2009-12-21

Galaxea, Journal of Coral Reef Studies 11: 1–9 (2009)

Original paper

Calibrated radiocarbon ages of beach rock samples and late Holocene sea-level change of Amami Islands, southwest Japan

Kunio OMOTO*

Department of Geography, College of Humanities and Sciences, Nihon University, Setagaya-ku, Tokyo 156–8550, Japan

* Corresponding author: K. Omoto
E-mail: omoto@chs.nihon-u.ac.jp

Communicated by Makoto Tsuchiya

Abstract A total of 87 beach rock samples were collected from 37 sites of Amami Islands in order to determine formative ages of beach rocks on Amami Islands, and to clarify the sea-level change during the late Holocene period. Beach rocks began to form 5,720 yrs cal BP on Yoron Island at first, and formed continuously between 4,050 yrs cal BP and 380 yrs cal BP on the sandy coasts of Amami Islands. Relative sea-levels during the late Holocene period on Yoron Island and Okinoerabu Island were slightly higher than those of the present sea-level. Geomorphic evidences indicate that the islands have probably uplifted by earthquakes occurred along the subduction zone of Eurasian Plate. However they have remained similar to the present since at least the past 4,000 years at Amami-Oshima Island.

Keywords beach rock, Amami-Oshima Island, Tokuno Island, Okinoerabu Island, Yoron Island, sea-level change, Holocene

Introduction

Beach rock provides a good recorder of the past sea-level as it is formed within the inter-tidal zone. And it often contain fossil shells, fragments of coral, foraminifera, diatoms and other marine biocarbonates providing good sample materials for ^{14}C dating. The Amami Islands (southern part of Satsunan Retto) are a chain of islands located between Kyusyu Island and Okinawa Island and continue about 450 km parallel to the eastern edge of the Eurasian Plate. They consist of four major islands from south to north: Yoron Island, Okinoerabu Island, Tokuno Island and Amami-Oshima Island respectively (Figs. 1 and 2).

The coastal geomorphology is characterized most often by rocky coasts where marine terraces develop at several levels, and which provide evidence of the Pleistocene or Holocene emergence. Beach rocks often develop on the sandy coasts of Amami Islands. Since Yonetani (1963, 1964) reported beach rocks develop on Amami Islands, many geomorphlogists and geologists have investigated and described beach rock distributions and characteristics.

The ^{14}C ages of beach rock samples collected from Amami Islands have previously been reported without isotope fractionation ($\delta^{13}C$). Isotope fractionation is essential in obtaining correct ^{14}C ages as recommended by Stuiver and Polach (1977). Therefore, the author could not include the ^{14}C ages reported previously. Omoto (2005a) measured isotope fractionations for the 400 beach

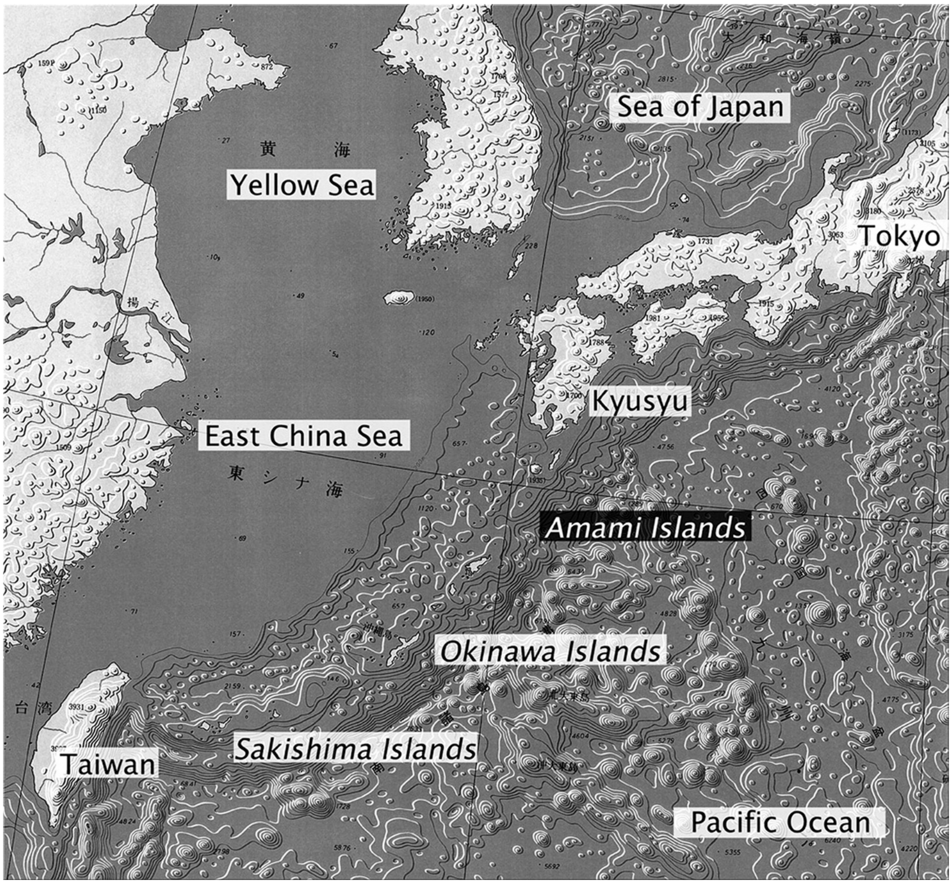

Fig. 1 Location map showing investigated Amami Islands

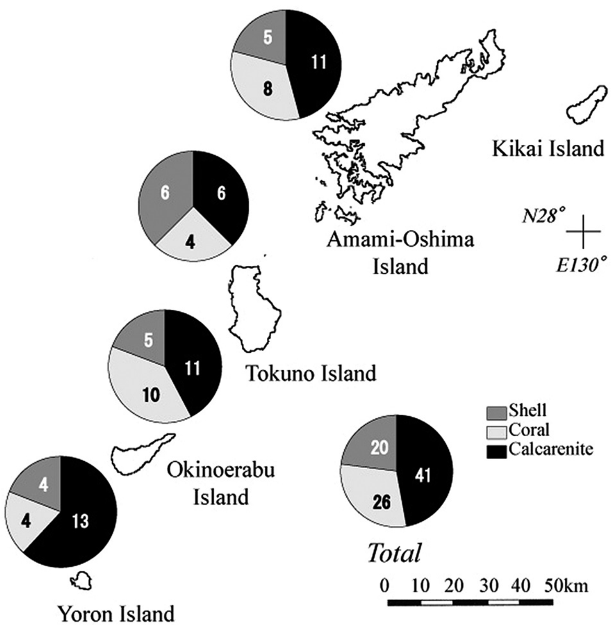

Fig. 2 Four graphs indicate rate of sample materials collected for ^{14}C datings and $\delta^{13}C$ analysis. Data were compiled from Omoto (2005a)

rock samples collcted from the Nansei Islands and obtained conventional ^{14}C ages.

The aim of this paper is to determine the formative periods of beach rocks that developed on the Amami Islands by calibrating ^{14}C ages reported by Omoto (2005a) and reconstructing the late Holocene sea-level change in the Amami Islands.

Materials

Previous studies and collection of samples

Amami-Oshima Island. Amami-Oshima Island is located about 400 km south of Kyusyu Island and covers 712 km^2. Bays, peninsulas and small islands are particularly numerous on the island showing "Ria" coast. Yonetani (1963) investigated beach rock development on Amami-Oshima Island and he found beach rocks on 35 beaches. But the formative ages of the beach rocks remain unknown. Omoto investigated the island and collected beach rock samples from 10 sites however he could not find whole beach rocks from 35 sites described by Yonetani (1963). The sample materials collected consist of 11 calcarenites, 8 fossil corals and 5 fossil shell samples respectively. Elevations of the sampling sites were within a range between −0.5 m and +0.5 m a.s.l.

Tokuno Island. Tokuno Island is located about 30 km southwest of Amami-Oshima Island and has an area of 248 km^2. Shorelines of this island are rather simple compared with Amami-Oshima Island. Marine terraces with high sea-cliffs develop particularly along the west coast. Koba and Takahashi (1975) collected *Hydnophora microconos* (LAMARCK) (TH-084) and *Goniastrea pectinata* Ehrenberg (TH-101) embedded in beach rocks from Kinen. They were located at mean high tide level and slightly higher than mean high tide level respectively. Their ^{14}C ages were 1,655±115 yrs BP and 1,440±115 yrs BP without isotope fractionation (Omoto 1976). Omoto investigated the island and collected 16 beach rock samples from 4 sites. They consist of 6 calcarenites, 4 fossil corals and 6 fossil shell samples. Elevations of the sampling sites were within a range of −0.4 m and +0.7 m a.s.l.

Okinoerabu Island. Okinoerabu Island is located about 30 km southwest of Tokuno Island with an area of 95 km^2. Coastlines of Okinoerabu Island are rather smooth on the southern coast, however small bays and peninsulas develop on the north facing coast. The island consists mainly of Quaternary limestone beds, namely the Ryukyu Limestone Group. Marine terrace development on the island was investigated in detail by Koba (1974) and Koba et al. (1980). The ^{14}C age of beach rock collected from Ohtukan showed 1,265±110 yrs BP (TH-162: *Goniastrea* sp.: 0.6 m a.s.l.) without isotope fractionation (Omoto et al. 1976). Omoto investigated the island and collected 26 beach rocks from 11 sites. They were 11 calcarenites, 10 fossil corals and 5 fossil shell samples. Elevations of the sampling sites were within the range between −0.5 m and +1.0 m a.s.l.

Yoron Island. Yoron Island is located about 30 km southwest of Okinoerabu Island and ca. 20 km to the northern end of Okinawa Island. Its area covers 21 km^2. The coastline of this island is as non-complex as Okinoerabu Island; however it has an embayment opening to the northwest at Chabana. Hori et al. (1972 and 1973) investigated beach rocks in detail and attempted to analyze cementing mechanisms and the process of beach rock formation based on chemical and X-ray analysis of the fabrics. They reported two ^{14}C ages collected from Akazaki (1,030±80 yrs BP) and Kurohana (1,420±80 yrs BP) without isotope fractionation (Hori et al. 1973). Omoto investigated and collected 21 beach rocks from 12 sites. They were 13 calcarenites, 4 fossil corals and 4 fossil shells samples. Elevations of the sampling sites were within a range of −0.6 m and +0.8 m a.s.l. Whole samples collected from Amami Islands are listed in Table 1.

Methods

^{14}C dating and δ^{13}C analysis

Chemical assays for ^{14}C dating were carried out based on the ^{14}C dating manual (Omoto 1993). Fossil coral samples were fresh enough for ^{14}C datings and showed clear grow- ing structure inside. Re-crystallizations and contaminations caused mainly by algae were carefully checked under microscopic observations prior to chemical assay, and unsuitable sample materials were removed. Species of fossil coral samples collected from Amami Islands were *Montipora*, *Goniastrea*, *Platygyra*, *Porites*, and *Acropora* sp. while almost of all shell samples were *Tridacna squamosa*. Calcarenite samples were composed of fine grained fragments of fossil corals, foraminifera, diatoms and other biocarbonates. More than 95% (weight percent) of them were dissolved in hydrochloric acid.

^{14}C datings and δ^{13}C analyses for beach rock samples were carried out at the Radiocarbon Dating Laboratory of Nihon University by the author. The δ^{13}C values of sample materials were measured by IsoPrime mass-spectrometer (Micromass Co. Ltd.). The same carbon dioxide used for β-counting (^{14}C dating) was introduced into the apparatus.

Calibrations of equipment have been carried out by using standard samples of N.B.S., I.A.E.A. and Oztech samples. Standard deviation in δ^{13}C measurement was smaller than 0.05‰. ^{14}C dates have been corrected for isotope fractionations (δ^{13}C). Conventional ^{14}C dates were

2009-12-21

Table 1 Calibrated ^{14}C ages (median values) of beach rock samples collected from Amami Islands. (After Omoto 2005a)

Lab. nr	Material	Elev. (m)	δ ^{13}C ‰	Conv. Age	Cal. Age
Amami-Oshima Island					
NU-1219	Calcarenite	0.5	-0.65	1460±90	1014
NU-1220	*Tridacna sq.*	0.0	1.33	1225±90	777
NU-1221	Calcarenite	0.0	1.28	4030±85	4052
NU-1222	Calcarenite	0.3	-0.26	910±65	523
NU-1223	*Montipora* sp.	0.0	0.44	1210±65	759
NU-1224	Calcarenite	0.0	-0.53	980±65	573
NU-1225	*Tridacna sq.*	0.0	-0.02	2540±80	2204
NU-1226	*Goniastrea* sp.	1.0	-1.09	3010±80	2792
NU-1227	Calcarenite	0.2	2.05	3000±80	2781
NU-1228	Coral	0.1	1.56	2690±80	2408
NU-1229	Coral	0.2	0.45	2950±85	2721
NU-1230	*Cyphastrea* sp	-0.5	0.36	2880±85	2623
NU-1231	Calcarenite	0.0	1.06	2980±80	2758
NU-1232	Coral	0.0	1.79	2540±80	2204
NU-1233	Calcarenite	-0.5	-2.06	1770±80	1323
NU-1234	Calcarenite	0.0	0.82	3320±80	3168
NU-1235	*Tridacna sq.*	0.0	1.42	3460±85	3338
NU-1236	*Tridacna sq.*	0.0	1.51	3310±85	3154
NU-1237	Calcarenite	0.6	1	2880±80	2625
NU-1238	*Montipora* sp.	-0.5	-0.15	2850±80	2590
NU-1239	*Tridacna* sq.	0.6	0.85	2870±80	2613
NU-1240	Calcirudite	0.0	-0.36	930±65	538
NU-1241	Calcarenite	-0.5	0.48	3120±85	2912
Tokuno Island					
NU-1172	Calcarenite	-0.2	-3.28	3210±75	3024
NU-1173	*Tridacna* sq.	-0.2	4.43	1970±65	1526
NU-1174	*Polites* sp.	-0.2	1.14	4870±85	5163
NU-1175	*Tridacna* sq.	-0.4	2.74	1240±65	783
NU-1176	*Polites* sp.	-0.4	1.66	1970±65	1526
NU-1177	Calcarenite	-0.4	1.39	2230±65	1831
NU-1178	Calcarenite	0.7	2.12	2600±75	2272
NU-1180	Calcarenite	0.6	2.17	2640±75	2331
NU-1181	*Tridacna* sq.	0.2	3.47	2250±75	1835
NU-1182	*Tridacna* sq.	-0.1	3.84	1830±65	1377
NU-1183	Calcarenite	-0.3	2.62	2070±70	1644
NU-1184	*Tridacna* sq.	0.6	2.88	1530±70	1085
NU-1185	Calcarenite	0.5	2.23	2040±65	1610
NU-1186	*Tridacna* sq.	0.4	4.67	1180±65	731
NU-1187	Coral	0.7	1.38	1600±65	1158
NU-1188	Coral	0.6	1.03	1410±65	960
Okinoerabu Island					
NU-1091	Calcarenite	-0.5	2.86	1310 ±70	849
NU-1092	*Goniastrea* sp.	0.0	2. 9	740±60	380
NU-1089	*Goniastrea* sp.	0.0	0.82	2280±90	1892
NU-1090	Calcarenite	0.4	2.38	1810±70	1359
Okinoerabu Island					
NU-1087	Calcarenite	-0.5	2.81	3910±75	3768
NU-1088	*Polites* sp.	-0.5	-0.94	3880±80	3850
NU-1200	Calcarenite	-0.1	1.51	3580±120	3482
NU-1201	*Tridacna sq.*	0.0	1.33	3190±70	2997
NU-1101	*Tridacna sq.*	0.0	4. 77	2500±85	2161
NU-1102	Calcarenite	0.4	2.47	2800±75	2540
NU-1103	Calcarenite	1.0	3.18	2950±80	2723
NU-1104	*Tridacna sq.*	0.6	3.34	2710±70	2430
NU-1105	*Montipola* sp.	0.6	1.69	2810±70	2552
NU-1106	Calcarenite	0.6	2.13	2910±70	2675
NU-1107	Calcarenite	0.8	2.42	3120±70	2906
NU-1098	Calcarenite	-0.3	2.35	1830±70	1379
NU-1099	*Polites* sp.	-0.5	2.62	2310±75	1928
NU-1100	*Cyphastrea* sp	-0.5	2.03	2200 ±70	1795
NU-1095	Calcarenite	0.0	0.15	2050±65	1621
NU-1096	*Tridacna sq.*	0.0	4.01	1590±65	1148
NU-1097	Coral	0.0	0.89	3690±85	3607
NU-1112	*Goniatrea* sp.	0.0	4.28	1190±60	739
NU-1093	*Goniastrea* sp.	0.0	3.64	1610±65	1168
NU-1094	Calcarenite	1.0	2.1	2000±70	1563
NU-1108	*Tridacna sq.*	0.0	3.33	2860±75	2604
NU-1109	Calcarenite	0.0	2.87	2830±75	2571
NU-1110	*Tridacna sq.*	0.0	4.57	3030±75	2811
NU-1111	*Goniastrea* sp.	0.3	3.2	2640±70	2330
Yoron Island					
NU-997	Calcarenite	0.0	2.68	3060±70	2838
NU-995	Calcarenite	0.0	3.37	2530±75	2195
NU-993	Calcarenite	0.8	3.64	1670±65	1224
NU-994	*Tridacna sq.*	0.8	3.62	1720±65	1273
NU-990	*Tridacna sq.*	0.0	3.02	1580±70	1136
NU-991	*Tridacna sq.*	0.8	4.27	1480±65	1032
NU-992	Calcarenite	0.8	2.38	1720±65	1273
NU-981	Calcarenite	0.0	1.78	1870±70	1418
NU-982	Calcarenite	0.7	2.29	1810±70	1359
NU-984	Calcarenite	0.6	2.17	1040±70	610
NU-985	Calcarenite	0.0	3. 82	980±65	573
NU-986	Coral	-0.6	1.34	1600±65	1158
NU-987	Calcarenite	0.5	1.57	2150±70	1738
NU-988S	Calcarenite	0.8	2.45	2610±70	2287
NU-989	Calcarenite	0.0	2.38	2880±80	2625
NU-1002	Goral	0.5	3.09	2030±65	1598
NU-1001	Calcarenite	0.0	2.95	1370±65	915
NU-1000	Coral	0.0	2.77	5340±90	5712
NU-998	Coral	0.8	1.93	2240±70	1843
NU-999	Calcarenite	0.8	2.63	2940±75	2712

calibrated by IntCal 04 computer program (Stuiver et al. 2005). The marine reservoir effect (400 years: Stuiver et al. 1986) is automatically corrected using the modeled marine ^{14}C calibration curve (e.g. Marine04: Hughen et al. 2004). However the calibration of marine samples is complicated by local and regional deviation from the global average. Accounting for this deviation, a local correction value, or ΔR—the difference between the modeled ^{14}C age and the actual ^{14}C age of surface water for the surveyed island—needs to be corrected (Stuiver et al. 1986). Deviation is caused on a marine sample when it was influenced by ^{14}C –depleted deep ocean water (up-welling) and meteoric water (dominant water flow from island). However author could not find any suitable ΔR for the Amami Islands then he assumed ΔR was equal to zero.

Results

Isotope fractionation

A total of 87 beac h rock samples were collected from 37 sites of four major islands. They consisted of 41 calcarenite samples, 26 fossil coral samples and 20 fossil shell samples respectively. Isotope fractionation ranged between 4.8‰ and −3.3‰ and the average $\delta^{13}C$ value over four islands was 2.0‰. It is notable that the average $\delta^{13}C$ values of 3 islands (50 samples) were outside the range of 0±2‰ given for marine carbonates and organisms by Geyh and Schleicher (1990). The maximum and minimum $\delta^{13}C$ values for calcarenite samples in the Amami Islands were 3.8‰ and −3.3‰ respectively, while the average was 1.7‰. The maximum and minimum $\delta^{13}C$ values for coral samples were 4.3‰ and −0.9‰ respectively, and the average value indicated 1.5‰. In addition, maximum, minimum and average $\delta^{13}C$ values for fossil shell samples were 4.8‰, 0.0‰ and 3.0‰ respectively. In the Amami Islands, average $\delta^{13}C$ value for beach rock samples decrease gradually from southern Yoron Island (2.7‰) to northern Amami-Oshima Island (0.5‰).

^{14}C age of beach rock

Amami-Oshima Island. The oldest ^{14}C age given for beach rock samples collected from Amami-Oshima Island was 4,052 yrs cal BP and the youngest age was 523 yrs cal BP.

^{14}C ages continue within $\pm 3\sigma$ error range from 3,338 yrs cal BP to 2,204 yrs cal BP, and from 1,323 yrs cal BP to 523 yrs cal BP respectively. But it has broken between 4,052 yrs cal BP and 3,338 yrs cal BP, and between 2,204 samples collected from Amami Islands. (After Omoto 2005a) yrs cal BP and 1,323 yrs cal BP respectively.

Tokuno Island. The oldest ^{14}C age of beach rock samples collected from Tokuno Island was 5,163 yrs cal BP and youngest age was 538 yrs cal BP. ^{14}C ages of beach rock samples after 5,163 yrs cal BP is 3,024 yrs cal BP and continue from 2,331 yrs cal BP to 2,272 yrs cal BP, and from 1,831 yrs cal BP to 731 yrs cal BP respectively. The ages intermit between 5,163 yrs cal BP and 3,024 yrs cal BP, and between 3,024 yrs cal BP and 2,331 yrs cal BP respectively.

Okinoerabu Island. The oldest ^{14}C age given for beach rock samples collected from Okinoerabu Island was 3,850 yrs cal BP and the youngest age was 380 yrs cal BP. ^{14}C ages continue from 3,850 yrs cal BP to 3,482 yrs cal BP, and from 2,997 yrs cal BP to 380 yrs cal BP respectively however it is broken between 3,482 yrs cal BP and 2,997 yrs cal BP.

Yoron Island. The oldest ^{14}C age of beach rock samples was 5,721 yrs cal BP and the youngest age was 573 yrs cal BP. ^{14}C ages continue from 2,838 yrs cal BP to 573 yrs cal BP however it is intermitted between 5,721 yrs cal BP and 2,883 yrs cal BP.

Discussions

Formative period of beach rock

Marine carbonates and organisms have been transported from their original locations to the inter-tidal zone by ocean waves, deposited on the beach, cemented by calcium carbonate and then became beach rock. Hence their ages never indicate directly the correct formative periods for the beach rocks but indicate only the time of deaths of the marine organisms.

Russell (1959) reported that some beach rock had been cemented since World War II. Yonetani (1963) investigated beach rock development on the Tokuno Island, and

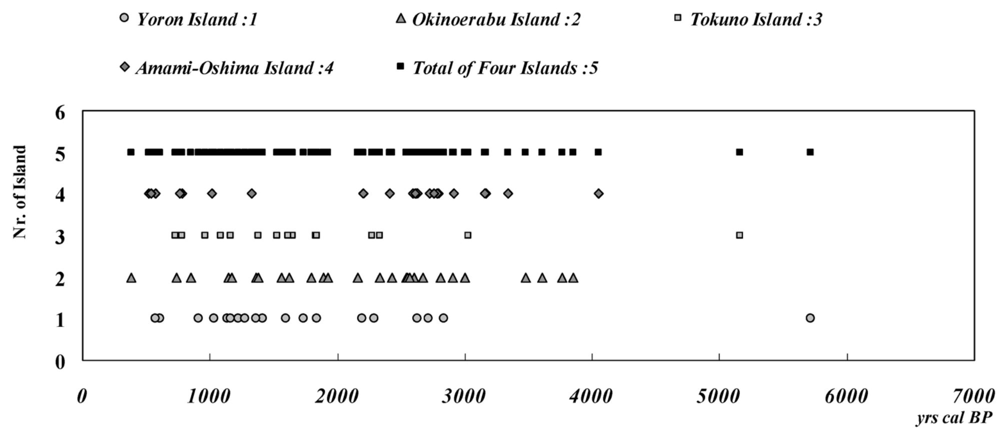

Fig. 3 Correlations of ^{14}C ages of beach rocks collected from Amami Islands. The islands expressed with figures from 1 to 4 indicate Amami-Ohshima Island, Tokuno Island, Okinoerabu Island and Yoron Island, respectively. Data were compiled from Omoto (2005a)

found "nails" and a "silver comb" at Sadaiguma. He estimated that these items might have been used within the last 200 years. While Takenaga (1965) found fragments of a "soy sauce bottle" at Kametoku beach and he considered that the beach rock might have been formed within the last 100 years. These facts suggest the difference in time between transportation of material and its cementing has occurred in very short time probably within ca.10 years. Consequently ^{14}C age of beach rock indicates maximum age and the genuine formative age seems to exist within the error range ($\pm 1\sigma$).

Omoto (2006) proposed that beach rocks might have formed in every case during the late Holocene period. The cemented strata of beach rocks dip usually seaward and landward slabs (the highest slab) are considered to have been formed prior to the seaward ones. The idea is based on the principle of sedimentation.

Many geologists and geomorphologists believe that the sea-level has not changed drastically in the last 5,000 BP, so that the beach rocks have always been formed under the inter-tidal zone. This means that the beach rocks collected from the inter-tidal zone may indicate different ages even if they were collected at the same elevation. And a fossil shell or coral sample collected from the upper part of the slab (beach rock) may not always indicate the oldest ages, because there remains a possibility that ^{14}C dated material was transported and fixed at a slightly higher position after an older sample material was included in beach deposits.

Omoto considers if two ages overlapped within $\pm 3\sigma$ error range, these beach rocks have been formed continuously otherwise they were formed individually. Complete ^{14}C ages of beach rock samples collected from Amami Islands are shown in Fig. 3. Beach rocks began to form 5,721 yrs cal BP on Yoron Island at first and the last formation was 380 yrs cal BP on Okinoerabu Island. In the Amami Islands beach rocks were formed at three stages; i.e. 5,720 yrs cal BP, 5,160 yrs cal BP, and continuously between 4,050 yrs cal BP and 380 yrs cal BP respectively. The ages of beach rock formation differ apparently according to the islands surveyed. Several time differences among the islands may be distinguished in Fig. 3.

Middle -Late Holocene sea-level change

Marine terraces that developed at several levels on the Amami Islands provide a good evidence for the emergence of the island. Ota and Hori (1980) estimated the elevations of marine terraces formed in the last interglacial period (MIS-5e) and the Holocene period however they have not always estimated formative ages using reliable and radiometric data. The estimated average rates of uplift during the Holocene at Amami-Oshima Island, Tokuno Island, Okinoerabu Island and Yoron Island were 0.5 m/ka, 1.1 m/ka, 0.2 m/ka and larger than 0 m/ka respectively. Elevations of beach rocks also believed that they indicate past sea-level. Therefore it is possible to reconstruct the past sea-level change by using the elevations and ^{14}C ages of beach rocks.

Takahashi and Koba (1975) investigated the southern part of Tokuno Island and concluded that the sea-level which formed beach rocks and notches could have been 2-3 m higher than the present sea-level, although beach rocks were collected from mean high tide level (TH-084) and slightly higher than mean high tide level (TH-101). The raw ^{14}C ages showed 1,440±115 yrs BP and 1,655 ±115 yrs BP respectively (Omoto 1976). Unfortunately no radio- metric ages have obtained directly from notches which marked obviously higher elevations than the pre- sent sea- level. The late Holocene sea-level is assumed to have been nearly the same level as to the present sea-level. The above facts indicate that the island has slightly uplifted, unless beach rocks were formed in a different environment. The cause of the difference is that beach materials were influenced by meteoric water whose calcium carbonate cemented the soft beach materials and then formed beach rock (Omoto 2004, 2005b). Accordingly the higher sea- level at 1,440~1,655 yrs BP proposed by Takahashi and Koba (1975) should be reduced smaller value than 1 m.

Koba et al. (1980) reported a high sea-level at 2,000 yrs BP on Okinoerabu Island. The evidence of the high sea-level was based on two ^{14}C ages of coral samples and topography. There develop stacks and notches consisted of Ryukyu Limestone Group on the island. One of coral samples was embedded in beach rock however other was taken from a top of pedestal (1.5 m a.s.l.). The latter sample consists of *in situ* corals limestone which remained on the bench. Authors considered that the pedestal should have been formed at Holocene high sea-level and they estimated high sea-level at 2.4 m, 1.8 m and 1.1 m a.s.l. respectively with the highest age of 3,000~2,000 yrs BP (raw ^{14}C age). They also pointed out that sea-level had dropped around 1,300 yrs BP. The above evidence in- dicates that the island has uplifted intermittently.

Late Pleistocene and Holocene marine terraces develop at several levels on the Amami Islands. These evidences proof that the islands have uplifted intermittently. Kikai Island, east of Amami-Oshima Island is characterized with uplifted coral reefs at several levels whose highest surface is named Hyakunodai (224 m a.s.l.). $^{230}Th/^{234}U$ age of Ryukyu limestone collected from Hyakunodai was measured and and correlated with MIS-5e (Konishi et al. 1974). The island locates at the nearest distance to the plate boundary where Ryukyu trench divides Eurasian Plate and Philippine Sea Plate. Depart from the plate boundary elevations of uplifted marine terraces decrease gradually to the westward. Considering these geomorphic evidences the islands have probably uplifted and tilted since MIS-5e by huge earth- quakes occurred along the subduction zone of Eurasian Plate. Geo-history and or tendency of upheavals and tiltings of the islands may have continued throughout the Holocene period.

Figure 4 shows relationship between whole ^{14}C ages of beach rock samples and their elevations of sampling sites. The sea-level seems higher than present so far as we see

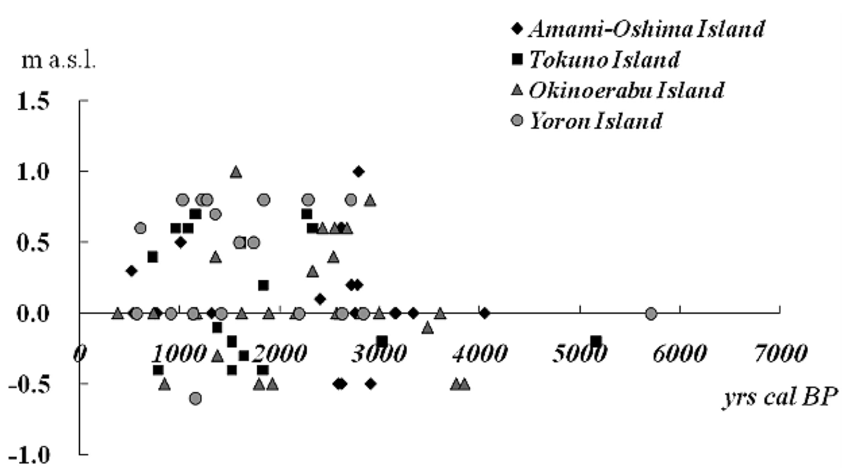

Fig. 4 ^{14}C ages vs. elevations of beach rock samples collected from Amami Islands. Local tide range is ±0.8 m. Data were compiled from Omoto (2005a)

Fig. 3, but we must consider the amount of tide change reaching up to ca. 1 m. Beach rocks whose elevations below mean sea-level are usually covered with sea algae that make it difficult to find materials for ^{14}C datings. Therefore sample materials for ^{14}C datings have often been collected above mean sea-level and from the landward (higher) slabs. As a result, elevations of almost all of the beach rocks drawn in Fig. 4 indicate rather higher locations. Most beach rocks continue more than 1m below present sea-level. Almost the entire beach rocks observed in the surveyed area was situated within a range corresponding to the present inter-tidal zone (ca. ± 1 m). The evidence indicates that the sea-level has never changed dramatically during the late Holocene.

Based on these pieces of evidence, the past relative sea-level existed at a slightly higher level in the uplifted coasts of Okinoerabu and Yoron Island where developed lower marine terrace and emerged notches. These geomorphic characteristics suggest new upheavals occurred during the late Holocene. However it stood at a level similar to the present one on the stable coasts, that is, it has maintained nearly the same level as the present one since at least 4,000 yrs cal BP.

Conclusions

A total of 87 beach rock samples were collected from 37 sites among 4 of the Amami Islands. ^{14}C ages were corrected for $\delta^{13}C$ then they were calibrated by IntCal 04 program (Stuiver et al. 2005). Based on the calibrated ages, formative periods of beach rocks and sea-level change during the late Holocene were discussed. Their results are summarized as follows:

1. Within the Amami Islands, beach rocks began to form at 5,720 yrs cal BP at Yoron Island at first, and continued between 4,050 yrs cal BP and 380 yrs cal BP within the range of the inter-tidal zone. Formative periods of beach rocks differ among four islands.

2. In the tectonically stable islands, sea-level has remained similar to the present one for at least the past 4,000 years however relative sea-levels of Okinoerabu Island and Yoron Island were slightly higher than that of the present one. This fact generally may be accepted as it reflects crustal movements probably triggered by huge earthquakes, occurring at a subduction zone along the Eurasian Plate.

Acknowledgments

I would like to dedicate this paper to late Professor Emeritus Kiyoshi Yamazato for his continuous encouragement on my coral reef studies. I am grateful to Professor Motoharu Koba of Kansai University who identified coral samples and Miss Wakana Koreeda helped with chemical assays. I express my gratitude to Prof. William D. Patterson, Department of English Literature, College of Humanities and Sciences, Nihon University for his suggestions and improvement of my manuscript. Field surveys, ^{14}C dating and analyses of isotope fractionations ($\delta^{13}C$) were supported by a Scientific Grant in Aid from College of Humanities and Sciences, Nihon University.

References

Geyh MA, Schleicher H (1990) Absolute age determination. Springer-Verlag, Berlin

Hori N, Araki T, Terai M, Horiuchi K (1972) Mechanism of beach rock formation and its geomorphic significance. Proc Gener Meet Assoc Jap Geogr: 51−52 (in Japanese)

Hori N, Horiuchi K, Araki T, Terai M (1973) Development of beach rock and its cause—An example of Yoron Island—. Proc Gener Meet Assoc Jap Geogr: 16−17 (in Japanese)

Hughen KA, Baillie MG L, Bard E, Beck JW, Bertrand CJH, Blackwell PG, Buck CE, Burr GS, Cutler KB, Damon PE, Edwards RL, Fairbanks RG, Friedrich M, Guiderson TP, Kromer B, MacCormac G, Manning S, Ramsey CB, Reimer PJ, Reimer RW, Remmele S, Southon JR, Stuiver M, Talamo S, Taylor FW, van der Plicht J, Weyhenmeyer CE (2004) Marine04 marine radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon 46: 1059−86

Koba M (1974) Coastal geomorphology of Okinoerabu Island and postglacial sea-levels. Ann Tohoku Geogr Assoc 26: 37−44 (in Japanese)

Koba M, Omoto K, Takahashi T (1980) Late Holocene higher sea-level and its radiocarbon dates in Okierabu-jima, Ryukyus. The Quat Res 19: 317−320 (in Japanese)

Konishi K, Omura A, Nakamichi O (1974) Radiometric coral ages and sea level records from the late Quaternary reef complexes of the Ryukyu Islands. Proc 2nd Int Coral Reef Symp: 595–613

Omoto K (1976) Tohoku University radiocarbon measurements III. Sci Rep Tohoku Univ 7th Ser (Geogr) 26: 135–157

Omoto K, Nakata T, Koba M (1976) Tohoku University radiocarbon measurements IV. Sci Rep Tohoku Univ 7th Ser (Geogr) 26: 299–310

Omoto K (1993) Radiocarbon dating manual. Dept Geogr Coll Hum & Sci Nihon Univ: 1–102 (in Japanese)

Omoto K (2004) Radiocarbon ages and isotope fractionations of beach rock samples collected from the Nansei Islands, southwestern Japan. Radiocarbon 46: 539–550

Omoto K (2005a) Radiocarbon ages and isotope fractionations of beach rock samples collected from the Nansei Islands, southwest of Japan—Data sets and their statistical analyses—. Proc Inst Nat Sci Nihon Univ 40: 1–27 (in Japanese)

Omoto K (2005b) Isotope fractionations and radiocarbon ages of fossil coral, shell and calcarenite samples collected from the Nansei Islands, southwestern part of Japan. Int Conf Isotopes Env Studies—Aquatic Forum 2004—25–29 October 2004, Monaco. IAEA-F3-CN-118: 254–255

Omoto K (2006) Isotope fractionations and radiocarbon ages of beach rock samples collected from Okinawa Island, southwest of Japan. Proc 10th Int Coral Reef Symp: 511–518

Ota Y, Hori N (1980) Late Quaternary tectonic movement of the Ryukyu Islands, Japan. The Quat Res 18: 221–240 (in Japanese)

Russell RJ (1959) Caribbean beach rock observations. Z Geomorph NF 3: 227–236

Stuiver M, Polach HA (1977) Discussion reporting of ^{14}C data. Radiocarbon 19: 355–363

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

Stuiver M, Reimer PJ, Reimer R (2005) CALIB 04 Radiocarbon Calibration. Execute Version 5.0.2html

Takahashi T, Koba M (1975) Reef flat and beach rocks of southern Tokunoshima, Ryukyu Islands. Sci Rep Tohoku Univ 7th Ser (Geogr) 25: 189–196

Takenaga K (1965) Beach rock and lagoon on Yoron Island, Ryukyu Archipelago. Geogr Rev Jpn 38: 739–755 (in Japanese)

Yonetani S (1963) A preliminary study on beach rock in northern part of Amami Oshima. Geogr Rev Jpn 36: 519–527 (in Japanese)

Yonetani S (1964) The beach rock on the southwest of Japan. Bunka Hokoku, Shigaku-hen, Kagoshima Univ 12: 83–94 (in Japanese)

Received: 18 July 2009
Accepted: 26 October 2009