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784. URANIUM-SERIES AGE OF THE RIUKIU LIMESTONE ON HATERUMA ISLAND, SOUTHWESTERN RYUKYUS*

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Abstract. Uranium-series analyses of seventy-four coral samples imply that the Pleistocene Riukiu Limestone (Hanzawa, 1935) on Hateruma, Ryukyu Islands, were formed during at least four stages of high sea stand, two interstadials (ca. 81 and 103 ka B.P., respectively) and two interglacials (the last and penultimate ones). The oldest coral date was 300^{+40}_{-31}ka obtained from a *Porites* sample which was collected at a locality of about 33 m above the sea. Maybe this date is suggestive that the coral reef has already formed at the time of an another high sea stand (correlative to the stage 9 of the marine oxygen isotope record) in the place where the island is at present. The tidal flat around the coast of the island is likely to have been built since the last thousands years. The Riukiu Limestone on Hateruma is thus correlative with some of Pleistocene uplifted coral reefs on Barbados (Bender *et al.*, 1979), New Guinea (Bloom *et al.*, 1974) and Kikai (Konishi *et al.*, 1974) dated previously, and the tidal flat limestone with the Raised Coral Reef Limestone on Kikai (Ota *et al.*, 1978) and with the reef complex I on the Huon Peninsula, New Guinea (Bloom *et al.*, 1974).

Among marine terraces which were divided into eight steps (T1 through T8) by Ota *et al.* (1982), T2 and lower five terraces (T4 to T8) are inferred to be erosional in origin, based on the results of ^{230}Th/^{234}U age determination of corals which were collected on the same surface of the terraces. Ota *et al.* (1982) documented that the former shoreline of each terrace shows progressive westward tilting. The maximum uplift rate of approximate 0.3 m/ka is calculated in the eastern part of the island, assuming the constant rate of tectonic uplift and a sea level 6 m higher of the present one at the time of T3 terrace formation (ca. 128 ka B.P.). Accordingly, Hateruma is considered to have been situated tectonically in the compressive field since the last interglacial.

Introduction

The island of Hateruma is located in Lat. 24°02.4' to 24°04.0' N. and 123°45.1' to 123°48.6' E., southwestern end of Ryukyu Islands. It is roughly elliptical in shape having a length of about 5.9 km and a width of 2.9 km at its widest part and has an area of about 15 km^2. The island is flat as a whole, its highest point is 59.5 m above the sea, and staircase morphology is typically developed on it. The basement rock exposed at very limited small area on the island is dark bluish-gray colored siltstone, ranging in age from Upper Miocene to Pleistocene, which has been named the Shimajiri Group. This stratum is overlain by the reefy limestone which is a few to tens meters in thickness and covers almost all island.

After the initiative work of Hanzawa (1935) who divided into two time-stratigraphic units,

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Pleistocene Riukiu Limestone and Holocene Raised Coral Reef Limestone, the limestone on Hateruma was classified into four morphostratigraphic units by Kawana and Oshiro (1978). They estimated by the ^{14}C method that their latest unit, the Surface IV, was formed approximately 30 ka (kilo anno = 1,000 years) B.P. By using the non-destructive $^{226}Ra/^{238}U$ dating technique, Konishi (1980) verified the first radiometric date of Middle Pleistocene from the raised coral reefs in the Ryukyu Islands area, for two coral samples from the Surface I and II of Kawana and Oshiro (1978), and revised the age estimation of Kawana and Oshiro for the Surface IV to be the last interglacial (ca. 120 to 130 ka B.P.). Emergent marine terraces on the island was recently subdivided into eight steps, T1 through T8, by Ota *et al.* (1982). They inferred, from the width of terraces, height of terrace riser, thickness and facies of limestone and presence of specific raised coral reef surface features, that only two terraces, T1 and T3, are constructive raised coral reefs formed in association with rising sea level, and that the other steps, T2 and T4 to T8, are erosional in origin. In addition, their conclusions founded on the results of the $^{230}Th/^{234}U$ dating for seven corals were that T3 was formed during the last interglacial and T1 during the preceding one. In the process of this study, the author has found and preliminarily reported the existence of limestone units which were formed during the times of two interstadials, ca. 80 and 102 ka B.P., respectively (Omura, 1983).

As stated above, age determination of the coralline limestone on Hateruma seems to have been under way little by little. The reliable radiometric dates, however, are definitely insufficient for age assignments of the entire limestone on the island and for correlation with those in other areas. The main aim of the present work is to gain enough numbers of $^{230}Th/^{234}U$ coral dates from Hateruma, as the most fundamental data, in order to discuss the tectonic history of the island and sea level change and relate them to various Pleistocene events in other areas.

Samples

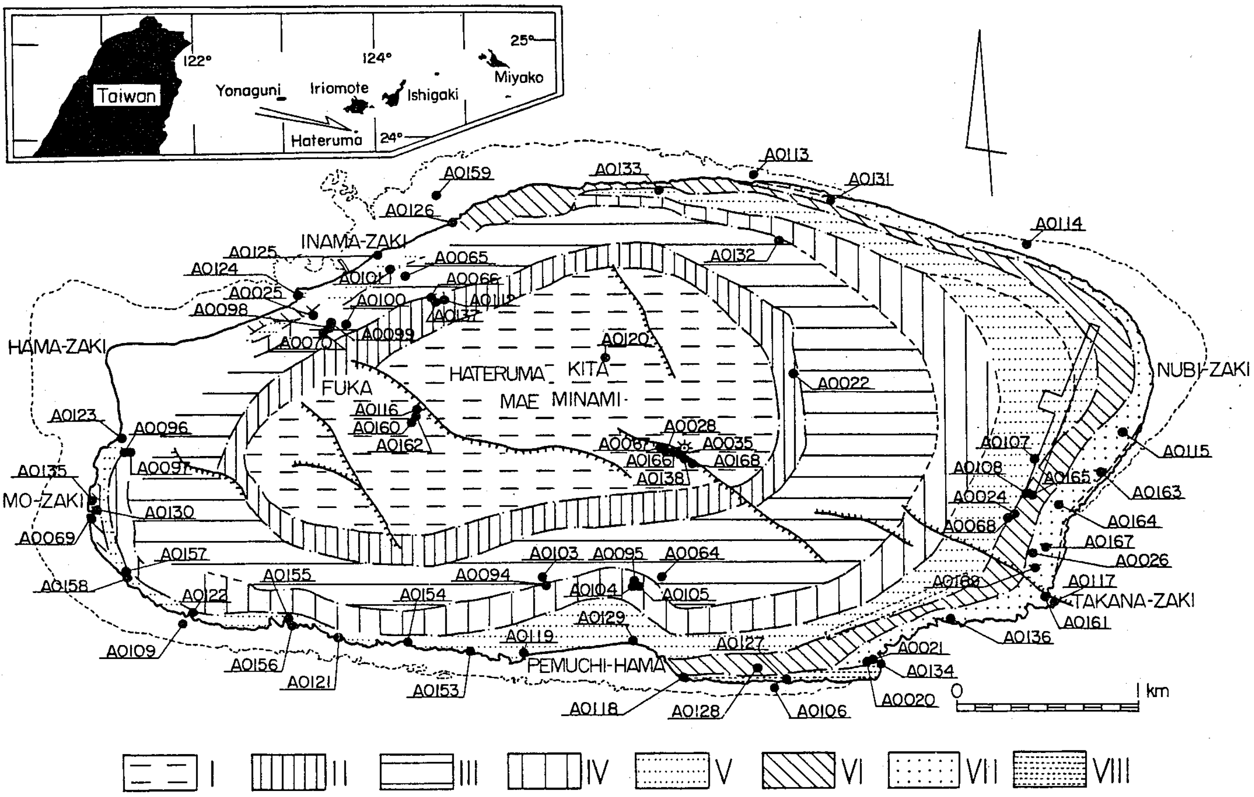
Seventy-four samples of hermatypic corals, which included ten genera, were chosen for dating purpose mainly from the reefy limestone on Hateruma Island, Southwestern Ryukyus. Among them, sixty-nine samples were taken from the Riukiu Limestone which was considered to be Pleistocene in age by Hanzawa (1935), and five from the limestone forming the present tidal flat around the coast of the island. Table 1 lists numbers, taxonomy and elevation of the samples analyzed in this study, and the terrace number of their localities, which were defined by Ota *et al.* (1982). The localities of all samples are plotted on the map showing their classification of geomorphic surface (Text-fig. 1).

Natural exposures of the Riukiu Limestone is very limited in number on the island except the coastal area, and therefore man-made outcrops like quarries, road-cuts and gullies, or even some gigantic masses of limestone dug in the cause of soil amendment were used effectively for field observation. However, they are not yet sufficient to examine geologically the Riukiu Limestone on Hateruma, based on the detailed litho- and biofacies analyses.

In the present study, coral samples for dating were collected as equably as possible from all of the morphostratigraphic units of Ota *et al.* (1982). Number of samples collected from each unit are shown in a figure (Text-fig. 2) mentioned later. Mode of occurrence and mineralogical nature of fossil corals were examined very carefully in the processes of searching coral samples suitable for dating. Most of samples for dating were selected, with some exceptions, from large-sized (more than 50 cm in diameter) coral colonies which were still in their original position of growth. One sample (A0131) was fair-sized (about 70 cm in diameter) but was apparently included as a gravel in non-reef facies (probably fore-reef facies) of limestone. Six samples (A0096, A0097, A0116, A0138, A0160 and A0162) could not be decided whether they are in situ or not. The field test for diagenetic altera-

Table 1. List of the fossil coral samples from the Riukiu Limestone on Hateruma. (KK-series samples were collected by Prof. K. Konishi of the Kanazawa Univ., OHB-series by Prof. Y. Ota of the Yokohama National Univ., Dr. N. Hori of the Hiroshima Univ. and Prof. A. L. Bloom of the Cornell Univ., and others were collected by the author himself. See Text-fig. 1 for the terrace number.)

Code Number	Sample Number	Genera	Elevation	Terrace
AO020	KK7807071-2		10 m	VII
AO021	KK7807071-3		10	VII
AO022	KK7807053-1	*Cyphastrea*	43	II
AO024	KK7807054-2		13	VI
AO025	KK7807051-2		9	III ?
AO026	KK7807084-1		8	VII
AO028	KK780706-2	*Porites*	48	I
AO035	81-11-28-1	*Goniastrea*	48	I
AO064	OHB801103-1	*Porites*	30	III
AO065	OHB801103-2	*Porites*	20	III
AO066	OHB801103-1	*Porites*	33	II
AO067	OHB801104-2	*Goniastrea*	48	I
AO068	OHB801104-8	*Porites*	15	V
AO069	OHB801105-3	*Porites*	5	VI
AO070	OHB801105-7	*Porites*	20	III
AO094	81-11-30-2	*Porites*	24	IV
AO095	81-12-5-2	*Porites*	23	IV
AO096	81-12-5-4	*Porites*	10	IV
AO097	81-12-5-5	*Favites*	10	IV
AO098	81-12-2-1	*Porites*	19	III
AO099	81-12-2-2	*Porites*	19	III
AO100	81-12-2-3	*Porites*	22	III
AO101	81-12-2-8	*Porites*	15	V
AO103	81-11-30-3	*Porites*	24	III
AO104	81-12-5-1	*Porites*	20	IV
AO105	81-12-5-3	*Cyphastrea*	18	IV
AO106	81-12-4-4	*Favia*	0	—
AO107	81-12-6-1	*Porites*	14	V
AO108	81-12-4-7	*Porites*	11	VI
AO109	81-12-1-2	*Acropora*	0	—
AO112	81-12-2-5	*Porites*	34	II
AO113	81-12-3-2	*Goniastrea*	0	—
AO114	81-12-3-4	*Goniastrea*	0	—
AO115	81-12-3-5	*Goniastrea*	3	VII
AO116	81-12-1-1A	*Goniastrea*	35	I
AO117	81-11-29-1	*Leptoria*	12	VII
AO118	81-11-29-7	*Montipora*	3	VIII
AO119	81-11-30-5	*Porites*	1	V
AO120	81-12-4-9	*Goniastrea*	43	I
AO121	81-11-30-8	*Porites*	5	V
AO122	81-12-1-3	*Porites*	3	V
AO123	81-12-5-6	*Porites*	2	V
AO124	81-12-2-4	*Porites*	3	VIII
AO125	81-12-2-7	*Porites*	4	V ?
AO126	81-12-2-9	*Porites*	3	VI ?
AO127	81-11-29-5	*Montipora*	4	VIII
AO128	81-11-29-6	*Montastrea*	7	VI
AO129	81-11-30-4	*Porites*	4	V
AO130	81-12-1-5A	*Porites*	2	VI
AO131	81-12-3-3	*Porites*	7	VII
AO132	81-12-3-1	*Porites*	26	III
AO133	81-12-2-10	*Porites*	8	V
AO134	81-11-29-4	*Porites*	8	VII
AO135	81-12-1-5B	*Montastrea*	3	VI
AO136	81-11-29-3	*Porites*	11	VII
AO137	81-12-2-6	*Porites*	32	II
AO138	81-12-4-1	*Favites*	48	I
AO153	81-11-30-6	*Porites*	3	V
AO154	81-11-30-7	*Montipora*	3	V
AO155	81-11-30-9A	*Montipora*	4	V
AO156	81-11-30-9B	*Cyphastrea*	4	V
AO157	81-12-1-4A	*Porites*	4	V
AO158	81-12-1-4B	*Favia*	4	V
AO159	81-11-30-1	*Goniastrea*	0	—
AO160	81-11-30-11	*Platygyra*	35	I
AO161	81-11-29-2	*Porites*	12	VII
AO162	81-12-1-1B	*Goniastrea*	35	I
AO163	81-12-3-6	*Porites*	3	VII
AO164	81-12-3-7	*Platygyra*	5	VII
AO165	81-12-4-8	*Porites*	11	VII
AO166	81-12-4-2	*Goniastrea*	48	I
AO167	81-12-4-5	*Porites*	7	VII
AO168	81-12-4-3	*Goniastrea*	48	I
AO169	81-12-4-6	*Porites*	7	VII



Text-fig. 1. Map showing the localities of fossil corals mentioned in this paper. (Roman numerals from I to VIII in the legend denote the terrace number of Ota *et al.*, 1982)

tion of a coral was to examine the existence of the secondary low-Mg calcite by the minute observation under a magnifier and the staining method using Feigl's solution. Ten genera listed in Table 1 are almost representatives of corals in reef facies of the Riukiu Limestone on Hateruma. *Porites* was the most predominant genus of all, due to its abundance and well-preservation in many exposures.

Uranium-Series Dating

Chemical and analytical procedures employed in uranium-series dating have been described previously (Omura, 1976). The coral fragments were mechanically cleaned, crushed into small (less than 5 mm in diameter) piecies, scrubbed ultrasonically in distilled water, dried in a drying furnace at low temperature (lower than 50°C), and ground to a fine (less than 200 mesh) powder. The concentration of uranium and thorium isotopes and the activity ratios of $^{234}U/^{238}U$, $^{230}Th/^{232}Th$ and $^{230}Th/^{234}U$ were measured by the alpha-spectrometry method, using a 4096 channels multi-channel pulse height analyzer coupled with four systems of silicon solid-state detectors. The Harwell spike solution of ^{232}U and ^{228}Th (Ivanovich and Warchal, 1981) was used as a yield tracer to check the overall chemical yield of uranium and thorium isotopes. The mineralogy of all specimens was examined with special care by X-ray diffraction analysis prior to the chemical treatment.

Results of the isotopic measurements on uranium and thorium are given in Table 2. The quoted errors are standard deviations (one sigma) derived from counting statistics.

Analyses of X-ray diffraction patterns proved that no or only a trace to 2 – 3 % low-Mg calcite was contained in all samples used here. Besides the mineralogical composition, it must be known whether the samples have been a closed system with respect to uranium and intermediate nuclides between ^{238}U and ^{230}Th.

The possibility of post-mortem addition or loss of uranium is considered from the age dependence of its concentration. There is, however, no systematic change in uranium concentration of the fossil corals with age (Table 2). It may, therefore, be safely said that the coral samples dated here have been closed system for uranium since the death of organisms. On the other hand, the ^{234}U/^{238}U activity ratios seem to decrease toward its secular equilibrium value of 1.00 with the ages of samples. This fact adds support to the inference that closed system respect to uranium isotopes has been held on throughout their diagenetic history.

^{230}Th/^{234}U ages are calculated on the assumption that each sample was initially free of ^{230}Th. Such an assumption is supported by the observation that ^{232}Th concentrations in more than half samples in the table do not exceed the lower limit of detection (0.02 ppm). For the samples in which measurable amount of ^{232}Th was detected, ^{232}Th concentration is not much exceeding the limit, and furthermore the ^{230}Th/^{232}Th activity ratio is very much higher than those (1.4 to 3.0) in Ryukyuan present-day corals (Omura, 1976).

The above evidences suggest that all of the ^{230}Th/^{234}U ages in Table 2 are fully reliable.

Age and Correlation of the Riukiu Limestone on Hateruma

Barbados in the West Indies, the Huon Peninsula of New Guinea and Kikai in the Ryukyu Islands can be listed as the three major type localities for the Pleistocene coral reefs which have been chronologically studied by using the uranium-series dating techniques. The existence of several interstadials at intervals of approximately 20 ka, following the last interglacial, have been clearly vindicated in those regions by Bender *et al.* (1979), Bloom *et al.* (1974), Konishi *et al.* (1974) and others. In this paragraph, I attempt the age assignments of the Riukiu Limestone on Hateruma and the correlations of them with the counterparts in such areas.

As above-mentioned, it was extremely difficult to investigate the Riukiu Limestone in detail all over the island of Hateruma, because of the limited numbers of outcrops. That means the difficulty in minute facies analyses of the Riukiu Limestone which is overlaying the staircase topography of this island. For this reason, the nature and size of each reef complex could not be made clear in this study, although the Riukiu Limestone on Hateruma is very likely to be a composite of several reef complexes. Here, renaming the morphostratigraphic units defined by Ota *et al.* (1982) as Hateruma I, II, III, and so on, the ages of them are estimated and such units are correlated with the Pleistocene uplifted coral reefs reported from Barbados, Huon Peninsula and Kikai.

The ^{230}Th/^{234}U dates which are younger than the age (120 to 130 ka) of the last interglacial were obtained for the first time from the Riukiu Limestone on the other island than Kikai in the Ryukyu Islands region (Table 2). The other dates, except the oldest one in the table, are nearly equivalent to the ages of two interglacials the last and penultimate ones. The oldest coral date is 300^{+40}_{-31} ka of A0066 sample which is a *Porites* collected at a locality of about 33 m above the sea. This date imply that the coral reef has already been formed at that time in the place where the island is at present. In comparison with the ages of the coral reefs in above-mentioned areas, ^{230}Th/^{234}U dates may be arranged into five or possibly six groups as shown in Table 2, which are thousands years (younger than 10 ka), approximately 70 to 90 (81 ± 3, in average) ka, 100 to 106 (103 ± 1) ka, 110 to 158 (128 ± 7) ka, 190 to 260 (207 ± 3) ka, and 300 or more ka, respectively. In other words, the Pleistocene Riukiu Limestone on Hateruma is considered to have been formed during four or possibly five stages, which include two interstadials, two interglacials and possibly an another interglacial correlative to the stage 9 inferred from the isotope record of core V28-238 (Shackleton and Opdyke, 1973: Table 3).

Text-fig. 2 is a simplified topographic cross section in which eight steps of marine terraces developing on the island of Hateruma is schematically

Table 2. Isotopic composition and estimated ages of fossil corals from the Riukiu Limestone on Hateruma.

Code Number	Isotope Concentration				Activity Ratio			Estimated Age (ka)
	^{238}U (ppm)	^{234}U (dpm/g)	^{232}Th (ppm)	^{230}Th (dpm/g)	^{234}U/^{238}U	^{230}Th/^{232}Th	^{230}Th/^{234}U	
A0109	4.05 ± 0.04	3.44 ± 0.03	< 0.02	0.0292±0.0016	1.14 ± 0.01		0.00847±0.00046	0.92±0.05
A0114	2.93 ± 0.03	2.55 ± 0.03	< 0.02	0.0691±0.0031	1.17 ± 0.01		0.0271±0.0012	3.0 ± 0.2
A0113	2.80 ± 0.03	2.39 ± 0.03	< 0.02	0.0974±0.0030	1.14 ± 0.01		0.0408±0.0013	4.5 ± 0.2
A0106	2.70 ± 0.03	2.35 ± 0.03	< 0.02	0.116 ± 0.005	1.17 ± 0.01		0.0492±0.0022	5.5 ± 0.3
A0159	2.29 ± 0.04	1.92 ± 0.03	0.0219±0.0035	0.106 ± 0.004	1.13 ± 0.02	20.1±3.3	0.0550±0.0022	6.0 ± 0.5
A0119	2.88 ± 0.03	2.33 ± 0.03	< 0.02	1.11 ± 0.02	1.09 ± 0.01		0.475 ± 0.009	69 ± 2
A0096	2.57 ± 0.03	2.12 ± 0.02	< 0.02	1.02 ± 0.01	1.11 ± 0.01		0.482 ± 0.008	71 ± 2
A0118	2.81 ± 0.03	2.26 ± 0.02	< 0.02	1.26 ± 0.02	1.08 ± 0.01		0.555 ± 0.011	87 ± 3
A0125	2.70 ± 0.03	2.24 ± 0.02	0.0266±0.0036	1.27 ± 0.01	1.12 ± 0.01	199 ± 27	0.566 ± 0.009	89 ± 3
A0126	2.53 ± 0.02	2.05 ± 0.02	< 0.02	1.16 ± 0.01	1.09 ± 0.01		0.564 ± 0.008	89 ± 2
A0108	2.62 ± 0.03	2.18 ± 0.02	< 0.02	1.25 ± 0.01	1.12 ± 0.01		0.573 ± 0.009	91 ± 3
A0153	2.72 ± 0.03	2.24 ± 0.02	0.0314±0.0039	1.29 ± 0.02	1.11 ± 0.01	171 ± 21	0.574 ± 0.009	91 ± 3
A0124	2.84 ± 0.03	2.28 ± 0.03	< 0.02	1.39 ± 0.02	1.08 ± 0.01		0.607 ± 0.011	100 ± 3
A0101	3.53 ± 0.03	2.63 ± 0.02	0.0409±0.0044	1.79 ± 0.02	1.11 ± 0.01	183 ± 20	0.616 ± 0.009	102 ± 3
A0157	2.63 ± 0.03	2.19 ± 0.04	0.0206±0.0036	1.39 ± 0.02	1.13 ± 0.01	281 ± 49	0.623 ± 0.011	103 ± 3
A0094	2.42 ± 0.02	1.98 ± 0.02	< 0.02	1.24 ± 0.01	1.10 ± 0.01		0.623 ± 0.008	104 ± 3
A0127	2.82 ± 0.03	2.37 ± 0.03	< 0.02	1.50 ± 0.02	1.12 ± 0.01		0.632 ± 0.012	106 ± 4
A0129	2.65 ± 0.03	2.22 ± 0.02	0.0526±0.0050	1.40 ± 0.02	1.12 ± 0.01	111 ± 11	0.631 ± 0.010	106 ± 3
A0130	2.74 ± 0.03	2.22 ± 0.02	< 0.02	1.43 ± 0.02	1.09 ± 0.01		0.644 ± 0.010	110 ± 3
A0021	2.73 ± 0.05	2.24 ± 0.04	0.0278±0.0070	1.47 ± 0.03	1.10 ± 0.02	221 ± 55	0.656 ± 0.019	112 ± 7
A0133	2.62 ± 0.02	2.11 ± 0.02	< 0.02	1.37 ± 0.04	1.08 ± 0.01		0.652 ± 0.018	112 ± 6
A0097	2.52 ± 0.02	2.10 ± 0.02	< 0.02	1.38 ± 0.02	1.12 ± 0.01		0.657 ± 0.012	113 ± 4
A0158	2.63 ± 0.05	2.19 ± 0.04	0.0258±0.0034	1.44 ± 0.02	1.12 ± 0.02	233 ± 30	0.660 ± 0.014	114 ± 4
A0020	2.88 ± 0.06	2.41 ± 0.05	0.0334±0.0057	1.60 ± 0.03	1.12 ± 0.02	199 ± 34	0.664 ± 0.017	115 ± 5
A0107	2.78 ± 0.03	2.34 ± 0.03	0.0292±0.0033	1.58 ± 0.02	1.13 ± 0.01	225 ± 25	0.675 ± 0.010	118 ± 3
A0135	2.33 ± 0.03	1.91 ± 0.02	< 0.02	1.28 ± 0.02	1.10 ± 0.01		0.671 ± 0.011	118 ± 4
A0163	2.74 ± 0.03	2.27 ± 0.02	0.0200±0.0039	1.53 ± 0.02	1.11 ± 0.02	318 ± 61	0.672 ± 0.012	118 ± 4
A0103	3.57 ± 0.03	2.93 ± 0.03	< 0.02	1.97 ± 0.02	1.10 ± 0.01		0.675 ± 0.010	119 ± 4
A0165	2.80 ± 0.03	2.27 ± 0.02	0.0229±0.0035	1.54 ± 0.02	1.09 ± 0.01	281 ± 43	0.680 ± 0.011	121 ± 4
A0095	2.69 ± 0.03	2.23 ± 0.02	0.0252±0.0039	1.53 ± 0.02	1.11 ± 0.01	254 ± 40	0.686 ± 0.011	122 ± 4
A0024	2.65 ± 0.06	2.23 ± 0.05	< 0.02	1.54 ± 0.05	1.13 ± 0.02		0.691 ± 0.027	123 ± 9
A0123	2.85 ± 0.03	2.37 ± 0.02	< 0.02	1.64 ± 0.02	1.12 ± 0.01		0.693 ± 0.012	124 ± 4
A0115	2.46 ± 0.03	2.01 ± 0.02	< 0.02	1.41 ± 0.01	1.10 ± 0.01		0.701 ± 0.011	128 ± 4

A0132	2.81 ± 0.03	2.36 ± 0.03	< 0.02	1.13 ± 0.01	1.13 ± 0.01		0.705 ± 0.011	128 ± 4
A0069	2.71 ± 0.03	2.28 ± 0.02	0.0362±0.0055	1.62 ± 0.03	1.13 ± 0.01	187 ± 29	0.711 ± 0.014	130 ± 5
A0121	2.62 ± 0.03	2.18 ± 0.02	< 0.02	1.54 ± 0.02	1.11 ± 0.01		0.708 ± 0.011	130 ± 4
A0134	2.78 ± 0.03	2.31 ± 0.03	< 0.02	1.65 ± 0.02	1.12 ± 0.01		0.712 ± 0.012	131 ± 5
A0025	2.74 ± 0.08	2.17 ± 0.06	< 0.02	1.54 ± 0.02	1.06 ± 0.02		0.709 ± 0.023	132 ± 8
A0136	2.53 ± 0.03	2.12 ± 0.04	< 0.02	1.53 ± 0.02	1.12 ± 0.01		0.720 ± 0.012	133 ± 5
A0169	2.66 ± 0.03	2.20 ± 0.03	< 0.02	1.59 ± 0.02	1.11 ± 0.01		0.719 ± 0.012	133 ± 5
A0098	2.72 ± 0.03	2.24 ± 0.02	< 0.02	1.61 ± 0.02	1.10 ± 0.01		0.722 ± 0.011	135 ± 4
A0026	2.69 ± 0.05	2.22 ± 0.04	0.0243±0.0070	1.61 ± 0.04	1.10 ± 0.02	276 ± 80	0.725 ± 0.023	136 ± 9
A0070	2.80 ± 0.04	2.29 ± 0.03	< 0.02	1.66 ± 0.02	1.10 ± 0.01		0.725 ± 0.019	136 ± 7
A0122	2.50 ± 0.03	2.04 ± 0.02	0.0260±0.0034	1.48 ± 0.02	1.10 ± 0.01	237 ± 32	0.724 ± 0.012	136 ± 5
A0164	2.60 ± 0.03	2.12 ± 0.02	0.0288±0.0048	1.54 ± 0.02	1.09 ± 0.01	223 ± 37	0.726 ± 0.013	137 ± 5
A0161	2.63 ± 0.03	2.16 ± 0.02	0.0233±0.0041	1.96 ± 0.02	1.10 ± 0.01	282 ± 50	0.732 ± 0.013	138 ± 5
A0128	2.21 ± 0.03	1.83 ± 0.02	< 0.02	1.35 ± 0.02	1.11 ± 0.01		0.738 ± 0.013	140 ± 5
A0167	2.52 ± 0.03	2.10 ± 0.02	0.0347±0.0041	1.57 ± 0.02	1.11 ± 0.01	188 ± 22	0.747 ± 0.012	143 ± 5
A0068	2.76 ± 0.03	2.27 ± 0.02	< 0.02	1.71 ± 0.03	1.10 ± 0.01		0.753 ± 0.015	147 ± 6
A0117	2.45 ± 0.03	2.01 ± 0.02	0.0211±0.0029	1.52 ± 0.02	1.10 ± 0.01	301 ± 41	0.756 ± 0.012	148 ± 5
A0065	2.64 ± 0.03	2.14 ± 0.03	0.0220±0.0030	1.65 ± 0.02	1.08 ± 0.01	312 ± 43	0.771 ± 0.012	155 ± 5
A0099	2.66 ± 0.02	2.17 ± 0.02	0.0241±0.0032	1.69 ± 0.02	1.09 ± 0.01	291 ± 39	0.779 ± 0.011	158 ± 5
A0100	2.76 ± 0.03	2.20 ± 0.02	0.0257±0.0037	1.70 ± 0.02	1.07 ± 0.01	277 ± 40	0.775 ± 0.012	158 ± 5
A0154	3.35 ± 0.03	2.73 ± 0.03	0.0438±0.0050	2.30 ± 0.03	1.09 ± 0.01	219 ± 25	0.844 ± 0.012	191 ± 8
A0112	2.48 ± 0.03	2.00 ± 0.02	0.0222±0.0029	1.69 ± 0.02	1.08 ± 0.01	316 ± 41	0.844 ± 0.012	192 ± 8
A0105	3.45 ± 0.05	2.83 ± 0.04	0.0391±0.0044	2.40 ± 0.02	1.10 ± 0.01	256 ± 29	0.850 ± 0.014	194 ± 9
A0155	3.32 ± 0.03	2.69 ± 0.03	< 0.02	2.29 ± 0.02	1.09 ± 0.01		0.851 ± 0.012	196 ± 8
A0131	3.02 ± 0.04	2.38 ± 0.04	< 0.02	2.02 ± 0.02	1.05 ± 0.01		0.853 ± 0.015	201 +11 −10
A0116	3.39 ± 0.04	2.67 ± 0.03	0.0277±0.0031	2.30 ± 0.02	1.06 ± 0.01	346 ± 39	0.862 ± 0.012	207 ± 9
A0028	2.65 ± 0.07	2.20 ± 0.06	< 0.02	1.92 ± 0.03	1.11 ± 0.02		0.873 ± 0.029	208 +22 −18
A0104	3.11 ± 0.04	2.49 ± 0.03	0.0332±0.0055	2.15 ± 0.03	1.07 ± 0.01	270 ± 44	0.867 ± 0.016	208 +12 −11
A0137	2.65 ± 0.03	2.17 ± 0.02	< 0.02	1.89 ± 0.02	1.10 ± 0.01		0.872 ± 0.014	208 +10 − 9
A0162	2.72 ± 0.03	2.17 ± 0.02	< 0.02	1.88 ± 0.02	1.07 ± 0.01		0.867 ± 0.013	209 ± 10
A0067	2.73 ± 0.03	2.15 ± 0.02	0.0229±0.0052	1.87 ± 0.03	1.06 ± 0.01	340 ± 77	0.870 ± 0.018	212 +14 −12
A0166	2.75 ± 0.03	2.24 ± 0.02	< 0.02	1.96 ± 0.02	1.09 ± 0.01		0.876 ± 0.013	212 +10 − 9
A0156	2.79 ± 0.03	2.25 ± 0.03	< 0.02	1.97 ± 0.03	1.08 ± 0.01		0.876 ± 0.016	214 +13 −11
A0035	2.65 ± 0.06	2.13 ± 0.05	0.0724±0.0041	1.87 ± 0.06	1.07 ± 0.03	108 ± 26	0.878 ± 0.033	217 +28 −22
A0022	2.56 ± 0.06	2.06 ± 0.04	0.0246±0.0062	1.83 ± 0.04	1.08 ± 0.02	309 ± 77	0.888 ± 0.028	223 +22 −20
A0168	2.77 ± 0.03	2.23 ± 0.03	< 0.02	1.99 ± 0.02	1.08 ± 0.01		0.892 ± 0.015	226 +13 −12
A0064	2.57 ± 0.03	2.06 ± 0.02	< 0.02	1.84 ± 0.02	1.08 ± 0.01		0.893 ± 0.016	227 +14 −13
A0120	2.77 ± 0.03	2.22 ± 0.02	0.0233±0.0046	1.98 ± 0.03	1.08 ± 0.01	354 ± 69	0.893 ± 0.016	227 +14 −13
A0138	2.94 ± 0.03	2.35 ± 0.02	< 0.02	2.12 ± 0.03	1.07 ± 0.01		0.901 ± 0.014	235 +14 −13
A0160	2.48 ± 0.03	2.00 ± 0.02	0.0287±0.0037	1.85 ± 0.02	1.08 ± 0.01	269 ± 35	0.924 ± 0.014	256 +16 −14
A0066	2.50 ± 0.03	2.00 ± 0.02	0.0304±0.0070	1.91 ± 0.04	1.07 ± 0.01	262 ± 60	0.955 ± 0.022	300 +40 −31

Table 3. Stages and their ages when the uplifted coral reefs on Hateruma were formed.

Stage	N*	Years B.P.	Isotope Stage**
1	(7)	81,000 ± 3,000	5
2	(6)	103,000 ± 1,000	5
3	(35)	128,000 ± 7,000	5
4	(20)	207,000 ± 3,000	7
5 ?	(1)	300,000 or more	9

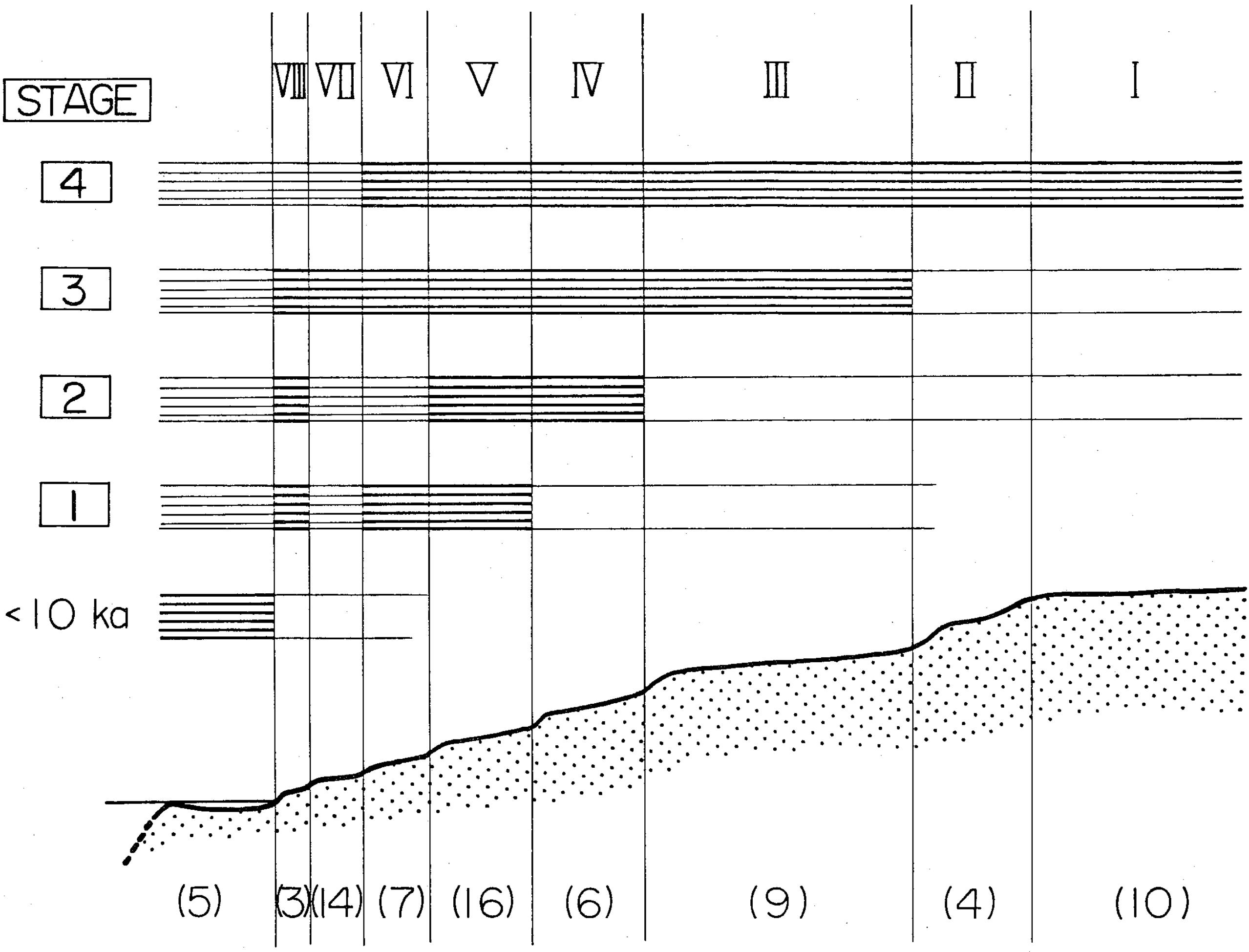
*N, number of samples

** after Shackleton and Opdyke (1973)

illustrated. In the text-figure, the terrace numbers of Ota *et al.* (1982) are given by using Roman numerals from I to VIII and parenthesized figures mean number of coral samples collected from respective terrace. The stripes drawn in bold strokes over the cross section denote that the samples assigned to each stage were collected from the under terrace, and the portion drawn in fine stripes that the corals alive during each stage were not found so far. Namely, Text-fig. 2 shows that the coral dates of the stage 4 were obtained from the terraces I to VI, those of the stage 3 from III to VIII, those of the stage 2 from IV, V and VIII, and those of the stage 1 from V, VI and VIII. No coral date suggestive of Pleistocene was found from the limestone forming the present tidal flat around the coast of Hateruma. The tidal flat is thus considered to have been built since the last thousands years. It may be

Table 4. Correlation of the uplifted coral reefs on Hateruma with the counterparts reported from Barbados, Huon Peninsula and Kikai.
(One and two star marks mean that the uplifted coral reefs in each area are defined as morphostratigraphic and time-stratigraphic units, respectively.)

Barbados*	Huon Peninsula, New Guinea**	Ryukyu Islands	
		Kikai**	Hateruma*
Mesolella et al. (1969) and others	Bloom et al. (1974) and others	Konishi et al. (1974) and others	this paper
——	Reef Complex I (5 - 9 ka)	Raised Coral Reef Limestone (2 - 7 ka)	Tidal Flat Limestone
——	Reef Complex II ? (28 - 29 ka)	——	——
——	Reef Complex IIIb (41 ka)	Araki Limestone (35 - 45 ka)	——
Barbados 0 ? (60 ka)	Reef Complex IV (61 ka)	Younger Member of Riukiu Limestone (55 - 65 ka)	——
Barbados I (82 ka)	Reef Complex V (85 ka)	Middle Member of Riukiu Limestone (80 - 100 ka)	Hateruma VIII (81 ± 3 ka)
Barbados II (105 ka)	Reef Complex VI (107 ka)		Hateruma IV (103 ± 1 ka)
Barbados III (127 ka)	Reef Complex VII (118 - 142 ka)	Older Member of Riukiu Limestone (120 - 130 ka)	Hateruma III (128 ± 7 ka)
198, 220, 242, 268 (ka)			Hateruma I (207 ± 3 ka)
Barbados X, XI			
Barbados XII, XIII			? (300 or more ka)
Barbados XIII ?			



Text-fig. 2. Schematic illustration of eight steps of marine terraces on Hateruma. (Topographic cross-section is drawn not to scale. Roman numerals indicate the morphostratigraphic units of Ota *et al.*, 1982. Parenthesized figures mean number of coral samples dated. See text for details.)

put in another way that the sea level has attained at least up to the highest point among the localities of coral samples assigned to each stage. The morphostratigraphic units on Hateruma are conclusively correlative, as summarized in Table 4, with the Holocene and Pleistocene coral reefs reported from Barbados, Huon Peninsula and Kikai, respectively.

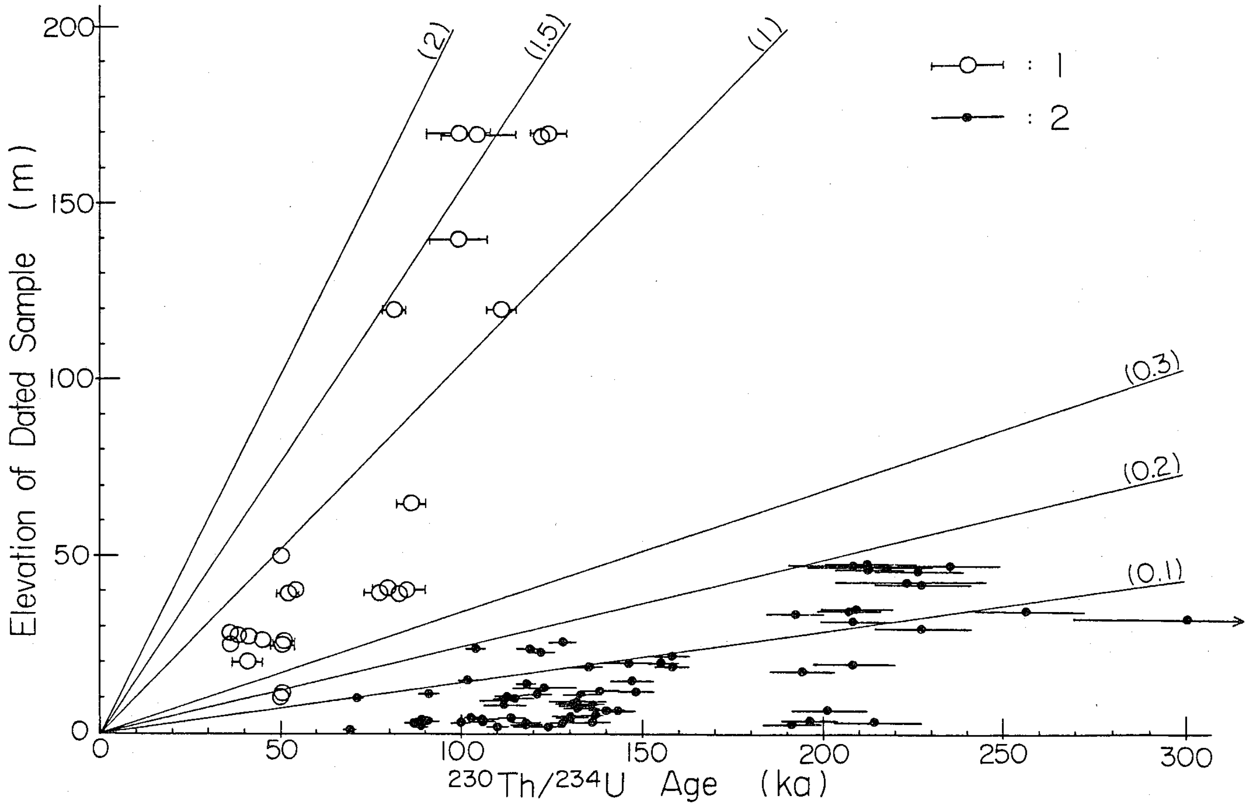
The occurrence of corals dated to be older (for an example, 214^{+13}_{-11} ka of A0156 sample) from the lower terrace (the terrace V for the sample) may suggest that the limestone of younger than the time of the last interglacial was formed as a small-scaled fringing reef in the limited parts and/or a very thin veneer. In either case, the lower terraces of IV to VIII are very likely to have been eroded since emerging ashore, because of no surface features peculiar to raised coral reef, narrowness of terrace and poor occurrence of coral heads. It may therefore be said that the terraces on Hateruma are partly (only terraces I and III) constructive and partly (the other terraces) erosional in origin.

Sea Level and Tectonic History

The elevation of the terraces I through VIII must involve at least two variables, the sea level at the time of reef formation and the tectonic uplift since then. In order to interpret the geology and geomorphology of Hateruma in terms of sea level and tectonic history, it is the first consideration to settle the present altitude of the paleosea level of the time when each reef was formed. As stated above, it may be safely said that the paleosea covered up the terraces I and III during the last and preceding interglacials, respectively. Because the author could not confirm the reef-crest elevation as yet, the paleosea level is supposed here as a first-order model to have attained up to the present elevation of the break in topographic surface, the boundary between the terraces II and III, during the last interglacial.

Ota *et al.* (1982) evaluated, by using a precesion altimeter, for the present elevation of the then sea level to vary from 40 — 41 m in eastern part of the island to about 20 m in western part. They concluded from this fact that the island of Hateruma has been progressively tilting westwards. Assuming that uplift has been constant in each block bounded by some faults as seen in Text-fig. 1 and that the paleosea level during the terrace III time (128 ± 7 ka B.P.) was plus 6 m relative to the present datum (Bloom *et al.*, 1974; and others), the uplift rate of Hateruma is calculated to be 0.27 m/ka in eastern part of the island and 0.11 m/ka in western part, respectively. These values are an order of magnitude lower than a value of 1 — 2 m/ka estimated for the last interglacial emerged reef (Older Limestone Member of Riukiu Limestone: Konishi *et al.*, 1974) on Kikai. Text-fig. 3 verfies such a difference in neotectonic rate of vertical movement between the islands of Hateruma and Kikai. In addition, the absence of the Holocene Raised Coral Reef Limestone uplifted on the island like Kikai also may support that the uplift rate of Hateruma is much lower than that of Kikai.

Konishi (1980) has previously pointed out a great difference in the rate of neotectonic uplift between the islands of Kikai and Hateruma, after



Text-fig. 3. Comparison on elevation of dated corals from the Riukiu Limestone and uplift rates between the islands of Kikai and Hateruma.
(1 and 2 show the samples collected on Kikai and Hateruma, respectively. Data on coral samples of Kikai were referred from Konishi *et. al.*, 1974 and others, and unpublished dates also are plotted. Parenthesized figures mean the uplift rate in unit of m/ka.)

he evaluated the uplift rate of Hateruma to be so low or even in the magnitude of practically almost none. By the citation of the theory of Uyeda and Kanamori (1979), he attributed this difference to the disparity in mode of subduction of the West Philippine Sea plate. Both Kikai and Hateruma are the most trenchward islands in the Central and Southwest Ryukyu blocks, respectively, which are bounded by the Miyako Depression. Depending on Konishi (1980), Kikai has been uplifted rapidly and tilted towards the Asian continent through compression arisen from gently (25° — 35° in dipping angle of the Wadati-Benioff zone) subsiding of the West Philippine Sea plate as the "Chilean-type" of plate convergence by Uyeda and Kanamori (1979). On the other hand, the Southwest Ryukyu block inclusive of Hateruma sits next to a steeply dipping (55° — 65° in average and more at the lower tip) Wadati-Benioff zone and is now in the tensile field behind the frontal arc like the case of "Mariana-type" of plate convergence.

The resultant obtained in this study implies that Hateruma has been situated tectonically in the compressive field since the last interglacial. Although the uplift rate of this island is undoubtedly lower than that of Kikai, its maximum is comparable to the value estimated from one of the standard traverses, the Christ Church traverse, settled on Barbados by Bender *et al.* (1979). Without the tectonic uplift of such an order, it is hardly possible that the dates suggestive of two interstadials after the last interglacial are obtained from the fossil corals in the Riukiu Limestone on Hateruma.

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波照間島琉球石灰岩のウラン系列放射年代：琉球弧の中でも西南琉球ブロック中のもっとも海溝側に位置する波照間島の琉球石灰岩について，その形成時代を明らかにするため，74個の礁性サンゴ化石から ^{230}Th/^{234}U 年代値を求めた。その結果，本島の琉球石灰岩は更新世後期の4回の高海水準期（おおよそ81,000年と103,000年前の2度の亜間氷期と，128,000年と207,000年前の2回の間氷期）に形成されたことが明らかになった。本研究で得られた最古のものは，$300,000^{+40,000}_{-31,000}$年で，この年代値は，より以前の（深海底有孔虫酸素同位体比ステージ9に対比される）間氷期に現在の波照島の位置にすでにサンゴ礁が形成されていたことを示唆している。潮汐平底を構成している石灰岩から採集された5個のサンゴ化石は，いずれも10,000年以若の年代（920±50年～6,000±500年）を示した。すなわち，現在島の周囲を縁取って発達している潮汐平底は，過去数千年間にわたって形成されてきたものといえよう。このように，波照間島の琉球石灰岩を，西インド諸島のBarbados島，ニューギニアHuon半島や中部琉球ブロック中の喜界島などの更新統隆起サンゴ礁に対比することが可能になった。

各段丘から採集されたサンゴ化石の年代測定結果にもとづき，Ota *et al*. (1982) によって8段に細分された海成段丘（T1～T8）のうち，上位から2段目（T2）と下位の5段（T4～T8）は，侵食面と考えられる。さらに，彼らは地形学的手法によって，各段丘形成時の旧汀線高度を求め，本島が西方へ傾動していると結論した。今回，最終間氷期に形成されたことが確証されたT3面の旧汀線高度と，隆起運動の等速性および当時の古海水準を現在より6m高かったと仮定することにより，本島の最大隆起速度は，おおよそ0.3m/1,000年と計算される。以上の事実を考えあわせると，波照間島は，最終間氷期以降，造構造的には圧縮場におかれてきたと思われる。

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