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Developmental history of a coral reef complex controlled by the sea-level change and terrigenous influx - the Pleistocene Ryukyu Group of Nakijin Village, Okinawa Prefecture.

By

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with 6 Text-figures

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Abstract: The Pleistocene coral reef complex, the Ryukyu Group, is widely distributed in Nakijin Village, Okinawa Prefecture. The geology and stratigraphy of the group was investigated on the basis of sedimentological and topographic characteristics. Because the Quaternary carbonate was deposited under a strong control of the sea-level change, information on paleodepth was as much as extracted by use of the recent knowledge on the living subtropical reef biota.

We subdivided the Ryukyu Group into three units. Unit 1 consists of alternating deposits of different facies in lower and thick coral limestone in upper. It is highly terrigenous in the northeastern Motobu Peninsula due to a strong influx of silisiclastics. The alternation seen in localities along the northern coast of the Motobu Peninsula indicates several cyclic change in paleodepth. Unit 2 covers a large area and exhibits a zoning in distribution of different facies parallel to the present altitude. From the coast to the high-lying area, the facies generally changes from rhodolith limestone, through clastic limestone, and to coral limestone. This distribution pattern is consistent with that of the present coral reef complex around the Ryukyu Islands. The unit 3 mainly consists of coral limestone and restricts its distribution in the lowermost terrace along the coast.

Kouri Island shows much better development of the coral limestone than the northern Motobu Peninsula. Moat facies developed on the tops of units 1 and 2 in the island is obscure in the peninsula. This regional difference in reef development is associated with the difference in depositional settings; especially intensity of the terrigenous influx. The basement rocks are widely exposed in the middle-southern Motobu Peninsula, and the Ryukyu Group in the northern peninsula contains a large amount of silisiclastics which had probably been disturbing the growth of the reef-forming corals. In Kouri Island, where is separated from the peninsula by a relatively deep strait, the terrigenous influx did not sufficiently affect the carbonate deposition.

The cyclic facies change found in unit 1 is hardly seen in units 2 and 3. The columnar sections of unit 1 indicate a short-term and small amplitude of sea-level change, which may correspond to the climatic characteristic of the Early Pleistocene (mostly before 0.7-0.5 Ma). From the Middle Pleistocene, both the interval and amplitude of sea-level increased. The amplitude was too large to record the cyclic facies change, and the younger units (units 2 and 3) were deposited mainly during sea-level highstands.

I. INTRODUCTION

The Pleistocene of the Ryukyu Islands (the Ryukyu Group) is well known as carbonate sediment deposited in a coral reef complex. Because of the large uplifting rate, the Ryukyu Group exposes one of the best sections of the Pleistocene coral reef complex. It also forms distinct limestone terraces caused by the large amplitude of the sea-level change (exceeds 100 m).

The limestone section displays cyclic facies changes consisting of repetition of coral, rhodolith, and detrital limestones. Origin of the facies variation has long been discussed by several researchers who intensively worked since the restoration from the US occupation. However, the sedimentological studies (Nakamori, 1986; Iryu and Matsuda, 1988; Iryu et al., 1995; Honda et al., 1993) indicate that the facies are mostly controlled by the paleo-depth; e.g. the coral limestone is formed shallower than -50 m, and the rhodolith limestone is between -50 to -150 m. They further suggest that the cyclicity of the facies change was produced by the Pleistocene glacio-eustatic sea-level change. This improvement of the facies depth-meter and accumulation of the Pleistocene climatic data allow us to reconsider the stratigraphy of the Ryukyu Group, and the attempt is now ongoing in several localities (Irabu Island - Honda et al., 1993; Toku Island - Nakamori et al., 1995; Ie Island - Fujishiro, 1996MS). Studies on paleosols by Jiju (1995) and stable carbon isotope (Matsuda, 1995) also provide an useful tool to subdivide the carbonate sections of the Ryukyu Group.

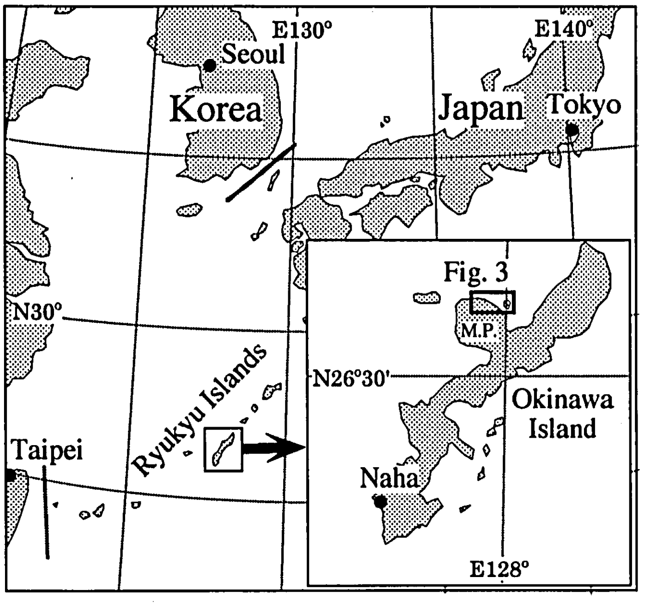

Fig. 1. Locality of the geological map of the study area (Fig. 3). M.P. = Motobu Peninsula.

Although the Ryukyu Group is largely dominated by carbonate sediments, it locally contains siliciclastics; especially in Okinawa Island. The siliciclastics are normally coarse-grained (sandstone-conglomerate) and distributed in several separated localities; each of them is given different stratigaphic names. They have been paid less attention by sedimentologists than carbonates, and therefore their depositional age and process are still poorly understood.

The subject of this study is the Ryukyu Group distributed in Nakijin Village, in Okinawa Island. The group includes carbonate exhibiting various facies and siliciclastic sediment called as the Unten Facies (Takayasu, 1976). Purpose of this study is understanding of the stratigraphy and depositional processes with the present consensus on the depostional model of the Ryukyu Group.

II. STUDY AREA AND PREVIOUS WORK

Nakijin Village (around 26°40'N and 127°00'E) occupies the eastern part of the Motobu Peninsula of Okinawa Island (Fig. 1), and includes Kouri Island located NE of the Motobu Peninsula. The study area consists of limestone terraces located on the northern part of the peninsula which are developed upon the basement rocks forming hills (Yaedake - 451 m, and Otowadake - 271 m).

The terrace geomorphology is most obvious in Kouri Island; showing three terraces in 107-90 m, 65-50m, and around 20 m in altitude. In the NW part of the village (Imadomari to Sakiyama) a terrace occurs between 15 to 20 m in altitude, which northern and eastern margins are fringed by a row of small scale elevations (20-30 m in altitude). The similar landscape is developed in the NE part of the village (Tokijin to Unten), however the terrace (20 to 30 m in altitude) is margined by a cliff in north and the terrace surface gently dips to south.

Geology of the study area can be divided into two; the Paleozoic-Mesozoic basement rocks and the Pleistocene Ryukyu Group. According to Fujita (1983a) who studied the geology of the Motobu Peninsula, the Mesozoic and Paleozoic strata shows a complicated distribution due to several faults of N-S and NE-SW directions. The basement rocks of the study area are mainly belong to the Yonamine

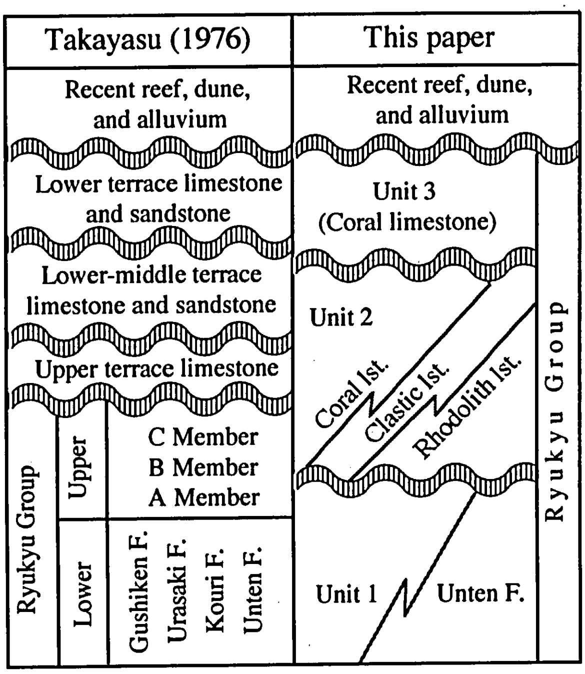

Fig. 2. Comparison between the stratigraphies of Takayasu (1976) and this study. F. : Facies, lst. : limestone.

Formations which is a debris flow sedimentary complex containing allochtonous blocks of the Permian-Triassic limestone and chert. Fujita (1983b) reported Early Cretaceous radiolarians from the mudstone of this formation.

The Ryukyu Group of this area was intensively researched by Takayasu (1976). He concluded that the limestone is divided into a thick older limestone (the Ryukyu Group in his definition) and thin younger terrace limestones (Fig. 2). His paper was one of the first studies which tried to introduce facies analysis of the Ryukyu Group and to reconsider the traditional view of reef development on the basis of the terrace geomorphology.

III. THE RYUKYU GROUP OF NAKIJIN VILLAGE

A. Stratigraphy framework

Although since Takayasu (1976) the Ryukyu Group of Nakijin Village has not been researched much in details, improvement of facies analysis of the Ryukyu Group achieves a new interpretation of stratigraphy of the Ryukyu Group of the other areas (e.g. Nakamori, 1986; Nakamori et al., 1995; Honda et al., 1993). We found that the geological map of Takayasu (1976) was constructed by facies identification which is basically the same to ours. However, his stratigraphic framework based on the lithofacies should be reconsidered. Difference in the lithofacies is not age-dependent, but is rather depth-dependent. The paleo-depth of a certain location should be basically indicated by a value of the relative sea-level minus the present altitude. Furthermore, investigation of coral community of the limestone helps refining the paleodepth because reef-forming corals are quite sensitive to environmental conditions, especially depth (e.g. Nakamori, 1986, 1987). With this viewpoint, the Ryukyu Group of this area was here subdivided into three (1-3) units.

The geological map (Fig. 3) shows that the exposed lithofacies are largely variable among the different areas. The northwestern Nakijin Village is dominated by the rhodolith limestone of unit 2. The detrital limestone of unit 2 mainly occupies the central part of the village. The terrace of the northeastern part of the village consists mainly of the coral limestone of unit 1. Kouri Island is mostly covered by unit 2 which shows a concentric zonation of the facies distribution parallel to terrace geomorphology.

The Unten Facies (Takayasu, 1976) mainly distributed around Unten, is characterized by siliciclastic sediment, and has been separated from the limestone units of the Ryukyu Group. However, a series of outcrops of the northeastern part of this area shows gradual facies change from the siliciclastic "Unten Sandstone" to the lowermost part of the carbonate Ryukyu Group. The Unten Facies is thought to be formed by a local siliciclastic sedimentation, and thus in this paper included in the lowermost unit of the Ryukyu Group. Nakamura et al. (1996) suggest that the landscape from Unten Bay to the Haneji Inland Sea was developed due to an alluvial erosion by a meandering river.

Because the depositional settings are much different between in the northern Motobu Penninsula (Fig. 4) and on Kouri Island (Fig. 6), the stratigraphies of the two areas are separately described in the following.

B. Northern Motobu Peninsula

Unit 1 is exposed in the areas with an altitude of 0-40 m (Fig. 4). Lithofacies is various; conglomerate, sandstone, detrital limestone, and coral limestone. However, the lower part of the unit is generally more terrigenous than the upper part, and the top of the unit normally exhibits the coral-rich facies. The coral limestone largely occupies the terrace surface around Tokijin and is distributed at small-scale elevations

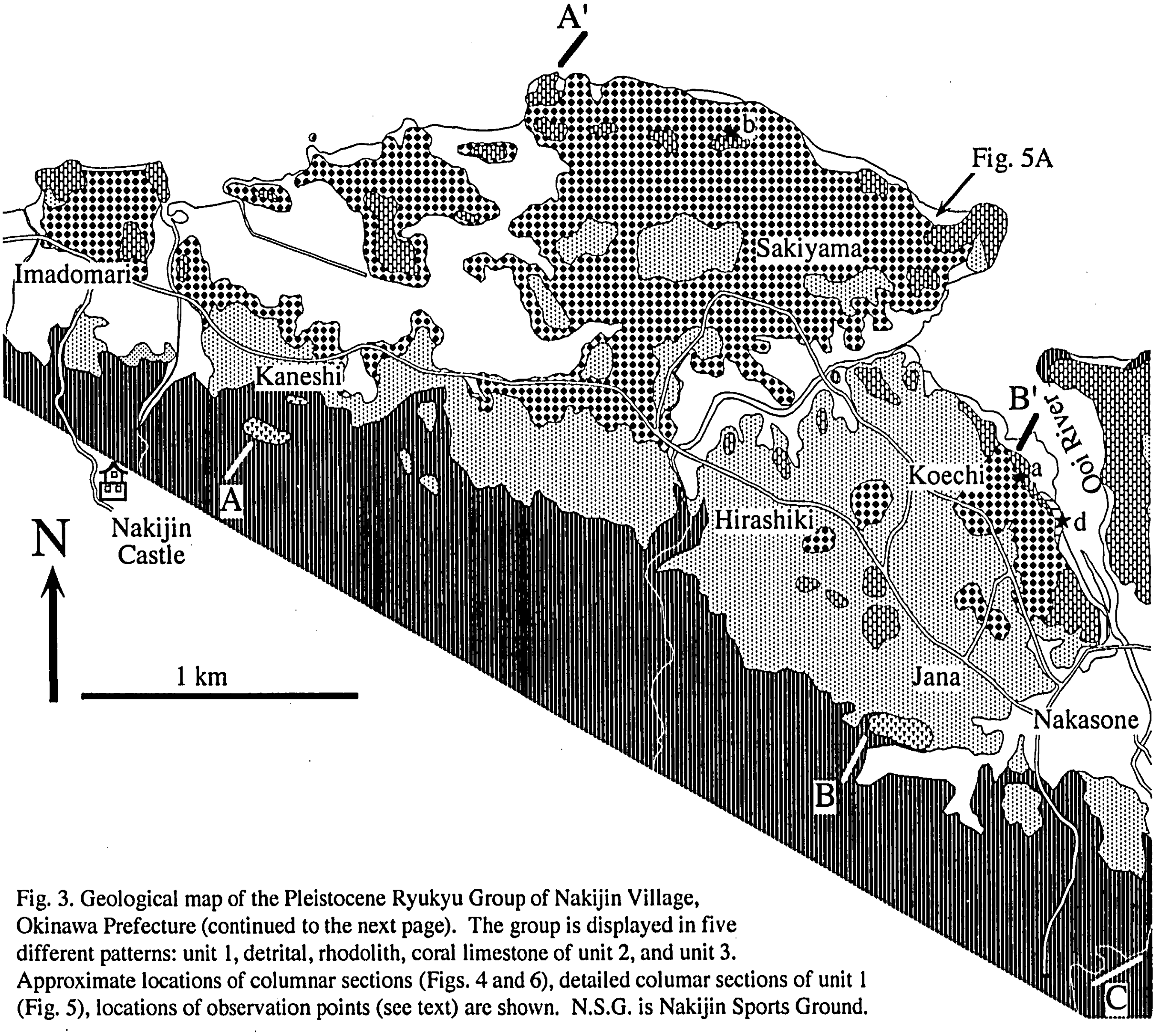

Fig. 3. Geological map of the Pleistocene Ryukyu Group of Nakijin Village, Okinawa Prefecture (continued to the next page). The group is displayed in five different patterns: unit 1, detrital, rhodolith, coral limestone of unit 2, and unit 3. Approximate locations of columnar sections (Figs. 4 and 6), detailed columar sections of unit 1 (Fig. 5), locations of observation points (see text) are shown. N.S.G. is Nakijin Sports Ground.

in Imadomari, Sakiyama, and Koechi areas (Figs. 3 and 4). The corals are largely recrystallized, however the limestone east of Sakiyama (point a; Fig. 3) obviously contains screlactinian corals such as *Porites* sp. and *Montastrea* sp., which characterize a shallow marine environment.

The northern coast of the peninsula exposes several continuous sections of unit 1 (Fig. 5). A 22 m long (altitude -1~+21 m) section of north of Sakiyama shows an alternation of coral and detrital limestones (Fig. 5A). The section starts from the rhodolith limestone and 4.5 m thick detrital limestone which contains brachiopods, gastropods, and rhodoliths. They are followed by thin (1 m) coral-rich limestone containing toppled colonies, 2.5 m thick detrital limestone containing *Diaseris* sp. (a coral), another thin (1 m) layer of coral-rich limestone, and 4.5 m thick detrital limestone. These detrital limestones normally yeild large foraminiferas; *Cycloclypeus* sp. and *Operculina* sp. The litho- and biofacies indicate that these limestone was deposited in a relatively deep (deeper than -50m) environments. From 13 m in altitude, the section exposes coral limestone, in which *Montastrea* sp., *Favites* sp., and *Fungia* sp. occur in their living position. This coral community indicates a shallow (shallower than -50 m, probably even shallower) environment. The coral limestone is cowered with detrital limestone containing *Operculina* sp. which indicates the paleodepth again became deeper (than -50 m).

At outcrops on a cliff along the coast and beside the road

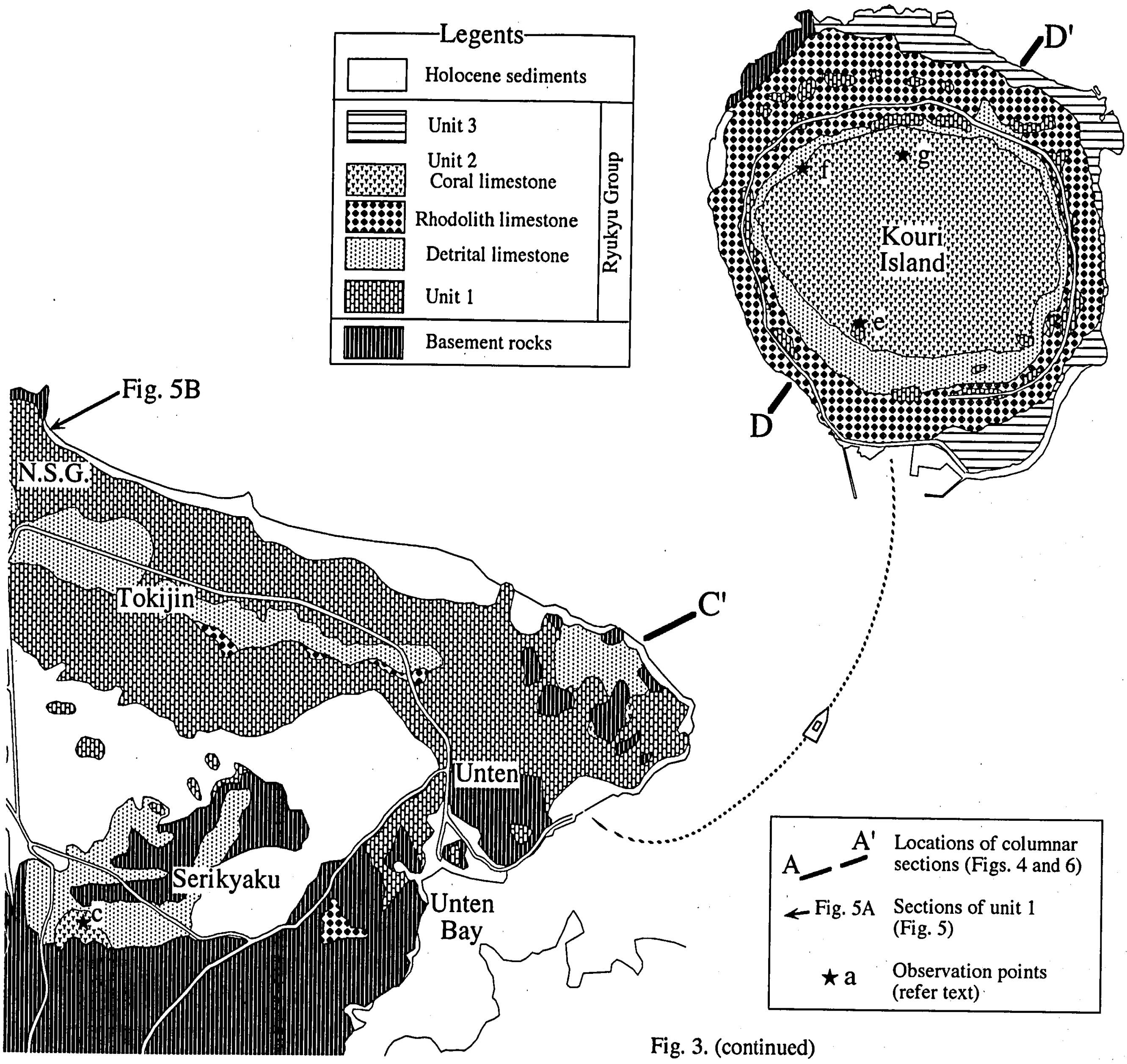

Fig. 3. (continued)

around Nakijin Sports Ground (N.S.G. in Fig. 3), a 29 m (8-36 m in altitude) long section displays a cyclic facies change (Fig. 5B). It starts from clastic limestone containing brachiopods and gastropods until 12.5 m. This limestone is rich in terrigenous material. Above this, 1.5 m thick limestone contains screlactinian corals which are poorly preserved and unidentified even in a genus level. From 16 m, the section becomes continuous. The base is a 3 m brachiopod clastic limestone which is followed by rhodolith limestone (1 m), clastic limestone (1 m), coral limestone (1 m), and thin reddish brown siltstone. This succession overall indicates upward-shallowing. The siltstone contains charcoal and is interpreted as a paleosol. From 22 to 25 m, section again exposes an upward-shallowing facies change consisting of rhodolith, clastic, and coral limestones. It is covered with 6 m rhodolith limestone with a paleosol-like siltstone layer on the top. The paleosol is overlain by 5 m thick coral limestone containing *Favites* sp. and *Fungia* sp.

Several localities including point b (Fig. 3) north of Sakiyama, expose the boundary between the coral limestone of unit 1 and the rhodolith limestone of unit 2. At point b, the boundary surface is undulating which may indicates a subaerial erosion of the coral limestone of unit 1. The coral community consists of *Porites* sp., *Montastrea* sp., and *Fungia* sp., but excludes *Acropora* sp. that suggests a shallow (upper than -50m in depth) reef slope environment. The rhodolith limestone contains larger foraminiferas such as, *Cycloclypeus* sp. and *Operculina* sp. The paleodepth clearly

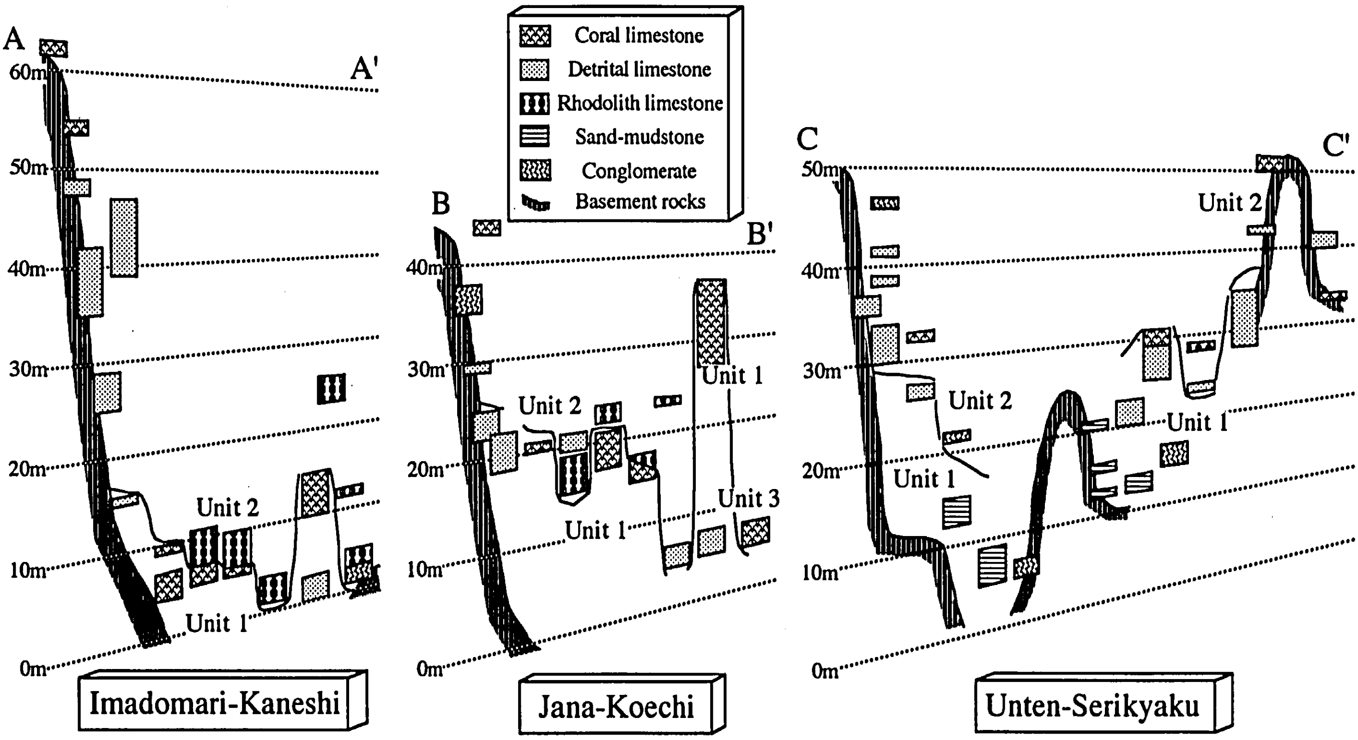

Fig. 4. Columnar sections of the Ryukyu Group of the northern Motobu Peninsula, Nakijin Village. The Locations are roughly shown in the geological map (Fig. 3; A - A', B - B' and C - C'). The boundaries between the different units are traced by lines. The top of unit 1 generally exhibits an undulating surface.

increased in the periods between deposition of the two facies (coral and rhodolith limestones). However, if the coral limestone of unit 1 was subjected to a subaerial erosion, the paleodepth had been once decreasing and then increase down to deeper than -50m (the paleodepth of the rhodolith limestone).

Unit 2 exposes in a large area of the middle to western Nakijin Village. Facies types of unit 2 varies depending on regions and altitudes. The low-altitude terrace from Imadomari to Sakiyama is largely covered with the rhodolith limestone facies intercalated with large foraminiferal (*Cycloclypeus* sp. and *Operculina* sp.) beds. Along the southern margin and the middle part of the distributing area of the Ryukyu limestone, clastic limestone is largely exposed. The clastic limestone is locally very terrigenous and is rather regarded as calcareous sandstone and mudstone around Kaneshi and south of Hirashiki. The sandstone normally contains the fragments of oyster shells and encrusting calcareous algae which indicates an environment of a rocky shore. The conglomerate including clasts of the basement rock is normally formed near the boundary with the basement rocks (Fig. 4).

Distribution of the coral limestone of unit 2 is limited in small separated areas. They are located in Kaneji (altitude 64 m), Jana (altitude 44 m), east of Serikyaku (altitude 33 m) and west of Unten (altitude 52 m). The outcrop east of Serikyaku (point c; Fig. 3) displays relatively well-preserved coral community including *Diaseris* sp. and *Fungia* sp. which indicates a reef-slope environment.

Unit 3 is only exposed along the western side of the Ooi River (point d; Fig. 3). It is a 9 m thick coral limestone. Corals are well-preserved *Acropora* sp., *Favites* sp., and *Fungia* sp. and indicates a very shallow environment.

C. Kouri Island

Unit 1 is exposed in scattered localities of 64-40 m in altitude. The facies of unit 1 is coral limestone for all the localities and does not show a cyclic change which can be found in unit 1 of the northern Motobu Peninsula. It is largely covered with rocks of unit 2, and therefore a thick section cannot be found except for an abandoned limestone

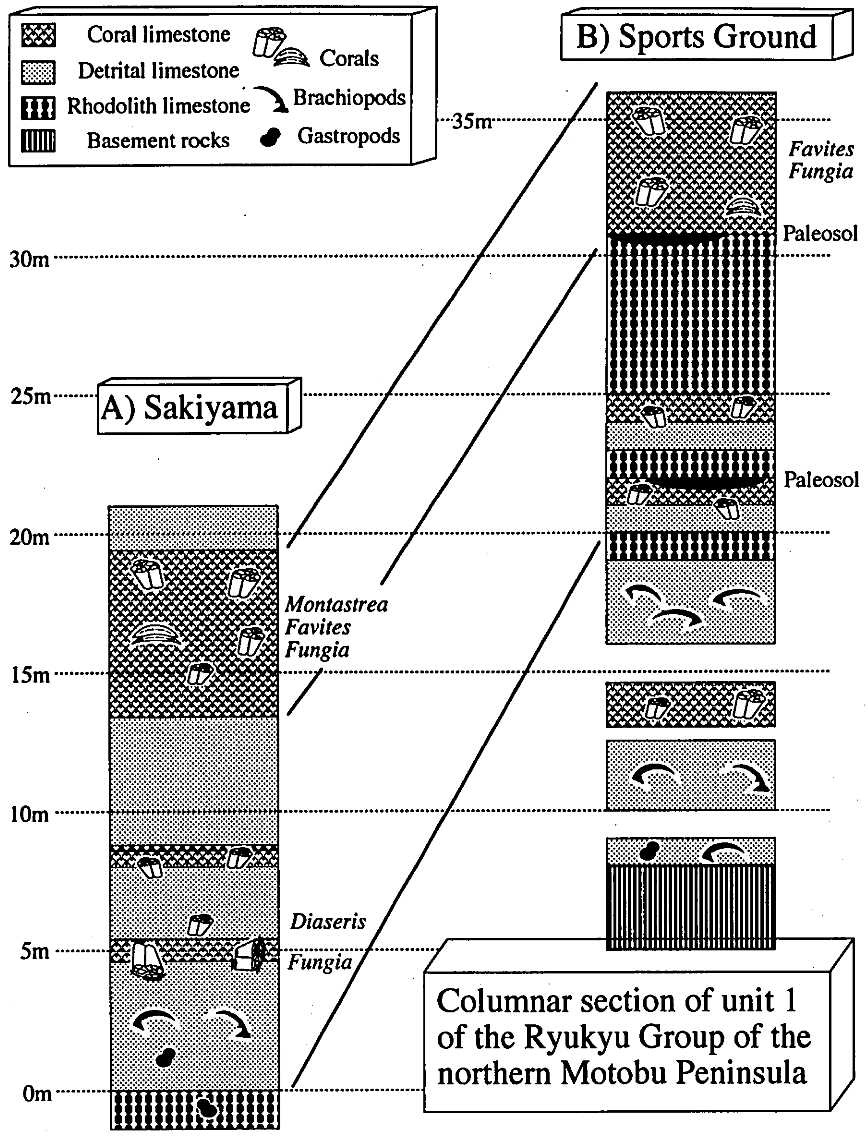

Fig. 5. Two columnar sections of unit 1 of the Ryukyu Group exposed along the northern coast of the Motobu Peninsula. Locations of the sections are shown in the geological map (Fig. 3). The facies change of the sections indicate cyclic change in paleodepth of the limestone.

quarry (point e; Fig. 3) where a 16 m long section is exposed. The section of the quarry consists of coral limestone containing *Porites* sp., *Favia* sp., and *Favites* sp. They overall indicate a shallow environment although some of the coral colonies show allochtonous occurrences.

Unit 2 of Kouri Island exhibit a concentric distribution of the different facies (Fig. 3) which may reflect the concentric terrace geomorphology of the island (Fig. 6). The area lower than 50 m in altitude is normally covered with rhodolith limestone including large foraminiferal (*Cycloclypeus* sp. and *Operculina* sp.) layers. From 50 to 65 m in altitude, clastic limestone is largely distributed. The clastic limestone contains fragments of coral colonies and generally changes into coral limestone in high altitude. This facies change is observed at point f (Fig. 3). The lower altitude area of the coral limestone is characterized by laminar-shaped colonies (*Echinophyllia* sp. and *Cyphastrea* sp.) which indicate a reef slope environment. Whereas, the coral limestone on the uppermost terrace of Kouri Island contains massive and branching coral colonies. A small quarry at point g (Fig. 3) displays well-preserved coral community

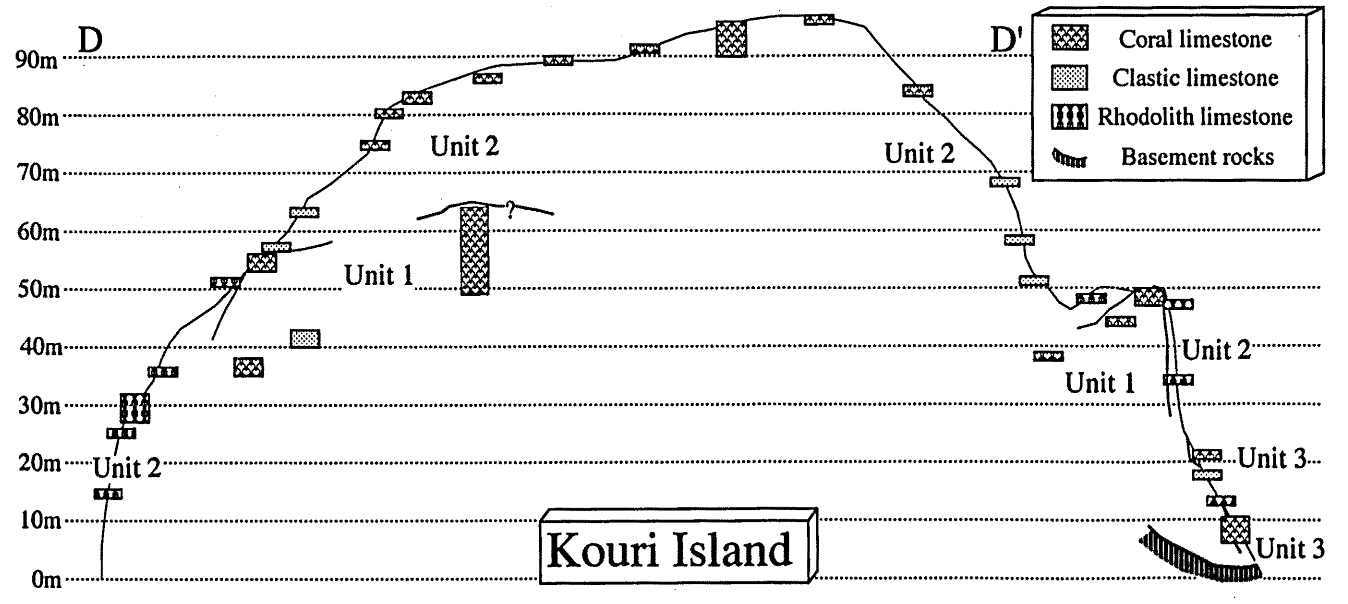

Fig. 6. Columnar sections of the Ryukyu Group of Kouri Island, Nakijin Village. The location is roughly shown in Fig. 3 (D - D'). The boundaries between the different units are traced by lines. The top of unit 1 is not traced fully because of the limited exposure.

consisting of branching *Acropora* sp., *Platygyra sinensis*, *Fungia* sp., *Pavona* sp., *Cyphastrea* sp. This community is typical in a moat environment.

The concentric distribution of different lithofacies and coral communities resembles facies pattern of the present atoll-like coral reef. When the moat facies was developed on the top of the island, the relative sea-level reached +107 m. In this case, paleodepth of the rhodolith limestone was deeper than -57 m that is consistent with the depth of rhodolith-dominating sediment (Iryu and Matsuda, 1988).

Unit 3 is the coral limestone fringing the margin of Kouri Island. The maximum altitude of unit 3 reaches +22 m. *Favites* sp. and *Platygyra* sp. were found.

As mentioned above, Kouri Island exhibits three terrace surfaces (107-90 m, 65-50m, and around 20 m). The lowermost terrace is formed by unit 3. The uppermost one is the moat surface of unit 2, and the middle terrace may have been originated from a coral reef of unit 1 which were later covered with clastic limestone of unit 2.

IV. DISCUSSION

A. Stratigraphic correlation between the northern Motobu Peninsula and Kouri Island

Because we did not determine the age of the Ryukyu Group, an efficient correlation between the limestone sections is impossible. However, we consider that depositional periods of the same-numbered units are roughly correlated between the northern Motobu Peninsula and Kouri Island. This correlation is supported by the following geologic and stratigraphic evidences which are common for both areas (Figs. 3, 4 and 6).

1) The upper part of unit 1 consists of coral limestone and tends to be exposed in small scattered localities. It is largely covered with the rocks of unit 2.

2) The unit 2 shows facies distribution which is generally parallel to the altitude (paleodepth). The shallowest facies (coral limestone) records the maximum relative sea-level highstand (+107 m in Kouri Island and +64 m in the northern Motobu Peninsula).

3) Distribution of the unit 3 is restricted to the lowermost terrace along the coast side localities.

If the stratigraphic framework of this study is correct, we are able to discuss difference in the (relative) uplifting rate of two areas. The highest altitudes of coral limestone of three different units indicate the three sea-level highstands. They are 40 m, 64 m and 9 m (for units 1, 2, and 3, respectively) in the northern Motobu Peninsula, whereas 65 m, 107 m, and 22 m in Kouri Island. The high values in Kouri Island may suggest that Kouri Island had a larger uplifting rate than the northern Motobu Peninsula.

B. Local conditions controlling the carbonate deposition

The Pleistocene sediments of the northern Motobu Peninsula and of Kouri Island differs in amount of siliciclastic material and development of coral limestone.

These differences must be associated with local conditions of depositional settings. Calcareous sandstone of unit 1 around Unten (previously defined as the Unten Facies) is maybe related to an alluvial siliciclastic sedimentation in an area between Unten Bay and the Haneji Inland Sea. In the northern Motobu Peninsula, unit 2 is still terrigenous, especially in the middle and southern part of the distributing area of the Ryukyu Group. Whereas, the Ryukyu Group of Kouri Island is mostly pure carbonate, that is related to the strait south of the island which has been restricting the terrigenous influx from the southern and eastern terrigenous sources.

The tops of units 1 and 2 are commonly formed by coral limestone, however the coral facies is much different between in the northern Motobu Peninsula and in Kouri Island. In occurrence of moat facies (point g) and shallow water facies in the island (point e) indicate that the reefs reached a mature stage of development, forming terrace. The stratigraphy suggests that the reefs were a 'keep-up' type (Neumann and MacIntyre, 1985). Whereas in the peninsula, the terrace geomorphology is not obvious for the tops of the unit 1 and 2. Corals do not indicate the shallowest environment, but are rather ones living on a reef-slope. The reefs probably 'gave-up' (Neumann and MacIntyre, 1985) with a rapid sea-level change, especially ones of unit 1, which are exposed in scattered elevations along the northern coast of the peninsula.

Terrigenous influx generally restricts the development of reef and carbonate deposition (Mount, 1984). In many of recent reef complexes, corals are separated from a terrigenous source by a topographically depressed strait or lagoon (Hopley, 1982). This is probably the case of the Ryukyu Group of Nakijin Village.

C. Global sea-level controlling the carbonate deposition

Because the development of a coral reef complex, in general, responds to the global sea-level change (e.g. Bard et al. 1990), the stratigraphy of the Ryukyu Group could be compared with the sea-level curve. For the Quaternary, global sea-level change is mostly discussed by the oxygen isotope of foraminiferas extracted from deep-sea cores. The oxygen isotopic curve compiled by Williams et al. (1988) indicate that the cyclicity changed from a small amplitude and a short interval (ca. 40 k.y.) to a large amplitude and a long interval (ca. 100 k.y.) during a period of 0.7-0.5 Ma. If the sea-level is reasonably calculated by the direct translation from the absolute value of oxygen isotope, the amplitude of the sea-level change was approximately 50 m before 0.7 Ma, and more than 100 m after 0.5 Ma.

Columnar sections of unit 1 of the northern Motobu Peninsula (Fig. 5) clearly record facies change associated with fluctuation of the relative sea-level. Each sedimentary cycle, typically an upward shallowing from rhodolith-clastic to coral limestones, is quite thin (less than several meters) and were deposited during both transgressive and regressive periods. Therefore, they were most reasonably deposited during a period of a small amplitude and a short interval.

Unconformable relation among unit 1, 2, and 3 of the Ryukyu Group must have been developed by a large amplitude of the relative sea-level change. Because the top of unit 2 reaches +107 m in altitude on Kouri Island, the amplitude exceeded more than 100 m. At least, the major portions of units 2 and 3 was deposited only during sea-level highstands. This circumstance is consistent with the global sea-level curve after 0.5 Ma.

These remarks will gain more confidence if absolute ages are determined, though they have not been determined in areas like Okinawa Island, where limestone hardly preserve primary aragonite which is available for U-series and ESR dating. Nannofossils have posibillity even on limestone suffered by diagenesis to some extent (Honda et al., 1993), though they provide a relatively coarse resolution during the period of 390-830 ka. Sr stable isotope (Jiju, 1994; Kaneko and Ito, 1995) is also helpful, though it is difficult to gain a higher resolution than several-hundreds ka (Ito, 1993).

V. CONCLUDING REMARKS

Using the latest knowledge on the living subtropical reef biota and on the Pleistocene sea-level change, we researched geology and stratigraphy of the Ryukyu Group of Nakijin Village. Our stratigraphic division and facies analysis indicate that the carbonate deposition and development of a coral reef complex has been strongly controlled by both of global and local environmental conditions. Although many other conditions should be carefully considered, the global sea-level and terrigenous influx are especially important for the case of Nakijin Village. We are also able to conclude that unit 1 was deposited during both sea-level highs and lows whereas the most of units 2 and 3 were deposits of sea-level highstands. Several studies in other areas (e.g. Toku Island - Nakamori et al., 1995; Ie Island - Fujishiro 1996MS) suggest the same tendency in stratigraphy; the older cyclic sediments covered by the younger sediments of sea-level highstands. It may be possible to apply the subdivision of the Ryukyu Group to many of other areas.

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