Short Article

Uranium-series Age of the Highest Marine Terrace of the Upper Pleistocene on Kikai Island, Central Ryukyus, Japan

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The uplifted Pleistocene marine terraces in Kikai Island have been investigated using radiometric dating since the 1960s. The highest terrace was called the Hyakunodai Terrace, which is divided into three blocks by faults, assigned in this study as Block C, Block B and Block A in ascending order of height. Previous studies indicate that Block A was formed during Marine Isotope Stage (MIS) 5e and that MIS 5c corals were distributed on the cliff between Blocks A and B based on Uranium-series dating. We carried out careful fieldwork and report more precise α -spectrometric U-series ages of Blocks A and B. Fossil corals showed eight Mid- to Late Pleistocene dates ranging from 154.8 ± 6.4 to 97.7 ± 3.0 ky (2σ) and three Middle Pleistocene ages (>450 ky). Mid- to Late Pleistocene dates are divided into three age groups, 154.8 ± 6.4 – 142.7 ± 5.8 ky, 122.1 ± 3.8 ky and 108.2 ± 3.2 – 97.7 ± 3.0 ky, corresponding to MIS 6, 5e and 5c, respectively. While all age groups were obtained from Block A, Block B only contains MIS 5c and Middle Pleistocene corals. The MIS 5c outcrop at Block A contains clear reef structure (bindstone) and the coral assemblages indicate depositional depth ranging from 5 to 15 m. These facts suggest that the highest terrace was formed during MIS 5c. Exposure of MIS 5e or 6 corals is possibly due to erosional effect during MIS 5c transgression.

Keywords : Uranium-series dating, Kikai Island, coral reef terrace, Marine Isotope Stage 5c, Hyakunodai Terrace

I. Introduction

Changes in sea level positions, whether eustatic or tectonically induced, are well recorded in uplifted marine terraces. Such terraces, which contain many information on paleo-environment, developed more extensively in tectonically active areas, thus emergent coasts are excellent sites for reconstructing sea level history and paleo-environment.

Kikai Island, located in Central Ryukyus, is an actively raising island consisting of uplifted

Pleistocene and Holocene marine terraces. Many radiometric dates of fossil corals from the marine terraces have been reported since the 1960s (*e.g.* Konishi, 1967 ; Konishi *et al.*, 1974 ; Omura, 1988a). The dates indicate that the highest terrace, which is called the Hyakunodai Terrace by Nakagawa (1969), was formed during Marine Isotope Stage (MIS) 5e. Using the MIS 5e age of the Hyakunodai Terrace, Ota and Omura (1992) estimated the uplift rate in Kikai Island to be 1.8 m/ky since the last interglacial.

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However, the reported MIS 5e dates from the Hyakunodai Terrace have uncertainties such as reliability and accuracy due to insufficient evaluation of the samples dated. On the other hand, reliable dates have been reported from the lower Pleistocene terrace and the uncertainties in the distribution of carbonate sediments during MIS 4 to 3 have been cleared recently (Omura *et al.*, 2000 ; Sasaki *et al.*, 2004 ;

Inagaki *et al.*, 2005).

We carried out fieldwork to collect new samples for U-series dating from the Hyakunodai Terrace and improved the accuracy and reliability of dates. In this paper, we report new evidence showing that the Hyakunodai Terrace was formed during MIS 5c rather than MIS 5e as previously reported.

Fig. 1 Location and topographic map of Kikai Island

1. Location map, 2. Topographic map based on 1 : 25,000 topographic map published by the Geographical Survey Institute in 1997. Contour interval is 10 m, thick line is 50 m interval, 3. Topographic map modified from 1 : 10,000 topographic map published by the Kyushu Regional Agricultural Administration Office in 1995. Contour interval is 5 m, thick line is 15 m interval. Number shows sample number. Closed circles mean dated samples in this study. Open circles and underlined number mean samples dated by the previous studies. Numbers in parenthesis mean re-dated samples. Transect X—X' is the location of profile shown in Fig. 2.

II. Previous investigation of the Hyakunodai Terrace

Hanzawa (1935) described the geology of Kikai Island and divided the limestone facies on this island into two stratigraphic units, Pleistocene Riukiu Limestone and Holocene Raised Coral Reef Limestone. The basement of Kikai Island is composed of Pliocene Somachi Formation (Nakagawa, 1969). Nakagawa (1969) named a flat plane over 150 m in altitude the Hyakunodai Terrace and further defined the reefal coral limestone distributed on this terrace the Hyakunodai Formation based on lithofacies and morphostratigraphy. The Hyakunodai Formation is divided into three blocks by N–S trending faults (Nakagawa, 1969; Fig. 1). For convenience, we named these blocks Block C, Block B and Block A in ascending order of height, respectively (Fig. 1).

Konishi (1967) divided the Riukiu Limestone into three members based on radiometric dating and named the coral limestone distributed on the Hyakunodai Terrace (Blocks A and B) the older member of Riukiu Limestone (>200 ky). Konishi *et al.* (1970, 1974) dated the older member of Riukiu Limestone as 120–130 ky (Table 1), and estimated the uplift rate of Kikai Island as 1–2 m/ky during the past 130,000 years.

Omura *et al.* (1985) reported U-series ages combined with electron spine resonance ages of the Pleistocene limestone (Table 1) and revealed that a part of the Pleistocene limestone on the island is Middle Pleistocene deposited during two stages of high sea stand,

MIS 7 and MIS 9. In addition, coral limestone deposited approximately 100 ky is distributed up to a height of 170 m (Block B). Omura (1988 a) integrated all the U-series dates (Table 1) and suggested that the Pleistocene deposits on Kikai Island were composed of Middle and Upper Pleistocene which are further divided into two and five time stratigraphic units, respectively. He inferred that the coral limestone developed during MIS 5e was distributed on Hyakunodai Terrace (200 m; Block A) and the MIS 5c limestone was distributed on the cliff between Blocks A and B of the Hyakunodai Terrace.

III. Uranium-series dating

Eleven fossil coral samples including re-dated samples were collected from 9 localities on Blocks A and B of the Hyakunodai Terrace (Fig. 1) and dated using α -spectrometric U-series dating after Omura (1988 b). Except for MI-26 coral rubble, all samples were preserved in growth position.

Table 2 shows the uranium and thorium isotopic compositions and dates with the initial $^{234}\text{U}/^{238}\text{U}$ ratios. Three Middle (>450 ky) and eight Late Pleistocene dates (from 97.7 ± 3.0 ky to 154.8 ± 6.4 ky; 2σ) were obtained. We checked the reliability of these dates following the five-step screening method of Omura *et al.* (1995). Although the isotopic compositions of U and Th seem to satisfy the five criteria, X-ray diffraction analyses results show that the calcite contents of two samples (MI-44 and MI-46) are more than 5%, that is the two samples

Table 1 Uranium and thorium isotopic compositions and $^{230}\text{Th}/^{234}\text{U}$ dates reported in previous works on fossil coral samples collected at elevations above 160 m

Sample No.	Genus	Height (m)	Block	^{238}U (ppm)	$^{234}\text{U}/^{238}\text{U}$ (activity ratio)	$^{230}\text{Th}/^{234}\text{U}$ (activity ratio)	$[^{234}\text{U}/^{238}\text{U}]_0$ (activity ratio)	Date (ky)	References
OA047	<i>Acropora</i>	170	A	3.60 ± 0.04	1.07 ± 0.02	0.708 ± 0.011	1.10 ± 0.03	131 ± 4	Konishi <i>et al.</i> (1974)
OA073	<i>Acropora</i>	170	B	3.15 ± 0.08	1.02 ± 0.03	0.692 ± 0.026	1.03 ± 0.04	127 ± 9	Konishi <i>et al.</i> (1974)
AO007*	<i>Goniastrea</i>	180	B	3.19 ± 0.10	1.12 ± 0.03	0.602 ± 0.039	1.159 ± 0.040	99 ± 9	Omura <i>et al.</i> (1985)
AO009	<i>Goniastrea</i>	180	B	3.23 ± 0.07	1.08 ± 0.05	0.621 ± 0.038	1.107 ± 0.067	104 ± 11	Omura <i>et al.</i> (1985)
AO084	<i>Porites</i>	210	B	2.71 ± 0.03	1.01 ± 0.01	0.980 ± 0.020	1.033 ± 0.033	>450	Omura <i>et al.</i> (1985)
AO239	<i>Montastrea</i>	205	A	2.74 ± 0.07	1.11 ± 0.01	0.696 ± 0.018	1.158 ± 0.014	126 ± 12	Omura (1988a)
AO246	<i>Porites</i>	180	B	2.76 ± 0.05	1.11 ± 0.02	0.622 ± 0.015	1.148 ± 0.027	103 ± 9	Omura (1988a)
AO248	<i>Goniastrea</i>	170	B	2.86 ± 0.05	1.02 ± 0.02	0.967 ± 0.021	1.056 ± 0.056	347 ± 71 –43	Omura (1988a)
AO266	<i>Porites</i>	200	B	2.62 ± 0.03	1.12 ± 0.01	0.683 ± 0.013	1.170 ± 0.014	121 ± 9	Omura (1988a)
AO268	<i>Porites</i>	205	B	2.71 ± 0.03	1.12 ± 0.01	0.734 ± 0.013	1.179 ± 0.015	138 ± 10	Omura (1988a)

* Re-identified as *Plesiastrea versipora* as shown in Table 2.

could be open-system for uranium and thorium isotopes. We obtained more precise dates from re-dated samples (MI-50 and MI-20), which are consistent with the previous dates of AO007 and AO268 (Tables 1 and 2).

Taking into account the statistical error of

dates, these eight reliable ages (Table 2) can be divided into four age groups, 97.7 ± 3.0 – 108.2 ± 3.2 ky, 122.1 ± 3.8 ky, 142.7 ± 5.8 – 154.8 ± 6.4 ky, and >450 ky, that can be correlated with MIS 5c, 5e, 6 and Middle Pleistocene, respectively.

Table 2 Uranium and thorium isotopic compositions and $^{230}\text{Th}/^{234}\text{U}$ dates of fossil corals collected from Block A and B of the Hyakunodai Terrace

Sample No.	Species	Height (m)	Block	Aragonite contents (wt%)	^{238}U (ppm)	$^{230}\text{Th}/^{232}\text{Th}$ (activity ratio)	$^{234}\text{U}/^{238}\text{U}$ (activity ratio)	$^{230}\text{Th}/^{234}\text{U}$ (activity ratio)	$[^{234}\text{U}/^{238}\text{U}]_0$ (activity ratio)	Date (ky)
MI-17	<i>Acropora palifera</i>	195	A	100	4.208 ± 0.032	> 180	1.106 ± 0.007	0.6011 ± 0.0058	1.140 ± 0.009	97.7 ± 3.0
MI-50*	<i>Plesiastrea versipora</i>	180	B	-	3.038 ± 0.019	> 300	1.113 ± 0.007	0.6215 ± 0.0054	1.152 ± 0.009	103.0 ± 3.0
MI-22	<i>Porites</i> sp.	195	A	99	2.900 ± 0.020	> 180	1.107 ± 0.007	0.6266 ± 0.0055	1.144 ± 0.009	104.5 ± 3.0
MI-46	not identified	203	A	80	3.000 ± 0.018	> 300	1.108 ± 0.006	0.6397 ± 0.0057	1.147 ± 0.008	<u>108.2 ± 3.2</u>
MI-20*	<i>Porites</i> sp.	205	A	-	2.769 ± 0.018	> 170	1.111 ± 0.006	0.6859 ± 0.0061	1.157 ± 0.009	122.1 ± 3.8
MI-44	<i>Goniopora</i> sp.	200	A	75	2.968 ± 0.019	> 500	1.099 ± 0.007	0.7076 ± 0.0062	1.143 ± 0.010	<u>129.7 ± 4.4</u>
MI-26	<i>Plesiastrea versipora</i>	200	B	98	2.415 ± 0.179	> 350	1.092 ± 0.019	0.7427 ± 0.0074	1.138 ± 0.011	142.7 ± 5.8
MI-27	<i>Acanthastrea</i> sp.	203	A	97	2.838 ± 0.021	> 200	1.099 ± 0.008	0.7729 ± 0.0073	1.155 ± 0.012	154.8 ± 6.4
MI-15	<i>Goniastrea</i> sp.	203	A	98	2.276 ± 0.023	> 200	1.017 ± 0.010	1.0266 ± 0.0137	-	>450
MI-18	<i>Porites</i> sp.	170	B	99	2.622 ± 0.017	> 330	1.042 ± 0.006	1.040 ± 0.009	-	>450
MI-23	<i>Pavona</i> sp.	203	A	98	2.942 ± 0.021	> 180	1.020 ± 0.006	1.048 ± 0.011	-	>450

* Re-dated samples, MI-20 and MI-50, are the same as AO268 and AO007 in the Table 1, respectively.

Errors for $^{230}\text{Th}/^{234}\text{U}$ dates are statistical errors (2σ). Two underlined dates are evaluated to be less reliable.

Fig. 2 Topographic profile based on the EDM measurements along transect X–X' shown in Fig. 1

Numbers inside squares mean the depositional depth estimated from coral assemblage during MIS 5c, or relative sea level position.

IV. Age of the Hyakunodai Terrace

Figure 2 shows a topographic profile of the Hyakunodai Terrace using data measured by an electronic distance measurement (EDM). We can distinguish two steps at elevations of *ca.* 200 m and *ca.* 190 m corresponding to Blocks A and B, respectively. While Block A contains MIS 5c, 5e, 6 and Middle Pleistocene corals, only 5c and Middle Pleistocene corals were found on Block B.

The MIS 5c samples MI-17 and MI-22 at Block A were taken from bindstone deposits (after Embry and Klován, 1971), about 3 m thick (height of outcrop). This bindstone consists of an assemblage of *Porites* sp., *Favia speciosa*, *Cyphastrea* sp., *Goniastrea* sp., *Acropora palifera* (encrusting) and other hermatypic corals, indicating depositional depths of 5–15 m (Sugihara *et al.*, 1999; Sagawa *et al.*, 2001). The elevation of the samples and the depth range of the corals put the relative sea level position during MIS 5c between 200–210 m, higher than the position of the highest terrace (Fig. 2). On the other hand, although the 5c coral (MI-50) at Block B was collected from framestone deposits (Embry and Klován, 1971), it was difficult to estimate the depositional depth from the species *Plesiastrea versipora*.

MIS 5e corals were also found on Block A. However distinct coral limestones, such as bindstone or framestone, were not observed at any outcrops on the terrace surface. In addition, it is difficult to estimate the depositional depth of these coral limestones based only on the coral species *Porites*, although the depositional depth can be confined to be shallower than 50 m (Iryu *et al.*, 1998). There is no doubt that MIS 5e sediments were distributed in Kikai Island, because a few fossil corals in growth positions were found. However, the scale of their distribution is still unclear.

MIS 6 (MI-26 and MI-27) corals from Blocks A and B were collected at elevations of 200 m and 203 m, respectively (Table 2). Although MI-26 in Block B was from a coral rubble, MI-27 in Block A was a part of a distinctive bindstone (Embry and Klován, 1971) outcrop with a thickness of about 3 m. However, like the MIS 5e coral samples, coral species of *Plesiastrea*

versipora and *Acanthastrea* sp. are not useful as sea level indicators. The age of MI-26 and MI-27 samples corresponding to MIS 6 is still unconfirmed because only one autochthonous sample was obtained and the date still had a large error. More precise investigations of coral assemblages and more accurate radiometric dates are needed to discuss the distribution of MIS 6 sediments in Kikai Island.

These results produce some questions. First, why MIS 5e sediments are absent on the Hyakunodai Terrace? One possibility is that the sediments may have been eroded during the transgression of MIS 5c. The effect of erosion in the development of coral reef terraces has been studied by Speed and Cheng (2004). The deposition of MIS 5c corals possibly synchronized with the erosion of older deposits during the MIS 5c transgression. Another possibility of the absence of MIS 5e sediments is that the environment, such as water depth or water temperature, was unsuitable for development of coral reefs.

Next, there is a question why MIS 6 corals were distributed on the highest terrace in Kikai Island. The MIS 6 sediments were possibly formed during temporary sea level high stand. High-resolution oxygen isotope records reveal millennial- and centennial-scale climate variability through out the late MIS 6 and Termination II (Cannariato and Kennett, 2005). These records show that climate oscillation during late MIS 6 is similar to MIS 3 interstadial, and Termination II climatic oscillation appears to have been the Bølling-Allerød-Yonger Dryas oscillation. Evidently, sea level fluctuations for short time scales are anticipated.

Many previous studies suggested that the Hyakunodai Terrace was formed during MIS 5e. However, we conclude that the Hyakunodai Terrace was formed during MIS 5c when the relative sea level position was at *ca.* 200–210 m (Fig. 2), based on the new U-series dating and the detail topographic measurements.

V. Uplift rate of Kikai Island

Although the age of the Hyakunodai Terrace was confirmed to be MIS 5c and the relative sea level during MIS 5c was estimated to be between 200 and 210 m (Fig. 2), two main prob-

lems still arise in calculating the uplift rate. First, there is a doubt in assuming a constant uplift because many faults run through Kikai Island. Three major faults cross the Hyakunodai Terrace. Based on elevations of MIS 5c fossil corals on Blocks A and B (Fig. 1), the vertical component shift of the fault between the two blocks is estimated between 0 and *ca.* 20 m. Ota and Omura (1992) did not discuss the effect of fault actions on their calculations of uplift rate. Second is the uncertainty of eustatic sea level position during MIS 5c. Although sea level during MIS 5c has been estimated in many sites, there are significant differences in the assessment of the paleo-sea level position. Potter *et al.* (2004) reported that the MIS 5c sea level at 101 ky was at -14 ± 4 m. Using this value and assuming constant uplift, the uplift rate since MIS 5c is estimated to be 2.1–2.3 m/ky.

We tested the value of 2.1–2.3 m/ky by comparing to the uplift rate after the last interglacial and Holocene. However, because the distribution of MIS 5e sediments is still inconclusive, we cannot calculate the uplift rate after the last interglacial using the same method. Therefore, we estimated the elevation of MIS 5e sediments (labeled the expected elevation) using the sea level curve of Potter and Lambeck (2003). Based on this curve, the difference in the sea level positions between MIS 5c (94–107 ky; *ca.* –60––20 m) and MIS 5e (125 ky; 0 m) is 20–60 m and based on our study, the expected elevation is *ca.* 220–270 m. Consequently, the uplift rate since the last interglacial is calculated to be 1.8–2.2 m/ky. On the other hand, the oldest Holocene corals and Holocene high stand (HHS; 7 ky) corals found on Kikai Island were distributed at *ca.* –20 m and +6 m, respectively (Ota *et al.*, 2000) and sea levels at that time are *ca.* –40––50 m and *ca.* 0 m, respectively (Lambeck *et al.*, 2002). Thus, the uplift rates after Holocene and HHS are estimated to be 2.0–3.0 m/ky and 0.9 m/ky. There is no significant difference between each estimated uplift rate except for after HHS, which suggests that faults action has not been large since the last interglacial.

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(J+E) in Japanese with English abstract.

中部琉球喜界島に発達する上部更新統最高位段丘の形成年代

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〔要 旨〕

中部琉球に位置する喜界島には、更新世および完新世の海成段丘がそれぞれ数段発達する。そのうち、島の中央部に発達する最高位の平坦面は百ノ台段丘と呼ばれ、南北方向の断層により3分されている。本論では、それらを高位から、それぞれA, B, Cブロックと呼ぶ。これまで、最高位のブロックAはMIS 5eに形成され、MIS 5c相当の堆積物はブロックAおよびBの間にわずかに分布していると考えられてきた。本研究で、百ノ台(ブロックAおよびB)の精密地形測量を行うとともに、そこから採集した化石サンゴの高精度ウラン系列年代測定を行った結果、中部～上部更新統の年代値(>450 ky, $154.8 \pm 6.4 - 97.7 \pm 3.0$ ky; 2σ)が得られた。それらは、ウラン系列年代測定の測定限界、あるいはそれを越える

>450 kyを示唆するものを除けば、MIS 6, 5e, 5cに対比される3つの年代グループ($154.8 \pm 6.4 - 142.7 \pm 5.8$ ky, 122.1 ± 3.8 ky, $108.2 \pm 3.2 - 97.7 \pm 3.0$ ky)に区分される。ブロックAから3ステージすべての年代値が得られたのに対し、ブロックBからは5cと中部更新統相当の年代しか得られなかった。ブロックAから得たMIS 5c相当のサンゴ化石は、明瞭なbindstoneから採集されたものであり、化石サンゴ群集からみて、当時の堆積水深が5～15 mだったと推定される。これらの事実は、喜界島の最高位段丘がMIS 5cに形成されたことを示唆するとともに、MIS 6やMIS 5eのサンゴが露出することは、MIS 5cの海進時における侵食作用によるものと推察される。

キーワード：ウラン系列年代測定、喜界島、サンゴ礁段丘、海洋酸素同位体ステージ5c、百ノ台段丘

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