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Giorgio SPADA [5] & Georgios ECONOMOU [6]

EVOLUTION OF RELATIVE SEA LEVEL IN OKINAWA (JAPAN) DURING HOLOCENE

Abstract: Evelpidou N., Kawasaki S., Karkani A., Saitis G., Spada G. & Economou G., *Evolution of relative sea level in Okinawa (Japan) during Holocene.* (IT ISSN 0391-9838, 2019).

Sea level indicators, such as tidal notches and beachrocks, may provide valuable information for the relative sea level (RSL) changes of an area. The study area, Okinawa, belongs to the Ryukyu Islands, Japan (Pacific Ocean), forming the emerged part of an active island arc, where the Philippine Sea plate is subducting beneath the Asian continent. Evidence of emergence has been noted by various studies. Beachrocks have also been studied, however, detailed examinations of their spatial extent and cement characteristics has not been accomplished. The purpose of this study is to discuss the RSL evolution in Okinawa through the re-evaluation of reported sea level indicators, with additional observations of beachrocks and notches and RSL predictions. Our findings suggest that the majority of Okinawa beachrocks have formed in the intertidal zone. Although the vertical uncertainty of the produced SLIPs is relatively large, there is a good agreement between the different types of sea level indicators. Comparisons with RSL predictions as well as the presence of uplifted notches further suggest that Okinawa island is generally characterized by an uplift trend, which is larger in its southern part.

Key words: Sea level indicators; beachrocks; notches; relative sea level changes; Japan.

INTRODUCTION

Sea level changes are driven by long- and short- term processes. Eustatic sea level changes are owed to variations in the mass or volume of the oceans and have a global impact, while relative sea level (RSL) changes are related to changes of the land with respect to the sea surface (Rovere & *alii*, 2016). In this framework, fossil palaeo-shorelines may be identified through various types of sea-level indicators, such as notches, beachrocks, benches, or archaeological remains, and they may provide evidence for RSL changes. Geomorphological investigations can be particularly useful in the identification of coastal subsidence/uplift (e.g. Stiros & *alii*, 2000; Morhange & *alii*, 2006; Kelsey & *alii*, 2006; Benac & *alii*, 2008; Shimazaki & *alii*, 2011; Dura & *alii*, 2011, 2016).

Beachrocks have proven particularly useful in the absence of other sea level indicators or when coupled with other available sea level indicators (e.g. Erginal & *alii*, 2010; Vacchi & *alii*, 2012; Stattegger & *alii*, 2013; Karkani & *alii*, 2017). Although they have received some debate regarding their formation zone and their accuracy as sea level indicators (e.g. Kelletat, 2006), their cement mineralogy and morphology are indicative of the diagenetic environment (Gischler, 2007), and therefore examination of cement characteristics can allow determining the spatial relationship between the past shoreline and beachrock formation zone (Mauz & *alii*, 2015).

Marine notches are coastal undercuttings extending along marine cliffs. They owe their development to various chemical, physical, biological or mechanical processes. Marine notches are particularly well developed on limestone coasts and are widely used to reconstruct RSL changes and

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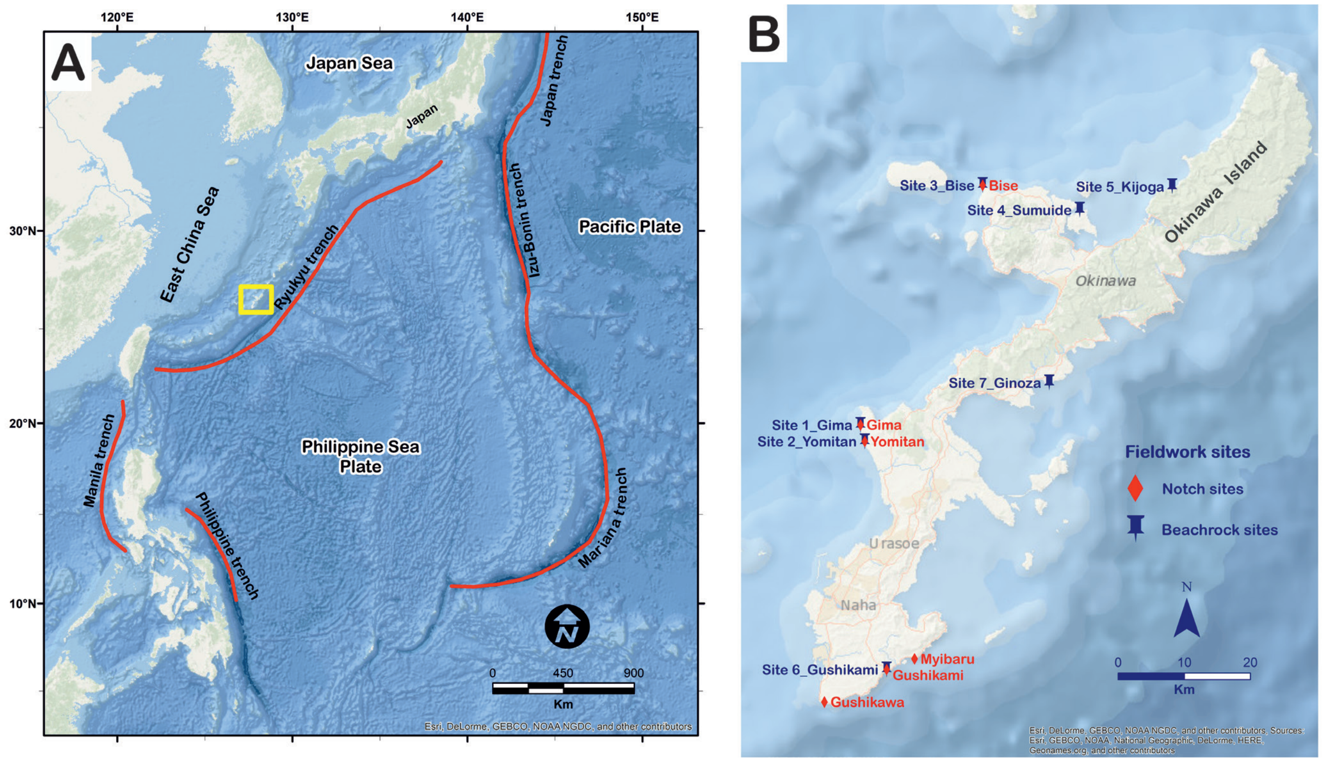


FIG. 1 - Geographic and tectonic setting of the study area. A) Okinawa island is highlighted in the yellow box, B) location of beachrock and notch sites studied in this work.

vertical tectonic displacements (e.g. Pirazzoli, 1996; Moses, 2013; Evelpidou & *alii*, 2012; 2014; 2017; Goodman-Tchernov & Katz, 2016; Schneiderwind & *alii*, 2017; Faivre & Butorac, 2018). According to Trenhaile (2014), the height of marine notches, formed by tidal wetting and drying and salt weathering, depends on the tidal range while their inward depth is controlled by climate, wave exposure and the development stage within the cycle of formation and collapse. Tidal notches, in particular, are known as precise sea level indicators, undercutting limestone cliffs in the mid-littoral zone (Pirazzoli, 1986), and constitute very important erosional geomorphological sea-level indicators (Evelpidou & Pirazzoli, 2015). They develop due to the higher rates of bioerosion near the mean sea level, in relation to the upper and lower limits of the intertidal range. Their profile is an excellent sea level indicator, providing information on the duration of a sea level stillstand and on the mode of sea level change, i.e. gradual or rapid (e.g. Evelpidou & Pirazzoli, 2014; Evelpidou & *alii*, 2016)

In this context, our paper focuses on the beachrocks and notches of the coastal zone of Okinawa (Japan) in an attempt to evaluate the RSL changes of the area during the Holocene.

STUDY AREA

Geological setting

Okinawa forms the largest island of the Ryukyu Islands group (fig. 1a, b). The Ryukyu Islands are separated from the continental shelf of East Asia (East China Sea shelf) by the Okinawa Trough, a deep and narrow submarine basin that extends to depths of more than 1000 m and runs along the northwestern side of the islands. The Okinawa Trough is an active back-arc rifting basin behind the Ryukyu arc, since at least the late Miocene (Gungor & *alii*, 2012; Park & *alii*, 1998), triggered by the northwest subduction of the Philippine Sea Plate. Its maximum water depth approaches 2300 m in the south and progressively decreases to 200 m in the north.

The southeastern side of the Ryukyu Islands is bounded by the Ryukyu Trench, which extends to depths of more than 5000 m. Two deep straits through the Ryukyu Islands, the Tokara and Kerama Gaps, divide the Ryukyu Islands into three island groups, known as the Northern, Central, and Southern Ryukyus. Okinawa belongs to the Central Ryukyus.

The surficial geology of the Ryukyu Islands is characterized by a wide distribution of the Pleistocene Ryukyu Group consisting mainly of reef-building limestone, generally referred to as the Ryukyu Limestone (Kawamura & *alii*, 2016). The Ryukyu Group overlies the Late Miocene to Early Pleistocene Shimajiri Group, which consists mainly of marine mudstone and sandstone (in contrast to the limestone of the Ryukyu Group), and pre-Late Miocene basement rocks.

Okinawa Island is narrow and elongated in an NE-SW direction. In the northern and central parts of the island, mountainous topography formed by pre-Neogene sedimentary rocks is dominant, while hills and terraces are sporadically distributed and restricted to the coastal areas (Kawamura & *alii*, 2016). The hills and terraces are formed by the Pleistocene Ryukyu Group, consisting of limestone, sand, and gravel. In contrast to the northern and central parts, the southern part consists mainly of hills, terraces, and coastal plains. The hills and terraces are formed by the underlying Shimajiri Group consisting mainly of mudstone and sandstone, and by the overlying Ryukyu Group consisting mainly of limestone (Kawamura & *alii*, 2016).

Beachrocks of Okinawa Island

Due to the need of thoroughly understanding the formation process of beachrocks in Okinawa Island, a number of studies have taken place during the last years (e.g. Danjo & Kawasaki, 2012, 2013, 2014, 2016). Most of the beachrock outcrops in Okinawa Island were found to have formed due to the precipitation of High Magnesium Calcite HMC (Danjo & Kawasaki, 2013). The biological processes from surface microorganisms (e.g. local bacteria) may highly contribute towards the precipitation of HMC. The precipitation of HMC is particularly favored by the bacteria that use ureolysis. By studying and analyzing the microorganisms who initiate the processes of beachrock formation, it is possible to understand the main regulatory factors of a study area.

The bacteria that may be responsible for the cementation process may be found in the overlying sandy sediments of beachrocks. Concentrations of urea may be found in the sea water from biodegradation of dead fish, as well as urine from mammals, amphibians, and fish (Maita & *alii*, 1973). In Okinawa Island in particular, five colonies of bacteria were found exhibiting urease activity in the sand (Danjo & Kawasaki, 2014). The bacteria stimulate the hydrolysis of urea, $CO(NH_2)_2$. For Okinawa's beachrocks, the most ureolitic active bacteria is Pararhodobacter sp (Danjo & Kawasaki, 2016). Pararhodobacter sp. are Gram-negative, rod-shaped, aerobic, chemoorganotrophic bacteria, which are moderately halophilic and the bacterium is approximately 1 μm in diameter and 3 μm in length (Foesel & *alii*, 2011).

Previous research on Okinawa sea level changes

A number of studies were carried out in the Ryukyu Islands for RSL changes (e.g. Delibrias & Pirazzoli, 1983; Kawana & Pirazzoli, 1984; 1985; Ota & *alii*, 1985; Omoto, 2001; 2004). For Okinawa Island, in particular, Pirazzoli (1978) refers to evidence of emergence in the southern part, such as mushroom-rocks, raised notches, benches and reef flats, indicating several sea level stands. In the northernmost part of Okinawa, beachrocks and notches indicate that the uplift was generally less in comparison to the southern part (Pirazzoli, 1978). According to Pirazzoli (1978), during great earthquakes, relative movements of uplift, subsidence, tilting, or undulation occur in one or several blocks, depending on the position of the epicenters; however, subsidence, must often be simply of a temporary nature, because a long-term uplift trend seems to prevail in most regions, even if it occurs at different rates.

Pirazzoli & *alii* (1985) used barnacles in order to deduce the RSL changes in Ryukyu Islands and found that a sudden upheaval, up to more than 3 m in some places, occurred at about 2355 yrs BP in the southern part of Okinawa Island. Furthermore, based on barnacle samples collected between +1.0 ± 0.4 and +1.6 ± 0.3 m, Pirazzoli & *alii*, (1985) suggested that the relative MSL has been somewhat higher than at present in several Ryukyu Islands slightly before and until ~600 yrs BP.

According to Kawana & Pirazzoli (1985), a number of indicators (notches, coral reefs, beachrocks and barnacles) suggest an uplift reaching + 2.5 m in central and south Okinawa. Kawana & Pirazzoli (1985) attribute this uplift to differential block movements and suggest a magnitude of 7.4, based on the amount of vertical displacement and the size of the uplifted area. The same authors suggest that the notches in the south and central Okinawa developed during a period of sea level stability between about 6700 and 2350 yrs BP. In a similar manner, on the west coast of central Okinawa Island, crustal movements had taken place slightly later, if not at the same time, than in the south coast (Kawana & Pirazzoli, 1983).

Beachrocks have also been studied in the Ryukyu Islands (e.g. Omoto, 2001; 2004; Omoto & *alii*, 2003). According to Omoto (2004), beachrocks from Okinawa Island began to form at ~6900 BP and the last formation was around 400 BP. The ages of beachrock formation differ in the surveyed islands, but beachrocks in Okinawa Island were formed continuously between 4800 BP and ~400 BP (Omoto, 2004). 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 & *alii*, 2003).

MATERIALS AND METHODS

Detailed spatial mapping of beachrock slabs was performed during autumn 2015 and 2016, in the coastal zone of Okinawa island (fig. 1b). At each site, we carried out one or more transects to: i) measure the width and elevation/depth of beachrock slabs (with respect to the biological mean sea-level) and, ii) sample the top beds of the front (seaward) and the end (landward) of each beachrock slab (Desruelles & *alii*, 2009; Vacchi & *alii*, 2012; Karkani & *alii*, 2017). No sample was obtained from Kijoga site, as the beachrock has been characterized as cultural heritage. In order to perform petrographic analysis, stained thin sections were studied using transmitted light microscope and under SEM.

For each site, the time and the GPS coordinates were collected, with an average horizontal accuracy of ± 5 cm, and the observed features were photographed and measured in relation to sea level at the time of observation. Precise elevation / depth measurements were obtained using a 3 m metal bar with centimeter division and built-in spirit level with a precision of ± 0.2 m. Multiple measurements were performed and the average is provided as the elevation/depth value. Beachrock width was measured using a measuring tape and all data were recorded using a PVC slate.

Furthermore, notches were also recorded and mapped. Former sea-level positions were deduced from emerged tidal notches. Notch geometries, namely the height, inward depth and vertex depth from sea level, were measured according to Pirazzoli (1986) and Evelpidou & *alii* (2014). Several measurements were performed at each location to improve their accuracy.

FIG. 2 - Beachrock sites in Okinawa, Japan: a) At Yomitan site, beachrocks have a width of 18.6 m reaching an elevation of + 1.18 m, b) At Sumuide quarrying signs are evident in the seaward part of the beachrocks, c) Kijoga site, where the beachrock has been characterized as cultural heritage, d) Ginoza site, characterized by a well-developed beachrock reaching 21 m width.

Depth / elevation measurements from both beachrocks and notches were subsequently corrected for tide and atmospheric pressure during the fieldwork period. Tidal data were obtained from Naha tidal station, in Okinawa and all reported values are corrected. It should be noted that no tidal data were available for two sites (Gushikawa, Myibaru) during the fieldwork period. The average spring tidal range varies from 1.3 to 1.9 m along the coasts of the island arc (Pirazzoli & *alii*, 1985). In Okinawa, the local mean tidal range is ~1.25 m while the average spring tidal range is about 1.7 m (Stiros & Pirazzoli, 2005). In addition, error estimations for depth / elevation measurements were applied by taking into consideration the wave conditions and the measuring method. The wave's effect on vertical measurements during fieldwork ranged between 0.05 to 0.2 m and the measuring method included an uncertainty of 0.2 m (square root of 0.05^2 to $0.2^2 + 0.2^2$).

In total, 17 thin sections from beachrock samples of Okinawa Island were prepared to perform petrographic, microstratigraphic and geochemical analyses. The thin sections were analyzed for the determination of their mineralogical composition and microstratigraphy using a Leica DMLP (Leica Microsystems GmbH, Wetzlar, Germany) petrographic microscope, with a digital camera and the corresponding image treatment software. The chemical and mineralogical composition of the consolidated sediment as well as the cement, were examined with a JEOL JSM 5600 Scanning Electron Microscope (SEM) equipped with an Oxford Link Energy Dispersive Spectrometer (EDS) (Oxford Instruments). The chemical composition of the minerals was determined using natural minerals and synthetic oxide standards, and 20 kV accelerating voltage with 1.5 nA beam current. Microanalyses were performed on epoxy resin-impregnated polished and platinum coated thin sections. All the microscopy and SEM-EDS examinations were conducted at the Institute of Geology and Mineral Exploration (IGME), Greece.

In order to evaluate the relative sea level changes in the study area, a database of relative sea level index points (SLIPs) in Okinawa was developed. Samples were assigned a particular indicative range depending on their type and characteristics (e.g. Vacchi & *alii*, 2016). The associated vertical error for the produced SLIPs was obtained by adding in quadratic individual errors of the indicative range and the sampling error (ranging from 0.2 to 0.5 m). For the beachrock samples obtained during this study, the cement characteristics were taken into account and only samples showing clear intertidal formation (Mauz & *alii*, 2015) were converted into SLIPs (cf. Shennan & *alii*, 2015). All radiocarbon ages were recalibrated by using Calib 7.10 (Stuiver & *alii*, 2019) with the Marine13 curve (Reimer & *alii*, 2013). The list of calibrated ages is available as supplementary material.

We further used biological sea level indicators, reported in literature for the study area. Barnacles, as biological indicators, have been used in several studies to deduce relative sea level changes and co-seismic movements (e.g. Pirazzoli & *alii*, 1985; Morhange & *alii*, 2001; Jaramillo & *alii*, 2017). According to Laborel & Laborel-Deguen (1994, 1996) Chthamalus barnacles live at the upper limit of the midlittoral erosion zone and are in general poor sea level indicators (Laborel & Laborel-Deguen, 1996); their vertical range is so irregular (from a few centimeters to several meters) and it is difficult to compare the upper limit of fossil Chthamalus to that of the corresponding living population, therefore no accuracy better than + 0.5 m or even + 1 m may be expected (Laborel & Laborel-Deguen, 1996). However, present day distributions of *Chthamalus challengeri* have been reported from the coast of Izu Peninsula (central Japan), indicating that this barnacle occurs between 0.2 m below MSL and 0.1-0.2 m above MSL (Kitamura & *alii*, 2014).

The vertical zonation of the barnacle, *Octomeris sulcata*, has been discussed by Pirazzoli & *alii* (1985). The authors have reported several variations in the vertical zonation of *Octomeris sulcata* ranging from the low to the high tidal range and, for this reason, we have adopted this indicative range.

To interpret the observational RSL data, we considered predictions from two Glacial Isostatic Adjustment (GIA) models, which have been obtained using the open source program SELEN developed by Spada & Stocchi (2007). SELEN solves the Sea Level Equation (Farrell & Clark, 1976) taking into account for deformational, gravitational and rotational effects on sea level. In the two GIA runs performed, we have implemented in SELEN the recent ICE-6G (VM5a) model by Peltier & *alii* (2015) and the one progressively developed by the Research School of Earth Sciences of the National Australian University (ANU) (see Lambeck & *alii*, 2003 and subsequent contributions).

RESULTS

Beachrock distribution

For the purposes of this study, seven beachrock sites were visited and measured (fig. 2; tab. 1). At Gima, located in the western coast of Okinawa Island, a continuous beachrock slab was found with a width of 19.6 m (fig. 3). The beachrock was measured between + 0.37 m and a maximum elevation of + 0.99 m. In the northern part of the beach, quarrying marks on the beachrock slab are extensive. A few kilometers south of Gima, at Yomitan, a continuous beachrock was found reaching a maximum width of 18.6 m (fig. 3), extending between + 0.37 and + 1.18 m.

In the northwestern part of Okinawa, a beachrock was mapped at Bise, with a width of 13.5 m, extending parallel to the coast for ~320 m (fig. 3). The beachrock lies between sea level and + 0.68 m in relation to mean sea level. A few kilometers to the east, at Sumuide, Yagaji island, the beachrock extends parallel to the coast for approximately 130 m, with a total width of 11.9 m (fig. 3). Quarrying signs are also evident in this site. The beachrock is not well-preserved and appears eroded, however elevation measurements have shown it lies between + 0.95 m and + 0.74 m in relation to sea level.

At Kijoga (NNW part of Okinawa), the beachrock has been characterized as cultural heritage and for this reason no samples were obtained. The beachrock, however, is very extensive in relation to other sites, parallel to the coast for more than 800 m. Two transects were accomplished (at low tide). The maximum width was measured in the second transect reaching 30 m (fig. 4). Overall, the maximum depth measured reaches - 0.13 m while its maximum elevation was found at + 0.83 m.

A beachrock of limited extent and width, reaching 8.3 m, was identified at Gushikami, in the southern part of Okinawa. The beachrock lies in the back of a limestone platform, between - 0.21 and - 0.39 m below mean sea level (fig. 4). At Ginoza (central-eastern coast of Okinawa), the beachrock extends parallel to the coast for about 270 m, however it appears rather eroded. At its best preserved part, it maintains a width of 21 m, extending between - 0.22 m to + 0.63 m, although it locally reaches + 0.96 m (fig. 4).

TABLE 1 - Location and characteristics of the studied beachrocks in Okinawa Island.

Location	Latitude N	Longitude N	Width (m)	Landward slab Height in relation to sea level (m)	Seaward slab Height in relation to sea level (m)	Landward slab Height in relation to sea level (m) corrected	Seaward slab Height in relation to sea level (m) corrected
Gima	26° 25′ 03.5″	127° 42′ 48.9″	19.6	+ 0.62	± 0	+ 0.99	+ 0.37
Yomitan	26° 23′ 51.5″	127° 43′ 09.7″	18.6	+ 0.81	± 0	+ 1.18	+ 0.37
Bise	26° 42′ 32.2″	127° 52′ 47.00″	13.5	+ 0.61	- 0.12	+ 0.68	- 0.05
Sumuide (Yagaji isl.)	26° 40′ 44.2″	128° 00′ 41.9″	11.9	+ 0.39	+ 0.6	+ 0.74	+ 0.95
Kijoga (a)	26° 42′ 26.4″	128° 08′ 26.6″	14.4	+ 0.56	+ 0.05	+ 0.83	+ 0.32
Kijoga (b)	26° 42′ 21.9″	128° 08′ 14.3″	30	+ 0.1-0.2	- 0.35	+ 0.37	- 0.13
Gushikami	26° 07′ 10.7″	127° 44′ 56.7″	8.3	+ 0.5	+ 0.32	- 0.21	- 0.39
Ginoza	26° 28′ 08.6″	127° 58′ 12.6″	21	+ 0.5	- 0.35	+ 0.63	- 0.22

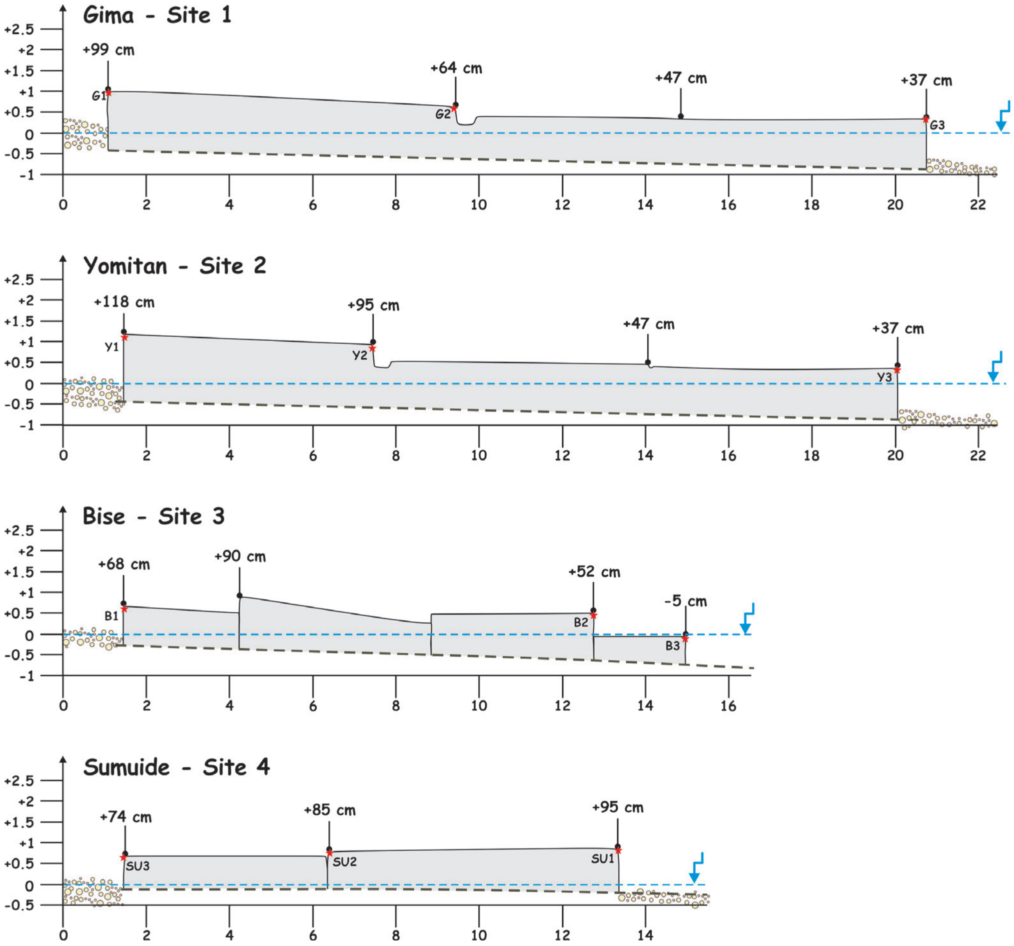


FIG. 3 - Transects of the beachrock outcrops at Gima, Yomitan, Bise and Sumuide (Yagaji Island).

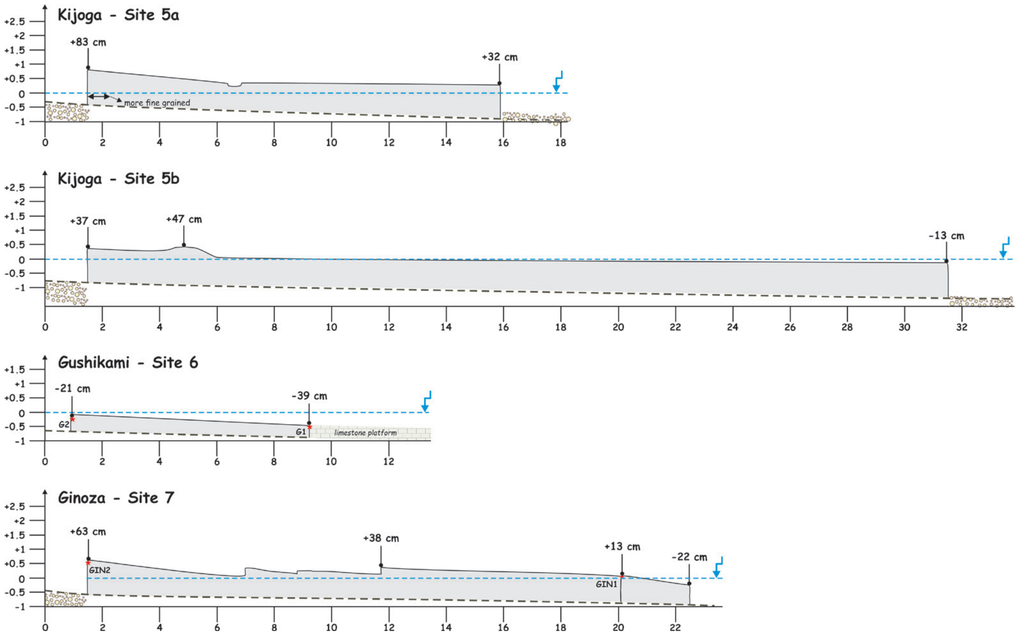


FIG. 4 - Transects of the beachrock outcrops at Kijoga, Gushikami and Ginoza.

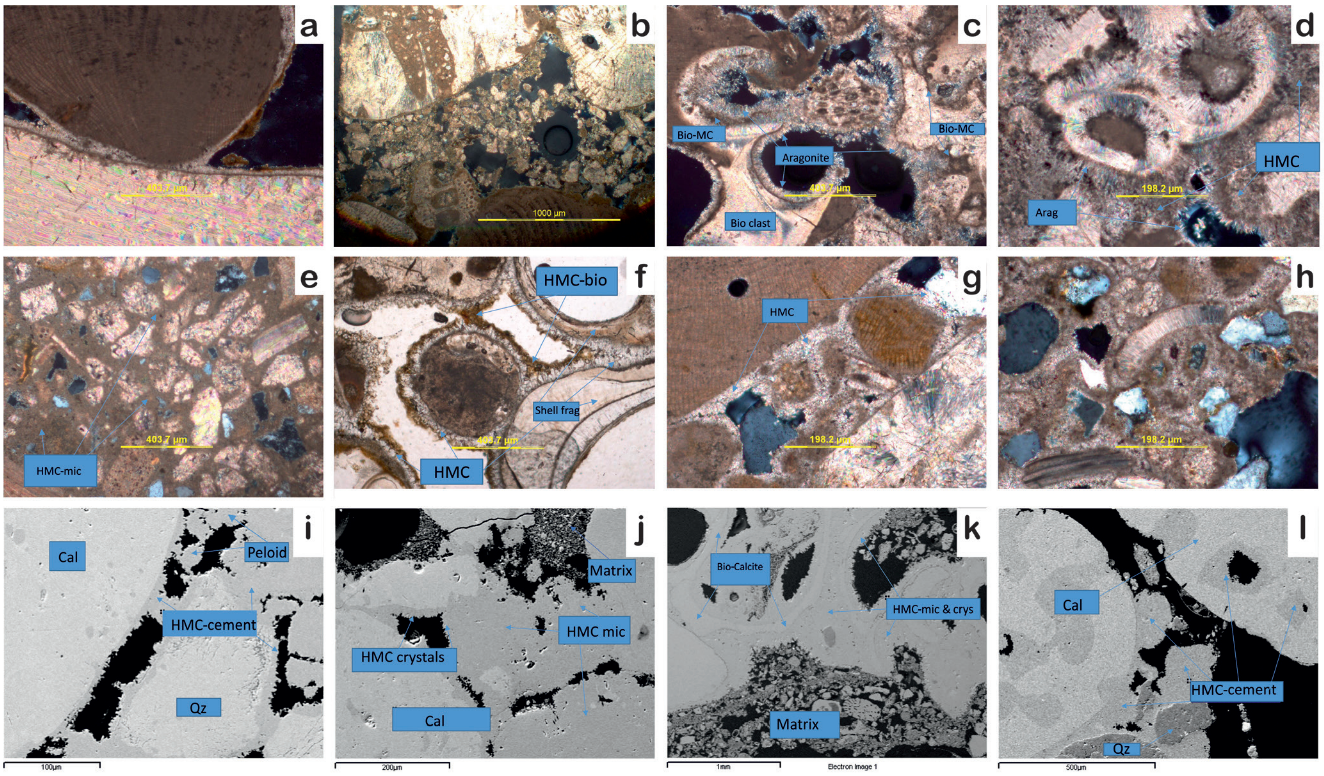


FIG. 5 - Cement observations from Okinawa beachrocks (see tab. 2 for details). Qz stands for quartz, Cal is calcite, Arag is Aragonite, HCM is high magnesium calcite, mic is microcrystalline.

Cement observations

The examination of beachrock thin sections using both petrographic microscope and scanning electron microscope showed a coherent pattern (fig. 5). The majority of samples (tab. 2 e.g.: G2, G3, GIN1, GIN2, GG1, GG2a,b, SU 2, SU3, Y3) consist of well-medium rounded and sorted lithoclasts and grains with a high percentage of bioclasts, > 50% (forams, gastropods and lithified algae parts) (tab. 2 e.g.: B2, G1, G3, GIN1, GG1, GG2a,b, SU1, SU2, SU3, Y1, Y2, Y3). The combination of well-rounded and well-sorted sedimentary material and the high contribution of consolidated bioclasts indicate a coastal environment with significant wave activity. Additionally, meniscus cement and pellets have been noted in many beachrocks (tab. 2 e.g.: B2, B3, G2, G3, GG1, GG2a,b, Y1, Y2, Y3).

The observed beachrock cements are mainly composed of thick isopachous High Magnesium Calcite (HCM) crystals in both micritic and sparitic forms, which indicate a low- middle intertidal environment. This type of cement is also observed as coating surrounding lithoclasts and bioclasts. However, well developed crystals of aragonite as main bounding material or as a prefilling have been observed in the beachrock samples from Bise (B1, B2), Gima (G1), Ginoza (GIN1, GIN2) and Gushikami (GG1) (tab. 2). Crystals of aragonite indicate a low intertidal or even subtidal zone cementation (e.g. Tucker and Wright, 1990). The beachrock samples of Bise (B1, B2) are worth a special mention, where thick aragonite layers as cement coexist with matrix material (Mg-Calcite, Anorthite, Mica, Montmorillonite), indicating a more terrestrial cementation environment. However, sample B3 is characterized by HMC with sparitic infilling cement, suggesting middle intertidal zone.

The micritic HMC can form meniscus cement and peloidal (or pellet) concentrations, indicating a marine vadose cementation with higher sea water contribution than meteoric water. No evidence of meteoric cement was observed and the collected samples contain at least one of the calcareous constituents deposited within the intertidal zone.

Last but not least, microbial activity has been noted in all samples. The characteristic of microbial activity is the micritic envelopes covering sediment particles (e.g. Tucker and Wright, 1990). Microbial activity presence is the first phase occurring on the sediment particles that triggers the precipitation of calcite.

Notches

Uplifted notches were identified in the coastal zone of Okinawa Island (fig. 1, 6). Tab. 3 indicates the studied sites and includes information regarding notch measurements at each site. Furthermore, the table includes notch measurements from past researches in the study area. The elevation of notches measured in the study area ranged between + 61 cm and + 219 cm above mean sea level. In the southernmost part of Okinawa, at Gushikawa, a continuous uplifted notch at about + 240 cm was identified (uncorrected for tide). A few kilometers to the northeast, at

TABLE 2 - Mineralogical/chemical characteristics of the sampled beachrocks from Okinawa Island based on SEM and microscopic examination.

Sample	Elevation/ depth (m)	Component materials of beachrock	Main minerals	Cement composition	Suggested cement precipitation mechanism	Figure
Gima 1 (G1)	+ 0.99	Poorly rounded, medium sorted lithoclasts and grains. High contribution of bioclasts.	Calcite, Mg-Calcite, Quartz, Dolomite	High Mg-Calcite in microcrystalline and sparitic form, Aragonite	intertidal zone, physicochemical precipitation+ low microbial activity	fig. 5a
Gima 2 (G2)	+ 0.64	Medium rounded, sorted lithoclasts, grains. Medium contribution of bioclasts. Pellet structures and meniscus form	Calcite, Mg-Calcite, Dolomite	Thick High Mg-Calcite in microcrystalline layers	Medium- low intertidal zone, physicochemical precipitation + low microbial activity	fig. 5i
Gima 3 (G3)	+ 0.37	Medium rounded poorly sorted lithoclasts, grains. High contribution of bioclasts. Meniscus form	Calcite, Mg-Calcite, Dolomite	Mg-Calcite in microcrystalline layers.	intertidal zone, physicochemical precipitation + High microbial activity	
Yomitan 1 (Y1)	+ 1.18	Rounded, medium sorted lithoclasts, grains. High contribution of bioclasts. Meniscus form.	Calcite, Mg-Calcite, Dolomite	High Mg- Calcite in microcrystalline form	Intertidal zone, physicochemical precipitation + high microbial activity	fig. 5j
Yomitan 2 (Y2)	+ 0.95	Rounded, medium sorted lithoclasts, grains. High contribution of bioclasts. Meniscus form.	Calcite, Mg-Calcite, Dolomite	High Mg- Calcite in microcrystalline form	Intertidal zone, physicochemical precipitation + high microbial activity	
Yomitan 3 (Y3)	+ 0.37	Well rounded, medium sorted lithoclasts, grains. High contribution of bioclasts. Meniscus form.	Calcite, Mg-Calcite, Dolomite	High Mg- Calcite in microcrystalline form and matrix	High Intertidal zone, physicochemical precipitation + high microbial activity	fig. 5b
Bise 1 (B1)	+ 0.68	Rounded, medium sorted lithoclasts, grains. Bioclasts present	Quartz, Calcite, Aragonite, Montmorillonite, Mica	Aragonite and matrix (Clay minerals)	High intertidal zone, physicochemical precipitation + microbial activity	fig. 5c
Bise 2 (B2)	+ 0.52	Rounded, well sorted lithoclasts, grains. High contribution of bioclasts. Pellet structures.	Quartz, Calcite, Anorthite, Mg-Calcite, Dolomite, Aragonite, Mica	Aragonite and matrix (Clay minerals)	High intertidal zone, physicochemical precipitation + microbial activity	fig. 5d
Bise 3 (B3)	- 0.05	Calcitic structure (coral?). Contribution of bioclasts. Pellet structures.	Calcite, Mg-Calcite, Dolomite	High Mg-Calcite with sparitic infillings	intertidal zone, physicochemical precipitation	
Sumuide 1 (SU1)	+ 0.95	Poorly rounded, medium sorted Lithoclasts, grains. High contribution of bioclasts.	Calcite, Quartz, Mg-Calcite, Dolomite, mica	Thick High Mg- Calcite in microcrystalline and sparitic form. Matrix infilling	Intertidal zone, physicochemical precipitation + medium microbial activity	fig. 5e
Sumuide 2 (SU2)	+ 0.85	Medium rounded and sorted lithoclasts, grains. High contribution of bioclasts	Calcite, Quartz, Mg-Calcite,	Isopachous microcrystalline High Mg- Calcite	Low-Mid Intertidal zone, physicochemical precipitation + medium microbial activity	
Sumuide 3 (SU3)	+ 0.74	Medium rounded and sorted lithoclasts, grains. High contribution of bioclasts	Calcite, Quartz, Mg-Calcite,	High Mg- Calcite in microcrystalline and sparitic form	Low-Mid Intertidal zone, physicochemical precipitation + medium microbial activity	
Gushikami 1 (GG1)	- 0.39	Well-rounded lithoclasts, grains. High contribution of bioclasts. Meniscus formations	Calcite, Mg-Calcite, Aragonite Dolomite	Thick High Mg-Calcite, bladed Aragonite	Intertidal zone, physicochemical precipitation + low microbial activity	
Gushikami 2a, b (GG2a, b)	- 0.21	Well-rounded lithoclasts, grains. High contribution of bioclasts. Meniscus formations	Calcite, Mg-Calcite, Dolomite	Thick High Mg- Calcite, Large Calcite Crystals matrix	Intertidal zone, physicochemical precipitation + low microbial activity	fig. 5f, k
Ginoza 1 (GIN1)	+ 0.13	Well-rounded and sorted lithoclasts, grains. High contribution of bioclasts.	Calcite, Mg-Calcite, Aragonite Dolomite	Thick High Mg-Calcite, small crystals Aragonite	Mid-High Intertidal zone physicochemical precipitation	fig. 5g, l
Ginoza 2 (GIN2)	+ 0.63	Well-rounded and sorted lithoclasts, grains. Contribution of bioclasts.	Calcite, Anorthite, Mg-Calcite, Dolomite, Aragonite, Mica	Thick High Mg-Calcite, Aragonite	Mid-High Intertidal zone, physicochemical precipitation + low microbial activity	fig. 5h

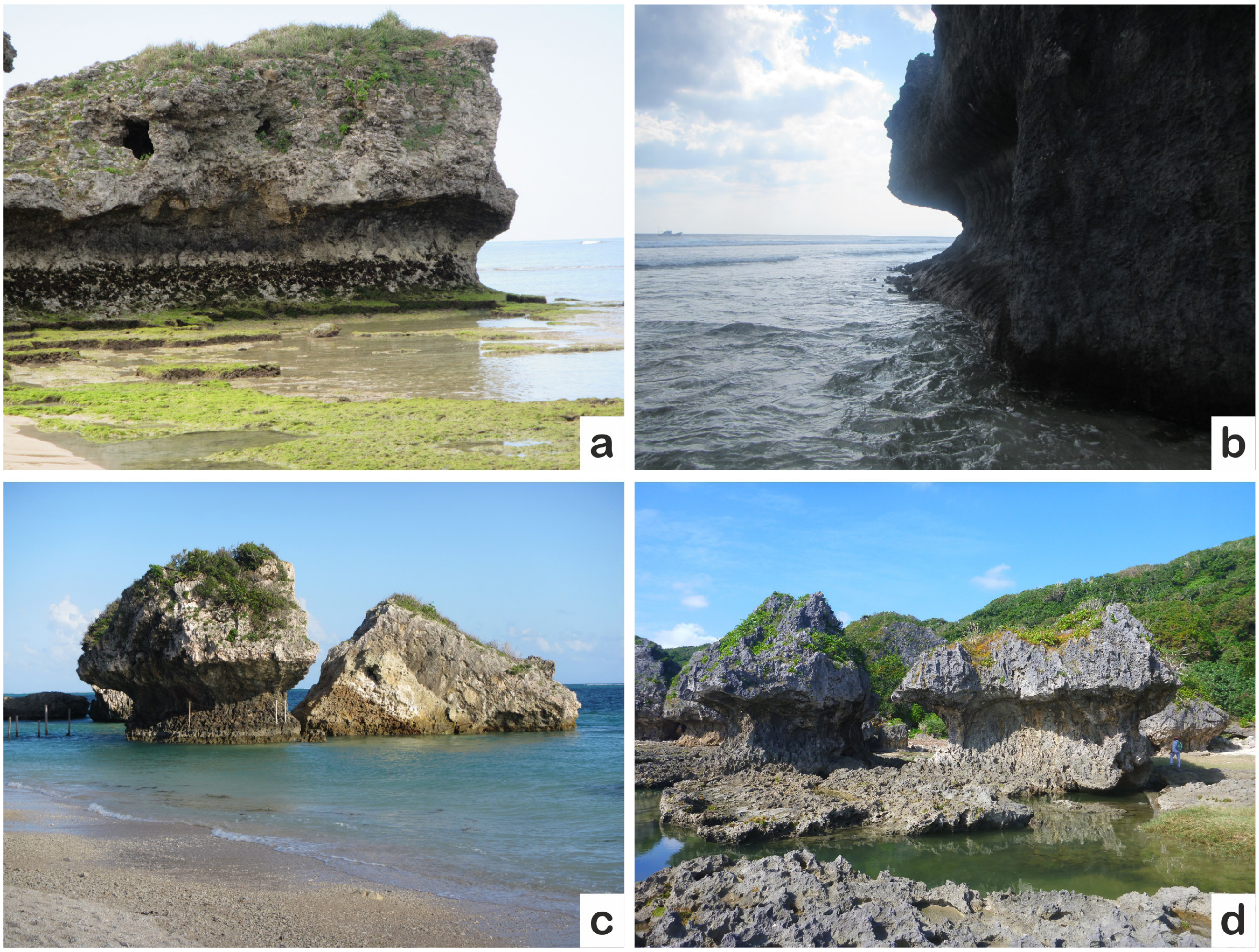


FIG. 6 - Notch sites in Okinawa, Japan: a) Gima site, with beachrocks showing signs of quarrying, b) At Gushikawa site, the notches reach an elevation of + 240 cm (vertex depth from sea level), c) Uplifted notch at Myibaru site, d) at Gushikami, the most remarkable features are the mushroom notches, with a vertex between + 204 and + 219 cm.

Gushikami, a number of mushroom notches were found. The vertex elevation from sea level varied between + 204 and + 219 cm. Repeated measurements of their height has shown an average value of 198 cm while their inward depth was measured between 100-110 cm. At Myibaru (southern Okinawa), a continuous notch was found with its vertex at + 68 cm (uncorrected for tide), having a height of 58 cm and an inward depth of 30 cm.

At the WSW coast of Okinawa, at Yomitan site, a continuous uplifted notch is located at an average elevation of 212 cm (+ 205 to + 219 cm). Repeated measurements of its height suggest values between 122 and 170 cm, while its average inward depth is 98 cm. At Gima, just a few kilometers to the north, a continuous notch was measured at about + 181 cm above mean sea level, with a height of 75 cm and an inward depth 55 cm (fig. 6). A second notch was also identified with its vertex at + 61 cm, with a height of 80 cm and an inward depth of 20 cm.

In the northwest part of Okinawa, at Bise, a continuous notch was found at about + 81 cm above mean sea level. Its height varied between 80-90 cm while its inward depth was measured between 40 and 58 cm.

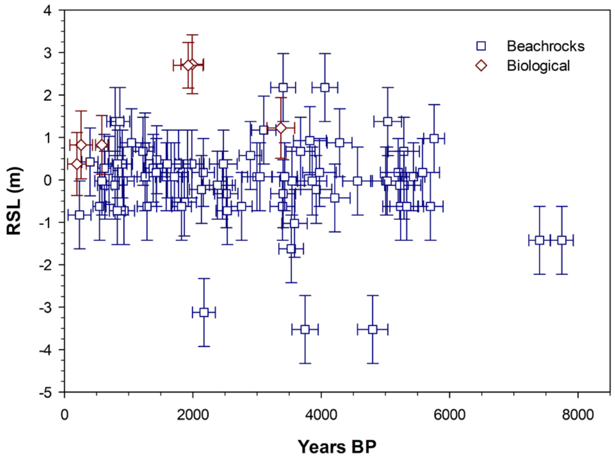
DISCUSSION

The beachrocks in the coastal zone of Okinawa

In the northwestern part of Okinawa the oldest beachrock has been dated by Omoto & *alii* (2003). A ^{14}C age of 6890 ± 90 BP given to a calcarenite sample collected from Bise Point, according to Omoto & *alii* (2003). According to our cement studies of Bise beachrocks, they have been formed in the upper intertidal zone. Furthermore, at Sumuide, Yagaji island, according to Omoto (2003), two beachrock generations exist; the older one was dated around 2000 yrs BP and quarried while the younger one around 1000 yrs BP. Based on our results the beachrocks at Sumuide have formed in the intertidal zone.

Relative sea level changes

A number of sea level studies have taken place in the wider study area. Koba & *alii* (1982) studied the RSL sea level changes in the Ryukyu Islands through the use of coral reefs and concluded that sea level between 1700-



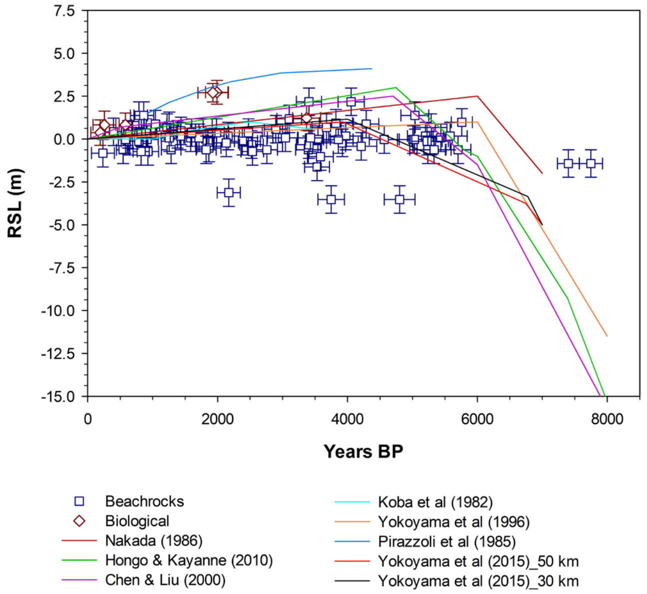


FIG. 7 - A) Plot of sea level data from Okinawa Island, B) comparison of RSL index points from Okinawa Island with sea level curves derived from the wider study area.

3500 yr B.P. was stable and was the highest in the Holocene, reaching less than 1.0 m above the present sea level. Ota (1987) summarized and reviewed the relative sea level curves for Japan by various authors and concluded that RSL rose very rapidly between ~15,000-6000 BP, correlated with the postglacial rise in sea level, called 'Jomon Transgression' in Japan. He further deduced that all RSL curves show a slightly higher level than the present at about 6000 BP (culmination of the Jomon/postglacial transgression). The age and height of this culmination shows regional and local differences reflecting the different tectonic history of each area and its age ranges from 5000 to 7000 BP. Ota (1987) further noted at least two minor negative tendencies in sea level after the 'culmination': A RSL fall at ~4000-5000 BP in several locations and at ~2000-3000 BP. Nakada & *alii* (1991) also studied the Late Pleistocene-Holocene sea-level changes in Japan by comparing observational and modelling data. Yokoyama & *alii* (2015) studied the RSL changes in the island of Iriomote (southern Okinawa trough) and concluded to a Holocene-high-stand of 2.7 m at ~3500 years ago, after which sea level gradually fell to present level. They have attributed 1 and 1.5 m above present day sea level to GIA for the last ca. 4000, and consider the residual as indicative of the long-term lithospheric uplift rate of the island (Yokoyama & *alii*, 2015).

In an attempt to contribute to the study of RSL changes of the area, we performed a coupled analysis of beachrocks and biological sea level indicators in order to re-assess the RSL changes in Okinawa Island.

In fig. 7a, we have plotted the RSL index points deduced from past sea level studies, with a particular focus on beachrocks. Approximately 71 ^{14}C datings of beachrocks from Okinawa Island have been reported by Omoto (2004, 2005, 2007). Although no cement observations have been reported for the beachrock samples, we have taken into

TABLE 3 - Significant size of notches in Okinawa Island.

Site	Vertex depth from MSL (cm)	Corrected vertex depth from MSL (cm)	Height (cm)	Inward depth (cm)	Reference
Gushikawa, Kyan cape	+ 240				This study
Myibaru	+ 68		58	30	This study
Gima	+ 180 / + 180	+ 181	60 / 75	50 / 55	This study
	+ 60	+ 61	80	20	This study
	+ 134	+ 112	190	107	This study
	+ 90	+ 68	170	90	This study
Yomitan	+ 186 / + 200	+ 205 / + 219	170 / 122	95 (104, 123) / 72	This study
Bise	+ 55 / + 54	+ 81	90 / 80	58 / 40	This study
Gushikami	+ 260-270 / + 250 / ?	+ 219 / + 204	255 / 180 / 160	100-110 / 100 / 110	This study
Giza-banta (S Okinawa)		+ 350 / + 360			Kawana & Pirazzoli (1985)
Ōdo		+ 265 ± 15			Kawana & Pirazzoli (1985)
Miyagi Isl.		+ 75			Kawana & Pirazzoli (1985)

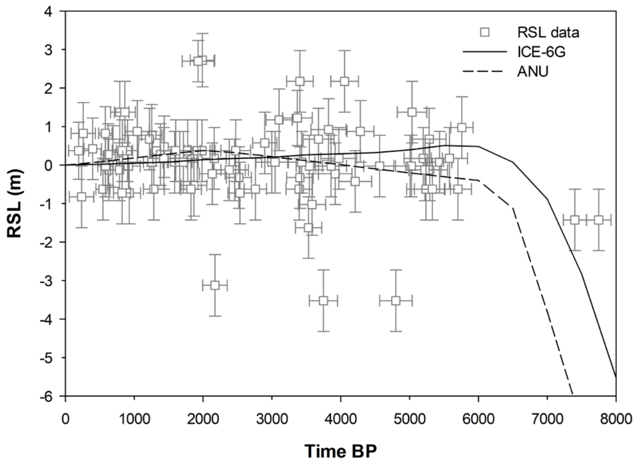


FIG. 8 - Comparison of RSL index points from Okinawa Island with RSL curves for Okinawa, obtained solving numerically the Sea Level Equation. The GIA models ICE-6G (VM5a) (solid) and ANU (dashed) have been employed.

account cement observations derived from this study and adopted an indicative range between mean high tide and mean low tide. The associated vertical error was obtained by adding in quadratic individual errors both the indicative range (1.25 m, Mean High Tide to Mean Low Tide) and the sampling error (0.5 m; e.g. Vacchi & *alii*, 2016). In addition, the beachrock samples obtained during this study have been correlated with the age results from Omoto (2004, 2005, 2007), in order to produce SLIPs with cement information.

Due to the mesotidal regime of the study area, the vertical uncertainty of the SLIPs is relatively large. There is, however, a good agreement between SLIPs produced by the beachrocks and the biological sea level indicators. The oldest beachrocks samples suggest a RSL of about ~-1.4 ± 0.8 m around ~7160 ± 90 BP.

In order to obtain a clearer idea regarding the relative sea level changes in the study area, we have plotted the RSL index points with a number of sea level curves published for the wider study area (fig. 7b). All curves plotted in fig. 7b suggest a sea level high-stand between ~4000-6000 years BP with a magnitude of ~1-3 m.

SLIPs were compared with two modelled curves (fig. 8), obtained using the open source program SELEN developed by Spada & Stocchi (2007), which solves the Sea Level Equation (Farrell & Clark, 1976) taking into account for deformational, gravitational and rotational effects on sea level. The two GIA computations show, for the site of Okinawa, qualitatively similar results, with a slight high-stand of a few tens of centimetres occurring in the last ~6000 and in the last ~4000 years for ICE-6G (VM5a) and the ANU models, respectively (fig. 8).

The oldest beachrock samples are in close agreement with the prediction by ICE-6G. However, the largest cluster of RSL data is between ~500-5500 BP. A comparison with the predicted curves suggests that the area is generally characterized by an uplift trend; however, differential movements may have also taken place, as a number of data lie below the curves (fig. 8). The distribution of RSL data suggests that the uplift is larger in the southern part of Okinawa Island. This is further supported by the presence of notches found from the northwestern part to the south part of Okinawa. They have a higher elevation toward the south, between + 204 and 219 cm (sites Gushikawa, Gushikami see tab. 3), in relation to the north part, where they reach an elevation of + 81 cm (e.g. site Bise).

CONCLUSIONS

Our study has shown that the majority of beachrocks in Okinawa have formed in the intertidal zone. Based on a coupled analysis of beachrocks and biological indicators, from published data and our observations, we produced SLIPs, which were further compared with GIA predictions for Okinawa Island. GIA computations show qualitatively similar results, with a slight high-stand occurring in the last ~6000 and ~4000 years for ICE-6G (VM5a) and the ANU models, respectively. The oldest beachrocks samples suggest a RSL of about ~-1.4 ± 0.8 m around ~7160 ± 90 BP, which is in close agreement with predictions. A comparison of the produced SLIPs with the predicted curves suggests that the area is generally characterized by an uplift trend. This is further supported by the presence of uplifted notches, which have a higher elevation toward the south of Okinawa Island.

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