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The recovery process of broken *Acropora* branches at Mizugama, Okinawa Island, Japan

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Four dominant species of scleractinian coral, *Acropora gemmifera, A. digitifera, A. millepora* and *A. hyacinthus* were investigated on the reef front of Mizugama reef, Okinawa Island, Japan. Recovery processes involving tissue pigmentation and polyp formation were characterized for each colony. The broken surface area was smaller and the rate of axial polyp formation was faster for *A. hyacinthus* than for *A. gemmifera*. Furthermore, some branches of *A. gemmifera* formed a mound-like shape in the central lesion area, which seemed to delay the formation of an axial polyp. The mound was formed when sediment accumulated on the lesion, prior to tissue coverage. This study indicates that the differences in polyp formation and polyp recovery varies among species, which in turn are affected by environmental factors but also inherent, species specific, constraints.

Keywords
coral, *Acropora* branch, breakage, polyp formation, typhoon, Okinawa

1 Introduction

The genus *Acropora* exhibits high species diversity on coral reefs in the Indo-Pacific region. This genus, especially branching *Acropora* colonies[1, 2], is known to be susceptible to breakage. Although this genus may be likely to undergo breakage, their recovery rate appears to be more rapid than massive corals. BAK[3] suggested that branching *Acropora* are more capable of regeneration and healing compared to non-branching corals. Furthermore, HIGHSMITH[4] suggested that the breaking of branches, otherwise known as fragmentation, is very common in branching corals and has most likely evolved as an adaptation, enhancing distribution in high energy environments. It is reported that the linear growth of broken branches of corymbose type corals, such as *Acropora nasuta*, is significantly faster than adjacent intact branches[5]. *Acropora* breakage occurs frequently, especially during the typhoon season in the Ryukyu Islands.

Okinawa Island is located in an area frequently impacted by typhoons[6] and subject to some typhoon damage almost every year. However, few studies have focused on coral recovery and polyp formation, and it is unknown whether the recovery process varies among *Acropora* species. KAWAGUTI[7] reported on the processes involved in polyp formation in the genus *Acropora*, and KOBAYASHI[5] described the degree of regeneration of fragmented branches in *Acropora nasuta* and *A. formosa*, although differences among species have not been previously addressed.

In this study, the recovery process of *Acropora* colonies damaged artificially, and damaged by a typhoon, were examined. The objective of this study was to observe the recovery rate of damaged *Acropora* colonies and to compare the recovery process among *Acropora* species with different branch characteristics.

2 Materials and methods

2·1 Study site

This study was conducted on a fringing reef near the mouth of Hija River, Mizugama, on the west coast of the central part of Okinawa Island (Fig. 1). The reef had a high coral coverage in 1996, which included many branching *Acropora* colonies.

Hija River discharges a moderate amount of domestic and agricultural sewage and industrial waste. Nevertheless, previous studies have indicated that this influence did not have adverse effects on coral growth in the study area, even the day after heavy rain[8], in spite of the fact that

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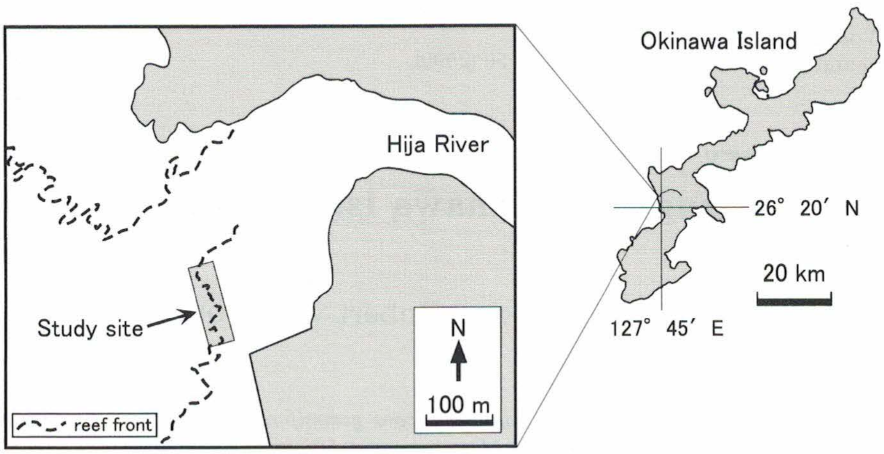

Fig. 1 Okinawa Island and Mizugama reef, showing experimental site.

juvenile coral mortality was high[9].

2·2 Field method

This investigation was carried out from October to December 1995 and October 1996 to February 1997. Each colony sampled was located on the reef front at approximately 1.2 m depth (below datum). Five colonies of the four most dominant species, *Acropora gemmifera, A. digitifera, A. millepora*, and *A. hyacinthus* were selected for investigation. The size of all corals used in this study ranged between 15–25 cm diameter.

Because of the absence of typhoons impacting Mizugama Reef during the 1995-study period, *Acropora* corals were artificially broken off, so as to simulate typhoon effects. However, near the end of September in 1996, Typhoon 96-21 damaged coral reefs in Okinawa and its effects on *A. gemmifera* were investigated.

In 1995, five branches were broken per colony, approximately 2 cm in length from the branch tip, and the diameter of the broken area of each branch was measured. Following this, the recovery of the colony was observed continually throughout the study period. The following categories were used to classify stages in the recovery process (Fig. 2).

Stages of tissue pigmentation—

a: non-pigmented stage;

b: pigmented stage (including partially or lightly pigmented);

Stages of polyp formation—

A: pre-recovery stage (polyps do no exist);

B: axial polyp stage (axial polyp is formed and elevated);

C: non-axial polyp stage (polyps, excluding the axial polyps, are formed and elevated);

D: projection stage (axial and other polyp(s) begin to extend).

In some branches, the early recovery process was delayed due to algae invasion, of both filamentous and coralline algae, and by sediments. No tissue covered the lesion during this delay period. This delayed process was termed 'o'. Another process involved the formation of 'mound', and was termed 'm'. During this process an axial polyp formation, however the calice was closed.

3 Results

3·1 Surface area of breakage

The surface area of the lesions varied among species (Table 1; ANOVA, $p < 0.01$). *A. gemmifera* had a significantly larger surface area (t-test, $p < 0.01$), and *A. hyacinthus* had a significantly smaller surface area (t-test, $p < 0.01$) than the other species (Table 1). No clear differences were evident between *A. digitifera* and *A. millepora*. No significant differences were found between the lesion areas that were artificially inflicted on *A. gemmifera* and those that were inflicted by the typhoon.

3·2 Recovery from physical damage

3·2·1 Recovery process Once the branches were broken, the bare skeleton was white. Recovery began by tissue extending over the damaged skeleton, which started from the ridge of the undamaged part of the branches and extended to the center of the lesion. Tissue pigmentation and then polyp formation followed this process. However, polyp formation was not consistent and varied among species, and even varied within colonies. Therefore, the process of recovery was classified as follows.

Two types of polyp formation were evident (Fig. 2). The first type was generally evident in every species observed[7]. Accordingly, this type was termed the normal type, where an axial polyp ini-

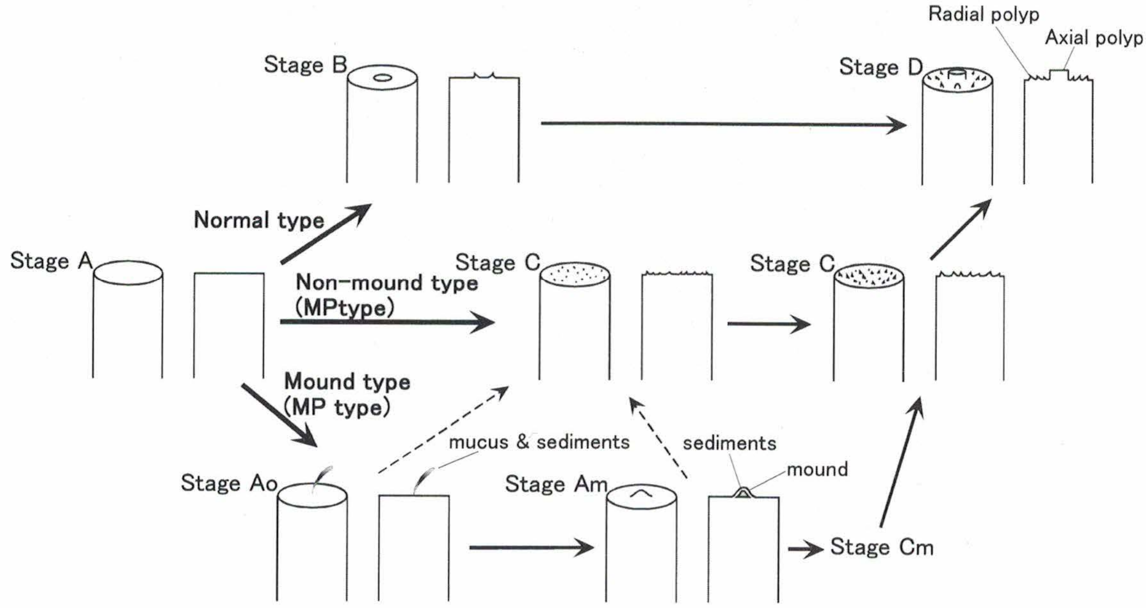

Fig. 2 Type distinction of the polyp formation process. MP type: Multi-polyped type.

Table 1 Comparison of lesion sizes besed on diameters and surface areas. Significant comparisons are underlined (t-test, $p < 0.01$).
A. Average of lesion size on four species; B. Average of lesion size of *Acropora gemmifera* broken by artificial damage in 1995 and typhoon damage in 1996.

A.

	A. gemmifera	*A. digitifera*	*A. millepora*	*A. hyacinthus*
Lesion diameter (mm)	12.1	8.1	7.4	5.1
Lesion surface area (mm^2)	117.1	52.1	43.9	20.1

B.

	Artificial damage in 1995	Typhoon damage in 1996
Lesion diameter (mm)	12.1	11.1
Lesion surface area (mm^2)	117.1	100.0

tially formed at the center of the lesion (Stage B, above), in early recovery. This axial polyp gradually became elevated, and other small polyps formed around the axial polyp (Stage D, above).

For the second type of polyp formation, no axial polyps formed in the early stage. Instead, many small polyps were observed (Stage C, above). These polyps also became raised (elevated), but slowly and eventually reached Stage D. Therefore, this type was termed the multi-polyped type, abbreviated to as the MP type.

Furthermore, an uncommon condition occurred in which some branches released mucus that trapped sediment in the MP type. Those branches were categorised as 'mound type', as tissue covered the lesion before sediment was totally removed (Fig. 3). On the other hand, branches that did not undergo mound formation were termed 'non-mound type'.

Table 2 Frequency of recovery types of four species.

	Normal type	Multi-polyped type	
		Non-mound type	Mound type
A. gemmifera	35	10	30
A. digitifera	55	15	0
A. millepora	22	46	4
A. hyacinthus	67	2	0

The variety of these recovery types, exhibited among the four species studied, was generally different (Table 2). The non-mound type was common for *A. millepora*, and the mound type characteristic of *A. gemmifera*. However, in each species, the

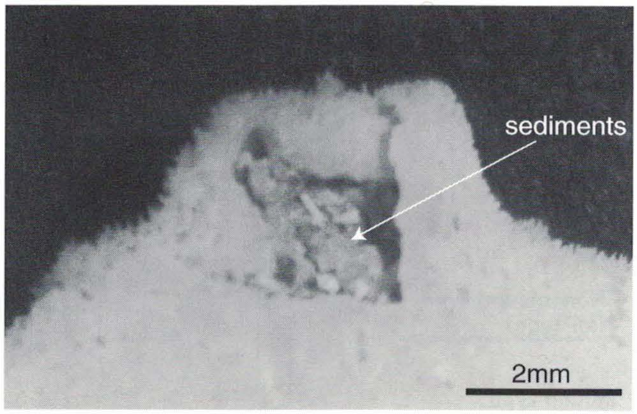

Fig. 3 A cross section of a 'mound'. Sediments that covered the coral skeleton made a mound.

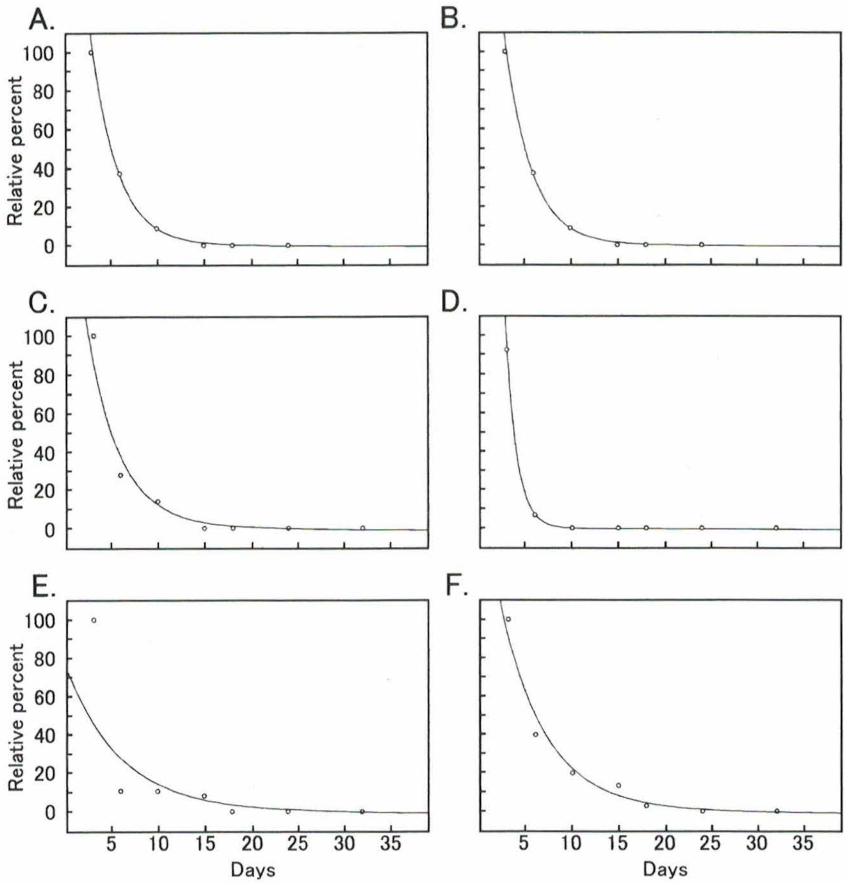

Fig. 4 Rate of change from non-pigmented to pigmented branches. A. Normal type: *A. gemmifera*; B. Normal type: *A. digitifera*; C. Normal type: *A. millepora*; D. Normal type: *A. hyacinthus*, E. Non-mound type: *A. millepora*; and F. Mound type: *A. gemmifera*.

normal type occurred at least to some extent.

3·2·2 Recoveryrate Ratesoftissuepigmentation－Each lesion underwent pigmentation within 18 days of the incurred breakage (Fig. 4). In the normal type, *A. hyacinthus* quickly pigmented, significantly faster than other species (Wilcoxon test, $p<0.01$). In the MP type, there was no significant difference between the normal type and the non-mound type in *A. millepora*. A significant difference was found between the normal type and the mound type in *A. gemmifera* (Wilcoxon test. $p<0.01$).

Rates of polyp formation—Figure 5 illustrates the relative percentage of branches that reached Stage D. The differences among the four species were not obvious in the normal type category, except that *A. hyacinthus* exhibited faster polyp formation than *A. millepora* and *A. gemmifera* in the early recovery stages. However, the differences among species were clear between the normal type and the MP type. The mound type was not apparent in *A. gemmifera* during the study period in 1995, and 120 days after the typhoon in 1996, only a few branches of *A. gemmifera* reached Stage D.

4 Discussion

The 'normal type' of recovery reported in this study was similar to reports on *Acropora* recovery in previous studies[5, 7]. Therefore, the normal healing type can be regarded as the general recovery process within *Acropora* colonies. *A. hyacinthus*, with narrow branches showed the most rapid pigmentation. In this study, however, there were greater differences in polyp formation than there were differences in rates of tissue pigmentation. A clear difference among species was evident when branches began linear growth after Stage D (Fig. 5). The rate of lesion healing was related to the volume of the regenerating part undergoing calcification.

KAWAGUTI[7] reported that plural axial polyps appear when the diameter of the broken surface

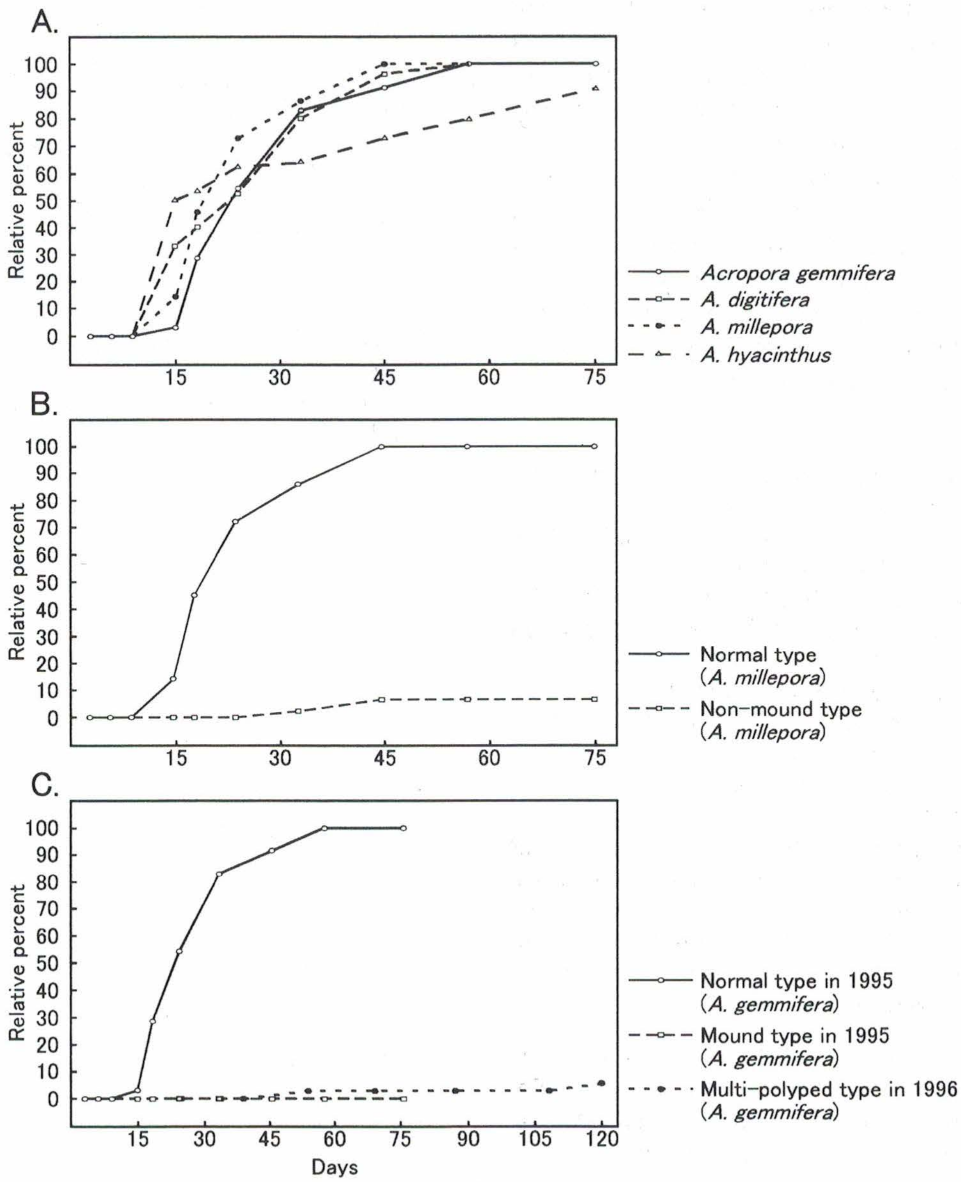

Fig. 5 Rate of polyp formation of branches that reached Stage D. A. Comparison of 'normal' type of polyp formation for four species; B. Comparison of polyp formation between the 'normal type' and the 'non-mound type' for *A. millepora*; and C. Comparison of polyp formation between the 'normal type' and 'mound type' for *A. gemmifera*.

exceeds a certain size. Such polyp formations corresponded to Stage C within the multi-polyped type. However, those polyps seemed to differ from the axial polyp in diameter and shape. Further studies could investigate what function the multi-polyped stage plays in the recovery process of *Acropora* colonies.

The mound and the non-mound types seemed to delay recovery. Mounds appeared when sediments, which remained at the center of the lesions (Fig. 2), covered tissue. Mounds presumably resulted in a delayed axial polyp formation, although the lesion area was eventually completely covered. Mound formation seemed to be related to the surface area of lesion. Wider branches required more time to cover their lesions, although these time lags were generally short, usually only three days or less. Mounds typically formed on *A. gemmifera* (Table 2). The reason why polyp formation was delayed in non-mound types was not clear.

In Okinawa, typhoons tend to affect reef corals annually, at least to some degree. During the typhoon season, corals may become stressed and the resilience of each colony may deteriorate if these processes are hindered by human factors such as pollution from rivers. In some cases, complete recovery may not be expected.

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沖縄本島水釜海域におけるミドリイシ属サンゴの破損した枝の回復過程

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造礁サンゴの破損した枝の回復過程を明らかにするため，沖縄本島水釜の裾礁礁縁において優占する枝状のミドリイシ4種，オヤユビミドリイシ (*Acropora gemmifera*)，コユビミドリイシ (*A. digitifera*)，ハイマツミドリイシ (*A. millepora*)，クシハダミドリイシ (*A. hyacinthus*) について調査を行った．破損し骨格が露出した傷口は，全般的に最初に透明なサンゴ組織が被覆した後，徐々に組織の着色が進む一方でポリプの形成が行われた．しかし回復の進行過程は群体間で差異がみられた．枝が細いために破損部の傷口面積が小さいクシハダミドリイシは，枝が最も太く傷口面積の大きいオヤユビミドリイシと比較して，明らかにポリプ形成が速かった．さらに，オヤユビミドリイシのいくつかの破損枝では傷口の中央部にマウンド状の突起がみられ，そのような被損枝では頂端ポリプの形成が明らかに遅れることが観察された．このマウンド状突起は，破損部においてサンゴ組織が傷口を塞ぐ前に沈積した堆積物を，組織・骨格で覆うことにより形成されており，そのため頂端ポリプの形成が阻害されたものと考えられる．本研究から，被損したミドリイシの枝は，環境要因の影響のみならず形態・枝の太さといった種特有の条件によって，ポリプ形成および回復過程の特徴に種による変化が生じることが示唆される．

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