CORAL REEF EVOLUTION AT THE LEEWARD SIDE OF ISHIGAKI ISLAND, SOUTHWEST JAPAN

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ABSTRACT. In comparison with windward coral reefs, the facies and evolution of leeward coral reefs has been discussed to a lesser extent. By accelerator mass spectrometry (AMS) carbon-14 dating of coral specimens collected from the trench excavated across a modern coral reef during a fishery port repair, we revealed the internal facies and Holocene evolution of a leeward reef in Ishigaki Island, Ryukyu Islands, southwest Japan. The reef facies can be split into three facies: the tabular *Acropora* framework facies, the tabular *Acropora* reworked facies, and the unconsolidated bioclast facies. The tabular *Acropora* reworked facies first formed a ridge by 3500 BP. Then, the tabular *Acropora* framework facies grew both upward and seaward. The accumulation rates of the tabular *Acropora* framework facies ranged from 2.2 to 8.3 m/ka. Thus, the reef framework facies and accumulation rates of this leeward reef is similar to those of windward reefs, although the age of the reef top is younger than that of windward reefs.

INTRODUCTION

Drilling on coral reefs has demonstrated the internal facies and the evolution of coral reefs in association with Holocene sea-level change (e.g. Davies and Montaggioni 1985; Neumann and Macintyre 1985; McLean and Woodroffe 1994; Cabioch et al. 1999). The development of coral reefs has been well described in association with Holocene sea-level rise, and the response of reef framework to this sea-level rise is categorized into three patterns: catch-up, keep-up, and give-up (Neumann and Macintyre 1985). Most reefs in the western Pacific have been shown to be catch-up type reefs, which caught up with sea level after sea-level stabilization in the Holocene (e.g. McLean and Woodroffe 1994). In most regions of the western Pacific, sea level reached its present level at around 5000 BP. In-situ corals (mainly *Acropora* spp.) accumulated to form the reef crest, which caught up with the sea level by 4000 BP. Then, upward growth of the reef was terminated due to the stable sea level, and the lateral expansion of the reef occurred. Finally, the backreef structure of the reef flat such as moats, motus, cays, and tombolos have formed by bioclasts derived from the reef framework (McLean and Woodroffe 1994; Kan et al. 1997a; Yamano et al. 2001).

These studies have concentrated in windward reefs, and the facies and evolution of leeward coral reefs has been discussed to a lesser extent. Hopley and Barnes (1985) examined the development of a continuous reef (Orpheus Island, the Great Barrier Reef of Australia) stretching from the windward side to the leeward side by an analysis of cores taken from both sides of the reef, and indicated that the leeward reef had formed after the establishment of the windward reef. Kan et al. (1997a) examined the leeward side of a continuous reef (Tonaki Reef, Ryukyu Islands) and also suggested the delayed evolution of the reef framework at the leeward side in comparison with the windward side. They revealed that, at the leeward side, abundant branching *Acropora* thickets formed prior to the establishment of the reef framework. They considered that the thickets formed due to the windward reef formation that provided the calm environment as branching *Acropora* are generally distributed in a calm water environment (e.g. Geister 1977; Done 1983). Recently, the internal facies of a leeward reef is examined in detail in Pleistocene reefs in the Caribbean (Pandolfi et al. 1999). Their study showed that no significant difference in the prominent coral (*Acropora palmata*) at windward and leeward reefs, suggesting the importance of the information of other sediment constituents for

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the recognition of the reef setting. In this study, we extend these previous works by examining the internal facies and the Holocene evolution of a modern leeward reef which is independent of the establishment of the windward reef.

STUDY SITE

Tonoshiro Reef is located on the southern coast of Ishigaki Island, Ryukyu Islands, southwest Japan (Figure 1a,b). The northern wind is dominant throughout the year, and thus this reef is located at the

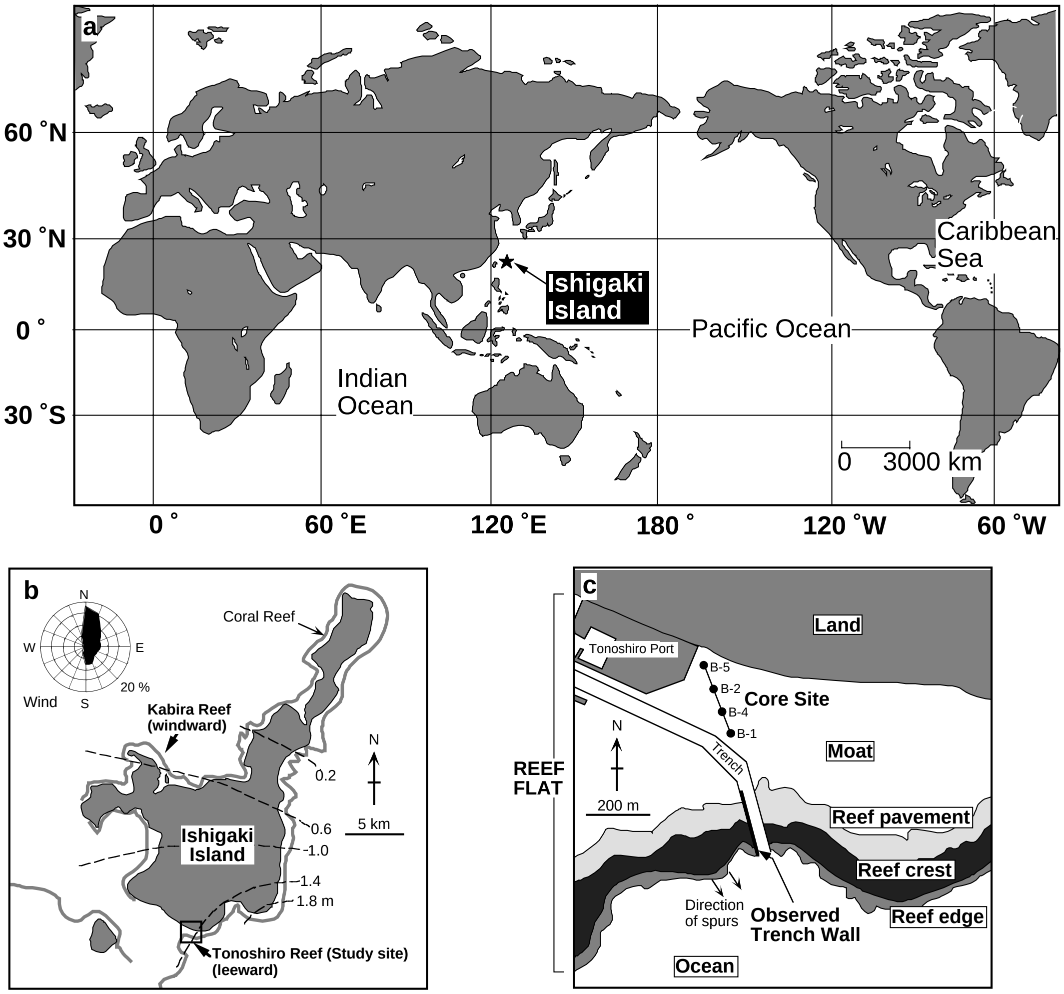

Figure 1 a) Location of Ishigaki Island and b) Tonoshiro Reef. The wind rose depicts annual distribution. Tonoshiro Reef is located at the leeward side of the island. Kabira Reef at the windward side is also indicated. Ishigaki Island shows significant sudden uplift and tilting at around 2000 BP due to tectonic movement (Kawana 1987, 1989). Dashed lines show the amount of uplift at that time (Kawana 1987). c) Geomorphological map of Tonoshiro Reef and observed trench and core sites. The trench cuts the reef obliquely.

leeward side of the island. The well-developed fringing reef exhibits a distinct topographical zonation from land to ocean: moat, reef pavement, reef crest, and reef edge (Figure 1c). Dredging during a fishery port repair in 1985 exposed a submarine trench wall about 300 m in length and 4–7 m in height stretching from the reef edge to the moat of this modern fringing reef (Figure 1c). The trench sites are found elsewhere in the Ryukyu Islands and the Great Barrier Reef of Australia, providing the good opportunity to observe the continuous reef section (Kan and Hori 1991, 1993; Kan et al. 1995, 1997a,b).

Holocene relative sea-level changes for Ishigaki Island due to eustasy and hydro-isostasy can be derived from Nakada (1986). The sea level has reached its present level at 6000 BP and has been stabilized since then. However, there has been sudden uplift and tilting of Ishigaki Island during the late Holocene (Figure 1b), which has caused the relative sea level to fall. The magnitude of uplift is greatest in the southeastern part of the island where it reaches 2 m, whereas the magnitude is smallest at the northern end of the island (Kawana 1987). The elevation of erosional notches show about 1.4 m of uplift in the vicinity of Tonoshiro Reef. This coastal uplift is suggested to have been produced by a large earthquake that occurred about 2000 BP (Kawana 1989). Thus, Tonoshiro Reef is considered to have been uplifted tectonically around 2000 BP to a height of 1.4 m.

METHODS

Water depths of the reef surface were measured by a staff with scales along the top of the trench at an interval of 5 m. They were corrected based on the calculated tide values at Ishigaki Port and were described by the depths below the mean sea level (MSL). Hermatypic corals were classified mainly by genus and growth forms. Abundances of corals were measured by the line transect method (Loya 1978) at an interval of 50 m.

Descriptions of the internal reef facies were carried out from the reef surface to the foot of the trench wall at an interval of 10 m along the trench by SCUBA diving. We also analyzed cores taken from the moat of Tonoshiro Reef during the construction of a fishery farm (Figure 1c). We collected 21 fossil coral specimens from the trench wall and 1 fossil coral specimen from the core (B-1), whose growth orientation was examined to determine whether they were in situ.

Coral samples were quarried out into cubes, cleaned by distilled water, and dried up in one day at 110 °C. To remove the effect of possibly altered carbonate (Burr et al. 1992), the samples were subject to acidification in 5% hydrochloric acid, resulting in the percentage ratio of dissolution ranging from 24.9% to 43.7%. The samples were rinsed repeatedly with distilled water. Finally, 15 mg of powdered samples were used for graphitization with 3 mg Fe.

^{14}C ages of coral samples were measured by using a HVEE Tandetron accelerator mass spectrometer (AMS) at Nagoya University (Nakamura et al. 2000). Carbon isotope ratio, ^{14}C/^{12}C, was measured for graphite targets prepared from coral samples as well as for those from Hox-II (NIST oxalic acid standard). Routinely, 45 targets are measured successively for 30 min in a day (a batch rum), and three batches are repeated to check the reproducibility of each batch measurement. Six out of 45 targets are from Hox-II standard, to be used to check the quality of each batch run, i.e., the reproducibility of the ^{14}C/^{12}C measurement. The 1-σ standard deviation of ^{14}C/^{12}C ratio measurements, typically less than ±0.4% for six Hox-II targets, was included as well as statistical uncertainty of ^{14}C counts, to evaluate the error of ^{14}C/^{12}C ratio for each target. Since the ^{14}C count rate for Hox-II targets was more than 60 cps, total ^{14}C counts were greater than 100,000, resulting in a statistical uncertainty of ±0.3% (±25 yr error in age). When three batch results were averaged to evaluate the ^{14}C/^{12}C ratio of each sample, a typical ^{14}C/^{12}C measurement error was ±0.3–0.4%, corresponding to

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±25–30 yr error in ^{14}C age, for samples younger than several thousand years BP. The age determinations were based on the Libby half-life of 5568 yr, and errors were indicated as ±1 σ.

The dates were corrected both for isotopic fractionation and for marine reservoir effect. We used the average marine reservoir age of surface ocean (–400 yr; Stuiver et al. 1986; Stuiver and Braziunas 1993). In Ishigaki Island, Hideshima et al. (2001) showed the reservoir age of –350 ± 25 yr. Thus, both values are in good agreement with each other.

RESULTS

Surface Topography and Reef Zonation

As this trench cut the reef obliquely (Figure 1c), the spur and groove system is outcropped at the seaward side of this trench wall (Figure 2). This reef is rarely exposed to air during low tides, and living corals (mainly *Acropora*) are distributed on the reef (Figure 2). The distribution of corals corresponds to wave energy (e.g. Geister 1977). Tabular *Acropora* occur on the seaward side of the reef where ocean swell breaks, whereas branching *Acropora* occur on the landward side of the reef where wave action is calm due to wave breaking on the reef edge (Roberts et al. 1975). Behind the reef, bioclastic sediments are distributed in the moat, where living corals are rare.

Internal Facies and Accumulation Rates

The internal facies of Tonoshiro Reef flat are shown in Figure 2. All of the specimens showed Holocene ages that also appear in Table 1. Part of the Pleistocene reef facies was found in the cores obtained from the moat. This facies is a highly leached lithology that is red-colored and contains weathered soil. The reef flat is composed of three main sedimentary facies (tabular *Acropora* framework facies, tabular *Acropora* reworked facies, and unconsolidated bioclast facies) that were defined according to their sedimentary structure. Furthermore, the tabular *Acropora* framework facies can be divided into three subfacies (reef crest subfacies, spur subfacies, and paleo-groove subfacies) based on the age and the sedimentary structure. The detail of each facies and subfacies as follows.

1. Tabular Acropora Framework Facies

Tabular in-situ *Acropora* accumulated to form this facies. The thickness of this facies is more than 6 m. The corrected ^{14}C ages (–400 yr; Stuiver et al. 1986; Stuiver and Braziunas 1993) range from 4145 (Sample IS-30) to 180 BP (IS-6). There is a distinct gap in the age at a point of 85 m from the reef edge. In the seaward side, *Acropora* framework make up reef-front spur structure. Thus, this facies can be split into three subfacies according to ages, constituents, and surface topography.

1-1. Reef crest subfacies. This subfacies stretches from the point of 85 m to 135 m from the seaward end of the reef and corresponds to the present-day reef crest. The age ranges from 4145 BP to 2725 BP. This subfacies accumulated at a rate of 2.2 (IS-18 to IS-17) and 8.3 m/ka (IS-15 to IS-14). The rate of lateral reef crest expansion was 75 m/ka during the interval from 3490 to 3025 BP (IS-23 to IS-17). From 3025 to 2725 BP (IS-17 to IS-14), a lateral rate of 33 m/ka occurred.

1-2. Paleo-groove subfacies. This subfacies stretches from the point of 50 m to 85 m from the seaward end of the reef and has been infilled by in-situ large *Porites* in addition to in-situ *Acropora*. The age of this subfacies (1195–560 BP) is significantly younger than those of the reef crest subfacies. The growth rate of *Porites* colony was shown to be 1.2 cm/yr from the analysis of annual bands (Abe, unpublished data). Thus, the groove was infilled at rates of 5.7 (IS-26 to IS-27), 7.4 (IS-12 to IS-28), and 12 m/ka (*Porites* colony).

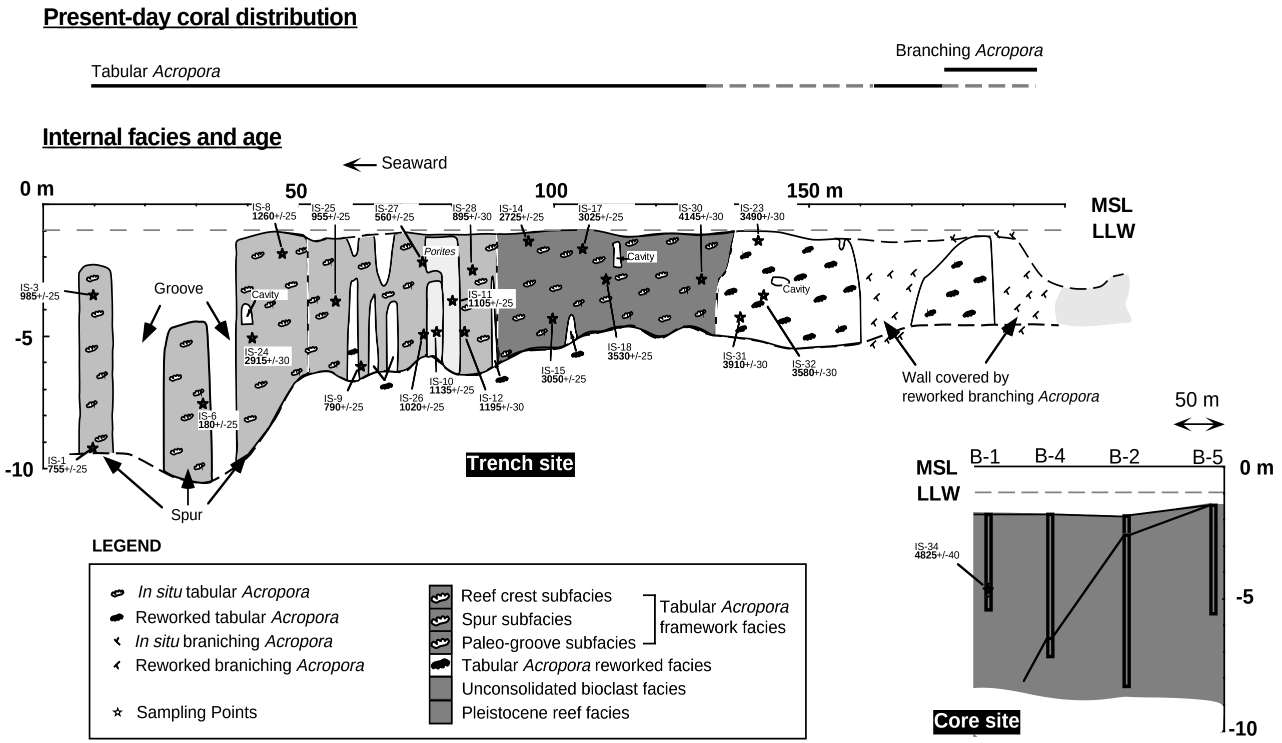

Figure 2 The present-day distribution of corals, internal facies, and radiocarbon ages (Table 1) of the trench wall (left) and cores (right) at Tonoshiro Reef. MSL and LLW show the mean sea level and the mean lowest low water level at Ishigaki Port, respectively.

Table 1 Radiocarbon dating of coral specimens from Tonoshiro Reef

Sample ID	Site (m)[a]	Depth (cm from MSL)	Material	Lab code (NUTA2-)	$\delta^{13}C$ (PDB)	^{14}C age (BP)	Error (1 σ)	Corrected age (BP)[b]	Error (1 σ)	Facies	Growth orientation
IS-3	10	341	Encrusting *Acropora*	1007	1.16	1385	25	985	25	Spur subfacies	Up
IS-1	10	941	Massive Faviidae	1003	0.84	1155	25	755	25	Spur subfacies	Up
IS-6	32	755	Massive *Porites*	964	–0.85	580	25	180	25	Spur subfacies	Up
IS-24	42	507	Massive Faviidae	862	0.40	3315	30	2915	30	Spur subfacies	Up
IS-8	46	186	Encrusting *Acropora*	965	0.40	1660	25	1260	25	Spur subfacies	Up
IS-25	58	356	Massive Faviidae	863	–0.09	1355	25	955	25	Paleo-groove subfacies	Up
IS-9	62	615	Massive *Porites*	966	–0.14	1190	25	790	25	Paleo-groove subfacies	Up
IS-27	76	221	Tabular *Acropora*	865	0.29	960	25	560	25	Paleo-groove subfacies	Up
IS-26	76	483	Tabular *Acropora*	864	–0.73	1420	25	1020	25	Paleo-groove subfacies	Up
IS-10	77	491	Massive *Porites*	963	–2.42	1535	25	1135	25	Paleo-groove subfacies	Up
IS-11	80	371	Massive *Porites*	857	–1.32	1505	25	1105	25	Paleo-groove subfacies	Up
IS-12	82	470	Tabular *Acropora*	1009	–1.46	1595	25	1195	25	Paleo-groove subfacies	Up
IS-28	85	248	Massive *Porites*	957	–2.87	1295	30	895	30	Paleo-groove subfacies	Up
IS-14	95	136	Branching coral	1000	2.65	3125	25	2725	25	Reef crest subfacies	Up
IS-15	100	406	Tabular *Acropora*	860	–0.56	3450	25	3050	25	Reef crest subfacies	Up
IS-17	105	167	Tabular *Acropora*	1001	2.13	3425	25	3025	25	Reef crest subfacies	Up
IS-18	110	278	Tabular *Acropora*	1002	1.38	3930	25	3530	25	Reef crest subfacies	Up
IS-30	130	251	Tabular *Acropora*	958	0.87	4545	30	4145	30	Reef crest subfacies	Up
IS-31	137	426	Tabular *Acropora*	959	–0.04	4310	30	3910	30	Tabular *Acropora* reworked facies	Down
IS-23	140	138	Tabular *Acropora*	861	1.24	3890	30	3490	30	Tabular *Acropora* reworked facies	Down
IS-32	141	343	Tabular *Acropora*	1008	–0.67	3980	30	3580	30	Tabular *Acropora* reworked facies	Down
IS-34	400	400	Tabular *Acropora*	999	–0.90	5225	40	4825	40	Unconsolidated bioclast facies	Down

[a] Meters from the seaward end of Tonoshiro Reef (Figure 2)

[b] Marine reservoir effect of –400 years (Stuiver et al. 1986; Stuiver and Braziunas 1993)

1-3. Spur subfacies. This subfacies is outcropped at the seaward end of this trench and corresponds to the present-day reef edge where spurs are established. The age ranges from 2915 to 180 BP. The accumulation rate was 1.9 m/ka (IS-24 to IS-8).

2. Tabular Acropora Reworked Facies

Rubbles of tabular *Acropora* accumulated to form this facies. The age of the specimens collected in this facies range from 3910 to 3490 BP. This facies forms the landward part of the reef and corresponds with the present-day reef pavement. If we assume the corals in the tabular *Acropora* reworked facies to have been deposited soon after their death, this facies accumulated at a rate of 6.9 m/ka (IS-31 to IS-23)

3. Unconsolidated Bioclast Facies

This facies is situated behind the reef. The wall of the trench across this facies has collapsed, and we cannot see the exact internal structure of this facies in the trench. However, we can see the structure of this facies in the cores. Unconsolidated bioclasts, such as coral fragments, coralline algae and molluscs, compose this facies. The thickness of this facies is about 4 m at the landward part of the moat. This facies corresponds to the preset-day moat. Allochthonous tabular *Acropora* specimen in the core showed the age of 4825 BP.

DISCUSSION

Coral Reef Evolution

The oldest age of coral specimens is 4825 BP (IS-34, Table 1). So, the formation of the reef occurred when sea level was relatively stable after 6000 BP and within 1.4 m or less of its present position (Figure 3a). Assuming the corals in the tabular *Acropora* reworked facies to have been deposited soon after their death, the historical development of Tonoshiro Reef is described as follows (Figure 3b).

1. Formation of a ridge by transported and in-situ *Acropora* (–3500 BP).
   A ridge formed by a mixture of transported and in-situ *Acropora*. The ridge can form potentially by storm events as Blanchon et al. (1997) suggested.
2. Formation of reef crest and spur (3500 BP–present). The reef crest grew both vertically and laterally seaward after the establishment of the reworked-*Acropora* ridge. In the seaward end of the reef, spurs formed.
3. Infill of groove (1200 BP–present). Groove was infilled by both in-situ and transported *Acropora* and massive *Porites*. Massive *Porites* colonies are generally distributed in a moat or lagoon area where wave action is calm (Done 1983). The *Porites* found here made up a huge colony at a height of at least 5 m and grew more than 300 years (Abe, unpublished data), although it was located on seaward groove structure near the sea surface. This suggests that it grew probably in the calm environment provided by the growth of the spur, the infill of the groove and the leeward setting of this reef.
4. Establishment of an ecological zonation (–present). Finally, branching *Acropora* occurred on the reef pavement, corresponding to wave energy (Geister 1977; Done 1983) to form an ecological zonation on the reef (Figure 2). In Tonoshiro Reef, their distribution is restricted on the surface of the reef, and in-situ branching *Acropora* was not found in the internal facies (Figure 2), suggesting their occurrence was close to the present time.

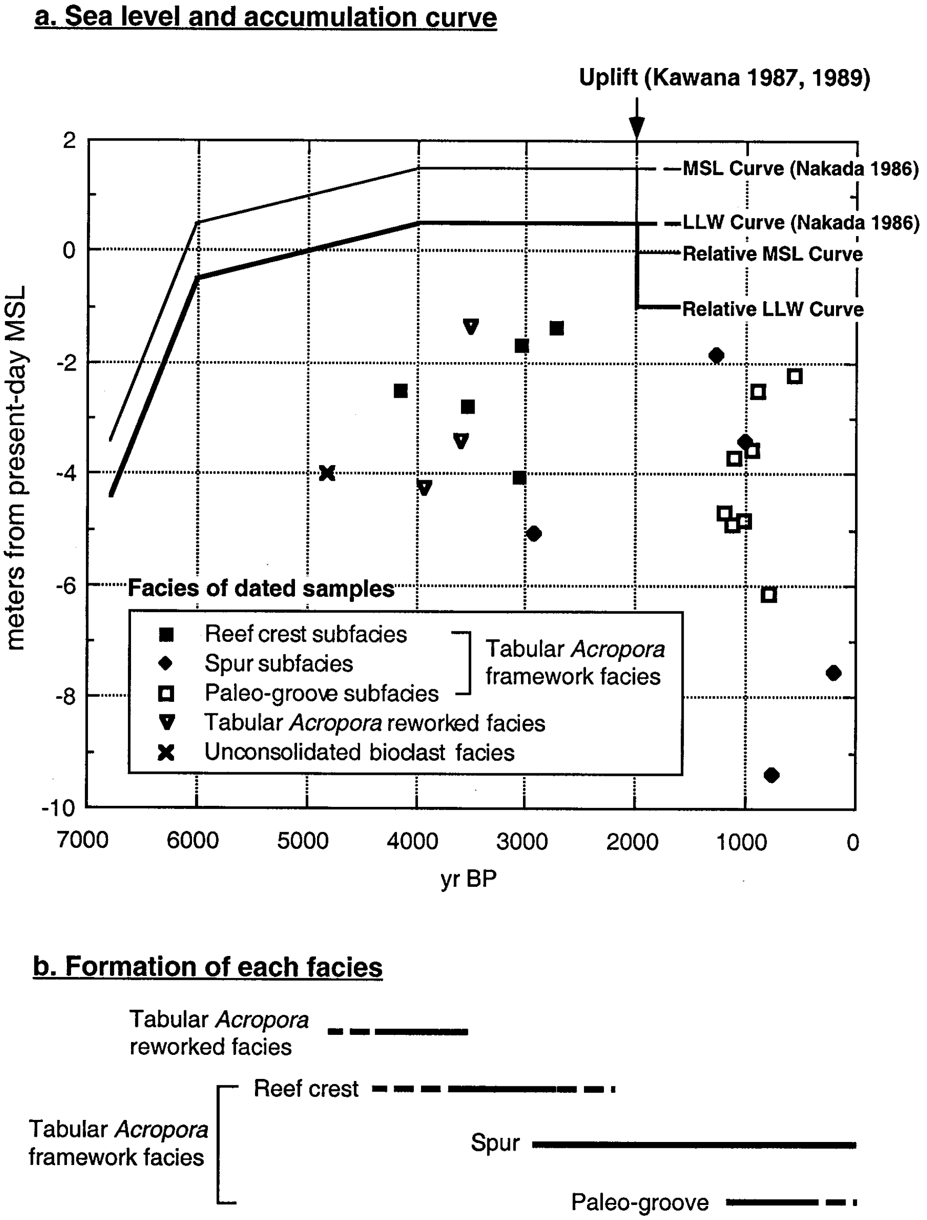

Figure 3 a) Comparison of the relative sea-level curve from Nakada (1986) and Kawana (1987, 1989) with the age-depth data derived from the Tonoshiro Reef. b) Interpreted temporal evolution of each facies. Radiometric counting errors (± 1 σ) are smaller than the width of the symbols.

Comparison with Other Reef Systems

The timing of catch-up with sea level of windward reefs is shown to be around 7000–4000 BP (e.g. Davies and Montaggioni 1985; McLean and Woodroffe 1994). In Ishigaki Island, a windward reef (Kabira Reef, Figure 1b) caught up with sea level at around 4000 BP (Yamano et al. 2001). The age of the top of Tonoshiro Reef (around 3500 BP) is younger than that of windward reefs as shown in Hopley and Barnes (1985). Tectonic uplift occurred in Ishigaki Island at around 2000 BP (Kawana 1989) caused the aerial exposure of the Kabira Reef crest during low tides and no corals are distributed there (Yamano et al. 2001), whereas Tonoshiro Reef is rarely exposed to the air and living corals are distributed on the reef, although the amount of uplift (1.4 m) is greater than that of Kabira Reef (0.6–0.8 m) (Kawana 1986). This result also suggests the delayed evolution of the reef. The uplift event did not make Tonoshiro Reef aerially exposed, as the reef had not reached the sea level yet at that time.

For facies and accumulation rates, the windward reef crests are composed of tabular or encrusting *Acropora*, and general vertical accumulation rates of windward reef crests are 1–4 m/ka (Kayanne 1992). The vertical accumulation rate of Kabira Reef crest facies ranged from 1.3 to 6.4 m/ka (Yamano et al. 2001). The vertical accumulation rates of leeward Tonoshiro Reef (2.2–8.3 m/ka) are similar to those of windward reefs, which fact was also shown by Hopley and Barnes (1985) and Kan et al. (1997a) in the leeward part of continuous reefs. Lateral expansion rates of Tonoshiro Reef (33 and 75 m/ka) are similar to Kabira Reef (58 and 149 m/ka) and another windward reef (37 and 45 m/ka, Kan and Hori 1993). The framework of Tonoshiro Reef (Figure 2) is constructed by in- situ tabular *Acropora*, which is also shown in the leeward side of Tonaki Reef (Kan et al. 1997a). Thus, the framework facies of the leeward reefs are also similar to those of windward reefs. However, branching *Acropora* thickets shown in Kan et al. (1997a) did not occur in Tonoshiro Reef, as Tonoshiro Reef had no windward reef formation prior to its development.

The leeward reefs might have the same productivity of carbonates as windward reefs, although their evolution was delayed. Furthermore, other indicators than tabular *Acropora*, such as bioclastic constituents, should be needed for the recognition of paleo-reef setting as Pandolfi et al. (1999) suggested.

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REFERENCES

Blanchon P, Jones B, Kalbfleich W. 1997. Anatomy of a fringing reef around Grand Cayman: storm rubble, not coral framework. *Journal of Sedimentary Research* 67:1–16.

Burr GS, Edwards RL, Donahue DJ, Druffel ERM, Taylor FW. 1992. Mass spectrometric ^{14}C and U-Th measurements in coral. *Radiocarbon* 34(3):611–8.

Cabioch G, Camoin GF, Montaggioni LF. 1999. Postglacial growth history of a French Polynesian barrier reef tract, Tahiti, central Pacific. *Sedimentology* 46:985–1000.

Davies PJ, Montaggioni LF. 1985. Reef growth and sea-level change: the environmental signature. *Proceedings of the Fifth International Coral Reef Congress* 3: 477–515.

Done TJ. 1983. Coral zonation: its nature and significance. In: Barnes DJ, editor. *Perspectives in coral reefs*. Townsville Australia: AIMS. p 107–47.

Geister J. 1977. The influence of wave exposure on the ecological zonation of Caribbean coral reefs. *Proceedings of the Third International Coral Reef Symposium* 1:23–9.

Hideshima S, Matsumoto E, Abe O, Kitagawa H. 2001. Marine reservoir correction estimated from annually banded coral from northwest Pacific Ocean. *Radiocarbon* this issue.

Hopley D, Barnes R. 1985. Structure and development of a windward fringing reef, Orpheus Island, Palm Group, Great Barrier Reef. *Proceedings of the Fifth International Coral Reef Congress* 3:141–6.

Kan H, Hori N. 1991. Methodology and conceptual design for geomorphological surveying of submarine 'road cut' in modern reef-flats. *Geographical Sciences* 46:68–81.

Kan H, Hori N. 1993. Formation of topographic zonation on the well-developed fringing reef-flat, Minna Island, the Central Ryukyus. *Transactions, Japanese Geomorphological Union* 14:1–16.

Kan H, Hori N, Kawana N, Kaigara T, Ichikawa K. 1997a. The evolution of a Holocene fringing reef and island: reefal environmental sequence and sea level change in Tonaki Island, the Central Ryukyus. *Atoll Research Bulletin* 443:1–20.

Kan H, Hori N, Nakashima Y, Ichikawa K. 1995. The evolution of narrow reef flats at high-latitude in the Ryukyu Islands. *Coral Reefs* 14:123–30.

Kan H, Nakashima Y, Hopley D. 1997b. Coral communities during structural development of a fringing reef flat, Hayman Island, the Great Barrier Reef. *Proceedings of the 8th International Coral Reef Symposium* 1: 465–70.

Kawana T. 1987. Holocene crustal movement in and around the Sekisei Lagoon in Okinawa Prefecture, Japan. *Earth Monthly* 9:129–34. In Japanese, original title translated.

Kawana T. 1989. Quaternary crustal movement in the Ryukyu Islands. *Earth Monthly* 11:618–30. In Japanese, original title translated.

Kayanne H. 1992. Deposition of calcium carbonate into Holocene reefs and its relation to sea-level rise and atmospheric CO_2. *Proceedings of the 7th International Coral Reef Symposium* 1:50–5.

Loya Y. 1978. Plotless and transect methods. In: Stoddart DR, Johannes RE, editors. *Coral reefs: research methods*. Paris: UNESCO. p 197–217.

McLean RF, Woodroffe CD. 1994. Coral atolls. In: Carter RWG, Woodroffe CD, editors. *Coastal evolution, Late Quaternary shoreline morphodynamics*. New York: Cambridge University Press. p 267–302.

Nakada M. 1986. Holocene sea levels in oceanic islands: implications for the rheological structure of the earth's mantle. *Tectonophysics* 121:263–76.

Nakamura T, Niu E, Oda H, Ikeda A, Minami M, Takahashi H, Adachi M, Pals L, Gottdang A, Suya N. 2000. The HVEE Tandetron AMS system at Nagoya University. *Nuclear Instruments and Methods in Physics Research* B172:52–7.

Neumann AC, Macintyre IG. 1985. Reef response to sea level rise: keep up, catch up or give up. *Proceedings of the Fifth International Coral Reef Congress* 3:105–10.

Pandolfi JM, Llewellyn G, Jackson JBC. 1999. Pleistocene reef environments, constituent grains, and coral community structure: Curaçao, Netherlands Antilles. *Coral Reefs* 18:107–22.

Roberts HH, Murray SP, Suhayda JN. 1975. Physical processes in a fringing reef system. *Journal of Marine Research* 33:233–60.

Stuiver M, Braziunas TF. 1993. Modeling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10,000 BC. *Radiocarbon* 35(1):137–89.

Stuiver M, Pearson GW, Braziunas T. 1986. Radiocarbon age calibration of marine samples back to 9000 cal yr BP. *Radiocarbon* 28(2):980–1021.

Yamano H, Kayanne H, Yonekura N. 2001. Anatomy of a modern coral reef flat: a recorder of storms and uplift in the late Holocene. *Journal of Sedimentary Research* 71:295–304.