

RADIOCARBON AGES AND ISOTOPE FRACTIONATIONS OF BEACHROCK SAMPLES COLLECTED FROM THE NANSEI ISLANDS, SOUTHWESTERN JAPAN

Kunio Omoto

Department of Geography, College of Humanities and Sciences, Nihon University, 24-40, 3 Chome, Sakurajosui, Setagaya-ku, Tokyo 156-8550, Japan. Email: omoto@chs.nihon-u.ac.jp.

ABSTRACT. A total of 294 beachrock samples were collected from 116 sites on 15 islands in the Nansei Islands chain, southwestern Japan, and were radiocarbon dated. The beachrocks began to form at about 6900 BP and some are still under development in the islands. Values of isotope fractionations of different materials making up the beachrocks ranged between +9.4‰ and –5.7‰. Isotope fractionations outside the range of 0 ± 2‰ suggest that these beachrocks were strongly influenced by underground water and running freshwater when they were cemented. The sea level during the late Holocene has remained the same for at least the past 5000 yr, except for several uplifted coasts.

INTRODUCTION

Beachrocks are observed frequently on the tropical and subtropical sandy beaches where the soft beach sediments, including fossil shells, fragments of corals, and other biocarbonates, are well cemented within the intertidal zone by calcium carbonate (Figure 1). Therefore, they are not only good indicators of the past sea level, but they also provide good sample material for radiocarbon dating. The beachrocks occur in thin beds dipping seaward at less than 15 degrees.

Figure 1 Beachrock observed at Tuha, Ohgimi Village, Okinawa Prefecture, central part of the Nansei Islands

The Nansei Islands (Ryukyu Retto) are a chain of islands consisting of more than 300 smaller islands between Kyusyu and Taiwan, extending about 1200 km parallel to the eastern edge of the Asian plate. The Nansei Islands are divided into 3 major island groups from north to south: the Amami Islands, Okinawa Islands, and Sakishima Islands, respectively (Figure 2). They are subject to the influence of Kuro Shio (warm current), which originates from the North Equatorial Current, forming many coral reefs.

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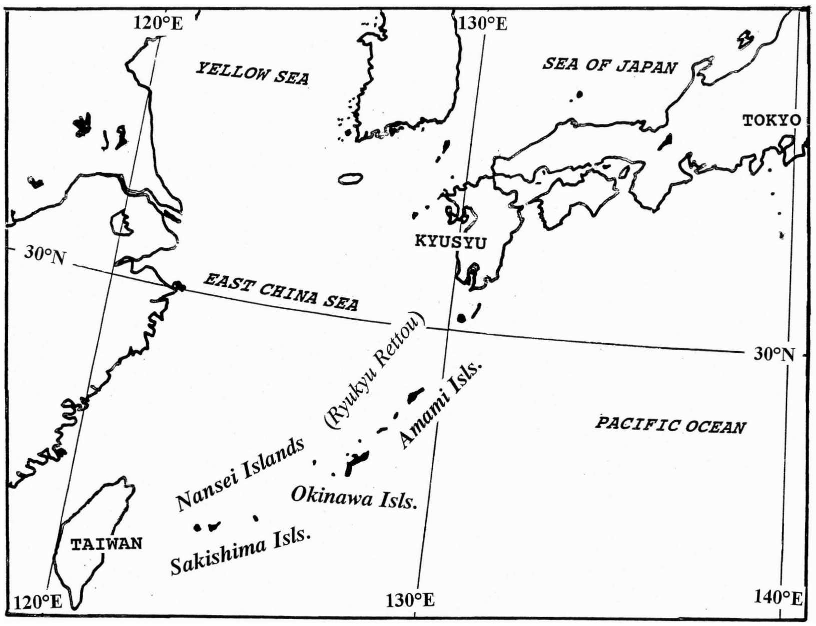

Figure 2 Index map of the surveyed islands

These islands consist of Paleozoic rocks, metamorphic rocks, volcanic rocks, and Quaternary raised coral limestones (Kawana 1988). The coastal geomorphology is characterized most often by rocky coasts, but in other places marine terraces develop at several levels which indicate evidence of Pleistocene or Holocene emergence. On the sandy beaches of the Nansei Islands, beachrocks are observed frequently within the range of the intertidal zone.

Yonetani (1963) was the first geographer to introduce the term "beachrock" in Japan. Since that time, many geomorphologists and geologists have shown interest in the distribution and characteristics of beachrocks found in the Nansei Islands. A number of beachrocks have been ^{14}C dated by numerous scientists (Omoto 1976; Omoto et al. 1976; Takahashi and Koba 1980; Kawana 1981; Ota et al. 1985; Kawana and Pirazzoli 1985; Tanaka 1986, 1990; and others). Takahashi and Koba (1980) and Tanaka (1986) attempted to compile statistics of them. However, great portions of them have not yet been corrected by isotope fractionation. Therefore, the author could not include a great deal of the ^{14}C dates reported previously.

The ^{14}C ages of beachrock samples collected from the Nansei Islands have previously been reported by the author without isotope fractionations (Omoto 1994–2001a), and later with isotope fractionations (Omoto 2001b–2003b; Omoto et al. 2003; Omoto 2003c, 2004).

Locations of each sampling site were determined either by GPS or calculations based on a 1:25,000 scale map. Elevations of each sampling site of beachrocks, beach profiles, and local tide changes were measured with a Nikon Laser Level or a Nikon Total Station. ^{14}C datings and analyses of isotope fractionations for beachrock samples were carried out by the author at the Radiocarbon Dating Laboratory of Nihon University. ^{14}C dates have been corrected for isotope fractionations ($\delta^{13}C$), then 400 yr (Stuiver and Braziunas 1993) were subtracted due to the ocean reservoir effect.

The aim of this paper is to determine the age of beachrock formations and to reconstruct the late Holocene sea-level changes and/or tectonic movements in the Nansei Islands. Another purpose is to identify the origin of calcium carbonate which cemented soft marine carbonates to beachrock, based on the isotope analysis. In order to accomplish these aims, 294 beachrock samples were collected from 116 sampling sites on 15 islands in the Nansei Islands.

COLLECTION OF BEACHROCK SAMPLES AND RESULT OF ISOTOPE ANALYSES

Samples Collected from Amami Islands

The Amami Islands are located in the northern part of the Nansei Islands. A total of 87 beachrock samples were collected from 4 islands, namely Amami Oshima Island (28°20′N, 129°30′E), Tokuno Island (27°45′N, 128°58′E), Okinoerabu Island (27°22′N, 128°35′E), and Yoron Island (27°02′N, 128°26′E). They consist of 41 calcarenite samples, 26 fossil coral samples, and 20 fossil shells (Table 1).

Table 1 The items of beachrocks collected from the Nansei Islands. Data were compiled from Omoto (1994–2004).

Island name	Calcarenite[a]	Coral	Shell	Total	Nr of sites
Amami Islands					
Amami-Oshima Island	11	8	5	24	10
Tokuno Island	6	4	6	16	4
Okinoerabu Island	11	10	5	26	11
Yoron Island	13	4	4	21	12
Subtotal	**41**	**26**	**20**	**87**	**37**
Okinawa Islands					
Okinawa Island	4	12	15	31	18
Izena Island	3	1	3	7	4
Aguni Island	4	1	1	6	4
Ie Island	14	2	11	27	6
Zamani Island	2	1	10	13	6
Kume Island	15	10	10	35	4
Subtotal	**42**	**27**	**50**	**119**	**42**
Sakishima Islands					
Iriomote Island	5	3	4	12	5
Ishigaki Island	9	13	9	31	12
Miyako Island	11	5	9	25	14
Yonakuni Island	3	2	2	7	3
Hateruma Island	3	2	8	13	3
Subtotal	**31**	**25**	**32**	**88**	**37**
Total	**114**	**78**	**102**	**294**	**116**

[a]Calcirudite samples are included.

All samples were ^{14}C dated and reported without isotope correction (Omoto 1999d, 1999f, 2000a, 2000d). Therefore, the values of the isotope fractionations of the 87 samples gave later measurements and ranged between 4.77‰ and –3.28‰ (Table 2).

Table 2 Statistical data of isotope fractionations of beachrocks collected from the Nansei Islands. Data were compiled from Omoto (1994–2004).

	Calcarenite[a]				Coral				Shell				Total		
Island	nr	max	min	aver	nr	max	min	aver	nr	max	min	aver	max	min	aver
Amami Islands															
Amami-Oshima Island	11	2.05	–2.06	0.26	8	1.79	–0.15	0.74	5	1.51	–0.02	1.02	2.05	–2.06	0.45
Tokuno Island	6	2.62	–3.28	1.26	4	1.68	1.03	1.3	6	4.67	2.74	3.67	4.67	–3.28	2.16
Okinoerabu Island	11	3.18	0.15	2.34	10	4.28	–0.94	2.11	5	4.77	3.33	4	4.77	–0.94	2.57
Yoron Island	13	3.82	1.52	2.62	4	3.09	1.34	2.28	4	4.27	2.77	3.42	4.27	1.34	2.71
Subtotal	**41**	**3.82**	**–3.28**	**1.71**	**26**	**4.28**	**–0.94**	**1.54**	**20**	**4.77**	**–0.02**	**3.04**	**4.77**	**–3.28**	**1.96**
Okinawa Islands															
Okinawa Island	4	5.63	1.78	3.07	12	2.48	–5.97	–0.61	15	4.06	–4.67	0.63	1.42	–5.15	–0.54
Izena Island	3	1.59	1.18	1.32	1	–0.16	–0.16	–0.16	2	3.42	2.72	3.07	3.42	–0.16	1.66
Aguni Island	3	1.42	0.53	1.02	1	–3.49	–3.49	–3.49	3	1.15	–5.15	–1.13	6.03	0.15	2.28
Ie Island	14	2.89	0.15	1.9	2	3.51	0.63	2.07	11	6.03	0.95	2.79	5.63	–5.97	0.46
Zamani Island	2	3.15	2.28	2.72	1	2.74	2.74	2.74	10	5.07	1.18	3.32	5.07	1.18	3.18
Kume Island	15	3.42	0.17	1.82	10	2.31	–2.08	0.44	10	3.37	0.52	2.1	3.43	–2.08	1.49
Subtotal	**41**	**5.63**	**0.15**	**1.386**	**27**	**3.51**	**–5.97**	**0.001**	**51**	**6.03**	**–5.15**	**1.554**	**6.03**	**–5.97**	**1.46**
Sakishima Islands															
Miyako Island	11	4.72	–2.54	1.46	5	2.66	0.42	1.21	9	5.41	1.36	3.44	5.41	–2.54	2.12
Ishigaki Island	9	9.4	–2.54	5.39	13	7.04	–1.1	2.14	9	9.4	1.92	5.07	9.4	–1.1	4.03
Iriomote Island	5	8.4	–0.37	3.28	3	2.44	0.51	1.68	4	8.37	3.5	5.46	8.4	–0.37	3.93
Hateruma Island	3	3.3	2.48	2.83	2	1.81	1.4	1.61	8	4.45	2.09	3.48	4.45	1.4	3.04
Yonakuni Island	3	2.35	0.92	3.33	2	3.57	0.1	1.79	2	6.7	2.3	4.5	6.7	0.1	2.37
Subtotal	**31**	**9.4**	**–2.54**	**2.948**	**25**	**7.04**	**–1.1**	**1.817**	**32**	**9.4**	**1.36**	**4.879**	**9.4**	**–2.54**	**3.11**
Total	**113**	**9.4**	**–3.28**	**1.71**	**78**	**7.04**	**–5.97**	**1.54**	**103**	**9.4**	**–5.15**	**3.04**	**9.4**	**–5.97**	**2.112**

[a] Includes calcirudite.

Samples Collected from Okinawa Islands

The Okinawa Islands are located in the middle part of the Nansei Islands. A total of 119 beachrock samples were collected from 39 sites among 5 islands, namely, Okinawa Island (26°30′N, 128°00′E), Aguni Island (26°35′N, 127°14′E), Ie Island (26°43′N, 127°47′E), Zamami Island (26°13′N, 127°19′E), and Kume Island (26°20′N, 126°47′E). They consist of 42 calcarenite samples, 27 fossil coral samples, and 50 fossil shells (Table 1). An additional 7 dates (Ushikubo 2002) obtained from Izena Island (26°56′N, 127°56′E) were added to this paper. They consist of 3 calcarenites, 1 fossil coral, and 3 fossil shell samples.

The isotope fractionations of the 119 samples ranged between 6.03‰ and –5.97‰ (Table 2).

Samples Collected from Sakishima Islands

The Sakishima Islands are located in the southernmost part of the Nansei Islands. A total of 36 newly analyzed beachrock samples were added to the former report (Omoto 2001). A total of 88 beachrock samples were collected from Iriomote Island (24°20′N, 123°50′E), Ishigaki Island (24°24′N, 124°11′E), Miyako Island (24°27′N, 125°21′E), Yonakuni Island (24°27′N, 123°00′E), and Hateruma Island (24°03′N, 123°47′E). They consist of 31 calcarenite samples, 25 fossil coral samples, and 32 fossil shells (Table 1).

The isotope fractionations of the 88 samples ranged between 9.40‰ and –2.54‰ (Table 2).

DISCUSSION

Isotope Fractionations of Beachrock

Isotope fractionations of 294 beachrocks ranged between 9.40‰ and –5.97‰ (Table 2). The average value of isotope fractionation over the 15 Nansei Islands was 1.95‰. It is noticeable that the average values of isotope fractionations of 11 islands (191 samples) were outside the range of 0 ± 2‰ (Table 2). In the Amami Islands, the value of isotope fractionation decreases gradually from the southern Yoron Island (2.71‰) to the northern Amami Oshima Island (0.45‰).

The maximum and minimum values of isotope fractionation for calcarenite samples in the Nansei Islands were 9.40‰ and –3.28‰, respectively, while the average value was 1.71‰ (Table 2). The maximum and minimum values of isotope fractionation for coral samples were 7.04‰ and –5.97‰, respectively, and the average value was 1.54‰. In addition, the maximum, minimum, and average values of isotope fractionation for fossil shell samples were 9.40‰, –5.15‰, and 3.04‰, respectively (Table 2).

Figure 3 shows the relationship between ^{14}C ages and isotope fractionations of beachrocks collected from the Nansei Islands.

Formative Ages of Beachrocks

The sample materials used in ^{14}C dating are primarily marine carbonates and organisms. Marine organisms such as corals and shells embedded in the beach materials were carried from their original habitats to the intertidal zone by ocean waves, deposited on the beach, cemented by calcium carbonate and then became beachrock. Therefore, the age would indicate only the time of death of the marine organisms, not the formative age of the beachrock.

Kawana and Pirazzoli (1984) posited that the *Tridacna squamosa* (Lamarck) in the beachrocks collected from Miyako Island is not much older than the formation of the beachrocks themselves. The

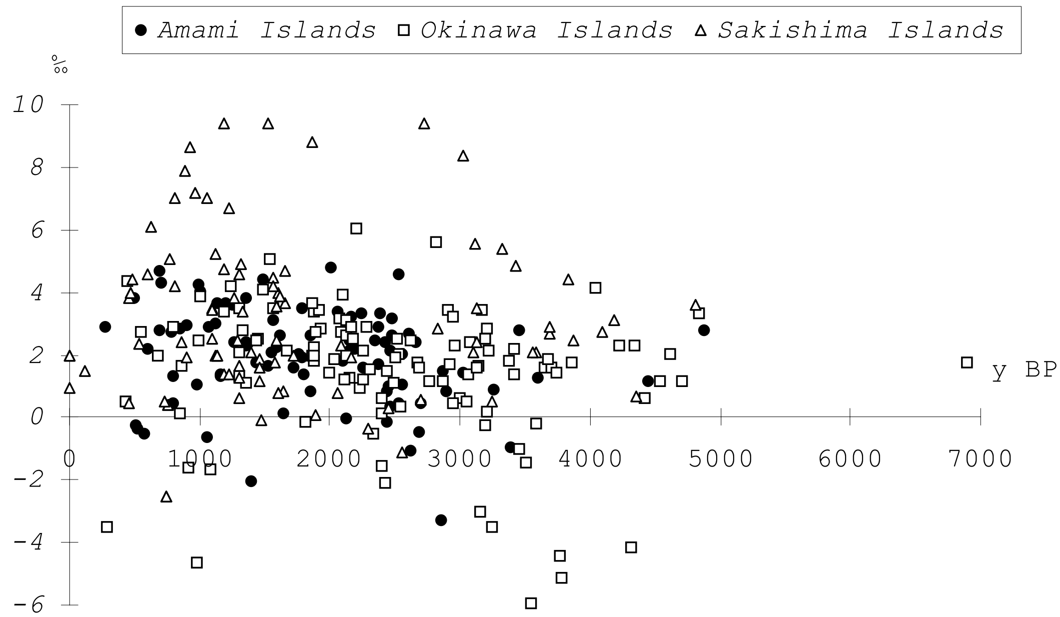

Figure 3 ^{14}C ages versus isotope fractionations of beachrocks collected from the Nansei Islands. Data were compiled from Omoto (1994–2004).

cemented strata of beachrocks have the same seaward slope as the nearby beach. The landward slabs are considered to have been formed earlier than the seaward slabs. Therefore, samples for ^{14}C datings were often collected from the landward slabs. When the seaward width of the beachrock exceeded 50 m, not only the top layer of the beachrock but also the middle and seaward specimens were collected to check the growth rate of the beachrock. Kawana and Pirazzoli (1984) reported that the seaward growth of beachrock was 4.2 cm/yr at Miyako Island. Omoto (1999c) measured the vertical growth rate of beachrock at Agui Island and recorded an average growth rate of 0.15 cm/yr. Based on these figures, beachrocks formed within a rather short timespan.

The author also tried to collect 3 different types of sample materials—fossil shell, fossil coral, and calcarenite (or calcirudite) samples—from each sampling site in order to compare their ages. Whenever the ^{14}C ages coincided within the range of the ±3 σ error, the author used whole data to estimate the age of beachrock formation. But the author excluded an age from the discussion when it differed greatly from other dates or outside the range of the ±3 σ error.

Whole ^{14}C dates of beachrock samples collected from the Nansei Islands are shown in Figure 4. According to the ^{14}C dates obtained from the Amami Islands, the beachrock began to form at about 4500 BP and the last formation was ~400 BP. The ages of beachrock formation differs according to the islands surveyed; however, beachrocks formed continuously between 3600 and 400 BP.

The ^{14}C age of 6890 ± 90 BP given to a calcarenite sample collected from Bise Point, west coast of Okinawa Island, was the oldest age among the 294 beachrock samples collected from the Nansei Islands (Omoto et al. 2003). The ^{14}C dates obtained indicate that beachrock from the Okinawa Islands began to form at ~6900 BP and the last formation was approximately 400 BP. The ages of beachrock formation differ by surveyed islands, but beachrocks in the Okinawa Islands were formed continuously between 4800 BP and ~400 BP.

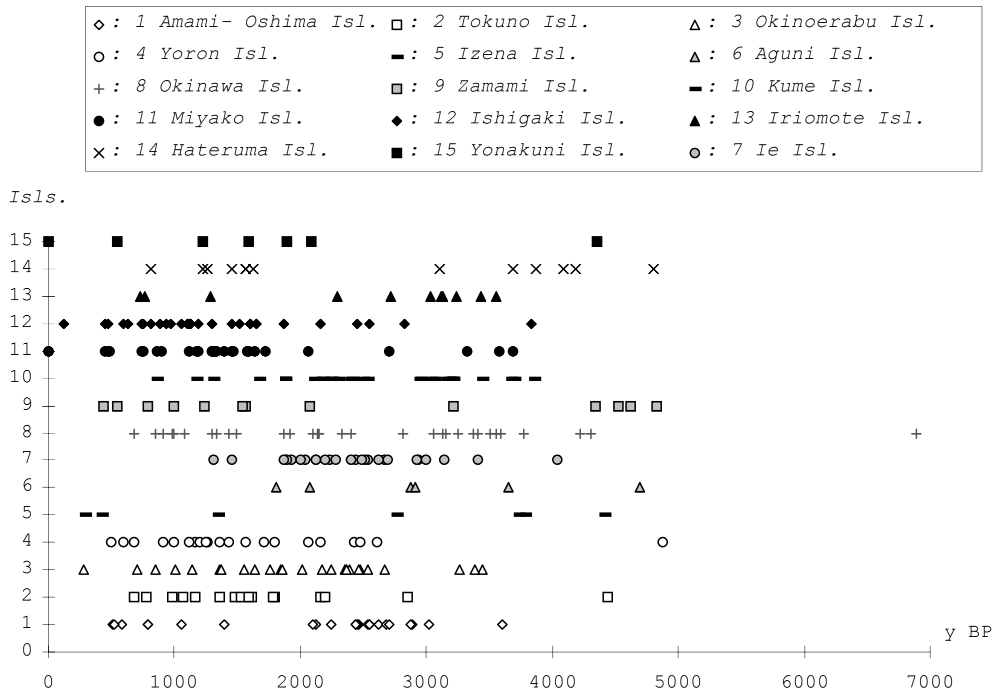

Figure 4 Correlation of ^{14}C ages of beachrocks collected from the Nansei Islands. Data were compiled from Omoto (1994–2004). The islands expressed with figures from 1 to 4, 5 to 10, and the figures from 11 to 15 belong to the Amami, Okinawa, and Sakishima Islands group, respectively.

The beachrocks began to form at 4800 BP in the Sakishima Islands, but there was an intermittent period after which beachrock formations have continued since 4300 BP.

In the Nansei Islands, beachrock began to form at about 6900 BP and is still forming now on some islands. Several time differences among the islands surveyed may be seen in Figure 4.

Late Holocene Sea-Level Change

The marine terrace surfaces that develop at several levels provide good evidence for the emergence of an island. In the Nansei Islands, other researchers have reported on the distribution, elevations, formative ages, Holocene sea level, and tectonic movements of Tokuno Island, Okinoerabu Island, Okinawa Island, Aguni Island, Ie Island, Kume Island, Miyako Island, Hateruma Island, and Yonakuni Island (Koba et al. 1982; Koba 1983; Kawana and Pirazzoli 1984; Kawana 1985; Kan et al. 1991; and others). However, marine terrace surfaces develop poorly in Amami Oshima Island, Zamami Island, Ishigaki Island, and Iriomote Island. The former islands indicate that they have been under active tectonic movements, while the later islands were under a rather stable or submerged environment at least through the Holocene period. Numerous geomorphologists and geologists have reported on the neotectonic movements in the Nansei Islands (Konishi et al. 1974; Nakata et al. 1979; Ota and Hori 1980; Ota et al. 1982; Kawana 1985; Ota and Omura 1992; and others). The results were compiled and summarized recently by Machida et al. (2001).

Beachrock is believed to have formed within the intertidal zone, and is, therefore, a good indication of the past sea level. By using the ^{14}C age and elevation of beachrock, it is possible to reconstruct past sea-level change. Almost all of the beachrocks observed in the surveyed area were situated within a range corresponding to the present intertidal zone (about ±1 m). But in several islands such as Okinoerabu Island, the west coast of Okinawa Island, Ie Island, the southeast coast of Kume Island, and Hateruma Island, beachrocks were obvious on a higher place above the present high tide level. These facts indicate that the islands have been uplifted by local tectonic movements (Omoto 1999c, 1999d, 2000c, 2003a, 2003b; Omoto et al. 2003), otherwise these beachrocks were formed in a different environment.

The latter cause may be explained as follows: Beach materials were influenced by freshwater or underground water, the calcium carbonate of which cemented the soft beach materials and then formed beachrock (Omoto 2000c, 2003a).

Figure 5 shows the relationship between ^{14}C dates and elevations of whole beachrock samples collected from the Nansei Islands. The sea level seems higher than the present sea level, but we must consider the amount of tide change reaching 1 m.

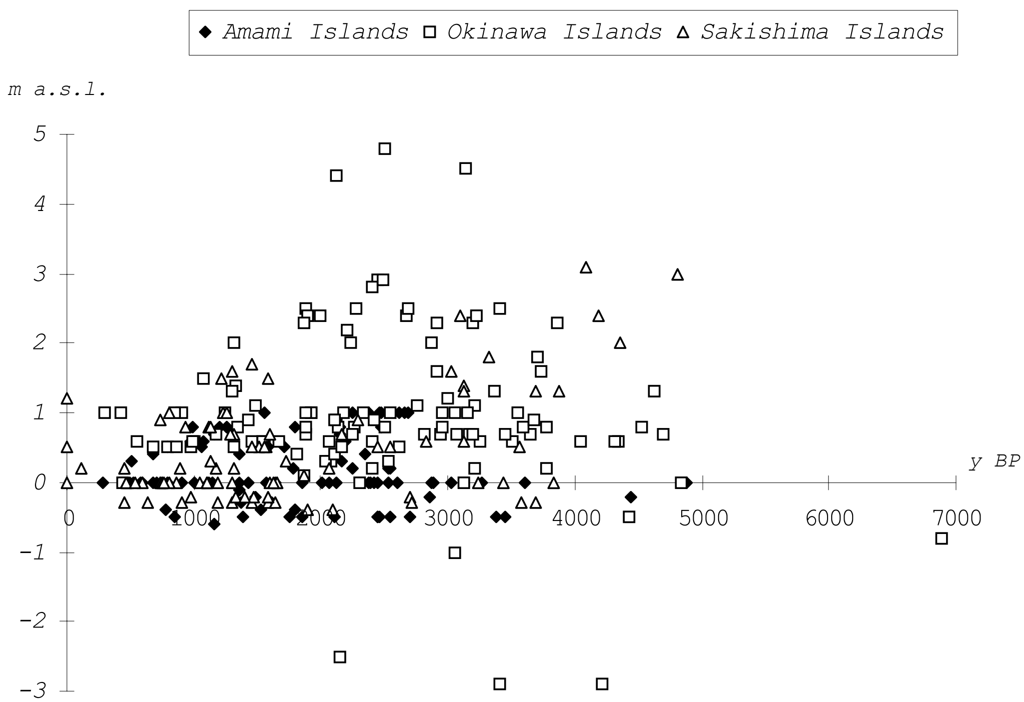

Figure 5 ^{14}C ages versus elevations of beachrocks collected from the Nansei Islands. Data were compiled from Omoto (1994–2004).

Based on these pieces of evidence, the past sea level that existed was similar to the present one; that is, it has maintained nearly the same level since at least 5000 BP, except for several uplifted coasts.

Origin of Calcium Carbonate Cemented Beachrock

Since Russel (1962 and 1963) suggested the origin of calcium carbonate came from underground water, many scientists have tried to identify the origin of the calcium carbonate that cemented beach sediments and formed beachrock. Yet, no one has succeeded in obtaining indisputable evidence in spite of carrying out several experiments and analyses (Yonetani 1964, 1966; Takenaga 1965; Hori et al. 1972, 1973; Stoddart and Cann 1965). The author proposes that the isotope fractionation of beachrock may give us a key to solving the problem. That is, if the calcium carbonate originates in seawater, it must indicate nearly the same value of marine organisms. If it differs from the average value of marine organisms, then the origin of calcium carbonate is underground water or freshwater. Therefore, the figure of isotope fractionation is a key in solving the origin of calcium carbonates.

The average value of isotope fractionation ($\delta^{13}C$) of marine organisms and carbonates has been reported by Vogel and Ehhalt (1963), Stuiver and Polach (1977), Geyh and Schleicher (1990), and Stuiver and Braziunas (1993). Geyh and Schleicher (1990) reported that the value was within the range of 0 ± 2‰. Although the average isotope fractionation of beachrock samples collected from the Nansei Islands was 1.95‰, the average isotope fractionations of 11 islands were outside the range of 0 ± 2‰ (upper limitation of marine organisms and biocabonate). In addition, the maximum value of isotope fractionations ($\delta^{13}C$) showed +9.40‰ (Table 2). The values for the figure are 4 times larger than those reported by the above authors.

The author considers that the materials making up the beachrocks were obviously affected by different origins of calcium carbonate provided when they were cemented in the intertidal zone. One of the pieces of evidence is the influence of freshwater and underground water. The author often observed that the sand beaches where beachrocks developed were eroded by several streams and spring water flows at low tide level. Further evidence is the existence of submarine limestone caves along the islands. The caves were formed when the sea level dropped during the last glaciations. In such caves, running water flowed down and became underground water. When the waters reached the saltwater area, upwelling might have occurred. Thus, they influenced the growth of marine inhabitants nearby. However, the author needs further evidence to demonstrate the relationship as to the cause of higher isotope fractionation.

SUMMARY

A total of 294 beachrock samples were collected from 116 sites on 15 islands in the Nansei Islands chain (Table 1). The samples were ^{14}C dated and their isotope fractionations were measured (Table 2). The result of this study is summarized as following:

1. Isotope fractionation ($\delta^{13}C$) of all beachrock samples range between +9.40‰ and –5.97‰, with an average of 1.95‰.
2. Figures for isotope fractionation decrease from the southern Sakishima Islands to the middle Okinawa Islands. In Amami Islands, the decrease is gradual from the southern Yoron Island towards the northern Amami Oshima Island.
3. Among 11 islands, the average value of isotope fractionation was outside the range of 0 ± 2‰. This fact suggests that when beachrock was being formed, beach sediments were influenced by an obviously different origin of calcium carbonate, from underground water or freshwater.
4. In the Nansei Islands, beachrocks were formed within the range of the intertidal zone between approximately 6900 BP and the present day. However, several time differences in the formative period of beachrocks exist among the islands surveyed.
5. In the tectonically stable islands, there is no evidence indicating prominent upheaval throughout the late Holocene. Therefore, the elevations and ^{14}C ages of the beachrock samples in those islands would indicate past sea level change. Judging from the evidence, the late Holocene sea level has remained similar to the present one since at least the past 5000 BP, except for several uplifted coasts.

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