Upper Triassic mid-oceanic shallow water ecosystems of the Panthalassa Ocean: insights from the Sambosan Accretionary Complex, Southwest Japan

PEYBERNES, Camille

Abstract

Reef proliferation and carbonate platform expansion took place during the Late Triassic. These major trends are mainly documented in the Tethys realm. The main goal of this study is to improve our understanding of mid-oceanic carbonate platforms of the West Panthalassa during the Late Triassic. Special focus is given to the shallow water depositional settings and to the ecological structure and evolution of reef ecosystems. We investigate Upper Triassic carbonates of the Sambosan Accretionary Complex in Southwest Japan. Detailed microfacies analysis has been carried out on thin sections from twenty four localities at Kyushu Island, Shikoku Island and Honshu Island. Our results highlight the evolution of mid-oceanic shallow water environments of the West Panthalassa domain during the Late Triassic and refine the correlation of the Sambosan limestone with coeval shallow water carbonates of the Tethys and East Panthalassa domain. This work provides valuable data to improve Early Mesozoic paleogeographic reconstructions.

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Upper Triassic mid-oceanic shallow water ecosystems of the Panthalassa Ocean: insights from the Sambosan Accretionary Complex, Southwest Japan

THESE

TEXTE

présentée à la Faculté des Sciences de l’Université de Genève pour obtenir le grade de Docteur ès Sciences, mention Sciences de la Terre

par

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de
Grenoble (France)

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Thèse de Monsieur Camille PEYBERNES intitulée :

"Upper Triassic Mid-oceanic Shallow Water Ecosystems of the Panthalassa Ocean: Insights from the Sambosan Accretionary Complex, Southwest Japan"

La Faculté des sciences, sur le préavis de Madame R. MARTINI, professeuse associée et directrice de thèse (Département des sciences de la Terre), Madame E. VENNIN, professeure (Unité de formation et de recherche Sciences Vie, Terre et Environnement, Département Environnement, Terre, Evolution, Climat, Université de Bourgogne, Dijon, France), Monsieur L. KRYSTYN, professeur (Geozentrum der Universität Wien, Institut für Paläontologie, Wien, Austria) et Monsieur T. ONOUE, professeur (Department of Earth & Environmental Sciences, Kumamoto University, Japan), autorise l'impression de la présente thèse, sans exprimer d'opinion sur les propositions qui y sont énoncées.

Genève, le 22 mars 2016

Thèse - 4914 -

Le Doyen

N.B.- La thèse doit porter la déclaration précédente et remplir les conditions énumérées dans les "Informations relatives aux thèses de doctorat à l'Université de Genève".
“The naturalist will feel [...] astonishment [...] after having examined the soft and almost gelatinous bodies of these apparently insignificant coral-polypifers, and when he knows that the solid reef increases only at the outer edge, which day and night is lashed by the breakers of an ocean never at rest.”

Charles Darwin, The Structure and Distribution of Coral Reefs, 1842

Whitsunday Island, South Pacific, Capt. Beechey’s voyage
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Abstract

After the End Permian mass extinction, Triassic marine ecosystems, and especially shallow water carbonate environments are deeply impoverished with respect to biotic composition. Reef recovery was not fully accomplished before the Late Triassic. Reef proliferation and carbonate platform expansion took place during the late Middle Triassic (Ladinian) and the Late Triassic. Maximum of reef abundance and diversity were reached during the Late Ladinian-Early Carnian and Late Norian, in relation with the onset of large carbonate platforms. These major trends are mainly documented in the Tethys realm. Coeval shallow water environments of the Panthalassa domain remain poorly understood. Since most of the Triassic oceanic lithosphere has been subducted, remains of panthalassic carbonate platforms crop out primarily in Circum-Pacific accretionary complexes and terranes.

The main goal of this study is to improve our understanding of mid-oceanic carbonate platforms of the West Panthalassa during the Late Triassic. Special focus is given to the shallow water depositional settings and to the ecological structure and evolution of reef ecosystems. To reach this objective, we investigate Upper Triassic carbonates of the Sambosan Accretionary Complex (SAC) in Southwest Japan. During fieldtrips in 2012 and 2013, twenty four localities in Kyushu Island, Shikoku Island and the Kii Peninsula (Honshu Island) have been sampled, some of them for the first time. Detailed microfacies analysis have been carried out on thin sections. Additionally samples have been dissolved for conodont extraction to improve the biostratigraphic framework of the Sambosan limestone.

Paleontological content analysis of limestone clasts embedded in volcanioclastic matrix from several localities revealed a Ladinian?–Lower Carnian reef biota association. This assemblage notably includes scleractinian corals, calcareous sponges, calcareous algae, foraminifers and microproblematica. Seventeen species are reported for the first time in Japan among the thirty-three that are identified.

Reef limestone has been the purpose of in-depth investigation. Microfacies analysis and biotic composition, along with field observations led us to identify two types of reef. The first corresponds to microbialite-rich, Ladinian?–Lower Carnian reefs including numerous microproblematica. The second correspond to sponge-dominated Late Carnian to Norian-Rhaetian? reefs. The stratigraphic attribution is based on biotic associations and biostratigraphic markers including conodonts. Multivariate analyses based on compilation of two hundred and one genera of calcareous sponges, foraminifers and microproblematica from eighteen reef
localities of the Tethys and Panthalassa oceans show a strong biogeographic affinity between reef biota of the SAC and those of Oman (South Tethys domain) during the Ladinian-Carnian as well as during the Norian-Rhaetian. Additionally, our results suggest connections with the East Panthalassa domain (i.e., North America terranes) during the Norian-Rhaetian.

Overall analysis of the limestone microfacies from Shikoku Island documents the various depositional settings of the SAC carbonate platforms. Biostratigraphic markers allow us to refine the dating of some of these microfacies. Based on microfacies comparisons with ancient and recent analogues, a new speculative depositional model of the SAC carbonate platform(s) is proposed.

Until now, microfacies of the Upper Triassic limestone from the Kii Peninsula have been poorly investigated. In this study, we describe the microfacies of the Upper Triassic limestone from the central part and eastern part of the Kii Peninsula and compare them with their counterparts in other localities of the SAC.

To date, only Upper Triassic foraminifer associations have been reported from the SAC (except some rare occurrences of Paleozoic taxa). During this study we found at Mt. Sambosan type locality an enigmatic foraminifer assemblage that has affinity with some Lower Jurassic associations of the Tethys realm. This discovery indicates that carbonate sedimentation at the top of panthalassic seamount of the SAC may have lasted until the Early Jurassic.

The Sambosan limestone commonly occurs as clasts in polymict breccias that are here described in detail. Based on the lithologic composition, two main types of breccia are distinguished. The absence of shear fabrics and the highly heterogeneous composition suggest that these breccia represent mass-movement deposits that result from seamount collapse in the mid-oceanic realm, probably near the outer trench.

This study improves our understanding of the mid-oceanic limestone of the SAC and more generally of Upper Triassic shallow water carbonates. In particular, our results highlight the evolution of mid-oceanic shallow water environments of the West Panthalassa domain during the Late Triassic and refine the correlation of the SAC limestone with coeval shallow water carbonates of the Tethys and East Panthalassa domain. This work provides valuable data to improve Early Mesozoic paleogeographic reconstructions.
Résumé

Au Trias, après la crise biologique de la fin du Permien, les écosystèmes marins sont profondément modifiés. L’ensemble des environnements carbonatés peu profonds est durablement affecté jusqu’à plusieurs millions d’années après la crise. Plus précisément, le rétablissement des récifs ne sera pleinement accompli qu’au Trias supérieur. La fin du Trias moyen (Ladinien) et le Trias supérieur correspondent à une période de prolifération des écosystèmes récifaux ainsi que de développement et d’expansion de l’ensemble des plateformes carbonatées. De la fin du Ladinien au début du Carnien ainsi qu’à la fin du Norien, les récifs connaissent leur maximum d’abondance et de diversité. Conjointement, de vastes plateformes carbonatées se mettent en place. Ces grandes tendances dans l’évolution des environnements carbonatés peu profond sont principalement basées sur l’étude d’affleurements situés dans le domaine téthysien. Leurs équivalents en dehors de la Téthys restent mal connus. A cause de la subduction de la quasi-totalité de la lithosphère océanique triasique, les reliques des plateformes carbonatées de l’ancien Océan Panthalassa (l’ancêtre de l’Océan Pacifique) ne sont préservées que sous la forme de fragments, piégés dans les complexes d’accrétion et les terranes actuellement situés sur le pourtour du Pacifique.


L’étude détaillée du contenu paléontologique de clastes calcaires issus de brèches à matrice volcaniclástique provenant de plusieurs localités, a permis de mettre en évidence une association faunistique caractéristique des récifs du Ladinien ?–Carnien inférieur. Cet assemblage comprend notamment des coraux scléractiniaires, des éponges calcaires, des


Les calcaires du Trias supérieur de la Péninsule de Kii, jusqu’à présent très peu étudiés du point de vue des microfaciès, sont décrits et comparés avec les autres localités du Complexe d’Accrétion du Sambosan.

Jusqu’à présent, les associations de foraminifères décrites dans le Complexe d’Accrétion du Sambosan ont toutes été attribuées au Trias supérieur (à l’exception de rares occurrences de taxons paléozoïques). Au cours de ce travail, nous avons trouvé à la localité type du Mont Sambosan un assemblage de foraminifères ayant des affinités avec les associations du Jurassique inférieur du domaine téthysien. Cette découverte indique que la sédimentation carbonatée au sommet des îles océaniques du Complexe d’Accrétion du Sambosan aurait pu continuer jusqu’au Jurassique inférieur.

Enfin, les calcaires du Trias supérieur du Sambosan étant souvent présents au sein de brèches polygéniques, ces dernières sont décrites en détail et des hypothèses sont proposées quant à leur formation. Sur la base de leur composition lithologique, deux principaux types de brèches sont distingués. L’absence de structure de cisaillement et le caractère hautement polygénique de ces brèches suggèrent que ces dernières correspondent à des dépôts gravitaires résultant...
d’effondrements d’îles océaniques dans un milieu océanique ouvert et proche de la fosse de subduction.

Résumé
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Chapter 1: Introduction

1.1. The Triassic world: paleogeography, climate and biosphere evolution

The Triassic (252 Ma to 201 Ma, ICS 2015) is a period of important changes in the biosphere (e.g., Tucker and Benton 1982; Stanley 1988; Payne and Van de Schootbrugge 2007; Benton et al. 2013). This period follows the end-Permian mass extinction (Raup 1979; Sepkoski 1981; Raup and Sepkoski 1982; Benton and Twitchett 2003; Benton and Newell 2014) and includes the appearance of important terrestrial and marine taxa such as dinosaurs (Benton et al. 2014), mammals (Lucas and Luo 1993; Datta 2005), scleractinian corals (Stanley 1981; Stanley and Fautin 2001) and calcareous nannofossils (Bralower et al. 1991; Onoue and Yoshida 2010; Gardin et al. 2012). During the Triassic the paleogeography was very peculiar: all continents were merged into a single supercontinent, the Pangea (Ziegler et al. 1982). Situated in the intertropical belt (30°North to 30° South), the Tethys ocean indented the Pangea and connected the huge Panthalassa Ocean to the east (Fig. 1.1).

Fig. 1.1 Paleogeography during the Late Triassic. Base map modified after Flügel (2002), Climate (italic) after Boucot et al. (2013)
The Triassic climate is usually considered to be mostly arid, especially in the Tethys region (Stefani et al. 2010), with extreme continentality (hot summers and relatively cold winter) and a strong monsoonal circulation (Parrish 1993; Mutti and Weissert 1995; Sellwood and Valdes 2006). More humid episodes, such as the Carnian Pluvial Event (Simms and Ruffell 1989; Dal Corso et al. 2015; Ruffell et al. 2015) punctuated the Triassic climatic history. The Triassic is characterized at first order by a long term cooling (Korte et al. 2005; Kiessling 2010). Recently, Trotter et al. (2015) identified, from $\delta^{18}O$ record in conodont apatite, three major warming cycles: in the Early Triassic, in the mid-Late Carnian and in the Late Norian. Cooler intervals in the Late Ladinian–Early Carnian and Early–Middle Norian correspond to the two well-identified reef blooms of the Late Triassic (Flügel 2002).

1.2. Shallow water carbonate deposition during the Late Triassic

In the aftermath of the end-Permian crisis, recovery of benthic marine communities occurred during the Early and Middle Triassic (Stanley 1988; Flügel 2002; Galfetti et al. 2008; Brayard et al. 2011; Hofmann et al. 2014a, b; Vennin et al. 2015). Proliferation and latitudinal expansion of reef ecosystems happened during the Late Triassic (Flügel 2002; Kiessling 2010). The rise of carbonate production led to the onset of extensive platforms, especially in the Tethys Ocean (Fig. 1.1). The Middle and early Late Triassic platforms of The Dolomites and the following Norian Dolomia Principale/Haupt Dolomite Fm. (e.g., Bosellini and Rossi 1974; Gaetani et al. 1981; Wendt 1982; Maurer 2000; Gianolla et al. 2003; Russo 2005; Emmerich et al. 2005; Marangon et al. 2011; Gattolin et al. 2015) and the Norian-Rhaetian Daschtein limestone of the Northern Calcareous Alps (e.g., Dullo 1980; Wurm 1982; Enos and Samankassou 1998; Haas et al. 2010; Martindale et al. 2013a, b) are the most impressive representatives of these Upper Triassic carbonate platforms and have been extensively studied. Other coeval platforms of the Tethys realm crop out in Sicily (Senowbari-Daryan et al. 1982; Di Stefano and Senowbari-Daryan 1985; Di Stefano et al. 1990), Slovenia (Turnsek et al 1982; Buser et al. 1982; Ramovs 1987; Gale et al. 2013, 2014), Greece (Schäfer and Senowbari-Daryan 1982; Senowbari-Daryan et al. 1996), Turkey (Okay and Altiner 2004; Senowbari-Daryan and Link 2011), Caucasus (Belyaeva and Punina 1994), Iran (Senowbari-Daryan 2005; Fürsich et al. 2005; Senowbari-Daryan et al. 2010), Himalaya (Bhargava and Bassi 1985; Kristan-Tollmann 1984), Oman and United Arab Emirates (Bernecker 1996, 2005, 2007; Maurer et al. 2008), off-shore Australia (Röhl et al. 1991; Kristan-Tollmann and Gramann 1992) Indonesia (Martini et al. 1997, 2000, 2004) Papua New Guinea (Kristan-Tollmann 1990) and Thailand (Ueno et al. 2012). These
Tethyan carbonates platforms are typically characterized by wide lagoonal settings in the platform interior and reefal environments at the platform margin. In the lagoons, abundant involutinids (aragonitic foraminifers), megalodonts (bivalves) and dasycladacean (calcareous algae) flourished. Reef environments were dominated by calcareous sponges, scleractinian corals and microproblematica (e.g., Dullo 1980; Senowbari-Daryan 1982; Gazdzicki 1983; Di Stefano and Senowbari-Daryan 1985; Flügel 2002; Bernecker 2005).

Upper Triassic marine environment of the North America Craton (i.e., Northwest Pangea) are well-developed (e.g., Oldow 1981) but reefs are much rarer than in Tethys (one notable exception is a Carnian reef at Pardonet hill, British Columbia, Zonneveld et al. 2007). Nevertheless corals and calcareous sponges have been reported from Nevada (Senowbari-Daryan and Stanley 1992; Roniewicz and Stanley 2013). On the other hand, Upper Triassic carbonate platforms developed in relation with island arcs located in the East Panthalassa Ocean (Lime Peak, Reid and Tempelman-Kluit 1987; Summit point, Stanley and Senowbari-Daryan 1986; Martin Bridge Fm., Stanley et al. 2008). These old island arcs are nowadays accreted as terrane to the American craton (e.g., Stikinia, Wallowa). Some Upper Triassic shallow water limestone have also been reported from Mexico and Peru (Stanley et al. 1994; Stanley 1994; Senowbari-Daryan and Stanley 1994).


As demonstrated above, most of our knowledge on Triassic marine environments is founded on Tethyan sedimentary records. However, during the Late Triassic, the Panthalassa Ocean was wider than the Pacific today (Flügel 2002) and therefore represented an important part of the Earth surface. Nevertheless, since most of Triassic oceanic crust has been subducted, little is known about Panthalassic environments. Therefore, the study of Upper Triassic carbonate platforms that originated from the Panthalassa Ocean, and are nowadays accreted in the circum-Pacific domain, is pivotal to the understanding of global shallow water environment evolution during the Late Triassic.

1.3. Aims of the study

This thesis is part of the REEFCADE project (REEF and CArbonate build up DEvelopment) which aims at comparing sedimentological and micropaleontological data between localities in
the Tethys and Panthalassa provinces in order to decipher the local, regional and global factors that controlled the evolution of shallow water carbonate systems. It is a long term research effort, started in 2006, and sponsored by the Swiss National Science Foundation (SNSF).

The main goals of the present work are to improve our knowledge of the shallow water carbonate sedimentation during the Late Triassic and to better understand the paleoecology, biogeography and evolution of mid-oceanic ecosystems in the Western Panthalassa domain. This study is based on the investigation of the Upper Triassic limestone that crop out in the Sambosan Accretionary Complex (SAC), Southwest Japan (Fig. 1.2). The SAC is a narrow belt (few kilometers) of the Outer zone of Southwest Japan that can be followed from the Ryukyu Islands in the south to the Kanto Mountains (Honshu Island) in the north (Matsuoka 1992; Onoue and Sano 2007).

Fig. 1.2 Location of the Sambosan Accretionary complex in South West Japan and coeval accretionary complexes in East Asia (left corner). Modified after Isozaki et al. (2010).
Our work mainly focuses on localities at Shikoku Island and Kii Peninsula (Honshu Island) and completes the previous investigations of the SAC limestone, carried out by Tetsuji Onoue, Jérôme Chablais and colleagues in Okinawa Islands, Kyushu Island, Shikoku Island and in the Kanto Mountains (Honshu Island). Other parts of the REEFCADE project include the study of Upper Triassic carbonates of the Antimonio and Vizcaino (Mexico) and Wallowa (USA) terranes as representative of the Eastern Panthalassa domain.

1.4. Geological setting of the Sambosan Accretionary Complex

During all the Phanerozoic, Japan was located at the convergent margin between the South China block and the subducting Paleo-Pacific plates (i.e., Izanagi, Kula, Pacific, Philippine) (Isozaki 1997; Isozaki et al. 2010; Wakita 2013). As a consequence, the Japanese archipelago mainly consists of a younging southward succession of tectonic units composed of accreted oceanic material and intrusive and volcanic rocks (magmatic arc system). This succession of tectonic units is covered by thick volcano-sedimentary sequences in Northeast Japan but is well visible in Southwest Japan (Isozaki 1997), where accretionary complex belts (i.e., Akiyoshi, Mino Tamba, Chichibu, Shimanto) and their metamorphosed counterpart (i.e., Sangun, Sambagawa) crop out (Fig. 1.3). The Mino-Tamba and Chichibu accretionary complexes and their coeval plutonic belts represent remnants of arc-trench system developed during the Jurassic between the Asian continent and Pacific Ocean (Panthalassa) (Isozaki 1997). They resulted from the subduction of the Izanagi plate which lasted from the Early Jurassic to the Early Cretaceous time (Maruyama and Seno 1986; Isozaki and Maruyama 1991; Otsuki 1992; Osozawa 1994; Maruyama 1997; Maruyama et al. 1997; Wakita and Metcalfe 2005; Isozaki et al. 2010). Nowadays, these units are referred to as ‘belts’ but were formerly called terranes (e.g., Ichikawa et al. 1990; Matsuoka 1992).
Accretionary complexes (AC) are composed of oceanic lithologies such as deep and shallow water limestone, OIB basalts, ribbon cherts, terrigenous mudstone and sandstone. The original succession of these lithologies is reconstructed according to the Ocean Plate Stratigraphy model (OPS, Wakita and Metcalfe 2005) (Fig. 1.4). The idealized stratigraphic succession of OPS consists of pillow basalt, limestone, radiolarian cherts, siliceous shales and shales and sandstone in ascending order (Isozaki et al. 1990; Wakita and Metcalfe 2005; Kusky et al. 2013; Safonova et al. 2015).
In more detail, two main types of occurrence are recognized in the Jurassic accretionary complexes of Japan: coherent and chaotic. Coherent stratigraphic units are composed of imbricated thrust sheets that consist of sequences of radiolarian ribbon cherts, siliceous mudstones and turbidites in ascending order (Matsuoka and Yao 1990; Matsuoka 1992; Isozaki 1997; Wakita and Metcalfe 2005). They represent the offscrapped, upper parts of the OPS (Wakita and Metcalfe 2005) and are well exposed in the Inuyama area (Mino-Tamba AC) and in Honshu Island and Togano area (Chichibu AC) in Shikoku Island (Isozaki 1997). Chaotic-type units (Fig. 1.5) are characterized by block-in-matrix mode of occurrence (i.e., mélange sensu Raymond 1984). Blocks of various size, age and lithology are chaotically scattered in argillaceous matrix (Isozaki 1997). Chaotic-type units result from the progressive disruption of OPS during accretionary processes (Wakita 2012). The Sambosan Accretionary Complex correspond to this chaotic type unit or mélange (Isozaki 1997).
The ‘Sambosan formation’ was first introduced by Suzuki (1931) in the geological map of Kochi (Shikoku Island). Matsuoka and Yao (1990) and Matsuoka (1992) defined the ‘Sambosan suberrane’ as an olistostromal sequence (i.e., chaotic-type units *sensu* Isozaki 1997) with limestone, basalt and chert blocks embedded in a Upper Jurassic–Lower Cretaceous mudstone matrix. In this work, we follow Onoue and Sano (2007) who defined the Sambosan Accretionary Complex (SAC) as a latest Jurassic to earliest Cretaceous subduction-generated accretionary complex in Southwest Japan. The SAC is tectonically separated from the Jurassic Chichibu AC to the north, and from the Lower Cretaceous to Paleogene Shimanto AC to the south. Tectonic boundary between the SAC and the Shimanto AC is referred to as the Butsuzo Tectonic Line (BTL, Fig. 1.2, 1.3).

Recently, the SAC has been correlated with the Sambagawa belt which corresponds to the metamorphosed equivalent of the Sambosan AC (Fig. 1.6; Isozaki et al. 2010; Aoki et al. 2014).
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**Fig. 1.6:** Cross section of the Japanese active margin during the Early Cretaceous (modified after Aoki et al. 2014). AC: Accretionary Complex, FAB: Fore Arc Basin, HP-AC: High Pressure Accretionary Complex.

The Chichibu belt (including the SAC) is considered by some authors as a tectonic outlier of the Mino-Tamba accretionary complex (Isozaki 1997). However, in the Mino-Tamba belt, Upper Triassic shallow water limestone are absent (but deep water limestone of late Upper Triassic age occur in Tanai area, Takano et al. 2010; Sano et al. 2010).

Accretionary complexes coeval with the SAC are exposed in North East Japan, Far East Russia and in the Philippines (Fig. 1.2). The North Kitakami-Oshima belt in the northeast of Honshu Island and the southwest of Hokkaido Island (Fig. 1.3) is equivalent to the Chichibu belt (Isozaki et al. 2010; Wakita 2013). Further North, correlative accretionary complexes crop out in the Sikhote-Alin region of Far East Russia (Kojima 1989; Faure and Natal’In 1992), especially in the Khabarovsk complex (Kojima et al. 1991), Nadahanda terrane (Kemkin 2012) and Taukha terrane (Kemkin and Taketani 2008). In South East Asia, Jurassic-Early Cretaceous accretionary complexes exposed in the Calamian Islands (North Palawan block, the Philippines) have been correlated to coeval accretionary complexes of Japan (Faure and Ishida 1990; Zamoras and Matsuoka 2001; Zamoras and Matsuoka 2004). They include Upper Paleozoic and Upper Triassic limestone (Kiessling and Flügel 2000).

1.5. Approaches

To better understand the evolution of shallow water ecosystems and related depositional settings, this study combines sedimentological and paleontological approaches to provide constrains on the biostratigraphy, biogeography and paleogeography of the SAC.
**Sedimentology**

Intensive sampling of 23 localities in Kyushu Island, Shikoku Island and in the Kii Peninsula (Honshu Island) and subsequent microfacies analysis on 455 thin sections have been carried out to further document the petrographical properties of the SAC limestone. Our results provide additional data to build a theoretical depositional model of the Upper Triassic carbonate platform(s) deposited at the top of Panthalassic seamount(s). Our results are compared with coeval platforms of the Tethys and Panthalassa Oceans.

**Paleontology**

In this work, we report new occurrences of shallow water biota which complete the paleontological inventory of the SAC limestone. Our results highlight the biodiversity of mid-oceanic shallow water environments during the Late Triassic.

**Biostratigraphy**

Assemblage-based biostratigraphy combined with conodont biostratigraphy (38 limestone samples of 2 to 4 kg each have been dissolved for this study) allow us to refine the stratigraphic framework of the SAC and more generally to discuss the significance of biostratigraphic markers that are present in the Upper Triassic platform carbonates worldwide.

**Paleobiogeography**

In this study, multivariate analyses are used to quantitatively assess the biogeographical distribution patterns of Upper Triassic reef biota and discuss the biogeographic affinities between reef localities of the Tethys and Panthalassa Oceans. Statistical tests are applied to confirm the significance of our results.

**Paleogeography and geodynamics**

The aforementioned methods provide data that can improve paleogeographic reconstructions, and especially the original location of Upper Triassic build-ups in the West Panthalassa. Additionally, field observations are opportunities to document the geologic structure and lithologic composition of the SAC and infer the processes that occurred during the collapse and the accretion of the seamount(s).
1.6. Thesis organisation

In Chapter 2 we describe a new Ladinian?-Carnian reef biota that was found in limestone clasts from the SAC at Shikoku Island.

In Chapter 3, we investigate ten reef limestone localities of the SAC at Shikoku Island. Two types of reef are characterized based on field observations, microfacies analysis and biotic content inventory. The biostratigraphy of reef limestone from the SAC at Shikoku is refined and biogeographic affinities with coeval reef fauna of the Tethys and Panthalassa realms are quantitatively assess, using multivariate analyses and statistical test.

In Chapter 4, eight microfacies are identified in the limestone units of the SAC at Shikoku Island and a new depositional model of the SAC build-up(s) is proposed.

Chapter 5 reports the mode of occurrence and microfacies of the Upper Triassic limestone in the Kii Peninsula (Honshu Island). Comparison with the other SAC limestone units is carried out.

In Chapter 6, an enigmatic foraminifer association of Lower Jurassic affinity is reported from a limestone clast at the Sambosan type locality (Shikoku Island). Implications for the geological history of the Sambosan limestone are discussed.

In Chapter 7, we present field observations and microfacies analysis of several breccia units that crop out in the SAC. Two types of breccia are identified by the mean of Non-metric Multidimensional Scaling (NMDS). These breccia are interpreted as mass movement deposits on the seamount(s) flanks and surrounding seafloor. We discuss the implications of these observations for the geological history of Mesozoic oceanic rocks from the Panthalassa Ocean.

References


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Suzuki (1931) Kochi sheet of the geological map of Japan.


Chapter 2: Upper Triassic (Ladinian?-Carnian) reef biota from the Sambosan Accretionary Complex, Shikoku, Japan

Abstract
The Middle and Late Triassic was a time of important reef development. This evolution, which is primarily documented in the Tethys realm, comprised several phases from the Anisian to the Rhaetian. To help elucidate the less constrained reef evolution in the Panthalassa domain, samples of reef limestone were collected from several localities along the Sambosan Accretionary Complex in Shikoku Island, southwest Japan. In this paper, we report a well-preserved and comprehensive reef biota, including several taxonomic groups, such as scleractinian corals, calcified sponges, calcareous algae, foraminifers, and microproblematica. Seventeen species are described for the first time in Japan among the 33 that are identified in this study. The assemblage-based biostratigraphy and index taxa indicate a Ladinian?-Carnian age. This new finding corresponds to an older reef limestone than has been previously identified in the Sambosan Accretionary Complex and may represent the initiation of shallow-water carbonate deposition on western Panthalassa seamounts. This work also provides valuable insights on reef ecosystem biodiversity in the Panthalassa domain during the Middle? to Late Triassic.

2.1. Introduction

After the dramatic End Permian extinction, a recovery and proliferation of reef ecosystems occurred during the Middle and, especially, the Late Triassic. This period was characterized by the rise of reefs that were dominated by coralline sponges and scleractinian corals. Based on compositional differences of the coral and sphinctozoan sponge associations, four taxonomic turning points have been established: Middle Anisian to Early Ladinian, Late Ladinian to Early Carnian, Middle and Late Carnian to Early Norian, and Norian to Rhaetian (Flügel 2002). This evolution is predominantly documented in the Tethys realm. To confirm this evolution of reef ecosystem in the Panthalassa domain, more data are needed. The Late Ladinian to Early Carnian (formerly called the Ladinian-Cordevolian) corresponds to the first reef optimum of the Upper Triassic (Flügel 2002). According to this author, although they belong to different stages, Ladinian and Carnian reefs share many characteristics (i.e., biotic composition, paleogeographical setting, and reef types), but above all they are chiefly characterized by the abundance of microproblematica (e.g., Tubiphytes) and microbial crusts. In the Panthalassa, Ladinian-Carnian shallow water biocollections are very rare, and their description focuses mainly on corals (Roniewicz and Stanley Jr 1998). To improve our knowledge of Panthalassan reefs, this paper describes and illustrates new Triassic biota from the reef limestone of the Sambosan Accretionary Complex (SAC), in Shikoku Island, southwest Japan (Fig. 2.1a, b).

Limestone units that outcrop in the SAC represent the remains of atoll-type carbonates that were deposited at the top of seamounts in the Panthalassa during the Late Triassic (Kanmera 1969; Tamura 1990; Onoue and Sano 2007; Chablais et al. 2010b). Previous studies of reef limestone in the SAC have evidenced the presence of a lower-middle Norian reef association at the Kamase locality, Kyushu (Onoue and Stanley 2008), a Norian reef biota at Inaba cave, Shikoku (Chablais et al. 2010c) and some representatives of Carnian biota in a few limestone clasts at Koguchi locality, Kyushu (Senowbari-Daryan et al. 2012). Moreover, numerous paleontological studies have described a single taxonomic group from the reef limestone of the SAC. Corals have been reported from Kyushu (Kanmera 1964; Stanley and Onoue 2015), Shikoku (Kobayashi 1931; Okuda et al. 2005; Stanley and Onoue 2015) and the Kii Peninsula (Yamato Omine Research Group 1976; Okuda and Yamagiwa 1978; Okuda 2006). Other studies have reported the occurrence of algae (Endo and Horiguchi 1967; Mori 1983; Senowbari-Daryan et al. 2012), foraminifers (Kristan-Tollmann 1991; Chablais et al. 2011) and sponges (Chablais et al. 2010c; Senowbari-Daryan et al. 2012). However, Ladinian-Carnian reef biota remain poorly documented in the SAC. The aims of this paper are (1) to document
occurrences of new reef biota from Shikoku, (2) to discuss the age of the reef limestone that outcrops in Shikoku, and (3) to compare the Tethyan and Panthalassan Ladinian-Carnian reef ecosystems.

Fig. 2.1 Location maps of studied localities. a Distribution of the Sambosan Accretionary Complex in Japan, modified after Chablais et al. (2011). b Location of the studied localities in Shikoku Island. c–e Maps showing location of studied outcrops: c Loc. 1 Tsuno, d Loc. 2 Mt. Sambosan, e Loc. 3 Mt. Ishidate and Loc. 4 Konose Kyo.
2.2. Geological setting
The Sambosan Accretionary Complex (according to Onoue and Sano 2007) is a narrow belt in southwest Japan. It is distributed from the Ryukyu Islands in the south to the Kanto Mountains in the north (Fig. 2.1a). The SAC represents the southern marginal portion of the Chichibu belt and is separated from the Shimanto Accretionary Complex to the south by the Butsuzo Tectonic Line (BTL) (Fig. 2.1a). The SAC is composed of basalts, cherts, mudstones and sandstones, and limestone. The limestone units are devoid of siliciclastic material, and the biotic content indicates an Upper Triassic age. The terrigenous-free limestone is interpreted as atoll-type limestone that was deposited at the top of oceanic seamounts (Kanmera 1969; Tamura 1990; Onoue and Sano 2007; Onoue and Stanley 2008; Chablais et al. 2010b). The Upper Triassic limestone units mostly outcrop either (1) as massive limestone slabs or (2) as limestone clasts that are embedded in a volcaniclastic matrix (VCM) (Fig. 2.2a, b). The limestone slabs are laterally tens of meters to kilometers in size. The limestone clasts are a few centimeters to a few decimeters in diameter and form a breccia with a volcaniclastic matrix (VCM breccia) and basaltic clasts. The first mode of occurrence resulted from the dismantling of the seamount in the trench and/or in the accretionary wedge during the accretion-subduction processes, whereas the second is usually interpreted as debris flow and debris avalanche deposits on the flank of midoceanic seamount prior to the accretion (Onoue and Sano 2007; Chablais et al. 2010a). The breccia units are often in close vicinity to massive limestone slabs. Interestingly, most of the investigated limestone clasts were found close to the BTL. The Ladinian?-Carnian reef biota presented in this study predominantly occur in limestone clasts of the VCM breccia.

2.3. Materials and methods
The studied material, which was collected at four localities (Loc. 1–Loc. 4) in central and eastern Shikoku (Fig. 2.1b), comes exclusively from limestone clasts that are part of the VCM breccia. To our knowledge, none of these localities, except the type locality of the Sambosan limestone near Kochi, have previously been studied in detail. Sixty-eight thin-sections were prepared, scanned with a high-resolution film scanner (Nikon CoolScan 4000 ED) and observed in transmitted light with an optical microscope. Large polished slabs (max. 30 × 20 cm) were prepared for some of the samples to illustrate the geometries and morphologies of the reefal textures. Cathodoluminescence using a CI8200 MK5-optical cathodoluminescence with a cold cathode was used on a few samples to reveal specific sedimentological features that are concealed in transmitted light. We used beam conditions of 15 kV at 50–60 mA with an
unfocused beam of approximately 1 cm. The observation chamber had a residual pressure of 80 mTorr. The samples were not coated. The thin-sections were photographed in a dark room with a digital camera: with a normal exposure for natural light and with a long exposure under cathodoluminescence. The parameters were kept fixed to avoid additional treatment. Neither filters nor standards were used for image calibration.

Fig. 2.2 Outcrops and reef limestone polished slabs. a Reef limestone blocks in VCM Loc. 1 Tsuno. b Limestone clast in VCM breccia Loc. 2 Mt. Sambosan. c Reef limestone polished slab CP127 Loc. 1 Tsuno. d Reef limestone polished slab CP127 Loc. 1 Tsuno. B Brachiopod, C Scleractinian coral, S Sphinctozoan sponge
2.4. Facies

The reef limestone from the four localities can be described as coral-sponge-microproblematica boundstone (Fig. 2.2c, d). Sphinctozoan sponges, corals, and *Tubiphytes* form a very loose reef framework. Usually, peloid-microproblematica grainstone-packstone sediment fills the interstices between skeletal elements. Additionally, peloidal and clotted micrite also occupy an important volume of the rock. Most of the peloids forming the peloidal and clotted micrite are tiny (10–40 μm in diameter) and are possibly of microbial origin (Chafetz 1986; Reid 1987). Encrusting organisms and microbial crusts bind the skeletal elements and the peloidal matrix. Voids that are infilled with isopachous cements are locally observed. A general description and the characteristics of the facies for each locality are detailed below.

**Loc. 1 Tsuno, Fig. 2.1c (samples CP120–CP132) 33° 27.870N–133° 11.868E**

The outcrop is situated in a small riverbed, which was dry in March 2012, 2 km north of the town of Tsuno (Tsuno district, Kochi prefecture) (Fig. 2.1c). Reefal limestone blocks of tens of centimeters to few meters are embedded in green volcaniclastic and sparry calcite matrix. All of the collected blocks correspond to coral-sponge boundstone with minor amounts of microproblematica and algae. The preservation is good despite minor silicification. The taxonomic diversity is high (25 species were determined). The primary framebuilders (mainly corals and sponges) are encrusted by several generations of microbial crust and sessile organisms. There are a few voids with isopachous cements, and peloid-microproblematica grainstone-packstone sediment and peloidal-clotted micrite fill the interstices between the skeletal elements.

**Loc. 2 Mount Sambosan, Fig. 2.1d (samples CP15, CP18, CP 20–25, CP215, JC325G) 33° 34.438N–133° 42.741E**

This area corresponds to the Sambosan limestone type locality and was first described by Kobayashi (1931) and then investigated by the Yamato Omine Research Group (1981), Okuda et al. (2005), Chablais (2010) and Stanley and Onoue (2015). The studied outcrop is located along the Ryugado Skyline Road, below the castle (Konan district, Kochi prefecture) (Fig. 2.1d). Reef limestone clasts of few centimeters in diameter occur in a VCM breccia that is in a fault relationship with a large limestone slab. Limestone clasts of other facies (e.g., peloid-echinoderm grainstone and intraclast-bioclast floatstone) are also present in this breccia unit. The reef facies can be described as *Tubiphytes*-sponges boundstone. *Tubiphytes* and sponges
form a loose framework with abundant interstitial sediment (peloidal and clotted micrite, and peloid microproblematica packstone grainstone). Many large voids are infilled with isopachous cements that occupy the remaining space between the framebuilders. The reef limestone in this locality is relatively well preserved, except for the sponges that are often strongly recrystallized.

**Loc. 3 Mount Ishidate, Fig. 2.1e (samples CP62, CP66) 33° 46.800–N 134° 4.019E**

Small reef limestone clasts (few centimeters in diameter) have been collected from VCM breccia along the trail that leads to the Mount Ishidate summit (Kito district, Tokushima prefecture) (Fig. 2.1e). Clasts are composed of sponge-Tubiphytes-Microproblematica boundstone. Most of the samples are poorly preserved, but some organisms can still be recognized, especially sponges and microproblematica.

**Loc. 4 Konose Kyo, Fig. 2.1e (samples CP40, 41) 33° 47.009N–134° 4.969E**

Reef clasts that are embedded in VCM were found on a mountain crest 200 m above the road in Konose Kyo (Kito district, Tokushima prefecture) (Fig. 2.1e). These clasts are a few centimeters in size. All of the clasts that were collected at this locality display reef facies that correspond mainly to sponge-Tubiphytes boundstone, with several large voids that are infilled with isopachous cements. Other outcrops of the SAC in Konose Kyo have been studied by Ishida (1983, 1987), Onoue et al. (2004) and Chablais (2010). The samples are recrystallized but include well-preserved sponges and foraminifera.

### 2.5 Biotic content

**Scleractinian corals**

Scleractinian corals are relatively rare in the SAC although several authors have described Carnian and Norian taxa (Kanmera 1964; Okuda and Yamagiwa 1978; Okuda et al. 2005; Okuda 2006; Onoue and Stanley 2008; Stanley and Onoue 2015). In our samples, corals are represented mainly by phaceloid forms and subordinately by thamnasteroid forms. Corals collected at Loc. 1 Tsuno can be separated into three categories and cautiously assigned to a genus.
**Retiophyllia** sp. (Fig. 2.3a)
Material: Several specimens in Loc. 1 Tsuno (samples CP120, 121, 123–127).
Description: Phaceloid colony with corallites of 1.5–2 cm in diameter. 41–49 septa. No collumella. Depending on the section, few to many densely arranged dissepiments are observed in the corallite periphery (compare Figs. 2.3a with 2.8).
Remarks: Four species of genus *Retiophyllia* are known in the SAC. *Retiophyllia* cf. *R. frechi*, which was reported from Kyushu (Stanley and Onoue 2015), closely resemble in size and number of septa (40–48) the species that are described herein. *Retiophyllia tosaensis* is smaller and has more dissepiments (4–5 per millimeter) and septa. It has been found at Mt. Sambosan (Loc. 2) in VCM breccia together with the Carnian coral *Craspedophyllia* ramose (Stanley and Onoue 2015). *Retiophyllia eguchii* from Kyushu (Kanmera 1964) and *Retiophyllia wasabiniensis* from Kii Peninsula (Okuda and Yamagiwa 1978) also have small-sized corallites and possess more septa and dissepiments. In the material described in this paper, the recrystallization prevented reliable septa cycle analysis and thus determination at the specific level remains questionable. However, considering the size of the corallites and the number of septa, our specimens are closely related to *Retiophyllia* cf. *R. frechi*.
Stratigraphic and geographic distribution: *Retiophyllia* is a common Triassic genus including many species widely distributed in the Tethys and Panthalassa domain.

**Scleractinia** sp. 1 (Fig. 2.3b)
Material: Two specimens in Loc. 1 Tsuno (sample CP127).
Description: Phaceloid colony with closely arranged small corallites (0.5 cm in diameter). Corallite sizes and arrangements resemble immature specimens of *R. tosaensis* that were described by Stanley and Onoue (2015). However, this specimen is very recrystallized, which precludes the determination of the species.

*Thamnasteriamorpha okudai* Stanley and Onoue 2015 (Fig. 2.3c)
Material: Two specimens in Loc. 1 Tsuno (sample CP127).
Description: Thamnasterioid colony. Columella is sometimes visible. This specimen is strongly similar to *Thamnasteria* sp. in Kanmera (1964), Yamato Omine Research Group (1976) and Okuda and Yamagiwa (1978). In their recent revision of corals from the SAC, Stanley and Onoue (2015) attributed specimens that were previously assigned to *Thamnasteria* sp. to a new species, *Thamnasteriamorpha okudai*.
Stratigraphic and geographic distribution: Upper Triassic of Japan: Koguchi, Kyushu (Kanmera 1964; Stanley and Onoue 2015), Wasabidani, Honshu (Yamato Omine Research Group 1976; Okuda and Yamagiwa 1978; Stanley and Onoue 2015) and Tsuno, Shikoku (this study).

Fig. 2.3 Scleractinian corals and Zardinia. a Corallite of Retiophyllia sp. with numerous dissepiments CP127. b Coral sp.2 CP127. C Thamnasteriomorpha okudai CP127F. d–f Zardinia perisulcata, d–e Slightly oblique longitudinal sections CP127R, f transversal section CP131. g Oblique section exhibiting the internally chambered construction CP131B. h Zardinia sp. showing several stems closely clustered together CP131. Scale bars are 5 mm
Calcareous sponges

Coralline or hypercalcified sponges include sphinctozoan, inozoan, chaetetids, disjectoporids and spongimorphids. Their description follows the nomenclature in Senowbari-Daryan and García-Bellido (2002), Finks and Rigby (2004) and Senowbari-Daryan and Rigby (2015). Corallines sponges are frequent in the Sambosan limestone, but recrystallization often precluded an accurate determination. Nevertheless, well-preserved sponges were discovered at Loc. 1 Tsuno and Loc. 4 Konose Kyo.

Sphinctozoans

Sphinctozoans are a group of sponges with an aragonitic or Mg-calcitic basal skeleton. They represent a highly polyphyletic taxon (Müller-Wille and Reitner 1993).

Zardinia perisulcata Dieci et al. 1968 (Fig. 2.3d–h)

Material: Five specimens in Loc. 1 Tsuno (samples CP127R, 128, 131B, 132) and two specimens in Loc. 2 Konose Kyo (samples CP41A, 41C).

Description: Conical sponge composed of several chambers, subrectangular in longitudinal section. The spongocoel is axial and is pierced by numerous perforations. The exowall is imperforate and segmentation is not visible from the outside. A reticular filling skeleton exhibiting several irregularly arranged longitudinal tubes is observed.

Remarks: In one sample (Fig. 2.3h), several stems, each of which is defined by an axial spongocoel, seem to be clustered closely together. This feature would reflect the branching of this specimen. This morphology is close to Zardinia? sp. 2 Senowbari-Daryan and Schäfer (1983; pl. 3, Fig. 6 and pl. 4, Figs. 5, 6, 7).

Stratigraphic and geographic distribution: The genus Zardinia was introduced from the Carnian of the Dolomites (Dieci et al. 1968) and is reported from the Ladinian of the Northern Alps (Wolff 1973), Anisian of Carinthia (Flügel 1986), Carnian of Slovenia (Buser et al. 1982), Carnian of Oman (Bernecker 1996, Senowbari-Daryan et al. 1999), Lower Carnian of Slovenia (Senowbari-Daryan 1981), Wetterstein limestone of Hungary (Flügel et al. 1992), Carnian of Greece (Hydra island, Senowbari-Daryan and Schäfer 1983), Lower Carnian Cipit Boulder Dolomites (Sánchez-Beristain 2010), Carnian Leckkogel beds (Dullo and Lein 1982). As far as we know, Zardinia is reported here for the first time in Japan.
Cryptocoelia zitteli Steinmann 1882 (Fig. 2.4a, b)

Material: One specimen in Loc. 1 Tsuno (sample CP130C), one in Loc. 3 Mt. Ishidate (sample CP66A).

Description: Cryptocoelia zitteli consists of several crescent-shaped chambers that define overlapping flat segments. The chamber walls are porate, and a narrow retrosiphonate spongocoel runs through the skeleton. The chambers are stabilized by wide trabecules, which are also called pillar, which constitute the primary basal skeleton. Characteristically, these trabecules are laminated and are composed of coarse crystalline, and therefore lighter material. In our samples, the lamination of pillars is difficult to see probably due to diagenesis overprint. Vesiculae fill the chambers and constitute a secondary basal skeleton (Müller-Wille and Reitner 1993).

Remarks: The growth strategy, paleobiology, and taxonomic affinities of this species are discussed in Müller-Wille and Reitner (1993). These authors also emphasize the frequent encrustation of this sponge by small Tubiphytes.

Stratigraphic and geographic distribution: Cryptocoelia zitteli is one of the most frequent sponges in the Ladinian and the Carnian reefs of the Tethys (Bernecker 1996). Ladinian of the Northern Calcareous Alps (Wolff 1973), Carnian of Oman (Bernecker 1996), Carnian of Greece (Senowbari-Daryan and Schäfer 1983), Lower Carnian of Slovenia (Senowbari-Daryan 1981), Ladinian-Carnian of Hungary (Flügel et al. 1992), Lower Carnian of the Dolomites. Chablais et al. (2010c) mentioned Cryptocoelia sp. in their study of the Norian reef of Japan. However, Carnian specimens such as C. zitteli are here reported for the first time in Carnian of Japan.

?Solenolmia sp. (Fig. 2.4c)

Material: One specimen from Loc. 4 Konose Kyo (sample CP41D).

Description: In transversal section of the sponge shows an axial spongocoel and reticular filling skeleton that is similar to C. zitteli. The morphology of the chambers is difficult to assess but their arrangement in transversal section suggests a crescent-like shape.

(Senowbari-Daryan and Reid 1987). Other Triassic species of the genus, such as *Solenolmia radiata* and *Solenolmia magna*, occur in the Ladinian-Carnian of the Northern Calcareous Alps (Dullo et al. 1987) and Hungary (Velledits et al. 2011).

**Celyphia zoldana** Ott et al. 1980 (*Fig. 2.4d*)

Material: One specimen at Loc. 1 Tsuno (sample CP127L).

Description: Encrusting sponge composed of upright growing globular chambers. The walls are approximately 150 μm thick and are pierced by ostia.

Stratigraphic and geographic distribution: Abundant in Anisian reefs of the Dolomites (Senowbari-Daryan et al. 1993; Emmerich et al. 2005) and Anisian-Ladinian Wetterstein limestone in the Northern Calcareous Alps (Velledits et al. 2011). Other species of the genus *Celyphia* have been reported from Oman (Senowbari-Daryan and Bernecker 2009) and Oregon (Summit Point, Martindale et al. 2012). It is reported for the first time in Carnian of Japan (this work).

**Celyphia? minima** Senowbari-Daryan et al. 1993 (*Fig. 2.4e*)

Material: Several specimens from Loc. 2 Mt. Sambosan (samples CP20, 23) and Loc. 3 Mt. Ishidate (sample CP66A).

Description: Small sponge that consists of elongated irregular chambers (approximately 1 mm in diameter). Ostia are sometimes visible in the wall (*Fig. 2.4e, arrows*). In our material, the connections between chambers are not clearly defined. The walls are composed of calcite that is darker in comparison with *Celyphia zoldana*.

Remarks: Senowbari-Daryan et al. (1993) and Emmerich et al. (2005) published several pictures of *Celyphia? minima* that underline the variable morphology of this sponge.

Stratigraphic and geographic distribution: Abundant in Anisian reefs of the Dolomites (Senowbari-Daryan et al. 1993; Emmerich et al. 2005) and Anisian Ladinian Wetterstein limestone (Velledits et al. 2011). It is reported for the first time in Japan (this work).

**Stylothalamia dehmi** Ott 1967 (*Fig. 2.4f*)

Material: One specimen at Loc. 2 Mt. Sambosan (sample CP22).

Description: Small specimen composed of several crescent-like chambers with pillars as filling structure. The walls are pierced by numerous pores (diameter 0.06–0.1 mm). This specimen correspond to the asiphonate form of *Stylothalamia dehmi* (Senowbari-Daryan and Schäfer 1983).
Chapter 2: Ladinian ?–Carnian reef biota
Fig. 2.4 Calcereous sponges. a, b Cryptocoelia zitelli a longitudinal oblique section CP130C, b oblique section CP66A. c ?Solenolminia sp., transversal section CP41D. d Celyphia zoldana CP127L. e Celyphia minima; note the ostia (arrows) CP20B. f Stylothalamia dehmi that encrusts Tubiphytes sp. CP22. g, h Uvanella irregularis, illustrating various growth forms CP130C, CP41D. i, j Uvanella? lamellata CP123, CP127D. k Close-up view of Uvanella? lamellata chambers; note the presence of tubes (arrows) CP127D. l, m Transmitted light (l) and cathodoluminescence (m) view of Uvanella? lamellata chambers; note the sharp boundary between the wall and the surrounding clotted micrite CP127L. n ?Murania kazmierczaki with typical encrusting pattern and associated microbial crust CP127I. o Close-up view of ?Murania kazmierczaki, note the apical processes (arrows) CP123. p Close-up view of ?Murania kazmierczaki; note the polygonal shape in transversal sections CP124. Scale bars a–j, n 1 mm; k, m 0.5 mm o, p 0.2 mm

Remarks: Holotype of Stylothalamia dehmi (Ott 1967) and specimen shown in Senowbari-Daryan et al. (1999) are composed of neomorphic calcite. Revision by Senowbari-Daryan (1990) demonstrated the original micritic skeleton, as observed in our material.

Stratigraphic and geographic distribution: Ladinian of Northern Calcareous Alps (Ott 1967), Carnian of Slovakia (Jablonsky 1971), Carnian of Slovenia (Senowbari-Daryan 1981), Carnian of Greece (Senowbari-Daryan and Schäfer 1983), Carnian of Oman (Senowbari-Daryan et al. 1999). It is reported for the first time in Japan.

Uvanella irregularis Ott 1967 (Fig. 2.4g, h)
Material: Several specimens Loc. 1 Tsuno (sample CP130C), Loc. 2 Mt. Sambosan (sample CP25) and Loc. 4 Konose Kyo (sample CP41D).
Description: Uvanella is a typical encrusting Triassic genus that consists of small, asiphanate chambers (Bernecker 1996). The irregular shape and the size of the segments characterize Uvanella irregularis. Vesiculae and large pores are sometimes present.
Stratigraphic and geographic distribution: Uvanella irregularis occurs in Western Tethys and Oman and are mainly Carnian (Senowbari-Daryan 1981; Dullo and Lein, 1982; Senowbari-Daryan and Schäfer 1983; Boni et al. 1994; Bernecker 1996; Rüffer and Zamparelli 1997). Martindale et al. (2012) reported Uvanella irregularis also from the Lower Norian of Oregon and Chablais et al. (2010c) Uvanella sp. in Norian reef of Japan.

Uvanella? lamellata Senowbari-Daryan 1981(Figs. 2.4i, j, 2.8)
Material: Several specimens in Tsuno (sample CP127).
Description: Encrusting aggregate of irregular rounded asiphanate chambers. The wall consists of more or less laminated micrite and sometimes includes irregularly arranged tubes. Micritic filaments, which obviously come from the wall, are sometime present in the chambers. Important variations in chamber size and wall thickness are observed in the same specimen.
Many bubble-like structures with micritic and, more or less laminated walls, have been described from several Carnian limestone localities around the world (see the list in Senowbari-Daryan and Bernecker 2009). They are usually referred to as “chambered” microbial crust or as doubtful *Uvanella? lamellata*. In this paper we use the name *Uvanella? lamellata* for this type of encrusting organism. Nevertheless, the sponge affinity of these structures remains an open question. In particular, thin micritic filaments that are observed in some of the chambers question the sponge affinity of *Uvanella? lamellata*. The presence of tubes in the wall of some *Uvanella? lamellata* specimens are also puzzling features (Fig. 2.4k). *Carniphytes multisiphonatus* (formerly called “Tubiphytes” multisiphonatus) presents similar tubes in the micritic cortex but the general morphology is different. Permian *Tubiphytes sosioensis* Senowbari-Daryan and Flügel 1993 (see also Sano and Kanmera 1996) also bear some similarities to *Uvanella? lamellata* but the chambers are smaller, the walls are thicker, and the outline is less defined. The encrustation pattern is also different. The systematic position of *Uvanella? lamellata* clearly requires deeper investigation. The cathodoluminescence analysis revealed the sharp boundary between the wall of *Uvanella? lamellata* and the surrounding microbial clotted micrite (Fig. 2.4l, m). This feature suggests that *Uvanella? lamellata* and the surrounding microbial clotted micrite correspond to different calcification processes. Thus, the skeleton building of *Uvanella? lamellata* differed from microbially induced calcification processes and may have been the result of more biologically controlled mineralization.

Remarks: Senowbari-Daryan and Bernecker (2009) emphasized the abundance of *Uvanella? lamellata* (or this type of microbial crust) in Ladinian-Carnian reefs as well as their role in the stabilization of the reef frame and the contribution to carbonate production.

Stratigraphic and geographic distribution: *Uvanella? lamellata* is known from the Lower Carnian of Slovenia (Senowbari-Daryan 1981) and the Carnian of Oman (Bernecker 1996; Senowbari-Daryan and Bernecker 2009). It is reported for the first time in Japan (this work).

**Other sponges**

*Murania kazmierczaki* Reitner 1992 (Fig. 2.4n–p)


Description: *Murania kazmierczaki* is an encrusting sponge with a secondary calcitic skeleton. In thin-section, it appears as thick crusts (hundreds of micrometers) that are composed of numerous, closely arranged columns of clinogonial yellow–orange calcite. The upper surface bears short apical processes (Fig. 2.4o). Columns are polygonal (irregularly pentagonal to
hexagonal) in cross section (Fig. 2.4p). No spicules were observed. The crust-forming morphology and the exclusive occurrence within the several generations of sessile organisms and microbial crust covering the primary framebuilders allow Murania spp. To be distinguished from the isopachous cements that usually fill reef voids and cavities.

Remarks: In the study of the Cipit Boulders of the Cassian Formation (Dolomites, northern Italy), Sánchez-Beristain and Reitner (2012) emphasized the binding role of Murania kazmierczaki in the Cassian reef. These authors reported that Murania kazmierczaki is mainly present in the Precorynella-Margarosmilia association and sometimes also in association with Dendronella articulata. In the first association it occurs as the primary encruster on top of Precorynella (an “in zoan” sponge) and is never found on corals. In our samples, Murania kazmierczaki settled mainly on corals and sometimes in association with Dendronella articulata.

Stratigraphic and geographic distribution: Murania is a genus present from the Carnian to the Albian (Schlagintweit 2004). Murania kazmierczaki is known only from the Lower Carnian of The Dolomites (Sánchez-Beristain and Reitner 2012). It could be reported for the first time in Japan (this work).

**Red algae (Solenoporaceans)**

Solenoporacean algae are common in Upper Triassic reefs. In our material, solenoporacean algae are represented by two recognizable specimens (?Parachaetetes sp. and Dendronella articulata) from Loc. 1 Tsuno. Poorly preserved fragments have been found at Loc. 1 Tsuno and Loc. 2 Mt. Sambosan. The fragments may belong to Parachaetetes sp. or Solenopora sp. The well-preserved specimens are determined as follows.

**?Parachaetetes cf. P. cassianus** (Flügel 1961) (Fig. 2.5a)

Material: One specimen from Loc. 1 Tsuno (sample CP127Q).

Description: Nodular thallus composed of concentric layers of cell rows. The maximum cell diameter is approximately 100 μm, and the wall is approximately 30 μm in thickness. The distance between the cell layers is 500–1000 μm in longitudinal section and 150–300 μm in cross section. Because of the recrystallization, the shape of the cells is difficult to assess. This specimen strongly resembles Parachaetetes cassianus and its dimensions fit with those compiled in Senowbari-Daryan et al. (2006). However a thickening of the wall, which is
normally diagnostic of the genus (Senowbari-Daryan and Link 2005; Senowbari-Daryan et al. 2006), is not clearly visible. Alternatively, this specimen may belong to *Solenopora triasina*. Stratigraphic and geographic distribution: *Solenopora* and *Parachaetetes* are common genera in Upper Triassic reefs. *Parachaetetes cassianus* occur in Carnian limestone clast at Koguchi locality, Sambosan Accretionary Complex of Kyushu, southwest Japan (Senowbari-Daryan et al. 2012).

*Dendronella articulata* Moussavian and Senowbari-Daryan 1988 (*Fig. 2.5b, d*)

Material: Several poorly preserved specimens in Loc. 1 Tsuno (samples CP127E, 127N, 127Q, 127U).

Description: The material consists of fragments of irregular bush-like branching thalli. Branches are circular in transversal section (diameter range from approximately 100 to 200 μm). Filaments are not visible due to strong recrystallization.

Remarks: *Dendronella articulata* is found in association with *?Murania kazmierczaki*.

Stratigraphic and geographic distribution: Carnian of the Dolomites (northern Italy) (Moussavian and Senowbari-Daryan 1988; Russo et al. 1991; Barattolo et al. 1993; Sánchez-Beristain 2010), Carnian of Oman (Senowbari-Daryan and Bernecker 2009). It is reported for the first time in Japan (this work).

**Cyanophycean calcimicrobes**

Calcimicrobes are only determined at the genus level in this study because of their high morphological variability and lack of diagnostic features.

*Girvanella* sp. (*Fig. 2.5c*)

Material: The genus *Girvanella* is relatively common in Loc. 1 Tsuno (samples CP120, 124, 126–127) and Loc. 2 Mt. Sambosan (sample CP25).

Description: *Girvanella* is a cyanophycean calcimicrobe that is composed of several loosely associated tube-like cells. They correspond to filamentous unbranched calcified mucilaginous sheath and show affinities with the recent genus *Plectonema* (Riding 1991). *Girvanella* occurs either as an encrusting organism on corals and sponges or as isolated clusters of tubes.

Remarks: *Girvanella* is thought to be an important lime mud producer in the Paleozoic (Pratt 2001). Regarding the abundance of *Girvanella* in our samples, this statement can probably be
enlarged to Upper Triassic reefs even if this calcimicrobe is not always well preserved and is thus not well recognizable. The presence of the cyanobacteria *Girvanella*, which is assumed to be a photoautotroph (Pratt 2001), suggests a depositional setting within the photic zone for the reef limestone of the SAC.

Stratigraphic and geographic distribution: The related species *Girvanella fasciculata* Schäfer and Senowbari Daryan (1983) is described from the Carnian of Oman (Senowbari-Daryan and Bernecker 2009) and from the Lower Carnian of the Dolomites (Sánchez-Beristain 2010).
Fig. 2.5 Algae and calcimicrobes. a Parachaetetes cf. P. cassianus CP127Q. b Dendronella articulata (D) encrusted by ?Murania kazmierczaki (M) and Radiomura cautica (R). c Girvanella sp. d Dendronella articulata CP127U. e Gosaukammerella eomesozoica CP127D. Scale bars a, b, d, e 1 mm; c 0.2 mm

Foraminifers

Foraminifers are relatively abundant in the Sambosan limestone but preservation of the wall structure is often poor. The determination, taxonomy, and classification are based on Zaninetti (1976) and Loeblich and Tappan (1988) along with more recent papers. Characteristic (reef and age diagnostic taxa) and well-preserved specimens are presented below. Foraminiferal associations found in the limestone blocks are also reported.

Porcelaneous foraminifers

*Cucurbita infundibuliforme* Jablonský 1973 (*Fig. 2.6a–c*)

Material: Six specimens from Loc. 1 Tsuno (sample CP130), three specimens from Loc. 2 Mt. Sambosan (samples CP21, 24B), fourteen from Loc. 4 Konose Kyo (samples CP40, 41).

Description: *Cucurbita* is a genus of reef-dwelling foraminifer with amphora-like chambers and a thick apertural neck (Gale et al. 2012). *Cucurbita*-like foraminifer taxonomy has been controversial for a long time (e.g., Zaninetti 1977; Borza and Samuel 1978; Senowbari-Daryan 1983). The review by Gale et al. (2012) led to a much simpler and convincing taxonomic frame that we follow. Based on the observation of thick apertural necks, most of the specimens from the SAC are assigned to *Cucurbita infundibuliforme* Jablonsky 1973. A few other specimens that exhibit long apertural necks may belong to *Cucurbita longicollum* Senowbari-Daryan 1983.

Stratigraphic and geographic distribution: Upper Triassic (Carnian) of Oman (Bernecker 1996; Senowbari-Daryan and Bernecker 2009), Lower Carnian of Slovenia (Senowbari-Daryan 1981), Carnian of Hungary (Flügel et al. 1992), Carnian of Sicily (Carrillat and Martini 2009), Carnian of Kyushu (Senowbari-Daryan et al. 2012).

*Hydrania dulloi* Senowbari-Daryan 1983 (*Fig. 2.6d*)

Material: One specimen from Loc. 3 Mount Ishidate (sample CP66A) and eight from Loc. 4 Konose Kyo (sample CP41).
Description: *Hydrania dulloi* is a typical reef foraminifer that is characterized by an irregularly coiled tube that ends in an elongated amphora-shaped collar. When only the neck is visible, it is difficult to discriminate *Cucurbita longicollum* and *Hydrania dulloi*.

Stratigraphic and geographic distribution: Lower Carnian of the Northern Calcareous Alps (Rüffer and Zamparelli 1997), Carnian of Sicily (Carrillat and Martini 2009), Carnian of Greece (Senowbari-Daryan 1983), Carnian of Kyushu (Senowbari-Daryan et al. 2012).

*Arenovidalina chialingchiangiensis* Ho 1959 (Fig. 2.6e)

Material: Several specimens from Loc. 1 Tsuno (samples CP122, 123, 127).

Description: *Arenovidalina chialingchiangiensis* is a planispiral foraminifer that is characterized by a thick lamellar umbonal region that results in a strongly biconvex test.

Stratigraphic and geographic distribution: Anisian of the Dolomites (Emmerich et al. 2005), Anisian-Ladinian of the Northern Calcareous Alps (Rüffer and Zamparelli 1997), Ladinian-Carnian of Slovenia (Buser et al. 1982), Middle Triassic of China (Ho 1959). It is reported for the first time in Japan (this work).

**Microgranular-agglutinated foraminifers**

*Paleolituonella meridionalis* (Luperto 1965) (Fig. 2.6f)

Material: Several specimens from Loc. 1 Tsuno (samples CP127, 128) and Loc. 2 Mt. Sambosan (sample CP24A).

Description: *Paleolituonella meridionalis* changes from a trochospiral to a linear uniseriate form during ontogeny. Its main characteristics are chamber enlargements during the linear stage and inflated walls between the chambers.

Remarks: Several species of *Paleolituonella* spp. Have been introduced in the literature (*P. meridionalis, P. minima, P. reclinata, P. angulata*). However, they are morphologically similar to each other and should be considered as synonyms (Rettori, pers. comm.). In this work, all of the specimens have been attributed to *Paleolituonella meridionalis* Luperto 1965.

Stratigraphic and geographic distribution: This species is common (but rarely abundant) in Middle and Upper Triassic shallow-water carbonates of the Tethys.
Fig. 2.6 Foraminifers. a–c Cucurbita infundibuliforme CP21, CP41C, CP130B. d Hydrania dulloi CP41D. e Arenovidalina chialingchiangse CP122. f Paleolituonella meridionalis CP24A. g Piallina bronnimanni CP124. h Piallina tethydis CP125. i Ammobaculites/ Reophax CP127L. j Trocholina cordevolica CP41C. k–l Ophtalminids CP127, CP123. m Endotriada sp. CP121. n Nodosarid CP121 o, p Koskinobullina socialis CP127 K. q, r Nubecularids CP127D. s Terebella sp. CP127D. t Serpulid CP120. Scale bars 0.2 mm except i, s, t 0.5 mm

Piallina tethydis Rettori and Zaninetti 1993 (Fig. 2.6g) and Piallina bronnimanni Martini et al. 1995 (Fig. 2.6h)

Material: Piallina spp. are present at Loc. 1 Tsuno (samples CP124, 125) and possibly at Loc. 4 Konose Kyo (sample CP41D).
Description: *Piallina* is a Carnian genus that is characterized by three stages in their ontogeny (trochoid, triserial, and trochospiral, respectively). *Piallina tethydis* has subangular chambers, while *Piallina bronnimanni* is smaller and has more rounded chambers. Accordingly, specimens that are larger than 200 μm with triangular chambers are attributed to *Piallina tethydis* and the smaller one with rounded chambers is attributed to *Piallina bronnimanni*.

Stratigraphic and geographic distribution: The genus *Piallina* is known from Carnian of Turkey (Rettori et al. 1993) and Serbia (Martini et al. 1995), and from Ladinian and Carnian of China (Payne et al. 2011).

*Ammobaculites/Reophax* (Fig. 2.6i)

Material: Several specimens from Loc. 1 Tsuno (samples CP121, 123, 127).

Description: Agglutinated trochospiral? to uniserial foraminifers with thick walls and triangular chambers are described as *Ammobaculites/Reophax*. The lack of diagnostic features does not allow a more accurate determination. Agglutinated particles are sometimes well visible.

Remarks: *Ammobaculites/Reophax* genera are common in interstitial reef sediments at the Tsuno locality.

Stratigraphic and geographic distribution: Common, long-range (Carboniferous to Holocene) taxon.

*Aragonitic foraminifers (Involutinids)*

*Trocholina cordevolica* Oberhauser 1964 (Fig. 2.6j)

Material: One specimen from Loc. 4 Konose Kyo (sample CP41).

Description: The high conical test, which is formed by a trochospirally enrolled, undivided tubular chamber, is characteristic of the genus *Trocholina* (Rigaud et al. 2013). This form is tentatively attributed to *Trocholina cordevolica* that is also cited in the literature as *Lamelliconus cordevolicus* Oberhauser (e.g., Sánchez-Beristain et al. 2013).

Remarks: Involutinids are very rare in reef limestone of the SAC. The specimen of *Trocholina cordevolica* was found in association with *Zardinia perisulcata*, *C. zitteli*, *Hydrania dulloi* and *Cucurbita infundibuliforme*.

Stratigraphic and geographic distribution: *Trocholina cordevolica* is reported from Spain (Pérez-López et al. 2005), Israel (Korngreen and Benjamini 2006), the Dolomites (Di Bari and Laghi 1994; Sánchez-Beristain et al. 2013), and Thailand (Kobayashi et al. 2006). It is reported for the first time in Japan (this work).
Encrusting foraminifers

**?Koskinobullina socialis** Cherchi and Schroeder 1979 (Fig. 2.6o, p)

Material: Several poorly preserved specimens in Loc. 1 Tsuno (sample CP127K).

Description: Small bubble-like cells (80–200 μm long) with light calcitic walls that are more or less arranged in rows. Colonies are composed of several layers that form a crust up to 1 mm. These structures are tentatively attributed to ?Koskinobullina socialis. They differ from nubecularid foraminifers (described below) by the cell arrangement and wall composition.

Remarks: ?Koskinobullina socialis is associated with other encrusting organisms in clotted microbial fabrics.

Stratigraphic and geographic distribution: Carnian to Paleocene (Moussavian and Vecsei 1995), common in Jurassic reefs (Dupraz and Strauss 1999; Ples et al. 2013). In the Upper Triassic it is reported from the Carnian of the Dolomites (Sánchez-Beristain et al. 2013), Lower Norian of Oregon (Martindale et al. 2012), and Rhaetian of the Northern Calcareous Alps (Martindale et al. 2013). It is reported for the first time in Japan (this work).

**Nubeculariid foraminifers (Fig. 2.6q, r)**

Material: Several specimens in Loc. 1 Tsuno (sample CP127D).

Description: Small bubble-like cells with dark micritic walls more or less arranged in rows. They differ from ?Koskinobullina socialis by thick micritic walls and a less dense arrangement of chambers.

Stratigraphic and geographic distribution: Nubecularia, one the most common representatives of the nubeculariids, is reported from Norian of the Northern Calcareous Alps (Bernecker 2005), Norian of Oman (Bernecker 2005), Lower Norian of Oregon (Martindale et al. 2012). It is here first reported from Japan.

Foraminiferal association

The species that are mentioned above occur in association with other foraminifers of minor interest for biostratigraphic and paleoecological purposes. The assemblages commonly contain *Endotriada* spp. and “*Trochammina*” sp. together with Ophthalminids, Nodosarids and Duostominids (Fig. 2.6k–n). Encrusting species such as *Planiinvoluta carinata* and *Tolypammina gregaria* are sometimes present.
Microproblematica

Microproblematica are organisms of unknown biological affinity. They are frequent in the SAC and are often present even in poorly preserved samples. The micritic nature of the skeleton of many of these organisms might explain their relatively good preservation in recrystallized limestone.

Tubiphytes group

*Tubiphytes* Maslov 1956 (sometimes called *Shamovella*, see Senowbari-Daryan 2013), and similar organisms, are one of the most abundant microproblematica group of Late Paleozoic and Mesozoic shallow-water carbonates. The systematic position of these organisms has been the subject of different interpretations. Various groups have been proposed such as sponges, hydrozoans, algae, cyanophycean or foraminifers. Taxonomical and biological affinities of organism that are related to *Tubiphytes* are discussed in Riding and Guo (1992), Senowbari-Daryan and Flügel (1993), and Senowbari-Daryan (2013), and references therein. Morphologically, microproblematica that belong to the *Tubiphytes* group are composed of one or more internal cavities that are surrounded by a more or less dense micritic cortex (or envelop). In this paper, we follow the recent revision of the Triassic *Tubiphytes* organisms that has been proposed by Senowbari-Daryan (2013).

*Tubiphytes* sp. (*Fig. 2.7a–c*)

Material: Common microproblematica, present in all investigated localities (Loc. 1 Tsuno, samples CP127, CP129–130; Loc. 2 Mt. Sambosan, samples CP20–25; Loc. 3 Mt. Ishidate CP62, 66A; Loc. 4 Konose kyo, samples CP40–41).

Description: Ramified and unramified specimens with a large elongated tongue-shaped skeleton and an internal cavity composed of a single narrow tube are determined as *Tubiphytes* spp. The internal cavity is often hidden by diagenetic silicification.

Remarks: On the basis of small morphological differences with respect to the type species *Tubiphytes obscurus* Maslov 1956, Senowbari-Daryan (2013) defined three new Triassic species of the genus *Tubiphytes*. However, due to preservation, section orientation, and the morphological plasticity of these organisms, it is not possible to discriminate among the different new species that are introduced by this author in our material.

Stratigraphic and geographic distribution: From Carboniferous to Cretaceous (Jurassic and Cretaceous “*Tubiphytes*” are called *Crescentiella*, Senowbari-Daryan et al. 2008) and distributed worldwide.
Fig. 2.7 Microproblematica, brachiopods and worm tubes. 

**a** Tubiphytes boundstone (B) brachiopod, (I) ?Isnella misiki, (P) Plexoramea cerebriformis, (Pg) Plexoramea gracilis, (T) Tubiphytes sp. CP24A. 

**b**, **c** Tubiphytes sp. CP62A, CP25. 

**d** ?Isnella misiki JC325B. 

**e** Plexoramea cerebriformis CP25. 

**f** ?Plexoramea cylindrica CP25. 

**g** Plexoramea gracilis CP24A. 

**h** Ladinella porata CP66C. 

**i** Radiomura cautica CP123. 

**j** Baccanella floriformis CP130C. 

Scale bars **a** 5 mm; **b**–**f**, **h**–**j** 0.5 mm; **g** 0.25 mm.
Plexoramea cerebriformis Mello 1977 (Fig. 2.7e, f)

Material: Common microproblematica present in all studied localities (Loc. 1 Tsuno, samples CP124, 127–128, 131; Loc. 2 Mt. Sambosan, samples CP21–22, 24–25; Loc. 3 Mt. Ishidate, samples CP66; Loc. 4 Konose Kyo, samples CP41).

Description: *Plexoramea cerebriformis* is composed of a thin micritic twig network that surrounds the internal cavity, which is not always visible. The main characteristic is the lack of a defined outer wall, and thus a diffuse transition to the surrounding sediments is observed (Senowbari-Daryan 2013). In the literature, *Plexoramea cerebriformis* is sometime confused with *Tubiphytes carinthiacus* Flügel. However, specimens that exhibit a clear boundary to the surrounding sediment may belong to *Plexoramea cylindrical* Senowbari-Daryan 2013 (Fig. 2.7f).

Stratigraphic and geographic distribution: Anisian-Ladinian of the Dolomites (Emmerich et al. 2005), Anisian-Ladinian of Hungary (Velledits et al. 2011), Ladinian-Carnian of the Northern Calcareous Alps (Rüffer and Zamparelli 1997), Ladinian-Carnian of Thailand (Fontaine et al. 1988) Carnian of Oman (Senowbari-Daryan et al. 1999), Carnian of Hungary (Flügel et al. 1992), Carnian of the Dolomites (Sánchez-Beristain 2010), Carnian Wetterstein limestone of Slovenia (Bole 2002). One occurrence is reported from the Norian of Sicily (Senowbari-Daryan 1984). It is reported for the first time in Japan (this work).

Plexoramea gracilis (Schäfer and Senowbari-Daryan 1983) (Fig. 2.7a, Pg)

Material: Common in Loc. 2 Mt. Sambosan (sample CP24A), Loc. 3 Mt. Ishidate (sample CP66B) and Loc. 4 Konose Kyo (sample CP41).

Description: *Plexoramea gracilis* is a thin, branched microproblematica with micritic network in the internal part and was formerly placed in the genus *Tubiphytes*. Internal cavities are not observed. The diameter is usually approximately 4 mm. Fragments that correspond to this description are tentatively determined as *Plexoramea gracilis*.

Remarks: This species is limited to the Ladinian-Carnian and was an important debris producer in reefs of the western Tethys (Senowbari-Daryan 2013).

?Isnella misiki Senowbari-Daryan 2007 (Fig. 2. 7d)

Material: Several specimens from Loc. 1 Tsuno (sample CP130) and Loc. 2 Mt. Sambosan (samples CP24A, JC325B).

Description: *Isnella misiki* is composed of a dark micritic envelop that surrounds a small coiled tube. The coiling of the tube defines an internal cavity. Similar organisms are referred to as *Labes atramentosa* in the Jurassic (Schlaginweit and Gawlick 2009).

Stratigraphic and geographic distribution: Ladinian-Carnian reefs of the Tethys realm (Senowbari-Daryan 2007).

**Other Microproblematica**

*Baccanella floriformis* Pantic 1971 (Fig. 2.7j)

Material: Common microproblematica, present in almost all studied localities (Loc. 1 Tsuno, sample CP130; Loc. 2 Mt. Sambosan, samples CP215B; Loc. 4 Konose Kyo, sample CP41D).

Description: *Baccanella floriformis* is a common microproblematicum in Triassic marine carbonates. It is composed of cauliflower-shaped white calcite aggregates. It occurs as a reef dweller in sediments between framebuilders. Remarks: The biological affinity of *Baccanella floriformis* is uncertain. It has been compared to *Microcodium* in the original description (Pantic 1971).

Stratigraphic and geographic distribution: Common in Middle and Upper Triassic shallow-water carbonates of Tethys.

*Ladinella porata* Ott 1968 (Fig. 2.7h)

Material: Several specimens at Loc. 1 Tsuno (samples CP129, 132) and Loc. 4 Mount Ishidate (sample CP66C).

Description: *Ladinella porata* is a small microproblematicum that is composed of one or more crescent-like to hemispherical segments that consist of closely associated tubes, which are slightly curved to the periphery. Tubes are usually more visible in the central part of the organism.

Stratigraphic and geographic distribution: Widely distributed in Anisian to Carnian limestone of the Tethys (one doubtful occurrence in the Norian of Sicily is reported in Senowbari-Daryan (1984), reinterpreted here as a *Cayeuxialike organism*). Upper Anisian of Carinthia (Flügel 1986), Anisian-Ladinian of Hungary (Velledits et al. 2011), Anisian-Ladinian of The Dolomites (Emmerich et al. 2005; Brandner et al. 1991; Fois 1981), Ladinian-Carnian of the Northern
Calcareous Alps (Rüffer and Zamparelli 1997), Ladinian-Carnian of Thailand (Fontaine et al. 1988), Carnian of Slovenia (Senowbari-Daryan 1981), Carnian of Oman (Senowbari-Daryan et al. 1999), Carnian of Hungary (Flügel et al. 1992), Carnian of the Dolomites (Sánchez-Beristain 2010), Carnian Wetterstein limestone of Slovenia (Bole 2002). Senowbari-Daryan et al. (2012) also reported occurrence of *Ladinella porata* in Carnian limestone clast from Kyushu.

*Radiomura cautica* Senowbari-Daryan and Schäfer 1979 *(Fig. 2.7i)*

Material: Common microproblematicum, presents in all studied localities (Loc. 1 Tsuno, samples CP120, 123, 130C, 132; Loc. 2 Mt Sambosan, sample CP22; Loc. 3 Mt Ishidate, samples CP62A, 66B; Loc. 4 Konose Kyo, samples CP41C, 41D).

Description: *Radiomura cautica* is composed of several irregularly arranged spherical chambers of variable size. The diagnostic feature of this organism is the structure of the wall that usually appears similar to “iron powder in a magnetic field” (Senowbari-Daryan and Bernecker 2009). Various growth forms of *Radiomura cautica* are described in Wurm (1982). Encrusting or free-living growth forms can be observed.

Remarks: *Radiomura cautica* have been compared with sphinctozoan sponges (Wurm 1982; Senowbari-Daryan 1984) but the structure of the chamber walls is different (Senowbari-Daryan and Bernecker 2009).

Stratigraphic and geographic distribution: Long-range microproblematicum (Middle Triassic-Upper Jurassic), very common. In Japan it has been reported in the Carnian by Senowbari-Daryan et al. (2012) and in the Norian by Chablais et al. (2010c).

**Brachiopods**

*Gosaukammerella eomesozoica* (Flügel 1972) *(Fig. 2.5e)*

Material: Several specimens in Loc. 1 Tsuno (sample CP127D) and Loc. 2 Mt. Sambosan (sample CP215B).

Description: Although it was considered to be a microproblematicum for decades, *G. eomesozoica* is now interpreted as an encrusting strophomenid brachiopod that inhabited cryptic reef environments (Senowbari-Daryan and Flügel 1996). The specimen in Fig. 2.5e shows a diagnostic convex pedicle valve with a symmetrically arranged tubular structure that
allowed settling on the substrate (here on a coral, but commonly on sponges in the Tethys, Senowbari-Daryan and Flügel 1996), and also shows a flat brachial valve.

Stratigraphic and geographic distribution: *Gosaukammerella eomesozoica* occurs in the Norian-Rhaetian of the Northern Calcareous Alps (Bernecker 2005), Sicily (Senowbari-Daryan 1984), Oman (Bernecker 1996, 2005), and the Philippines (Kiessling and Flügel 2000), and few Carnian localities in Hungary (Flügel et al. 1992) and Oman (Senowbari-Daryan and Bernecker 2009). As far as we know, *Gosaukammerella eomesozoica* is here reported for the first time in Japan. This new occurrence in Japan emphasizes the wide distribution of *Gosaukammerella eomesozoica* (Bernecker 2005).

Apart from *Gosaukammerella*, diverse other encrusting and free-living brachiopods are present in the Carnian blocks of the SAC. Similar brachiopod shells are sometimes referred to as thecideid brachiopods in the literature (e.g., Sánchez-Beristain 2010).

**Polychaetes**

Polychaetes tubes are common components of reef limestone in the SAC. Based on the wall composition, two groups are recognized: agglutinated worm tubes and serpulids.

**Agglutinated worm tubes**

*Terebella* sp. (*Fig. 2.6s*)

Material: Several specimens from Loc. 1 Tsuno (samples CP120, 122, 127D, 127GL1, 127M, 130), Loc. 2 Mt. Sambosan (samples CP22, 24B) and Loc. 3 Mt. Ishidate (sample CP66).

Description: Agglutinated worm tubes are isolated or encrusting tubes with irregular dark walls that are composed of agglutinated micrite. Only a few studies on Triassic limestones have assigned agglutinated worm tubes a specific taxon (or even described them). Nevertheless, agglutinated tubes such as *Terebella lapilloides* Münster 1833 are reported in the Carnian Cipit Boulder of the Cassian formation (Sánchez-Beristain 2010), and they are considered to be common reef dwellers/encrapaters in Jurassic reefs (Dupraz 1999; Olivier et al. 2004). Moreover, similar agglutinated worm tubes have been reported from the Upper Triassic of Oman as *Porferitubus buseri* Senowbari-Daryan 1984 in Bernecker (1996). *Porferitubus* can be distinguished from *Terebella* by perforations of the wall. In the Paleozoic, agglutinated worm...
tubes are often called “Tartharella-like polychaetes worm tubes” but are also referred to as *Terebella* sp. (Pratt, 1995; Della Porta et al. 2002).

Remarks: *Terebella* is generally interpreted as a sciaphilic organism and was adapted to low oxygen conditions, for example in cryptic environments between microbialitic columns (Fürsich and Werner 1991; Olivier et al. 2004).

Stratigraphic and geographic distribution: Similar agglutinated worm tubes are common in Phanerozoic carbonate rocks.

**Indeterminate serpulids** (Fig. 2.6t)

Material: Several specimens mainly from Loc. 1 Tsuno (samples CP120, 127U).

Description: Serpulid tubes are characterized by light calcitic walls. Most often serpulids are single tubes that are encrusted on reef builders.

Stratigraphic and geographic distribution: Serpulids are common components of Phanerozoic carbonate rocks.

### 2.6. Discussion

**Correlation of outcrops**

The noticeable homogeneity of the limestone clasts that are found in the four studied localities is testified by the analogous mode of occurrence, microfacies and distribution of reef taxa (Table 2.1). Indeed, all of the reef limestone clasts were found in similar VCM breccia and can be described as coralsponge-microproblematica boundstone. Furthermore, reef limestone clasts from the different localities have many taxa in common. These observations stress their common origin, which allows this material to be treated as a unique overall biota assemblage despite several local but minor differences.
Table 2.1 Distribution of the taxa described in the text

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Loc. 1</th>
<th>Loc. 2</th>
<th>Loc. 3</th>
<th>Loc. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tsuno</td>
<td>Mt. Sambosan</td>
<td>Mt. Ishidate</td>
<td>Konose Kyo</td>
</tr>
<tr>
<td><strong>Scleratinian Corals</strong></td>
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<tr>
<td>Retiophyllia sp.</td>
<td>x</td>
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<tr>
<td>Scleractinia sp. 1</td>
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<td>Thamnasteriamorpha okudai</td>
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<tr>
<td><strong>Sponges</strong></td>
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<tr>
<td>Celyphia ? minima</td>
<td>-</td>
<td>x</td>
<td>x</td>
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<td>Celyphia zoldana</td>
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<td>-</td>
<td>-</td>
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<td>Cryptocoelia zittel</td>
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<td>-</td>
<td>x</td>
<td>-</td>
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<tr>
<td>?Murania kazmierczaki</td>
<td>x</td>
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<tr>
<td>? Solenolmia sp.</td>
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<td>-</td>
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<td>x</td>
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<tr>
<td>Stylothalamia dehmi</td>
<td>-</td>
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<td>Uvanella irregularis</td>
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<td>x</td>
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<tr>
<td>Uvanella? lamellata</td>
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<td>-</td>
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<td>-</td>
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<td>Zardinia perisulcata</td>
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<td><strong>Red algae (Solenoporacean)</strong></td>
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<td>? Parachaetetes cf. C. cassianus</td>
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<td><strong>Cyanophycean Calcimicrobe</strong></td>
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<tr>
<td>Girvanella sp.</td>
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<tr>
<td><strong>Foraminifers</strong></td>
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<tr>
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<td>?</td>
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<td>Cucurbita infundibuliforme</td>
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<td>x</td>
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<td>x</td>
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<td>Piallina bronnimanni</td>
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<td>?</td>
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<td>?</td>
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<td>Piallina tethydis</td>
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<tr>
<td>Trocholina cordevolica</td>
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<td>x</td>
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<tr>
<td><strong>Microproblematica</strong></td>
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</tr>
<tr>
<td>Baccanella floriformis</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>? Isnella misiki</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Ladinella porata</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Plexoramea cerebriformis</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>x</td>
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<tr>
<td>Plexoramea gracilis</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Radiomura cautica</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Tubiphytes spp.</td>
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<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td><strong>Brachiopods</strong></td>
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</tr>
<tr>
<td>Gosaukammerella eomesozoica</td>
<td>x</td>
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<td>-</td>
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</tr>
<tr>
<td>Thecideid brachiopods</td>
<td>x</td>
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<td>-</td>
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<td><strong>Polychaetes</strong></td>
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<td></td>
</tr>
<tr>
<td>Terebella sp.</td>
<td>x</td>
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<td>-</td>
<td>?</td>
</tr>
<tr>
<td>Serpulids</td>
<td>x</td>
<td>?</td>
<td>x</td>
<td>?</td>
</tr>
</tbody>
</table>
Biostratigraphy

The biostratigraphy of Upper Triassic reefs is based on foraminifers, problematica and some reef builders that are associated with reef fauna (i.e., corals and sponges; Bernecker 2005). In this paper, two methods are used to refine the biostratigraphical frame of the Sambosan shallow-water reefal limestone in Shikoku. The first is the occurrence of biostratigraphic markers. The second is the analysis of biotic associations with respect to other coeval faunal assemblages from different localities of the Tethys and Panthalassa oceans. However, a comparison with the eastern Panthalassa is difficult because of the scarcity of Ladinian-Carnian reef fauna in North American terranes and craton. Only rare occurrences are reported currently from the Late Ladinian of Nevada (Roniewicz and Stanley Jr 1998), and the Late Carnian of British Colombia (Zonneveld et al. 2007; Martindale et al. 2010). Thus, our results are mainly compared with Tethyan reef biota. In the next sections, we present the most significant biostratigraphic markers from the Upper Triassic reefs of Shikoku and a comparative analysis of the biotic association.

Biostratigraphic markers

Several of the species that are mentioned above are considered to be reliable biostratigraphic markers that distinguish the Ladinian-Carnian from the Norian-Rhaetian. Indeed, the compilation of stratigraphic ranges of some of the taxa described above shows that many of the identified taxa are restricted to specific Triassic stages. These include the sponges *Zardinia* spp. (Anisian to Carnian), *C. zitteli* (Ladinian to Carnian), the foraminifers *Trocholina cordevolica* (Late Ladinian to Carnian), *Piallina* spp. (Ladinian to Carnian) and the microproblematica *Ladinella porata* (Anisian to Carnian), *Plexoramea cerebriformis* (Anisian to Carnian) and *Plexoramea gracilis* (Ladinian-Carnian,). These taxa are widely considered as biostratigraphic markers in the literature. Species belonging to genus *Zardinia* are exclusively Anisian to Carnian (Senowbari-Daryan 1990; Senowbari-Daryan et al. 1999). *Cryptocoeia* includes Norian-Rhaetian species but *C. zitteli* is restricted to the Ladinian-Carnian (Müller-Wille and Reitner 1993, Senowbari-Daryan and Bernecker 2009). *Trocholina cordevolica* is considered as an index fossil for the late Ladinian- Carnian by many authors (Trifonova 1993; Di Bari and Laghi 1994; Pérez-López et al. 2005; Korngreen and Benjamini 2006; Sánchez-Beristain et al. 2013). *Plexoramea gracilis* is limited to the Ladinian-Carnian (Senowbari-Daryan 2013). *Ladinella porata* occurs only until the end of the Carnian (Bernecker 2005). Thus, it is a good biostratigraphic marker for Upper Triassic reefs.
The presence of some Ladinian-Carnian biostratigraphic markers in reef limestone blocks of the SAC in Shikoku, and the comparison with other well-known reef fauna assemblages (see below) points to an age at least as old as the Lower Carnian and possibly even older. Therefore, a Ladinian? to Carnian age is proposed here for the described reef ecosystems of the SAC in Shikoku. This confirms an early Late Triassic reef development on the top of these oceanic seamounts of Panthalassan origin. To date, the oldest age of SAC reefs in Japan was Carnian (Senowbari-Daryan et al. 2012).

**Comparisons**

As established in the last section, the biota of the reef limestone in Shikoku includes numerous Ladinian-Carnian taxa. Moreover, the assemblage has a close affinity with Ladinian to Carnian reef assemblages of the Tethys realm, and particularly with the Carnian reefs of Oman and the Upper Ladinian-Lower Carnian Cipit Boulders of the Dolomites (northern Italy). A comparison with these two coeval reef environments is detailed below.

**Carnian of Oman**

The Carnian limestones of Oman have been investigated by Bernecker (1996), Senowbari-Daryan et al. (1999), and Senowbari-Daryan and Bernecker (2009). The primary results are summarized in Bernecker (2005). A rich Carnian reef biota was described and the age diagnostic association includes the corals *Volzeia badiota*, *Rhopalodendron juliensis* and *Margarophyllia crenata*, the sponges *C. zitteli*, *Zardinia sp.*, and *Uvanella irregularis*, the serpulid *Barbarafera carnica*, the foraminifers *Paraophtalmidium* spp. and *Cucurbita infundibuliforme*, and the microproblematicum *Ladinella porata*. The material described in our study often displays associations that are similar to those identified in the Carnian of Oman (i.e., *C. zitteli*, *Z. perisulcata*, *U. irregularis*, and *C. infundibuliforme* frequently occur together).

**Upper Ladinian-Lower Carnian Cipit Boulders of the Dolomites**

The most striking similarities appear when comparing our material with the Cipit Boulders from the Cassian Formation of the Dolomites (northern Italy). The Cipit Boulders have been the subject of many paleontological studies since the 19th century (e.g., Richtofen 1860; Sánchez-Beristain 2010; Tosti et al. 2014). Many sponge taxa such as *Zardinia perisulcata* have been introduced from this area (Dieci et al. 1968). More recently Sánchez-Beristain (2010) and Sánchez-Beristain and Reitner (2012) performed an extensive study of the biota of the Cipit
Boulders and discussed the ecology of that reef environment. They described several reef fauna associations, including corals (*Margarosmilia, Retiophyllia*), sponges (*Precorynella, Murania*), encrusting brachiopods, solenoporacean algae, *Girvanella, Koskinobullina socialis*, along with microbialitic crusts and thrombolytic structures. They also reported *Lamelliconus cordevolicus* (= *Trocholina cordevolica*). That assemblage bears striking similarities to the samples from Loc. 1 Tsuno, especially regarding the numerous sessile organisms and microbial crusts that formed a complex encrusting sequence upon the primary framebuilders.

**Preservation of the reef limestone**

Regarding the lithology of the Ladinian?-Carnian reef limestone of the SAC, we observed that the clasts that are enclosed in the breccia with a volcaniclastic matrix (VCM breccia) are overall better preserved than the nearby limestone slabs. In a similar way, the outstandingly preserved Cipit Boulders are also set in volcaniclastic sediments (e.g., Russo et al. 1997; Tosti et al. 2014). Accordingly, this mode of occurrence would explain the excellent preservation of the limestone, meaning that the circulation of diagenetic fluids was more difficult in volcaniclastic sediments, which prevented the recrystallization (Scherer 1977; Brachert and Dullo 1994; Russo et al. 1991). These repeated observations in different regions highlight the potential for an enhanced preservation of the reef limestone clasts when associated with volcaniclastic sediments.

**Reef ecology**

In reef ecosystems, sessile organisms and microbial crusts (secondary framebuilders) form encrustation sequences upon primary framebuilders (e.g., phaceloid corals, larger sphinctozoan and red algae). In our material, two types of encrustations have been observed. The first corresponds to thick encrustations (up to 1 cm), which are mainly on corals, and the second consists of thin encrustations (10–100 μm) on other framebuilders such as sponges, solenoporacean algae and *Tubiphytes*. The thick encrustation sequences include various organisms such as *Uvanella? lamellata, Gosaukammerella eomesozoica, ?Koskinobullina socialis, ?Murania kazmierczaki, Radiomura cautica, Girvanella* sp., undetermined sponges, microproblematica and microbial crusts (Fig. 2.8). The smaller encrustations usually comprise *Uvanella irregularis, Celyphia* spp. and microbial crusts. The thick and complex sequences of encrustations would reflect the reef ecological succession, but among the investigated samples no specific pattern of encrustation sequences has been identified.
Regional correlation and reef evolution in the SAC

Carnian reefs biota have been described from several other localities in the SAC (Fig. 2.9). Especially interesting are the reef limestone clasts from the locality of Koguchi in Kyushu that show strong similarities in biotic content with our material (Kanmera 1964; Senowbari-Daryan et al. 2012). More precisely, taxa that occur both in Shikoku and at Koguchi locality are: corals *Retiophyllia* spp., *Thamnasteriamorpha okudai*, algae *Parachaetetes* cf. *P. cassianus*, foraminifers *Cucurbita infundibuliforme*, *Hydrania dulloi*, *Paleolituonella meridionalis*,
microproblematica Ladinella porata, Plexoramea gracilis, Radiomura cautica and potentially the sponge Solenolmia. Additionally, Carnian corals, including Thamnasteriamorpha okudai, have been reported from the Daifugendake area on the Kii Peninsula, Honshu (Yamato Omine Research Group 1976; Okuda and Yamagiwa 1978; Okuda 2006; Stanley and Onoue 2015). Interestingly, the Carnian reef limestone that crops out in these two localities occurs also as limestone clasts that are embedded in a volcaniclastic matrix (VCM breccia). This observation corroborates the interpretation that the different Carnian limestone units of the SAC experienced a similar geological history despite their current wide distribution along this tectonic belt (approximately 550 km from the Koguchi locality in the southwest to the Daifugendake area in the northeast). It follows that these coeval limestone units, which are characterized by the same biota, originated at least from the same area of Panthalassa, if not from the same seamount.

The present study documents widespread Ladinian?-Carnian reef limestone and extends the stratigraphic range of reefs in the SAC. The reefs reported in this work likely represent the initiation of the carbonate platforms at the tops of Panthalassa seamounts. Consequently, Norian reefs that have been previously described in the SAC (Kamase reef, Onoue and Stanley 2008; Inaba reef, Chablais et al. 2010c) represent a later stage in the Upper Triassic reef evolution of the Panthalassa build-ups.

Fig. 2.9 Stratigraphic framework of the Sambosan limestone. Stratigraphic ranges are from Onoue and Sano (2007) [1]; Onoue and Stanley (2008) [2]; Chablais et al. (2010c) [3]; Chablais et al. (2011) [4]; Senowbari-Daryan et al. (2012) [5] and this study. Chronostratigraphy after the International Commission on Stratigraphy 2015.
Paleobiogeography
The geographic distribution of the taxa described in the previous sections confirms a strong biogeographical affinity of the Ladinian-Carnian reef biota of the SAC with those of the Tethyan domain. This Tethyan affinity has already been observed for bivalves (Tamura 1990, 1992; Onoue and Tanaka 2002, 2005), foraminifers (Kristan-Tollmann 1991; Chablais et al. 2011), sponges and microproblematica (Senowbari-Daryan et al. 2012) and microcoprolites (Senowbari-Daryan et al. 2010), both for Carnian and Norian-Rhaetian ages. More precisely, Chablais et al. (2011) proposed a stronger affinity with the Southern margin of the Tethys on the basis of semi-quantitative analysis of foraminifer diversity, and that interpretation is consistent with results of the present paper. Accordingly, we can state that the Upper Triassic reef biota of the Tethys and western Panthalassa are rather similar and mainly include cosmopolitan taxa. However, concerning coral fauna of the SAC, Stanley and Onoue (2015) mentioned some affinities with the Tethys but also reported six endemic taxa among the ten that were presented in their study, which suggest a biogeographical isolation. Nevertheless, based on the literature and our results, significant endemism is not evident for other taxonomic groups.

2.7. Conclusions
Our study of the reef limestone clasts of the Sambosan Accretionary Complex in several localities of Shikoku Island (Japan), led us to:
• Report reef biota, including seventeen species described for the first time in Japan, such as the calcareous sponges Zarditina perisulcata, C. zitteli, Celyphia zoldana, Celyphia? minima, Stylothalamia dehmi, Uvanella? lamellata, ?Murania kazmierczaki; solenoporacean red algae Dendronella articulata; foraminifers Arenovidalina chialingchiangensis, Trocholina cordevolica, ?Koskinobullina socialis, Piallina bronnimanni, Piallina tethydis and nubeculariid foraminifers; brachiopod Gosaukammerella eomesozoica and the microproblematicum Plexoramea cerebriformis. This supports a high biodiversity of Carnian reefs in Panthalassa.
• Propose a Ladinian-Carnian age for this reef limestone based on biostratigraphic markers and biotic assemblages and to discriminate within the SAC between Ladinian-Carnian and Norian reefs at a regional scale.
• Support the close biogeographical affinity of the SAC with the Tethyan realm despite difficulties in the comparison with poorly documented eastern Panthalassa, Ladinian-Carnian reef fauna.

• Provide new and valuable data for paleobiogeography and paleobiodiversity studies that will inform global databases such as the PaleoReefs database or the Paleobiology database. This is particularly relevant because little is known about Carnian reef biota of the Panthalassa realm.

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Chapter 3: Reefs of the SAC at Shikoku Island

Chapter 3: Paleoecology, biogeography and evolution of reef ecosystems in the Panthalassa domain during the Late Triassic: Insights from the reef limestone of the Sambosan Accretionary Complex, Shikoku, Japan

Abstract
Upper Triassic reefs from the Panthalassa realm have been understudied in comparison to their Tethyan counterparts and are therefore pivotal to understanding the global reef evolution during the Late Triassic. To fill this gap, we investigated Upper Triassic reef limestone from ten localities of the Sambosan Accretionary Complex in Shikoku Island, Japan. Biotic assemblages, quantitative microfacies analysis and integrated biostratigraphy allow us to characterize two types of reefs, those attributed to the Ladinian–Early Carnian and those attributed to the Late Carnian–Rhaetian. At the regional scale, our data refine the biostratigraphic framework of the Upper Triassic Sambosan limestone. At the global scale, multivariate analyses support a strong paleobiogeographic affinity of the western Panthalassa reef biota with those of the South Tethys Ocean during the Ladinian–Carnian and Norian–Rhaetian and indicate connections with East Panthalassa reefs during the Norian–Rhaetian.

A similar version is in review in ‘Palaeogeography, Palaeoclimatology, Palaeoecology’ as Peybernes C, Chablais J, Onoue T, Escarguel G, Martini R (submitted) Paleoecology, biogeography and evolution of reef ecosystems in the Panthalassa domain during the Late Triassic: Insights from the reef limestone of the Sambosan Accretionary Complex, Shikoku, Japan
3.1. Introduction

Reefs are high-biodiversity ecosystems that are extremely sensitive to environmental changes. Fossil reefs therefore constitute important records of oceanic environment evolution during geological times. The Late Triassic is a period of important reef development (Stanley, 1988; Flügel, 1981, 2002). This development led to significant carbonate production worldwide and contributed to the expansion of carbonate platforms during the Late Triassic. During the Triassic, reef ecosystems experienced several changes with regards to their distributional patterns, paleogeographic settings, taxonomic composition and biodiversity (Flügel 2002; Bernecker 2005). Reef evolution during the Triassic is typically viewed as a three step process (Stanley 1988; Flügel 2002). After the end-Permian crisis, during the Early Triassic, bioconstructed deposits are dominated by microbial buildups (but see Brayard et al. 2011; Vennin et al. 2015). Reef recovery occured largely in Western Tethys and South China during the Anisian (e.g., Payne et al. 2006) and was followed by a reef proliferation during the Ladinian–Early Carnian. Important changes later occurred in the reef taxonomic composition during the Late Carnian–Early Norian turnover (Flügel 2002). During the Norian–Rhaetian, reef ecosystems reached their maximum latitudinal distribution and highest biodiversity before experiencing a significant crisis at the end of the Triassic (Flügel 2002). This global reef evolutionary trend is particularly well documented in the Tethys realm. However, Upper Triassic reefs of the Panthalassa domain have received less attention so far. Because most of the pre-Jurassic oceanic crust has been subducted, the study of the Triassic sediments from the Panthalassa realm is primarily based on the remains of former oceanic islands and volcanic arcs preserved in circum-Pacific accretionary complexes and terranes. Panthalassic reefs are reported in allochthonous terranes in the American cordillera (e.g., Stikinia, Reid and Ginsburg 1986; Wallowa, Stanley and Senowbari-Daryan 1986; Antimonio, Stanley et al. 1994; see also the review by Martindale et al. 2015) and in the Western Pacific archipelagos (Philippines, Flügel and Kiessling 2000; Japan, Kanmera 1969; Onoue and Stanley 2008; Chablais et al. 2010b). These Panthalassic reefs have been the focus of several sedimentological and paleoecological investigations in the recent decades (e.g., Onoue and Stanley 2008; Chablais et al. 2010b; Martindale et al. 2012).

To improve our understanding of reef evolution in the Panthalassa during the Late Triassic, we investigated reef limestone from the Sambosan Accretionary Complex (SAC) in Shikoku Island, Southwest Japan (Fig. 3.1a, b). The terrigenous-free limestone units of the SAC are interpreted as being the remains of shallow water atoll-type carbonates deposited on top of
Panthalassic seamounts during the Late Triassic and accreted to the Asian margin during the Late Jurassic–Early Cretaceous (Kanmera 1969; Onoue and Sano 2007; Chablais et al. 2010a). Occurrences of reef facies and fauna were mentioned in the earliest studies of the Sambosan limestone (Kobayashi 1931; Kanmera 1964; Kanmera 1969). Corals, in particular, have been reported from Kyushu (Kanmera 1964; Stanley and Onoue 2015), Shikoku (Okuda et al. 2005; Stanley and Onoue 2015), and Kii Peninsula (Yamato Omine Research Group 1976; Okuda and Yamagiwa 1978; Okuda 2006). Several former studies described microfacies and the biotic composition of the reef limestone in the SAC of Kyushu and Shikoku Islands (Kanmera 1969; Onoue and Stanley 2008; Chablais et al. 2010b; Senowbari-Daryan et al. 2012). These studies focused on single reef locality. In this paper we describe 10 reef localities along the SAC of Shikoku Island and provide the detailed biotic contents and quantitative assessment of the reef components for 9 of them. Special focus is given to the paleoecology of the reef environment, especially on the biotic associations between framebuilders, microencrusters and microbialites. Quantitative data significantly enhance our understanding of ancient reef ecosystems and allow us to reliably discriminate between different types of reefs. Our results are especially relevant when compared with similar quantitative analyses performed on coeval reef settings (e.g., Martindale et al. 2012, 2013a). Comparisons with coeval reefs in the Tethys and Panthalassa oceans provide data and constraints on the paleobiogeography of Upper Triassic reef biota that are pivotal to improving Late Triassic paleogeography reconstructions (Chablais et al. 2011; Martindale et al. 2015). Therefore, the objectives of this paper are (1) to report the occurrence of reef limestone from new localities in central and eastern Shikoku Island; (2) to quantitatively describe the biotic composition and reef structure of both new and previously studied reef localities of the SAC; (3) to provide biostratigraphic constrains on reef evolution in the western Panthalassa; (4) to correlate and quantitatively compare the reefs from the SAC with their counterparts in the Tethys and Panthalassa domains; and (5) to discuss the paleobiogeographic affinity of the reef biota of the SAC.

In this study we follow the reef definition by Riding (2002) in which all “calcareous deposits created by essentially in-place sessile organisms” are considered to be reef. This structural definition does not include any size or hydrodynamic requirement (e.g., elevation above the seafloor, resistance to waves). This definition particularly fits to our case study because, in the SAC, reef facies are often not identified in the field. The lack of stratigraphic successions and the strong recrystallization make reef facies recognizable only in thin sections. Additionally, because the limestone crops out as isolated massive units, criteria such as topographic elevation above the seafloor are not applicable. As a consequence, several microfacies criteria are used...
in this study to undoubtedly identify true bioconstructed reef limestone. First, a significant amount of reef builder organisms (e.g., sponges, corals) must be present in the sample for it to be considered reef limestone. Ideally, the reef builders must be in-place, but it is often difficult to assess this criterion in thin sections. Moreover, in both modern and ancient reefs, broken and more or less reworked reef components are common, especially at the reef crest (Fagerstrom and Weidlich 2005; Martindale et al. 2013a). Second, the presence of microbial crusts and sessile organisms bounding the reef builders together particularly helps to identify reef limestone. These binders usually represent an important part of the reef and underline the reef framework, making it more recognizable especially when reef builders are recrystallized. Third, reef builders and binders typically define cavities that are filled with thick isopachous cement. Even if they are not totally restricted to reef facies, these cavities represent a valuable clue in identifying reef limestone because, along with builders and binders, they prove the presence of a reef framework. These three criteria allow us to reliably recognize reef limestone even with poorly preserved material. In other studies dealing with Upper Triassic reefs, several facies that do not completely fulfill these three criteria are sometimes included in reef limestone *sensu lato* (e.g., Wurm 1982; Martindale et al. 2013a). These studies are based on more or less continuous limestone exposure where clear reef zonations can be established. For example, the relation between the fore-reef rudstone and the clearly bioconstructed part of a reef (reef core) could be determined in such preserved settings. In the SAC, such peri-reefal facies were also observed but the link with the bioconstructed facies remains hypothetical. In this study, when some facies did not fully meet the aforementioned criteria, they were excluded from the analyses. These excluded facies will be part of a separate facies analysis (Chapter 4) focused on the different depositional settings that characterize the SAC build-up(s).
Fig. 3.1 Location maps of the studied localities. a Location of the Sambosan Accretionary Complex in southwestern Japan. b Location of studied areas in Shikoku. c–f Location of studied localities in Tsuno area (c), Mount Sambosan area (d), Befu and Kito area (e), Wajiki area (f).

3.2. Geological setting

The Sambosan Accretionary Complex (SAC) is a narrow belt of the Outer Zone of Southwest Japan that can be followed from the Ryukyu Islands to the Kanto Mountains (Honshu) (Matsuoka 1992; Onoue and Sano 2007) (Fig 3.1a). The Butsuzo Tectonic Line (BTL) represents the boundary between the SAC and the Shimanto Accretionary Complex to the south.
Typical lithologies of the SAC are basaltic rocks, shallow water limestone, limestone breccia and bedded chert. The basaltic rocks are geochemically referred to as oceanic island basalt of hotspot origin (Ogawa and Taniguchi 1989; Ishizuka et al. 2003; Onoue et al. 2004; Safonova et al. 2015). The predominance of normal hotspot type OIB implies that the basalts were erupted to form a seamount by an intraplate volcanism that occurred in a mid-oceanic realm (Onoue et al. 2004). The shallow-water limestone, limestone breccia, and bedded chert are interpreted to be the sediments at the top of a mid-oceanic seamount, its upper flank, and adjacent ocean floor, respectively (Onoue and Sano 2007). Biostratigraphic markers reported from the Sambosan limestone indicate that the deposition of shallow water carbonates ranges from the Ladinian–Carnian to the Rhaetian (Onoue and Sano 2007; Chablais et al. 2011; Peybernes et al. 2015). Based on conodont occurrence (Metapolygnathus nodosus) in inter-pillow lava limestone from Kyushu Island, the age of the eruption of the seamount(s) was estimated to be late Upper Carnian (Onoue and Sano 2007). Nevertheless, Ladinian–Lower Carnian reef biota reported from Shikoku suggests an earlier initiation for the carbonate sedimentation (Peybernes et al. 2015).

In the SAC, reef limestone units primarily outcrop either (1) as limestone clasts that are embedded in a volcanioclastic matrix (VCM) or (2) as massive limestone slabs (Fig. 3.2). The limestone clasts are a few centimeters to a few decimeters in diameter and form a breccia with a volcanioclastic matrix and basaltic clasts (VCM breccia). The massive limestone slabs are tens of meters to kilometers in size. The first mode of occurrence (VCM breccia) is typically interpreted as debris flow and debris avalanche deposits on the flank of a mid-oceanic seamount prior to the accretion at the trench (Onoue and Sano 2007; Chablais et al. 2010a), whereas the second (massive limestone slabs) probably resulted from the dismantling of the seamount in the trench and/or in the accretionary wedge during the accretion-subduction processes. The breccia units are often in close vicinity to massive limestone slabs or even in fault contact with them (Fig. 3.2a). In such cases (i.e., Mt. Sambosan and Mt. Ishidate), limestone clasts of the VCM breccia and the massive limestone slabs are treated separately as two distinct localities (e.g., Loc. 4 Mt. Sambosan 1 and Loc. 5 Mt. Sambosan 2).
Chapter 3 : Reefs of the SAC at Shikoku Island

Fig. 3.2 Mode of occurrence of reef limestone in the SAC. **a** Outcrop view of Mt. Sambosan showing a massive white limestone slab (Loc. 1 Mt. Sambosan 1) in fault contact (F) with VCM breccia (Loc. 2 Mt. Sambosan 2). **b** Close up view of the VCM breccia showing reef limestone clasts (LC) embedded in volcaniclastic matrix (VCM).

3.3. Studied areas

Between 2012 and 2013, the Sambosan limestone localities in central and eastern Shikoku were systematically investigated. Material for this study comes from 10 localities where reef limestone has been collected, most often associated with other limestone facies that are not considered in this paper. These localities are described below and key information is summarized in Table 3.1.

Tsuno area

The Tsuno area includes three localities: Loc. 1 Inaba cave, Loc. 2 Tsuno windmill, and Loc. 3 Tsuno (Fig. 3.1c). At Loc. 1 Inaba cave, reef limestone occurred as karstified massive limestone slabs of hundreds of meters laterally and as limestone blocks along the nearby Shimanto River. The Inaba cave has been investigated by Onoue et al. (2009) and Chablais et al. (2010b). Some samples described by these authors are used for point counting and thin section mapping. Loc. 2 Tsuno windmill is a new locality on the mountain crest northwest of Tsuno town where karstified massive limestone slabs crop out. In contrast, reef limestone blocks occurred in a VCM megabreccia at Loc. 3 Tsuno. This locality is described in more detail by Peybernes et al. (2015).
Mount Sambosan area

The Mount Sambosan area corresponds to the Sambosan type locality (Yamato Omine Research Group, 1981) and has been studied by several authors including Kobayashi (1931), Yamato Omine Research Group (1981), Okuda (2005), Chablais (2010), and Peybernes et al. (2015). There, limestone crop out as massive limestone slabs (Loc. 4 Mt. Sambosan 1) and as clasts in matrix-supported VCM breccia (Loc. 5 Mt. Sambosan 2) (Fig. 3.1d). The massive limestone slab is in fault contact with the breccia unit (Fig. 3.2). According to Stanley and Onoue (2015), at Mt. Sambosan (Loc. 4), the massive white limestone slab is composed of clast-supported polymict limestone breccia that represent talus deposits. In this study we only focus on the reefal parts of the Sambosan type locality, as described in the introduction (see section 3.1).

Befu/Kito area

This area includes four localities: Loc. 6 Befu, Loc. 7 Mt. Ishidate 1, Loc. 8 Mt. Ishidate 2, and Loc. 9 Konose Kyo (Fig. 3.1e). At Loc. 6 Befu the limestone units are too poorly preserved for relevant reef facies analysis but yield an interesting conodont fauna. Thus, the reef facies of this locality are not studied in details but the conodont fauna is described in section 3.5.4. The conodonts have been found in reefal blocks that most likely detached from the nearby cliff. Loc. 7 Mt. Ishidate 1 and Loc. 8 Mt. Ishidate 2 correspond to two localities along the trail leading to the Mt. Ishidate summit. The first corresponds to massive reef limestone slabs and the second to reef limestone clasts embedded in a VCM matrix. Loc. 9 Konose Kyo is situated on a mountain crest in Konose Valley where reef limestone clasts occurred in a VCM matrix. Few additional samples, previously collected along the road close to Loc. 9 Konose Kyo by Chablais (2010) have also been used. Loc. 9 Konose Kyo and Loc. 8 Ishidate 2 are further described in Peybernes et al. (2015).

Wajiki area

The locality in Wajiki area (Loc. 10 Road 28) is situated in a quarry above the Road 28 (Fig. 3.1f) and is described here for the first time. Reef limestone clasts crop out, along with basaltic clasts and limestone clasts of other facies, in a VCM breccia. This unit is in tectonic contact with recrystallized massive limestone slabs. This mode of occurrence is very similar to Loc. 5 Mt. Sambosan 2.
Table 3.1: Studied localities.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Coordinates</th>
<th>Mode of occurrence</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsuno area (Tsuno, Kochi prefecture)</td>
<td>Loc. 1 Inaba</td>
<td>33° 26.322'N 133° 5.134'E</td>
<td>Massive limestone slab</td>
</tr>
<tr>
<td></td>
<td>Loc. 2 Tsuno windmill</td>
<td>33° 27.437'N 133° 8.356'E</td>
<td>Massive limestone slab</td>
</tr>
<tr>
<td></td>
<td>Loc. 3 Tsuno</td>
<td>33° 27.996'N 133° 11.775'E</td>
<td>Limestone clasts in VCM breccia</td>
</tr>
<tr>
<td>Mount Sambosan area (Konan, Kochi prefecture)</td>
<td>Loc. 4 Mt. Sambosan1</td>
<td>33°34.482'N 133° 42.686'E</td>
<td>Massive limestone slab</td>
</tr>
<tr>
<td></td>
<td>Loc. 5 Mt. Sambosan 2</td>
<td>33° 34.452'N 133° 42.733'E</td>
<td>Limestone clasts in VCM breccia</td>
</tr>
<tr>
<td>Befu/Kito area (Kami, Kochi prefecture and Naka, Tokushima Prefecture)</td>
<td>Loc. 6 Befu</td>
<td>Massive limestone slab</td>
<td>CP59</td>
</tr>
<tr>
<td></td>
<td>Loc. 7 Mt. Ishidate1</td>
<td>33° 46.808'N 134° 3.586'E</td>
<td>Massive limestone slab</td>
</tr>
<tr>
<td></td>
<td>Loc. 8 Mt. Ishidate2</td>
<td>33° 46.800'N 134° 4.063'E</td>
<td>Limestone clasts in VCM breccia</td>
</tr>
<tr>
<td></td>
<td>Loc. 9 Konose kyo</td>
<td>33° 47.009'N 134° 4.969'E</td>
<td>Limestone clasts in VCM breccia</td>
</tr>
<tr>
<td>Wajiki area (Anan, Tokushima prefecture)</td>
<td>Loc. 10 Road 28</td>
<td>33° 52.516'N 134° 33.078'E</td>
<td>Limestone clasts in VCM breccia</td>
</tr>
</tbody>
</table>

3.4. Material and methods

For this study, 260 thin sections were prepared (2.3 × 3.5 cm and 4.7 × 3.5 cm), scanned with a high-resolution film scanner (Nikon CoolScan 4000 ED) and observed in transmitted light under an optical microscope (Zeiss Axioskop). For all samples, microfacies were described and reef fauna determined (see Supplementary material 3.1). Forty-eight well-preserved samples were selected for point counting analysis. Thin sections showing only a specific reef organism and used for taxonomic purposes were not selected for point counting to avoid overestimation of a single biotic group.

To establish robust biostratigraphic ages, limestone samples were dissolved in 10% acetic acid for conodont extraction. After sieving and picking, samples were mounted on conductive aluminum support. An ultra-thin coating (ca. 10 nm) of gold was then deposited on the samples by low vacuum sputter coating prior to imaging with a Jeol JSM 7001F Scanning Electron Microscope (Department of Earth Sciences, University of Geneva, Switzerland).

Point counting is used to quantitatively assess the relative abundances of reef components. Following Flügel (2004), 300 points were randomly counted (grain bulk method) on scanned thin sections by using an image analysis software (JMicr0vision). Recursive and random grids were both tested and results were similar. The random grid fit better with the studied thin
sections because the recursive grid could trigger some bias if counted points systematically follow major fractures or other diagenetic features. Nevertheless, even if a random grid is preferred, our method provides similar results to those commonly used in other studies (e.g., Blendinger 1994; Olivier et al. 2004; Martindale et al. 2010, 2013a) and, therefore the results can be compared.

Hierarchical cluster analysis (hCA) has been applied to quantitatively assess the taxonomic similarities between reef communities. To date, these methods have rarely been used for paleoecological and paleobiogeographical investigations of Late Triassic reef biota (Schäfer 1979; Stanley 1979; Stanton and Flügel 1987; Yarnell 2000; Rosenblatt 2010; Sanchez-Beristain 2010). We performed cluster analyses on two different datasets. The first one records the occurrence of 56 species or higher rank taxa of calcareous sponges, microproblematica and foraminifers reported from the 10 studied localities of the SAC (see section 3.5.2). The second dataset is a taxonomically homogenized compilation of the occurrence of 201 genera of calcareous sponges (117 genera), microproblematica (17 genera) and foraminifers (67 genera) from 18 geographical areas (“region” sensu Veron, 1995 or “domain” sensu Flügel, 2002) in the Tethys and Panthalassa realms. Calcareous sponges, microproblematica and foraminifers were selected for the cluster analyses because: (1) they are important reef builders and dwellers that accurately represent the Triassic reef communities; (2) they show high diversity that allow them to be used for multivariate analysis; and (3) they are rather easy to identify at the generic level (compared to corals or algae, for example) and are therefore often reliably reported in the literature. These three groups can be included in the same analysis because they share similar ecologies (juvenile planktonic stage and adult benthic stage, either sessile or with little displacement). Major revisions in coral taxonomy (e.g., Roniewicz 1989) since the original publications make the comparisons of corals between reef sites difficult (Martindale et al., 2015); therefore, they are not included in this study.

Hierarchical cluster analyses (hCA) were performed using PAST software (v. 3.05) with a UPGMA algorithm and Dice (= Sørensen) coefficient of taxonomic similarity: 

$$S_{\text{Dice}} = \frac{2C}{A+B},$$

where A and B are the number of taxa in samples A and B, and C is the number of taxa shared by A and B. The Dice coefficient was selected because of the double weight given to shared presences and thus relative underweighting of absences and unique occurrences that might be due to sampling bias and does not reflect real differences in taxa distribution (Brayard et al. 2007). This makes the Dice coefficient highly reliable for biogeographical analyses even when comparing biogeographic areas with unequal sampling effort because it emphasizes similarity
rather than differences among sampling units (Cheetam and Hazel 1969; Garcia-Bellido and Rodriguez 2005). In particular, The Dice coefficient is moderately affected by differences in taxonomic richness between the studied localities (Shi 1993; Arias 2006). The Dice coefficient has been commonly used in other paleocological and paleobiogeographical studies (e.g., Aberhan 1998, 2001; Garcia-Bellido and Rodriguez 2005; Arias 2006; Hopkin 2009; Niu et al. 2011; Brayard and Escarguel 2013; Brayard et al. 2015). The statistical significance of the taxonomic dissimilarity between the obtained clusters was tested through Analysis of Similarity (ANOSIM) and the relative contribution of each taxon to the overall inter-cluster compositional dissimilarity was evaluated through SIMPER analysis, using the Dice coefficient for each analysis (Clarke 1993).

Even with the Dice coefficient of similarity, localities with close generic richness may cluster together, making it difficult to determine whether this grouping is due to genuine biogeographic reasons or to a taxonomic richness-induced bias unrelated with the biogeographical history of the studied localities (Smith 1988; Niu et al. 2011). In other words, it is worth knowing if the clusters identified through hCA do reflect biogeographically controlled, richness-free similarities in taxonomic composition or similarities in taxonomic richness that may not be directly explained by the biogeographical history. To untangle the potential effect of taxonomic richness and composition on the cluster analyses we first converted the Dice similarity matrix \( S_{\text{dice}} \) into a dissimilarity matrix \( D_{\text{dice}} = 1 - S_{\text{dice}} \). Baselga (2010, 2012) showed that \( D_{\text{dice}} \) can be additively decomposed into two independent components: a compositional dissimilarity matrix known as the Simpson dissimilarity matrix \( D_{\text{Simp}} \) with \( D_{\text{Simp}} = \frac{c}{\min(A,B)} \); Simpson, 1960), and a richness dissimilarity matrix referred to as the Nestedness dissimilarity matrix \( D_{\text{nest}} \) where: \( D_{\text{Dice}} = D_{\text{Simp}} + D_{\text{Nest}} \Rightarrow D_{\text{Nest}} = D_{\text{Dice}} - D_{\text{Simp}} \). Finally, a comparison of \( D_{\text{dice}} \) ("total" taxonomical dissimilarity), \( D_{\text{Simp}} \) (compositional dissimilarity) and \( D_{\text{nest}} \) (richness dissimilarity), using one-tailed Mantel tests (9 999 permutations), allows the separate effect of richness (Nestedness) and compositional (Simpson) dissimilarities on the “total” (Dice) taxonomic dissimilarity to be assessed.

3.5. Results

The main reef components in the Sambosan limestones are recrystallized sponges, microbialites and microproblematica. Consequently, most of the analyzed samples can be described as sponge-microbialite boundstones. To improve the accuracy of description, the determination of minor reef components and relative abundances are required. Accordingly, an inventory of reef
components, point-counting results and thin section mapping are presented in the following sections.

3.5.1. Reef biota
Reef limestone of the SAC contains a comprehensive reef biota including scleractinian corals, calcareous sponges, red algae, mollusks, brachiopods, echinoderms, worm tubes, foraminifers and microproblematica. Reef taxa from the SAC at Shikoku Island are reported below and are illustrated in Figs. 3.3 and 3.4 (see also Chablais et al. 2010 and Peybernes et al. 2015). We also mention some sponges, foraminifers and microproblematica reported from the Koguchi locality at Kyushu Island (Senowbari-Daryan et al. 2012) because we included them in the cluster analyses.

Corals are primarily represented by phaceloids and thamnasterioid growth forms. Despite the numerous descriptions in the literature (Okuda 2006; Okuda et al. 2005; Stanley and Onoue 2015), they are relatively rare in the SAC.

Calcareous sponges include Sphinctozoan, Inozoan, Chaetetids, Spongiomorphids and Disjectoporids. Sphinctozoan (segmented sponges) are the most frequent. They are represented by Celyphia? minima (Fig. 3.3l), Celyphia zoldana, Cryptocoelia sp., Cryptocoelia zitteli, Colospongia sp., Discosiphonella sp., Jablonskia andrusovi, Paradeningeria sp., Permocorynella sp., Solenolmia manon manon, Stylothalamia dehmi, Uvanella irregularis, Uvanella ? lamellata, and Zardinia perisulcata (Chablais et al. 2010; Senowbari-Daryan et al. 2012; Peybernes et al. 2015). Inozoan are unsegmented sponges that are often difficult to distinguish from Sphinctozoan. Because longitudinal sections are required for reliable attribution to this taxon, only a few specimens can be tentatively attributed to Inozoan. Chablais et al. (2010) reported Peronidella sp. at Loc. 1 Inaba. Chaetetids are abundant at Loc. 1 Inaba and Loc. 4 Mt. Sambosan 1 (Fig. 3.4g). Disjectoporids and Spongiomorphids are less frequent and are represented by Disjectopora sp. and Spongiomorpha sp. (Chablais et al. 2010). The encrusting sponge Murania kazmiierzaki is present at Loc. 3 Tsuno (Peybernes et al. 2015).

Foraminifers, especially porcelaneous taxa, are frequent. It is widely accepted that Upper Triassic carbonates recorded the appearance and expansion of many new species of porcelaneous reefal foraminifers (Chablais et al. 2011). The reef environment undoubtedly provides numerous protected ecologic niches colonized by these organisms (Chablais et al. 2011), explaining the coeval diversification of porcelaneous reefal foraminifers related to the reef expansion during the Late Triassic. For the purpose of the paper we divided foraminifer
assemblages into categories according to their ecological strategy rather than their systematic position.

Ophtalmidids and other porcelaneous foraminifers are frequent in the interstitial sediment between the reef frameworks. Among them, _Cucurbita infundibuliforme_ (Fig. 3.3e) and _Hydrania dulloii_ occur in cement-rich microbialite (often in association with the sponges _Zardinia_ sp. and _Cryptocoelia zitteli_), whereas _Galeanella_ sp. (Fig. 3.3b) occurs preferentially in grainstone-packstone sediment that infills the interstices between sponges.

Encrusting foraminifers are sessile forms that lived attached to framebuilders. They are frequent in reef limestone of the SAC. Common species are _Flaschofelia anisica_ (Fig. 3.3f), _Alpinophragmniunm perforatum_, _Planiinvoluta carinata_ (Fig. 3.3c), and _Tolypammina gregaria_. _Koskinobullina socialis_ and Nubecularids occasionally occur (Peybernes et al. 2015). No preference for a particular type of substrate has been observed for any of them.

Cosmopolitan forms are ecologically tolerant species that are found in reef facies but they are also present in other settings such as back-reefs and lagoons. This group is primarily represented by “_Trochammina_” sp., _Endotriada_ sp., Duostominids (Fig. 3.3a) and Nodosarids.

Bivalve shell fragments, gastropods, echinoderms and brachiopods are common in interstitial reef sediment. Echinoderms are represented by crinoid sticks, urchin spines and holothurian sclerites. Free-living brachiopods are common (Fig. 3.4a) as well as sessile brachiopods (_Gosaukammerella eomesozoica_, Fig. 3.4b), which attach to sponges and corals.

Microproblematica are organisms of uncertain systematic affinity. _Tubiphytes_ (Fig. 3.3l) and similar organisms represent one of the most abundant groups of microproblematica in Upper Triassic reefs especially in the Carnian (Senowbari-Daryan 2013). Members of this group include several growth forms ranging from fragile micritic tubes (e.g., _Plexoramea gracilis_) to thick organisms that are able to build reef frameworks (_Tubiphytes obscurus_). Several other encrusting and free-living microproblematica of minor importance are present. Among them, _Baccanella floriformis_ (Fig. 3.3g), _Actinotubella gusici_ (Fig. 3.3h), _Ladinella porata_ (Fig. 3.3i), _Radiomura cautica_ (Fig. 3.3j) and _Microtubus communis_ (Fig. 3.3k) are the most frequent.

Attached or free-living worm tubes that are composed of agglutinated clotted micrite (_Terebella_ sp., Fig. 3.4d) are common. Serpulids tubes have light calcitic walls and are relatively rare in the reef limestone of the SAC. They occur either as single encrusting tubes or as colony-like bundles of tubes (_Filograna_ sp., Fig 3.4e–f).

Red algae are important reef constituents. Solenoporacean are present in reef limestone of the SAC but are often poorly preserved. _Parachaetetes_ sp., _Solenopora_ sp. and _Dendronella articulata_ have been reported (Peybernes et al. 2015). Dasycladacean are virtually absent.
Cyanobacteria sheaths (*Girvanella* sp.) are common, especially at Loc. 3 Tsuno. While common in other facies, calcimicrobes such as *Garwoodia* or *Cayeuxia* are rare or absent in reef facies.

**Fig. 3.3** Reef biota of the SAC. a–f Foraminifers. a Duostominid CP212. b *Galeanella* sp. CP74. c Sessile foraminifer *Planinvoluta carinata* (arrow) that encrusts a sponge (S) CP178. d *Decapoalina schaeferae* CP75. e *Cucurbita infundibuliforme* CP181. f Sessile foraminifer *Flatschakofelia anisica* CP178. g–l Microproblematica. g *Baccanella floriformis* in a reef limestone clast set in volcaniclastic matrix (VCM) CP215. h *Actinotubella gusici* CP6. i *Ladinella porata* JC383A. j *Radiomura cautica* CP222. k *Microtubus communis* CP6. l Asssociation of Microproblematica *Tubiphytes* sp. (T) and sponges *Celyphia? minima* (C) CP23.
3.5.2. Biotic associations

Biotic associations provide valuable insight into the ecological structure of the reef ecosystem and also provide important biostratigraphic data. The distribution of identified taxa in the reef limestone of the SAC at Shikoku is summarized in Supplementary material 3.1. Data are compiled from Chablais et al. (2010) and Peybernes et al. (2015, this study). Coral fauna of the SAC were recently reviewed by Stanley and Onoue (2015) and, therefore, they are not included in this paper.

Hierarchical cluster analyses (hCA) allow us to quantitatively assess the taxonomic similarities between the reef communities from different localities. The distribution of sponges, foraminifers and microproblematica was summarized in a presence/absence matrix, which is used for the cluster analysis (UPGMA with the Dice coefficient of similarity). Other taxa, such as algae, were not selected because of their low diversity and scattered distribution among the
samples. Data from the reef limestone clasts of the Koguchi locality at Kyushu (Senowbari-Daryan et al. 2012) are included in the analysis.

Cluster analysis based on taxa occurrences clearly shows that the reef localities at Shikoku are divided into two main groups (Fig. 3.5). The first cluster, termed Reef Type 1, includes five localities: Loc. 3 Tsuno, Loc. 5 Mt. Sambosan 2, Loc. 7 Mt. Ishidate 2, Loc. 8 Konose Kyo and the Koguchi locality. The second cluster, termed Reef Type 2, is comprised of Loc. 1 Inaba, Loc. 2 Tsuno windmill, Loc. 4 Mt. Sambosan 1, Loc. 7 Mt. Ishidate 1 and Loc. 10 Road 28. Similar results are observed with other clustering methods (e.g., neighbor-joining) and coefficients of similarity (e.g., Jaccard, Simpson). The ANOSIM test strongly supports the differences between Reef Type 1 and Reef Type 2 ($p = 0.0078 **$).

![Dendrogram showing the results of a hierarchical cluster analysis (UPGMA, Dice coefficient of similarity) based on the occurrences of calcareous sponges, microproblematica and foraminifers in the studied localities of the SAC.](image)

In terms of the biotic association, characteristic taxa of the cluster Reef Type 1 are *Zardinia perisulcata*, *Uvanella irregularis*, *Cryptocoelia zitelli*, *Celyphia* spp., *Cucurbita infundibuliforme*, *Tubiphytes* sp., *Plexoramea cerebriformis*, *Plexoramea gracilis* and *Ladinella porata*. *Uvanella? lamellata* and *Piallina* spp., *Hydrania dulloi* and *Trocholina cordevolica* occasionally also occur in the localities of this cluster. The cluster Reef Type 2 is characterized by the abundance of Chaetetids, and the presence of *Galeanella* sp. and *Microtubus communis*. *Decapoalina schaeferae*, *Alpinophragmium perforatum* and *Actinotubella gusici* are subordinate taxa that are also present in the same localities.
SIMPER analysis reveals that the separation between the two main clusters is primarily driven by the occurrence of *Tubiphytes* sp. and *Plexoramea gracilis* in Reef Type 1 (contributing to 5.2% and 4.8% of the overall between-cluster taxonomical dissimilarity, respectively). Grouping patterns within each cluster are more difficult to interpret and may only reflect sampling heterogeneities among localities.

3.5.3. Reef structures

The reef structure is commonly divided into two main categories: the reef framework (primary and secondary framebuilders) and the interstitial reef sediments including sedimentary grains, microbialites and cements (Table 3.2, 3.3, Fig. 3.6).

The reef framework constitutes the reef architecture and is composed of primary framebuilders (i.e., organisms whose carbonate skeletons form the reef structure) and secondary framebuilders that include binding microbial crust and encrusters. Secondary framebuilders are sessile organisms smaller than the primary framebuilders acting as a substrate. In the Sambosan reef limestone, primary framebuilders are represented by sponges, corals, *Tubiphytes* and solenoporacean. Most of the sponges, corals and solenoporacean are strongly recrystallized. However, this recrystallization follows the main feature of the primary skeleton (i.e., sponge chambers, coral septa, solenoporacean cells). Each group can therefore be easily distinguished from the others. Rarely, sponges may encrust other organisms. To be consistent, all sponges are considered as primary framebuilders. Similarly, solenoporeacean algae are sometimes only sediment contributors, but most of the solenoporacean specimens seem to remain in the erected life position and are encrusted; therefore, they act as primary framebuilders and deserve to belong to this category. Colonial serpulid worm tubes (*Filograna* sp.) are also considered to be primary framebuilders. The *Tubiphytes* category includes all *Tubiphytes*-like organisms (i.e., *Tubiphytes*, *Plexoramea*) interpreted to be mainly in the life position and acting as framebuilders. *Tubiphytes* are often interpreted as encrusters in other studies (e.g., Martindale et al., 2013a) but not in this work because most of the time no evidence of encrustation on other organisms is visible. Moreover, they noticeably define cavities and sometimes act as a substrate for other organisms. Nevertheless, fragments of *Plexoreamea cerebriformis* and *Plexoramea gracilis* are counted as non-encrusting microproblematica (dwellers) and could be considered important sediment producers (Senowbari-Daryan 2013).
Table 3.2: Relative abundances of reef components.

<table>
<thead>
<tr>
<th>Loc.</th>
<th>Reef framework</th>
<th>Interstitial reef sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary framebuilders</td>
<td>Spanses</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Inaba</td>
<td></td>
<td>43.8</td>
</tr>
<tr>
<td>2 Windmill</td>
<td></td>
<td>28.6</td>
</tr>
<tr>
<td>3 Tsuno</td>
<td></td>
<td>6.7</td>
</tr>
<tr>
<td>4 Mt. Sambosan</td>
<td></td>
<td>19.9</td>
</tr>
<tr>
<td>5 Mt. Sambosan</td>
<td></td>
<td>10.2</td>
</tr>
<tr>
<td>7 Mt. Ishidate</td>
<td></td>
<td>56.7</td>
</tr>
<tr>
<td>8 Mt. Ishidate</td>
<td></td>
<td>11.6</td>
</tr>
<tr>
<td>9 Konose Kyo</td>
<td></td>
<td>7.8</td>
</tr>
<tr>
<td>10 Road 28</td>
<td></td>
<td>21.0</td>
</tr>
</tbody>
</table>

| N: number of samples used for point-counting; Mean % value [associated 95% “exact” Clopper-Pearson confidence interval]; Important value in bold. |
Secondary framebuilders are represented by encrusting organisms and microbial crusts. The encrusting organism group (also called epibiont) is primarily composed of sessile microproblematica (e.g., *Radiomura cautica*, *Microtubus communis*) but also of sessile foraminifers, serpulids, agglutinated worm tubes and encrusting brachiopods (e.g., *Gosaukammerella eomesozoica*). Microbial crusts (formerly called spongiostromata) form a defined layer of more or less clotted and laminated micritic material, binding other framebuilders. They are often associated with encrusting organisms.

Interstitial reef sediment composed of skeletal and non-skeletal grains, microbialite, and cements fill the space between the framebuilders. Skeletal grains (i.e., reef dwellers) are represented by foraminifers, fragments of echinoderms, mollusks, brachiopods and non-encrusting microproblematica (e.g., *Plexoramea* spp., *Baccanella floriformis*). Non-skeletal grains include peloids and ooids. Smaller peloids with a loose lining composed the peloidal and clotted micrite. Most of the ooids and spar-rimmed peloids are recrystallized and, along with peloids and dwellers, constitute a cement-rich grainstone facies. Microbialites are deposits controlled by benthic microbial communities (Burnes and Moore 1987; Riding 2000). In the thin sections, they appear as micritic, peloidal, clotted and/or laminated textures. In the Sambosan reef limestone they are primarily represented by peloidal and clotted micrite (thrombolite), and secondarily by a more or less laminated microbial crust (considered to be secondary framebuilders, see above). Peloidal and clotted micrite are composed of tiny peloids (10 to 40 µm in diameter) that are more or less clustered and, occasionally, surrounded by a thin spar rim. This texture is also variously reported as automicrite (Wolf 1965; Keim and Schalger 1999), peloidal micrite (Russo et al. 1997), internal micrite (Reid et al. 1990) or peloidal cement (Flügel 2004). Peloidal and clotted micrite is typically interpreted as being microbially induced precipitate (Chafetz 1986; Reid 1987). Conversely, denser micrite is considered to be depositional carbonate mud and is counted separately. Peloidal and clotted micrite occurs in reef cavities and is associated with various reef builders. Clotted peloidal micrite within framework cavities has commonly been linked to anaerobic bacteria (Tosti et al. 2014 and reference therein). In many cases, fenestrae are observed in the peloidal and clotted micrite. Peloidal and denser micrite may include small dwellers such as porcelaneous foraminifera and tiny bioclasts. Two types of cements fill the remaining space of the reef limestone. The first corresponds to granular to blocky cements that occupy the interstices between grains and infilled small fenestrae. This type of cement may be slightly overestimated in the point counting due to recrystallization processes. The second type of cement corresponds to tanned isopachous cements that cover voids and cavities within the reef framework. A
secondary generation of blocky sparite fills the remaining porosity. These isopachous cements are often considered to be early cements resulting from efficient water pumping through the reef cavities (Riding 2002). This type of cement is especially abundant at Loc. 5 Mt. Sambosan 2. Cements in fracture are not considered for the point counting. The relative abundances of reef components were assessed using point counting. The mean values and associate 95% “exact” Clopper Pearson confidence intervals of the relative abundances of reef components for each locality are presented in Table 3.2. The relative importance of the reef framework versus the interstitial sediments is shown in Table 3.3. Additionally, the relative abundances of the main reef components are displayed in Fig. 3.6.

Table 3.3: Relative abundance of reef framework and interstitial sediments.

<table>
<thead>
<tr>
<th>Localities</th>
<th>% reef framework</th>
<th>% interstitial sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loc. 1 Inaba</td>
<td>54.2</td>
<td>45.8</td>
</tr>
<tr>
<td>Loc. 2 Windmill</td>
<td>33.8</td>
<td>66.2</td>
</tr>
<tr>
<td>Loc. 3 Tsuno</td>
<td>33.0</td>
<td>67.0</td>
</tr>
<tr>
<td>Loc. 4 Mt. Sambosan 1</td>
<td>39.0</td>
<td>61.0</td>
</tr>
<tr>
<td>Loc. 5 Mt. Sambosan 2</td>
<td>25.2</td>
<td>74.8</td>
</tr>
<tr>
<td>Loc. 7 Mt. Ishidate1</td>
<td>62.3</td>
<td>37.7</td>
</tr>
<tr>
<td>Loc. 8 Mt. Ishidate2</td>
<td>24.4</td>
<td>75.6</td>
</tr>
<tr>
<td>Loc. 9 Konose Kyo</td>
<td>19.5</td>
<td>80.5</td>
</tr>
<tr>
<td>Loc. 10 Road 28</td>
<td>29.9</td>
<td>70.1</td>
</tr>
</tbody>
</table>

Loc. 3 Tsuno, Loc. 5 Mt. Sambosan 2, Loc. 8 Mt. Ishidate 2 and Loc. 9 Konose Kyo clearly show similar mean relative abundances of reef constituents (Tables 3.2 and 3.3; Fig. 3.6). They are characterized by high abundances of Tubiphytes and peloidal and clotted micrite. The reef framework represents a relatively low volume and does not exceed 33%. Up to 80% of the rock volume is occupied by the interstitial sediment. These localities correspond to Reef Type 1, as defined by our cluster analysis (see section 3.5.2). Loc. 1 Inaba, Loc. 2 Tsuno windmill, Loc. 4 Mt. Sambosan1 and Loc. 7 Mt. Ishidate 1 present some similarities regarding the frequency of reef components. They are characterized by the abundance of sponges and a significant reef framework (40–60% of the rock volume) and correspond to Reef Type 2, as defined by our cluster analysis (see section 3.5.2). The reef structure pattern at Loc. 10 Road 28 is less clear. The reef framework volume is relatively low (approximately 30%) but sponges are comparatively abundant (21%) and Tubiphytes are rare.
Overall, the relative abundances of reef components allow us to distinguish between two types of reefs that are consistent with those revealed by the cluster analysis based on biotic associations. These two independent and concordant analyses emphasize the distinction that can be drawn between two types of reefs in the SAC at Shikoku.

Thin section mapping of characteristic samples for each reef type are shown in Fig. 3.7, aiming at illustrating the two types of reef. The reef framework of Reef Type 1 is composed of sponges...
and *Tubiphytes* that define voids and cavities filled with isopachous cements (Fig. 3.7a, b). Microproblematica and clotted and peloidal micrite are abundant. Alternatively, the reef framework of Reef Type 2 is composed of Chaetetids and other sponges (Fig. 3.7c, d). Microbial crusts associated with *Microtubus communis* are frequent and the interstitial reef sediment is composed of peloid-bioclast-oids packstone-grainstone.

**Fig. 3.7** Reef microfacies. a–b Reef facies Type 1 (Ladinian–Carnian), note the abundance of *Tubiphytes* and Microproblematica, CP24B. c–d Reef facies Type 2 (Upper Carnian–Norian), note the presence of *Microtubus communis* in microbial crust and the abundance of chaetetid sponges, IR6.
3.5.4. Conodonts

Thirty four samples of shallow water limestone were processed for conodont extraction. Microfacies analysis was also performed on the same samples. Age-relevant conodonts were found at Loc.1 Inaba, Loc. 4 Mt. Sambosan 1 and Loc. 6 Befu (Fig. 3.8). The determination was by M. Orchard and the taxonomy follows Orchard (2014). Parvigondolella? sp. occur at Loc.1 Inaba (CP104) in massive limestone slabs. At Loc. 4 Mt. Sambosan 1, conodonts were found in blocks situated between the well-exposed massive limestone slab and the limestone VCM breccia (Fig. 3.2). Microfacies and biotic content show that these blocks are related to the massive limestone slab. Here the conodont fauna consists of ?Quadralella sp. (CP213-9), Primatella stanleyi (CP213-4) and Krassodontus roberti alpha morphotype (CP214-5). The conodont fauna at Loc. 6 Befu is composed of Quadralella sp. (CP59-1), Carnepigondolella samueli (CP59-5), Carnepigondolella cf. spatulata (CP59-4) and Quadralella lobata (CP59-9). Biostratigraphic implications of these conodont assemblages are discussed in section 3.6.3.

3.5.5. Comparison with reef biota from the Tethys and Panthalassa

Quantitative analysis based on the taxonomic composition of selected Upper Triassic reefs from the Tethys and Panthalassa oceans were used to assess the biostratigraphic and biogeographic affinities of the reef fauna from the SAC. Reef taxa occurrences from the Panthalassa and Tethys oceans were compiled from the literature to be compared with our data. The compilation is restricted to time intervals and areas where reef fauna have been thoroughly investigated and where sponges, microproblematica and reef-dwelling foraminifer assemblages are described in detail. These areas correspond either to one extensively studied locality or to a composite record of several localities closely related to each other in time and space. Two time intervals are considered: Ladinian–Carnian and Norian–Rhaetian. For some areas, Upper Anisian reef fauna were added to the Ladinian–Carnian interval. The time slices used in this analysis correspond to well-established reef fauna associations, separated by the Carnian/Norian turnover (Flügel, 2002). The occurrences of sponges, microproblematica and foraminifers from the literature were attributed to 16 areas (8 for the Ladinian–Carnian and 8 for the Norian–Rhaetian) according to their paleogeographical location in the Late Triassic. Regarding the data from Japan, reef biota corresponding to the two main clusters of Fig. 3.5 were included in the analysis as Japan Reef Type 1 and Japan Reef Type 2. For each reef area, the generic richness and references are summarized in Table 3.4. The table of taxonomic occurrence used for the cluster analysis is presented in Supplementary material S2.
Taxon occurrences have been compiled at the species level but are treated at the generic level to minimize the discrepancies in taxa identification between authors. Indeed, using the genus level avoids most of the systematic bias that essentially resides at the species level (Brayard et al. 2007). Paleobiogeographic studies are often based on genus-level analyses (e.g., Belasky et al. 2002; Niu et al. 2011). Sponge and foraminifer genera were updated when necessary, according to recent literature (e.g., Senowbari-Daryan and Garcia-Bellido 2002; Gale et al. 2012). Because they are not often identified at the genus level in the literature, Duostominids and Nodosarids are treated at the family level.

Total generic richness is higher on the western and northern Tethys margin than on the southern Tethys margin and in the Panthalassa (Fig. 3.9, Table 3.4). The same pattern is observed when sponges, foraminifers and microproblematica are considered separately. The variation of generic richness in areas represented at both time intervals (Ladinian–Carnian and Norian–Rhaetian) shed light on the evolution of reef diversity during the Late Triassic. Generic richness is generally higher in the Norian–Rhaetian than in the Ladinian–Carnian except for Japanese reefs where the generic richness remains stable, and for Slovenian reefs, where it decreases. The increased reef diversity during the Norian–Rhaetian is well-known (Flügel 2002). However the stable pattern of reef diversity in Japan and its decrease in Slovenia, still require explanation.

![Fig. 3.9 Reef generic richness in Tethys and Panthalassa.](image)

87
<table>
<thead>
<tr>
<th>Areas</th>
<th>Time interval</th>
<th>Number of genera</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Dolomites</td>
<td>Anisian-Carnian</td>
<td>74</td>
<td>34</td>
</tr>
<tr>
<td>Slovenia</td>
<td>Upper Anisian-Carnian</td>
<td>50</td>
<td>27</td>
</tr>
<tr>
<td>Northern Calcareous Alps</td>
<td>Ladinian-Carnian</td>
<td>55</td>
<td>21</td>
</tr>
<tr>
<td>Hungary</td>
<td>Upper Anisian-Carnian</td>
<td>52</td>
<td>21</td>
</tr>
<tr>
<td>Sicily</td>
<td>Ladinian-Carnian</td>
<td>36</td>
<td>12</td>
</tr>
<tr>
<td>Greece</td>
<td>Carnian</td>
<td>25</td>
<td>14</td>
</tr>
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<td>Turkey</td>
<td>Carnian</td>
<td>23</td>
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</tr>
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<td>Oman</td>
<td>Carnian</td>
<td>26</td>
<td>12</td>
</tr>
<tr>
<td>Japan Reef Type 1</td>
<td>Ladinian-Carnian</td>
<td>31</td>
<td>10</td>
</tr>
<tr>
<td>Slovenia</td>
<td>Norian-Rhaetian</td>
<td>35</td>
<td>14</td>
</tr>
<tr>
<td>Northern Calcareous Alps</td>
<td>Norian-Rhaetian</td>
<td>74</td>
<td>33</td>
</tr>
<tr>
<td>Iran</td>
<td>Norian</td>
<td>69</td>
<td>44</td>
</tr>
<tr>
<td>Sicily</td>
<td>Norian</td>
<td>89</td>
<td>55</td>
</tr>
<tr>
<td>Turkey</td>
<td>Norian</td>
<td>41</td>
<td>25</td>
</tr>
<tr>
<td>Oman</td>
<td>Norian</td>
<td>46</td>
<td>17</td>
</tr>
<tr>
<td>Japan Reef Type 2</td>
<td>Norian</td>
<td>32</td>
<td>9</td>
</tr>
<tr>
<td>Oregon (USA)</td>
<td>Norian</td>
<td>23</td>
<td>11</td>
</tr>
<tr>
<td>Yukon (Canada)</td>
<td>Norian</td>
<td>34</td>
<td>15</td>
</tr>
</tbody>
</table>
Uniques are taxa characterized by a single occurrence in the dataset. They are not necessarily all genuine endemic taxa because they may also occur in reef localities that are not considered in this study. However, they provide information regarding the level of endemism of the taxonomic assemblages under scrutiny (Brayard et al. 2007). In our dataset, uniques represent approximately 32.8% of the genera (66/201). Uniques are predominantly sponge genera (41% of the sponge genera and 23.9% of the total genera). Foraminifers include 25.4% of uniques (8.5% of the total genera). Only 5.9% of Microproblematica genera are single occurrence taxa (0.5% of total genera). The Dolomites (Ladinian–Carnian), Sicily, Iran and Turkey (Norian–Rhaetian) show the highest percentage of uniques (13.5%, 21.3%, 18.8% and 14.6% respectively) that correspond primarily to sponge genera.

Hierarchical cluster analysis (based on the UPGMA algorithm with the Dice coefficient of similarity) was applied to the compiled dataset. On the one hand, the Mantel tests (see section 3.4) show a strong and highly significant positive correlation between the Dice (“total”) and Simpson (compositional) dissimilarity matrices ($R = 0.7685; p \leq 0.0001$ ***). On the other hand, the correlation between the Dice and the Nestedness (richness) dissimilarity matrices is not significant ($R = -0.06244; p = 0.7423$). Thus, clusters based on the Dice coefficient are not significantly affected by differences in taxonomic richness but reflect richness-free variations of taxonomic composition between the different localities of interest.

The dendrogram resulting from the hCA identifies two main clusters (Fig. 3.10). The first one includes all Ladinian–Carnian reef fauna and the Japan Reef Type 1. The second cluster comprises all Norian–Rhaetian reef fauna and the Japan Reef Type 2. The ANOSIM strongly supports the validity of these two main groups ($p \leq 0.0001$). Therefore, the dendrogram reliably allows us to distinguish the Ladinian–Carnian reef faunas from the Norian–Rhaetian ones. Relationships within each main group are less straightforward but are, in general, consistent with the paleogeographic position of the reef localities (Fig. 3.11). Paleobiogeographic implications of these groupings are discussed below (see section 3.6.5).

SIMPER analysis assesses the contribution of each taxon to the two-cluster main structure identified by hCA. Accordingly, the Ladinian–Carnian cluster is primarily distinguished from the Norian–Rhaetian one by the genera Ladinella, Plexoramea, Zardinia, Jablonsksya and Alpinothalamia. Conversely, the Norian–Rhaetian cluster is primarily distinguished from the Ladinian–Carnian one by Alpinophragmium, Decapodalina, Galeanella, Paradeningeria and Microtubus. Nevertheless, the contribution of each of these taxa to the overall among-cluster taxonomic dissimilarity is rather low ($\leq 2\%$ in all cases).
Chapter 3: Reefs of the SAC at Shikoku Island

3.6. Discussion

3.6.1. Preservation bias

The preservation of microfacies differs between massive limestone slabs and limestone clasts in VCM breccia. As previously observed (Chablais et al. 2010a; Peybernes et al. 2015), limestone clasts and blocks of the VCM breccia are less recrystallized than the massive limestone slabs. This difference in preservation has a significant impact in species determination but does not significantly affect point counting results because the main categories of reef components are still recognizable. Therefore, reef limestone clasts and massive reef limestone slabs can be reliably compared using quantitative microfacies analysis.

3.6.2. Types of Reef

Framebuilders in the SAC are predominantly represented by calcareous sponges, small coral colonies and *Tubiphytes* that correspond to low-growing communities. These observations contrast with the high-growing communities (mainly phaceloid corals and coralline sponges).
characterizing the Norian and Rhaetian Dachstein reefs in Western Tethys (Stanton and Flügel 1987; Bernecker et al. 1999; Martindale et al. 2015). The reef builder growth forms and the abundance of interstitial sediments suggest that Upper Triassic reefs of the SAC did not stand high above the sea floor but were low relief reefs; therefore, they are better designated as reef mounds (Kiessling et al. 1999, Kiessling and Flügel 2002).

Our field observations, microfacies analysis, biotic assemblages and point counting results allow us to discriminate between two main types of reefs in the reef limestone from the SAC. A first distinction, based on the lithology and previously observed at the Mt. Sambosan locality by Okuda et al. (2005), can be drawn between massive white limestone slabs and grey limestone clasts embedded in the volcaniclastic matrix (VCM breccia) (see sections 3.2 and 3.3).

A comparison of the taxonomic content and biotic assemblages also shows clear differences between massive limestone slabs and limestone clasts (see section 3.5.2). Significant differences in the biotic composition between the lithologically different types of reefs are demonstrated by the reef taxa distribution (Supplementary material S1), the corresponding cluster analysis and ANOSIM (Fig. 3.5).

Microfacies analyses and reef component relative abundances reveal additional differences between the lithologically and biotically distinct reef limestones (see section 3.5.3), leading us to reliably distinguish two distinct types of reef. The grey limestone clasts in the VCM breccia are characterized by microbialite-dominated, coral-sponge reefs with abundant microproblematica, more interstitial sediments and a very loose reef framework (Reef Type 1), whereas the massive white limestone slabs typically correspond to sponge-dominated reefs with ooid-peloid-bioclastic grainstone that infill the voids within an important reef framework (Reef Type 2).

The key characteristics of each type of reef are summarized in Table 3.5. It is worth noting that, according to its biotic content, the reef limestone from Loc. 10 Road 28 (Fig. 3.1) more closely corresponds to Reef Type 2. However, their mode of occurrence, as clast in VCM breccia, and the unclear pattern presented by the relative abundances of reef components places doubt on the attribution to the Reef Type 2. We hypothesize that the reef limestone from Loc. 10 Road 28 may represents a transitional stage between Reef Type 1 and Reef Type 2.

The clear differences between the two types of reefs can be explained by temporal, geographical and ecological factors:
- They correspond to different ages;
- They are related to different depositional settings of the carbonate platform. For example, they may represent depth-related environmental variations and/or reflect the reef zonation;
They indicate coeval but different biotic associations of reef organisms. These three explanations are not exclusive of each other and may both play a role in the processes that led to the differences between the two reef types. As a consequence, biostratigraphic data are pivotal to discriminate between time-related differences and ecological differences.

3.6.3. Biostratigraphy
This section aims to discuss the already published biostratigraphic data of the SAC, as well as the dating of the two types of reefs on the basis of reef assemblages and conodont biostratigraphy. Former studies of the SAC limestone described several Upper Triassic biostratigraphic markers (e.g., Conodonts: Yamato Omine Research Group 1981; Ishida and Hirsh 2001; Onoue and Tanaka 2005; Onoue and Sano 2007; Foraminifers: Kristann Tollmann 1991; Chablais et al. 2011; Sponges: Chablais et al. 2010b; Senowbari-Daryan et al. 2012; Peybernes et al. 2015; and Corals: Kanmera 1964; Okuda et al. 2005; Stanley and Onoue 2015). Accordingly, the Sambosan limestone has been attributed to the Carnian to Rhaetian interval. Concerning reef facies in particular, the earliest reported evidence is of the Carnian reef biota from the limestone clasts at the Koguchi locality at Kyushu Island (Senowbari-Daryan et al. 2012) and the Ladinian–Carnian reef limestone clasts from Loc. 3 Tsuno, Loc. 5 Mt. Sambosan 2, Loc. 8 Mt. Ishidate 2 and Loc. 9 Konose Kyo at Shikoku Island (Peybernes et al. 2015). Younger Norian bioconstruction are represented by the Lower–Middle Norian reef at Kamase locality at Kyushu Island (Onoue and Stanley 2008) and the Norian reef at Loc. 1 Inaba cave, Shikoku Island (Chablais et al. 2010b). Moreover, Carnian and Norian corals have been reported at Kyushu (Kanmera 1964; Stanley and Onoue 2015), Shikoku (Okuda et al. 2005; Stanley and Onoue 2015) and the Kii Peninsula (Yamato Omine Research Group 1976; Okuda and Yamagiwa 1978; Okuda 2006).

Assemblage-based biostratigraphy
Reef fauna assemblages often allow a biostratigraphic differentiation between Carnian and Norian–Rhaetian reefs (Bernecker 2005). Indeed, Norian–Rhaetian reefs differ considerably from Carnian reefs with regard to their taxonomic composition and diversity (Flügel 2002). In Oman, for example, Upper Triassic reefs have been dated by their associations of reef builders and dwellers (Bernecker 2005). The Carnian fauna used for age determination consist of corals (Volzeia badiotica, Rhopalodendron juliensis, and Margarophyllia crenata), sponges
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(Cryptocoelia zitteli, Zardinia sp. and Uvanella irregularis), serpulids (Barbafera carnica), foraminifers (Paraophtalmidium sp. and Bispinella ovata=Cucurbita infundibuliforme according to Gale et al. 2012) and the microproblematicum Ladinella porata (Bernecker 2005). Conversely, typical Norian–Rhaetian fauna are characterized by foraminifers (Cucurbita spp., Kaeveria fluegeli, Galeanella spp., Alpinophragmium perforatum) and the problematical Microtubus communis (Bernecker 1996, 2005). *M. communis* in particular, is considered to be a marker of the central part of the Norian–Rhaetian reefs (Flügel 2004).

In the SAC of Shikoku, *Cryptocoelia zitteli, Zardinia sp., Uvanella irregularis* and *Ladinella porata* are present among other Ladinian–Carnian taxa at Loc. 3 Tsuno, Loc. 5 Mt. Sambosan 2, Loc. 8 Mt. Ishidate2, and Loc. 9 Konose Kyo (Peybernes et al. 2015). *Galeanella* spp., *Alpinophragmium perforatum* and *Microtubus communis* occur at Loc. 1 Inaba (Chablais 2010), Loc. 2 Tsuno windmill, Loc. 4 Mt. Sambosan 1 and Loc. 7 Mt. Ishidate 1. These occurrences, characterizing the Reef Type 2, are thus indicative of a Norian age. However, it is to be noticed that in Japan, the *Cucurbita* spp. are found predominantly in the limestone clasts assumed to be Ladinian–Carnian while they have also been reported from the Norian–Rhaetian in Oman.

Additional Norian markers from the massive limestone slabs (Reef Type 2) are *Decapoalina schaeferae* (= “Sigmoilina” schaeferae) (Gale et al., 2013b) and *Actinotubella gusici* (Senowbari-Daryan, 1984) as well as an abundance of Chaetetid sponges. Indeed, according to Flügel (2002), Chaetetid sponges are increasingly frequent during the Norian–Rhaetian.

The cluster analysis, including worldwide Upper Triassic reef fauna (see section 3.5.5), indicates that the taxonomic composition of Ladinian–Carnian reef fauna considerably differs from that of the Norian–Rhaetian (Fig. 3.10). In the resulting dendrogram, the biotic assemblage of Reef Type 1 clusters exclusively with Ladinian–Carnian reef fauna, whereas the biotic assemblage of Reef Type 2 belongs to a cluster exclusively composed of Norian–Rhaetian reef fauna. Therefore, our cluster analysis confirms the Ladinian–Carnian age of Reef Type 1 and the Norian–Rhaetian age of Reef Type 2.

The taxa showing the highest contribution to this two-cluster structuring in the SIMPER analysis (see section 3.5.5) can be considered the best biostratigraphic markers (i.e., short range and wide distribution) of our dataset, in spite of their overall low percentages of contribution to the between-cluster taxonomic dissimilarity. Indeed, they correspond to taxa typically considered to be biostratigraphically relevant (see section 3.6.3). The SIMPER analysis, therefore, quantitatively confirms the typically qualitative biostratigraphic statements. Most of the relevant biostratigraphic markers (according to the SIMPER analysis) are present in Japan.
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It is also worth noting that foraminifers do not appear as the most significant biostratigraphic markers in the Ladinian–Carnian, although they include the three most important biostratigraphic markers (i.e., *Alpinophragnmium*, *Decapoalina* and *Galeanella*) in the Norian–Rhaetian.

The assemblage-based biostratigraphy suggests that the differences between the two types of reef result from their different ages. Similarly, Okuda et al. (2005) have already proposed a Norian age for white limestone slabs at Loc. 4 Mt. Sambosan 1, whereas grey limestone clasts in breccia at Loc. 5 Mt. Sambosan 2 (“gray limestone included within the greenstone” in Okuda et al. 2005) are supposed to be Carnian in age, based on coral occurrences and facies affinity. Nevertheless, these authors only developed their view for the Mt. Sambosan localities. Here we suggest this statement be extended to most of the outcrops of the central and eastern Shikoku Island. Furthermore, a similar pattern in the mode of occurrence is observed at Kyushu Island. The coral and foraminifer assemblages and facies affinity of the larger limestone units at the Kamase locality indicate an Early to Middle Norian age (Onoue and Stanley 2008), whereas limestone clasts in VCM breccia at the Koguchi locality clearly contain Carnian reef fauna (Kanmera 1964; Senowbari-Daryan et al. 2012).

As demonstrated by Martindale et al. (2013b), biotic assemblages alone can sometimes be misleading and additional independent age indicators should be used to provide an accurate and more reliable dating. Therefore, conodont extraction has been performed on numerous samples to provide independent data for reef dating (see section 3.5.4).

**Conodont biostratigraphy**

Conodonts have been the subject of several investigations in the SAC (Yamato Omine Research Group 1981; Ishida and Hirch 2001; Onoue and Tanaka 2005; Onoue and Sano 2007; Yoshida and Onoue 2008). Most of the studies focused on chert or deep water limestone and rarely described the related microfacies. In this work, we specifically investigated shallow water limestone in particular and considered the microfacies of the samples from which the conodonts were retrieved. Surprisingly, among the different microfacies that were recognized (i.e., slope to lagoonal microfacies), conodonts were found only in reef limestone. Their occurrence in this facies in particular can be explained by the deposition of reef limestone at the platform margin, facing the open ocean where conodonts thrived.

The conodont element *Parvigondolella?* sp., found at Loc.1 Inaba, indicates a Late Norian–Rhaetian age for the massive limestone slabs of this locality. This is in agreement with the assemblage-based biostratigraphy proposed by Chablais et al. (2010) and this paper.
The reef limestone sample from Loc. 6 Befu contains the brachiopod *Gosaukamerella eomesozoica*, encrusting microproblematica and undetermined foraminifers. Unfortunately, strong recrystallization prevents microfacies correlations with other limestone units. Nevertheless, the conodont fauna constitute important biostratigraphic data for the dating of limestone units in this area. *Carnepigondolella samueli* is the index to the Upper Carnian samueli Zone (Orchard 2014). The co-occurrence of *Carnepigondolella* cf. *spatulata* (common in the spenceri Subzone of the samueli Zone) and *Quadralella lobata* (common from the base of the Black Bear Ridge section in British Columbia, Canada, through the zoae Subzone of the samueli Zone; see Orchard, 2014) confirms the attribution of the massive limestone slabs at Loc. 6 Befu to the Upper Carnian. 

At Loc. 4 Mt. Sambosan 1 *Primatella stanleyi* and *Krassodontus roberti* occur. In the Black Bear Ridge section, *Primatella stanleyi* is present in the angusta-dylani Subzone through the asymmetrica-Norigondolella sp. Subzone of the primitia Zone (Orchard 2014). Additionally, representatives of this species were illustrated from the Lower Norian of Feuerkogel (Krystyn 1973). The association with *Krassodontus roberti* alpha morphotype, which is common in the sagittale-beattyi Subzone through the acuminata-prominens Subzone of the primitia Zone, indicates a Late Carnian age for this massive limestone slab (Reef Type 2). The limestone slab at Loc. 4 Mt. Sambosan 1 is, therefore, slightly younger than the limestone unit at Loc. 6 Befu. The Yamato Omine Research Group (1981) reported, but did not illustrate, conodonts from several outcrops in the Mt. Sambosan area: *Epigondolella nodosa* and *Gondolella polygnathiformis* (Carnian), *Epigondolella postera* and *Epigondolella abnetis* (Norian), and *Misikella hernsteini* and *Misikella posthernsteini* (Rhaetian). In particular, they mentioned the Norian conodonts (*Epigondolella postera* and *Epigondolella abnetis*) from the massive limestone slab unit at Loc. 4 Mt. Sambosan 1. Thus, our results and the literature, suggest an extension of the age of Reef Type 2, previously attributed to the Norian–Rhaetian by assemblage-based biotratigraphy, to the Late Carnian.

In summary, according to the different lines of evidence discussed above, we are able to clearly distinguish two types of reefs corresponding to different ages: Ladinian?–Lower Carnian Reef Type 1 (occurring as clasts in VCM breccia) and Upper Carnian–Norian to Rhaetian? Reef Type 2 (mainly present in massive limestone slabs). As demonstrated above, the lithologic, petrographic and biostratigraphic distinction between the two types of reefs is reliable, despite some local uncertainties (e.g., reef limestone from Loc. 10 Road 28 has more affinity with Reef Type 2 but occurs as clasts in VCM breccia). Additionally, it should be noted that neither
massive limestone slabs nor limestone clasts in VCM breccia are exclusively of reefal facies. Nevertheless, our results from reef limestone provide a robust framework for further investigations.

Table 3.5 Characteristic and ages of the types of reef in the SAC of Shikoku.

<table>
<thead>
<tr>
<th>Reef Type 1</th>
<th>Reef Type 2</th>
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<tbody>
<tr>
<td>Localities</td>
<td>Loc. 3 Tsuno, Loc. 5 Mt. Sambosan 2, Loc. 8 Mt. Ishidate 2, Loc. 9 Konose Kyo</td>
</tr>
<tr>
<td>Mode of occurrence</td>
<td>Mostly grey clasts in VCM breccia</td>
</tr>
<tr>
<td>Microfacies characteristic</td>
<td>Abundance of peloidal and clotted micrite</td>
</tr>
<tr>
<td></td>
<td>-Abundance of microproblematica (especially Tubiphytes)</td>
</tr>
<tr>
<td>Conodonts</td>
<td></td>
</tr>
<tr>
<td>Inferred age</td>
<td>Ladinian? -Lower Carnian</td>
</tr>
</tbody>
</table>

3.6.4. Reef evolution

Reef limestone from the SAC of Shikoku records the evolution of a reef environment from the Ladinian?–Early Carnian to the Late Carnian–Norian–Rhaetian? and, provides pivotal information regarding reef evolution in the Panthalassa domain. The ages of the two types of reefs present in the SAC roughly correspond to the two main reef blooms that occurred during the Triassic (Earliest Carnian and Late Norian), as evidenced by Flügel (2002).

The Late Carnian–Early Norian corresponds to an important reef fauna turnover and represents the transition between typical Ladinian–Carnian to Norian–Rhaetian reef fauna (Flügel 2002). Transitional reef assemblages have been described from the Late Carnian to Early Norian in the Northern Calcareous Alps (Martindale et al. 2013b). According to our results, Upper
Carnian reef fauna of the SAC appear to have more affinity with Norian–Rhaetian assemblages than to the Lower Carnian ones.

In Reef Type 1, point counting analyses reveal that the volume occupied by the reef framework is relatively low, whereas peloidal and clotted micrite is abundant. Similar build-ups with reduced framework and high microbialite content are known from American terranes, especially those of higher paleolatitudes (Lime Peak, Yukon: Reid and Ginsburg 1986; Summit Point, Oregon: Martindale et al. 2012, 2015) and Ladinian–Carnian reefs of the western Tethys (Russo et al. 1997).

In Reef Type 2, calcareous sponges increased dramatically in importance. Data of relative abundances clearly indicates the dominance of calcareous sponges, especially in Loc. 1 Inaba cave and Loc. 7 Mt. Ishidate. In summary, we observe an evolution from microbialite-rich, Ladinian?–Lower Carnian reefs to sponge-dominated, Upper Carnian–Norian–Rhaetian? reefs. This trend corresponds roughly to the reef evolution observed in the Tethys (e.g., Tosti et al. 2014). The Middle and early Late Triassic is characterized by Permian-like reef construction dominated by *Tubiphytes*, calcareous sponges and microbialites (Stanley 1988; Tosti et al. 2014). Conversely, Norian–Rhaetian build-ups are dominated by calcareous sponges and corals with superstratal growth fabrics (Flügel 2002).

Another striking observation is the lack of high growing coral reefs in the Upper Triassic of Japan. This reef community usually characterizes the Rhaetian reefs in the Tethys (Schäfer 1979; Benercker et al. 1999). This could be explained either by the absence of Rhaetian reefs in the SAC or by different reef fauna assemblages in the Panthalassa during the Rhaetian.

3.6.5 Reef paleobiogeography

Quantitative analyses (see section 3.5.5) provide valuable insights regarding reef biodiversity and reef biogeographical affinities during the Late Triassic. According to our dataset, South Tethys and Panthalassa reefs exhibit lower generic richness than West and North Tethys reefs (Fig. 3.9). Other authors have stated that most Panthalassan reefs are of moderate to low diversity (e.g., Flügel 2002). The lower generic richness may partly be explained by the fewer number of studies in these regions compared to classical North Tethys reef localities. However, because the South Tethys and Panthalassa localities considered in this work are known and have been studied for decades, it seems reasonable to consider that the lower generic richness is, at least partly, a genuine biodiversity pattern. The high diversity of the north and west Tethys margin reefs suggests that these areas may represent a center of diversity during the Late Triassic, similar to the one observed in the modern Western Pacific for scleractinian corals and
larger foraminifers (Belasky 1996). Our data also show an eastward decrease in generic richness similar to the eastward decline in diversity of the Indo-Pacific coral fauna (Grigg and Hey 1992; Belasky and Runnegar 1993).

Generic endemism, estimated by the number of uniques, is generally low, except for the Dolomites in the Ladinian–Carnian and Sicily, Iran and Turkey in the Norian–Rhaetian. These areas are also often characterized by the high generic richness of their sponge fauna. Nevertheless, the relatively low endemism of the other reef areas suggests that no major barrier (geographical or ecological) for fauna dispersion was present in the intertropical zone during the Late Triassic. In particular, reef biota from the SAC is comprised of very few uniques, suggesting a relatively low endemism of reef fauna in western Panthalassa during the Late Triassic. This result contrasts with previous statements regarding the high endemism of coral fauna of the SAC (Stanley and Onoue 2015). The overall higher proportion of uniques among sponge genera compared to foraminifers and microproblematica could indicate that these organisms are less prone to efficient dispersion (which primarily occurs during the larval stage) and/or are less ecologically tolerant.

All of the reef areas studied here are considered to have been in the intertropical belt during the Late Triassic. Therefore, no significant latitudinal patterns are expected. However, a longitudinal biogeographic gradient in fauna distribution seems likely. Longitudinal faunal exchanges and connections between the Tethys and the Panthalassa during the Late Triassic were discussed by Kristan-Tollmann and Tollmann (1981), Newton (1988, 1990), Smith and Westermann (1990), Stanley and Yancey (1990), Stanley (1994), Chablais et al. (2011), and Martini and Rigaud (2014). The tropical eastern Pacific Ocean has been described as the most effective barrier (East Pacific Barrier, EPB) to the dispersal of warm water shelf fauna in modern oceans (Eckman 1953; Grigg and Hey 1992; Belasky 1996). The Panthalassa ocean, which was approximately twice as wide as the equatorial Pacific today (Flügel 2002), should have represented to some extent a biogeographic barrier for reef biota dispersion, leading to a more pronounced provincialism than today (Belasky et al. 2002). Nevertheless, seamount swarms and terranes may have acted as stepping stones for reef biota migration allowing intertropical trans-Panthalassic connections (Tozer 1982; Stanley 1994).

Several authors stated and emphasized the Tethyan affinity of the SAC biota (Kanmera 1964; Tamura 1990, 1992; Kristan-Tollmann 1991; Chablais et al. 2011; Senowbari-Daryan et al. 2012; Peybernes et al. 2015). However, their statements were based on qualitative observations and comparisons between uneven geographic areas (i.e., comparison of local outcrop with wide
regions). Our results allow us to quantitatively assess for the first time the biogeographical affinity of the SAC reef fauna with the Tethyan ones.

The cluster analysis, based on a taxonomically homogenous dataset, provides insights into the biostratigraphy and biogeography of the Late Triassic reef fauna. However, the resulting UPGMA dendrogram (Fig. 3.10) shows a rather low cophenetic correlation index of 0.79, indicating that it does not perfectly described the observed among-assemblage similarities. As the ordination analyses (PCoA and NMDS) of the same Dice similarity matrix do not evidence any clear gradational structure in the analyzed dataset (results not shown here), this is likely to be due to some inescapable sampling noises ultimately affecting the ultrametric (i.e., hierarchical) similarity structuring. As discussed above, the dendrogram independently confirms the attribution of the Japan Reef Type 1 and Japan Reef Type 2 to different time intervals (Ladinian?–Carnian and Late Carnian–Norian to Rhaetian?, respectively) but cluster analysis also allows us to tentatively explore the faunal relationship and global biogeographic patterns.

For the Ladinian–Carnian interval the Japanese reef assemblage is clearly more related to their South Tethys counterpart (Oman) than to their North and West Tethys counterparts (Figs. 3.10, 3.11). This confirms previous statements regarding the biogeographic affinity of Upper Triassic fauna of the SAC (Chablais et al. 2011; Senowbari-Daryan et al. 2012). However, the scarcity of Ladinian–Carnian reef fauna in North American terranes and craton prevents quantitative comparison with coeval Tethyan and West Panthalassa reefs. Therefore, biogeographic connections between West and East Pantalassa are probably missed due to this lack of data. Greece and Turkey assemblages show similarities that are consistent with their paleogeographic locations. North Tethys reef fauna are closely related to each other and the reef assemblage from Sicily appears to be isolated.

For the Norian–Rhaetian interval, Japanese reef fauna shows a strong affinity with the reef fauna from Oman, as in the Ladinian–Carnian interval. Moreover, the fauna affinity between the Yukon (i.e., Stikinia terrane) and Japan and Oman suggests that longitudinal migrations of reef fauna were effective in the Panthalassa Ocean during the Norian. However, the lack of diversified reef fauna on the American craton shelf margin prevents a complete understanding of eastern Panthalassa reef biogeography during the Late Triassic. The weak similarity between the Yukon and Oregon reef fauna \((S_{\text{Dice}}=0.39)\) is a puzzling result that questions the connections between the corresponding Stikinia and Wallowa terranes. In the Norian–Rhaetian interval, the fauna of Sicily, Northern Calcareous Alps and Iran show strong affinities to each other. In summary, according to our results, SAC reef faunas are more related to the South
Tethys reef assemblages in the Ladinian–Carnian and Norian–Rhaetian. Moreover, in the Norian–Rhaetian, South Tethys (Oman) and West Panthalassa (Japan), the reef fauna show affinities with East Panthalassa reef fauna of the Stikinia terrane (Yukon).

![Paleogeographic maps showing location of investigated reef areas](image)

**Fig. 3.11** Paleogeographic maps showing location of investigated reef areas (modified after Scotese, 2014). a Ladinian–Carnian reefs localities. b Norian–Rhaetian reef localities. Do: Dolomites; Gr: Greece; Hu: Hungary; Ir: Iran; Ja: Japan; NCA: Northern Calcareous Alps; Om: Oman; Or: Oregon; Si: Sicily; Sl: Slovenia; Tu: Turkey; Y: Yukon.

Biogeographic data often help to constrain paleogeographic reconstructions (e.g., Belasky and Runnegar 1994; Aberhan 1998; Johnston and Borel 2007; Brayard et al. 2009; Chablais et al. 2011). Nevertheless, the similarities between fauna should not be translated directly into the geographic distances that separate them (Belasky 1996). These paleobiogeographical patterns need to be confirmed with other taxa from various environments. In-depth investigations of
poorly studied localities are also needed to better assess biogeographic latitudinal and longitudinal gradients. Our quantitative approach of integrated reef fauna biogeography appears to be fruitful and requires further investigations involving other taxonomic groups, additional localities and complementary quantitative methods such as network-based analyses (e.g., computing Bootstrapped Spanning Networks; Brayard et al. 2007, 2009, 2015) or probabilistic approaches. Moreover, the spreading of global databases such as the Paleobiology Database, providing increasingly more data, is promising for the development of a better-constrained paleobiogeographical model.

### 3.7. Conclusion

Ten localities (including two new localities) of the Sambosan Accretionary Complex at Shikoku Island, where Upper Triassic reef limestone crop out, were extensively sampled. Field observations, biotic composition analysis, quantitative assessment of reef components and integrated biostratigraphy (conodont and reef assemblages) lead us to:

- Distinguish two types of reefs that differ in their mode of occurrence, reef fauna assemblages and reef component relative abundances;
- Propose a Ladinian–Lower Carnian age for the grey reef limestone occurring as clasts embedded in a volcaniclastic matrix (Reef Type 1) and a Upper Carnian–Norian to Rhaetian? age for the reef limestone that crops out as massive white limestone slabs (Reef Type 2);
- Highlight the reef evolution on Panthalassa seamounts from microbialite-rich, sponge-microproblematica-coral reefs during the Ladinian?–Early Carnian to sponge-dominated reefs during the Late Carnian–Norian to Rhaetian?. This evolution is closely comparable to reef evolution in the Tethys realm;
- Strengthen the South Tethys affinity of the reef biota from the SAC during the Ladinian?–Early Carnian and the potential connections with American terranes in the Norian–Rhaetian, as demonstrated by hierarchical cluster analyses and associated multivariate statistical treatments.

The results presented in this paper contribute to the better understanding of reef evolution and biogeography during the Late Triassic. This study provides useful information for further paleobiodiversity analyses and paleogeographic reconstruction and leads to a more accurate comprehension of paleobiogeographic patterns during the Middle and Late Triassic.


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**Table Supplementary data 3.1**

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Loc.1 Iraba</th>
<th>Loc.2 Tsuno windmill</th>
<th>Loc.3 Tsuno</th>
<th>Loc.4 Mt. Sambosan 1</th>
<th>Loc.4 Mt. Sambosan 2</th>
<th>Loc. 6 Befu</th>
<th>Loc.7 Mt. Ishidate1</th>
<th>Loc.8 Mt. Ishidate2</th>
<th>Loc. 9 Kousou Kyo</th>
<th>Loc. 10 Road 28</th>
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### Chapter 3: Reefs of the SAC at Shikoku Island

**Miliolipora cuvillieri** \(\times\) - - - - - - - N-R

**Nodosarids** \(\times\) \(\times\) \(\times\) \(\times\) \(\times\) - \(\times\) - - - - MT-UT

**Nubecularids** - - \(\times\) - - - - - - - - T-Cen

**Ophtalminids** \(\times\) \(\times\) \(\times\) \(\times\) - \(\times\) \(\times\) \(\times\) - UT

**Paleolitoumella meridionalis** \(\times\) - \(\times\) - \(\times\) - \(\times\) - - - \(\times\) - MT-UT

**Paraphtalmidium carpathicum** \(\times\) - - - - - - - - UT

**Piella bronnianni** - - \(\times\) - ? - - - ? - - L-C

**Piella tethydis** - - \(\times\) - - - - - - - - L-C

**Planiovoluta carinata** \(\times\) - - - \(\times\) - \(\times\) - - - - UT

**Tolypammina gregaria** \(\times\) - - - \(\times\) - - - - - - - UT

**Tunammina sp.** \(\times\) - - - - - - \(\times\) - - - - P-Cen

**Tropholina cordevolica** - - - - - - \(\times\) - - - L-C

### Microproblematica

**Actinotubella gusici** \(\times\) - - \(\times\) - - - - - - - N-R?

**Baccanella floriformis** \(\times\) \(\times\) \(\times\) \(\times\) \(\times\) - \(\times\) - \(\times\) - - MT-UT

**?Isella misiki** - - - - - \(\times\) - - - ? - - L-C

**Ladinella porata** - - \(\times\) - - - - \(\times\) - - - \(\times\) A-C

**Microtubus communis** \(\times\) \(\times\) - \(\times\) - - - - - ? - - N-R

**Plexoramea cerebriformis** - - \(\times\) - \(\times\) - - - ? - - - A-C

**Plexoramea gracilis** - - - - - \(\times\) - - \(\times\) - - - A-C

**Radiomura cautica** \(\times\) \(\times\) \(\times\) \(\times\) \(\times\) \(\times\) \(\times\) \(\times\) \(\times\) \(\times\) \(\times\) MT-J

**Tubiphytes sp.** \(?\) - \(\times\) - \(\times\) - - \(\times\) \(\times\) - - Carb-Cr

### Brachiopod

**Gosaukammerella eomesozoica** - - \(\times\) - \(\times\) \(\times\) - - - - \(\times\) - UT

**Free-living brachiopods** - - \(\times\) \(\times\) \(\times\) - - - - - - - T-Re

### Polychaetes

**Terebella sp.** \(?\) - \(\times\) - \(\times\) - \(\times\) - ? ? - Carb-Cen

**Serpulids** \(\times\) - \(\times\) - ? - \(\times\) \(\times\) ? \(\times\) - Ph

**Filograna sp.** - - \(\times\) \(\times\) - - - - - - - D-Re

A: Anisian, C: Carnian, Carb: Carboniferous, Cen: Cenozoic, Cr: Cretaceous, D: Devonian, J: Jurassic, L: Ladinian, MT: Middle Triassic, N: Norian, P: Pemian, Ph: Phanerozoic, R: Rhaetian, Re: Recent, UT: Upper Triassic
### Supplementary data 3.2

| Species               | Dolomites | Oman | Sicily | Turkey | Italy | Greece | Japan | USA | Yukon | Iran | Norian | Norian | Norian | Norian | Norian | Norian | Norian | Norian | Norian |
|-----------------------|-----------|------|--------|--------|-------|--------|-------|-----|-------|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Actinotubella         | 1 1 0 0   | 0    | 0      | 0      | 0     | 0      | 0     | 0   | 0     | 0    | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
| Aulotortus            | 0 0 0     | 0    | 0      | 0      | 0     | 0      | 0     | 0   | 0     | 0    | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
| Earlandinita          | 0 0 0     | 0    | 0      | 0      | 0     | 0      | 0     | 0   | 0     | 0    | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
| Endoteba              | 0 0 0     | 0    | 0      | 0      | 0     | 0      | 0     | 0   | 0     | 0    | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
| Earlandinita          | 0 0 0     | 0    | 0      | 0      | 0     | 0      | 0     | 0   | 0     | 0    | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
| Earlandinita          | 0 0 0     | 0    | 0      | 0      | 0     | 0      | 0     | 0   | 0     | 0    | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
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| Earlandinita          | 0 0 0     | 0    | 0      | 0      | 0     | 0      | 0     | 0   | 0     | 0    | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
| Earlandinita          | 0 0 0     | 0    | 0      | 0      | 0     | 0      | 0     | 0   | 0     | 0    | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
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Supplementary data 3.2 (continued)

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Chapter 4: Mid-oceanic shallow water carbonates of the Panthalassa domain: new microfacies data from the Sambosan Accretionary Complex, Shikoku Island, Japan

Abstract
During the Late Triassic, carbonate platforms expanded on continental shelves and island arcs. They have been studied in detail in the Tethys realm but coeval mid-oceanic shallow water environments of the Panthalassa domain have received less attention. To fill this gap, we investigated the Upper Triassic limestone of the Sambosan Accretionary Complex (SAC), Southwest Japan. A comprehensive sampling of the Upper Triassic limestone has been performed in Shikoku Island. Eight microfacies were identified, including two microfacies that are described in the SAC for the first time, and their biostratigraphy is refined. Quantitative microfacies analysis assesses the composition of the SAC limestone. Finally, a new speculative depositional model of the SAC carbonate rocks is proposed based on modern and ancient analogues. Special attention is given to the factors that have probably controlled the carbonate sedimentation at the top of the seamount(s).

A similar version has been submitted to ‘Facies’ as Peybernes C, Chablais J, Onoue T, Martini R (submitted) Mid-oceanic shallow water carbonates of the Panthalassa domain: new microfacies data from the Sambosan Accretionary Complex, Shikoku Island, Japan
4.1. Introduction

During the Late Triassic, wide carbonate platforms developed on the Tethys margins and constitute an important record of environmental changes. As a consequence, they have been extensively studied, especially in Western Tethys (e.g., Schäfer 1979; Dullo 1980; Gaetani et al. 1981; Wurm 1982; Stanton and Flügel 1989; Enos and Samankassou 1998; Iannace and Zamparelli 2002; Gianolla et al. 2003; Stefani et al. 2010; Gattolin et al. 2015). Upper Triassic carbonate platforms also developed in relation with island arcs that are nowadays terranes accreted in the American cordillera (Stanley and Senowbari-Daryan 1986; Reid and Tempelman-Kluit 1987; Stanley et al. 2008; Martindale et al. 2012). Conversely, mid-oceanic platform carbonates deposited at the top of seamounts in the Tethys and in the Panthalassa oceans are often poorly preserved and thus have received less attention (but see Bernecker 1996; 2007; Onoue and Sano 2007; Chablais et al. 2010b). Mid-oceanic shallow water carbonates are typically characterized by three particularities (Nakazawa, 2001):

- The lack of terrigenous input from nearby continent leads to different nutrient supply in the platform ecosystems.

- The oceanographic situation, in open marine setting rather than in more or less restricted basin, enhances water circulation through/over the platform. In particular, windward/leeward orientation appears as a major controlling factor of the platform morphology (Blendinger and Blendinger 1989; Egenhoff et al. 1999).

- The continuous subsidence of a seamount, induced by the cooling of the oceanic lithosphere as it moves away from the spreading ridge, represents a relatively simple control with respect to other tectonic settings.

Furthermore, mid-oceanic shallow water carbonates platforms may represent “stepping stones” for the migration of marine benthic species (e.g. Newton 1988; Stanley 1994) and are therefore crucial for the understanding of paleobiogeographic patterns. All these characteristics highlight the specificity of mid-oceanic shallow water carbonates which need to be studied in details to improve our knowledge of the overall carbonate platform structures and evolutions.

Nowadays, atoll-type carbonate platforms and banks comprise approximately 400 atolls in the Indo-Pacific region and 15 atolls or isolated platform in the Atlantic (Gischler and Lomando 1999). In the Late Mesozoic and Cenozoic mid-oceanic atoll-type environment and related biota are also well documented (e.g., Matthews et al. 1974; Premoli-Silva and Brusa 1978; Shiba 1979; Schlanger and Premoli-Silva 1986; Grötsch and Flügel 1992; Takayanagi et al. 2012; Skelton et al. 2013). However, few records of these environments are available for the Early
Mesozoic because most of the Pre-Jurassic oceanic crust has been subducted. Accreted remains of Upper Triassic mid-oceanic carbonate platforms are reported from the Tethys realm (e.g., in Oman: Searle and Graham 1982; Bernecker 1996, 2007) and Western Panthalassa (e.g., in Japan: Onoue and Sano 2007; in The Philippines: Kiessling and Flügel 2000). In this study, we investigate the Upper Triassic shallow water carbonate units that crop out in the Sambosan Accretionary Complex (SAC) of Shikoku Island, Southwest Japan (Fig. 4.1). According to its shallow water fauna assemblages, its low terrigenous content and its association with OIB basalts (Ogawa and Taniguchi 1989; Ishizuka et al. 2003; Onoue et al. 2004; Safonova et al. 2014, 2015), the Sambosan limestone have been interpreted since the 1960’s as atoll-type carbonates deposited at the top of panthalassic seamount(s) and located in the intertropical belt (Kanmera 1969; Tamura 1992; Onoue and Sano 2007). Since then, several authors published microfacies descriptions and paleoenvironmental interpretations (Kanmera 1969; Kristan-Tollmann 1991; Onoue and Stanley 2008; Chablais et al. 2010b). However, comprehensive depositional setting reconstructions of the Sambosan build-up(s) have been proposed only recently (Onoue and Stanley 2008; Chablais et al. 2010b). These models were solely based on data from Kyushu Island. The objectives of this study are thus (1) to quantitatively describe the microfacies of the Sambosan limestone found at Shikoku Island (Fig. 4.1, 4.2); (2) to present the associated biota and discuss their biostratigraphic implications; (3) to propose a new depositional model for the Sambosan limestone of Shikoku, based on ancient and modern analogues and integrating former microfacies analysis performed on material from Kyushu Island. A comparison between our results and former microfacies analyses shows that two microfacies from Shikoku have not been recognized in the SAC before and are described here for the first time.

### 4.2. Geological setting

The Sambosan Accretionary Complex (according to Onoue and Sano 2007) is a narrow belt in Southwest Japan, extending from the Okinawa Islands in the Ryukyu archipelago to the Kanto Mountains in Honshu Island (Fig. 4.1a). In Shikoku, the SAC is in fault contact with the Togano Group of the Chichibu Accretionary Complex to the north (Matsuoka 1992, Matsuoka et al. 1998). To the South, the SAC is separated from the Shimanto Accretionary Complex by the Butsuzo Tectonic Line (BTL). Characteristic lithologies of the SAC are Upper Triassic deep and shallow water carbonates, middle Upper Triassic OIB basalts, Middle Triassic to lower Upper Jurassic bedded cherts and Middle Jurassic to Lower Cretaceous trench-fill mudstone.
and sandstone (Kanmera 1969; Matsuoka and Yao 1990; Onoue et al. 2004; Onoue and Sano 2007). These units originated from the Panthalassa Ocean and were accreted to the South China Block during the Late Jurassic–Early Cretaceous (Mastuoka and Yao 1990; Matsuoka 1992, Isozaki 1996).

**Fig. 4.1** Location of the studied localities. a Location of the Sambosan Accretionary Complex in Southwest Japan. b Studied areas of the SAC in Shikoku Island. c Studied locality in Takayama area. d Studied locality in Seiyo area. e Studied localities in Tsuno area.
4.3. Mode of occurrence

In the SAC, four main modes of occurrences (MO) of limestone units are recognized:

- MO1 (Fig. 4.3a): Massive limestone slabs. These limestone units, tens of meters to several kilometers in size, correspond to large pieces of carbonate bank dismantled either during the travel of the seamount in the Panthalassa ocean or during the accretion processes in the trench and/or in the accretionary wedge (Wakita and Metcalfe 2005; Onoue and Stanley 2008).

- MO2 (Fig. 4.3b): Matrix-supported breccia with volcaniclastic matrix (VCM). Limestone blocks (several decimeters to meter in size) and clasts (few centimeters in diameter) are embedded in VCM and associated with altered basaltic clast and blocks. The limestone clasts are grey to dark grey. The red or green VCM is composed of sand to mud size grains of altered vesiculated basalt and volcanic glass shards. Volcaniclastic material is the most common volcanic rock in shallow submarine volcanoes and result from the mechanical breakup of lava flows or from explosive-eruptive fragmentation (Staudigel and Clague 2010). Significant amount of sparry calcite is also part of the VCM. This mode of occurrence is typically interpreted as debris flows and debris avalanches deposits on the flank of mid-oceanic seamounts (Onoue and Sano 2007; Chablais et al. 2010a).

- MO3 (Fig. 4.3c): Clast-supported breccia with limestone, basalt, chert and siliceous mudstone clasts embedded in a small amount of siliceous mudstone matrix. Onoue and Sano (2007) defined “siliceous mudstone” as rocks that “consists of radiolarians and siliceous sponge spicules, disseminated in the matrix of clay minerals and microcrystalline quartz”. In this study we follow this nomenclature even if some quartz grains may occasionally be coarser than clay and silt size. Based on the polymict nature and lack of clear shear deformation, this breccia is tentatively interpreted as debris flows and debris avalanches deposited on seamount flanks and/or in the trench before the accretion.

- MO4 (Fig. 4.4a): Bedded pelagic micritic limestone (siliceous micrite of Onoue and Sano 2007) intercalated with chert layers. This mode of occurrence corresponds to a succession of pelagic sediments that was preserved during the accretion. It is to be noticed that later tectonic processes during the incorporation of the seamount in the accretionary prism led to an increased complexity in the mingling of the different units described above (Wakita 2012).
Fig 4.2 Location of the studied localities. a Studied localities in Mt. Sambosan area. b List of samples from the sixteen studied localities. c Studied localities in Befu/Kito area. d Studied localities in Wajiki area.
4.4. Studied area

For this study, limestone exposures all along the SAC in Shikoku Island were systematically investigated (Fig. 4.1b). Sixteen localities have been comprehensively sampled. Main characteristics of each locality are presented below and summarized in Table 4.1.

Western Shikoku
In the Ehime prefecture, the Sambosan limestone crop out as massive slabs (MO1), limestone clasts in VCM (MO2) and bedded limestone (MO4) on the seashore at Loc. 1 Takayama area (Fig. 4.1c) and as limestone slabs (MO1) in the mountains near Seiyo city (Loc. 2 Seiyo area, Fig. 4.1d). Occurrences and microfacies were originally described by Chablais (2010). Geology of this area was reported by Matsuoka (1998).

Central Shikoku
In the Kochi prefecture, the Sambosan limestone crop out primarily in the Tsuno area and in the Mt. Sambosan area. Studied localities in Tsuno include Loc. 3 Inaba cave, Loc. 4 Tsuno windmill, Loc. 5 Tsuno road, and Loc. 6 Tsuno megabreccia (Fig. 4.1e). Reef limestone slab at Loc. 3 Inaba cave have been the purpose of several sedimentological and palaeontological studies (Kristan-Tollmann 1991; Onoue et al. 2009; Chablais et al. 2010c; Chapter 3). It has been attributed to the Norian, on the basis of its rich reef biota (i.e., sponges, foraminifers, algae and microproblematica). Limestone slabs of Loc. 4 Tsuno windmill were described in chapter 3. Loc. 5 Tsuno road is described here for the first time. This locality consists of several limestone slabs that crop out along the forestry road north of Tsuno town. Loc. 6 Tsuno megabreccia contains a rich Ladinian?-Carnian reef biota that was described in details by Peybernes et al. (2015). The Mt. Sambosan area is the type locality of the Sambosan limestone (Yamato Omine Research Group 1981). It was first described by Kobayashi (1931). The several outcrops on the Sambosan Mountain are here attributed to 3 localities (Fig. 4.2a). Loc. 7 Mt. Sambosan castle is located along the Ryugado skyline under the castle and comprises limestone slabs (MO1) and limestone clasts in VCM breccia (MO2). Loc. 8 Mt. Sambosan quarries consists of two quarries and several outcrops (MO1 and MO2) along the nearby trail south east the Ryugado skyline. Loc. 9 Ryugado cave is situated to the north of Mt. Sambosan. Samples come from massive slabs (MO1) at the cave location.
Eastern Shikoku
Sambosan limestone crop out in Befu/Kito area (Fig. 4.2c) and Wajiki area (Fig. 4.2d). Limestone units crop out along roads and rivers in Befu (Loc. 10), Konose (Loc. 11) and Hisaidani (Loc. 12) valleys. These three valleys are perpendicular to the SAC and thus represent excellent transversal sections of the accretionary complex, allowing an almost continuous mapping and sampling. Chert, basalt and limestone units from these localities were previously studied by Ishida (1983, 1987), Onoue et al. (2004) and Chablais (2010). Additionally, samples have been collected from limestone slabs (MO1) and limestone clast in VCM (MO2) along the trail going up to Mount Ishidate summit (Peybernés et al. 2015; Chapter 3). At Loc. 10 Befu, Loc. 12 Konose Kyo and Loc. 13 Hisaidani samples have been collected from massive limestone slabs (MO1), limestone clasts in VCM (MO2), limestone clasts in breccia with siliceous mudstone matrix (MO3) and bedded limestone intercalated with chert layers (MO4). At Loc. 14 Wajiki, the Naka River cut through the SAC and exhibit extensive exposure of clast-supported breccia with siliceous mudstone matrix (MO3) on its sides. Several limestone slabs (MO1) are also present at this locality. This area was mapped by Ishida (1977). Further East in the Wajiki area, two quarries, Loc. 15 Road 28 1 and Loc. 16 Road 28 2 respectively, provide additional outcrops in the easternmost part of the SAC in Shikoku Island. Limestone crop out as massive limestone slabs (MO1) and clasts in VCM (MO2) at Loc. 15 Road 28 1 and as clast in breccia with siliceous mudstone matrix (MO3) at Loc. 16 Road 28 2.

Fig. 4.3 Mode of occurrence of the SAC limestone. a MO1: Massive white limestone slab exposure in a quarry at Loc. 7 Mt. Sambosan. b MO2: outcrop of VCM breccia at Loc. 15 Road 28 1. Limestone (L) and basaltic (B) blocks are embedded in volcaniclastic matrix (VCM). c MO3: Polymict breccia with micritic limestone (L), chert (C), basalt (B) and mudstone (M) clasts, and matrix composed of siliceous mudstone and small grains of various lithologies, CP206 Loc. 12 Konose Kyo.
**Table 4.1**: Studied localities

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<th>Samples</th>
<th>Identified Microfacies</th>
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<td>JC263-288</td>
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<td>CP63-83</td>
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<td>CP187+-189+</td>
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*MO1*: massive limestone slab; MO2: limestone clasts in VCM breccia; MO3: limestone clasts in polymict breccia with mudstone matrix; MO4: bedded pelagic limestone intercalated with chert layers
4.5. Materials and Methods

At each locality samples have been collected from the best preserved parts of the limestone units. Microfacies analysis and biotic content inventory have been carried out for 530 thin sections (2.3 × 4 cm and 3.6 × 4.8 cm). They were classified according to Dunham (1962) supplemented by Embry and Klovan (1971). Samples were then attributed to microfacies according to their sedimentary components and texture. For each microfacies, some characteristic and well-preserved thin sections have been selected to document the relative abundances of grains, cement and matrix. These selected 38 samples were scanned with a high-resolution film scanner (Nikon CoolScan 4000 ED) and point counting was performed using JMicr0vision image analysis software (300 points, grain solid method, random grid, see Flügel 2004). Diagenetic features (i.e., calcitic veins and stylolites) are not taken into account.

4.6. Results

Microfacies description

Eight main microfacies have been recognized from our material (Table 4.2). Relative abundances of sedimentary components obtained by point counting are presented in Table 4.3. Additionally, pie charts (Fig. 4.4–11) illustrate the main components for each microfacies. The bioclast category correspond mainly to shell fragments but also to reef framebuilders, especially in MF4. Echinoderms are counted separately because of their significance in microfacies MF2 and MF6. Peloidal and clotted micrite include some microbial crusts, especially in MF4. Finally, the extraclast category mostly includes volcanic grains.

MF1: Radiolarian-filament mudstone-wackestone (Fig. 4.4)
Bedded micritic limestone intercalated with chert (MO4, Fig. 4a) or isolated blocks and clasts of white to light grey micritic limestone (MO2 and MO3). Major components are recrystallized radiolarian and filaments (pelagic thin-shelled bivalves). The microfacies varies from radiolarian-dominated mudstone-wackestone (MF1a) to filament-dominated mudstone-wackestone (MF1b).
<table>
<thead>
<tr>
<th>Microfacies type</th>
<th>Sedimentary grains</th>
<th>Benthic foraminifer associations</th>
<th>Localities</th>
<th>Mode of occurrence and lithologies</th>
<th>Facies interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF1: Radiolarian-filament mudstone-wackestone</td>
<td>Major: Radiolarian (MF1a) Filaments (MF1b) Subordinate: small bioclasts</td>
<td>No or very rare foraminifers</td>
<td>Loc. 1 Takayama, Loc. 2 Seyio, Loc. 7 Mt. Sambosan, Loc. 8 Sambosan Quarries, Loc. 10 Befu, Loc. 11 Mt. Ishidate, Loc. 12 Konose Kyo, Loc. 13 Hisaidani, Loc. 14 Wajiki</td>
<td>MO2, MO3, MO4 white light grey micritic limestone</td>
<td>Lower slope, Basin</td>
</tr>
<tr>
<td>MF2: Radiolarian siliceous mudstone (MF2a) associated with bioclast-echinoderm-peloidal packstone-grainstone (MF2b)</td>
<td>Major: radiolarian (MF2a); peloids echinoderms, foraminifers (MF2b) Subordinate: Filaments (MF2a); Coated grains, basaltic extraclasts (MF2b)</td>
<td>Endoteba sp., Endotebanella sp., Nodosarids, Duostominiids, Ophtalminids</td>
<td>Loc. 1 Takayama, Loc. 5 Tsuno road, Loc. 12 Konose Kyo, Loc. 13 Hisaidani, Loc. 14 Wajiki</td>
<td>MO3 or alternation of decimetric beds of red limestone and siliceous limestone</td>
<td>Slope</td>
</tr>
<tr>
<td>MF3: Bioclastic-intraclast rudstone-floatstone</td>
<td>Major: Intraclasts (mostly of reef facies), bioclastic fragments Subordinate: Peloids, calcimicrobes, oncoinds, aggregates, echinoderms</td>
<td>in the micritic matrix: Endoteba sp. Endotriada sp., Gsollbergella spiroloculiformis, Ophtalminids, encrusting tubular foraminifers</td>
<td>Loc. 5 Tsuno road, Loc. 7 Mt. Sambosan, Loc. 12 Konose Kyo, Loc. 15 Road 28 1</td>
<td>MO1, MO2 grey limestone with visible grains and cements</td>
<td>Fore-reef</td>
</tr>
<tr>
<td>MF4: Sponge-coral-microproblematica boundstone</td>
<td>Major: Sponges, corals, microproblematica, microbialites Subordinate: serpulids, mollusks, brachiopods, echinoderms, peloids, ooids</td>
<td>Cucurbita infundibiliforme, Hydrelia dulloi, Ophtalminids, Arenovidalina chialingchianse, Koskonobullina socialis, Endotriada sp., Ammobaculites/Reophax, Piallina spp., Alpinophragmium perforatum, Decapodina schaeferae, Galeanella sp., Nodosarids, Nubecularids, Encrusting foraminifers</td>
<td>Loc. 3 Inaba, Loc. 4 Tsuno windmill, Loc. 5 Tsuno road, Loc. 6 Tsuno Megabreccia, Loc. 7 Mt. Sambosan, Loc. 10 Befu, Loc. 11 Mt. Ishidate, Loc. 12 Konose Kyo, Loc. 15 Road 28 1</td>
<td>MO1; MO2, MO3 White to grey limestone. Recrystallised bioclast and spar-filled cavities are sometimes visible in hand samples</td>
<td>Reef</td>
</tr>
</tbody>
</table>
| MF5: Oncoid-calcimicrobe grainstone-rudstone | **Major** : Calcimicrobes, oncocids, aggregates, peloids  
**Subordinate** : bioclasts, intraclasts, echinoderms | **Major** : Calcimicrobes, oncocids, aggregates, peloids  
**Subordinate** : bioclasts, intraclasts, echinoderms | **Variostoma** sp., 'Trochammina' sp., *Agathammina* sp., *Endotriada* sp., *Ammobaculites/Reophax*, Duostominids, Involutinids, Ophtalminids, rare Nodosarids | Loc. 5 Tsuno road, Loc. 7 Mt. Sambosan, Loc. 8 Sambosan Quarries, Loc. 10 Befu, Loc. 14 Wajiki | MO2, MO3 grey oncoidal limestone | Backreef |
| MF6: Peloidal-echinoderm packstone-grainstone | **Major** : Peloids (including microcoprolites), echinoderms, coated grains, aggregates  
**Subordinate** : Ooids, oncocids, calcimicrobes, intraclasts, bioclasts, foraminifers | **Major** : Peloids (including microcoprolites), echinoderms, coated grains, aggregates  
**Subordinate** : Ooids, oncocids, calcimicrobes, intraclasts, bioclasts, foraminifers | *Diplotremina* sp. *Endotebra* sp., *Endotebanella* sp., 'Trochammina' sp., *Agathammina* sp., *Ammobaculites/Reophax*, *Tolypammina gregaria*, *Galeanella laticarinata*, ?Triasina hantkeni, Involutinids (micritised), Duostominids, Ophtalminids, Nodosarids, | Loc. 3 Inaba, Loc. 5 Tsuno road, Loc. 7 Mt. Sambosan, Loc. 8 Sambosan Quarries, Loc. 10 Befu, Loc. 11 Mt. Ishidate, Loc. 12 Konose Kyo, Loc. 13 Hisaidani | MO1, MO2 White to grey limestone grains often visible in hand samples | Open lagoon, shoal and sand bar |
| MF7: Involutinid wackestone-packstone | **Major** : Involutinids, locally megalodont shells  
**Subordinate** : gastropods, dasycladacean, echinoderms, peloids, microcoprolites, bioclasts | **Major** : Involutinids, locally megalodont shells  
**Subordinate** : gastropods, dasycladacean, echinoderms, peloids, microcoprolites, bioclasts | *Aulotortus* ex. gr. *communis*, *Aulotortus* ex. gr. *sinusus*, *Parvalamella friedli*, *Auloconus* sp., *Prorakusia* sp., rare 'Trochammina' sp., *Frondicularia* sp., Involutinids, Nodosarids, rare Duostominids, rare Ophtalminids, | Loc. 1 Takayama, Loc. 2 Seyio, Loc. 3 Inaba, Loc. 5 Tsuno road, Loc. 8 Sambosan Quarries, Loc. 9 Ruygado Cave Loc. 13 Hisaidani, Loc. 14 Wajiki, Loc. 16 Road 28 2 | MO1, MO2, MO3 Grey to dark grey limestone with megalodont shells. Complete Megalodont specimens are sometimes observed in the field | Open lagoon |
| MF8: Bioclast-microcoprolite wackestone-mudstone | **Major** : bioclasts, microcoprolites  
**Subordinate** : peloids | **Major** : bioclasts, microcoprolites  
**Subordinate** : peloids | Nodosarids, rare involutinids, rare opthalminids | Loc. 1 Takayama, Loc. 2 Seyio, Loc. 5 Tsuno road, Loc. 8 Sambosan Quarries, Loc. 9 Ruygado Cave, Loc. 10 Befu, Loc. 12 Konose Kyo, Loc. 14 Wajiki, Loc. 16 Road 28 2 | MO1, MO2, MO3 Light grey micritic limestone | Restricted lagoon |
MF2: Radiolarian mudstone (MF2a) associated with bioclast-echinoderm-peloidal packstone-grainstone (MF2b) (Fig. 4.5)

This microfacies is particularly well documented at Loc. 12 Konose Kyo where an alternation of centimetric to decimetric red limestone beds and siliceous limestone beds crops out. The siliceous limestone beds are radiolarian mudstone composed of recrystallized radiolarian, and occasionally filaments, set in a micritic to microsparitic matrix (MF2a, Fig. 4.5b). The red limestone beds correspond to densely packed bioclast-echinoderm-peloidal packstone-grainstone (MF2b Fig. 4.5c). Major components are peloids, echinoderms, foraminifers (Endotheba sp., Fig. 4.5e), recrystallized bioclasts, ooids (Fig. 4.5f), rare extraclasts (basaltic grains, Fig. 4.5d) and coated grains. In other localities, MF2 occur as clasts in breccia (MO3). In this case, MF2a and MF2b are separated either by stylolites or by gradual depositional contact (Fig. 4.5g). As far as we know, MF2 is described for the first time in the SAC.

MF3: Bioclast-intraclast rudstone-floastone (Fig. 4.6)

Massive limestone slab (MO1) and clasts in VCM breccia (MO2). This microfacies is highly heterogenous in term of grain sizes and components. Intraclasts and bioclasts are the most abundant (25.3% and 16.6% respectively). Most of the intraclasts are composed of microproblematica set in peloidal and clotted micrite and probably correspond to reefal and
peri-reefal facies (see MF4 below). Bioclasts, and especially bivalves and dasycladacean fragments, are recrystallised in light coarse sparite. Subordinate components are peloids, oncoids, calcimicrobes and aggregates. The matrix is mainly composed of dense micrite where porcelaneous foraminifers and ostracods are frequent (Fig. 4.6c, d, f). This microfacies is defined for the first time in the SAC limestone.

Table 4.3: Average relative abundances of sedimentary components in microfacies

<table>
<thead>
<tr>
<th>MF1 (n=6)</th>
<th>MF2 (n=4)</th>
<th>MF3 (n=4)</th>
<th>MF4 (n=7)</th>
<th>MF5 (n=4)</th>
<th>MF6 (n=5)</th>
<th>MF7 (n=4)</th>
<th>MF8 (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiolarians</td>
<td>6.61 [4.12-0.11]</td>
<td>6.16 [3.59-9.32]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
</tr>
<tr>
<td>Filaments</td>
<td>5.06 [2.83-8.11]</td>
<td>0.83 [0.08-2.39]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
</tr>
<tr>
<td>Peloids</td>
<td>0.00 [0.00-1.22]</td>
<td>15.83 [11.74-20.28]</td>
<td>7.07 [4.39-10.50]</td>
<td>5.00 [2.83-8.11]</td>
<td>22.67 [18.05-27.83]</td>
<td>37.26 [31.84-43.08]</td>
<td>0.84 [0.21-2.89]</td>
</tr>
<tr>
<td>Ooids</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.08 [0.00-1.84]</td>
<td>0.42 [0.36-3.83]</td>
<td>3.25 [1.61-6.04]</td>
<td>7.92 [5.19-11.67]</td>
</tr>
<tr>
<td>Coated grains</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.75 [0.08-2.39]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
</tr>
<tr>
<td>Aggregates</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>1.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>3.25 [1.61-6.04]</td>
<td>3.92 [1.61-6.04]</td>
<td>3.26 [1.61-6.04]</td>
</tr>
<tr>
<td>Oncoids</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>3.16 [0.21-2.89]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>17.67 [13.52-22.46]</td>
<td>0.86 [0.21-2.89]</td>
</tr>
<tr>
<td>Calcimicrobes</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>1.08 [0.21-2.89]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>8.33 [5.47-12.06]</td>
<td>0.07 [0.00-1.22]</td>
</tr>
<tr>
<td>Intraclasts</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>25.33 [20.51-30.65]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>1.06 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
</tr>
<tr>
<td>Echinoderms</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>3.67 [1.67-6.37]</td>
<td>0.33 [0.01-1.84]</td>
<td>0.00 [0.01-1.84]</td>
<td>17.52 [4.92-11.28]</td>
<td>5.42 [4.92-11.28]</td>
</tr>
<tr>
<td>Dasyycladacean</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.54 [0.01-1.84]</td>
<td>0.00 [0.01-1.84]</td>
<td>0.00 [0.01-1.84]</td>
<td>0.75 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
</tr>
<tr>
<td>Involutinids</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.27 [0.01-1.84]</td>
<td>14.42 [10.57-18.82]</td>
</tr>
<tr>
<td>Microcoprolites</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.42 [1.16-5.19]</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>0.00 [0.00-1.22]</td>
<td>3.99 [2.08-6.88]</td>
<td>1.75 [0.54-3.85]</td>
<td>0.10 [0.00-1.22]</td>
<td>0.67 [0.00-1.22]</td>
<td>2.46 [0.08-2.39]</td>
<td>3.67 [1.84-6.47]</td>
</tr>
<tr>
<td>Peloidal and clotted micrite</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>13.50 [2.08-6.88]</td>
<td>2.00 [1.84-6.47]</td>
</tr>
<tr>
<td>Dense micrite</td>
<td>87.45 [83.03-90.88]</td>
<td>31.69 [26.64-37.26]</td>
<td>31.89 [26.76-37.60]</td>
<td>1.43 [0.36-3.38]</td>
<td>1.58 [0.54-3.85]</td>
<td>1.46 [0.36-3.38]</td>
<td>67.08 [61.36-72.30]</td>
</tr>
<tr>
<td>Microspar</td>
<td>0.00 [0.00-1.22]</td>
<td>24.83 [19.89-29.95]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
<td>0.00 [0.00-1.22]</td>
</tr>
</tbody>
</table>

n: number of samples used for point-counting; Mean % value [associated 95% "exact" Clopper-Pearson confidence interval]; Important value in bold
Fig. 4.5 MF2 Radiolarian mudstone (MF2a) associated with bioclast-echinoderm-peloidal packstone-grainstone (MF2b). a Outcrop view of alternation of radiolarian mudstone and bioclast-echinoderm-peloidal packstone-grainstone. Hammer for scale. Loc. X Konose Kyo. b Radiolarian (arrows) mudstone CP60. c Bioclast-echinoderm-peloidal packstone-grainstone, note the presence of basalt extraclast (arrows) CP60. d Basalt extraclast in the echinoderm-peloidal packstone-grainstone CP237. e Endoteba sp. CP60. f Ooid and echinoderm fragment in echinoderm-peloidal packstone-grainstone CP237. g Radiolarian mudstone (MF2a) and bioclast-echinoderm-peloidal packstone-grainstone (MF2b). Note the sharp stylolithic contact (black arrow) and the gradual depositional contact (white arrow) JC229. h Pie chart showing the mean relative abundance of components of MF2.
Fig. 4.6 MF3 Bioclastic-intraclast rudstone-floastone. 

- **a**, **b** Bioclastic-intraclast rudstone-floastone showing intraclasts (in), calcimicrobes (ca) and recrystallized bioclasts (bio) CP30, CP177.
- **c**, **d** *Gsollbergella spiroloculiformis*. CP30, CP 176.
- **e** Encrusting organisms (arrows) on recrystallized bioclasts CP176.
- **f** Ostracod CP177.
- **g** Pie chart showing the mean relative abundance of components of MF3.
MF4: Sponge-coral-microproblematica boundstone (Fig. 4.7)
Massive limestone slabs (MO1), clasts in VCM (MO2) and clasts in breccia with siliceous mudstone matrix (MO3). This microfacies is composed of framebuilder skeletal elements such as calcareous sponges (Fig. 4.7a), corals (Fig. 4.7b), _Tubiphytes_ (Fig. 4.7b), Solenoporacean red algae (Fig. 4.7c) and encrusting organisms along with a significant amount of interstitial sediment, including reef dwellers. The interstitial sediment consists of peloid-bioclast-ooid packstone-grainstone and peloidal and clotted micrite which is potentially of microbial origin. Void and cavities in the reef framework are filled by tanned isopachous cements. The volume occupied by the reef framework is generally low (about 38%, Table 4.3) and the interstitial sediment is abundant, especially the peloidal and clotted micrite (26.7%). Based on biotic content and quantitative microfacies analysis, two types of reef have been distinguished in the SAC (Chapter 3). The first (Reef Type 1) correspond to Ladinian?-Carnian sponge-coral-microproblematica boundstone containing abundant peloidal and clotted micrite. The second (Reef type 2) correspond to Late Carnian–Norian-Rhaetian? sponge-dominated boundstone containing abundant peloid-bioclast-ooid packstone-grainstone as interstitial reef sediments. For detailed studies of reef limestone of the SAC of Shikoku the reader is referred to Chablais et al. (2010c), Peybernes et al. (2015) and Chapter 3. In the present paper, some samples composed of poorly sorted and reworked framebuilder fragments, peloids and ooids are included in MF4 because of their assumed close relationship with the boundstone facies.

MF5: Oncoid-calcimicrobe grainstone-rudstone (Fig. 4.8)
Clasts in VCM (MO2) and clasts in breccia with siliceous mudstone matrix (MO3). This microfacies is composed of calcimicrobes (Fig. 4.8b), oncoids, aggregates (Fig. 4.8c), peloids and coated grains. Occasionally intraclasts and rare ooids (CP171) occur. The calcimicrobes are remains of calcified cyanobacteria (formerly called porostromate oncoids). Specimens in our material are attributed to _Cayeuxia_ sp. and _Garwoodia_ sp. Duostominids are frequent (Fig. 4.8d). Coarse sparry cements fill the voids and fenestrae, which are frequent.

MF6: Peloidal-echinoderm packstone-grainstone (Fig. 4.9)
Many of the massive limestone slabs (MO1) are composed of well-sorted peloidal-echinoderm packstone-grainstone. This microfacies also occurs in clasts of the VCM breccia units (MO2). Major components are peloids, coated grains, aggregates and echinoderm fragments (essentially crinoids and some urchin spines). Subordinate components are ooids, oncoids, calcimicrobes, involutinids, intraclasts and bioclasts. Ooids are locally frequent. Intergranular
porosity is filled by syntaxial cement, intergranular cement and few depositional micrite. Peloids include microcoprolites and micritised grains which, in some case, exhibit a shape resembling involutinids foraminifers (see discussion below). Thin isopachous cements occasionally surround peloids and bioclasts. Bioturbations (Fig. 4.9c) are sometimes observed. At Loc. 7 Mt. Sambosan castle, microcoprolites corresponding to the first ontogenetic stage of *Parafavreina thoronetensis* (Brönnimann et al. 1972) occur (Fig. 4.9d, e).

**Fig. 4.7** MF4 Sponge-coral-microproblematica boundstone. a Sponge-microproblematica boundstone containing undetermined calcareous sponge (S) and chaetetid sponge (C), *Microtubus communis* (M), and microbial crusts (mc) CP223. b Coral-microproblematica boundstone containing coral (Co), *Tubiphytes* sp. (T) and voids infilled with isopachous and blocky cements (V) CP22. c Solenoporacean algae CP207. d *Cucurbita infundibuliforme* CP40. e *Microtubus communis* CP207. f Pie chart showing the mean relative abundance of components of MF4.
MF7: Involutinid wackestone-packstone (Fig. 4.10)
Dark grey limestone slabs (MO1) and clasts in breccia (MO2, MO3). Thick megalodont shells (bivalves) are sometimes presents and are locally abundant (Fig. 4.10b). Recrystallized involutinids are major components (Fig. 4.10c). Subordinately, gastropods, bivalve shells, dasycladacean algae (Fig. 4.10e), microcoprolites and echinoderms are observed. Dasycladacean are rare but of significance regarding depositional environment (photic zone indicator).

Fig. 4.8 MF5 Oncoid-calcimicrobes grainstone-rudstone. a Oncoid-calcimicrobe grainstone-rudstone. b Calcimicrobes CP116. c Aggregate CP91. d Variostoma sp. CP 3. e Pie chart showing the mean relative abundance of components of MF5.

MF8: Bioclast-microcoprolite wackestone-mudstone (Fig. 4.11)
Massive limestone slabs (MO1) and clasts (MO2, MO3). This microfacies is primarily composed of dark depositional micrite, microcoprolites and rare bioclast fragments (involutinids, echinoderms, gastropods, bivalves). Among the microcoprolites, the species Payandea japonica, Favreina tosaensis and Parafavreina? sp. (Fig. 4.11d, e) are recognized (Senowbari-Daryan et al. 2010a). Fenestrae filled by sparry calcite occasionally occur. Bioturbations were observed in some samples.
Facies interpretation

Pelagic environment
MF1 contains radiolarian and filaments (i.e., thin-shelled bivalves) which represent open marine biota and indicate deposition in a basinal environment (Reijmer et al. 1991; Maurer et al. 2003; Chablais et al. 2010b; Gale et al. 2014). Association with chert layers and/or inclusion of chert nodules supports this interpretation. Pelagic limestone must have been deposited above the CCD, probably on the lower slope or ocean floor surrounding the seamount. At Shikoku Island, alternating beds of chert and limestone were interpreted to have been deposited on the slope of a seamount (Matsuoka 1992). At Kyushu Island, calcareous nannofossils have been reported from pelagic limestone very similar to MF1 (Onoue and Sano 2007; Onoue and Yoshida 2010).

Slope environment
MF2 consists of an alternation of pelagic siliceous limestone (MF2a), which is characterized by open marine biota (i.e., radiolarian and filaments), and bioclast-echinoderm-peloid packstone-grainstone (MF2b) which probably represent event beds composed of coarser reworked sediments. Peloids, echinoderms, foraminifers, ooids and basaltic extraclast in MF2b were probably derived from the platform top and underlying volcanic pedestal and were redeposited by turbidity current (Reijmer et al. 1991; Preto 2012; Gale et al. 2014). In some samples, gradual depositional contact between MF2a and MF2b (Fig. 4.5g) illustrate the return of pelagic sedimentation after the deposition of the bioclast-echinoderm-peloid packstone-grainstone. In the Carboniferous Akiyoshi limestone (Honshu Island), limestone beds alternating with spicular chert were also interpreted to have been resedimented by gravity flows from a shallow-water environment into a deeper basin where spicular chert accumulated (Nakazawa 2001). Stylolithes and lateral splitting pressure solution seams in turbidite facies are indicators of extensive compaction (Chablais et al. 2010a). In addition to MF2, MF1 also likely deposited on the slope of the seamount(s).

Fore-reef environment
MF3 is mainly composed of intraclasts and bioclasts derived from platform margin setting (i.e., reefal and peri-reefal environments) that are embedded in dense micrite. This dense micrite indicates a relatively low water energy depositional setting, probably below the fair weather wave base. The angular shape of bioclasts and intraclasts, and the very poor sorting and packing
suggest that the various grains and clasts were gravitationally transported in a low energy environment relatively close to the source area. This interpretation is consistent with a deposition of debris in a mud-rich fore-reef area (Martindale et al. 2013). In the Carboniferous Akiyoshi limestone, Nakazawa (2001) interpreted similar intraclast rudstone with micritic matrix as debris flow deposits, which may be relatively proximal, compared with densely packed grainstones (MF2b in the present work). We hypothesize that the fragments could have been exported from the platform edge to the fore-reef setting by channels (grooves). Such transported reef debris are common after large storms and hurricanes (Martindale et al. 2013). However, Kiessling and Flügel (2000) proposed a slightly different interpretation for similar intraclastic floatstone from the Upper Triassic limestone of the Philippines. They considered also intraclasts and bioclasts as material transported toward low energy environments but within the reef area.

Reef and peri-reef environment
MF4 are boundstones that include various framebuilders such as calcareous sponges, scleractinian corals, microproblematica and solenoporacean algae, along with abundant microbialites. These organisms and related bioconstructions clearly indicate reef environments that were probably distributed along the bank margin and in the bank interior (patch reefs). The resolution of our microfacies analysis do not allow us to recognize detailed zonation such as reef front, reef crest and reef flat. The thick isopachous cement that fills the void between the framebuilders indicates efficient sea water circulation through the reef framework.

Back-reef and open lagoon environment
MF5 contain abundant cyanobacterial calcimicrobes, aggregates and fenestral fabrics which together characterize open lagoon setting (Kiessling and Flügel 2000; Chablais et al. 2010b). Cyanobacterial calcimicrobes in particular indicate, if considered to be autochthonous, a depositional environment within the photic zone. The loose packing and abundance of voids filled with sparry cement indicate an early cementation probably resulting from intense sea water flow within the sediment. The abundance of Duostominids in such microfacies was already mentioned by Dullo (1980), Haas et al. (2010) and Gale et al. (2013).

MF6 is well-sorted peloid echinoderm grainstone, suggesting a high water energy depositional setting. This microfacies is thus interpreted as sand bars that could be distributed in various environments in back-reef (sand apron) and lagoonal setting depending on the currents flowing
through the platform. Samples with ooids can be related to higher energy environment such as shoal. Coated grains are usually bioclasts with a micritised rim resulting from microboring and deposition of microbial micrite during the early diagenesis (Flügel 2004). Microboring and micrite coating indicate prolonged exposure at the sediment-water interface for these processes to occur before burial (Olòriz et al. 2004; Gale et al. 2013), suggesting a relatively low sedimentation rate. In their model of the Sambosan platform, Chablais et al. (2010b) interpreted the equivalent microfacies from Kyushu Island as deposit that can be distributed all over the lagoon and, when ooids are present, as shoal deposit at the leeward side of the carbonate platform.

Fig. 4.9 MF6 Peloid-echinoderm packstone-grainstone. a Peloid-echinoderm grainstone, note the presence of crinoid articles CP29. b Peloid-echinoderm grainstone CP33. c Burrow filled by grainstone in peloid-echinoderm packstone CP109. d, e Microcoprolites Parafavreina thoronetensis (d) longitudinal section and (e) transversal section CP17. f Diplo tremina sp. CP107. g Endoteba sp. CP29. h Endotebanella sp. CP47. i Pie chart showing the mean relative abundance of components of MF6.
Lagoonal environment

MF7 and MF8 are interpreted as sediment deposited in low energy, protected part of the lagoon. MF7 contains involutinids, megalodonts and dasycladacean algae. In the Upper Triassic platforms, involutinids are widely distributed from near reef environments to high energy sand shoal to muddy inner platform setting (Piller 1978; Schäfer and Senowbari-Daryan 1978; Gazdzicki 1983; Chablais et al. 2010a, 2011). Megalodonts are typical bivalves of the tropical lagoonal environment of the Tethys and Panthalassa oceans (Tamura 1983). Association of involutinids and dasycladacean algae characterizes open marine part of platform interior setting (Flügel 2004). In the SAC limestone, dasycladacean algae are present essentially in MF7 but are much rarer than in Tethyan coeval carbonate platforms. In the Late Norian-Rhaetian limestone of Sulawesi, microfacies where autochthonous lagoonal foraminifers and megalodonts occur, have been related to protected shallow subtidal areas (Martini et al. 1997). MF8 correspond to mud dominated limestone with very low abundance and diversity of skeletal and non-skeletal grains, suggesting deposition in a restricted lagoon. The abundance of gastropod in some samples is consistent with this interpretation. Gastropods are often considered to be tolerant to high temperature and salinity variations which characterize restricted part of lagoons (Wagner and Van der Togt 1973; Tucker and Wright 1990; Riegl et al. 2010).

4.7. Discussion

Remarks on the preservation and distribution of SAC limestone

Because of the long geological history of the limestone units from their deposition on the top of Panthalassic seamount(s) to the multiple tectonic processes occurring in the accretionary complex, limestone units in the SAC are usually poorly preserved (Chablais et al. 2010b). Nevertheless, thorough work in the field allowed us to collect some well-preserved samples, especially in limestone clasts of the breccia (MO2 and MO3). The main processes leading to bad preservation of limestone are in decreasing order of importance: recrystallization in sparry calcite, fracturation, silicification and dolomitisation. Dolomitisation is particularly represented at Loc. 7 Mt. Sambosan 1 castle. All microfacies seem to be equally affected by these processes. According to their shape, some peloids observed in MF6 are likely micritised involutinids. However, the recognition is too doubtful to reliably count them as involutinids. As a consequence, foraminifer abundance is probably underestimated in this microfacies. The
presence of micritised involutinids in MF6 suggests a depositional environment closely related to MF7. It is to be noticed that involutinids, which are aragonitic, are typically recrystallized in coarse sparry calcite, as in MF7. Micritised involutinids suggest that early diagenetic conditions were different in MF6. Sparry calcite counted as intergranular cement may in some case include dissolved and recrystallized bioclasts as revealed using cathodoluminescence microscopy.

In Shikoku Island, the different microfacies are homogeneously distributed among the localities (Table 4.1). The absence of geographical pattern in microfacies distribution results probably from mixing during the dismantling and accretion of the seamount(s).

Fig. 4.10 MF7 Involutinid wackestone-packstone. a Involutinid wackestone with echinoderm and mollusk fragments (black arrows) and involutinids (white arrows) JC273. b Involutinid packstone with thick megalodont shell (MS). Note the presence of bioturbation with geopetal feature (arrow) CP240. c Prorakusia sp. CP240. d Frondicularia sp. CP242. e Dasycladacean algae CP94. f pie chart showing the mean relative abundance of components of MF7.
Fig. 4.11 MF8 Bioclast-microcoprolite wackestone-mudstone. a Microcoprolite (arrows) mudstone CP2. b Mudstone with fenestrae (arrow) CP189+. c Gastropods and other mollusk shell fragments JC 287. d, e Microcoprolite *Payyande japonica* d transversal section and e longitudinal section CP2. f Pie chart showing the mean relative abundance of components of MF8.

**Comparison with other localities of the SAC**

Microfacies very similar to those of Shikoku Island have been reported from the SAC at Kyushu Island (Kanmera 1969; Onoue and Stanley 2008; Chablais et al. 2010b), in Honshu Island (Kanto Mountains, Chablais 2010) and in Okinawa Island (Chablais 2010; Yamashita et al. in revision). Correlation with the microfacies reported from Kyushu, Honshu and Okinawa Islands are presented in Supplementary material 4.1. Most of microfacies found in Shikoku were already described elsewhere in the SAC. However, MF2 and MF3 are recognized here for the first time. They correspond to slope and fore-reef environments and seem to be limited to Shikoku Island and the Kii peninsula (see Chapter 5). Nevertheless, further investigation of the SAC limestone is needed to confirm this observation.

The wide distribution of most of the microfacies (approximately 1500 km from Okinawa to the Kanto Mountain) suggests that the seamounts, from which they originated, were probably distributed in a wide area of thousands of square kilometers prior to their accretion at the trench. Chablais et al. (2010b) argued that “the distribution patterns of the Sambosan AC throughout
Japan points to an actual wide seamount province upon which Upper Triassic atoll-type carbonate developed”. The Maldives archipelago, which consists of a series of about 1300 small sand islands in the central Indian Ocean (Parker and Gischler 2011), may represents a modern analogous of the shallow water carbonate bank cluster recorded in SAC. Other authors (Taira et al. 1983, Kato and Saka 2006) explain the wide distribution of the Sambosan limestone by the displacement of limestone units during intense strike-slip faulting.

Foraminifer distribution
Most foraminifer species are widely distributed among the microfacies in Sambosan limestone (Chablais et al. 2011 and this work) except some porcelaneous and sessile foraminifers (e.g., Cucurbita, Hydrania, Galeanella, Alpinophragmium) that are restricted to reef limestone. In the same way, in modern atolls of the Maldives (Ari and Rasdhoo), Parker and Gischler (2011) described 8 assemblages of benthic foraminifera, distributed in 2 main groups: reefal and non reefal. Therefore, reefs appear to have played a major role in foraminifer distribution both in the Early Mesozoic and Recent. In more detail, foraminiferal assemblage variations in Ari and Rasdhoo atolls are primarily controlled by water depth (Parker and Gischler 2011). This may also be true for the Sambosan assemblages but it is not clearly visible from our foraminifer dataset.

Biostratigraphy and correlation
In the SAC, exact correlations between limestone units are often prevented by the poor biostratigraphic control and by the general scarceness of significant fossils. As a consequence, correlation typically rest on microfacies comparisons. Nevertheless, because of the rich biota, reef limestone biostratigraphy is better constrained than other facies. Reef limestone of the SAC range from the Ladinian–Carnian to the Norian–Rhaetian (Peybernes et al. 2015; Chablais et al. 2010c; Chapter 3). Two types of reef are distinguished and attributed to the Ladinian–Early Carnian and to the Late Carnian–Norian to Rhaetian respectively (Chapter 3). Other microfacies contain less diagnostic fauna. However, several biostratigraphic markers occurs in MF3, MF6 and MF7 (Fig. 4.12).

At Loc. 13 Hisaidani, conodonts Metapolygnathus aff. auriformis, M. primitius, M. polygnathiformis, M. aff. permicus, Ancyrogondolella spatulata, A. cf. triangularis, Mockina postera and M. cf. elongata from pelagic micrite alternating with bedded chert (MF1) indicate a Late Carnian–Middle Norian age (Ishida and Hirsh 2001). The occurrence of Gsollbergella spiroloculiformis in MF3 indicate a Carnian age (Rettori 1995; Rettori et al. 1998).
Parafarveina thoronetensis occur in MF6 at Loc. 7 Sambosan castle. In the Tethys realm, this microcoprolite range extends from the Norian to the Middle Liassic. It is particularly abundant in Rhaetian beds of Southern France (Brönnimann et al. 1972), USA (Kristan-Tollmann and Tollmann 1983), and Western Carpathian (Gazdzicki et al. 2000). This is the first mention of Parafarveina thoronetensis in the SAC. Occurrence of Galeanella laticarinata in MF6 at Loc. 10 Befu indicates a Norian-Rhaetian age (Zaninetti et al. 1992; Senowbari-Daryan et al. 1996; Martini et al. 1997; Hardenbol et al. 1998; Senowbari-Daryan et al. 2010b). The presence of ?Triasina hantkeni at Loc. 5 Tsuno road suggest that MF6 deposited during the Late Norian–Rhaetian (Gazdzicki 1983; Marcoux et al. 1993; Martini et al. 1997, 2004; Mancinelli et al. 2005). In MF7, the involutinids Aulotortus ex. gr. communis, Aulotortus ex. gr. sinuosus, Auloconus sp., Parvalamella friedli and Prorakusia sp. indicate a Carnian to Norian age. In Kyushu Island, lagoonal microfacies similar to MF7 have been attributed to the Late Carnian to Norian–Rhaetian based on the occurrence of typical Carnian to Norian bivalves (e.g., Gruenewaldia decussata, G. woehrmanni, and Paleoneilo elliptica), Middle Norian conodont assemblages (e.g., Epigondolella multidentata, E. medionorica, E. spiculata, and E. tozeri) and Norian–Rhaetian foraminifers (Aulotortus sinuosus, Auloconus permodiscoides, Aulotortus tenuis, Triasina hantkeni) (Onoue and Tanaka 2005; Chablais et al. 2010b). Beside, we found during this study a specimen of Aulosina oberhauseri in lagoonal limestone from the Kumagawa area at Kyushu Island. In the Tethyan domain, Aulosina oberhauseri is referred to the Norian–Early Rhaetian (Rigaud et al. 2012). In Oregon, the species occurs within the first 48 metres of the Black Marble Quarry, part of the Martin Bridge Formation, late Carnian–middle ? Norian in age (Rigaud et al. 2012). We noticed that conical involutinids (e.g., Trocholina, Lamelliconus), which are typical of the Carnian (e.g., Di Bari and Laghi 1994), are almost totally absent in lagoonal facies of Shikoku and Kyushu Islands (only one occurrence at Loc. 16 Road 28 2). The recrystallization cannot account totally for this observation because the general test morphology of involutinids is preserved during diagenesis. Therefore, the lack of conical involutinids suggests that protected lagoonal environments (M7 and MF8) were poorly developed in the SAC bank(s) during the Carnian and better characterized the bank(s) interior during the Norian–Rhaetian. Regarding the other microfacies, foraminifer assemblages of MF2, 5, 8 indicate a Late Triassic age but do not allow us to be more precise (Fig. 4.12). In MF8, Payandea japonica indicates a Late Carnian–Rhaetian age (Senowbari-Daryan et al. 2010a). MF2 and MF5 only contain long-range taxa such as Endotebanella sp. (Anisian–Rhaetian, Vachard et al. 1994; Martini et al. 2004) and Variostoma sp. (Anisian–Rhaetian, Rigaud et al. 2015).
Speculative depositional model

Shallow water carbonates of the SAC are interpreted to have been deposited on top of subsiding volcanoes (Kanmera 1969; Tamura 1992; Onoue and Sano 2007; Onoue and Stanley 2008). Vertical successions or lateral variations of microfacies are rarely observed in limestone units of Shikoku Island, except at Loc. 3 Inaba (Chablais et al. 2010c). Therefore, speculative reconstruction of the Sambosan carbonate bank(s) (Fig. 4.13) should rely on modern and ancient analogues. Modern atolls of the Indo-Pacific realm and Upper Triassic isolated carbonate platforms (e.g., Latemar in The Dolomites, Djebel Kawr in Oman) represent the best candidates for such model. However, regarding modern atolls, one must keep in mind that high growing scleractinian corals and coralline red algae, which represent the main reef builders today, were not as diversified nor abundant in Upper Triassic reefs. Furthermore, modern atoll morphology is primarily shaped by sea level variations related to the last glaciations (Gischler 2015). Comparison with recent atoll-type build-ups is thus crucial for the understanding of ancient isolated platforms but such modern analogues must be used cautiously.

Carbonate sedimentation on isolated platforms is controlled by several factors such as sea level variations, subsidence rate, nutrient supply, temperature, winds and currents, and seamount morphology.
Fig. 4.13 Speculative depositional model (modified after Onoue and Stanley 2008 and Handford and Louks 1993).
In a polar ice cap-free world such as the Late Triassic (Sellwood and Valdes 2006; Godderis et al. 2008; Preto et al. 2010) amplitude, rate and frequency of sea level variations are expected to be lower than in modern oceans (Haq et al. 1987; Embry 1988; Jacob and Sahagian 1993; Miller et al. 2005). Therefore, sea level variations were probably a minor controlling factor during the Late Triassic. On the other hand, continuous subsidence related to the trench-ward cooling of the oceanic lithosphere should have controlled the accommodation space of the SAC bank(s). Because of their isolated location, far from continental terrigenous input, nutrient supply to the bank ecosystems was probably low. However, endo-upwelling, which are characteristic of seamounts environment, may have increased the nutrient supply (Rougerie and Wauthy 1993). The Sambosan seamounts are supposed to be located in the intertropical belt of the West Panthalassa during the Late Triassic. Strong monsoon, which were prevalent in the Late Triassic (Parrish 1993; Mutti and Weissert 1995; Sellwood and Valdes 2006), should have somehow affected the sedimentation at the top of the Sambosan bank(s).

The platform geometry and distribution of the various depositional environments are strongly influenced by the windward/leeward orientation in both ancient (e.g., build-ups from The Dolomites: Blendinger and Blendinger 1989; Egenhoff et al. 1999) and modern isolated platforms (e.g. Eberli and Ginsburg 1989; Gischler and Lomando 1999; Harris et al. 2015). However, based on field transect measurements, the wind-induced asymmetry of the Latemar platform in The Dolomites was recently rejected by Marangon et al. (2011). In dismantled platforms, such as the SAC build-ups, the effects of dominant winds are extremely difficult to assess but should be present (Chablais et al. 2010b). It would potentially control the distribution of reefs and shoal (MF4–6) over the platform and especially at the platform margin.

The slope of isolated carbonate platforms and seamounts are typically steep (e.g., Emmerich et al. 2005; Marangon et al. 2011; Gischler 2006). MF2 is interpreted as succession of pelagic sedimentation (radiolarian mudstone) and event beds (bioclast-echinoderm-peloid packstone grainstone) deposited via turbidity currents on the seamount slope. Additionally, limestone clasts and blocks embedded in VCM matrix (MO2) are typically interpreted as debris flow and debris avalanches deposited on the flank of the seamount (Onoue and Sano 2007; Chablais et al. 2010a; Peybernes et al. 2015). Geophysical investigations of recent seamounts flanks frequently display debris avalanche and debris flow evidence (Lipman 1988; Moore et al. 1989; Keating 1998; Leslie et al. 2002; Clouard and Bonneville 2004; Hildenbrand et al. 2006; Staudigel and Clague 2010). Several catastrophic events (MO2) probably punctuated the background sedimentation (MF1and MF2) of the flanks of the seamount(s) (Fig. 4.13a).
The margins of the Sambosan bank(s) consisted probably of reef bodies and, in a smaller amount, of oolitic shoals (Fig. 4.13b). According to our field observations and microfacies analyses, reef limestones of the SAC most likely represent scattered patch reefs rather than continuous atoll margin barrier. Furthermore, they are characterized by low growing communities that should not have had the potential to build high, wave resistant bioconstructions. Therefore, we assume a bank model where small patch reefs are distributed along the bank edge and interior, intertwined with other microfacies. In a similar way, Sano and Kanmera (1996) considered that microbial-dominated carbonates from Permian mid-oceanic limestone of the Mino Accretionary Complex (Honshu Island, Japan) represent remnants of shallow water marine carbonate banks composed of lagoonal mudflat, sand bars and isolated and low relief mounds. These authors compared their results from Late Paleozoic Panthalassa build-ups with the platform edge topography of the Albian carbonate platform at Resolution Guyot, Central Pacific. Instead of wave resistant reefs at sea level, as in modern atolls, this Early Cretaceous oceanic bank had a submerged platform edge with sponge reefs and rudist and coral communities (Shipboard Scientific Party ODP 1993). Regarding Triassic analogs, the Latemar platform was formerly considered as an isolated atoll-like build-up (e.g., Egenhoff et al. 1999, Emmerich et al. 2005) but was recently reinterpreted as flat-topped, steep fronted platform dominated by microbialites (Marangon et al. 2011). In this model the outermost platform and margin are always submerged and are characterized by microbial boundstone associated with Tubiphytes and calcareous sponges which can extend down to 250m water depth (Marangon et al. 2011). The sponge-Tubiphytes boundstone with high microbialite content of the Ladinian?-Lower Carnian reefs of the SAC (Chapter 3) most probably deposited in similar settings. Such microbial margin in shallow subtidal zone are common in Late Paleozoic-Early Mesozoic carbonate platform (e.g., Carboniferous carbonate platforms of Spain: Della Porta et al. 2003; Chesnel et al. 2015; Permian Capitan Reef in USA, Tinker 1998; Ladinian Latemar build-up: Marangon et al. 2011; Carnian Sella platform in The Dolomites, Keim and Schlager 2001).

The bank interior of the SAC likely consisted of a partly protected shallow lagoon (Fig. 4.13b). In this context, MF5 to MF8 could be located all over the bank interior with various possible lateral distributions. MF5, MF6 and MF7 have many components in common (e.g., coated grains, aggregates, peloids, involutinids), suggesting that the depositional environment of these microfacies were probably in close relationship in a platform interior setting. MF8 possibly represents the more restricted inner part of the bank interior. Additionally, isolated patch reefs were also probably present in the lagoon, as in in the Maldives atolls today (Gischler 2006).
modern atolls, sand aprons are especially located behind windward reefs and indicate how sediment, produced at reef margins, is transported lagoonward (Gischler 2006). MF6, which is interpreted as sand bars, could have been distributed similarly.

In summary, instead of a true atoll-type platform with well-defined facies belts as suggested by Chablais et al. (2010b) in their figure 12, our microfacies analysis indicates that the typical Sambosan platform was more probably a carbonate bank with submerged margins and a mosaic of microfacies in the bank interior, whose distribution depends on diverse factors such as water energy, winds, salinity and temperature variations, nutrient supply and platform morphology. The bank margin was probably subjected to frequent collapse characterized by deposition of breccia (MO2) on the slope. These debris flow and debris avalanches have reworked limestone clasts ranging at least from the early Carnian to the Norian and possibly from the Ladinian (MF4) to the Rhaetian (MF6).

4.8. Conclusion

This study further documents the microfacies and depositional settings of the mid-oceanic shallow water environments recorded in the Upper Triassic limestone of the Sambosan Accretionary Complex (SAC). Sixteen localities of the SAC at Shikoku Island have been investigated and comprehensively sampled. Quantitative microfacies analysis and biotic content inventory lead us to:
- Identify eight microfacies, including two microfacies that are described in the SAC for the first time.
- Quantitatively assess the composition of each microfacies by the mean of point counting performed on high-resolution scanned thin sections.
- Refine the biostratigraphy of several microfacies.
- Propose a new depositional model for the Sambosan carbonate deposits. This model emphasizes the probable bank morphology of the platform which is assumed to be composed of a mosaic of microfacies, distributed according to several factors such as winds, currents and seamount morphology.

Our results provide valuable insights in the understanding of mid-oceanic tropical shallow water environments in the Panthalassa Ocean and more generally improve our knowledge of carbonate sedimentation and related ecosystems during the Late Triassic.
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**Supplementary material 4.1**: Correspondance of microfacies of the Sambosan limestone

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<th>Basin</th>
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<th>Onoue and Stanley (2008), Kyushu</th>
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<td>radiolarian biomicrite</td>
<td>MF-S 12 Radiolarian mudstone packstone</td>
<td>MF-O8 Radiolarian mudstone wackestone</td>
<td>MF-K9 Radiolarian Wackestone packstone</td>
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<tr>
<td>MF1b Filament mudstone wackestone</td>
<td>MF17 Filament wackestone packstone</td>
<td>shell biomicrite</td>
<td>MF-S13 thin shelled bivalve wackestone packstone</td>
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**Slope**

Radiolarian mudstone (MF2a) associated with bioclast-echinoderm-peloidal packstone-grainstone (MF2b)

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<th>Reef</th>
<th>MF3: Bioclast-intraclast rudstone-floastone</th>
<th>Porifera biolitithe</th>
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<td>MF3 sponge-coral-algal boundstone</td>
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<td>Sponge coral floastone</td>
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<td>Porifera-algae biolitithe</td>
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<td>Algal biolitithe</td>
<td>Coral rudstone</td>
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<td>Peloidal bioclastic packstone grainstone</td>
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**Backreef and open lagoon**

<table>
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<tr>
<th>MF5: Oncoid-calcimicro grainstone-rudstone</th>
<th>MF4 peloidal aggregate bioclastic packstone grainstone</th>
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<tr>
<td>MF5 calcimicrobial grainstone</td>
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| MF6: Peloidal-echinoderm packstone-grainstone | MF2 crinoidal algal packstone grainstone | Algal crinoid biopelsarite | MF-S2 Crinoidal algal packstone grainstone | MF-O 3 Crinoidal algal grainstone rudstone | MF-K2 Crinoidal algal clast supported microbreccia |
| MF13 peloidal bioclastic packstone grainstone | Peloidal grainstone packstone | MF-S5 Bioclastic peloidal packstone grainstone | MF-O 5 peloidal bioclastic packstone grainstone | MF-K 4 peloidal coated grains bioclastic packstone grainstone |
| MF15 oolitic coated grains packstone grainstone | MF-11 oolitic coated grains packstone grainstone |

| Lagoon | MF7: Involutinid wackestone-packstone | MF8 Megalodont floastone | foraminiferal biomicrite | MF-S7 Megalodont floastone rudstone | MF- K6 Megalodont floatstone |
| MF9 Echinoderm bioclastic wackestone packstone | MF-S8 Aulotortid bioclastic grainstone packstone | MF-K 7 Echinoderm bioclastic wackestone packstone |
| MF10 Aulotortid packstone | Aulotortid bioclastic wackestone packstone |

| MF8: Microcoprolitic mudstone | MF7 endotebid mudstone | MF-S9 Coprolitic bioclastic wackestone packstone | MF-O 7 Bioclastic mudstone wackestone |
| MF11 Coprolite bioclastic wackestone packstone | MF-S10 Molluscan burrowed wackestone |
| MF12 Molluscan burrowed wackestone | MF-K 5 Mudstone |
| MF6 mudstone | unfossiliferous limemudstone | MF-S 6 mudstone |
Chapter 5: Upper Triassic limestone of the Kii Peninsula (Honshu Island, Japan): mode of occurrence, microfacies and correlation

Abstract
Upper Triassic shallow water and reefal limestone extensively crops out in the Sambosan Accretionary Complex, Southwest Japan. In the Kii Peninsula (Honshu Island), the Sambosan Accretionary Complex is inadequately defined and Upper Triassic limestone is attributed to the broader South Chichibu belt. Former studies mainly focused on the paleontological content of the Upper Triassic limestone and microfacies have been poorly documented. To fill this gap, we carried out a microfacies analysis of Upper Triassic limestone from four localities in central and western Kii Peninsula. The biotic content is described with a special focus given to biostratigraphic markers. Our results are then compared to microfacies from other Upper Triassic limestone localities in Japan. This study refines the biostratigraphic control on the Upper Triassic limestone of the Kii Peninsula.
5.1. Introduction

In Southwest Japan, allochthonous Upper Triassic limestone units crop out in the Sambosan Accretionary Complex (SAC) which extends from the Ryukyus Islands in the South to the Kanto Mountain in the North (Fig. 5.1a). These limestone units are especially well known in Kyushu Island (Kanmera 1969; Onoue and Sano 2007; Chablais et al. 2010a) and Shikoku Island (Kobayashi 1931; Matsuoka 1992; Yamato Omine Research Group 1981; Chablais et al. 2010b; Peybernes et al. 2015). In the last decade, microfacies of the Sambosan limestone were described from outcrops in the Ryukyus Islands (Chablais 2010; Yamashita et al. in revision), Kyushu Island (Onoue and Sano 2007; Onoue and Stanley 2008; Chablais et al. 2010a), Shikoku Island (Chablais et al. 2010b; Chablais 2010 and this thesis) and the Kanto mountain in Honshu Island (Chablais 2010). Upper Triassic limestone also crops out in the Kii Peninsula (Honshu Island) but were less studied than its counterparts in other areas of the SAC (Fig. 5.1b).

Most of the previous studies concerning the Upper Triassic limestone of this region focused on geological mapping, paleontology and biostratigraphy (Yamato Omine Research Group 1976, 1979; Okuda and Yamagiwa 1978; Okuda 2006; Yao 2012; Stanley and Onoue 2015). Contrastingly, microfacies were poorly described. In this work, microfacies analysis was performed on limestone samples from four localities in the Kii Peninsula. Biotic content is also described with a special focus given to biostratigraphic markers. Results are then compared with other limestone units of the SAC and correlations based on microfacies are proposed.

5.2. Geological setting

Upper Triassic limestone crops out sporadically in the eastern part (Yura district, Wakayama prefecture) and central part (Yoshino district, Nara prefecture) of the Kii Peninsula (Fig. 5.1b). The SAC is not as much well-defined in the Kii peninsula as at Shikoku or Kyushu Islands. Here, Upper Triassic limestone and associated lithologies are usually attributed to the broader Southern Chichibu belt. Nevertheless, Yamato Omine Research Group (1976) already proposed to correlate Upper Triassic limestone blocks from the Southern Chichibu belt of the central Kii Peninsula with those from the Sambosan Group in Shikoku. In the Yura area, Matsuoka and Yao (1990) subdivided the Southern Chichibu belt into the Togano subterrane (Obiki and Yura formations) and the Sambosan subterrane (Kamiya Formation). However, it is important to point out that Upper Triassic limestone studied in this work does not occur in the Kamiya formation of the Sambosan subterrane but crops out in the Banshoyama Member of the Obiki Formation (Yao 1984, 2012). In the Kamiya Formation (Sambosan subterrane), limestone units
correspond to the Upper Jurassic-Lower Cretaceous Torinosu limestone (Kobayashi and Wernli 2013 and our own observations). Thus, according to previous works, the studied Upper Triassic limestone from the Yura area is not exactly correlative with the SAC limestone. A reason can be that in the Yura area the Southern Chichibu belt is very narrow (Yao 1984, 2012), making difficult the identification of tectonic units that are well-defined in other localities in Southwest Japan where the SAC extensively crop out.

5.3. Studied localities

In April 2013, four localities where Upper Triassic shallow water and reefal limestone crops out in the Kii Peninsula were investigated: Loc. 1 Wasabidani, Loc. 2 Daifugendake, Loc. 3 Osaka Dam and Loc. 4 Yura.

Loc. 1 Wasabidani (Fig. 5.1c; Samples CP151-156, 34°13'54.98"N, 135°58'39.79"E; Samples CP159-160, 34°14'11.57"N, 135°58'43.26"E).

Loc. 1 Wasabidani is situated in a small valley, 1.5 kilometer north east of Daifugen summit. Limestone occurs here as limestone clasts in breccia (mode of occurrence MO1) and as recrystallized massive limestone slabs (mode of occurrence MO2). The breccia (MO1) is clasts supported, well lithified and composed of grey limestone clasts and well preserved, basaltic clasts (Fig. 5.2a). Clasts are a few centimeters to a few decimeters in size. Only scarce volcaniclastic matrix (VCM), is present between the clasts. Upper Triassic corals and Permian fusulinids have been reported in this area by Yamato Omine Research Group (1976) Okuda and Yamagiwa (1978) and Okuda (2006), along with undetermined calcareous algae, spongiomorphids and stromatoporoids. Coral fauna have been revised by Okuda (2006) and Stanley and Onoue (2015). Our samples were collected approximately at Loc. 1 and Loc. 2 of Okuda and Yamagiwa (1978) and Loc. 2, 3 and 4 of Okuda (2006).

Loc. 2 Daifugendake (Fig. 5.1c; Samples CP146-148; 34°13'5.91"N, 135°59'13.29"E).

Samples have been collected from massive limestone slabs (mode of occurrence MO1) that crop out on a mountain crest, 2.5 kilometers south east of Daifugen summit. Limestone slabs are associated with siliceous mudstone (i.e., rocks composed radiolarians disseminated in the matrix of clay minerals and microcrystalline quartz, following the definition in Onoue and Sano 2007). This area has been mapped by the Yamato Omine Research Group (1976).
Fig. 5.1 Location maps. a Location of the Southern Chichibu belt (including the Sambosan Accretionary Complex) in Southwest Japan; black rectangle indicates the Kii Peninsula (Fig. 1b). b Location of South Chichibu belt in the Kii Peninsula; rectangles indicate the location of the studied area presented in Fig. 1 c, d, e respectively. c Daifugendake area. d Osako dam area. e Yura area.
Chapter 5: Microfacies of the Upper Triassic limestone of the Kii Peninsula

Loc. 3 Osako Dam (Fig. 5.1d; Sample CP161, 34°16'31.40"N, 136° 0'26.91"E; Sample CP162, 34°16'50.15"N 136° 0'11.73"E).
The first (CP161) of the two samples collected in the Osako dam area has been recovered from a massive limestone slab along the road 169, near the entrance of a tunnel (Fig. 5.2b). The second (CP162) has been collected in a cave carved in a massive limestone slab. Both correspond to mode of occurrence MO2. Osako Dam area have been mapped by the Yamato Omine Research Group (1979).

Loc. 4 Yura (Fig. 5.1e; Samples CP169-170, 33°58'29.84"N, 135° 4'34.97"E).
Limestone clasts (sample CP169) have been collected from limestone-cret-basalt breccia (mode of occurrence MO3) that outcrops along the road between Tatego and Shirasaki (stop 6b in Yao 2012). Limestone clasts are a few centimeters to a few decimeters in size and are associated with angular red chert clast and vesicular basaltic clasts (Fig. 5.2c). This breccia is associated with plurimetric limestone blocks (CP170), bedded cherts, sandstone and mudstone units. According to Yao (1984), the investigated limestone belong to the Banshoyama member of the Obiki formation.

**Fig. 5.2** Mode of occurrence (MO) of Upper Triassic limestone in the Kii Peninsula. a MO1: limestone clasts (L) and basaltic clasts (B) in clast-supported breccia Loc. 1 Wasabidani. b MO2: massive limestone slab (L) in fault contact with siliceous mudstone (M) Loc. 3 Osako dam. c MO3 Limestone (L) and chert (C) clasts in clast-supported polymict breccia (basalt clasts sometimes also occur). Loc. 4 Yura area
5.4. Results

Microfacies description

Loc. 1 Wasabidani
In this study, only limestone clasts considered to be Upper Triassic in age are described in details. Paleozoic (Carboniferous-Permian?) limestone, composed of microproblematica-boundstone, has been collected at Loc. 1 Wasabidani but are not described in this study.

MF1 peloid extracast bioclast grainstone (CP152, 154, 156 160GL) (Fig. 5.3b). Well-sorted grainstone with abundant peloids, echinoderms and recrystallized shell fragments. Small angular volcanic clasts are frequent. Foraminifer association includes *Ammobaculites/Reophax*? and small porcelaneous foraminifers (Fig. 5.3g). Ooids are rare. The microproblematica *Plexoramea cereriformis* has been recognized.

MF2 bioclast ooid grainstone-rudstone (CP153) (Fig. 5.4a). This microfacies is composed of well sorted coarse grains. Ooids and coated grains are abundant. Ooid nuclei are sometimes volcanic grains. Recrystallized, rounded shells and echinoderms fragments are frequent. Minor components are peloids and solenoporacean fragments. Intraclasts of boundstone constituted of encrusting organisms occasionally occur. Isopachous cements are preserved around the grains, indicating early submarine cementation.

MF3 Sponge-microproblematica boundstone (CP153-154-156-157-159) (Fig. 5.3c, d). Recrystallized sponges, acting as framebuilders, and encrusted by sessile organisms and microbial crusts compose this microfacies. The surrounding sediment consists of peloidal and clotted micrite and peloid-ooid grainstone. The microproblematica *Plexoramea gracilis, Radiomura cautica* and *Plexoramea cerebriformis* are present.

Loc. 2 Daifugendake

MF4 Recrystallized reef limestone (CP146-148). Grey massive limestone slabs at Loc. 2 Daifugendake are highly fractured and strongly recrystallized. This limestone contains peloids, small micritic foraminifers, echinoderms,
Chapter 5: Microfacies of the Upper Triassic limestone of the Kii Peninsula

gastropods and other undetermined bioclasts. Recrystallized sponges (spongiomorphids and chaetetids) locally occur, along with the microproblematica Tubiphytes sp. (Fig. 5.3f), Baccanella floriformis (Fig. 5.3e) and potentially Radiomura cautica. This biotic association clearly indicates a reef limestone even if boundstone facies is not recognizable because of the strong recrystallization.

Loc. 3 Osaka Dam

MF4 Recrystallised reef limestone (CP162).

This sample is very recrystallized and fractured. Nevertheless, large bioclasts (sponges?) and encrusting organisms are visible. This sample is therefore tentatively attributed to MF4. A micritic matrix occurs locally.

MF5 Involutinid wackestone (CP161) (Fig.5.3a).

Abundant, recrystallized involutinid foraminifers, evenly distributed in a dark micritic matrix, characterize this microfacies. Subordinate components are echinoderms and tiny bioclasts.

Loc. 4 Yura

MF6 Intraclast-bioclast floastone-rudstone (CP169-170) (Fig. 5.4b).

This microfacies is characterized by large, reefal intraclasts and recrystallized bioclasts such as sponge fragments, solenoporacean algae, corals, crinoids and undetermined shell fragments. The matrix is composed of bioclastic wackestone-packstone. Bioclasts in the matrix are small foraminifers and filaments (thin shelled bivalves, Fig. 5.4.c). In the intraclasts, Austrocolomia sp.? (Fig. 5.4d), Galeanella sp. (Fig. 5.4f), Uvanella sp., Baccanella floriformis have been determined. Some samples are heavily silicified (e.g., CP170), probably due to the abundant chert clasts in the breccia and surrounding siliceous rocks.

Microfacies interpretation and comparison with SAC limestone

Upper Triassic shallow water and reefal limestone of the SAC, and more broadly of the Southern Chichibu belt, has been considered as atoll-type shallow water carbonates, deposited at the top of panthalassic seamount(s) (Kanmera 1969; Tamura 1992; Onoue and Sano 2007; Chablais et al. 2010a). Depositional setting corresponding to the microfacies found in the Kii Peninsula are interpreted in this conceptual frame.
Chapter 5: Microfacies of the Upper Triassic limestone of the Kii Peninsula
Fig. 5.3 Microfacies (MF) of Upper Triassic limestone in the Kii Peninsula. a MF5 Involutinid wackestone including recrystallized involutinids (i) and echinoderms (e); CP161. b MF1 peloid extraclast bioclast grainstone including Plexoramea cerebriformis (Pc) note the abundant basaltic grains and volcanic shards (white arrows); CP152. c MF3 Sponge-microproblematica boundstone including recrystallized sponges (s), encrusting organism (eo) embedded in microbial crust (mc), and peloid-ooid grainstone infilling; CP154. d MF3 Sponge-microproblematica boundstone including recrystallized sponges (S), Plexoramea gracilis (Pg) and microbial crusts (mc); CP159. e-f reef fauna of MF4 e Baccanella floriformis (Bf) and indeterminate foraminifer (fo); CP146. f Tubiphytes sp.; CP148. g Porcelaneous foraminifer Arenoidalina sp. ?; CP156.

MF1 is interpreted as a shallow water deposit of open marine platform interior and platform margin. MF2 may represent a coarser counterpart of MF1. The presence of volcanic grains in MF1 and MF2 suggests that the volcanic basement was exhumed during their deposition. Similar microfacies are reported from Okinawa, Kyushu and Shikoku Islands but, there volcanic grains are generally absent.

MF3 correspond to reef limestone probably deposited at the platform margin or as patch reefs in the platform interior. MF4 is interpreted as recrystallized reef limestone and is probably equivalent to MF3 but the bad preservation prevent to confirm this statement. Reef limestone from central Kii Peninsula resembles some Upper Triassic reef limestones from Shikoku Island. Plexoramea gracilis and Plexoramea cerebriformis are common in Ladinian–Lower Carnian reef of Shikoku (Peybernes et al. 2015). Peloid-ooid grainstone, occurring as interstitial sediment between the framebuilders, is present in Norian-Rhaetian reefs of Shikoku, especially at Mt. Sambosan and at Inaba cave (Chablais et al. 2010).

Recrystallized involutinid foraminifers and abundance of micritic matrix in MF5 indicate deposition in protected part of the lagoon (Martini et al. 1997; Chablais et al. 2010a). Such lagoonal limestone are very common in other SAC localities (Onoue and Sano 2007; Chablais et al. 2010a; Chablais 2010; Chapter 4).

Finally, MF6 is interpreted as fore-reef deposit. Reef intraclasts and bioclasts probably derived from the platform edge and were transported into a low energy, muddy environment, possibly on the upper slope, below fair weather wave base. Filaments, which are pelagic/open marine organisms (Reijmer et al. 1991; Chablais et al. 2010; Gale et al. 2014), are found in the matrix and confirm the deposition in deep water setting. This microfacies has also been reported from Shikoku Island (Chapter 4).
Chapter 5: Microfacies of the Upper Triassic limestone of the Kii Peninsula
Fig. 5.4 Microfacies (MF) of Upper Triassic limestone in the Kii Peninsula. a Limestone and basalt (BC) clasts; Left part: MF2 bioclast ooid grainstone-rudstone including solenoporaean algae fragments (a) and reef intraclast (ri) note the basaltic nucleus (bn) of some ooids. Right part: MF3 Sponge-microproblematica boundstone including recrystallized framebuilder (f) encrusting organisms (eo) and Radiomura cautica (Rc); CP153. b MF6 intraclast-bioclast floastone-rudstone including reefal intraclast (in) and recrystallized bioclast (rb) set in dense micritic matrix (dm); note the presence of Uvanella-like encrusters in reef intraclast (black arrow); CP169. c Close up view of the dense micritic matrix showing the presence of filaments (white arrows) that indicate an open marine to pelagic depositional setting; CP169C. d-f Microfauna of MF6; d Austrocolomia sp. ?; CP169A; e Porcelaneous foraminifer; CP169C; f Galeanella sp.; CP169.

5.5. Discussion

Biostratigraphy

Biostratigraphy of the Upper Triassic limestone of the Southern Chichibu belt in the Kii Peninsula is mainly based on conodont and scleractinian corals occurrences. Okuda and Yamagiwa (1978), Okuda (2006) and Stanley and Onoue (2015) described Carnian corals from Loc. 1 Wasabidani. Carnian to Norian conodonts (Epigondolella nodosa, Epigondolella abnetis and Epigondolella postera) have been reported from white limestone blocks in the same locality by Okuda (2006). The Yamato Omine Research Group (1979) also reported Upper Triassic conodonts from limestone units in the Osako Dam area. In the Yura area, Yao (1984) mentioned the occurrence of the Upper Triassic conodont Epigondolella sp. in limestone blocks near our Loc. 4. This author also noted the occurrence of Jurassic corals (Thamnasteria sp. and Polyphylloseris sp.) and stromatoporoids (Actinostromaria sp. and Stromatopora sp.) in limestone clasts embedded in the limestone-chert breccia of Loc. 4 Yura. However, the coral specimens are not illustrated and thus the determination remains not confirmed because we did not found Jurassic limestone in the same outcrop. Reexamination of the original material of Yao (1984) would be necessary to confirm determination and dating of these specimens.

Biotic content of our samples includes several biostratigraphic markers allowing us to refine the dating of the described microfacies (Fig. 5.5). Occurrence of Plexoramea cereriformis in MF1 suggests a Ladinian–Carnian age. In the same way, co-occurrence of Plexoramea cereriformis and Plexoramea gracilis indicates a Ladinian–Carnian age for MF3 (Senowbari-Daryan 2013). No age diagnostic taxa have been found in MF2. As a consequence, the possibility that MF2 is Paleozoic in age cannot be totally excluded. MF4 contains Tubiphytes sp. which is found almost exclusively in Ladinian?–Lower Carnian reef limestone in other part of the SAC (Chapter 3). Involutinid wackestone (MF5) is a very common microfacies in Carnian to Rhaetian carbonate platforms of Tethys and Panthalassa Oceans (e.g., Gazdzicki
1983; Kiessling and Flügel 2000; Chablais et al. 2010a). The occurrence of the foraminifer Galeanella sp. in MF6 indicates a Norian-Rhaetian age for the intraclasts (Zaninetti et al. 1992; Hardenbol et al. 1998; Bernecker 2005), constraining the age of deposition of this floatstone-rudstone to the post-Norian. Nonetheless, no biostratigraphic markers have been found in the micritic matrix, precluding more precise dating.

Fig. 5.5 Stratigraphic framework of the microfacies of the Upper Triassic limestone in the Kii Peninsula.

**Co-occurrence of Paleozoic and Upper Triassic limestone**

At Loc. 1 Wasabidani, Paleozoic (Carboniferous?-Permian) limestone clasts also occur in the breccia (MO1) from which the Upper Triassic limestone clasts studied here were collected.

In the Yura area, the geological frame is more complex. Upper Triassic limestone crops out in close vicinity to both the huge Upper Carboniferous-Middle Permian limestone body of Shirasaki, located few hundreds of meters to the north (Yao 1984) and to Upper Jurassic-Lower Cretaceous Torinosu limestone units of the Kamiya Formation (Kobayashi and Wernli 2013) few kilometers to the South. Importantly, in other regions, where the Southern Chichibu belt is wider (i.e., Shikoku and Kyushu) Paleozoic and Triassic limestones rarely occur together in the same locality. Exceptions are in the Kumagawa area at Kyushu Island (Kobayashi 2007) and at Wajiki locality (Shikoku Island; Chapter 7). In the Kanto Mountains, Permian limestone and Jurassic Torinosu limestone, associated with the Upper Triassic one, are reported from the Gozenyama Formation which is to be considered equivalent to the SAC (Chablais 2010).
Additionally, it is worth noting that usually the Torinosu limestone occur preferentially in the north of the accretionary complex whereas the contrary is observed in Yura area.

**Comparisons with other localities**

According to our results, microfacies diversity is lower in the Upper Triassic limestone of the Kii Peninsula than in other part of the SAC. All microfacies can be attributed to shallow water carbonates deposited at the platform margin and in the platform interior. They correlate to microfacies already observed in other areas of the SAC, especially at Shikoku Island. Radiolarian-filament wackestone, a microfacies interpreted as basinal/pelagic limestone and common to abundant in other parts of the SAC, has not been found in the Kii Peninsula during this study. Additional sampling may change this view.

**5.6. Conclusion**

Our field investigations and microfacies analysis of the Upper Triassic shallow water and reefal limestone of the Southern Chichibu belt in the Kii Peninsula lead us to:

- Describe six microfacies that are analogous to microfacies described in various localities of the Sambosan Accretionary Complex.
- Refine the biostratigraphy of these microfacies, using age-diagnostic foraminifers and microproblematica.
- Highlight the peculiarities of Upper Triassic limestone distribution in the Southern Chichibu belt of the Kii Peninsula. In particular, the close occurrence of Paleozoic, Triassic and occasionally Jurassic limestone (Torinosu limestone) makes difficult the thorough recognition of the Sambosan Accretionary Complex in the Kii Peninsula and its strict correlation with counterparts at Shikoku and Kyushu Islands.

In summary, this study further documents the microfacies and micropaleontological inventory of the Upper Triassic limestone of the Kii Peninsula, which is demonstrated being correlative to the SAC limestone, and provide additional biostratigraphic constrains to the evolution of the shallow water and reefal environments in the West Panthalassa during the Late Triassic.

**References**

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Chapter 5: Microfacies of the Upper Triassic limestone of the Kii Peninsula
Chapter 6: Rhaetian or Lower Jurassic? foraminifer association from a limestone clast of the Sambosan Accretionary Complex (Shikoku, Japan) and its implication in the evolution of panthalassic seamounts.

Abstract
Upper Triassic mid-oceanic shallow water limestone outcrops from the Sambosan Accretionary Complex (Southwest Japan) are well-known and have been studied for decades especially at Kyushu and Shikoku Islands. However, an enigmatic foraminifer association has been recently found in a limestone clast at the Mt. Sambosan type locality (Shikoku Island). The association includes *Tethysiella pilleri*, *Coronipora* sp., *Spirillina* sp. and *Involutina* sp. and occurs in a dense micritic matrix that is interpreted as fissure filling sediment. The foraminifers have a close affinity with some Lower Jurassic assemblages of the Tethys Ocean. Carbonate sedimentation at the top of the panthalassic mid-oceanic seamounts cropping out in the Sambosan Accretionary Complex took place during the Late Triassic and, according to this study, probably lasted until the Early Jurassic.
6.1. Introduction

Upper Triassic mid-oceanic shallow water limestone crops out in the Sambosan Accretionary Complex (SAC) in Southwest Japan (Fig. 6.1a). The Sambosan limestone represents an important sedimentary record of the shallow water environmental conditions in the Panthalassa Ocean during the Late Triassic. Until now, except some rare occurrences of Paleozoic taxa (Kurata 1940; Kobayashi 2007; Chapter 7), foraminifer assemblages reported from the Sambosan limestone have been attributed to the Middle? to Late Triassic (Chablais et al. 2011; Peybernes et al. 2015). However, an enigmatic foraminifer association that questioned this stratigraphic range has recently been found at the Mt. Sambosan type locality (Shikoku Island, Fig. 6.1b). In this work, we illustrate this association and discuss its biostratigraphic implications. The limestone microfacies containing this foraminifer assemblage is described in detail and hypotheses regarding the depositional setting are proposed.

6.2. Geological setting

The SAC is an Upper Jurassic–Lower Cretaceous subduction-generated accretionary complex (Onoue and Sano 2007) that crops out extensively at Shikoku Island (Fig. 6.1a, b). At Mt. Sambosan type locality, limestone crops out along the Ruygado skyline, below the castle, as massive limestone slabs and as limestone clasts embedded in a volcaniclastic matrix (VCM) (Fig. 6.1d–e). This locality was first described by Kobayashi (1931) and is considered as the type locality of the Sambosan limestone (Yamato Omine Research Group 1981). Upper Triassic limestone in this area has been intensively studied since the original description (Kobayashi 1931; Yamato Omine Research Group 1981; Okuda et al. 2005; Chablais 2010; Stanley and Onoue 2015; Peybernes et al. 2015; Chapter 2). The massive limestone slab is attributed to the Late Carnian to Norian-Rhaetian based on conodonts and reef biotic association (Yamato Omine Research Group 1981; Okuda et al. 2005; Chapter 3). The reef limestone clasts in the volcaniclastic matrix (thereafter referred to as VCM breccia) have been attributed to the Ladinian?–Early Carnian based on the biotic association (Peybernes et al. 2015; Chapter 2). Limestone clasts of other microfacies (i.e., peloid-echinoderm grainstone; bioclastic-intraclast floatstone-rudstone; see Chapter 4) range from the Carnian to the Norian-Rhaetian (Chapter 4).


**Fig. 6.1** Location maps and outcrop view. **a** Location of the Sambosan Accretionary Complex (SAC) in South West Japan. **b** Studied locality of the SAC at Shikoku Island. **c** Studied locality in Mt. Sambosan area. **d** Outcrop view of Mt. Sambosan type locality; the studied sample was found as clast embedded in a breccia with volcaniclastic matrix (VCM) on the right of the picture. **e** Close-up view of the VCM breccia with limestone clasts (LC) embedded in volcaniclastic matrix (VCM).

### 6.3. Material and Methods

The studied sample (CP28) has been recovered from the VCM breccia at the Sambosan type locality (Fig. 6.1d–e). Four thin sections (2.3 × 3.5 cm) have been prepared (Fig. 6.2, 6.3), scanned with a high-resolution film scanner (Nikon CoolScan 4000 ED) and observed in transmitted light with an optical microscope. Cathodoluminescence using a Cl8200 MK5-
optical cathodoluminescence with a cold cathode was used on one thin section to reveal specific sedimentological features and foraminifer morphological characteristics that are concealed in transmitted light. We used beam conditions of 15 kV at 50–60 mA with an unfocused beam of approximately 1 cm. The observation chamber had a residual pressure of 80 mTorr. The sample was not coated. The thin-section was photographed in a dark room with a digital camera: with a normal exposure for natural light and with a long exposure under cathodoluminescence. The parameters were kept fixed to avoid additional treatment. Neither filters nor standards were used for image calibration.

6.4. Microfacies

The sample is composed of limestone clasts that are embedded in a matrix composed of volcaniclastic material (i.e., hyaloclastite, vesicular volcanic glass shards) and tiny limestone and basaltic grains (Fig. 6.2). The studied thin sections are centered on the limestone clast that contains the foraminifer association of interest (Fig. 6.2, 6.3). It is surrounded by numerous other limestone clasts that primarily correspond to microproblematica boundstone with *Baccanella floriformis*, *Radiomura cautica*, *Terebella* sp., *Celyphia*-like organisms (sponges?) and encrusting foraminifers (*Planiinvoluta* sp.). One of these clasts is best described as peloid-echinoderm-bioclast packstone (Fig. 6.2). The central limestone clast is composed of a bioconstructed part that is similar to the aforementioned microproblematica boundstone. In addition to this bioconstructed part, approximately 2/3 of the clast corresponds to a wackestone composed of tiny bioclasts, ostracods, microproblematica and shell fragments embedded in dense micrite. The foraminifer association of interest occurs in this dense micrite. Several smaller lithoclasts of microproblematica boundstone are also set in the micritic matrix. Contacts with the ostracod-bioclast-lithoclast wackestone are sharp and some grains of the microproblematica boundstone appear truncated. Careful observation of the sharp contact between the microproblematica boundstone and the ostracod-bioclast-lithoclast wackestone revealed that sessile organisms (serpulids?) have encrusted the surface of the microproblematica boundstone (Fig. 6.3c, g–h). The microproblematica boundstone surface is very irregular and exhibits several ‘cavities’ and depressions filled by the ostracod-bioclast-lithoclast wackestone. *Lenticulina* sp. occurs in the dense micrite that filled one of these cavities (Fig. 6.3e–f). One of the reef lithoclasts in the ostracod-bioclast-lithoclast wackestone is mainly composed of a calcareous sponge skeleton that is filled by dense micrite and includes *Involutina* sp. (Fig. 6.3i–j). This observation highlights that the sponge chambers were not filled by cement.
or matrix before the deposition of the ostracod-bioclast-lithoclast wackestone. Therefore, the microproblematica boundstone did not experience a strong diagenesis prior to the deposition of the ostracod-bioclast-lithoclast wackestone and was probably formed only slightly before.

![Thin section of the VCM breccia (a) and corresponding microfacies analysis (b)](image)

**Fig. 6.2** Thin section of the VCM breccia (a) and corresponding microfacies analysis (b)

### 6.5. Foraminifer association

The foraminifer association of interest is composed of small recrystallized specimens that are tentatively attributed to *Tethysiella pilleri* Blau 1987a (Fig. 6.4a–f), *Coronipora* sp. (Fig. 6.4n–o), *Involutina* sp. (Fig. 6.4g), *Turrispirillina* sp. (Fig. 6.4h–i) *Spirillina* sp. (Fig. 6.4j–m) and an indeterminate Involutinid (Fig. 6.4p). All these taxa are reported for the first time from the SAC.
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Fig. 6.3 Microfacies. a, d, i Scanned thin sections of the investigated sample. b–c Close-up views of thin section (a), showing the sharp contact (red line) between the microproblematica boundstone (mb) and the ostracod-bioclust-lithoclast wackestone (fw) and an indetermined organism (serpulid?) (arrow) that encrusted the microproblematica boundstone (mb). e–h Close-up views of thin section (d), e–f Lenticulina sp. in the ostracod-bioclust-lithoclast wackestone, g–h sessile foraminifer encrusting the microproblematica boundstone: micritic matrix of the ostracod-bioclust-lithoclast wackestone appears light orange in cathodoluminescence (f, h). j Close-up view of thin section (i), displaying reef lithoclast in the ostracod-bioclust lithoclast wackestone, note that the micritic matrix that fills the calcareous sponge skeleton contains Lower Jurassic? foraminifers (arrow).
**Tethysiella pilleri** (Blau 1987a) (Fig. 6.4a–f)

Description: small monocristalline high trochospiral tubular test.

Stratigraphic and geographic distribution: *Tethysiella pilleri* (formerly named *Praepatellina pilleri* Blau 1987a) is known from Liassic fissure infilling at the top of Upper Rhaetian limestone in Austria (Blau 1987a) and from Lower Liassic neptunian dykes in Hungary (Blau and Haas 1991). *T. pilleri* is also reported from the Bajocian of the Jura Mountain (Piuz 2004, 2008). Roniewicz et al. (2007) mentioned (but did not illustrate) *T. pilleri* in micritic floatstone facies of the early Norian Dachstein limestone from Austria.

**Spirillina** sp. (Fig. 6.4j–m)

Description: small monocristalline planispiral tubular test.

Remarks: Our specimens show strong similarities with *Spirillina? iranica* (Senowbari-Daryan et al. 2010) and *Spirillina truncata* (He 1990) but are smaller.

Stratigraphic and geographic distribution: *Spirillina* is known from the Rhaetian to Holocene (Loeblich and Tappan 1988). Similar small *Spirillina* sp. is reported from the Liassic of Austria by Blau (1987b). Our specimens are also very similar to those reported by Piuz (2004, 2008) from the Bajocian of the Jura Mountain and by Altiner (1991) from the Kimmeridgian–Valanginian of Turkey. In the Triassic *Spirillina* is known from the Rhaetian? of Iran (Senowbari-Daryan et al. 2010), Norian of China (He 1990) and Norian of Austria (Wurm 1982).

**?Turrispirillina** sp. (Fig. 6.4h–i)

Description: small monocristalline low trochospiral tubular test.

Remarks: Piuz (2004) attributed very similar specimens to the genus *Tethysiella*. Thus, our specimen could be alternatively attributed to *Tethysiella* sp.

Stratigraphic and geographic distribution: *Turrispirillina* is common in Upper Triassic (e.g., Wurm 1982; Senowbari-Daryan et al. 1982; Ruffer and Zamparelli 1997; Senowbari-Daryan et al. 2010) and Lower Jurassic limestone of the Tethys (e.g., Blau 1987a).
Fig. 6.4 Foraminifer association in the wackestone micritic matrix. a–f Tethysiella pilleri. g Involutina sp. h–i ? Turrispirillina sp. j–m Spirillina sp. n–o Coronipora sp. p Involutinid gen. and sp. ind. b, d, f, i, k, m: views in cross-polarized light showing the monocrystalline character of the test.
Coronipora sp. (Fig. 6.4n–o)
Description: planispiral test, involute on the umbilical side and ridge-like erected lamellae on the spiral side; wall hyaline.
Remarks: Our specimen is more similar to Coronipora etrusca (e.g., Blau 1987a, b; Blau and Haas 1991) than to Coronipora austriaca (Blau 1987b; Blau and Haas 1991; Böhm et al. 1999). Alternatively, this specimen could be attributed to Coronaserra which differs from Coronipora by the poor extension of its umbilical-side lamellae (Rigaud et al. 2013).
Stratigraphic and geographic distribution: Norian–Rhaetian and Early Jurassic of Tethys (Rigaud et al. 2013). Coronipora austriaca and Coronipora etrusca occur in Liassic fissure infilling of Austria and Hungary (Blau 1987a, b; Blau and Haas 1991; Velledits and Blau 2003). Coronipora etrusca have also been reported from the Rhaetian? of Iran (Senowbari-Daryan et al. 2010). Coronipora yushuensis occurs in the Norian of China (He 1990).

Involutina sp. (Fig. 6.4g)
Description: planispiral hyaline tubular test.
Remarks: Similar specimens are shown by Rigaud et al. (2015, fig. 2 H, I).
Stratigraphic and geographic distribution: Rhaetian to Early-Middle Jurassic of Tethys (Rigaud et al. 2015). Involutina is particularly abundant in Early Jurassic deposits on the top of drowned Triassic Tethyan carbonate platforms (Blau 1987b; Böhm et al. 1999; Rigaud et al. 2015).

Involutinid gen. sp. indet. (Fig. 6.4p)
Description: planispiral hyaline evolute tubular test; wall very thin; no lamellae. Lumen of the undivided tubular chamber rapidly increases in diameter.

6.6. Discussion

Biostratigraphy
The microproblematica boundstone facies, occurring either as limestone clasts in the VCM or as lithoclasts embedded in the ostracod-bioclast-lithoclast wackestone (Fig. 6.2), is very similar to the boundstone facies of the intensively studied Upper Triassic reef limestone of Mt. Sambosan type locality. Therefore, despite the absence of age-diagnostic fossils, this microfacies is attributed to the Late Triassic. On the other hand, the ostracod-bioclast-lithoclast
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wackestone contains foraminifers that are potentially younger than the microproblematica boundstone. As demonstrated by the foraminifer stratigraphic distributions (see section above), the foraminifer association has many taxa in common with some Lower Jurassic assemblages of the Tethys. In particular, the studied foraminifers show strong similarities with assemblages found in the Liassic red material that filled fissures opened in the Upper Rhaetian limestone (Oberrhätlimestones) of Austria (Blau 1987a, b). Similar assemblages also occur in a potentially Rhaetian section of the Nayband formation, Iran (Senowbari-Daryan et al. 2010) and in Hettangian–Sinemurian limestone of Hungary (Blau and Haas 1991). All the identified taxa are known from Upper Triassic limestone but they occur predominantly in the Lower Jurassic of Tethys. In their synthesis of foraminifer fauna from the SAC, Chablais et al. (2011) did not mentioned any Lower Jurassic foraminifer associations. Therefore, if the determinations and stratigraphic attribution of Tethysiella pilleri, Involutina sp., Spirillina sp. and Coronipora sp. to the Early Jurassic are correct, the described material represents the first mention of post-Rhaetian fauna in the Sambosan limestone. Nevertheless, the occurrences reported from Upper Triassic rocks of Western Tethys suggest that these taxa were already present in the Norian-Rhaetian. Additionally, due to their small size and the commonly recrystallized tests, these small Spirillinids and Involutinids have probably been often underestimated in former Triassic studies. Therefore, even if this association is unusual in Upper Triassic rocks, attribution of our material to the Early Jurassic remains uncertain. In the current state of our knowledge concerning the stratigraphic range of these small foraminifers it is too early to firmly exclude an Upper Triassic age for this assemblage. Reexamination of original Upper Triassic material from the Tethys (e.g., Wurm 1982; Roniewicz et al. 2007) and comparison with Japanese samples is needed to confirm the stratigraphic range of these foraminifer associations.

Hypotheses on the depositional setting

The depositional setting of the ostracod-bioclast-lithoclast wackestone containing the Rhaetian? or Lower Jurassic? foraminifers could be inferred from the microfacies analysis and the biostratigraphy discussed above. The ostracod-bioclast-lithoclast wackestone could be interpreted as sediment that filled fissures opened in the older microproblematica boundstone, possibly in relation with extensional stress. The sharp contact between the microproblematica boundstone and the ostracod-bioclast-lithoclast wackestone indicates that the former was already lithified during the deposition of the latter. Additionally, the sessile organisms encrusted at its surface indicate that the microproblematica boundstone was the host rock in which the ostracod-bioclast-lithoclast wackestone deposited. Furthermore, the irregular wavy boundary
between the two microfacies is interpreted as the result of submarine dissolution processes (Flügel 2004). Reef lithoclasts correspond to host rock reworked fragments eroded from fissure walls. This is a common feature in neptunian dykes (Flügel 2004). The described Rhaetian? or Lower Jurassic? foraminifer association is also consistent with this interpretation. As mentioned above, similar foraminifer assemblages typically occur in Liassic fissure infilling and neptunian dykes in the western Tethys realm (Blau 1987a; Blau and Haas 1991; Velledits and Blau 2003). An alternative interpretation, would be that the microproblematica boundstone was not the host rock but represents large lithoclasts set in the ostracod-bioclast-lithoclast wackestone. Following this interpretation, the lithoclasts may represent the reworking of older reef debris into a deeper, low energy environment. This interpretation is equivalent to that of MF3 Bioclast-intraclast rudstone-floatstone which is a common microfacies at Shikoku Island (see chapter 4). However, careful observation of the biotic content of the MF3 matrix in 28 thin sections from Mt. Sambosan type locality and other localities of the SAC has not revealed any of the foraminifer taxa described above or other Rhaetian–Lower Jurassic indicators. Moreover, the composition of MF3 is much more heterogenous (MF3 typically includes calcimicrobes, large bioclasts, oncoids and diverse foraminifer fauna). In Tethys, similar reworked elements (i.e., lithoclasts, echinoderms, ostracods and microproblematica) embedded in micritic matrix and associated with small Involutinids and Spirillinids are described in transgressive facies of the Dachstein limestone (Roniewicz et al. 2007). Additional microfacies analyses on new samples is needed to determine whether the observed texture results from fissure infilling or other processes (e.g., karstification, marine dissolution, or reworking).

In summary, the studied sample could be interpreted as an Upper Triassic reef limestone (microproblematica boundstone) that was dissected by neptunian dykes or dissolution cavities filled with younger marine sediment (ostracod-bioclast-lithoclast wackestone). The filling sediment includes a foraminifer association potentially of Rhaetian or Lower Jurassic age. This fissure filling likely represents the last carbonate deposit recorded in the SAC limestone. Later, clasts of this composite limestone were reworked into a volcaniclastic matrix (VCM), probably in the Jurassic during seamount collapse events (Onoue and Stanley 2008; Chablais et al. 2010; Chapter 4 and 7).

6.7. Conclusion

Until now, only Middle?–Upper Triassic (mainly Carnian–Norian) biota have been reported from the Mt. Sambosan type locality. In this work, we report an enigmatic foraminifer
association with Rhaetian? or Lower Jurassic? affinity. This assemblage occurs in ostracod-biocl ast-lithoclast wackestone interpreted as neptunian dyke or dissolution cavity infilling. However, other explanations (i.e., reworking of reefal lithoclasts in deeper, low energy sedimentary environments) is not completely excluded. This discovery suggests that carbonate sedimentation lasted until the Rhaetian and potentially until the Early Jurassic at the top of the panthalassic seamounts that crop out in the Sambosan Accretionary Complex. However, small Spirillinit and Involutinit occurrences in Triassic rocks remain poorly documented and need more in-depth studies to improve our knowledge of their stratigraphic distribution. Therefore, reexamination of existing material and further sampling, both in Tethys and Panthalassa domains, are needed to confirm our results.

References


He Y (1990) Devonian-Triassic stratigraphy and palaeontology from Yushu region of Qinchai, China.


Chapter 6: Rhaetian or Lower Jurassic? foraminifer association from a limestone clast
Chapter 7: Origin of the breccias from the Sambosan Accretionary Complex (Southwest Japan): insights from the lithologic composition and field observations

Abstract

Chaotic assemblages of various oceanic rocks such as shallow and deep water limestone, seamount basalts, bedded cherts and siliceous mudstones and sandstones are characteristic of accretionary complexes. Larger units of these chaotic assemblages are typically considered as tectonically disrupted remains of Ocean Plate Stratigraphy. However, smaller fragments of these oceanic rocks also occur in breccias that lack evidence of tectonic mixing. In this work, we describe the composition and mode of occurrence of the breccias that crop out in the Sambosan Accretionary Complex (Southwest Japan) and discuss the processes that potentially led to their formation. Two main types of breccia are defined. The breccia type B1 is composed of limestone and basaltic clasts set in a volcaniclastic matrix whereas the breccia type B2, is composed of limestone, chert, basalt and siliceous mudstone clasts embedded in a siliceous mudstone matrix. These two types of breccia are interpreted as the result of two phases of panthalassic seamount collapses in the open ocean setting.
7.1. Introduction

In Southwest Japan, Jurassic–Early Cretaceous accretionary complexes (i.e., Mino-Tamba Accretionary Complex and Chichibu Accretionary Complex) are characterized by the chaotic occurrence of various lithologies such as OIB basalts, deep and shallow water limestone, bedded cherts, siliceous mudstones and sandstones (e.g., Sano 1988a, b, 1989a, b; Matsuoka 1992; Onoue and Sano 2007). The original succession of these oceanic lithologies is usually reconstructed according to the Ocean Plate Stratigraphy model (Isozaki et al. 1990; Wakita and Metcalfe 2005; Kusky et al. 2013; Safonova et al. 2015). Accordingly, these units are interpreted as intra-plate seamount basalts, atoll-type carbonates, sea floor sediments, and trench-fill sediments, respectively. In accretionary complexes, these lithologies typically occur as chaotically mingled blocks of various size that are referred to as mélange (i.e., block-in-matrix assemblages that are mappable; Raymond 1984; Wakita 1988, 2012). The tectonic mixing of larger units (i.e., slabs that are a few tens of meters to kilometers in size) during their accretion is often well recognizable (e.g., Wakita 2012). Conversely, origin of mixing of smaller units (i.e., clasts that are a few centimeters to a few meters in size) is more challenging, and has been in some cases interpreted as the result of mass-movement deposits on seamount flanks (e.g., Matsuda and Ogawa 1993; Onoue and Stanley 2008; Osozawa et al. 2009; Chablais et al. 2010a).

This chapter aims to discuss the origin and formation of polymict breccias that crop out in the Sambosan Accretionary Complex (SAC) (Southwest Japan, Fig. 7.1). To achieve this objective, we report field observations and accurate description of the lithologic composition of various type of polymict breccias from 17 localities at Kyushu and Shikoku Islands and in the Kii Peninsula (Honshu Island). Multivariate analyses are applied to investigate the breccia compositional patterns. Our results are then compared with similar breccias in Japan. Finally, we discuss the probable genetic processes that led to the mixing of the various oceanic lithologies.

In this work, we defined brecca as block-in-matrix rock bodies consisting of more than 25% of angular clasts larger than 1cm (Conahgan et al. 1976). Rock bodies in which angular clasts are larger than 1 m (i.e., ‘blocks’ sensu Wakita 1988) are termed ‘megabreccia’ (Conahgan et al. 1976; Marangon et al. 2011). Units larger than a few meters are referred to as ‘slabs’ and are not considered to be part of the breccias that are studied here. However, it is worth noting that there is a continuum in size from clasts to slabs and that the aforementioned categories are purely descriptive and are not related to any genetic processes.
7.2. Geological setting

The Sambosan Accretionary Complex (SAC) is a subduction-generated Upper Jurassic–Lower Cretaceous accretionary complex in Southwest Japan (Onoue and Sano 2007) that is characterized by the chaotic occurrence of Upper Triassic shallow and deep water carbonates, middle Upper Triassic OIB basalts, Middle Triassic to lower Upper Jurassic bedded cherts and Middle Jurassic to Lower Cretaceous trench-fill mudstone and sandstone (Kanmera 1969; Matsuoka and Yao 1990; Onoue et al. 2004; Onoue and Sano 2007). The SAC extensively crops out along a narrow belt going from the Ryukyu Islands to the Kanto Mountains in Honshu Island (Fig. 7.1). It is separated from the Shimanto Accretionary Complex to the south by the Butsuzo tectonic line (BTL).
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7.3. Results

This study is based on field observations and microfacies analysis of 17 localities of the SAC at Kyushu Island, Shikoku Island and in the Kii Peninsula in Honshu Island (Fig. 7.1, Table 7.1). Lithologic composition of the breccia cropping out in the 17 localities are summarized in Table 7.2, together with the microfacies of limestone clasts. Detailed microfacies discussion and related sedimentological reconstruction of the Upper Triassic Sambosan limestone have been developed separately in Chapter 4 and 5.

Table 7.1 Geographic coordinates and number of samples (i.e., thin sections) of the studied localities

<table>
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<th>Areas</th>
<th>Localities</th>
<th>GPS Coordinates</th>
<th>Nb of samples (with thin sections)</th>
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</thead>
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<td>Loc.1 Ose</td>
<td>32° 17.120’N, 130° 36.300'E</td>
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<tr>
<td></td>
<td>Loc. 2 Koguchi</td>
<td>32° 17.485’N, 130° 36.187'E</td>
<td>20</td>
</tr>
<tr>
<td>Yamae</td>
<td>Loc. 3 Yamae</td>
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<td>Tsuno</td>
<td>Loc. 4 Tsuno</td>
<td>33° 27.870’N, 133° 11.868'E</td>
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</tr>
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<td>Mt. Sambosan</td>
<td>Loc. 5 Sambosan Castle</td>
<td>33° 34.438’N, 133° 42.741'E</td>
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<tr>
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<td>33° 46.399’N, 134° 1.852'E</td>
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</tr>
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<td></td>
<td>Loc. 9 Mt. Ishidate</td>
<td>33° 46.800’N, 134° 4.019'E</td>
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</tr>
<tr>
<td>Befu/Kito</td>
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<td>34° 13.916’N, 135° 58.663'E</td>
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</table>

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Lithologic composition

The breccias of the SAC are composed of limestone, basalt, chert and siliceous mudstone clasts (Fig. 7.2) set in volcaniclastic matrix (VCM) (Fig. 7.2a) or in a siliceous mudstone matrix (Fig. 7.2b). Most of the breccias are matrix-supported (Fig. 7.3a) but some are densely packed, clast-supported and present few or no matrix (Fig. 7.3b). In the latter case, clasts are often in stylolitic contact.

Fig. 7.2 Polished slabs of characteristic breccia of the SAC. a Breccia (B1) showing limestone (L) and basalt (arrow) clasts in volcaniclastic matrix (VCM), CP28 Loc. 5 Mt. Sambosan Castle. b Breccia (B2) showing limestone (L), chert (C), basalt (black arrow), siliceous mudstone (white arrow) clasts in siliceous mudstone matrix. CP WAJ, Loc. 13 Wajiki.

Limestone clasts occur in all breccias considered in this study. They are mostly angular but some show a lens shape (Fig. 7.4f, 7.5d) which probably results from boudinage and/or shearing processes. Upper Triassic and Paleozoic limestone clasts are distinguished based on their biotic composition. The latter occur at Loc. 13 Wajiki and Loc. 16 Wasabidani. Upper Triassic limestone clasts were attributed to 8 microfacies following (see Chapter 4). Both limestones originated from mid-oceanic shallow water carbonate platforms of the Panthalassa domain.
Fig. 7.3 Microfacies of the breccias. a Limestone clasts (MF4 and MF3) embedded in VCM composed of hyaloclastite (h) and other volcaniclastic material, CP15 Loc. 5 Mt. Sambosan Castle. b Clast-supported breccia with limestone (MF4, MF6) and basalt clasts (B), note the absence of VCM, CP156 Loc. 17 Wasabidani. c Clast-supported breccia with limestone (MF1, MF7), chert (C), basalt (arrow) and siliceous mudstone (m) clasts in siliceous mudstone matrix, CP87 Loc. 13 Wajiki. d Matrix-supported breccia with limestone (MF4, MF7, MF8) and basalt (arrow) clasts n siliceous mudstone matrix, CP205 Loc. 10 Konose Kyo Road.
Fig. 7.4 Outcrop views. a Clast supported breccia with white limestone, red chert and vesiculated basalt (arrow) clasts, Loc. 16 Yura. b Matrix supported breccia with white limestone clasts in VCM, Loc. 5 Mt. Sambosan Castle. c Well-lithified limestone-basalt breccia, Loc. 3 Yamae. d Loosely lithified limestone-basalt breccia, Loc. 14 Road 28 1. e Shear fabrics in limestone basalt breccia, Loc. 9 Mt. Ishidate. f Shear fabrics and lens-shaped clasts in limestone-chert-basalt-mudstone breccia, Loc. 15 Road 28 2.
Basaltic clasts and related volcanic rocks are also present in all breccias considered in this study. Basalt preservation varies from one outcrop to another. Some basalt clasts (Fig. 7.4a), contain vesiculae filled with calcite and sometimes zeolite (Kanmera 1969). Onoue et al. (2004) described the mode of occurrence, petrographic features and geochemical properties of basalts from the SAC at Kyushu and Shikoku islands (more precisely from Loc. 2 Koguchi, Loc.5 Sambosan Castle, Loc.10 Konose Kyo Road, Loc. 12 Hisaidani and Loc. 13 Wajiki). These authors identified blocks of vesiculated pillow lavas with interpillow limestone and subordinate massive lava, pillow fragment breccia and hyaloclastites. Petrographic analysis showed that the basalts are mostly aphyric basalt, clinopyroxene basalt and olivine basalt. Dolerite occurs locally. A geochemical affinity with an oceanic island basalt (OIB) is demonstrated (Ishizuka et al. 2003; Onoue et al. 2004; Safonova et al. 2014). Metamorphic mineral assemblages indicate that the basalts of the Sambosan Accretionary Complex have been metamorphosed under the medium to high grade zeolite facies (Ishizuka et al. 2003).

Green and brown chert clasts are observed in breccias at Loc.7 Befu 1, Loc. 10 Konose Kyo Road, Loc. 12 Hisaidani, Loc. 13 Wajiki and Loc. 15 Road 28 2. Red chert clasts occur at Loc. 15 Yura. The red color suggests that redox conditions during the deposition of chert were different from those of the green one. Most of chert clasts are angular and, in some of them, recrystallized radiolarian are recognized. Chert clasts are interpreted as fragments of bedded cherts from mid-oceanic sea floor (Onoue and Sano 2007).

Black siliceous mudstone clasts are minor components of the breccias at Loc.7 Befu 1, Loc. 10 Konose Road, Loc. 12 Hisaidani, Loc. 13 Wajiki and Loc. 15 Road 28 2. They appear as brown clasts in transmitted light (Fig. 7.3c) and contain quartz, K-feldspar, plagioclase, micas, few zircons and radiolarians. Onoue and Sano (2007) defined “siliceous mudstone” as rocks that “consists of radiolarians and siliceous sponge spicules, disseminated in the matrix of clay minerals and microcrystalline quartz”. In this study we follow this nomenclature even if some quartz grains may occasionally be coarser than clay and silt size. According to their terrigenous content, siliceous mudstones are interpreted as hemipelagic sediments deposited in a transitional environment from a mid-oceanic realm to a convergent margin (Onoue and Sano 2007).

Red or green volcaniclastic matrix (VCM) is the most common matrix in the SAC breccias (Table 7.2). It is composed of sand- to mud-size grains of altered vesiculated basalt, hyaloclastic material and volcanic glass shards (Fig. 7.3a). Significant amount of sparry calcite is also part of the VCM, especially in megabrecca at Loc. 4 Tsuno. Tiny (< 1mm in diameter) limestone clasts also occur within the matrix (Fig. 7.3a). Volcaniclastic material is the most common
volcanic rock in shallow submarine volcanoes and results from the mechanical breakup of lava flows or from explosive-eruptive fragmentation (Staudigel and Clague 2010). Furthermore, Chablais et al. (2010a) proposed that some VCM could be the result of volcanic seamount erosion during a large-scale gravitational collapse of the seamount body.

Fig. 7.5 Outcrop views. a Sharp (fault) contact between limestone and basalt unit, Loc. 7 Befu 2. b Sharp contact between limestone units and volcaniclastic material, Loc. 4 Tsuno. c Breccia resulting from tectonic mixing of limestone and basalt units, Loc. 7 Befu 2. d Boudinage of limestone and basalt clasts in VCM matrix, Loc. 7 Befu 2. e Limestone blocks embedded in loose VCM, Loc. 6 Mt. Sambosan Quarry. f Limestone basalt breccia showing grading (arrow), Loc. 2 Koguchi.
The siliceous mudstone matrix consists of dark terrigenous mudstone (brown in transmitted light Fig. 7.3c–d) and includes quartz, feldspar and radiolarians in a similar fashion to siliceous mudstone clasts. Tiny (< 1mm in diameter) chert and limestone clasts also occur in the matrix (Fig. 7.3d). They probably results from “crushing” processes that have affected the clasts.

Field observations.
Sedimentary and tectonic features have been observed at breccia outcrops during field investigation in 2012 and 2013. Most studied outcrops are only a few meters large laterally (Fig. 7.4b) but extensive breccia units crop out at Loc. 1 Ose, Loc. 2 Koguchi and Loc. 13 Wajiki. At Loc.1 Ose, the outcrop consists of a succession of several breccia units that are composed of limestone clasts and blocks set in VCM (Chablais et al. 2010a). At Loc. 2 Koguchi, matrix-supported limestone-basalt breccia extensively crops out in the bed of the Kuma River and grading is visible (Fig. 7.5f). At. Loc. 13 Wajiki, the Naka River crosses the SAC, displaying a 320 m long and approximately 10-15 m wide well-exposed section (Fig. 7.6). The section, which was mapped in April 2013, exhibits a succession of well-lithified, clast-supported, limestone-chert-basalt-mudstone breccia (Figs. 7.6c–f, 7.7), altered basalt (Fig. 7.6g) and siliceous mudstone units. Clasts are angular and range from a few centimeters to a few decimeters in size. Locally, alternations of limestone-rich and chert-rich zones are observed (Fig. 7.6c). The lateral variations are difficult to observe because the different units of the section are often separated by minor faults (Figs. 7.6e, 7.7b). The limestone clasts include several microfacies of Upper Triassic limestone (Table 7.2) and some Paleozoic reef limestone clasts locally occur (Fig. 7.6f). Shear fabrics are observed in some part of the outcrop, especially near the Paleozoic limestone blocks. Cherts are often microbrecciated (Fig. 7.7d,g). The siliceous mudstone contains terrigenous grains and radiolarians (Fig. 7.7h). Beside the well-exposed breccia units of Loc. 1 Ose, Loc. 2 Koguchi and Loc. 13 Wajiki, smaller outcrops show additional sedimentary and tectonic features. Most of the clasts that occur in the SAC breccias are angular without oriented fabric (Fig. 7.3). However, some other clasts exhibit a lens shape which likely results from boudinage during the accretion (Fig. 7.5d). Shear deformation are also occasionally observed (Fig. 7.4e–f). Some localities exhibit well-lithified breccias (Loc. 1 Ose, Loc. 2 Koguchi, Loc. 3 Yamae, Loc. 4 Tsuno, Loc. 5 Mt. Sambosan Castle, Loc. 7 Befu 1, Loc. 8 Befu 2, Loc. 10 Konose Road, Loc. 12 Hisaidani, Loc. 13 Wajiki, Loc. 16 Yura and Loc. 17 Wasabidani; Fig. 7.4a–c) whereas others present breccias with loosely lithified VCM matrix (Loc. 7.6 Mt. Sambosan quarry, Loc. 9 Mt. Ishidate and Loc. 11 Konose Kyo Crest, Fig. 7.4d–e). However, it is worth noting that differences in alteration and weathering processes may have
influenced the observed degree of breccia lithification. Moreover, at Loc. 15 Road 28 2 the breccia was probably originally well-lithified but has been fragmented by deformation processes (Fig. 7.4f).

**Fig. 7.6** Map and outcrop view of Wajiki section (Loc. 13). a Map showing the location of the Wajiki section. b Outcrop view of the Wajiki section. c Close up view of the limestone-rich and chert-rich alternation of the breccia. d Breccia showing clasts of various lithologies: green cherts, white limestone and black siliceous mudstone. e Fault contact between limestone-rich breccia and microbrecciated chert unit. f Large Paleozoic reef limestone block in deformed breccia. g Altered basalt unit.
In the SAC, contacts between large limestone and basalt units are often sharp and obviously of tectonic origin (Fig. 7.5a). Nevertheless, at the confluence between a small river and the Monobe River (i.e., Loc. 8 Befu 2), a highly deformed limestone-basalt breccia is situated at the boundary between limestone and basalt slabs (Fig. 7.5c), clearly representing the transition between them and most probably resulting from tectonic processes (see also Onoue and Nishizono 2014 Fig. 7.10). At Loc. 4 Tsuno, volcaniclastic material was clearly injected between limestone blocks either during the collapse of seamount-top carbonates on the seamount flanks or later on, after incorporation into the accretionary prism (Fig. 7.5b).

In summary, breccia outcrops of the SAC show evidence of both sedimentary features (i.e., grading, angular clast shape, no-sheared contacts and lack of clast orientation) and subsequent tectonic deformations (i.e., boudinage, shear fabrics and fault).

**Multivariate analysis**

The lithologic composition of the studied breccias is summarised in Table 7.2. Non-metric MultiDimensional Scaling (NMDS) using Dice coefficient was applied to this dataset (Fig. 7.8). NMDS has been chosen because of the non-metric nature of our dataset and the possibility to take into account similarity gradients with this method. Dice coefficient is especially suitable to our analysis because of the underweight given to shared absences, which may be linked to sampling bias. Multivariate analysis was performed with PAST software (version 3.06). Loc. 3 Yamae is not included in the NMDS because microfacies analysis was not carried out for this locality. NMDS, combined with minimum spanning tree, clearly shows two main groups of breccia (Fig. 7.8). The first group corresponds to breccias with VCM (Breccia type B1) whereas the second is composed of breccias with siliceous mudstone matrix (Breccia type B2). Chert and siliceous mudstone clasts occur exclusively in the breccias with siliceous mudstone matrix (except in Loc. 16 Yura where chert clasts occur in an undetermined red matrix). In more detail, the Coordinate 2 suggests that the breccias differ with respect to the microfacies of the limestone clasts. The breccias plotting in the upper part of the graph are dominated by reef and fore-reef (MF4 and MF3 respectively) limestone clasts whereas those plotting in the lower part are dominated by lagoonal facies (MF5 and MF7). Breccias where basinal limestone occurs (MF1) appear closely related.
Fig. 7.7 Breccia of Loc. 13 Wajiki. a Location of studied outcrop. b Fault contact between breccia, microbrecciated chert (d) and siliceous mudstone (e). c, f Microfacies (MF2) of limestone clasts. d, g Microbrecciated chert. e, h Black siliceous mudstone note the presence of fine quartz grains (black arrow) and radiolarian (white arrow).
Table 7.2: Lithologic composition of the various types of breccia of the Sambosan Accretionary Complex. The microfacies and ages of the limestone clasts of the breccia are also indicated.

<table>
<thead>
<tr>
<th>Area</th>
<th>Localities</th>
<th>Clasts</th>
<th>Matrix</th>
<th>Age of limestone clasts</th>
<th>Microfacies of Upper Triassic limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Limestone</td>
<td>Basalt</td>
<td>Chert</td>
<td>Mudstone</td>
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<tr>
<td>Kumagawa area</td>
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<td>Loc.1 Ose</td>
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<td>Loc. 2 Koguchi</td>
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<td>Tsuno area</td>
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<td>Mt. Sambosan area</td>
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<td>Befu/Kito area</td>
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<td>Loc. 13 Wajiki</td>
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<td>Loc. 14 Road 28 1</td>
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<td>Loc. 15 Road 28 2</td>
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<td>Daifugendake area</td>
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<td>Loc. 17 Wasabidani</td>
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</table>

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7.4. Discussion

Types of breccia

Based on our field observations, microfacies analysis and corresponding multivariate analysis, two main types of breccia are recognized. The breccia type B1 is characterized by limestone and basalt clasts embedded in volcaniclastic matrix (VCM) whereas the second, breccia type B2, is characterized by association of limestone, chert, basalt and siliceous mudstone clasts set in siliceous mudstone matrix. Polished slabs of characteristic samples for each types are shown in Figure 7.2. The Non-metric MultiDimensional Scaling (NMDS) indicates that the microfacies of limestone clasts are not randomly distributed in the different breccias. Interpretation of the Coordinate 2 of NMDS suggests that breccias including platform edge microfacies (reef and fore-reef) can be distinguished from those including platform interior microfacies (back-reef and lagoon). Additionally, breccias including basinal facies show strong similarities.

Fig. 7.8 Multivariate analysis. Results of the Non-metric MultiDimensional Scaling (with minimum spanning tree) based on the lithological composition and limestone microfacies of the Sambosan breccias (Table 7.2). Grey circles indicate the localities corresponding to the two type of breccias identified in the SAC (Breccia B1: limestone and basal clasts in VCM; Breccia B2: limestone, chert, basalt and siliceous mudstone clasts in siliceous mudstone matrix). Major trends regarding the depositional environments of the limestone clasts are indicated in italic.
Biostratigraphy

Precise dating of the breccia components is pivotal to the understanding of breccia formation. Limestone clasts are Middle? to Upper Triassic (Ladinian? to Norian-Rhaetian, Chablais et al. 2010b; Peybernes et al. 2015; Chapter 2, 3 and 4) and, in a lesser amount, Paleozoic (Carboniferous?-Permian?) in age. Basalt, chert and siliceous mudstone clasts have not been precisely dated during this study. However, in the Sambosan Accretionary Complex, the age of eruption of the basalt has been dated to the Late Carnian by conodonts found in inter-pillow limestone (Onoue and Stanley 2007). Reef biota retrieved from limestone clasts set in VCM at Shikoku indicate that eruption started in the Ladinian?-Early Carnian (Peybernes et al. 2015). Bedded chert units range from the Late Anisian to the Middle Jurassic (Matsuoka 1992; Onoue and Sano 2007). Radiolarian recovered from siliceous mudstones at Shikoku and Kyushu Islands indicate deposition during the Middle Jurassic to Early Cretaceous (Matsuoka 1992; Onoue and Sano 2007). More precise biostratigraphic control on both matrix and clasts could improve the stratigraphic framework.

Comparisons with former studies

Breccia B1 is commonly observed in many localities of the SAC. This type of breccia is reported from Kyushu (Kanmera 1969; Onoue and Sano 2007; Onoue and Stanley 2008; Chablais et al. 2010b), Shikoku (Chablais 2010; Peybernes et al. 2015), and the Kanto Mountain in Honshu Island (Chablais 2010) but seems to be absent in Okinawa Island (Chablais 2010). It is worth noting that chert clasts have been reported in VCM breccia only at Kyushu Island (e.g., Chablais et al. 2010b). During this study, we did not observed any chert clasts at the outcrops corresponding to the breccia type B1. While common in the SAC, the VCM-rich type of breccia (B1) seems rare in other Japanese accretionary complexes.

In the SAC, breccia type B2 is subordinate and occurs mainly in Eastern Shikoku. Similar breccia was described by Kanmera (1969) in the Kuma area (Kyushu Island) as lenticular bodies of conglomerate composed of pebbles and granules of angular chert, limestone, basalt and black mudstones clasts. In Shikoku, chert breccia units have been mapped by Matsuoka (1992) and by Ishida (1985, 1987), especially in the Wajiki area. Breccias with limestone chert and siliceous mudstone clasts occur also in other parts of the Southern and Northern Chichibu belt and in the Mino-Tamba accretionary complex. In the Yatsuji Formation of the Torinosu group of central Shikoku (Southern Chichibu belt), Kano and Jiju (1995) described a conglomerate composed of chert and limestone clasts in a mudstone matrix. The chert gravels are assumed to originate from the underlying accretionary complex and limestone clasts from the nearby
Torinosu-type carbonate mounds. This conglomerate deposited in channels between the carbonate mounds in a foreland basin. Breccias including limestone and chert clasts embedded in a siliceous mudstone matrix and associated with volcanic units also crop out in the Sawadani mélangé of the Northern Chichibu belt. In this area, Matsuda and Ogawa (1993) identified two stages of sedimentary mixing of oceanic material. In the first stage, Late Carboniferous–Late Permian limestone and chert clasts were mixed into a Late Permian siliceous mudstone, probably on the flank of a seamount in the pelagic environment. The second mixing occurred during the Early Jurassic at the trench, as indicated by the radiolarian in turbidites of terrigenous clastic rocks. The Wadano conglomerate in the Mino Accretionary Complex consists of clasts of limestone, chert, shale and sandstone in a sandstone matrix (Sano et al. 2013). This chert-rich breccia is considered to have been formed either by the collapse of seamounts and horsts of the oceanic plate at an outer trench, or by slope failure of the accretionary prism and subsequent submarine landslides (Saito and Tsukamoto 1993; Sano et al. 2013). It is worth noting that basaltic clasts, which are common in the SAC breccias, are rare in the Wadano conglomerate.

**Breccia formation**

According to Isozaki (1997) and Wakita (1988, 2012), mixing of the various oceanic lithologies in the Jurassic accretionary complexes of Japan is the result of sedimentary, diapiric and tectonic processes leading to the formation of mélanges. However, if tectonic processes such as offscraping and underplating (Okamura 1991; Wakita 2012), probably account for most of the mixing of the larger units (i.e., slabs), the majority of the cases described in this work cannot be correctly explained by tectonic mixing. The lack of shear fabrics suggests that most of the breccias described here are more probably of sedimentary origin. In block-in-matrix rock bodies, the lack of shear fabrics and the chaotic association of angular clasts of various lithologies are usually interpreted as evidence of sedimentary mixing during massmovement processes (Osozawa et al. 2009, 2011; Onoue and Stanley 2008). Extensive asymmetric shear fabrics are regarded by some authors as a defining characteristic of tectonic mélange (Onishi and Kimura 1995; Osozawa et al. 2009). In the SAC breccias, most of clast-matrix and clast-clast contacts are of depositional origin. Some shear fabrics are nevertheless observed, in particular in loosely lithified VCM of breccia type B1. Even when shear fabrics are present, they do not appear sufficient to explain the mixing of strongly heterogeneous lithologies (i.e., chert, basalt, limestone, siliceous mudstone clasts) (see also Osozawa et al. 2011).
Several authors already recognized the sedimentary origin of breccia units in the SAC as well as in other accretionary complexes in Japan. Based on comparison with modern Daiichi-Kashima and Erimo seamount collapses, near and in the Japan Trench (Kobayashi et al. 1987; Cadet et al. 1987; Konishi 1989), Onoue and Stanley (2008) inferred that breccias and megabreccias composed of limestone blocks and volcanic material (equivalent to breccia type B1 in this work) in the Kumagawa area result from submarine landslides on the seamount flanks. According to radiolarian biostratigraphic data from the volcanioclastic rocks succession and the total absence of the coarse-grained terrigenous clastic material, these authors conclude that the debris avalanches occurred in an open ocean setting during the late Middle to early Late Jurassic, just before the seamount encounter with coarse terrigenous sediments. These landslides are supposed to be linked to normal faulting related to extensional stress during the bending of the lithosphere near the trench (Kobayashi et al. 1998; Tsuru et al. 2000; Onoue and Stanley 2008). As a next step, Chablais et al. (2010a) recognized several mass-movement deposits such as rock falls, debris flows, turbidites and slumps at Loc. 1 Ose. These events are interpreted as seamount collapses, probably related to storms or tectonic events. They occurred during the Norian-Rhaetian as demonstrated by the presence of tests of *Aulotortus friedli* as reworked grains in the matrix (Chablais et al. 2010 a).

Similar tectono-sedimentary processes have been proposed to explain the dislocation and mixing of the Carboniferous Akiyoshi limestone (Sano and Kanmera 1991b; Sano 2006) and of the Carboniferous-Permian Tsukumi limestone (Sano and Tamada 1994a, b) in a trench context. However, in those last two cases, limestone blocks are redeposited in argillaceous and scaly mudstone matrix and no, or only few VCM is present. In the Yuwan accretionary complex of the Ryukyu Islands (Southwest Japan), Osozawa et al. (2009) identified multiple sedimentary and tectonic events leading to the formation of breccia and other block-in-matrix fabrics. The authors especially identified two sedimentary episodes corresponding to debris flows on the flank of seamounts and gravitational collapses into the trench of previously accreted terrigenous and oceanic material. The signature of these sedimentary events are overprinted by tectonic deformations during the accretion.

From the aforementioned examples, sedimentary mixing of oceanic units before incorporation in accretionary complexes appear widespread. By contrast, the Mugi mélange in the Shimanto accretionary complex exhibits shear fabrics, C-S structures, sandstone boudinage and crack filling veins which are both diagnostic of tectonic mélange (Onishi and Kimura 1995; Kimura et al. 2012). Such structures are rarely observed in the SAC breccias. In particular, shear fabrics leading to bed disruption are rare. In conclusion, our results well support a primary sedimentary
origin for most of the investigated breccia units. One notable exception is the limestone-basalt, shear-generated breccia situated at the boundary between limestone and basaltic slabs at Loc. 8 Befu 2 (Fig. 7.5c, see also fig. 10 in Onoue and Nishizono 2014). Criteria that designate the sedimentary versus tectonic origin of the breccias are summarized in Table 7.3.

**Table 7.3: Criteria to distinguish sedimentary versus tectonic origin of a breccia**

<table>
<thead>
<tr>
<th>Sedimentary features</th>
<th>Tectonic features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oligomict to highly polymict breccia (mixing of 2 to 4 lithologies)</td>
<td>Oligomict breccia (mixing of 2 lithologies)</td>
</tr>
<tr>
<td>No or few shear fabrics</td>
<td>Shear fabrics</td>
</tr>
<tr>
<td>Grading</td>
<td>Lens shaped clasts</td>
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<td></td>
<td>Boudinage</td>
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</table>

Based on the extensive shear fabrics and on the fact that basalts are metamorphosed in prehnite-pumpellyite to pumpellyite-actinolite facies, Wakita (2012) proposed that the basalt and limestone units in mélanges from the Mino Accretionary Complex were tectonically disrupted and incorporated at the bottom of the accretionary prism by underplating. However, such interpretation cannot be applied to the breccias of the SAC because of the scarcity of shear fabrics and low grade metamorphism of basalt clasts. According to our observations, breccia formation is, in majority of cases, better explained by sedimentary processes before the accretion. In that, our interpretation of breccia formation mainly follows opinions by Sano and Kanmera (1991b) Matsuoka (1992), Onoue and Stanley (2008) and Chablais et al. (2010a).

Nevertheless, in addition to the limestone-basalt-VCM breccia (B1) which was the main focus of aforementioned studies, we report and describe another type of breccia (B2). According to their lithologic composition, the 2 types of breccia result from similar mass-movement deposits but in different geologic contexts. Breccia type B1 is composed of lithologies that correspond to the seamount top and slope. Therefore, the debris avalanches that generated breccia B1 did not significantly reworked the sea-floor sediments. On the other hand, chert and siliceous mudstone clasts in breccia type B2 indicate that deeper sea floor sediments (bedded cherts and hemipelagic sediments) have been reworked during the corresponding mass-movement(s). This suggests deeper redeposition of collapse products, probably close to the trench owing to the presence of the hemipelagic siliceous mudstone matrix. These two types of
Breccias might be related to a single tectono-sedimentary event (e.g., storm, earthquake, slope failure) or to several of them, occurring at different times during the travel of the seamounts in the oceanic domain toward the trench. A more precise dating of the clasts (especially cherts and siliceous mudstones) and matrix is pivotal to better constrain the origin of the two types of breccia. Additional field observations are also needed to describe in detail the sedimentary processes involved in breccia formation.

Breccia B1 and B2 were later incorporated into the accretionary wedge during the Late Jurassic–Early Cretaceous (Matsuoka 1992). Well-lithified breccias without clast orientation suggest that sediment consolidation was already effective before the accretion and subsequent tectonic events. Nevertheless, shear fabrics and boudinage observed at some localities are evidence of secondary deformations which most probably occurred in the accretionary prism. Recently, it has been demonstrated that most mélanges of the Franciscan Complex in California have a sedimentary origin, with variable overprinting of tectonic strain (Wakabayashi 2011, 2012, 2015; Kusky et al. 2013). The authors notably observed that undeformed to little-deformed sedimentary breccias grade with increasing strain into what is commonly described as sheared mélange matrix.

The origin of Paleozoic limestone blocks in some studied breccias remains enigmatic but can be potentially linked to the reworking of older part of the accretionary prism. Such resedimentation and incorporation of upper plate rocks by submarine sliding have been recently reported from the Franciscan mélange (Wakabayashi 2011, 2012, 2015; Kusky et al. 2013) and in the Yuwan Accretionary Complex (Osozawa et al. 2009).

7.5. Conclusion

The investigation of 17 breccia localities of the Sambosan Accretionary Complex at Kyushu and Shikoku islands and in the Kii Peninsula (Southwest Japan) allowed us to:
- Distinguish two main types of breccia (Type B1 and type B2) based on their lithologic composition.
- Reveal a microfacies distribution pattern in the limestone clasts of the breccias. Multivariate analysis (Non-metric MultiDimensional Scaling) indicates that breccias including mostly limestone clasts from the platform interior can be distinguished from those with limestone clasts from the platform edge.
Recognize shear fabric as well as clast shape and distribution as valuable indicators of tectonic mixing, especially at the transition zone between two lithologies (e.g., basalt and limestone slabs).

The highly heterogenous lithologic composition and the lack of shear fabric in most of the studied breccias lead us to the conclusion that they are primarily of sedimentary origin. They most probably result from the collapse of panthalassic seamounts in the mid-oceanic realm (Breccia B1) and in or near the trench (Breccia B2). These breccias were subsequently deformed during their incorporation in the accretionary prism. Additional biostratigraphic constrains to the clasts and matrix deposition time, could confirm and refine our results.

References


Chapter 8: Conclusions and Outlooks

In this study, we present sedimentological and paleontological data from the Sambosan Accretionary Complex (SAC, Southwest Japan). Our results are mainly based on new outcrops from Shikoku Islands and significantly improve our understanding of Upper Triassic shallow water carbonate ecosystems of the Panthalassa Ocean. It fills a gap in knowledge because little was known until recently about these environments in Japan and more broadly in Panthalassa. We propose a paleoenvironmental reconstruction of mid-oceanic shallow water carbonate platforms and quantitatively assess the biogeographic connections between Tethys and Panthalassa domains. We also establish accurate stratigraphic correlations between the Upper Triassic reef limestone of the Western Panthalassa and those of Tethys and Eastern Panthalassa, using reef biotic associations and biostratigraphic markers. Our results provide valuable information to improve the paleogeographic reconstructions of the Panthalassa Ocean during the Late Triassic, especially regarding the paleoposition of terranes and seamount provinces. The sedimentological, biostratigraphical and paleocological analyses emphasize the need of integrated studies, combining several approaches to improve our knowledge of ancient shallow water carbonate platforms and reef environments.

Sedimentology

Microfacies inventory of the SAC limestone, which started with the work of Onoue and Sano (2007), Onoue and Stanley (2008), Chablais et al. (2010a) and Chablais (2010), has been completed by further sampling in already known and new localities at Kyushu Island (Appendix 1 and 2), Shikoku Island (Chapters 2, 3, and 4) and Honshu Island (Kii Peninsula, Chapter 5). Quantitative analyses such as point counting on scanned thin sections helped to assess the sedimentary composition of the different microfacies. This large microfacies dataset allow us to propose a new speculative depositional model for the SAC platform(s) (Chapter 4). In comparison to previous atoll-type reconstructions, this model emphasize the carbonate bank morphology of the SAC platforms that were characterized by low growing reef communities at the platform margin and by a mosaic of restricted to open marine facies in the platform interior.Two new microfacies, among the eight that are identified at Shikoku Island, further document the depositional setting of the upper and lower slope, respectively. In addition, microfacies of the Upper Triassic limestone of the Kii peninsula have been illustrated and described in detail for the first time (Chapter 5). This region was less studied than others areas.
in the SAC. Therefore, more extensive sampling would expand our knowledge of the microfacies diversity and micropaleontological content of the SAC limestone in this region.

Paleontology

Intensive sampling at Shikoku Island resulted in the discovery of new reef biotic associations that enhances the inventory of Upper Triassic shallow water biota of the SAC (Chapter 2). The limestone clasts embedded in volcaniclastic matrix contain the best preserved microfossils of our collection, probably because the circulation of diagenetic fluids was more difficult in volcaniclastic sediments, preventing the recrystallization. These clasts should be the preferential targets for future investigation of the microfauna of the SAC limestone and related Upper Triassic limestone of the Circum-Pacific domain. Multivariate analyses unravel patterns in biotic composition and help to reveal the taxonomic evolution of reef biota (Chapter 3).

Biostratigraphy

Reef biota assemblages have proved useful to improve the biostratigraphic framework of isolated limestone units (Chapters 2 and 3). Until now the reef limestone has been generally attributed to the Carnian–Rhaetian (Onoue and Stanley 2008; Chablais et al. 2010b; Senowbari-Daryan et al. 2012). The biotic associations identified during this study allow us to distinguish and clearly define two types of reef that are attributed to the Ladinian–Early Carnian and to the Late Carnian–Norian–Rhaetian respectively. Conodonts are also valuable biostratigraphic markers that greatly complemented the biostratigraphic investigation of the SAC limestone (Ishida and Hirsch 2001; Onoue and Tanaka 2005; Onoue and Sano 2007; Yamashita et al. in revision; this work Chapter 3). During this study, numerous limestone samples have been dissolved in acetic acid 10% to extract conodont elements. The idea was to improve the biostratigraphic framework given by the benthic foraminifers. Lagoonal limestone (megalodont-involutinid wackestone) appeared barren in conodonts. Several specimens have been found in peloidal-bioclastic grainstone-packstone but, surprisingly, most conodonts were recovered from reef limestone. Thus, reef facies should be the principal target for further conodont investigation of shallow water limestone in the SAC and coeval settings. In the SAC, most of the previous studies dealing with conodonts focused on chert or deep water limestone and rarely described the related microfacies. In this work, we specifically investigated shallow water limestone and considered the microfacies of the samples from which the conodonts were
retrieved. This led us to precisely correlate the deposition of reefal limestone with coeval deep water limestone and cherts in the SAC and with global stratigraphic charts as well.

*Paleobiogeography*

Our study offers a great opportunity to address paleobiogeographic issues such as pantropical distribution of fauna and the role of biologic dispersion across large oceanic masses. Indeed, according to our results, the wide Panthalassa Ocean does not appear as an efficient barrier in fauna dispersion during the Late Triassic (Chapter 3), at least at the taxonomic and temporal resolution used in this study. Similar observations have been already mentioned and discussed for several taxonomic groups in the Permian, Triassic and Jurassic (e.g., Newton 1988; Brayard et al. 2015). Biogeographic patterns of benthic shallow water biota are useful data for paleogeographical reconstruction. However, large dispersion potential of marine fauna is a hypothesis that must be taken into account before to translate paleobiogeographic affinities into paleogeographic distance (Newton 1988, Belasky 1996).

Multivariate analyses appear to be fruitful for deciphering the paleobiogeographic relationship between reef localities worldwide (Chapter 3). Thanks to the robust knowledge on the taxonomy of foraminifers, microproblematica and calcareous sponges acquired during this study, we compiled a taxonomically homogenized dataset, recording the occurrences of these reef biota in the Panthalassa and Tethys domains. Hierarchical cluster analyses applied to our dataset, show that reef biota of the SAC had strong taxonomic affinity with those of the carbonate platforms of Oman, indicating biogeographic connections between the South Tethys and the West Panthalassa domains during the Late Triassic. In the future, similar approach has to be applied to other environments and/or taxonomic groups to confirm these biogeographic patterns. Taxa restricted to one environment must be favored in multivariate analyses to reduce the effect of ecological signal and facies-related variations. Sampling bias is another obstacle that should be treated via statistical tests. The development of global databases, recording more and more occurrences worldwide provides valuable tools for future research on paleobiogeographical patterns.

*Paleogeography and geodynamics*

Our study also provides valuable data to improve paleogeographical reconstruction. High-resolution integrated biostratigraphy, quantitative paleobiogeographic relationships and sedimentological comparisons add spatial and temporal constrains to the onset, demise and
accretion of the SAC seamounts. By extension, these results help to unravel the paleogeography of the West Panthalassa during the Late Triassic. The SAC seamounts, and thus the corresponding tectonic plate, were situated in the intertropical belt, near the opening of the Tethys gulf. They were probably located closer to the South Tethys margin than to the North Tethys margin, as demonstrated by the high similarity of the reef biota with those of Oman (Chapter 3). Since the seamount(s) was accreted to the South China block during the Late Jurassic–Early Cretaceous (Matsuoka 1992; Isozaki 1997), the position of mid oceanic ridges and movement of tectonic plates could be assessed.

The various mode of occurrence of the SAC limestone shed light on the tectono-sedimentary events that occurred after its deposition on top of panthalassic seamounts. The SAC limestone primarily occurs as massive slabs and as clasts in breccia. Two types of breccia are distinguished according to two criteria: the presence of volcaniclastic matrix (Breccia type B1) in one hand and presence of chert and mudstone clasts (Breccia type B2) in the other hand (Chapter 7). They are primarily interpreted as mass-movement deposits resulting from seamount collapses events before the incorporation in the accretionary prism. Further investigations are needed to better constrain the stratigraphic framework of breccia formation. In particular, radiolarian extraction should be performed on chert and mudstone clasts of Breccia type B2. An improved stratigraphic framework of the breccia components would lead to a better-constrain timing of seamounts collapse and accretion. Structural analyses represent a complementary approach.

**Geological history of the seamounts incorporated in the Sambosan Accretionary Complex**

Based on the original data presented in this study and in the frame of the long term REEFCADE research project, started in 2006, we propose a scenario to tentatively reconstruct the geological history of the SAC seamount(s). The results obtained from the investigation of 63 localities all along the SAC indicate that shallow water carbonate sedimentation started at the top of seamount(s) in the Early Carnian and maybe even in the Ladinian (Chapters 2 and 3). This first stage of deposition is characterized by sponge-coral-microproblematica boundstone (Chapter 3) and peloidal grainstone (Chapter 5). Scarceness of conical involutinids (e.g., *Lamelliconus*) in megalodont-involutinid wackestone suggests that lagoonal facies were probably poorly developed at this time. Eruption of basalt continued at least until the Late Carnian as demonstrated by the occurrence of Upper Carnian conodont *Metapolygnathus nodosus* in inter-pillow limestone (Onoue and Sano 2007). During the Late Carnian–Norian, and most likely the
Rhaetian, sponge-dominated reefs developed at the platform margin and as patch-reefs in the platform interior (Chapters 3 and 4). Oncoid-calcimicrob rudstone-grainstone, peloid-echinoderm packstone-grainstone, megalodont-involutinid wackestone-packstone and bioclast-microcoprolite wackestone-mudstone deposited in the platform interior with various lateral facies distribution. Top-platform sediments were exported and redeposited in low energy environments on the upper slope (MF3 Bioclast-intraclast rudstone-floastone, Chapter 4).

Further down on the seamount slope, the sedimentation was characterized by alternations of fine pelagic siliceous limestone deposits and coarser event beds composed of reworked material from the platform. Radiolarian-filament mudstone-wackestone, associated with chert nodules and bedded chert, deposited on the lower slope and surrounding sea floor. A foraminifer assemblage found in a single sample from the Sambosan type locality (Shikoku Island) suggests that carbonate sedimentation was potentially maintained until the Early Jurassic (Chapter 6). Dismantling of the seamount during its travel toward the trench occurred in the middle Late Jurassic (Onoue and Stanley 2008) and led to the formation of limestone-basalt-volcaniclastic breccia. Moreover, occurrences of limestone-chert-basalt-siliceous mudstone breccia suggests that seamount collapses probably happened again near the trench, shortly before incorporation in the accretionary prism (Late Jurassic-Early Cretaceous, Mastuoka and Yao 1990; Matsuoka 1992; Isozaki 1996). Further investigations in the SAC would confirm this geological history.

**Future investigations of Upper Triassic shallow water limestone in the Panthalassa domain**

Since the first descriptions of the Upper Triassic limestone in the Sambosan Accretionary Complex (Kobayashi 1931), and especially in the last decade, almost all of the accessible outcrops of the Sambosan limestone have been investigated (Onoue and Sano 2007; Chablais 2010; this thesis). To move forward significantly, research should now focus on other localities in the Circum-Pacific domain that may provide additional and pivotal information regarding Upper Triassic shallow water and reefal environments in the Panthalassa realm. Investigation of new localities to identify well-preserved outcrops with portion of undamaged successions is one of the goals of the REEFCADE project. Accordingly, the most promising target for future research, briefly presented below, are Hokkaido Island (North Japan), Sikhote Alin (Far East Russia), Palawan and Busuanga Islands (the Philippines), and San Juan Islands (British Columbia) (Fig. 8.1).
Extensive fieldwork and sampling in these localities will allow us to improve the sedimentological and micropaleontological knowledge and to compare and/or correlate Upper Triassic shallow water limestone from these areas with the one from Southwest Japan.

Upper Triassic limestone exposures are less frequent in Northeast Japan than in Southwest Japan but are reported from the North Kitakami belt in Honshu Island (Suzuki et al. 2007; Ehiro et al. 2008), in the Oshima belt (Sakagami et al. 1969; Kawamura et al. 1986, 1997) and Hidakka belt (Hashimoto et al. 1975; Kato and Iwata 1989) in Hokkaido Island. Prof. Tetsuji Onoue (University of Kumamoto) kindly provided limestone samples from the Kamiiaso Complex (Oshima belt, southern Hokkaido Island). This black limestone contains megalodont shells, microcoprolites and foraminifers. Despite the very strong recrystallization, involutinids are relatively well preserved. Additionally Upper Triassic limestone clasts also crop out in the Idonnappu zone in southern central Hokkaido (Sakagami and Sakai 1979; Kiyokawa 1992; Ueda et al. 2000).

Upper Triassic reef limestone crops out in the Sikhote-Alin region (Far East Russia), and more precisely in the Dalnegorsk area, (Punina 1997a, b; Belyaeva 1997). The reef biota that has been reported in the scarce literature includes scleractinian corals, calcareous sponges, solenoporacean algae and foraminifers. The microfacies are not described in detail.
In South East Asia, Jurassic-Early Cretaceous accretionary complexes of the North Palawan blocks (Calamian Islands, The Philippines) are correlated to the SAC (Faure and Ishida 1990; Zamoras and Matsuoka 2001). In particular, Kiessling and Flügel (2000) reported from Busuanga Island and surrounding smaller islands 13 microfacies that are extremely similar to those of the SAC. These localities are the most promising target for future investigation of mid-oceanic carbonate platform of the West Panthalassa domain.

Regarding the East Panthalassa domain, biotic content of Upper Triassic shallow water limestone of the American terranes have been relatively well documented, especially the coral fauna (e.g. Stanley 1979; Caruthers and Stanley 2008; Roniewicz and Stanley 2013). Nevertheless, several reef localities in British Columbia still lack extensive microfacies analysis and micropaleontological inventory. For example, scleractinian corals and calcareous sponges have been reported from Eaglenest reef limestone (Stanley and Nelson 1996; Stanley and Senowbari-Daryan 1999) but microfauna and microfacies are not documented in detail and such analyses are needed (Martindale et al. 2015). In San Juan Island (Washington, USA), Upper Triassic limestone crops out with very similar mode of occurrence with respect to the limestone-basalt-volcaniclastic breccia of the SAC (Brandon et al. 1988; Igo and Adachi 1990; Brown et al. 2007). Well preserved foraminifers occur near Roche Harbor (Igo and Adachi 1990). Yamagata (2010) interpreted the nearby Deadman Formation as the expression of seamount subduction and accretion. In Vancouver Island, Upper Triassic limestone crops out in several localities but is often recrystallized or silicified. Nevertheless the close vicinity of the Wrangellia Large Igneous Province, which is assumed to be responsible of the Carnian Pluvial Episode (Greene 2008; Dal Corso et al. 2012), makes interesting the study of how such an event is recorded in nearby limestone rocks.

In conclusion, the Panthalassa Ocean has not yet revealed all its secrets. Future research will surely further unravel the mysteries concealed in the accreted remains of ancient oceanic islands and terranes that were scattered in this outstandingly huge ocean.

References


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**Appendix 1:** List of samples collected in Kyushu, Shikoku and Kii Peninsula (Honshu Island). The studied material is stored in the Department of Earth Sciences of the University of Geneva, Switzerland (Camille Peybernes, PhD Collection).

All limestone samples are considered Upper Triassic in age if not stated otherwise

<table>
<thead>
<tr>
<th>Localities</th>
<th>Samples</th>
<th>Comments</th>
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<td>Appendix 2b</td>
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<td>Honjo area</td>
<td>CP134-137</td>
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<td>CP216-218</td>
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<td>CP219</td>
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<td>CP209-210</td>
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<td>CP62-83</td>
<td>(chert breccia)</td>
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<td>Kii Peninsula</td>
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Appendix 3: Location maps of samples collected in Shikoku. a Loc. Inaba, Tsuno windmill, Tsuno road, Tsuno Megabreccia, Mt. Bandagamori. b Loc. Mt. Sambosan
Appendix 4: Location maps of samples collected in Shikoku. **a** Loc. Befu, Mt. Ishidate, Konose Kyo, Hisaidani. **b** Loc. Wajiki, Road 28
Appendix 5: Location maps of samples collected in the Kii Peninsula. 

- **a** Loc. Yura
- **b** Loc. Daifugendake, Wasabidani
- **c** Loc. Osako dam

![Location maps of samples collected in the Kii Peninsula](image-url)