Developmental Processes of Mangrove Habitat Related to Relative Sea-level Changes at the Mouth of the Urauchi River, Iriomote Island, Southwestern Japan

Kiyoshi FUJIMOTO* and Yasuhiro OHNUKI**

Abstract In order to clarify geomorphologically the developmental processes of the mangrove habitats of Iriomote Island, topographic and surface geological surveys were performed along four lines in and around the mangrove habitat at the mouth of the Urauchi River in northwestern Iriomote Island.

As a result, it was learned that the mangrove habitat of Iriomote Island has migrated in response to relative sea-level changes. It is especially worth noting that the mangrove habitat abruptly moved seaward by a relative sea-level fall that occurred about 1,000 yrs BP. During the rising sea-level phase between 2,000 yrs BP and 1,000 yrs BP, the mangrove forests of the island retreated, landward, which indicates that they are possibly more sensitive to sea-level changes than mangrove forests of tropical areas such as Micronesia and the Philippines, where landward movement of mangroves during this period has not recognized. On the other hand, at the *Rhizophora stylosa* habitat situated in the inner mangrove forest, it was found that the mangroves have maintained their habitat and position by accumulating mangrove peat against relative sea-level rise after 260 yrs BP.

Keywords Mangrove habitat, Relative sea-level changes, Radiocarbon dating, FeS₂ contents analysis, Aerial photograph, Iriomote Island

I. Introduction

Mangrove habitats are classified into three types based on their geomorphological situations, i.e., estuary or delta type, backmarsh or lagoon type, and tidal-flat type (Miyagi *et al.*, 1989). The tidal-flat type is found in the geomorphological environment that excludes estuaries, deltas, backmarshes and lagoons. This type of

habitat has little sediment supply and no geomorphological barrier against coastal processes. The frameworks for the estuary or delta type and backmarsh or lagoon type have been formed and maintained by fluvial processes and coastal processes, respectively, within a changing environment of sea level (Thom *et al.*, 1975; Kikuchi *et al.*, 1978; Woodroffe *et al.*, 1989, etc.). On the other hand, the tidal-flat type has been formed and maintained by mangrove peat accumulation with sea-level changes. Namely, the existence of the mangrove itself is the most important factor for the formation and maintenance of this type

* Forestry and Forest Products Research Institute

** Kyushu Research Center, Forestry and Forest Products Research Institute.

of habitat. Therefore, excessive deforestation on this type will induce severe loss of the habitat. Hence, the forests of this type must be managed carefully (Fujimoto and Miyagi, 1993). As mentioned above, understanding the formative and maintainable mechanisms of mangrove habitats are very important for sustainable use of mangrove forests. Moreover, in order to predict the effect of sea-level rise induced by global warming, it is necessary to clarify the formative processes of mangrove habitats with sea-level changes.

In Japan, there are valuable mangrove forests that define the northern limit of mangrove distribution in the world. However, the formative and maintainable mechanisms of the mangrove hab-

itats are still largely unknown. Though Kikuchi *et al.* (1978, 1980) discussed geomorphologically the formative processes of the mangrove habitat at the mouth of the Nakama River, there have as yet been no discussions based specifically on the distribution of organic materials of mangrove origin in sediment confirmed through radiocarbon dating. This study aims to clarify the formative and maintainable mechanisms of the mangrove habitat based on the concrete data of the distribution of organic materials of mangrove origin and radiocarbon dating at the mouth of the Urauchi River.

II. Study area

Iriomote Island, one of the Yaeyama Islands of

Fig. 1. Map showing the vegetation and landuse on the alluvial plain of the Urauchi River, the location of profiles shown in Fig. 2 and Fig. 3 and areas covered by aerial photographs in Photo 1.

southwestern Japan, has a total mangrove forest area of about 400 ha (Nakasuga, 1979). Almost all of the mangrove forests are situated at the mouths of rivers. The mangrove forests of the Urauchi are about 100 ha in area, almost the same as at the Nakama. The mangrove forest at the mouth of the Urauchi is situated in a lagoon-like environment surrounded by hills (Fig. 1). Thus, this mangrove habitat is similar to the backmarsh or lagoon type despite its geomorphological setting. A *Pandanus tectorius* thicket is situated behind the mangrove forest, and a fresh-water marsh, part of which is used as paddy field, is located behind the *Pandanus* thicket.

In the Yaeyama Islands, a tide station has been established at Ishigaki Harbor. The mean spring tidal range at the station is 179 cm. Almost all of the mangroves on Iriomote Island grow in the upper half of the tidal range. In Iriomote Island, the greater part of the root systems of *Rhizophora stylosa* and *Bruguiera gymnorrhiza*, which are the main species of the island, usually exist within 40 cm from the surface (Komiyama *et al.*, 1989 and Ninomiya *et al.*, 1989). Therefore, most of the organic materials of mangrove origin are believed to be deposited in the restricted environment between a level slightly lower than mean tide level and mean spring high tide level.

Emerged benches, beachrocks, and notches which formed during the late Holocene are found along the coast of Iriomote Island. Therefore, the formative processes of mangrove habitat of this area have likely been affected by relative sea-level changes.

III. Study method

Topographic profile surveys using tilting level and surface geological surveys using Hiller type sampler were conducted along four lines, two of which are located in the mangrove habitats. The other two lines were set in the fresh-water marsh behind the mangrove habitat (Fig. 1) to clarify the distribution of earlier mangrove forests. A bench mark situated on the right bank of the Urauchi near the Urauchi Bridge was used as the standard point for the leveling.

The substratum of the mangrove forest usually includes peat, humus and wood fragments. It is apparent that these organic materials are of mangrove origin. Therefore, the layer containing these organic materials was used as an indicator of the existence of past mangrove forests. In order to confirm the depositional environment of the layer in the sediment of the fresh-water marsh area, FeS_2 content analysis was conducted.

FeS_2 is a kind of authigenic mineral and is formed by chemical changes in SO_4^{2-} in the pore water of the surface sediment caused by sulfur reductase (Berner, 1970). FeS_2 content in sediment is determined by the concentration of SO_4^{2-} , oxidation-reduction potential, organism content for the reductase, and so on (Nakai *et al.*, 1982). In the sediments of mangrove habitats, much FeS_2 is formed because the SO_4^{2-} concentration in sea water is a thousand times greater than in fresh water (Nakai *et al.*, 1982), and there are much greater levels of organisms in mangrove habitat. The methodology of FeS_2 content analysis followed Shiragami (1985). FeS_2 content was indicated by the ratio of the sulfur weight in FeS_2 to

the sample weight. This is presented as FeS_2 -S content in this paper.

Radiocarbon dating was performed on six samples obtained from these four lines by Kyoto Sangyo University and the Japan Radioisotope Association. The radiocarbon ages were calculated using Libby's value, 5568 years, as the half life of ^{14}C . Measurement error indicates $\pm 1\sigma$.

The recent movement of the mangrove forest was examined using aerial photographs in connection with the relative sea-level changes observed at Ishigaki Harbor.

IV. Results

Fig. 2 shows vegetation, landform and geological profiles in the mangrove habitat. The man-

Fig. 2. Vegetation, landform and geological profiles in the mangrove forest. A: scale for trees.

grove forest mainly consists of *Rhizophora stylosa* and *Bruguiera gymnorrhiza*. The latter grows on slightly higher ground, such as natural levees and the banks of tidal creeks. On the other hand, *R.*

stylosa is found in relatively low areas between higher microlandforms.

Along profile a-a', the layer containing organic materials of mangrove reaches no lower than 0.8

Fig. 3. Landform and geological profiles on the fresh-water marsh behind the mangrove forest. Organic materials in these profiles include both mangrove and non-mangrove origin.

m below the present mean sea level. This layer consists of sand or sandy loam except for the inner part of the mangrove forest (around Loc. 11 to 20), where the ground level is relatively low and the sediment consists of a peaty deposit. Radiocarbon age indicating 260 ± 80 yrs BP (KSU-2181) was obtained from the basal horizon of the peaty deposit (0.3 to 0.4 m below the present mean sea level) at Loc. 17.

Along profile b-b', the layer containing organic

materials of mangrove is only 40 cm thick except for along the tidal creek (around Loc. 19). At the river side (around Loc. 0), a layer similar to the above is covered with a natural levee deposit. The boundary is 0.2 m below the present mean sea level. Radiocarbon dating indicated an age of $1,280 \pm 70$ yrs BP (N-6468) for wood fragments in the top horizon of the layer (0.2 to 0.3 m below the present mean sea level).

Fig. 3 shows landform and geological profiles in

Photo 1 Aerial photographs of the mangrove area at the mouth of the Urauchi River taken in 1963 by U.S. Armed Forces, which are administered by The Geographical Survey Institute, and in 1977 and 1986 by The Geographical Survey Institute. Use of these aerial photographs was allowed orally by the administrator of The Geographical Survey Institute.

the fresh-water marsh. Along profile c-c', an organic sand layer with wood fragments and stumps, whose facies is almost same as the layer containing organic mangrove materials along profiles a-a' and b-b', is overlain by an organic silt or clay layer. The boundary between the two layers lies 0.8 m to 1.2 m above the present mean sea level. Because of the high content of FeS_2 -S (over 3%) in the organic sand layer examined at Locs. 5 and 7, the layer is considered to be a marine deposit. Therefore, the wood fragments and stumps are presumed to be of mangrove origin. The stumps were identified as *Bruguiera gymnorhiza* from the tissue by Dr. Ikeda of the Kyushu Research Center of the Forestry & Forest Products Research Institute. These evidences indicate that mangrove forests existed in the area of the present fresh-water marsh. Radiocarbon dating indicated an age of 990 ± 30 yrs BP (KSU-2185) for a mangrove stump at Loc. 4 (sampling horizon: about 1 m above the present mean sea level).

Along profile d-d', a marine sand layer containing organic mangrove materials was also found below the paddy fields. Radiocarbon dating provided the following results: a mangrove stump from about 1 m above the present mean sea level at Loc. 8 indicated 990 ± 40 yrs BP (KSU-2184), wood fragments of mangrove from 0.6 to 0.7 m above the present mean sea level at Loc. 10 indicated $1,020 \pm 150$ yrs BP (KSU-2182) and a mangrove stump from about 0.6 m above the present mean sea level at Loc. 11 indicated $1,330 \pm 100$ yrs BP (KSU-2183).

Aerial photographs taken in 1963, 1977 and 1986 offer clear visual evidence of the recent dynamics

of the mangrove habitat (Photo 1). The photographs show that: 1. Mangroves invaded the inland *Pandanus* habitat between 1963 and 1977 (for example a-Loc. A); 2. The seaward margin of the *Pandanus* thicket retreated landward between 1963 and 1977 (a-Loc. B); 3. A landward expansion of mangroves did not occurred between 1977 and 1986; 4. A seaward expansion of mangrove area was not so rapid between 1963 and 1977, however it was extremely fast between 1977 and 1986 (b-Loc. C); and 5. The retreat of the seaward margin of the mangrove forest did not occurred between 1963 and 1986. These migration trends were recognized throughout the mangrove forests on Iriomote Island.

V. Discussion

The layer containing organic mangrove materials was found in the fresh-water marsh behind the present mangrove area as mentioned above. Four radiocarbon ages were obtained from the upper limit of the layer. These ages indicated about 1,000 yrs BP (slightly older at Loc. 11) despite of the location where the samples were obtained. The evidence shows that the mangrove forest of this area emerged rapidly at about 1,000 yrs BP.

Generally, during a stable period of sea level, the landward margin of a mangrove forest gradually moves seaward with the rise of ground level caused by sedimentation. Though it goes without saying that this process affected the migration of the landward margin of the mangrove forest at the mouth of the Urauchi, it is possible that an abrupt fall in relative sea-level also affected it because the mangrove forest emerged suddenly at

1,000 yrs BP. There are two possibilities as to the cause of the relative sea-level fall: seismic uplift, or the fall of the sea level itself.

Kawana (1987) presumed that an uplift occurred at a certain time after 1,000 yrs BP in the Yaeyama Islands area based on the radiocarbon ages obtained from shell fossils in the beachrocks of Iriomote and Ishigaki Islands. It is believed that strong earthquakes have been generated around the Yaeyama Islands from the thrusting of the Sakishima Deep-Sea Terrace under the southern Ryukyu Arc, associated with the subduction of the Philippine Sea Plate and also the spreading of the Okinawa Trough (Kawana, 1987). Along the coastal areas of the Yaeyama Islands, many coralline boulders which seem to have been transported by tsunamis are found not only on reef flats but also on land. Nakata (1990) indicated that many huge tsunamis have repeatedly washed over the southern Ryukyu Arc during the last several thousand years from many radiocarbon ages obtained from the tsunami boulders and the other tsunami deposits. He estimated that these tsunamis occurred at 200 yrs BP (i.e., the 1771 Meiwa tsunami), 500 yrs BP, 1,000 yrs BP, 2,000 yrs BP, 3,700 yrs BP and 4,400 yrs BP. There is no evidence that the earthquake of 1771 generated an uplift. However, it is possible that the earthquakes which occurred 1,000 yrs BP and 2,000 yrs BP generated an uplift, since Nakata (1990) indicated that the earthquakes were considerably stronger than the 1771 event. Hence, the possibility that the rapid emergence of mangrove forest which occurred about 1,000 yrs BP was caused by seismic uplift is strong.

The radiocarbon ages related to the mangrove

habitat development before 1,000 yrs BP were obtained from only two samples, i.e., $1,280 \pm 70$ yrs BP (N-6468) at 0.2 to 0.3 m below the present mean sea level of the riverward part of the profile b-b' and $1,330 \pm 100$ yrs BP (KSU-2183) at about 0.6 m above the present mean sea level of Loc. 11 on profile d-d'. At the sampling site of N-6468, the sediment containing organic mangrove materials lies deeper than 0.2 m below the present mean sea level, though the bottom horizon of the sediment was not recognized. These facts indicate that mangrove forests grew at a relatively lower level than the present mean sea level before 1,300 yrs BP. This means that the relative sea level before 1,300 yrs BP was lower than the present one.

In Micronesia and the Philippines, the sea level fell to about 2 m below the present one about 2,000 yrs BP. Almost all of mangrove forests of the tidal-flat type developed on the reef flat and the tidal flat which became a high tidal zone due to the fall in sea-level. These forests have maintained their habitat and position by accumulating mangrove peat with the subsequent sea-level rise (Fujimoto and Miyagi, 1993). The sea-level fall which occurred about 2,000 yrs BP was probably due to eustatic change because it has been recognized widely in the northwestern Pacific, not only in Micronesia and the Philippines, but also in Japan (Fujimoto, 1990; Fujimoto and Miyagi, 1993). There is no data to estimate the distributed area of mangroves at 2,000 yrs BP at the mouth of the Urauchi. However, it is possible to assume that the mangrove forest at 1,300 yrs BP spread seaward of the present position, and later retreated landward

with the relative sea-level rise as evidenced in the depositional structure and the radiocarbon age obtained from profile b-b'.

A radiocarbon age related to the mangrove habitat development after 1,000 yrs BP was obtained from the bottom of the peaty deposit on profile a-a', which indicated 260 ± 80 yrs BP. This fact suggests that a mature mangrove forest already existed around profile a-a' at 260 yrs BP and the sea level at that time stood below the present one because the horizon where the age was obtained is 0.3 m below the present mean sea level. It seems that against the relative sea-level rise after 260 yrs BP, the mangrove forest near the hill slopes has maintained its habitat by the sediment supply from the slopes; on the other hand, the inner mangrove forest distant from the hill slopes has maintained its habitat by accumulating mangrove peat.

The bed containing organic mangrove materials along profile b-b' is thinner than that along profile a-a', and it is not below the present mean sea level except for around Locs.0 and 19. Therefore, it seems that the respread of the mangrove forest to the location of profile b-b'

Fig. 4. Changes of annual mean tide level at Ishigaki harbor, Ishigaki Island next to Iriomote Island (by Ishigaki Local Meteorological Observatory).

Fig. 5. Relative sea-level changes and a schematic representation of the movement of the mangrove forest at the mouth of the Urauchi River. 1: radiocarbon age obtained from wood fragments of mangrove and mangrove peat, 2: radiocarbon age obtained from mangrove stump, 3: range of measurement error of radiocarbon dating ($\pm 1\sigma$). Solid line: estimation based on the direct evidences such as sedimentary structure and radiocarbon date, or tidal record and aerial photographs, broken line: estimation based on the indirect evidences.

occurred after 260 yrs BP.

The tidal data observed at Ishigaki harbor was used to discuss the cause of the recent dynamics of the mangrove habitat recognized by air-photograph interpretation. The data shows that mean tide level rose between the late 1960's and the mid-1970's and has been stable since that time (Fig. 4). The trend of the movement of the mangrove forest observed in the aerial photographs was synchronized with that of the change in mean tide level, though the seaward margin of the mangrove forest did not retreat despite of the relative sea-level rise between the late 1960's and the mid-1970's. These facts indicate that the dynamics of the mangrove forest have been mostly controlled by the relative sea-level changes, while the forest has the ability to maintain its

habitat up to a certain rise in sea-level.

Fig. 5 shows a relative sea-level changes curve and a schematic representation of the habitat movement of the vegetation on the alluvial plain at the mouth of the Urauchi during the last 1,300+ years estimated from radiocarbon ages, geomorphic and sedimentologic evidences and air-photograph interpretation.

VI. Conclusion

The mangrove forest at the mouth of the Urauchi has moved its location dynamically in response to relative sea-level changes. During the rising sea-level phase between 2,000 yrs BP and 1,000 yrs BP, the mangrove forest retreated landward. A relative sea-level fall which occurred about 1,000 yrs BP, apparently caused by seismic uplift, generated a rapid seaward movement of the landward margin of the mangrove forest. Air-photograph interpretation showed that the relative sea-level rise which occurred between the late 1960's and the mid-1970's caused a rapid landward expansion of mangrove forests.

In addition, the mangrove forest was found to have a latent ability to maintain both its position and habitat. The seaward margin of the mangrove forest did not retreat despite of the relative sea-level rise between the late 1960's and the mid-1970's. The mangrove forest has maintained its habitat by accumulating mangrove peat to the relative sea-level rise after 260 yrs BP.

In subsequent studies, it will be necessary to clarify the developmental processes of mangrove habitats before 1,300 yrs BP and to monitor the movement of mangrove forests in various type of site environments. These data will be useful for

predicting the effects of the various environmental changes such as sea-level changes and sediment supply fluctuations.

Acknowledgments

This study was conducted as a part of a mangrove research project supported by a grant from Science and Technology Agency of Japanese government. The authors are grateful to Professor Y. Kohda of the University of the Ryukyus for arranging the project, Professor O. Yamada of the Kyoto Sangyo University for undertaking the radiocarbon dating, and Professor N.L.R. Tate of Tohoku Gakuin University for revising English.

(Accepted November 22, 1994)

References

- Berner, R.A. (1970): Sedimentary pyrite formation. *Amer. Jour. Sci.*, **268**, 1-23.
- Fujimoto, K. (1990): Reexamination of Late Holocene sea-level changes in Japan. *Sci. Repts. Tohoku Univ., 7th ser. (Geogr.)*, **40**, 37-70.
- Fujimoto, K. and T. Miyagi (1993): Development process of tidal-flat type mangrove habitats and their zonation in the Pacific Ocean: A geomorphological study. *Vegetatio*, **106**, 137-146.
- Kawana, T. (1987): Holocene crustal movements in and around the Sekisei Lagoon area of the South Ryukyu Islands. *The Earth Monthly*, **9**, 129-134.
- Kikuchi, T., T. Tamura, H. Makita and T. Miyagi (1978): Arrangement of swamp forests and landforms of the alluvial plain in the lower Nakama River, Iriomote Island, Ryukyu Archipelago, Japan: I. Mangrove swamp. *Ann. Tohoku Geogr. Assoc.*, **30**, 71-81.
- Kikuchi, T., T. Tamura, H. Makita and T. Miyagi (1980): Arrangement of swamp for-

- ests and landforms of the alluvial plain in the lower Nakama River, Iriomote Island, Ryukyu Archipelago, Japan: II. *Barringtonia racemosa* forests and *Pandanus tectorius* thickets. *Ann. Tohoku Geogr. Assoc.*, **32**, 185-193.
- Komiyama, A., H. Moriya and K. Ogino (1989): A quantitative analysis of root system of mangrove tree species in Iriomote Island, southern Japan. *Galaxea*, **8**, 89-96.
- Miyagi, T., E. Melana, S. Hirano, K. Fujimoto and K. Ajiki (1989): The development of mangrove habitat and their landform condition in the Luzon Island, Philippines. Miyagi, T. and Maximino, G. eds.: *The processes of mangrove habitat development and their destruction by human impacts in Luzon Island, Philippines*. Pub. grants of APIC, 1-16.
- Nakai, N., T. Ohta, H. Fujisawa and M. Toshida (1982): Paleoclimatic and sea-level changes deduced from organic carbon ratios, C/N ratios and pyrite contents of cored sediments from Nagoya harbor, Japan. *The Quaternary Research*, Japan, **21**, 167-177.
- Nakasuga, T. (1979): Analysis of the mangrove stand. *Sci. Bull. Coll. Agr. Univ. Ryukyus*, **26**, 413-519.
- Nakata, T. (1990): Tsunami boulders produced by submarine earthquake. The research group on coral reef regions in Japan ed.: *Atsui shizen: Sangosho no kankyoshi (Tropics in Japan: Natural history of coral islands)*, 83-98, Kokonshoin, 372 p.
- Ninomiya, I., A. Tsujita and K. Ogino (1989): Root development in relation to substratum of mangrove forest, Iriomote. *Galaxea*, **8**, 97-104.
- Shiragami, H. (1985): The structure of alluvial formations deduced from FeS₂ contents of cored sediments taken from Hiroshima Plain. *Geographical Review of Japan*, **58A**, 631-644.
- Thom, B.G., L.D. Wright and J.M. Coleman (1975): Mangrove ecology and deltaic-estuarine geomorphology: Cambridge Gulf-Ord River, Western Australia. *J. Ecol.*, **63**, 203-232.
- Woodroffe, C.N., J. Chappell, B.G. Thom and E. Wallensky (1989): Depositional model of a macrotidal estuary and floodplain, South Alligator River, Northern Australia. *Sedimentology*, **36**, 737-756.

西表島浦内川河口部における相対的海水準変動に伴う

マングローブ林の立地形成過程

藤 本 潔*・大 貫 靖 浩**

西表島北西部の浦内川河口部マングローブ林において、マングローブ立地の形成過程を地形学的に明らかにするために、地形断面測量、堆積構造調査、堆積物の¹⁴C年代測定、およびFeS₂含有量分析を行った。また、1963年、1977年、および1986年の3時点で撮影された空中写真を用い、近年のマングローブ林の動態を把握した。

その結果、過去1,300年間に、このマングローブ林は、その成立場所を大きく変動させながら現在に至っていることが明らかになった。特に、1,000 yrs BP頃にはマングローブ林の内陸側林縁部が急速に淡水湿地化していることから、この時期に急激に相対的海面低下が起こった可能性が指摘された。

* 森林総合研究所

** 森林総合研究所九州支所

海面上昇期にあたる 2,000~1,000 yrs BP の間には、マングローブ林全体が内陸側へ後退した。この事実は、ミクロネシアやフィリピンのマングローブ林が、過去 2000 年間の海面上昇期に、海面上昇と共にマングローブ泥炭を蓄積することによって、その成立場所をほとんど移動させることなく現在に至った事実 (Fujimoto and Miyagi, 1993) とは大きく異なる。すなわち、西表島のマングローブ林は、熱帯地域のそれに比べ、海面上昇の影響がより顕著に現れると考えられた。しかし、1960 年代後半から 1970 年代半ばにかけて起こった 20 cm 程度の相対的な海面上昇に対しては、内陸側への進入は見られるものの海側林縁部の後退は認められないこと、また、260 yrs BP 以降の相対的な海面上昇に対してマングローブ泥炭を蓄積することによって立地を維持してきた事実が認められることから、ある程度の海面上昇に対しては立地を維持し得る潜在力をもつことが明らかになった。