Temporal changes in biotic and abiotic composition of shallow-water carbonates on submerged seamounts in the northwestern Pacific Ocean and their controlling factors

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Takayanagi H., Iryu Y., Oda M., Sato T., Chiyonobu S., Nishimura A., Nakazawa T., Ishikawa T. & Nagaishi K. 2012. — Temporal changes in biotic and abiotic composition of shallow-water carbonates on submerged seamounts in the northwestern Pacific Ocean and their controlling factors. *Geodiversitas* 34 (1): 189-217. http://dx.doi.org/10.5252/g2012n1a11

ABSTRACT
The lithology of Cretaceous to Pleistocene shallow-water carbonates, which were collected from 29 sites on 24 submerged seamounts in the northwestern Pacific Ocean using the Deep-sea Boring Machine System, are described. The shallow-water carbonate deposits examined in the present study can be roughly divided into three types based on their composition: Cretaceous, Eocene (to lowest Oligocene?), and Oligocene to Pleistocene. The Cretaceous type is characterized by an abundance of molluscs (including rudists), smaller foraminifers, microencrusters, non-skeletal grains (e.g., peloids, cortoids, and intraclasts), and microbial sediments. Most components have been micritized and possess thick micrite envelopes. The Eocene type is characterized by the dominance of larger foraminifers, *Halimeda* spp., nongeniculate and geniculate coralline algae, bryozoans, and dasycladacean algae. Scleractinian corals are very minor components. The Oligocene to Pleistocene type is similar in composition to the Eocene type, but it differs from the latter by the abundant occurrence of scleractinian corals and nongeniculate coralline algae. Corals, nongeniculate coralline algae, and *Halimeda* spp., which precipitate carbonates within closed to semi-closed spaces in and around their bodies (intra-tissue), are major components of the Eocene and Oligocene to Pleistocene types. In contrast, the Cretaceous-type sediments contain relatively more carbonates of extra-tissue origin (i.e. carbonates deposited in relatively open spaces around the bodies of organisms, such as rudists, as well as microbialite and ooids) than the Eocene and Oligocene to Pleistocene types. The changes in the major constituents of the carbonate factory depend on local environments, such as nutrient availability, as well as a global factor: seawater chemistry in the surface waters. Temporal variations in the abundance of the shallow-water carbonates on the examined seamounts suggest that carbonate accumulation was not necessarily controlled by climatic conditions; instead, it was related to the volcanism and tectonics that served as the foundations for reef/carbonate-platform formation.

KEY WORDS
shallow-water carbonate,
seamount,
northwestern Pacific Ocean,
seawater chemistry,
Late Cretaceous,
Cenozoic.

RÉSUMÉ
Évolution au cours du temps de la composition bioclastique ou azoïque de sédiments carbonatés peu profonds, prélevés sur quelques monts sous-marins du nord-ouest de l'océan Pacifique, et analyse des facteurs de contrôle.
Nous décrivons la lithologie de séries carbonatées de faible profondeur mais d'âges variés, Crétacé à Pléistocène, prélevés grâce à un appareil de forage en eau profonde sur 29 sites répartis sur 24 monts sous-marins du nord-ouest de l'océan Pacifique. Les dépôts étudiés peuvent être classés en trois catégories selon leur âge et leur composition : Crétacé, Éocène-?Oligocène inférieur, Oligocène-Pléistocène. Les dépôts de type « Crétacé » se caractérisent par leur richesse en mollusques (dont les rudistes), petits foraminifères benthiques, micro-encroûtements, allochems non-bioclastiques (tels que péloïdes, cortoïdes et intraclastes) et produits microbiens. La plupart de ces constituants ont été micritisés et présentent une épaisse enveloppe micritique. Les dépôts de type « Éocène » se caractérisent par l'abondance en grands foraminifères benthiques, fragments d'*Halimeda*, algues corallines articulées ou non, bryozoaires et algues dasycladales. Les coraux scléractiniaires sont très peu abondants. Les dépôts de type « Oligocène-Pleistocène » diffèrent peu des dépôts éocènes, si ce n'est qu'ils sont beaucoup plus riches en coraux scléractiniaires et d'algues corallines inarticulées. Les coraux, les algues corallines inarticulées et *Halimeda*, qui ont

la propriété de faire précipiter des carbonates dans des espaces ouverts à semi-ouverts, à l'extérieur ou à l'intérieur (dépôts intra-tissulaires) de leur corps sont les composants dominants des types « Éocène » et « Oligo-Pléistocène ». Par contre, les dépôts de type « Crétacé » contiennent relativement plus de carbonates extra-tissulaires (précipités dans des espaces relativement libres présents à l'extérieur des organismes, comme les rudistes, voire les microbialites et les ooïdes). En général, les changements de composition des constituants sédimentaires majeurs au sein de l'« usine à carbonates » relèvent de variations locales du milieu, tels les apports en nutriments, mais aussi de facteurs plus généraux, tel le chimisme des eaux marines de surface. Dans le cas présent, il apparaît que les variations temporelles dans les flux de dépôt des carbonates marins étudiés ne dépendent pas obligatoirement des seules conditions climatiques, mais que le volcanisme et la tectonique ont eu un rôle majeur dans la formation de ces récifs et plates-formes carbonatées.

MOTS CLÉS
carbonate peu profond,
mont sous-marin,
nord-ouest de l'océan Pacifique,
chimie de l'eau de mer,
Crétacé supérieur,
Cénozoïque.

INTRODUCTION

Many seamounts in the northwestern Pacific Ocean are commonly covered with shallow-water carbonate deposits. Based on lithological and chronological analyses, we showed that the timing of deposition of those shallow-water carbonates might not have been controlled by climatic conditions but was predominantly related to the volcanism and tectonics that served as the basement for reef/carbonate-platform formation (Takayanagi *et al.* 2007).

It is generally accepted that there are temporal changes in the biotic and abiotic composition of carbonate deposits on reefs/carbonate platforms (Wood 1999; Stanley 2006) and in the mineralogies of calcifying marine taxa and non-skeletal marine carbonates and evaporite (Sandberg 1983), both of which are controlled by secular variations in seawater chemistry, such as the Mg/Ca ratio (Hardie 1996; Stanley & Hardie 1998; Stanley 2006) and carbonate saturation states (Riding & Liang 2005a, b).

Some studies emphasize the importance of the land-ocean configuration as a controlling factor in the evolution (speciation and dispersion) of hermatypic organisms and the development of reefs/carbonate platforms. In Southeast Asia, for example, reefs/carbonate platforms are characterized by very limited zooxanthellate coral genera and zooxanthellate coral-dominated carbonates until the latest Oligocene to earliest Miocene (around the Paleogene-Neogene transition), which is called the "Paleogene gap" (e.g., Wilson & Rosen 1998). The "Paleogene gap" was ascribed to a change in the land-ocean configuration in Southeast Asia, because the post-Paleogene increases in diversity, endemicity, and origination rates of zooxanthellate corals in this region coincide with a tectonic event: the collision of the Australasian craton with the Southeast Asian craton. The gap between Australasia and the Southeast Asia mainland, with few shallow-water areas and landmasses, narrowed through the Paleogene; shallow-water areas increasingly emerged as the Australasian craton moved northward, colliding with the Southeast Asian craton during the transition between the Paleogene and the Neogene.

To improve our understanding of the evolutionary processes of reef/carbonate-platform builders, we need to examine temporal variations in shallow-water carbonates in a location where the depositional environment and tectonic setting are relatively stable. Shallow-water carbonates on seamounts in the northwestern Pacific Ocean fulfill this requirement much better than those in tectonically active areas. Thus, they provide an excellent archive of these processes; we can collect "continuous" records of reefs/carbonate platforms from the Cretaceous to the present by integrating lithological, paleontological, and chronological data from several seamounts.

Hence, the purposes of this study are to describe sedimentary facies and biotic and abiotic components and determine the depositional ages of shallow-water carbonates on the submerged seamounts in the northwestern Pacific Ocean; to classify the shallow-water carbonates on the basis of the biotic and abiotic composition; and to discuss the major controlling factors of such temporal changes in the composition.

MATERIAL AND METHODS

Samples examined in this study were collected between 1999 and 2008 during the series of cruises of the project entitled "Basic Researches on Exploration Technologies for Deep-sea Natural Resources", which is commissioned to Japan Oil, Gas and Metals National Corporation (JOGMEC) by the Ministry of Economy, Trade and Industry, Japan (METI). We include data on the lithology and ages of the shallow-water carbonates recovered from 29 sites on 24 seamounts on the Amami Plateau, Daito Ridge, Oki-Daito Ridge, Urdaneta Plateau, Kyushu-Palau Ridge, and Ogasawara Plateau in the northwestern Pacific Ocean (Fig. 1; Table 1). Portions of the data have been presented by Takayanagi *et al.* (2007). Data on the shallow-water carbonates on the unnamed seamount to the west of the Kita-Ryusei Seamount (Takayanagi *et al.* 2007) are not included in this study because their depositional age has not been determined.

Cores were drilled with the Deep-sea Boring Machine System (Nichiyu Giken Kogyo, Kawagoe, Japan and Williamson & Associates, Seattle, USA; Matsumoto & Sarata 1996), a wireline rock drill, installed aboard the R/V *Daini-Hakurei*. The cores are *c.* 40-45 mm in diameter. The lithology of the carbonate deposits is described following Takayanagi *et al.* (2007).

Chronological constraint is provided by calcareous nannofossil biostratigraphy (Table 2), planktonic foraminiferal biostratigraphy (Table 3), larger foraminiferal biostratigraphy (Table 4), and Sr isotope stratigraphy (Table 5). Benthic foraminifers are divided into larger and smaller foraminifers.

Calcareous nannofossil biostratigraphy

Standard smear slide methods were used for all samples. A Norland optical adhesive was used as a mounting medium. Calcareous nannofossils were examined under a polarizing light microscope at 1500× magnification. Age estimates for all calcareous nannofossil datums were based on correlation with the geomagnetic polarity time scale of Cande & Kent (1995).

Planktonic foraminiferal biostratigraphy

Planktonic foraminifers in well-indurated carbonates were identified in thin sections under a polarizing light microscope at 40× to 100× magnification.

Larger foraminiferal biostratigraphy

Larger foraminifers were identified, at a generic or higher taxonomic level, in thin sections under a light microscope at 20× to 100× magnification. The stratigraphic ranges of Cenozoic larger foraminifers in the northwestern Pacific Ocean followed Matsumaru (1974, 1996). Because the ranges of the larger foraminifers cannot be correlated with a precise stratigraphic framework, such as the biostratigraphy of planktonic taxa, the age constraints based on these data are approximate.

Sr isotope stratigraphy

Sr isotope analyses, for dating of the carbonate deposits, were performed at four laboratories: Activation Laboratories Ltd., Ancaster, Canada; Mitsubishi Materials Natural Resources Development Corp., Saitama, Japan; University of Colorado at Boulder, USA; and Kochi Institute for Core Sample Research, Kochi, Japan. The analytical methods used at the first three laboratories were described by Takayanagi *et al.* (2007), Nakazawa *et al.* (2008), and Kaufman *et al.* (1993), respectively. Those used at the Kochi Institute for Core Sample Research are given in the Appendix. Sr isotope ages of shallow-water carbonates on the following seamounts do not agree with those provided by calcareous nannofossil and larger foraminiferal biostratigraphy: Koniya Seamount (Jurassic); Daito 3316 and Oki-Daito 3336 Seamounts (Campanian); a peak of the Daito Ridge, Daito 3316 Seamount, unnamed seamount no. 2 on the Oki-Daito Ridge, Oki-Daito 3336, 430 and 432, and Basho Seamounts (earliest Oligocene); and Kosei Seamount (latest Oligocene). This chronological disparity is not within the scope of this study. The Geologic Time Scale of Gradstein *et al.* (2004) is used in this paper.

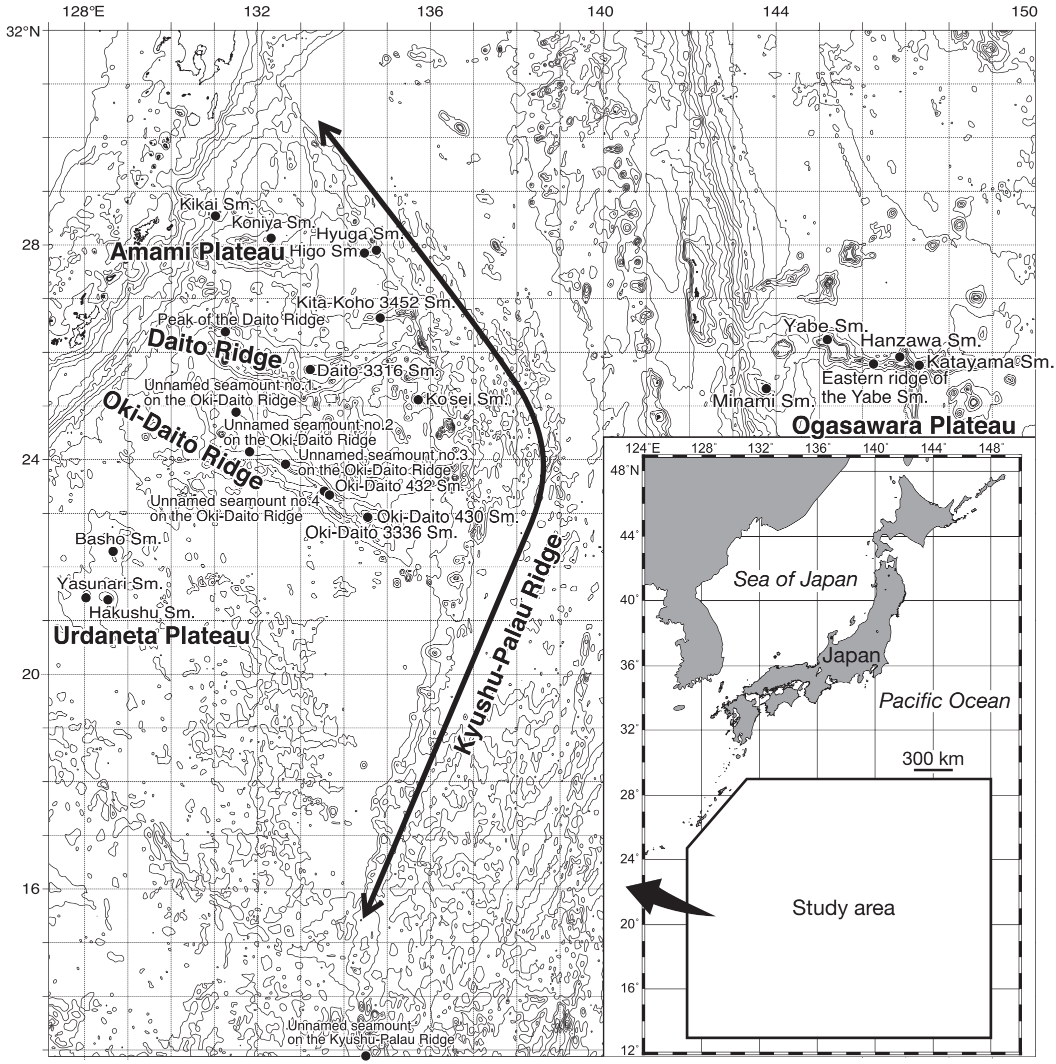


Fig. 1. — Locations of the seamounts where the shallow-water carbonates were recovered with the Deep-sea Boring Machine System installed aboard the R/V *Daini-Hakurei*. Abbreviation: **Sm**, seamount.

RESULTS

Lithology of shallow-water carbonates

Based on sedimentological and paleontological analyses, the carbonate deposits can be divided into three types. The depositional ages of the three types are clearly separated into three time intervals, Cretaceous, Eocene (probably including lowest Oligocene), and Oligocene to Pleistocene (Fig. 2). Hereafter, assigning the formation ages, we refer to them as C-type, E-type, and OP-type.

C-type

C-type carbonates were recovered from the Amami Plateau (Koniya Seamount) and the Ogasawara Plateau (Minami, Yabe, Hanzawa, and Katayama Seamounts and the eastern ridge of the Yabe Seamount) (Fig. 2). The major lithologies of the Cretaceous

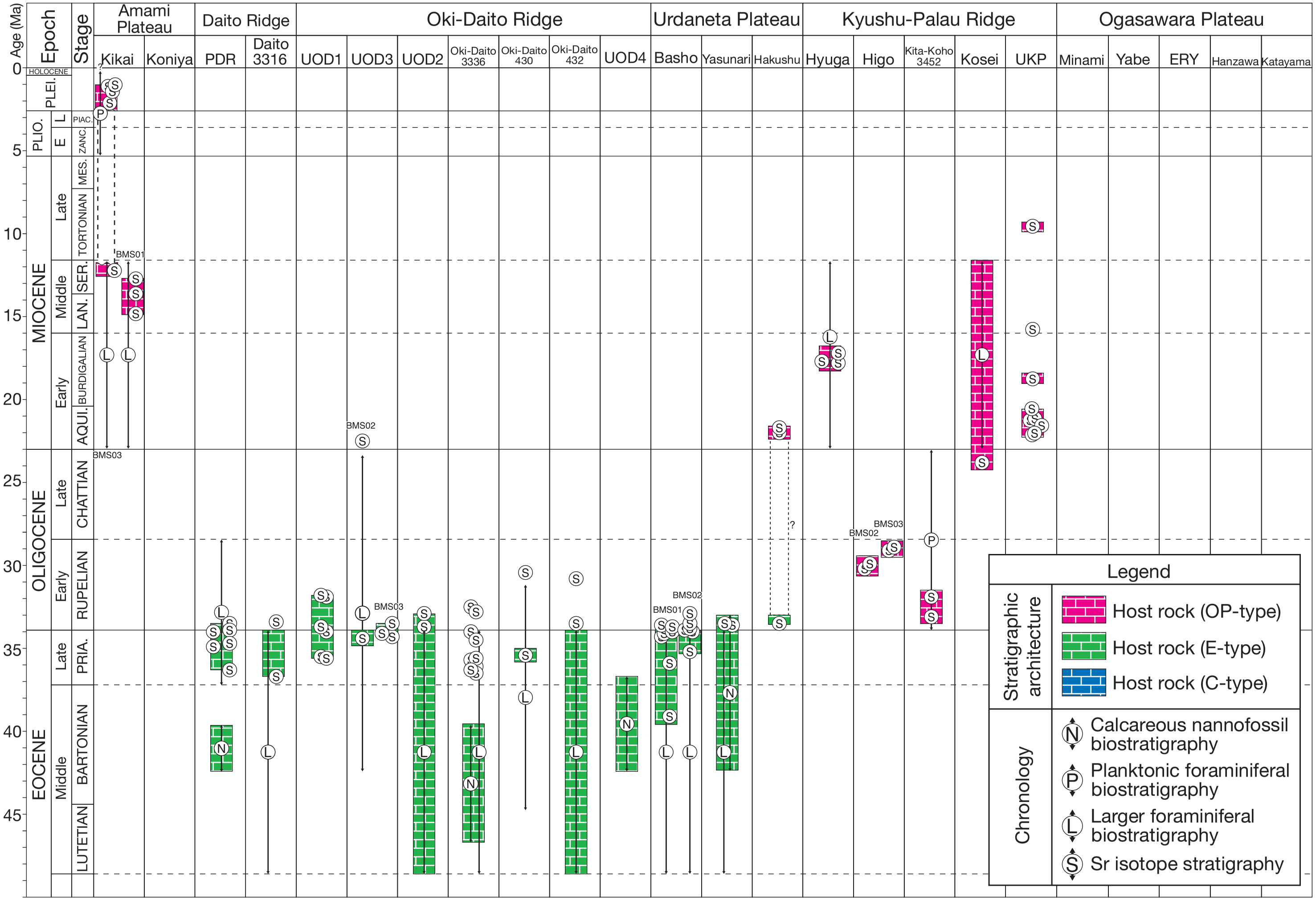


FIG. 2. — Correlation of the shallow-water carbonates from the seamounts examined in this study. Abbreviations: **ERY**, eastern ridge of the Yabe Seamount; **PDR**, peak of the Daito Ridge; **UKP**, unnamed seamount on the Kyushu-Palau Ridge; **UOD1**, unnamed seamount no.1 on the Oki-Daito Ridge; **UOD2**, unnamed seamount no. 2 on the Oki-Daito Ridge; **UOD3**, unnamed seamount no. 3 on the Oki-Daito Ridge; **UOD4**, unnamed seamount no. 4 on the Oki-Daito Ridge.

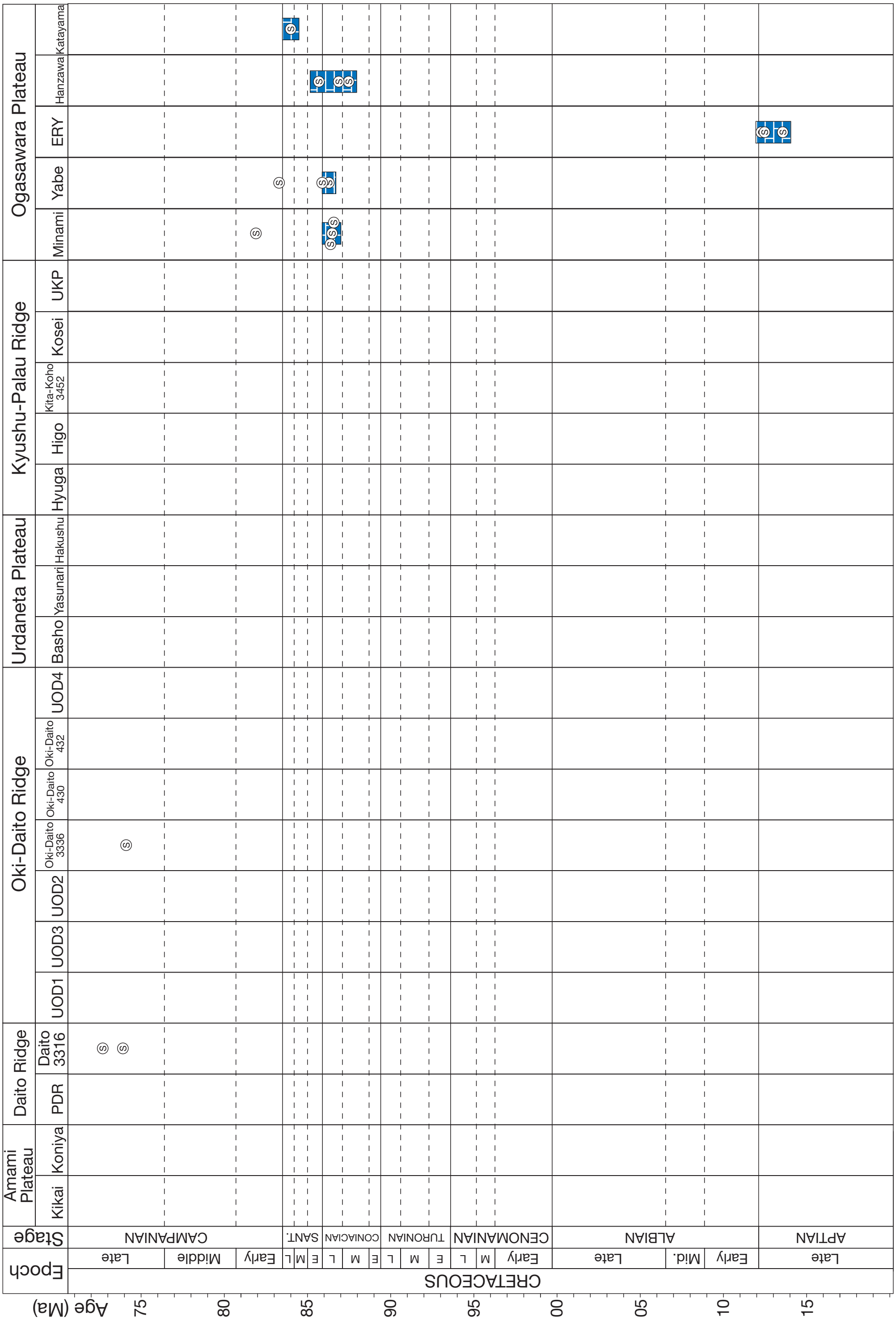


Fig. 2. — Continuation.

shallow-water carbonates are molluscan floatstone/rudstone, bioclastic rudstone, and bioclastic packstone/grainstone rich in non-skeletal grains (Fig. 3A). They commonly include pebble-sized molluscs (including rudists, some of which are assigned to the family Plagioptychidae Douvillé, 1888). Their microfacies are characterized by an abundance of molluscs, smaller foraminifers, microencrusters (*Bacinella* Radoičić, 1959 and *Lithocodium* Elliot, 1956), peloids, cortoids, and intraclasts (Fig. 3B). Microencrusters may have acted as a framework-builder, in part. Calcareous algae (solenoporacean and peyssonneliacean algae), larger foraminifers (including orbitolinids), calcified sponges, and echinoids are common; dasycladacean algae, bryozoans, ostracods, ooids, oncoids, and aggregate grains are minor components. Hermatypic corals are very scarce, and coralline algae are absent. Most of the biotic and abiotic components have been partially to completely dissolved and/or micritized; they have been replaced with sparry calcite cement and/or they possess thick micrite envelopes. Micritic envelopes and grains/clasts of a microbial origin are commonly found. Micritization in the C-type carbonates is much more extensive than in the younger types of carbonates. Generally, the C-type carbonates are well cemented; inter- and intragranular spaces, solution vugs, and cracks are completely filled with several generations of cement.

E-type

E-type carbonates were collected from the Daito Ridge (Daito 3316 Seamount and a peak of the Daito Ridge), the Oki-Daito Ridge (unnamed seamounts nos 1-4, Oki-Daito 3336, 430 and 432 Seamounts), and the Urdaneta Plateau (Basho and Yasunari Seamounts) (Fig. 2). Three major lithologies are recognized in the E-type carbonates: larger foraminiferal packstone/rudstone, *Halimeda* rudstone, and bioclastic packstone/grainstone/wackestone.

The larger foraminiferal packstone/rudstone was collected from the Daito 3316 Seamount, a peak of the Daito Ridge, the Oki-Daito 3336, 430, and 432 Seamounts, and unnamed seamounts nos 2-4 on the Oki-Daito Ridge. Larger foraminifers include *Nummulites* sp., *Discocyclina* sp., alveolinids, and *Operculina* sp. (Fig. 3C). Some larger foraminifers are bioeroded and possess micrite envelopes and remnants of micro-borings. Other bioclasts include molluscs, nongeniculate and geniculate coralline algae, bryozoans, dasycladacean algae, *Halimeda* spp., echinoids, planktonic and smaller foraminifers, corals, and ostracods (Fig. 3D). Non-skeletal grains, such as ooids (including superficial ooids), peloids, cortoids, aggregated grains, and intraclasts, do occur but constitute a minor component. Rhodoliths are common and are mostly pebble sized. The nuclei of some rhodoliths consist of nummulitid larger foraminifers, whereas others have been almost completely bioeroded and/or micritized. Generally, rhodoliths have envelopes composed of thin, encrusting nongeniculate coralline algae, with lesser amounts of encrusting bryozoans and encrusting foraminifers.

The *Halimeda* rudstone were recovered from the unnamed seamount no. 1 on the Oki-Daito Ridge and the Basho Seamount (Takayanagi *et al.* 2007: figs 5, 6). This rudstone consists mainly of *Halimeda* segments. The segments are generally oriented randomly and have been mostly dissolved to leave moldic porosity; the pores are partially or completely filled with sparry calcite cement. However, the segments are arranged more or less parallel to the bedding plane in the *Halimeda* rudstone on the unnamed seamount no. 1 on the Oki-Daito Ridge. Other bioclasts in the *Halimeda* rudstone include common to abundant bryozoans, larger foraminifers (including *Discocyclina* sp., *Nummulites* sp., and *Gypsina* sp.), dasycladacean algae, smaller foraminifers, nongeniculate and geniculate coralline algae and rare hermatypic corals (including *Stylophora* sp.), planktonic foraminifers, molluscs, echinoids, annelids, barnacles, and ostracods. Peloids are abundant; cortoids, intraclasts, and rhodoliths are common. Although the *Halimeda* rudstone may have been more porous, the pores have been filled with multigenerational infilling sediments, ranging in age from the Eocene to the Pleistocene.

Bioclastic packstone/grainstone/wackestone consist mainly of bioclasts including nongeniculate and geniculate coralline algae, smaller foraminifers, bryozoans, larger foraminifers, *Halimeda* spp., dasycladacean algae, echinoids, planktonic foraminifers, molluscs, ostracods, and corals. Rhodoliths are abun-

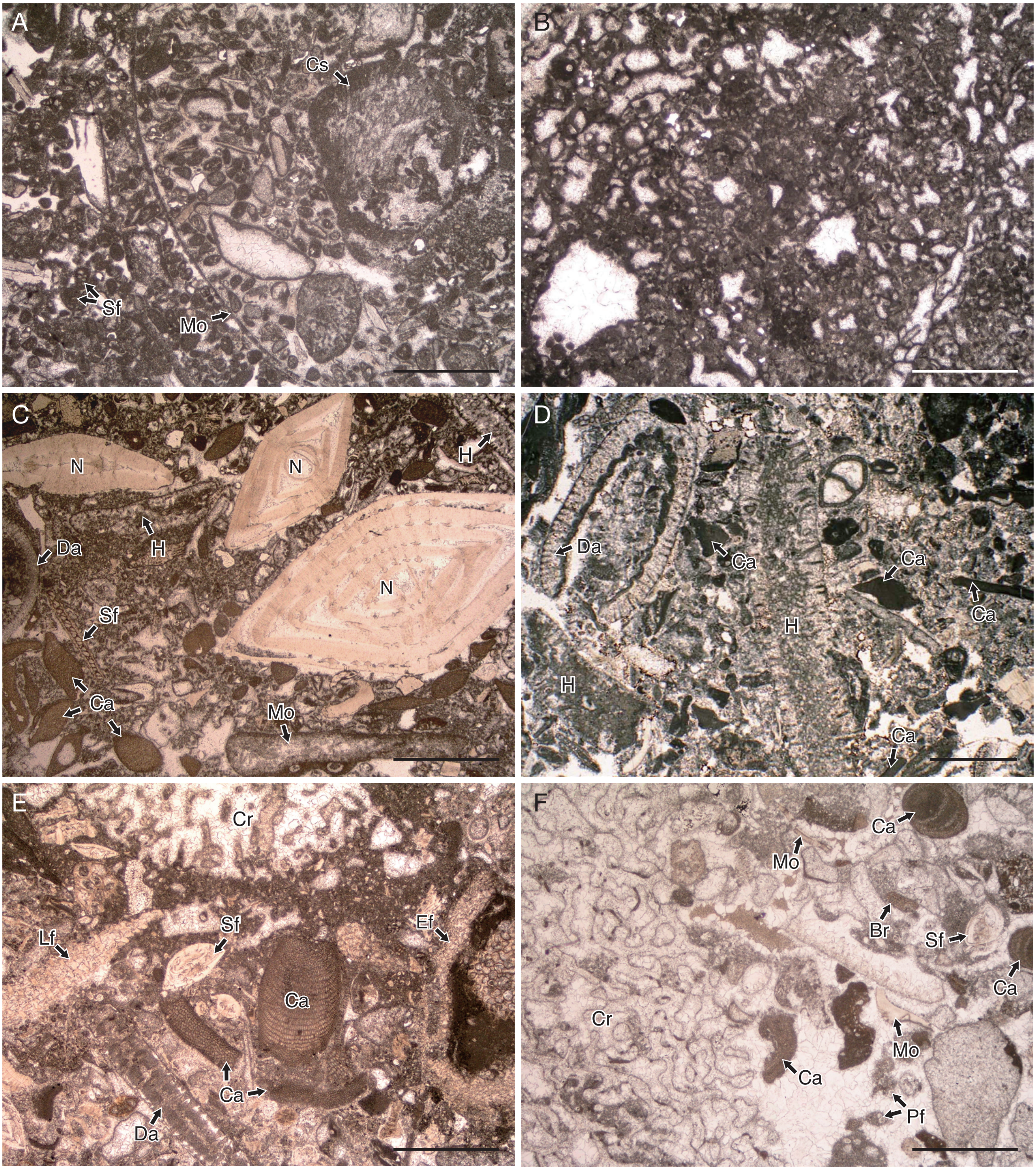


FIG. 3. — Photomicrographs of shallow-water carbonates from seamounts in the northwestern Pacific Ocean: **A**, Peloidal grainstone "matrix" of bioclastic rudstone, 1.16 mbsf in 99DCBMS07H drilled at the Hanzawa Seamount, Late Cretaceous (Coniacian to Santonian); **B**, Microencrusters (*Bacinella*), 1.32 mbsf in 06DSOG460BMS01 drilled at the eastern ridge of the Yabe Seamount, Early Cretaceous (Aptian); **C**, bioclastic grainstone with abundant nummulitid larger foraminifers, 0.60 mbsf in 04DSOD430BMS02 drilled at the Oki-Daito 430 Seamount, Late Eocene; **D**, bioclastic grainstone, 1.35 mbsf in 06DSOD419BMS02 drilled at the unnamed seamount no. 3 on the Oki-Daito Ridge, Late Eocene; **E**, bioclastic packstone "matrix" of coral rudstone, 0.47 mbsf in 04DSAM390BMS01 drilled at the Kikai Seamount, Middle Miocene; **F**, bioclastic grainstone/packstone "matrix" of coral rudstone, 0.04 mbsf in 08DSKP810BMS01 drilled at the unnamed seamount on the Kyushu-Palau Ridge, Late Miocene. Abbreviations: **Br**, bryozoan; **Ca**, coralline alga; **Cr**, coral; **Cs**, calcified sponge; **Da**, dasycladacean alga; **Ef**, encrusting foraminifer; **H**, *Halimeda* sp.; **Lf**, larger foraminifer; **Mo**, mollusc; **N**, *Nummulites* sp.; **Pf**, planktonic foraminifer; **Sf**, smaller foraminifer. Scale bars: 1 mm.

dant: their size, outer morphology, and composing organisms are the same as those from the larger foraminiferal packstone/rudstone. Non-skeletal grains, such as intraclasts, peloids, altered pumice, and volcaniclasts, constitute a minor component.

OP-type

OP-type carbonates were recovered from the Amami Plateau (Kikai Seamount), the Urdaneta Plateau (Hakushu Seamount), and the Kyushu-Palau Ridge (Higo, Kita-Koho 3452, Hyuga, and Kosei Seamounts and the unnamed seamount on the Kyushu-Palau Ridge) (Fig. 2). The major lithologies of the OP-type carbonates are coral floatstone/rudstone (Fig. 3E, F) and bioclastic packstone/grainstone. These carbonate rocks are characterized by abundant branching and massive corals, nongeniculate and geniculate coralline algae, bryozoans, smaller foraminifers, and molluscs. The corals are allochthonous; no *in situ* corals have been found. Corals in the Miocene to Pleistocene coral rudstone/floatstone are more diverse than those in the Oligocene coral floatstone. Rhodoliths are commonly made up of coral nuclei, and envelopes are composed mainly of encrusting nongeniculate coralline algae, with lesser amounts of encrusting bryozoans and encrusting foraminifers. Other bioclasts of the OP-type carbonates include planktonic and larger foraminifers (including *Lepidocyclina* sp., *Miogypsina* sp., *Amphistegina* sp., *Operculina* sp., and soritids), echinoids, *Halimeda* spp., ostracods, and dasycladacean algae. Common non-skeletal components include intraclasts and peloids.

Major components of shallow-water carbonates

Abundant scleractinian corals were found in the OP-type carbonates recovered from the Kikai, Higo, Kita-Koho 3452, Kosei, and Hyuga Seamounts, which contrasts well with their rare occurrence and absence in the C-type and E-type carbonates, respectively (Table 6). Corals are of massive, branching, and encrusting forms; no tabular coral was recovered. Because some essential characteristics are not preserved, corals are identified to the family or genus level. Extinct genera were not found in this study. Coral taxa recovered in this study are common in tropical to subtropical reef regions in the Pacific Ocean.

Coralline algae occur in the E-type and OP-type carbonates examined in this study, although they are missing from the C-type carbonates. Like corals, the algae are relatively more common to abundant and are one of the major components of the shallow-water carbonates from the Oligocene onwards. Coralline algae occur as bioclasts or form rhodoliths (Kikai, Higo, Basho, Oki-Daito 3336, 430 and 432 Seamounts and unnamed seamounts nos 1-3 on the Oki-Daito Ridge); much less commonly, they form a coralgal framework (Kikai Seamount). Mastophoid algae with large trichocytes, which dominate nongeniculate coralline algal assemblages in a present-day shallow reef environment, are absent in the E-type carbonates and are present in the OP-type carbonates. Rhodolith-forming nongeniculate coralline algae are associated commonly with encrusting foraminifers and/or encrusting bryozoans. Rhodoliths are frequently bioeroded; the borings are filled with a mixture of micrite and bioclasts and/or peloid.

Halimeda spp. were found in the E-type and OP-type carbonates. This alga is fairly abundant in the E-type carbonates on the unnamed seamount no. 1 on the Oki-Daito Ridge and Basho Seamount, where segments 5 to 15 mm long and <1 mm thick are tightly packed and oriented randomly (Takayanagi *et al.* 2007). In addition to such concentrated occurrences, *Halimeda* segments are common, although they are not volumetrically important, in the OP-type carbonates. Most of the *Halimeda* segments occur as molds; consequently, their identification to the species level is not possible.

Larger foraminifers were found in all types of carbonates. They are well preserved in general; in the C-type carbonates especially, their tests may be bioeroded and/or micritized to form thick micrite envelopes. Larger foraminifers constitute a minor component of the C-type carbonates; however, miliolid smaller foraminifers are more common in this type than in the E-type or OP-type carbonate. The E-type carbonates contain abundant larger foraminifers, such as *Nummulites* sp., *Discocyclina* sp., alveolinids, and *Gypsina* sp. Larger foraminifers, which include *Amphistegina* sp., *Miogypsina* sp., *Lepidocyclina* sp., *Operculina* sp., and soritids, constitute a major component of the OP-type carbonates.

Rudists are common in the C-type carbonates; however, they are neither *in situ* nor tightly packed to form a framework structure (Kauffmann & Johnson 1988; Wood 1999). This suggests that they may have grown scattered in a lagoonal environment (indicated by floatstone lithology commonly with a "matrix" of bioclastic packstone). Rudist shells are more or less bioeroded and possess thin to thick micrite envelopes or may have a microbial-micrite coating. This suggests that they served as a substrate on which epifauna and epiphytes could grow.

The C-type carbonates are rich in non-skeletal grains, such as peloids, intraclasts, and microbial grains, most of which have been partially or completely micritized and are identified as cortoids. Ooids, oncoids, and aggregate grains occur as minor components. The E-type and OP-type carbonates are relatively deficient in non-skeletal grains (except for rhodoliths) compared with the C-type carbonates.

DISCUSSION

A single core from this study is not long enough to delineate temporal changes in the biotic and abiotic composition of shallow-water carbonates and the timing of carbonate deposition from the Cretaceous onwards. However, more than 29 cores, ranging in age from Cretaceous to Pleistocene, were collected from 24 seamounts in an extensive area in the northwestern Pacific Ocean. Therefore, we addressed the above-mentioned issues by integrating lithological, paleontological, and chronological data from these cores.

Timing of carbonate deposition

Takayanagi *et al.* (2007) concluded that the timing of deposition of the shallow-water carbonates on the seamounts in the northwestern Pacific Ocean was related to volcanic activity and tectonic movements; both contributed to form foundations on which reefs/carbonate platforms could extend and grow. This conclusion is based on the fact that the shallow-water carbonates on the seamounts examined accumulated during or immediately after the edifice-forming volcanic activities, with the exception of those recovered from the Kikai Seamount (Nakazawa *et al.* 2008): Miocene and Pleistocene carbonates were deposited on a volcanic edifice formed in the Early Cretaceous (Hickey-Vargas 2005). The deposition of shallow-water carbonates on those seamounts was not necessarily related to paleoclimate. For example, large amounts of shallow-water carbonates accumulated during the Early Oligocene, a relatively cool period (Zachos *et al.* 2001), whereas limited carbonate deposits formed during the Early Miocene, a relatively warm period (Crowley & North 1991; Zachos *et al.* 2001). Our data from the current study provide supportive evidence to the conclusions of Takayanagi *et al.* (2007). Shallow-water carbonate deposition occurred during periods ranging from the Middle Eocene to the earliest Oligocene on the Daito Ridge (formed in the Late Cretaceous; Kinoshita 1980; Ueda 2004), from the Middle Eocene to the Early Oligocene on the Oki-Daito Ridge (formed in the Late Cretaceous to Early Paleocene; Katsura *et al.* 1994; Ueda 2004), from the Middle Eocene to the Early Miocene on the Urdaneta Plateau (formed in the Middle Eocene or earlier; Ozima *et al.* 1977), from the Early Oligocene to the Late Miocene on the Kyushu-Palau Ridge (formed in the Early Eocene to Late Oligocene; Tokuyama 2007), and during the Late Cretaceous on the Ogasawara Plateau (formed in the Late Jurassic to Early Cretaceous).

Temporal variations in composition of shallow-water carbonates

Calcifying marine taxa and abiotic calcareous precipitates can be roughly divided into two types based on their location of carbonate precipitation: intra-tissue type and extra-tissue type (Iryu & Yamada 1999). The former precipitates carbonates within closed to semi-closed spaces in and around its body; the latter secretes carbonates in relatively open spaces around its body. Abiotic calcareous grains, such as ooids and microbial carbonate, are assigned to the latter type. The results of this study indicate that the C-type carbonates are dominated by the extra-tissue type (e.g., molluscs, ooids, and microbialites). In contrast, the E-type and OP-type carbonates are rich in the intra-tissue type (e.g., corals, coralline algae, and *Halimeda* spp.). This contrasting feature may reflect different modes of seawater chemistry between the Cretaceous and the Eocene and from the Oligocene onwards, e.g., the saturation state of seawater with respect to calcium carbonate was relatively higher in the former period compared to the latter. This agrees well with the reconstruction of Phanerozoic variations in the surface seawater saturation ratio for carbonate minerals (Fig. 4; Riding & Liang 2005a, b) using estimates of past seawater ionic composition (Hardie 1996; Stanley & Hardie 1998) and atmospheric CO_2 levels (Berner & Kothavala 2001). The temporal distribution of the calcifying marine taxa presented in this study also largely agrees with those presented by Hardie (1996), Stanley & Hardie (1998), and Stanley (2006), who concluded that the Mg/Ca ratio of seawater has exerted strong control over the secular variations in calcifying marine taxa and their mineralogies during the Phanerozoic. In conclusion, the temporal change in the biotic and abiotic composition of shallow-water carbonates from the Cretaceous onwards reflects variations in the mineralogies and calcification sites of calcifying marine taxa and abiotic calcareous precipitates that have been controlled by seawater chemistry, such as the saturation state for carbonate minerals and the Mg/Ca ratio.

Our study indicates that carbonate factories analogous to modern coral reefs were initiated in the Oligocene, because hermatypic corals are common to abundant in the OP-type carbonates. Two hypotheses have been presented to explain the paucity of scleractinian corals during the Cretaceous to Eocene and their prevalence during the Oligocene or younger ages. Ries *et al.* (2006) attributed this to a change in the Mg/Ca ratio of seawater from the Cretaceous onwards. They concluded that slow calcification rates, resulting from the production of largely aragonitic skeletons in chemically unfavorable seawater (*m*Mg/Ca [molar ratio of Mg/Ca] < 2), probably contributed to the scleractinians' diminished reef-building role in the calcite seas of the Late Cretaceous and early Cenozoic. They also stated that calcification rates of corals were elevated in seawater with *m*Mg/Ca = 3.5, a level approached in the Oligocene, which resulted from the combined effect of a favorable ambient Mg/Ca ratio (*m*Mg/Ca > 2) for aragonite precipitation and a relatively high concentration of Ca compared with modern seawater (Stanley *et al.* 2005) (Fig. 5). Wilson & Rosen (1998) concluded that the lack of Paleogene zooxanthellate coral genera and zooxanthellate coral-dominated carbonates in Southeast Asia ("Paleogene gap") was caused by the land-ocean configuration in this area (see Introduction), whereas Rosen & Smith (1988) and McCall *et al.* (1994) stated that the collision of Australasia with Southeast Asia and the closure of the Tethys in the Middle East during the latest Oligocene to earliest Miocene triggered the emergence of the modern high diversity of scleractinian hermatypic corals in Southeast Asia. However, an increased abundance and diversity of the corals occurred in the Early Oligocene in the shallow-water carbonates in the northwestern Pacific Ocean (Fig. 4). Our finding agrees well with the data of Perrin (2002) and Kiessling (2009), who reported that modern-type coralgal reefs expanded globally during the Oligocene and Miocene. Therefore, the increased abundance and diversity of scleractinian hermatypic corals is a global phenomenon that occurred in the Oligocene, corresponding to a change in water chemistry from a calcite sea (Calcite II) to an aragonite sea (Aragonite III) (Stanley 2006).

Oceanic environments and nutrient availability in the northwestern Pacific

Nutrient availability has been considered one of the most critical factors controlling carbonate sedimentation/accumulation and reef development (Hallock & Schlager 1986; Hallock 1988; Mutti & Hallock 2003; Vecsei 2003). Hallock & Schlager (1986) and Hallock (1988) suggested that accretion and destruction, including bioturbation and bioerosion, of reefs/carbonate platforms are strongly influenced by nutrient availability. Nutrient-rich oceanic environments encourage the propagation of bioeroding organisms (Hallock 1988) and accelerate bioerosion (Highsmith 1980;

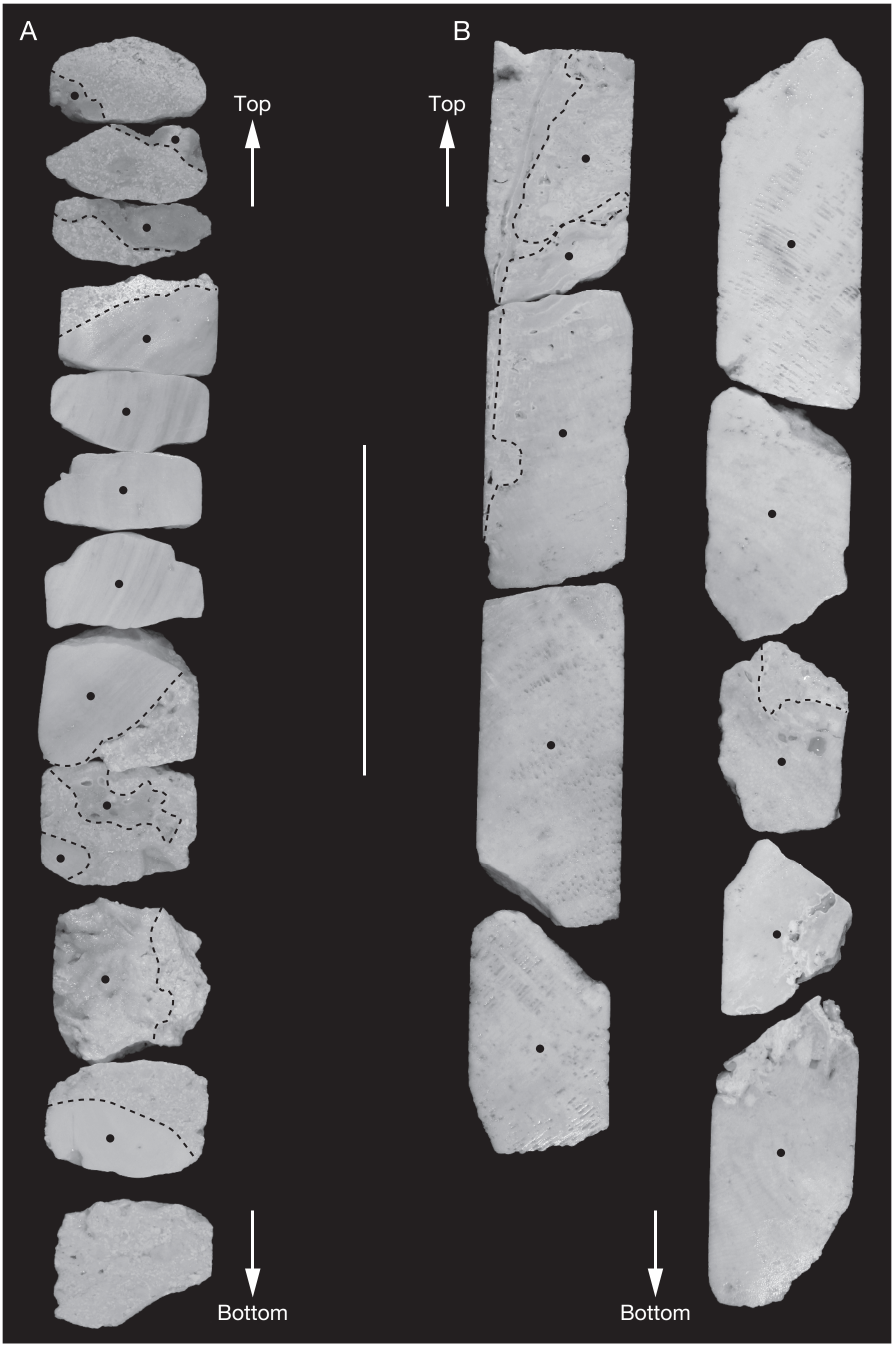


FIG. 4. — Oligocene coral floatstone from the seamounts in the northwestern Pacific Ocean. Dots indicate corals. Note that all corals are allochthonous. A dashed line denotes a boundary between a coral and "matrix". **A**, coral floatstone, 0.35 to 0.49 mbsf in 03DS-064BMS01 drilled at the Kita-Koho 3452 Seamount, Early Oligocene; **B**, coral floatstone, 0.20 to 0.85 mbsf in 03DS073BMS01 drilled at the Kosei Seamount, probably Late Oligocene. Scale bar: 10 cm.

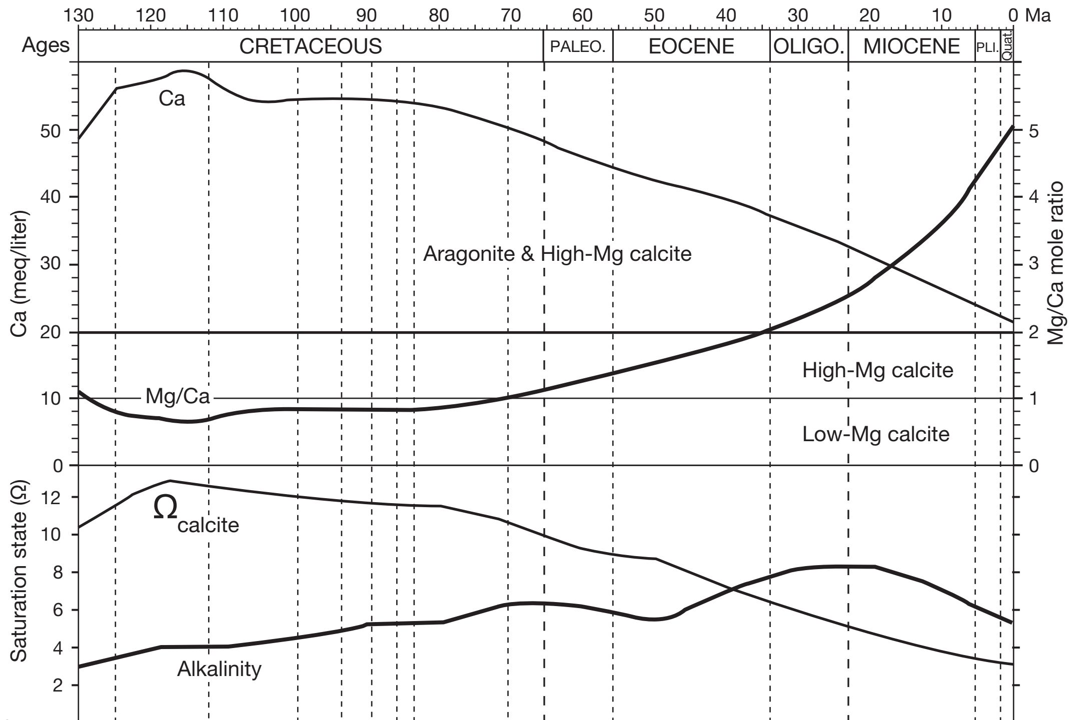
Smith *et al.* 1981; Brock & Smith 1983; Rose & Risk 1985; Hallock 1988). It is noteworthy that biotic components in the C-type carbonates were bioeroded and micritized much more extensively compared with those in the E-type and OP-type carbonates. This indicates enhanced activity of the endolithic (boring) microorganisms, such as algae, fungi, and sponges, in the Cretaceous carbonate factories and that the tropical to subtropical shallow-water regions in the Pacific Ocean were more eutrophic during the Cretaceous than in the younger times.

Eocene *Halimeda*-dominated deposits were recovered from the Basho Seamount and unnamed seamount no. 1 on the Oki-Daito Ridge. However, such deposits are not common in coeval shallow-water carbonates elsewhere. *Halimeda* segments in these deposits (particularly at the top of the Basho Seamount) are dominant enough to be compared with those in modern sediments in "*Halimeda* Banks", *in situ* accumulations in *Halimeda* bioherms (Marshall & Davies 1988; Phipps & Roberts 1988; Hine *et al.* 1988; Roberts *et al.* 1988; Rees *et al.* 2007). It has been well documented that the *Halimeda* bioherms develop under mesotrophic environments in tropical waters (Mutti & Hallock 2003). Therefore, the occurrence of *Halimeda*-dominant deposits on these seamounts seems to indicate a regional mesotrophic environment that was likely to have been caused by local upwelling. *Halimeda* spp. occurs in the OP-type carbonates examined in this study but is a rather minor component. It is probable that such a contrasting occurrence of *Halimeda* spp. reflects differences in the oceanographic settings during the Eocene (poorly stratified ocean) versus the Oligocene to Pleistocene (well-stratified ocean). This inference agrees well with the fact that the emergence of Antarctic ice sheets in the latest Eocene (Zachos *et al.* 2001) resulted in well-stratified oceans (Savin 1977; Corliss 1981; Boersma *et al.* 1987) and the consequent oligotrophication of shallow-water environments that stimulated the productivity and growth rate of reef-builders (Pomar & Hallock 2008), which may also be related to the more common occurrence of hermatypic corals from the Oligocene onwards.

CONCLUSIONS

We described the lithology and depositional ages of shallow-water carbonates collected from 29 sites on 24 seamounts in six locations (Amami Plateau, Daito Ridge, Oki-Daito Ridge, Urdaneta Plateau, Kyushu-Palau Ridge, and Ogasawara Plateau) in the northwestern Pacific Ocean. Based on their biotic and abiotic composition, the carbonates were classified into three types: Cretaceous, Eocene (to lowest Oligocene?), and Oligocene to Pleistocene (C-, E-, and OP-type, respectively). The C-type carbonates are distinguished by common to abundant molluscs (including rudists), smaller foraminifers, microencrusters (*Bacinella* and *Lithocodium*), and non-skeletal grains (peloids, cortoids, and intraclasts), as well as microbial sediments. The E-type carbonates are dominated by *Halimeda* spp. or nummulitid and discocyclinid larger foraminifers. Nongeniculate coralline algae and larger foraminifers were common to abundant from the Eocene to the Pleistocene. Scleractinian corals became common from the Oligocene onwards. The C-type is dominated by the intra-tissue type of calcifying marine taxa and calcareous precipitates, the carbonates of which were secreted in relatively open spaces around their bodies. In contrast, the E- and the OP-types are rich in the intra-tissue type, which precipitates carbonates within closed to semi-closed spaces in and around their bodies. These indicate that a carbonate factory comparable with a modern coral reef was initiated during the Oligocene, which suggests a shift in seawater chemistry, such as in the Mg/Ca ratio (from Calcite II to Aragonite III; Stanley 2006) and the saturation state for carbonate minerals (Riding & Liang 2005a, b). The increased abundance and diversity of hermatypic corals may have been caused by significant ocean stratification, which was initiated by the emergence of Antarctic ice sheets in the latest Eocene, and the consequent oligotrophication of shallow-water environments that stimulated the productivity and growth rate of reef builders.

Large amounts of shallow-water carbonates were deposited on the seamounts during the Oligocene, although it was a relatively cool period in the Cenozoic; in contrast, Early Miocene shallow-water



Stanley (2006)		Calcite II			Aragonite III
Sandberg (1983, 1985)		Calcite II	?		Aragonite III
		Cretaceous type	?	Eocene type	Oligocene to Pleistocene type
Major component	Abundant	Mollusc (including rudist) Benthic foraminifer Microencructer		Larger foraminifer Halimeda Coralline alga Bryozoan Dasycladacean alga Benthic foraminifer	Scleractinian coral Coralline alga Bryozoan Benthic foraminifer Mollusc
Major component	Common	Calcareous algae (solenoporacean and peyssonneliacean algae) Larger foraminifer Calcareous sponge Echinoid		Echinoid Mollusc Planktonic foraminifer	Larger foraminifer Planktonic foraminifer Echinoid
Major component	Rare	Dasycladacean alga Bryozoan Ostracod Scleractinian coral		Scleractinian coral Ostracod Annelid Barnacle	Halimeda Ostracod Dasycladacean alga
Non-skeletal component	Major	Cortoid Intraclast Peloid		Rhodolith	Rhodolith
Non-skeletal component	Minor	Aggregate grain Oncoid Ooid		Peloid Intraclast Cortoid	Intraclast Peloid
Bioerosion		Extensive		Poor (to Moderate)	Poor
Micritization		Extensive		Poor (to Moderate)	Poor
Calcification site		Extra-tissue type > Intra-tissue type		Extra-tissue type < Intra-tissue type	

FIG. 5. — Comparison of the temporal distribution of major components of carbonate producers, frequency of bioerosion and micritization, and patterns of calcification with secular variation in the Mg/Ca ratio and Ca concentration (Hardie 1996; Stanley & Hardie 1998; Stanley 2006) and carbonate saturation state and alkalinity (Riding & Liang 2005a).

carbonates are limited, despite the existence of a relatively warm climate during that time. These data suggest that the deposition of shallow-water carbonates on seamounts in the northwestern Pacific Ocean was not necessarily controlled by climatic conditions but rather was related to the volcanism and tectonics that served as foundations for reef/carbonate-platform formation.

Acknowledgements

The current study was conducted as part of the project entitled "Basic Researches on Exploration Technologies for Deep-sea Natural Resources", which is commissioned to JOGMEC by Ministry of Economy, Trade, and Industry (METI), Japan. We thank METI for approving publication of the data. We are grateful to D. Basso, S. Spezzaferri, Valéry Malécot and an anonymous reviewer for critical comments on the manuscript. Deep appreciation is expressed to M. Humblet for identifying corals and to M. Abe for making thin sections.

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Submitted on 7 March 2011;
accepted on 22 August 2011.

APPENDICES

Appendix 1. — Method used for Sr isotope analysis at Kochi Institute for Core Sample Research, Japan.

Before Sr isotope measurements were made, the mineral abundance of bulk-rock carbonate samples was determined by X-ray diffraction (XRD) analyses, following Suzuki *et al.* (2006). Sr isotope ratios were measured on the samples with limited amounts of diagenetic products, and non-carbonate materials were identified by thin-section observations and XRD analyses. After removing fine-grained sediments and rinsing in 1 M HCl, the samples were dissolved in purified HNO_3, and Sr was separated on an ion-exchange column (Brick 1986). The $^{87}Sr/^{86}Sr$ ratio was measured on a Thermo/Finnigan Triton thermal ionization mass spectrometer at Kochi Core Center, Japan. Separate analyses (n = 21) of NIST (National Institute of Standards and Technology) SRM (Standard Reference Materials) 987 gave the average value of 0.710246 ± 0.000007 (2σ). Numerical ages were determined by a comparison between the obtained $^{87}Sr/^{86}Sr$ value and the global calibration curve presented by McArthur & Howarth (2004).

Table 1. — List of drill cores of shallow-water carbonates examined in this study. Abbreviations: **E.**, Early; **L.**, Late; **M.**, Middle; **USM**, unnamed seamount.

Area	Locality	Core	Water depth (m)	Drilling depth (m)	Latitude (North)	Longitude (East)	Age	Major lithology
Amami Plateau	Kikai Sm.	04DSAM 390BMS01	2511	5.29	28°30.761’	131°02.594’	M. Miocene, Pleistocene	Coral rudstone
		04DSAM 390BMS03	2016	2.18	28°31.546’	131°05.519’	M. Miocene	Coral rudstone
	Koniya Sm.	04DSAM 393BMS01	1370	0.36	28°06.386’	132°18.143’	Cretaceous (detailed stage is unknown)	Bioclastic grainstone, intraclast grainstone
		04DSAM 393BMS02	1372	5.59	28°06.380’	132°15.114’	Cretaceous (detailed stage is unknown)	Packstone and grainstone with abundant peloids and/or intraclasts, *Orbitolina* floatstone
Daito Ridge	Daito 3316 Sm.	02DA16 BMS01	1401	5.57	25°41.345’	133°16.258’	L. Eocene	Bioclastic packstone
	Peak of the Daito Ridge	07DSDA401 BMS02	1997	6.72	26°27.048’	131°23.448’	M. Eocene and L. Eocene to earliest Oligocene	Bioclastic packstone and grainstone
Oki-Daito Ridge	Oki-Daito 3336 Sm.	04DSOD423 BMS01	1739	2.295	22°44.685’	134°34.234’	M. Eocene	Larger foraminiferal packstone/rudstone
	Oki-Daito 430 Sm.	04DSOD430 BMS02	2546	4.165	22°58.426’	134°30.811’	L. Eocene	Bioclastic packstone and grainstone
	Oki-Daito 432 Sm.	04DSOD432 BMS01	2208	8.557	23°27.229’	133°39.253’	M. to L. Eocene	Bioclast-peloid grainstone
	USM no. 1 on the Oki-Daito Ridge	05DSOD418 BMS01	2248	8.88	24°50.778’	131°33.278’	L. Eocene to E. Oligocene	*Halimeda* rudstone, *Halimeda* rudstone/floatstone
	USM no. 2 on the Oki-Daito Ridge	05DSOD421 BMS01	2348	1.70	23°52.281’	132°42.771’	M. to L. Eocene	Rhodolith floatstone, larger-foraminifer packstone
	USM no. 3 on the Oki-Daito Ridge	06DSOD419 BMS02	1345	2.06	24°09.351’	131°49.772’	L. Eocene	Bioclastic packstone
		06DSOD419 BMS03	1345	4.81	24°09.354’	131°49.768’	latest Eocene to earliest Oligocene	Bioclastic packstone, bioclastic grainstone, rhodolith-coral floatstone
	USM no. 4 on the Oki-Daito Ridge	07DSOD423 BMS01	2563	5.34	23°23.868’	133°44.040’	M. Eocene	Larger foraminiferal rudstone
Urdaneta Plateau	Basho Sm.	02DB16 BMS01	2290	10.71	22°19.030’	128°40.438’	M. to L. Eocene	*Halimeda* rudstone
		02DB16 BMS02	2495	3.21	22°19.815’	128°39.441’	L. Eocene	*Halimeda* rudstone

TABLE 1. — Continuation.

Area	Locality	Core	Water depth (m)	Drilling depth (m)	Latitude (North)	Longitude (East)	Age	Major lithology
Urdaneta Plateau	Yasunari Sm.	02DB09 BMS01	1835	4.13	21°28.744’	128°01.712’	M. Eocene to earliest Oligocene	Bioclastic wackestone, algal framestone
	Hakushu Sm.	01DB08 BMS01	1750	6.21	21°26.719’	128°31.101’	E. Oligocene and E. Miocene	Bioclastic packstone and grainstone
Kyushu-Palau Ridge	Hyuga Sm.	02DA10 BMS01	979	4.00	27°56. 171’	134°44.325’	E. Miocene	Bioclastic packstone and grainstone, algal framestone, coral floatstone
	Higo Sm.	03DS059 BMS02	1765	1.19	27°50.836’	134°31.798’	E. Oligocene	Coral floatstone
		03DS059 BMS03	1080	0.89	27°52.091’	134°34.771’	E. Oligocene	Bioclastic packstone and packstone/rudstone, coral framestone
	Kita-Koho 3452 Sm.	03DS064 BMS01	1130	1.05	26°41.163’	134°51.921’	E. Oligocene	Coral floatstone
	Kosei Sm.	03DS073 BMS01	526	1.61	25°08.218’	135°41.034’	latest Oligocene to M. Miocene	Coral floatstone
	USM on the Kyushu-Palau Ridge	08DSKP810 BMS01	2029	8.41	12°25.771’	134°32.494’	E., M., and L. Miocene	Coral rudstone
Ogasawara Plateau	Minami Sm.	99DCBM S05S	1333	3.51	25°20.012’	143°51.148’	Late Cretaceous (Coniacian to Campanian)	Molluscan floatstone, rudist floatstone, and bioclastic rudstone and packstone
	Yabe Sm.	99DCBM S06Y	1123	5.50	26°15.539’	145°08.487’	L. Cretaceous (Coniacian to Campanian)	Rudist-coral floatstone, bioclastic rudstone
	Eastern ridge of the Yabe Sm.	06DSOG460 BMS01	1684	6.26	25°48.582’	146°09.505’	Early Cretaceous (Aptian)	Bioclastic rudstone, grainstone, and packstone with abundant intraclasts and peloids
	Hanzawa Sm.	99DCBM S07H	1400	1.62	25°59.000’	146°59.071’	Late Cretaceous (Coniacian to Santonian)	Bioclastic rudstone and packstone/grainstone, peloidal grainstone/packstone, and peloid-cortoid grainstone
	Katayama Sm.	99DCBM S08K	1602	1.72	25°46.352’	147°28.115’	Late Cretaceous (Santonian)	Bioclast-peloid packstone/grainstone, bioclastic rudstone

TABLE 2. — Calcareous nannofossils from shallow-water carbonates on seamounts in the northwestern Pacific Ocean. Numbers denote relative abundance (%) of species. Abbreviations: **E**, early; **L**, late; **M**, middle; **Olig.**, Oligocene; **Sm**, seammount; **USM**, unnamed seamount. Occurence: **+**, present (not counted). *****, data previously reported by Takayanagi *et al*. (2007).

	Area	Oki-Daito Ridge				Urdaneta Plateau
	Locality	Oki-Daito 3336 Sm.	USM no. 1 on the Oki-Daito Ridge	USM no. 3 on the Oki-Daito Ridge	USM no. 4 on the Oki-Daito Ridge	Yasunari Sm.
	Core	04DSOD 423BMS01	05DSOD 418BMS01	06DSOD 419BMS02	07DSOD 423BMS01	02DB09BMS01
	Depth (m)	1.00-1.05*	0.22	0.01	4.92	0.22*
	Time (Berggren *et al.* 1995)	M. Eocene	Eocene	L. Eocene to Olig.	M. Eocene	L. Eocene to E. Olig.
	Zone (Martini 1971; Sissingh 1977) / Species	NP15-16	NP16-NP19	NP16-NP25	NP16-17	NP16-21
Cenozoic	*Calcidiscus formosus* (Kamptner, 1963) Loeblich & Tappan, 1978	+	13		4	+
	Chiasmolithus expansus (Bramlette & Sulivan, 1961) Gartner, 1970	+				
	Chiasmolithus grandis (Bramlette & Riedel, 1954) Radomski, 1968				+	
	Chiasmolithus solitus (Bramlette & Sulivan, 1961) Locker, 1968	+				
	Chiasmolithus titus Gartner, 1970		+			
	Coccolithus eopelagicus (Bramlette & Riedel, 1954) Bramlette & Sullivan, 1961		3		+	
	Coccolithus pelagicus (Wallich, 1877) Schiller, 1930	+	40		5	10
	Cyclicargolithus floridanus (Roth & Hay *in* Hay *et al*., 1967) Bukry, 1971			+	3	61
	Dictyococcites bisectus (Hay, Mohler & Wade, 1966) Bukry & Percival, 1971		39			29
	Discoaster barbadiensis Tan, 1927		2		+	
	Discoaster deflandrei Bramlette & Riedel, 1954		1	+		
	Discoaster saipanensis Bramlette & Riedel, 1954	+	1			
	Helicosphaera bramlettei Müller, 1970		+			
	Reticulofenestra reticulata (Gartner & Smith, 1967) Roth *in* Roth & Thierstein, 1972		28		+	
	Reticulofenestra umbilicus (Levin, 1965) Martini & Ritzkowski, 1968		2			
	Reticulofenestra spp.	+		+	76	
	Reticulofenestra spp. (small)		57			
	Sphenolithus moriformis (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967	+	13	+	12	
	Sphenolithus radians Delfandre *in* Grassé, 1952	+			+	

TABLE 3. — Planktonic foraminifers from shallow-water carbonates on seamounts in the northwestern Pacific Ocean. Abbreviations: **E**, early; **L**, late; **M**, middle; **Plio.**, Pliocene; **Sm**, seammount; **USM**, unnamed seamount. Occurences: **C**, common; **R**, rare; **VR**, very rare; **+**, present (not counted). Preservation: **M**, moderate; **P**, poor; **VP**, very poor. *****, data previously reported by Takayanagi *et al*. (2007).

Area	**Amami Plateau**			**Oki-Daito Ridge**				**Urdaneta Plateau**							**Kyushu-Palau Ridge**						
Locality	Kikai Sm.			Oki-Daito 430 Sm.	USM no. 1	USM no. 2		Yasunari Sm.					Hakushu Sm.		Kita-Koho 3452 Sm.			USM			
Core	04DSAM390 BMS03			04DSOD430BMS02	05DSOD418BMS01	05DSOD421BMS01		02DB09 BMS01					01DB08 BMS01		03DS064 BMS01			08DSKP 810 BMS01			
Depth (m)	0.20-0.30*	0.60-0.82*	1.65-1.77*	0.36-0.40*	0.22	0.22	0.37	0.14*	2.00*	2.10*	3.87*	3.90*	0.05*	0.12*	0.39*	2.03*	2.08*	0.02-0.22	0.87-1.00	1.00-1.21	1.21-1.37
Occurrence	VR	VR	VR	VR	R			R			R	VR			C						
Preservation	P	P	P	P	VP		VP			P	P				M	M	P	VP	P	VP	P
Age (Berggren *et al*. 1995)	Plio. or younger				Eocene								Miocene?	M. to L. Miocene	Oligocene?			E. Miocene	E. Miocene	E. Miocene	E. Miocene
Species																					
Dentoglobigerina altispira (Cushman & Jarvis, 1936)														+					+		+
Globigerina euapertura Jenkins, 1960																		+	+		
Globigerina nepenthes Todd, 1957														+							
Globigerina cf. *tapuriensis* Blow & Banner, 1962															+						
Globigerina sp.		+	+	+			+		+	+	+	+				+	+	+		+	+
Globigerinatheka sp.						+															
Globigerinella sp.										+							+				
Globigerinoides sacculifer (Brady, 1877)								+													
Globigerinoides trilobus (Reuss, 1850)													+								
Globigerinoides cf. *trilobus* (Reuss, 1850)																				+	
Globigerinoides sp.														+	+				+		+
Globoquadrina cf. *dehiscens* (Chapman, Parr & Collins, 1934)														+	+				+		
Globoquadrina aff. *dehiscens* (Chapman, Parr & Collins, 1934)																		+		+	
Globoquadrina venezuelana (Hedberg, 1937)																			+		+
Globoquadrina cf. *venezuelana* (Hedberg, 1937)																		+		+	
Globorotalia cerroazulensis (Cole, 1928)					+																
Globorotalia aff. *inflata* (d'Orbigny, 1839)	+																				
Hantkenina sp.					+																
Orbulina universa d'Orbigny, 1839								+						+							
Sphaeroidinellopsis aff. *seminulina* (Schwager, 1866)																					+
Sphaeroidinellopsis sp.																			+	+	

TABLE 4. — Larger foraminifers from shallow-water carbonates on seamounts in the northwestern Pacific Ocean. Abbreviations: **E**, early; **L**, late; **M**, middle; **Eoc.**, Eocene; **Olig.**, Oligocene; **Mioc.**, Miocene; **Plio.**, Pliocene; **USM**, unnamed seamount; **Sm**, seammount. Occurence: **+**, present (not counted). *****, data previously reported by Takayanagi *et al*. (2007).

Area	Amami Plateau														Daito Ridge											
Locality	Kikai Sm.													Koniya Sm.	Daito 3316 Sm.		Peak of the Daito Ridge									
Core	04DS AM390 BMS03				04DSAM390BMS01									04DS AM393 BMS02	02DA 16 BMS01		07DSDA401BMS02									
Depth (m)	0-0.06	0.85-0.90*	1.89-1.94*	1.98-2.00*	0.04-0.07	0.33-0.37	1.17-1.22*	1.22-1.26	2.84-2.90	3.06-3.11	3.29-3.33*	4.36-4.41*	5.00-5.03	1.81-3.96 (clast)	0.50*	1.03*	0.37-0.43	0.94-1.00	1.90-1.96	2.24-2.30	2.64-2.70	3.73-3.79	3.83-3.89	4.94-5.00	5.20-5.26	6.63-6.69
Age (Matsumaru 1974, 1996) / Species				E.-M. Miocene			E.-M. Mioc.				E.-M. Miocene				M.-L. Eocene		L. Eocene to E. Olig.						L. Eocene to E. Olig.			
Orbitolinidae gen. et sp. indet.														+												
Nummulites sp.															+	+	+		+	+			+	+	+	
Discocyclina sp.															+	+	+	+	+	+	+			+	+	+
Alveolinid																										
Gypsina sp.	+																	+			+		+		+	+
Operculinoides sp.																										
Amphistegina sp.	+	+	+	+	+	+	+	+	+	+	+	+	+									+				
Lepidocyclina sp.				+	+		+		+		+															
Miogypsina sp.				+		+	+	+	+	+	+	+														
Operculina sp.												+														
Soritid			+	+	+	+		+	+	+																

Area	Oki-Daito Ridge																									
Locality	USM no. 2 on the Oki-Daito Ridge						USM no. 3 on the Oki-Daito Ridge							Oki-Daito 3336 Sm.										Oki-Daito 430 Sm.		
Core	05DSOD-421BMS01						06DS OD419 BMS02	06DSOD-419BMS03						04DSOD423BMS01										04DS OD430 BMS02		
Depth (m)	0.15	0.30	0.36	1.38-1.40	1.52	1.62	1.44-1.50	0.36-0.41	0.54-0.60	1.12-1.17	2.95-3.00	3.58-3.64	4.09-4.15	0.48-0.52	1.72-1.77	2.70*	3.79*	3.85-3.91	5.92*	5.95-6.00	6.20-6.24	6.20-6.24	6.35-6.39*	0.50*	0.51-0.56	0.60*
Age (Matsumaru 1974, 1996) / Species	M.-L. Eocene						Late Eocene-Early Oligocene						L. Eoc. to E. Olig.			M.-L. Eocene			M.-L. Eocene		M.-L. Eocene		M.-L. Eocene	M.-L. Eocene		M.-L. Eocene
Orbitolinidae gen. et sp. indet.																										
Nummulites sp.	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Discocyclina sp.	+	+	+	+	+	+	+	+	+	+	+													+	+	+
Alveolinid														+	+	+	+	+	+	+	+		+	+		+
Gypsina sp.							+	+	+	+	+		+													

TABLE 4. — Continuation.

Area	Oki-Daito Ridge			
Locality	USM no. 2 on the Oki-Daito Ridge	USM no. 3 on the Oki-Daito Ridge	Oki-Daito 3336 Sm.	Oki-Daito 430 Sm.
Operculinoides sp.			+ + + + +	+
Amphistegina sp.				
Lepidocyclina sp.				
Miogypsina sp.				
Operculina sp.				+
Soritid				

Area	Oki-Daito Ridge										Urdaneta Plateau									Kyushu-Palau Ridge						
Locality	Oki-Daito 430 Sm.			Oki-Daito 432 Sm.							Basho Sm.					Yasunari Sm.				Hyuga Sm.				Higo Sm.		
Core	04DS OD430 BMS02			04DS OD432 BMS01							02DB16 BMS01	02DB16 BMS02				02DB09 BMS01				02DA10 BMS01				03DS059 BMS02		
Depth (m)	1.15*	1.17-2.22	1.29*	0.34-0.38	0.72*	0.75-0.80	1.48*	0.96-2.00	2.11-2.16	3.95-3.99	0.36*	0.25	0.35	c. 0.75*	c. 3.00*	2.25	2.26*	2.295*	3.90*	0.36*	1.47*	2.19*	3.98*	0.20*	0.67*	1.16*
Age (Matsumaru 1974, 1996) / Species	M.-L. Eocene		M.-L. Eocene		M.-L. Eocene		M.-L. Eocene			L. Eoc. to E. Olig.	Middle-Late Eocene				Middle-Late Eocene						Early-Middle Miocene					
Orbitolinidae gen. et sp. indet.																										
Nummulites sp.		+	+	+				+	+	+																
Discocyclina sp.	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+							
Alveolinid			+											+	+											
Gypsina sp.										+	+	+					+		+							
Operculinoides sp.		+		+		+		+	+				+													
Amphistegina sp.																			+					+	+	+
Lepidocyclina sp.																					+	+	+			
Miogypsina sp.																					+	+				
Operculina sp.					+											+										
Soritid																				+						

Area	Kyushu-Palau Ridge					
Locality	Higo Sm.				Kita-Koho 3452 Sm.	Kosei Sm.
Core	03DS059BMS03				03DS064BMS01	03DS073BMS01
Depth (m)	0.01*	0.07	0.11*	0.19*	0.72*	0.73*
Species/Age (Matsumaru 1974, 1996)						E.-M. Miocene
Orbitolinidae gen. et sp. indet						
Nummulites sp.						
Discocyclina sp.						
Alveolinid					+	
Gypsina sp.						
Operculinoides sp.						
Amphistegina sp.	+		+	+	+	+
Lepidocyclina sp.		+				
Miogypsina sp.						+
Operculina sp.					+	
Soritid				+		

Table 5. — 87Sr/86Sr and Sr isotope ages for shallow-water carbonates on seamounts in the northwestern Pacific Ocean. The ages were calculated following the global calibration curve proposed by McArthur & Howarth (2004). Abbreviations: **Labo.**, laboratory; **Sm.**, seamount; **USM**, Unnamed seamount; **E.**, Eocene; **O.**, Oligocene. *****, Data previously reported by Takayanagi *et al.* (2007). Laboratories (**Labo**): **1**, Activation Laboratories Ltd., Ancaster, Canada; **2**, Ontario, Canada, 2. Mitsubishi Materials Natural Resources Development Corp., Saitama, Japan; **3**, University of Colorado at Boulder, USA; **4**, Kochi Institute for Core Sample Research, Kochi, Japan.

Locality	Core	Depth (mbsf)	$^{87}Sr/^{86}Sr$	Error (± 2 σm)	Age (Ma)	Geological time	Labo.
Kikai Sm.	04DSAM390BMS01	0.04-0.07*	0.708805	±0.000005	13.6+0.2-0.1	Middle Miocene	1
		3.06-3.11*	0.708823	±0.000008	12.7+0.1<0.05	Middle Miocene	1
		5.00-5.03*	0.708788	±0.000005	14.8+<0.05-0.1	Middle Miocene	1
		5.16-5.29*	0.708919	±0.000020	8.9+0.5-0.7	Late Miocene	2
	04DSAM390BMS03	0.00-0.06*	0.709135	±0.000005	1.1+0.1-<0.05	Pleistocene	1
		0.85-0.90*	0.709138	±0.000008	1.0±0.1	Pleistocene	1
		1.77-1.79*	0.709084	±0.000004	2.1±0.1	Late Pliocene	1
		1.89-1.94*	0.709115	±0.000008	1.4±0.1	Pleistocene	1
		1.98-2.00*	0.708821	±0.000008	12.7±0.1	Middle Miocene	1
Koniya Sm.	04DSAM393BMS02	1.81-3.96	0.707037	±0.000009	150.6+0.2-0.1	Jurassic	1
Daito 3316 Sm.	02DA16 BMS01	0.49	0.707843	±0.000006	33.4±0.1	Early Oligocene	3
		1.76-1.81	0.707681	±0.000007	72.7±0.5	Campanian	4
		2.00-2.06*	0.707646	±0.000011	73.9±0.2	Campanian	2
		5.57	0.707751	±0.000007	36.7±0.1	Late Eocene	3
Peak of the Daito Ridge	07DSDA401BMS02	0.37-0.43	0.707832	±0.000008	33.5±0.3	earliest Oligocene	1
		0.94-1.00	0.707810	±0.000010	33.9+0.3-0.4	E./O. boundary	1
		1.90-1.96	0.707757	±0.000010	36.3+0.5-0.6	latest Eocene	1
		2.24-2.30	0.707779	±0.000008	34.9+1.1-0.6	latest Eocene	1
		3.83-3.89	0.707807	±0.000012	34.0+0.5-0.4	latest Eocene	1
		5.20-5.26	0.707781	±0.000008	34.7+1.1-0.5	latest Eocene	1
Oki-Daito 3336 Sm.	04DSOD423BMS01	0.48-0.52*	0.707891	±0.000004	32.5±0.1	Early Oligocene	1
		1.60-1.68	0.707761	±0.000007	36.1±1.0	Late Eocene	4
			0.707804	±0.000008	34.1+0.4-0.3	latest Eocene	4
			0.707769	±0.000007	35.6+1.0-0.9	latest Eocene	4
		2.68-2.88	0.707767	±0.000007	35.7±1.0	latest Eocene	4
			0.707757	±0.000007	36.3±1.1	Late Eocene	4
		3.55	0.707788	±0.000007	34.5+0.7-0.4	latest Eocene	4
		5.95-6.00	0.707755	±0.000007	36.5+1.2-1.0	Late Eocene	4
		6.24-6.27*	0.707639	±0.000027	74.1+<0.05-0.7	Campanian	1
		6.37	0.707874	±0.000005	32.8±0.1	Early Oligocene	3
Oki-Daito 430 Sm.	04DSOD430BMS02	0.51-0.56*	0.707856	±0.000007	33.1+<0.05-0.1	Early Oligocene	1
		1.45-1.52	0.707733	±0.000006	38.5-1.46	Middle Eocene	4
Oki-Daito 432 Sm.	04DSOD432BMS01	0.75-0.80*	0.707956	±0.000020	30.8±0.4	Early Oligocene	1
		2.75-2.79*	0.707834	±0.000007	33.5+0.1-<0.05	Early Oligocene	1
USM no. 1 on the Oki-Daito Ridge	05DSOD418BMS01	0.51	0.707925	±0.000007	31.8+0.05	Early Oligocene	3
		0.84-0.90	0.707770	±0.000007	35.5+1.0-0.9	latest Eocene	4
			0.707822	±0.000007	33.7±0.3	earliest Oligocene	4
		1.30-1.38	0.707768	±0.000007	35.6+1.0-0.9	latest Eocene	4
			0.707808	±0.000007	34.0±0.3	E./O. boundary	4
		8.31	0.707919	±0.000007	31.9±<0.05	Early Oligocene	3
USM no. 2 on the Oki-Daito Ridge	05DSOD421BMS01	0.37	0.707826	±0.000007	33.7±<0.05	Early Oligocene	3
		1.51	0.707871	±0.000006	32.9±<0.05	Early Oligocene	3

TABLE 5. — Continuation.

Locality	Core	Depth (mbsf)	$^{87}Sr/^{86}Sr$	Error (± 2 σm)	Age (Ma)	Geological time	Labo.
USM no. 3 on the Oki-Daito Ridge	06DSOD419BMS02	0.10-0.15	0.708283	±0.000009	22.5±0.3	Early Miocene	1
		1.44-1.50	0.707789	±0.000008	34.4±<0.05	Late Eocene	1
	06DSOD419BMS03	0.36-0.41	0.707801	±0.000008	34.1±<0.05	latest Eocene	1
		2.95-3.00	0.707795	±0.000010	34.3±0.1	latest Eocene	1
		4.09-4.15	0.707837	±0.000010	33.5±0.2	earliest Oligocene	1
Basho Sm.	02DB16BMS01	0.25*	0.707807	±0.000006	34.0±<0.05	Late Eocene	1
		0.35-0.47*	0.707764	±0.000011	35.9±0.2	Late Eocene	4
		3.90-3.94	0.707792	±0.000007	34.3+0.6-0.4	latest Eocene	4
		4.03*	0.707826	±0.000008	33.7±<0.05	Early Oligocene	1
		6.48*	0.707828	±0.000008	33.6±<0.05	Early Oligocene	1
		8.50-8.70	0.707800	±0.000007	34.1+0.4-0.3	latest Eocene	4
		10.70*	0.707805	±0.000006	34.0+0.1	Late Eocene	1
		10.70	0.707732	±0.000014	39.1+9.6-0.2	Middle Eocene	2
	02DB16BMS02	0.25*	0.707810	±0.000008	33.9±<0.05	Late Eocene	1
		0.35*	0.707837	±0.000006	33.5+0.1	earliest Oligocene	1
		0.40-0.45	0.707871	±0.000007	32.9+0.2-0.3	earliest Oligocene	4
			0.707772	±0.000007	35.2+1.1-0.7	latest Eocene	4
		2.28-2.44	0.707819	±0.000007	33.8±0.3	earliest Oligocene	4
		3.02*	0.707805	±0.000006	34.0+0.7-<0.05	Late Eocene	1
Yasunari Sm.	02DB09BMS01	0.16-0.18	0.708	±0.000006	33.6+0.2-0.3	earliest Oligocene	4
		2.08-2.14	0.708	±0.000007	33.4±0.3	earliest Oligocene	4
		2.25*	0.708	±0.000008	25,5	Late Oligocene	1
		2.25*	0.705	±0.000006	not determined	not determined	1
Hakushu Sm.	01DB08BMS01	0.275	0.708	±0.000006	22.0±<0.05	Early Miocene	3
		1.71-1.81	0.708	±0.000007	21.7±0.2	Early Miocene	4
		2.55	0.708	±0.000006	33.5+0.1-<0.05	earliest Oligocene	3
Hyuga Sm.	02DA10BMS01	1.35-1.49*	0.709	±0.000011	17.2±0.1	Early Miocene	2
		2.17-2.27*	0.709	±0.000012	17.8±0.1	Early Miocene	2
		3.75-4.00*	0.709	±0.000011	17.7±0.1	Early Miocene	2
Higo Sm.	03DS059BMS02	0.22-0.25	0.708	±0.000008	29.9+0.5-0.4	Early Oligocene	4
		1.00-1.22*	0.708	±0.000008	32.2±0	Early Oligocene	1
	03DS059BMS03	0.07*	0.708	±0.000008	28.9±0	Early Oligocene	1
		0.25*	0.708	±0.000008	29.1±0	Early Oligocene	1
		0.68-0.83	0.708	±0.000006	29.6±0.4	Early Oligocene	4
Kita-Koho 3452 Sm.	03DS064BMS01	0.22	0.708	±0.000007	32.0+0.3-0.4	Early Oligocene	2
		0.55-0.57*	0.708	±0.000011	33.1<0.05-0.1	earliest Oligocene	4
Kosei Sm.	03DS073BMS01	0.20-0.27*	0.708	±0.000014	23.8±0.1	Late Oligocene	2
USM on the Kyushu-Palau Ridge	08DSK P810BMS01	0.008	0.709	±0.000007	9.6±0.2	Late Miocene	4
		0.02	0.709	±0.000007	18.8±0.1	Early Miocene	4
		0.05	0.709	±0.000007	18.8±0.1	Early Miocene	4
		0.135	0.708	±0.000007	21.6±0.1	Early Miocene	4
		0.175	0.708	±0.000007	21.2±0.1	Early Miocene	4
		0.89	0.708	±0.000006	21.3±0.1	Early Miocene	4
		0.94	0.708	±0.000006	22.1±0.1	Early Miocene	4
		1.16	0.708	±0.000008	22.0±0.1	Early Miocene	4
		1.23	0.709	±0.000006	15.8±0.1	Middle Miocene	4
		1.255	0.708	±0.000007	20.6±0.1	Early Miocene	4

TABLE 5. — Continuation.

Locality	Core	Depth (mbsf)	$^{87}Sr/^{86}Sr$	Error (± 2 σm)	Age (Ma)	Geological time	Labo.
Minami Sm.	99DCBMS05S	0.78-0.80	0.708	±0.000008	81.9+0.8-1.1	Campanian	1
		1.17	0.707	±0.000007	86.4+0.5-0.3	Coniacian	4
		2.36	0.707	±0.000007	86.5+0.4-0.4	Coniacian	4
		0.30-0.40 (III)	0.707	±0.000006	86.3+0.4-0.4	Coniacian	4
Yabe Sm.	99DCBMS06Y	1.80	0.707	±0.000007	86.2+0.4-0.5	Coniacian	4
			0.707	±0.000007	85.8+0.4-1.0	Coniacian/ Santonian boundary	4
		3.92-3.94*	0.707	±0.000009	83.3±0.2	Campanian	1
Eastern ridge of the Yabe Sm.	06DSOG 460BMS01	0.03-0.09	0.707	±0.000008	112.5±0.1	Aptian	1
		2.68-2.73	0.707	±0.000010	113.6+0.2-0.3	Aptian	1
		4.36-4.42	0.707	±0.000006	112.3±0.1	Aptian	1
		7.605	0.707	±0.000008	113.6+0.2-0.3	Aptian	1
Hanzawa Sm.	99DCBMS07H	0.16	0.707	±0.000007	87.4+0.4-0.3	Coniacian	4
		0.16	0.707	±0.000007	86.8+0.3-0.4	Coniacian	4
		0.96-0.98*	0.707	±0.000008	85.7±0.1	Santonian	1
Katayama Sm.	99DCBMS08K	0.68-0.70*	0.707	±0.000007	84.0±0.1	Santonian	1

Table 6. — Hermatypic corals from shallow-water carbonates on seamounts in the northwestern Pacific Ocean. Abbreviations: **M.**, Middle; **E.**, Early; **Olig.**, Oligocene; **Sm.**, seamount. Occurences: **+**, present (not counted).

Area	**Amami Plateau**																	**Oki-Daito Ridge**			**Urdaneta Plateau**		**Kyushu-Palau Ridge**									
Locality	Kikai Sm.																	Oki-Daito 3336 Sm.			Basho Sm.		Hyuga Sm.						Higo Sm.	Kita-Koho 3452 Sm.		Kosei Sm.
Core	04DSAM390BMS03								04DSAM390BMS01									04DSOD423BMS01			02DB16BMS01		02DA10BMS01						03DS059BMS02	03DS064BMS01		03DS073BMS01
Depth (m)	0.20-0.39	0.39-0.60	0.60-0.82	0.82-1.00	1.00-1.30	1.50-1.77	1.90-1.98	2.00-2.14	0.41-0.66	0.52-1.00	1.58-1.70	2.60-2.66	2.68-2.94	3.46-3.70	3.68-3.90	4.30-4.45	4.78-5.00	3.10-3.14	3.60	3.60-3.65	1.70-1.75	3.96-4.01	0.70-1.56	1.80-2.00	2.27-2.40	2.55-2.67	2.75-2.85	3.00-4.00	0.65-0.70	0.55	0.95-1.00	0-1.61
Age / Species	Early Pleistocene						M. Miocene		Middle Miocene									M.-L. Eocene (or to earliest Oligocene?)			M.-L. Eocene (or to earliest Oligocene?)		Early Miocene						Early Oligocene			latest Olig.-M. Miocene
Acropora sp.																							+	+				+				
Cyphastrea sp.			+	+	+		+	+							+	+																
Cyphastrea chalcidicum (Forskål, 1775)				+																												
Faviidae gen. et sp. indet.			+																													
Favia sp.	+	+	+		+					+		+	+	+											+							
Galaxea cf. *astreata* (Lamarck, 1816)			+							+																						
Goniopora sp.																		+									+					
Millepora sp.										+			+				+															
Montipora sp.					+				+	+	+															+						
Pocillopora sp.																														+	+	
Porites sp.						+																										+
Stylophora sp.																			+	+	+	+								+	+	
Turbinaria sp.		+																														
Coral gen. et sp. indet.																													+			