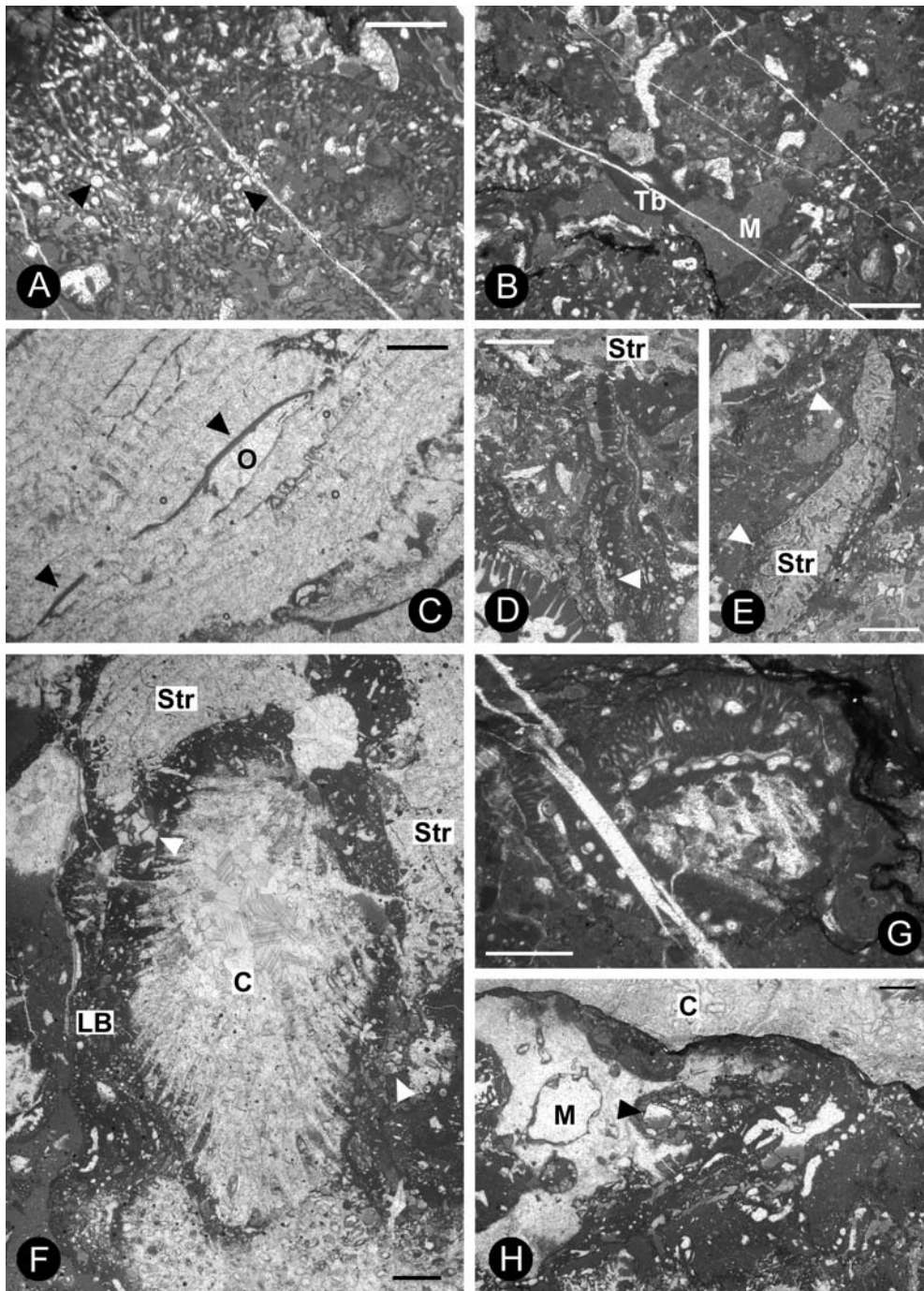
*Koskinobullina socialis* is an enigmatic fossil characterized by spherical to hemispherical vesicles 50–100  $\mu\text{m}$  in diameter (Fig. 5A–C). It has a thin (several  $\mu\text{m}$ ), radial-fibrous calcitic outer wall that exhibits regular, fine pores in places (Fig. 5B); and, the inner cavities are usually filled by sparite. Up to 1 mm thick colonies of *K. socialis* commonly occur in the restricted interspaces of frame-builders (Fig. 5A, B). *K. socialis* is quantitatively unimportant, although it does occur throughout the studied limestone. It is associated with *Iberopora bodeuri* (see Grainer and Berthou 2002; Helm et al. 2003; Fig. 5C), which consists of small bubble-like chambers about 50  $\mu\text{m}$  in length. This association forms crusts about 1 mm thick that extend laterally more than 10 mm.

*K. socialis* has been categorized as algae (Cherchi and Schroeder 1979, 1985) or foraminifers (e.g. Schmid 1996). Its vesicular morphology and distribution in re-

stricted spaces resemble *Wetheredella*, which has been compared with coccoid cyanobacteria by Kazmierczak and Kempe (1992). However, *K. socialis* in the samples exhibits comparatively spherical structures, and seldom shows the tubiforms that characterize *Wetheredella*.

“*Tubiphytes*” *morroneis* Crescenti 1969

“*Tubiphytes*” *morroneis* is an organism with central tubes (10–20  $\mu\text{m}$  in diameter) and an outer micritic envelope (10–50  $\mu\text{m}$  thick). Massive examples (2 mm in size) of this genus commonly exhibit growth lines in the outer envelopes (Fig. 5D). This genus occurs throughout the limestone under study, although the number of individuals is small. It is thought that the Jurassic–Cretaceous “*Tubiphytes*” *morroneis* differs from the Paleozoic species (e.g. Moussavian 1992), and the former has often been interpreted as a sessile foraminifer with endosymbiotic algae (e.g. Flügel 1981; Schmid 1995).



**Fig. 7** Microencrusters recognized in series of large thin sections (Fig. 6). The position of each view is shown in Fig. 6B. **A** *Lithocodium aggregatum* crust. Spherical chambers of *Troglotella incrustans* (arrows) occur in places. Length of bar is 1 mm. **B** Microbial crusts bind fine bioclasts, as commonly seen in the lower part of this specimen. Cavities within the microbial crusts are filled by lime-mud (*M*). "*Tubiphytes*" *morronensis* (*Tb*) is also present. Length of bar is 1 mm. **C** *Thaumatoporella parvovesiculifera* (arrows) within a massive stromatoporoid, which has grown from lower right to upper left. Open space (*O*) is recognized beneath *T. parvovesiculifera*. Length of bar is 1 mm. **D** *Koskinobullina socialis* (arrow) colonizing a shaded space below a stromatoporoid (*Str*), and being overgrown by *L. aggregatum*. Length of bar is 1 mm. **E** *Girvanella* sp. (arrows) directly encrusts the upper surface

of a stromatoporoid bioclast (*Str*). Its crust is less than 500  $\mu\text{m}$  thin. Length of bar is 1 mm. **F** *Lithocodium-Bacinella* association (*LB*) binding together coral (*C*) and stromatoporoid bioclasts (*Str*). Note that the threads of *Bacinella irregularis* (arrows) occur in cavities. Length of bar is 1 mm. **G** *Lithocodium / Troglotella* consortium encrusting a small bioclast. Length of bar is 1 mm. **H** Microencrusters developed below a massive coral (*C*). *B. irregularis* meshwork (arrow) develops around a mollusc shell (*M*; see also Fig. 6), and both are encrusted by other microencrusters (*L. aggregatum*, *T. parvovesiculifera* etc.). Note that lime-mud filling cavities in the *B. irregularis* meshwork appear as geopetal structures. Stylolite makes the boundary between coral skeleton and microbial crust. Length of bar is 1 mm

*Girvanella* sp.

The tubiform (about 10  $\mu\text{m}$  in diameter), calcareous microbe *Girvanella* sp. is regarded as a calcified cyanobacterial structure (e.g. Riding 1991) and occurs throughout the limestone under study. It commonly encrusts the surfaces of frame-builders and bioclasts (Fig. 5E, F), and forms folios sheets (<1 mm in thickness). *Girvanella* sp. also occurs in small open spaces between reef-building metazoans. Some *Girvanella* sp. filaments are associated with microbial crusts (Fig. 5G).

### Spatial distribution of microencrusters

#### Description of the large thin-sections

In order to examine spatial distribution of the above-mentioned microencrusters, we show the observation results of thin sections from a large sample (Fig. 6). The maximum thickness of this sample was about 33 cm, by reference to its geopetal structures, although the presence of stylolite structures suggests that some compaction has taken place. Part of reefal limestone consists of a large stromatoporoid (exposed in the middle of this sample) and a coral colony (at top). Interstices between reef-builders are partly filled with bioclasts (e.g. fragments of corals, stromatoporoids, calcareous algae, molluscs) and microencrusters/microbial crusts.

Approximately the lower 8 cm of this specimen are dominated by microencrusters, particularly *Lithocodium aggregatum* (Fig. 7A) and encrusting foraminifers (Fig. 6B). They normally encrust other individuals of microencrusters and bioclasts, and are surrounded by microbial crusts, which trap and bind fine-grained bioclasts (Fig. 7B). *Bacinella irregularis* fills some restricted spaces. "*Tubiphytes*" *morronensis* is also present in a narrow space of microbial crust, but its quantitative importance is low. The dense and repeated encrustations of various microencrusters and microbial crusts resulted in bindstone (Fig. 6B). This encrustation and the aggregation of *L. aggregatum* (Fig. 7A) formed in relatively open spaces.

The microencrusters/microbial crusts bindstone is covered by sediments including coral/stromatoporoid bioclasts (about 1–2 cm in diameter), and followed by a single massive stromatoporoid in growth position about 17 cm in height (Fig. 6A). Intraskelatal spaces, up to 2 cm in diameter, are developed in the stromatoporoid skeleton, and are filled by microencrusters, allomicrite and cement. *L. aggregatum* and *Thaumatoporella parvovesiculifera* are common in the intraskelatal spaces (Fig. 7C) in which they apparently fill. *L. aggregatum* exhibits the same upright growth direction as the stromatoporoids. Within the intraskelatal space, *T. parvovesiculifera* is accompanied with the lower open space (Fig. 7C), which is a common occurrence elsewhere. Therefore, this species grew over a stromatoporoid surface and was covered by a

subsequent growth of stromatoporoid rather than on a roof of the intraskelatal void.

Within the sediment located in upper left of this massive stromatoporoid, microencrusters commonly encrust bioclasts (up to 3 cm in diameter) of corals, stromatoporoids, calcareous algae and molluscs (Fig. 6A). The microencruster association in this area is dominated by *L. aggregatum* and *B. irregularis*, with less abundant *Koskinobullina socialis* (Fig. 7D) and *Girvanella* sp. (Fig. 7E). Association of *B. irregularis* and *L. aggregatum* often covers more than two bioclasts (Fig. 7F) and stabilizes the bioclastic sediments (Fig. 6B). *L. aggregatum* commonly encrusts small bioclasts (less than 2 mm in diameter; Fig. 7G). Allomicrite and fine-grained bioclasts fill remaining spaces.

A massive coral rests with upright growth orientation exposed in the upper part of the studied specimen. Microencrusters, including *L. aggregatum*, *B. irregularis* and *T. parvovesiculifera* occur beneath the coral skeleton. Some of them clearly exhibit a downward growth direction (Fig. 7H), which implies that their growth started from overhanging coral and they were able to live in a sheltered setting.

#### Quantitative analysis

Mapping of the components in the thin sections (Fig. 6; shows approximately 373  $\text{cm}^2$  of the entire area) permits quantitative analysis. The percent of area covered by each component in the specimen under study is shown in Table 1, and the percent for each subcomponent of microencrusters and microbial crusts is shown in Table 2.

These results document the importance of microencrusters and microbial crusts, although their ratio (15.8%) is smaller than for coral (23.0%) or stromatoporoid

**Table 1** Percentages of major components in the large thin-sections (Fig. 6A)

Component	%
Stromatoporoid	42.5
Coral	23.0
Microencrusters and microbial crusts	15.8
Bioclasts	11.2
Allomicrite and fine-grained bioclasts	7.2
Cements	0.3

**Table 2** Percentages of subcomponents of microencrusters and microbial crusts in the large thin-sections (Fig. 6B). Other microencrusters and microbial crusts include *Koskinobullina socialis*, *Tubiphytes morronensis*, *Girvanella* sp. and microbial crusts

Component	%
Other microencrusters	35.0
<i>Lithocodium aggregatum</i>	28.2
<i>Lithocodium</i> and <i>Bacinella</i>	25.0
Encrusting foraminifers	5.6
<i>Bacinella irregularis</i>	4.8
<i>Thaumatoporella parvovesiculifera</i>	1.4



(42.5%). In contrast, allomicrite and fine-grained bioclasts occupy only a small area (7.2%) of the section under study. Thus, micritic sediments in outcrops were largely produced by microencrusts and microbial crusts. Cements occupy only a very small area (0.3%).

Among the “microencrusts and microbial crusts,” *L. aggregatum* and *B. irregularis* are most significant and together account for nearly 60% of the area. Much of the other microencrusts and microbial crusts subcomponent includes microbial crusts. We conclude that the trapping and binding of bioclasts by microencrusts and microbial crusts was a very significant process in the specimen under study.

## Discussion

### Characters and roles of microencrusts

The paleoecological role and the microenvironment of each microencruster will be discussed here based on its spatial distributions. *Lithocodium aggregatum* and *Bacinella irregularis* are frequently associated (see also e.g. Leinfelder et al. 1993; Dupraz and Strasser 1999). They commonly encrust relatively large bioclasts and play a significant role in agglutination and stabilization (Fig. 7F). Their contribution to crust formation is the greatest of all the microencrusts (Table 2). Although the two species were intimately associated, under the microscope, they do exhibit some differences in the spatial distribution. *L. aggregatum* generally occurs in open microenvironments such as on the surfaces of bioclasts, frame-builders or other microencrusts (e.g. Figs. 4C, and 7G). In contrast, *B. irregularis* tends to fill relatively enclosed spaces, and more commonly exhibits irregular growth (e.g. Figs. 4A, D, 7F, H). Similar occurrence of *B. irregularis* was reported by Ourribane et al. (2000). In addition, *L. aggregatum* solely encrusts open substrates (Fig. 7G), but *B. irregularis* rarely does. Comparing these two dominant microencrusts, we conclude that *B. irregularis* was more adapted to restricted microenvironments, whereas *L. aggregatum* was more capable of encrusting in open environments.

*L. aggregatum* and other encrusting foraminifers repeatedly encrusted each other (Fig. 6B), and together with microbial crusts, formed a thick bindstone. However, other encrusting foraminifers lacked the ability to agglutinate large bioclasts alone.

“*Tubiphytes*“ *morronensis*, *Thaumatoporella parvovesiculifera*, *Koskinobullina socialis* and *Girvanella* sp. are quantitatively minor components of the limestone studied. However, we might have underestimated the importance of *Girvanella* sp., because even under a microscope its calcified filaments are often difficult to differentiate from microbial crusts (Fig. 5G). These subordinate microencrusts commonly joined to contribute to crust formation, and they do show variation in spatial distribution. “*Tubiphytes*“ *morronensis* often grew on coarse bioclasts (Fig. 5D), and may have stabilized sed-

iments in open microenvironments, even though it could dwell in restricted space (Fig. 7B). *T. parvovesiculifera* commonly scalloped hard substrates such as stromatoporous skeletons, and it also grew in sheltered cavities. *K. socialis* often encrusts directly on reefal metazoans (Fig. 5A), and also occurs in shaded spaces (Fig. 7D). A similar occurrence was reported by Helm and Schülke (1998) who indicated that *K. socialis* is restricted to the early stage of crust formation. This species may have preferred to grow consolidate substrate such as metazoan skeletons. This species exhibits thick development in a relatively restricted space in the specimen studied (Fig. 5A), whereas Cherchi and Schroeder (1985) reported a thick colony on a convex substrate from Cenomanian in northern Spain.

### Significance of microencrusts in the Torinosu Limestone

This study is the first documentation of a significant microencrusts/microbial crusts contribution to carbonate production in the upper Jurassic–lower Cretaceous Torinosu Limestone. More importantly, our observations of large thin-sections allow the recognition of their encrusting/binding occurrence, which is not recognizable at outcrops in the field. Outcrops show a scattered distribution of reef-building organisms mostly in growth position enclosed in a micritic matrix, which supports the erroneous conclusion that the reefal facies represents a low-energy, mound-like deposit (cf. Kano 1988; Kano and Jiju 1995). Our thin-section observations clearly indicate that much of the micritic matrix (more than two-thirds; Table 1) consists of microencrusts and microbial crusts that played a major role in encrusting metazoans, binding reef debris, and agglutinating large skeletal fragments. This abundance of microencrusts and microbial crusts were previously unknown in the Torinosu Limestone.

These findings led us to reconsider the depositional environments and processes of the Torinosu Limestone, since the previous environmental interpretation as a low-energy mound (Kano 1988; Kano and Jiju 1995) was not based on the recognition of microencrusts and microbial crusts. The apparent micritic matrix is largely originated from microencrusts and microbial crusts rather than allomicrite, and therefore a low-energy condition is not necessary to be taken into account for this limestone. The microencrusts and microbial crusts might have formed a reef-like structure that potentially persisted against a high-energy condition. Actually, Leinfelder (1992) reported the binding and the stabilization of reef debris by microencrusts and microbial crusts from high-energy reefs.

In comparison with microencruster associations of the European upper Jurassic reefs, the association of this study broadly resembles to “high-diversity association” or “*Bacinella* - *Lithocodium* association” described by Leinfelder et al. (1993) and Schmid (1996). These European

associations were interpreted as shallow-very shallow facies. Our association is also comparable to the encrustation scenarios 1 and 2 of Dupraz and Strasser (1999), which were formed under relatively clear water and oligotrophic conditions. Clear and shallow marine environments reconstructed from the microencruster association of Torinosu Limestone is consistent to abundance of reef-forming metazoans and is the same as the previous interpretation (Kano 1988; Kano and Jiju 1995). However, our investigation only focuses on one of many bodies of the Torinosu Limestone. Further research needs to be done to recognize variation in the microencruster association and the corresponding environments for other limestone bodies.

Our microencruster association includes *B. irregularis*, *T. parvovesiculifera*, *K. socialis*, *Iberopora bodeuri* and “*Tubiphytes*” *morroneis*, which have been newly reported in Japanese upper Jurassic–lower Cretaceous limestone. The finding of these species confirms that the distribution of the European upper Jurassic microencruster association should have been extended as far as Japan, which lies in the Tethyan gateway (Leinfelder et al. 2002).

## Conclusions

1. Tethyan microencruster association is present in an uppermost Jurassic–lowermost Cretaceous limestone (the Torinosu Group) in southwestern Japan (Nomura Town, Ehime Prefecture). It is abundant especially in reefal facies.
2. The microencruster association consists of *Bacinella irregularis*, *Lithocodium aggregatum*, *Thaumatoporella parvovesiculifera*, *Koskinobullina socialis*, *Iberopora bodeuri*, *Girvanella* sp. and “*Tubiphytes*” *morroneis*, with the first two of these taxa being quantitatively most important. They are comparable to the European high-diversity association or *Bacinella-Lithocodium* association (Leinfelder et al. 1993; Schmid 1996), indicating a shallow-water condition. Except for *L. aggregatum* and *Girvanella* sp., recognized taxa are described from the Japanese Mesozoic for the first time.
3. Spatial distribution of the microencrusters was used to interpret the paleoecological role and microenvironment. *B. irregularis* and *L. aggregatum* agglutinate relatively large bioclasts. *L. aggregatum*, encrusting foraminifers and microbial crusts were capable of forming bindstone. *B. irregularis* was adapted to restricted microenvironments. *K. socialis* tends to encrust metazoan skeletons in both open and shaded environment.
4. Much of the apparent micritic matrix originated from microbial crusts and microencrusters that encrusted/stabilized reefal debris. The encrusted structure might have had potential for surviving in high-energy water. This finding refutes the previous reconstruction that Torinosu Limestone was deposited in a low-energy

environment. According to our results, the depositional environment can be characterized as shallow and clear water, and microencrusters/microbial crusts constructed reefal structures together with reef-forming metazoans.

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