Plio-Pleistocene reef evolution of Kita-daito-jima, Japan

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Abstract: Kita-daito-jima is a carbonate island lying on a lithospheric forebulge of the Philippine Sea Plate. The carbonate deposits on this island consist of the Daito (Pliocene) and Kaigunbo (~123 ka) Formations. The Daito Formation comprises three unconformity-bounded units. Unit 1 is dominated by framestone, which crops out around an interior basin. Unit 2 is divided into two subunits. The lower subunit, Subunit 2a, includes the reef-core facies that constitutes the main body of the peripheral rim and the backreef facies exposed at the cliffs lining the interior basin. The upper subunit, Subunit 2b, which crops out around the highest point of the island, is constructed by framestone and bioclastic packstone. Unit 3 is scattered on the eastern coast and consists mainly of bioclastic packstone. The Kaigunbo Formation lies as an abutment on the coastal cliff.

The stratigraphic succession, the configuration of the lithofacies, and the coral assemblages enable one to depict the island's evolution. Unit 1 formed on a submerged shallow-water platform; the thick atoll and associated lagoonal deposits accumulated on the karstified platform, represented by Subunit 2a. The atoll then progressively degraded while Subunit 2b formed, and no distinct reefs extended at the latest stage of deposition of this subunit. The shoal with coral patches extended on the eastern part of the island during the deposition of Unit 3. Fringing reefs formed during the last interglacial stage (Kaigunbo Formation).

Key words: reef, Kita-daito-jima, foraminiferal macroids, corals, Pliocene, Pleistocene

Contents

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1. INTRODUCTION

The Daito Islands (25°27.1'-57.6'N, 131°10.8'-19.8'E), consisting of Kita-daito-jima, Minami-daito-jima, and Oki-daito-jima, are located in the northwestern region of the Philippine Sea, approximately 350–400 km east of Okinawa-jima (Fig. 1). These islands lie on the lithospheric forebulge of the Philippine Sea Plate, which subducts beneath the Eurasian Plate.

Kita-daito-jima is famous as a carbonate island (MacNeil, 1954), where a deep boring into the reef deposits was performed (Ladd et al., 1970; Steers & Stoddart, 1977). The Kita-daito-jima Borehole was drilled 209.3 m below the ground surface (mbgs) in 1934, and coring advanced down to 431.7 mbgs in 1936 (Sugiyama, 1934, 1936). The recovered material consists exclusively of shallow-water carbonates, the upper 100 m of which are pervasively dolomitized. Ota (1938) examined the petrography and chemistry of the dolomites. Hanzawa (1940) defined 5 bio- and lithostratigraphic zones within the borehole core, showing that the drilling reached down to the Oligocene (Chattian) carbonates. In 1992, Ohde & Elderfield gave a detailed chronology of the borehole carbonates using Sr-isotope stratigraphy, and they also illustrated a tectonic and geologic history of this island's last 25 million years.

Several investigations have been conducted on the carbonate deposits exposed on Kita-daito-jima since the 1980's (Furukawa, 1985; Nakamori et al., 1994; Noda, 1998). However, significant disagreement exists among the stratigraphy established in these studies. We conducted a thorough stratigraphic investigation in a previous study, concluding that our work basically supports the Nakamori et al. version (Nambu et al., 2003). Sedimentary facies of the carbonate deposits on this island, however, were not fully described in these previous studies. This paper aims to describe the facies and anatomy of the carbonate deposits and reconstruct the evolution of the island.

2. GEOMORPHOLOGY

Kita-daito-jima is semi-triangular in shape, pointed towards the south, and is about 3.7 km from north to south and about 4.9 km from east to west. This island has been regarded as an elevated atoll (e.g. Flint et al., 1953; Schlanger, 1965) because of its geomorphologic similarity to modern atolls: it is composed of a peripheral rim and an interior basin (Fig. 1).

Kita-daito-jima is locally flanked by abrupt cliffs (< 20 m) that are prominent in the western part of the island. The northern and eastern coasts of Kita-daito-jima step down gradually towards the shorelines and display several terrace levels, each of which is 10 m to 50 m wide. Surf benches, 1 m to 5 m wide, are locally remarkable in the intertidal zones. Although hermatypic corals and nongeniculate coralline algae grow on the surf benches and island slopes, no active reefs form.

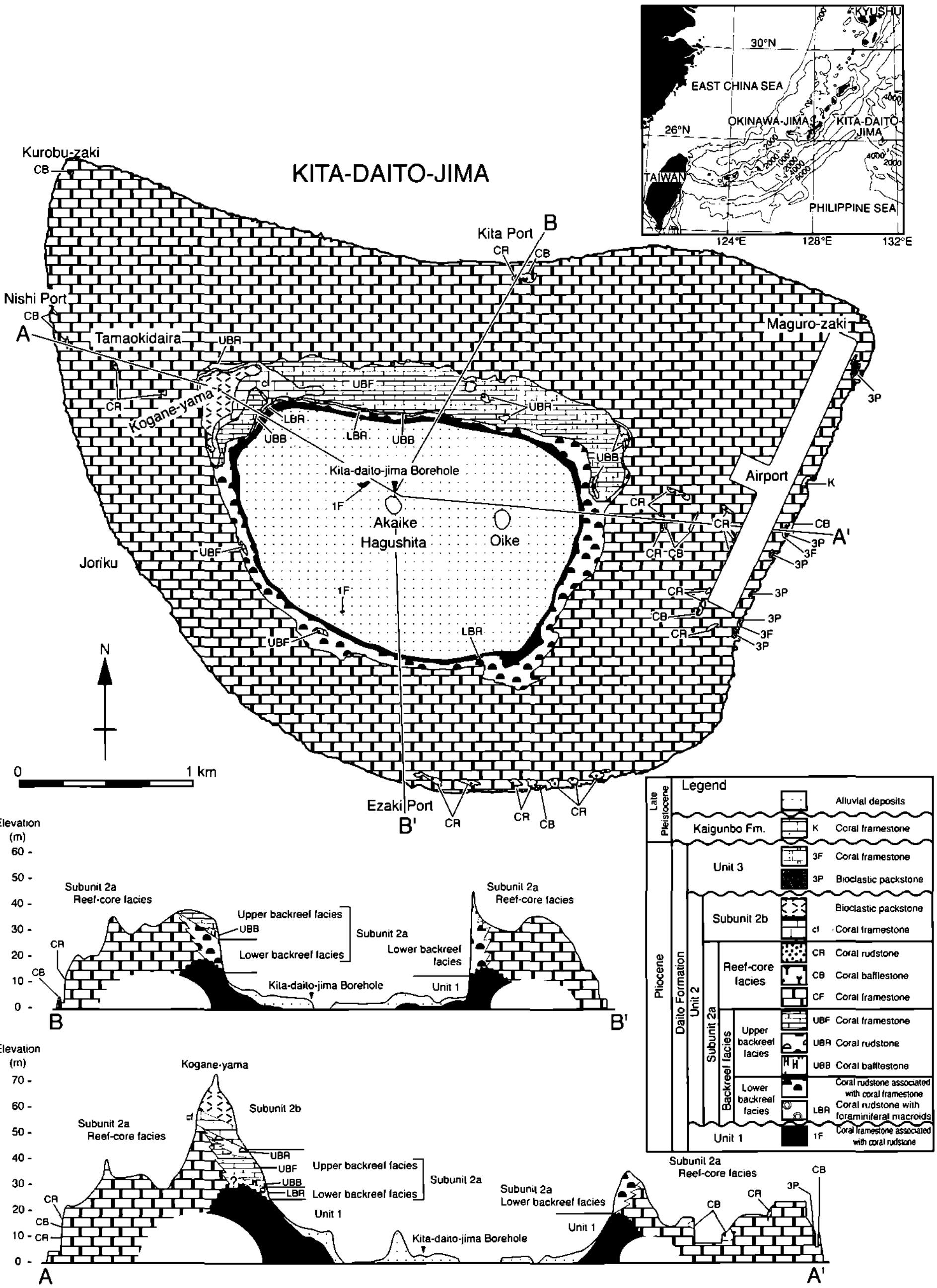


Fig. 1: Geologic map and cross sections of Kita-daito-jima (modified from Nambu et al., 2003).

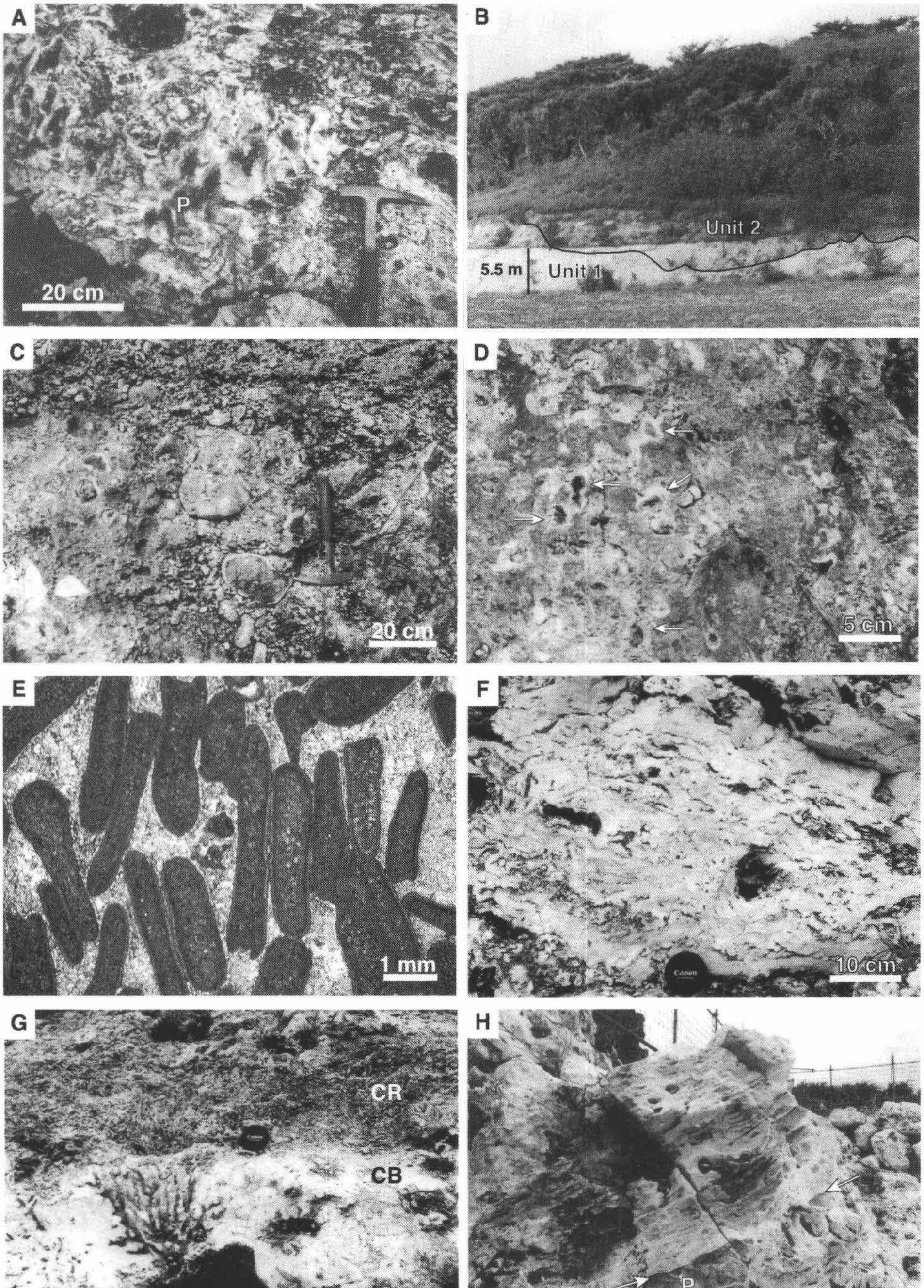
The peripheral rim is about 0.5 km to 1.8 km wide, mostly ranging in elevation from 10 m to 50 m, and consists of inner and outer ridges. The inner ridge is wider and higher than the outer ridge. The latter bifurcates in the northern part of the island. The highest point of the island, Kogane-yama (74 m), lies on the inner ridge. The peripheral rim is cut by a depression in the southeastern part of the island, which SCHLANGER (1965) regarded as a channel connecting the open sea and the lagoon of Kita-daito-jima atoll. The interior basin is about 1.4 km from north to south and about 2.1 km from east to west, is less than 20 m in elevation, and is surrounded by bluffs and slopes up to 50 m high. The basin is veneered mainly with red soil.

3. STRATIGRAPHY

The carbonate deposits cropping out on Kita-daito-jima comprise the Daito Formation overlain by the Kaigunbo Formation. The deposits of the Daito Formation were pervasively dolomitized at 1.6 Ma to 2.0 Ma (KAWANA & OHDE, 1993), whereas those of the Kaigunbo Formation were not subject to dolomitization.

The Daito Formation is divisible into three units. Unit 1 is dominated by framestone rich in hemispherical corals and crops out in the interior basin (Fig. 2 A). Unit 2, resting unconformably on Unit 1 (Fig. 2 B), is divided into two subunits: lower Subunit 2a and upper Subunit 2b. The lower subunit consists of the reef-core facies that constitutes the main body of the peripheral rim and the backreef facies exposed at the cliffs that line the interior basin. The reef-core facies is represented by framestone (Fig. 2 F) associated with bafflestone (Fig. 2 G) and rudstone. The lower backreef facies consists mainly of rudstone (Figs. 2 C and 2 D) and the upper backreef facies is chiefly made up of framestone and bafflestone and frequently contains *Halimeda* segments (Fig. 2 E).

Fig. 2: Outcrop photographs and a thin-section photomicrograph of reef and associated lagoonal deposits of the Daito Formation on Kita-daito-jima.
(A) Framestone of Unit 1 containing hemispherical corals (Unit 1). P = *Porites* sp.
(B) Stratigraphic relationship between Unit 1 and Subunit 2a. Note that rudstone of lower backreef facies of Subunit 2a rests on framestone of Unit 1 with a sharp, irregular contact. A line indicates the lithologic boundary.
(C) Rudstone of lower backreef facies of Subunit 2a. Note that the rudstone consists mainly of up to cobble-sized, well-rounded clasts of corals.
(D) Rudstone of lower backreef facies of Subunit 2a. Note that foraminiferal macroids (arrows) are present. The macroids are composed of encrusting foraminifers and much less common thin, encrusting nongeniculate coralline algae.
(E) *Halimeda* segments in the matrix of coral framestone of upper backreef facies of Subunit 2a.
(F) Framestone of reef-core facies of Subunit 2a. Note that laminar to tabular corals and encrusting nongeniculate coralline algae accumulate to display a bindstone-like texture.
(G) Probable exposure surface in reef-core facies of Subunit 2a. Note that rudstone rests on bafflestone with a sharp contact. CR = coral rudstone, CB = coral bafflestone.
(H) Bioclastic packstone of Unit 3 unconformably overlying framestone of reef-core facies of Subunit 2a. Arrows indicate the lithologic boundary. P = *Porites* sp.


A
P
20 cm
B
Unit 2
5.5 m
Unit 1
C
20 cm
D
5 cm
E
1 mm
F
10 cm
G
CR
CB
10 cm
H
P
20 cm

Subunit 2b, cropping out around Kogane-yama, which is the highest point on the island, is constructed of framestone and bioclastic packstone. Unit 3 is exposed sporadically on the eastern coast at elevations of 10 m to 20 m and unconformably overlies the reef-core facies of Subunit 2a (Fig. 2 H). This unit consists of cross-bedded bioclastic packstone associated with framestone. The Kaigunbo Formation, composed mainly of framestone, occurs at an abutment on a seacliff lining the eastern coast at elevations less than 11 m.

The stratigraphic and geochemical lines of evidence imply that there is not a significant hiatus between Unit C1 (upper ~50 m of carbonates from Kita-daito-jima Borehole; IRYU & YAMADA, 1999) and Unit 1, but that these units were subject to different episodic dolomitizations (SUZUKI, 2004). The strontium isotope stratigraphy revealed that the dolomitization within Unit C1 occurred at ~2.0 Ma (OHDE & ELDERFIELD, 1992), and that Units 1 through 3 were dolomitized at 1.6 Ma to 2.0 Ma (KAWANA & OHDE, 1993). INAGAKI (2000) reconstructed an age-depth section of the Kita-daito-jima atoll for the last 25 million years, showing that the Daito Formation formed in the Pliocene. Uranium-series and electoric spine resonance (ESR) ages show that the Kaigunbo Formation formed during the last interglacial stage (marine isotope stage 5e) (KAWANA et al., 1991; OMURA et al., 1991; KOBA et al., 1991; OTA & OMURA, 1992).

4. SEDIMENTARY FACIES

The classification of the carbonate rocks basically follows DUNHAM (1962) and EMBRY & KLOVAN (1971) in this paper. The framestone can be subdivided into two types. One is characterized by the occurrence of autochthonous corals embedded in the bioclasts of corals, coralline algae, foraminifers, and mollusks, displaying a floatstone-like texture. The other involves hemispherical, tabular, and laminar hermatypic corals (coral morphology follows NAKAMORI (1986)) and nongeniculate coralline algae that accumulate to show a bindstone-like texture. The former is much more frequent than the latter, and thus, the term "framestone" is used to indicate the former unless otherwise stated.

4.1. Daito Formation

4.1.1. Unit 1

This unit is composed of framestone and rudstone containing coral clasts, but the latter is much less abundant. The framestone contains copious autochthonous hermatypic corals and nongeniculate coralline algae, forming mounds (7 m to 55 m in width and 2 m to 9 m in height) in certain places. Generally, the mounds are better developed and reach a higher altitude on the southern slope than on the northern slope. Framestone with a bindstone-like texture is more frequently found on the southern slope than on the northern slope. Various forms of hermatypic corals are included. Predominant corals are the hemispherical; tabular and laminar forms are commonly found. In contrast, branching corals are rare. Nongeniculate coralline algae range from common to abundant at most of the sites. *Lithophyllum prototypum* is the most plentiful of all of the species. Mastophoroid coralline algae possessing large trichocytes, which generally characterize modern tropical shallow coralline algal assemblages, have not been found. An encrusting foraminifer, *Acervulina* sp., commonly occurs. Accompanied by nongeniculate coralline algae, this foraminifer encrusts *in-situ* corals to form up to 5-cm-thick crusts or composes pebble- to rarely cobble-sized nodules called foraminiferal macroids (HOTTINGER, 1983).

The rudstone contains up to boulder-sized, rounded coral clasts that are commonly encrusted by *Acervulina* sp. and nongeniculate coralline algae. The taxonomic compositions and morphologies of the corals are similar to those in the framestone.

4.1.2. Unit 2

4.1.2.1. Subunit 2a

Subunit 2a is constructed by reef-core and backreef facies. The reef-core facies is made up of framestone and much less common bafflestone and rudstone. The framestone is rich in *in-situ* hemispherical (*Porites* spp. and faviids), tabular (*Acropora* spp.), and laminar corals. Nongeniculate coralline algae vary from common to abundant throughout this facies. The coralline algal assemblage is dominated by *Lithophyllum prototypum* and *Spongites* spp. The framestone with a bindstone-like texture is observed in some places, although it is more commonly found in the coastal areas rather than in inland areas. The bafflestone includes thinly branching corals (*Acropora* spp. and *Montipora*? sp.) with a "matrix" of well-cemented bioclastic packstone. As with the bindstone-like framestone, the bafflestone is found more commonly in the coastal areas than in inland areas. However, this does not necessarily indicate that the bindstone-like framestone and the bafflestone co-occur or are closely related. The bafflestone does not form a distinct bed and progressively grades horizontally and vertically into the framestone with or without a bindstone-like texture. Well-developed spur and groove systems are observed at the seacliffs. These spurs and grooves are arranged more or less perpendicular to the present coastline. The grooves are filled largely with the rudstone of well-rounded coral clasts. Some probable exposure surfaces are identified at several horizons on the western coast (Fig. 2 G), where neither karstification nor red stain is recognized.

The lower backreef facies consists mainly of rudstone, and the upper backreef facies is composed chiefly of framestone and bafflestone with abundant *Halimeda* segments. The rudstone of the lower facies contains well-rounded clasts of hemispherical, tabular, and thinly branching corals and mollusks. The coral clasts are generally poorly sorted and range in mean diameters less than 20 cm. The nongeniculate coralline algae and *A. inhaerens* encrust coral clasts and bioclasts to form the irregular crusts and foraminiferal macroids (Fig. 2 D). Concentrated macroids occurred in the upper part of the lower backreef facies. They are ellipsoidal in shape, ranging in mean diameters from 1 cm to 10 cm. The nuclei of the macroids, if preserved, are mostly coral clasts, but in some cases they are lacking or are unidentified due to extensive bio-erosion. In certain places, the rudstone includes localized mounds of framestone, which are less than 5 m wide and less than 1 m high. Hemispherical, laminar, tabular, and thinly branching corals are also concentrated here. The framestone and bafflestone of the upper backreef facies contain laminar and tabular corals and autochthonous and semi-autochthonous branching corals, respectively. These corals do not pile up or inter-grow. The *in-situ* crusts of nongeniculate coralline algae are uncommon. The *Halimeda* segments in the upper backreef facies are thick and sturdy. This segment morphology can be correlated with a "shallow *Halimeda* suite", defined by Boss & Liddel (1987).

4.1.2.2. Subunit 2b

Subunit 2b comprises framestone overlain by bioclastic packstone. The framestone includes small (10 cm to 20 cm diameter) hemispherical corals with few nongeniculate coralline algae. The packstone is composed mainly of medium to very coarse sand-sized bioclasts of benthic foraminifera, nongeniculate coralline algae, *Halimeda*, less abundant mollusks, and encrusting foraminifers. Planktonic foraminifers are rarely found.

4.1.3. Unit 3

This unit is composed of bioclastic packstone accompanied by framestone. The main constituents of the packstone are fine to coarse sand-sized bioclasts of benthic foraminifers, nongeniculate coralline algae, mollusks, echinoids, and corals. Most of the bioclasts, however, have been dissolved to leave a moldic porosity, which gives the packstone a mud-like appearance. Clasts of hemispherical and branching corals are rarely concentrated to form rudstone. Planar cross-bedding is common, with the maximum dip reaching 35°. Ripples with wavelengths ranging from 1.0 m to 1.6 m were locally observed. The framestone, containing *in-situ* hemispherical and tabular corals, is a minor component of this unit. It forms thin beds (< 1.7 m) or low-relief mounds (< 5 m in width and < 1 m in height).

4.2. Kaigunbo Formation

The main lithology of this formation is framestone. A conglomerate containing gravel and blocks of the dolomites occurs to fill in depressions and erosional notches. The framestone is rich in hemispherical, tabular, and thickly to thinly branching hermatypic corals, such as *Porites* sp., *Goniopora* sp., *Montipora* sp., *Cyphastrea* sp., and *Pocillopora* sp. Common nongeniculate coralline algal species include *Hydrolithon onkodes* and *Lithophyllum insidum.* These species dominate shallow (< 15 m depth) coralline algal assemblages in the present-day and Pleistocene Ryukyus (Iryu, 1992).

5. EVOLUTION OF THE ISLAND

The results from DSDP Site 445 have shown that the Daito Ridge, on which the Daito Islands are located, has migrated northward from an equatorial position over the past ~50 Ma (Klein & Kobayashi, 1980). The islands have uplifted since they reached the lithospheric forebulge of the Philippine Sea Plate at 4 Ma to 6 Ma (Seno, 1989; Ota et al., 1991; Ohde & Elderfield, 1992).

The hermatypic coral community found in the framestone of Unit 1 is characterized by the occurrences of hemispherical *Porites* spp. and faviids, tabular *Acropora* spp., and the absence of pectinids. Therefore, this community is comparable with Community C of SAGAWA et al. (2001). Taking into consideration the paleo-environment determined by the coral community (5 m to 20 m depth) and the configuration of Unit 1, we infer that this unit accumulated by the formation of a submerged shallow-water bank (Fig. 3 A).

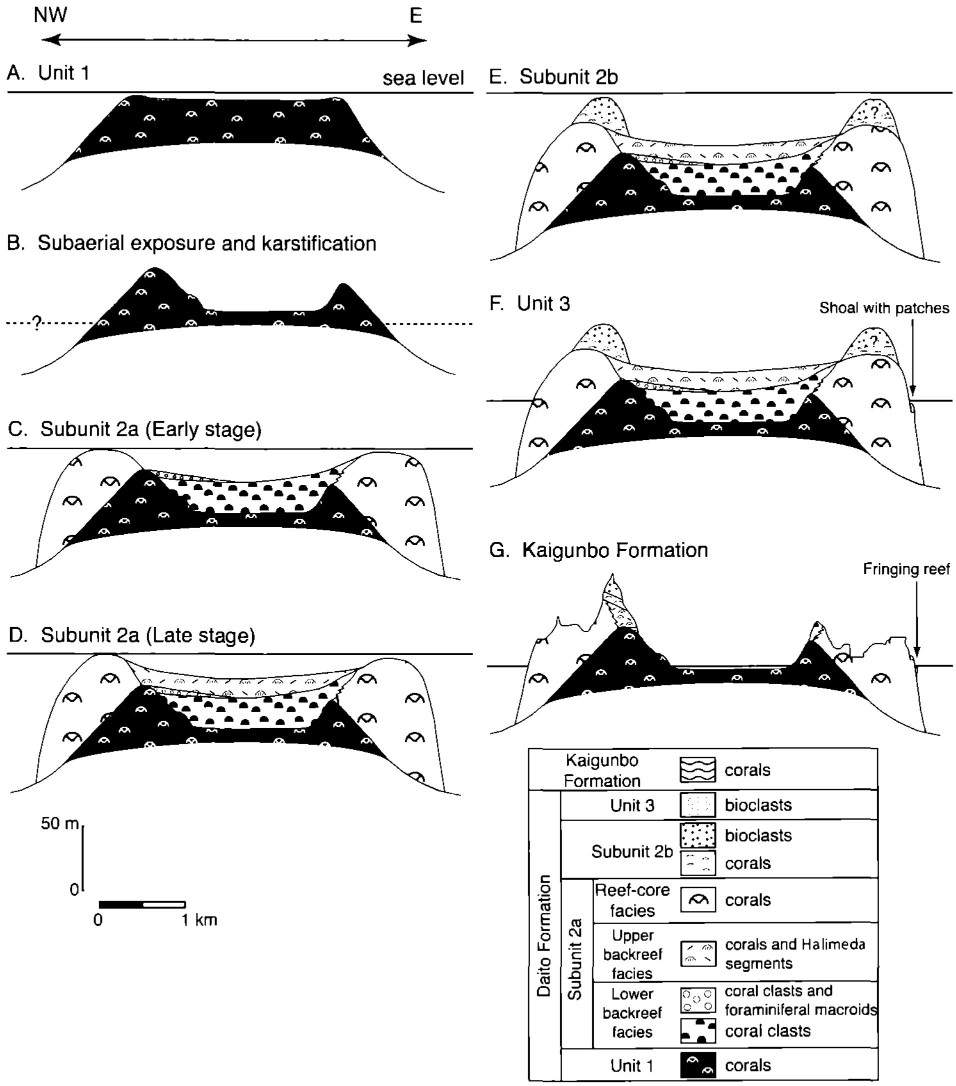


Fig. 3: Paleodepositional history of the Daito and Kaigunbo Formations on Kita-daito-jima reconstructed by interpretative sections.

The anatomy of Subunit 2a shows that a reef system and an associated lagoon developed on the karstified platform (Fig. 3 B) to form an atoll (Figs. 3 C and 3 D). The framestone and bafflestone occur repeatedly at seacliffs. Community C is recognized in the framestone. The bafflestone includes thinly branching *Acropora* spp. and *Montipora*? sp., which characterize Community A (SAGAWA et al., 2001) and are indicative of a shallow lagoon to reef crest environment. The alternating occurrences of Communities A and C at seacliffs suggest repeated sea-level changes and/or progradation and retrogradation of the reefs. The existence of exposure surfaces indicates that the reef core was subject to repeated, episodic subaerial exposures. The lower backreef facies contains foraminiferal macroids composed mainly of *Acervulina* sp. Similar foraminiferal and foraminiferal-algal macroids have been reported from relatively deep settings in modern tropical seas, such as the Ryukyus (TSUJI, 1993; HOHENEGGER, 1994; IRYU et al., 1995), the Gulf of Aqaba (HOTTINGER, 1983), and the Red Sea proper (PILLER & PERVESLER, 1989). Their occurrences are confined generally to sites at which the depth is greater than ~40 m and strong currents prevail. As *Acervulina* can inhabit the more shallow environments (e.g. 23 m depth off Ishigaki-jima, the Ryukyus; HATTA & UJIIÉ, 1992), it can be inferred that Kita-daito-jima macroids are formed at depths greater than 20 m. However, the framestone of Unit 1 that includes the macroids is rich in hermatypic corals, which are thought to have grown at depths of 5 m to 20 m (Community C, SAGAWA et al., 2001). We, therefore, believe that the Kita-daito-jima macroids may have formed only in a limited depth zone that centered at 20 m. In contrast to macroids from the Ryukyus and the Red Sea, those from Kita-daito-jima are thought to have formed in the restricted lagoonal environment. Nevertheless, the process at which these macroids formed in such a calm-water setting is uncertain at the present time. The framestone and bafflestone of the upper back reef facies are characterized by containing thick and sturdy *Halimeda* segments, which can be assigned to a "shallow (< 24 m depth) *Halimeda* suite" (BOSS & LIDDEL, 1987). Consequently, it is possible that the depth of the lagoon was constant or became shallower during the deposition of Subunit 2a. The nongeniculate coralline algal assemblages of Unit 1 and Subunit 2a differ from those in modern coral reefs in the overwhelming dominance of *Lithophyllum prototypum*.

After the deposition of Subunit 2a, the Kita-daito-jima atoll may have been progressively degraded while Subunit 2b formed (Fig. 3 E). A few hermatypic corals grew and, at the latest stage of the deposition of this subunit, a small shoal of bioclastic sand formed. It is impossible to specify possible reasons for the degradation of the coral reef.

The sea level fell after Subunit 2b was deposited so that the island emerged and karstified. This sea level fall can be estimated as greater than 60 m on the basis of the maximum elevation of Subunit 2b (74 m) and the minimum elevation of the unconformable boundary between Unit 2 (Subunit 2a) and Unit 3 (10 m). The packstone of Unit 3 is sporadically distributed on a terrace on the eastern coast, displaying well-defined, high-angle cross-bedding. Such distribution and characteristic sedimentary structure denote that the packstone may have accumulated on a shoal where coral patches were scattered (Fig. 3 F). As the island has uplifted for the last 4 to 6 million years, it is likely that the presumed relative sea-level changes during the deposition of the Daito Formation were caused by eustasy.

Hermatypic organisms inhabited submarine cliffs to form localized, small-scaled, fringing reefs during the last interglacial periods (Fig. 3 G). The species compositions of the coral and nongeniculate coralline algal assemblages found in the Kaigunbo Formation are similar to those of present-day reefs in the west Pacific, including the Ryukyu Islands.

6. CONCLUSIONS

The carbonate deposits on Kita-daito-jima comprise the Pliocene Daito and upper Pleistocene Kaigunbo Formations. The main body of the carbonates is constructed by thick atoll deposits (Unit 2) lying on framestone, which formed on a submerged shallow-water platform (Unit 1) and then karstified before the deposition of Unit 2. Shoal and associated coral patch deposits (Unit 3) are scattered on a terrace of the eastern coast. These carbonate deposits were pervasively dolomitized at 1.6 Ma to 2.0 Ma. The Kaigunbo Formation lies at an abutment on the seacliffs and consists of framestone that formed in localized, small-scaled fringing reefs. Our research results clearly show that Kita-daito-jima is not a simple, elevated atoll, and that the evolution of the island is much more complicated than has been previously considered in famous studies.

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