Ground lowering rates of reef-limestone terraces estimated from the height of pedestal rocks in Kikai-jima, Japan

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Abstract

In Kikai-jima, southwestern Japan, many pedestal rocks occur on the surface of Holocene raised coral-reef terraces with known dates of emergence. The rate of surface lowering of these limestone terraces was calculated from the height of pedestals and the time since the terraces emerged. The rates obtained under subtropical region are ca 100–300 mm/ky, which are the same order as the rate of surface lowering of reef limestone under tropical regions and greater than rates from pedestals under erratics in temperate or cold regions. The higher rate we find appears to be due to two factors: lithology, with high porosity; and the climatic conditions in a subtropical climate, i.e., warm temperatures (22°C) and a large amount of precipitation (at least 2000 mm/y). Since the surface lowering for older terraces reaches to up 170 cm, <u>The higher rate of lowering of raised terraces call attention to </u>geomorphologists for studying neotectonics and historical development of landforms must attention to estimating the original height of terraces and height of ancient shore line, i.e., height of uplifting.

Keywords: pedestal rocks; ground lowering rates; chemical weathering; limestone; uplifted terraces

Keywords: pedestal rock; reef limestone; chemical weathering; coastal terraces; surface lowering rate

Introduction

Many studies have been made of karst denudation (e.g., Jennings, 1985, 70–87; Ford and Williams, 1989, 96-126), but there is little information about the long term solution rates of bare rock surface. Direct solutional lowering of bare rock surfaces made of limestone has been estimated from *pedestals*, which are protected from corrosion by a non-carbonate boulder that acts as an umbrella. Pedestals are found on glacially scoured rock surfaces, the boulders being glacial erratics. The height of the pedestal is a measure of the corrosion of the surface since the last glaciation. From this method, various rates of surface lowering have been reported. We have found many limestone pedestals with a boulder caprock in Kikai-jima, Ryukyu Islands, Japan. These pedestals are found on the surface of Holocene raised coral reef terraces for which the date of emergence is known. The caprock boulders are also made of coral-reef rock, which is believed to be transported by tsunamis or large waves during typhoons. Since the boulders can be assumed to have been transported and settled on the reef flat (reef pavement) before emergence, the height of the pedestal is a measure of the corrosion of the surface since emergence. From this method, various lowering rate of coral-reef terraces under subtropical climate were inferred.

Study Area and Pedestal Characteristics

Study area and uplifted coral-reef terraces

The study area is Kikai-jima (Kikai Island), located in the Central Ryukyus (Ryukyu Islands – see Figure 1) situated to the southwest of mainland Japan; there are several dozen islands and islets. Kikai-jima lies at the edge of the Eurasian Plate, under which the Amami Plateau on the Philippine Sea Plate is subducting (Uyeda and Ben-Avraham, 1972). As a result, intermittent crustal uplifts, associated with large earthquakes which have occurred several times along the subduction zone during the Holocene, have uplifted several coral-reef terraces to differing altitudes (Nakata et al., 1978; Ota et al., 1978). The surface of these terraces is composed mainly of reefoid limestones (coral limestones) resting unconformably on wave-cut benches (Ota et al., 1978).

These Holocene raised coral-reef terraces are classified into four levels according to altitude (Nakata et al., 1978; Ota et al., 1978; Sasaki et al., 1998; Sugihara et al., 2003). For example, according to ^{14}C dating of fossil corals collected from the terraces, and aerial photo-interpretation and detailed topographic profiling, Ota et al. (1978) have established the present altitudes of terraces and their emerged ages as follows: 10–15 m (6.0 ka) for Terrace I, 5–7 m (3.7 ka) for Terrace II, 3–5 m (3 ka) for Terrace III and 1.5–2 m (1.5 ka) for Terrace IV. Based on evidence from the coral species *P. verrucosa*, together with sedimentological and geomorphological evidence, Sugihara et al. (2003) showed that the relative paleo-MSLs (mean sea levels) for these terraces are 8.5–8.9 m (7.0–8.1 ka) and 10.8–11.1 m (6.3–7.0 ka) for Terrace I, 5.0–5.3 m (4.1–6.3 ka) for Terrace II, 4.0–4.3 m (3.1–4.1 ka) for Terrace III and 1.9－2.5 m (1.4–3.1 ka) for Terrace IV. They also found that raised coral-reef terraces formed in response to repeated seismic uplifts 6.3, 4.1, 3.1 and 1.4 ka ago. These data show that the time of emergence and the age of seismic uplifts are similar. and that the initial uplift for each terrace is about 5-8 m for Terrace I, about 2 m for Terrace II, 1.5-3 m for Terrace III and 1.5-2 m for Terrace IV.

Lithology of coral limestone

Limestone comprising raised coral-reef terraces consists mainly of aragonite (100% for lower terraces and > 93% for upper terraces) with accessory calcite (Minoura, 1979). The bulk chemical composition (wt%) is CaO 54.5, Fe_2O_3 0.047, Al_2O_3 0.038, SiO_2 0.06, MnO 0.002, P_2O_5 0.008, H_2O 2.01 etc. (Fujinuki, 1971). The physical and mechanical properties of the limestone vary widely: porosity 2.5–30.4 %, dry bulk density 1.89–2.56 g/cm^3, hydraulic conductivity (permeability) 1x10^{-1}–10^{-3} cm/sec, and uniaxial compressive strength 6.1–59.2 MPa (Shinjo and Nakamura, 1975; Mori et al., 1997). This limestone is porous, allowing rainwater to percolate slowly through it. The sponge-like porous limestone layer serves as an excellent aquifer, or natural underground reservoir. Rainfall slowly filters through it and eventually flows out of natural springs in cliffs behind the terraces or as outflow along the coastline after several years (Urushibara-Yoshino et al., 2001).

Soils and climatic and tidal conditions

Thin veneer soils (10–30 cm thick) were found on Terraces I and II, but no soils were found on Terraces III and IV. This is consistent with the findings of Nagatsuka and Maejima (2001), that: (1) bare rock outcrop continues for ca. 1.5 ka after emergence, taking ca. 3.0 ka to develop Lithosols; (2) Initial Rendzina-like soils (Rendzic Leptosols, Lithic Rendolls) begin to develop at 3.5-3.9 ka after emergence; and (3) the soils having age 50–55 ka have changed to Brown Rendzina-like soils (Mollic Leptosols, Eutropeptic Rendolls). These authors also reported that these soils contain 20–30 % clay fraction and have near-neutral pH values of 6.4-7.9.

The historical natural vegetation was a subtropical forest consisting mainly of evergreen trees and shrubs. However, this vegetation was cleared for sugar-cane and is now limited to a very small area on the terrace cliffs.

According to meteorological data from Seiwa sugar-mill (Fig. 1) on Kikai-jima from 1966 to 1990, the mean annual temperature for the region is 22.3°C and the mean annual precipitation is 2277 mm (Maejima et al., 2005). The warmth-index and the humidity index are respectively 208°C and 13.0, implying a humid subtropical rain forest climate (Kira, 1949). The average water deficit from 1941 to 1970 was 25 mm/y (Urushibara-Yoshino, 1988). At Naze Tidal Observatory in Amami-oshima, 40 km west of this island, the mean tidal range is about 1.13 m. The mean high water level of spring tide (MHWL) is 0.8 m above MSL.

Characteristics of Pedestal Rocks and Data Collection

Characteristics of pedestal rocks and boulders

Boulders with pedestals are found on the raised coral-reef terraces in the eastern part of this island. Figure 2 shows typical boulders with pedestal found on Terrace I, II and III. Although a few boulders are found on Terrace IV, they have no pedestals. The features of the pedestals are very similar to those of typical limestone pedestals shown in geomorphological textbooks (e.g., Jennings, 1985, Figure 28; Ford and Williams, 1989,

Figure 4.9). Pedestals are formed just under a boulder that acts as an umbrella, giving protection from corrosion.

Every pedestal has a boulder on its head. The boulders are composed of coral-reef limestones, like the pedestals, and are certainly not glacial erratics. Kawana and Nakata (1994) have reported that many large Holocene boulders are distributed on land and reef flats in the southern Ryukyu Islands including Okinawa-jima, Miyako-jima, Irabu-jima, Tarama-jima, Ishigaki-jima and other small islands; also a block on land in Ishigaki-jima has a pedestal. Their interest is in the origin of the boulders, which they concluded had been transported by tsunamis.

Data collection and results

A total of 22 pedestals were found in this area. Fig. 1 shows the pedestal locations. We have determined the altitude of the base of the pedestals, the height of the pedestals and the sizes of the boulders on pedestals using a laser range finder and a tape measure. The height of three or four portions around the pedestal was measured and their values were averaged. The measurement error is less than 10 cm in low pedestals and 20 cm in high pedestals. Based on the distribution map of Holocene coral reef terraces shown by Ota et al. (1978) and the altitude data for the base of the pedestal rock, we have identified the terraces for each pedestal as Terraces I to IV. Although Sites 13−21 are located in the "terrace riser between Pleistocene and Holocene coral terrace" zone, according to the classification of Ota et al. (1978), our present study identifies these sites as Terrace I, based on the altitude of the base of the pedestal rock and the surrounding topography.

All data obtained are shown in Table I. Fourteen pedestals were found on Terrace I and six on Terrace III. Only two pedestals were found on Terrace II. The highest pedestal (h = 170 cm) was at Site 15 on Terrace I, and the lowest pedestal (h = 5 cm) was at Site 9 on Terrace III. The data show that higher pedestals are formed on higher terraces; lower pedestals are found on lower terraces. The largest boulder has a size of about 30.8 x 12.2 x 11.1 m, at Site 21 and the smallest is 3.8 x 1.8 x 1.1 m at Site 12.

Discussion

Formative process for pedestals

Kawana (1996) suggested that several Holocene limestone boulders at the northern coast of Kikai-jima (Terrace IV) have been transported by tsunami or storm waves. We also suggest that some boulders found on the Terrace III are transported by these processes. But some boulders found at the higher terraces might have come from behind the cliff (see Fig. 1) as a result of falling. The necessary data on their origin and the time for transporting and settlement have not been determined. Although the time of transport and origin are not known, the formative process of pedestals is considered to be as follows:

(1) A boulder was transported and settled on the reef flat prior to emergence.

(2) The reef flat emerged due to crustal uplift, and was raised to become a Holocene terrace made of reef limestone.

(3) The surface of the terrace starts to lower due to corrosion by rainfall, but limestone under the boulder is protected from corrosion and survives as a pedestal.

(4) The height of the pedestal increases gradually with time.

Rates of ground lowering of limestone terraces (Solution rates of limestone)

The pedestal heights shown in Table I indicate some scatter even on a single terrace: 65–170 cm for Terrace I, 50–60 cm for Terrace II and 5–35 cm for Terrace III. This scattering is believed to be due to the difference in the rate of surface lowering as a result of the distinct geomorphological setting of each site. Terraces I, II and III emerged 6.3, 4.1 and 3.1 ka ago. Figure 3 shows the relationship between pedestal heights (*h*: mm) and emerged age of terraces (*t*: 1000 yrs).

As mentioned before a few boulders on Terrace IV (1.4 Ka) have no pedestals. This shows that the formation of pedestal begins more than 1.4 ka after emergence. The delay may be derived from that pedestals on the lower terraces with a height of about 2 m are difficult to create because not only the terrace surface but also the surface under the boulders are washed and eroded by waves at high tide (tidal range 1.6 m in MHWL) and storm events. The surface lowering of reef limestone in tropical climate under the intertidal and subaerial environments have been reported as follows: (1000 mm/ky at Red Sea: MacFadyen, 1930; 2700–6700 mm/ky at SW Australia: Revelle and Fairbridge, 1957; 260 mm/ky at Aldabra Atoll (Indian Ocean): Trudgill, 1976) and beach rock (300 mm/ky at Bikini Atoll: Revelle and Emery, 1957; 500 mm/ky at Heron Island, GBR: Stephenson, 1961). These data imply that the reef flat and the lowest terraces in the present study have been also lowered at the similar rate.

The Terrace III emerged following a 1.5-3 m uplift associated with the earthquake occurred 3.1 ka. But Supposing that the formation of the pedestals at the Terrace III started at the time

, the rates of ground lowering (i.e., solution rates) of limestone terraces can be estimated from the height of the pedestal and the time of emergence of the terraces. Figure 3 shows the relationship between pedestal heights (*h*: mm) and formative time (*t*: 1000 yrs).

The equation for a best-fit curve through the three average heights can be expressed by:

This equation shows that the rate of lowering is not a linear but an exponential function of time, with a lowest rate at the initial stage. Assuming that a linear relationship between the height of pedestal and time existed for the whole period, we obtain an average rate of lowering for each terrace. Using the maximum values for pedestal height at each terrace, we can estimate the maximum rate of ground lowering to be 270 mm/ky for Terrace I, 146 mm/ky for Terrace II and 113 mm/ky.

We compare the rate obtained at Kikai-jima to that of reef limestone in tropical coasts and that from pedestals under glacial erratics.

The rate of solution at Kikai-jima is the same order as the rate of surface lowering of reef limestone (1000 mm/ky at Red Sea: MacFadyen, 1930; 2700–6700 mm/ky at SW Australia: Revelle and Fairbridge, 1957; 260 mm/ky at Aldabra Atoll (Indian Ocean): Trudgill, 1976) and beach rock (300 mm/ky at Bikini Atoll: Revelle and Emery, 1957; 500 mm/ky at Heron Island, GBR: Stephenson, 1961) under the intertidal and subaerial environments. Porous limestone and tropical climate are common phenomena in Kikai-jima and other coasts. On the other hand, the rates obtained in the present study are an order of magnitude greater than values obtained from pedestals under glacial erratics, which range from 15 to 60 mm/ky (Table II): 15 mm/ky in Maren Mts, Switzerland (Bögli, 1961); 12 mm/ky in Clare-Galway, Ireland (Williams, 1966); 42 mm/ky in Leitrim, Ireland (Williams, 1966); 42 mm/ky in Craven, England (Sweeting, 1966); 32 mm/ky in Mt Jaya, West Irian, Indonesia (Peterson, 1982); 60 mm/ky in Patagonia (Maire et al., 1999). These pedestal rocks under glacial erratics are made of Carboniferous hard limestone and marble with small porosity under temperate or cold climate regions.

Higher rate in Kikai-jima under subtropical condition than that of other pedestal rocks under glacial erratics seems to be explained from the climatic condition. Jakucs (1977, pp.109-113) claimed that (1) wet tropical karst is coming to be regarded as a zone of higher surface limestone solution than temperate karst because of the great amount of surface runoff aided by vegetal and biological activity (high organic acid and high biogenic CO_2), and (2) corrosive action of tropical waters is largely limited to the surface and near-surface where they become rapidly saturated. The high porosity of reef limestone facilitates the rate of lowering.

The soil formation on the Terraces II and I

, although the process is different as follows: solution by rain in Kikai-jima and several erosion processes such as solution by rain and sea water, salt weathering, biological and biochemical actions in other coasts.

These equations show that the (constant) rate of solution is 435 mm/ky for the maximum height and 331 mm/ky for the mean height, and that solution begins about

2.4−2.5 ka after emergence. This delay is consistent with the absence of pedestals under boulders on Terrace IV, for which the emergence time is 1.4 ka.

The lower rates in the initial stage is considered as: (1) pedestals are difficult to create because the lower terraces are often washed and eroded by waves at high tide (tidal range 1.6 m in MHWL) and storm events, and sea water might have a different effect than rain water; and (2) blocks on lower terraces are easily re-transported by storm waves and tsunamis.

The solution rates obtained in the present study (330–440 mm/ky) are similar to that obtained at Iheya-jima (420 mm/ky: Takenaga 1968). The rates are an order of magnitude greater than values obtained from pedestals under glacial erratics, which range from 15 to 42 mm/ky (Bögli, 1961; Sweeting, 1966; Williams, 1966; Peterson, 1982). The difference appears to the difference in climatic conditions between glacial sites and Kikai-jima, for which the temperature is higher (22.3°C) with more precipitation (ca. 2300 mm); the temperature is the more important effect (Smith and Atkinson, 1976).

Using the height of pedestal rocks, various rates of surface lowering have been reported: 15 mm/ky in Maren Mts, Switzerland (Bögli, 1961); 12 mm/ky in Clare-Galway, Ireland (Williams, 1966); 42 mm/ky in Leitrim, Ireland (Williams, 1966); 42 mm/ky in Craven, England (Sweeting, 1966); 32 mm/ky in Mt Jaya, West Irian, Indonesia (Peterson, 1982). Takenaga (1968) reported a limestone pedestal (height 30-70 cm) with a sandstone boulder (not erratic) on a reef flat in Iheya-jima, Japan, and estimated the lowering rate to be 420 mm/ky.

The rate of solution at Kikai-jima is the same order as the rate of surface lowering of reef limestone (1000 mm/ky at Red Sea: MacFadyen, 1930; 2700–6700 mm/ky at SW Australia: Revelle and Fairbridge, 1957; 260 mm/ky at Aldabra Atoll (Indian Ocean): Trudgill, 1976) and beach rock (300 mm/ky at Bikini Atoll: Revelle and Emery, 1957; 500 mm/ky at Heron Island, GBR: Stephenson, 1961). These data are for reef limestone in tropical environments. This fact suggests that the solution rates are controlled not only by climatic conditions but also by lithology. We have no data about the effect of lithology on the solution rates – there is scope for further work.

Concluding Remarks

From the heights of pedestals on three terraces with known age of emergence at Kikai-jima, with a subtropical climate condition, the rates of ground lowering of limestone terraces (solution rates of limestone) is estimated to be 100–300 mm/ky. This value is the same order the rate of reef limestone under tropical region and as several times greater than for pedestals under glacial erratics in temperate or cold regions. The higher rates in Kikai-jima appear to derive from (1) lithology with high porosity and (2) the climatic conditions of high temperature and plentiful precipitation. 削除？

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Figure captions

Table I Physiographical setting of study sites for field measurements. D_l, D_s and D_d are three dimensions of boulder, i.e., long axis, short axis and height, respectively.

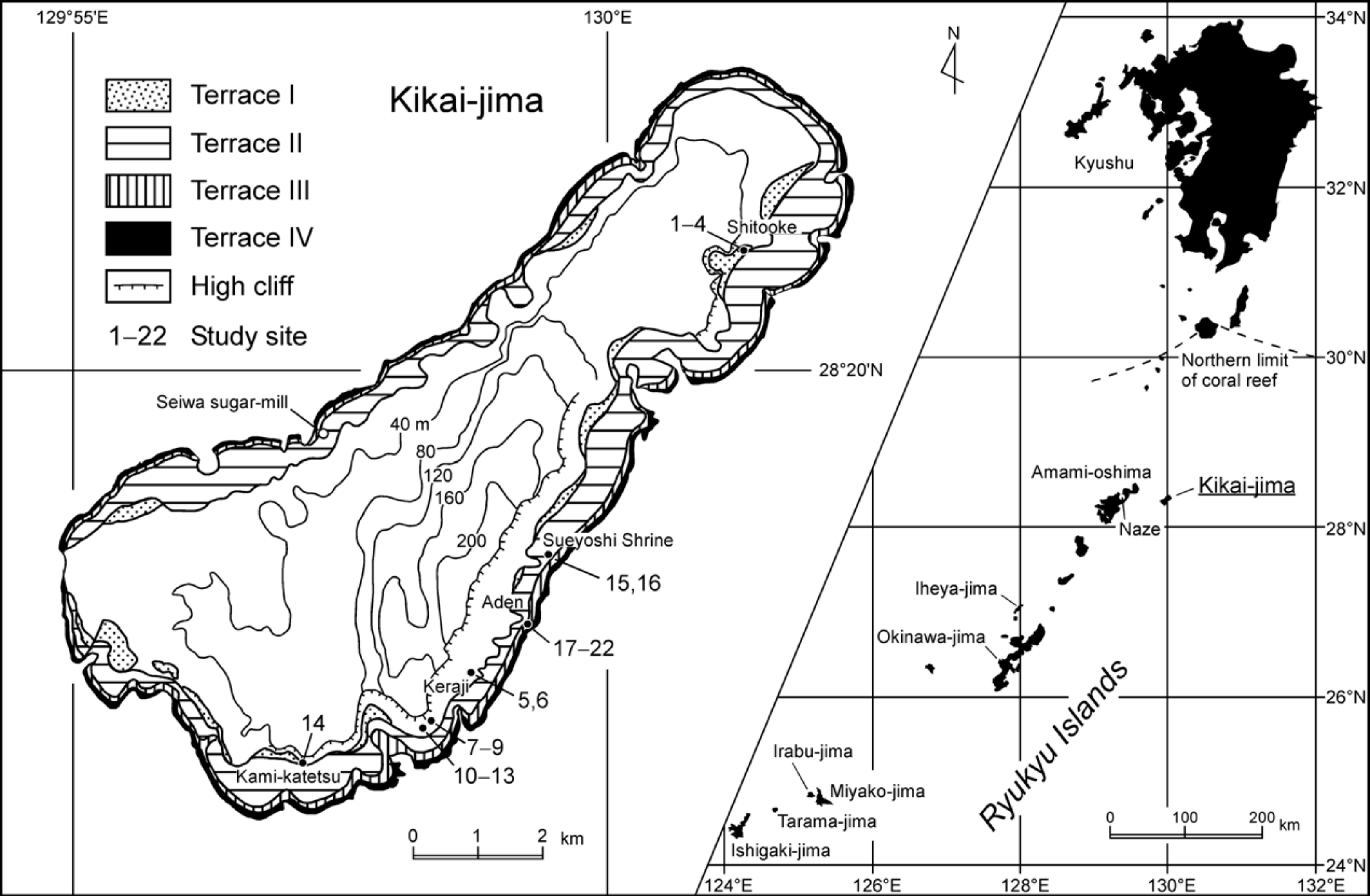
Figure 1. Study area and distribution of pedestal rocks. Holocene coral reef terraces and the line of northern limit of coral reef are from Ota et al. (1978).

Figure 2. Typical pedestals on each terrace surface. (a) Pedestal on Terrace I at Site 2. The height of the pedestal is 120 cm. (b) Pedestal on Terrace I at Site 15. The height of the pedestal is 170 cm. (c) Pedestal on Terrace II at Site 5. The height of the pedestal is 50 cm. The lower part of the pedestal is hidden under soil, approximately 20 cm deep. The block on this pedestal was first reported by Takenaga (1968) as a ‘negro head’ transported from the outer face of a reef by storm waves. Takenaga did not estimate the rate of lowering, because the dating data for the terrace surface were not then available. (d) Pedestal on Terrace III at Site 7. The height of the pedestal is 30 cm.

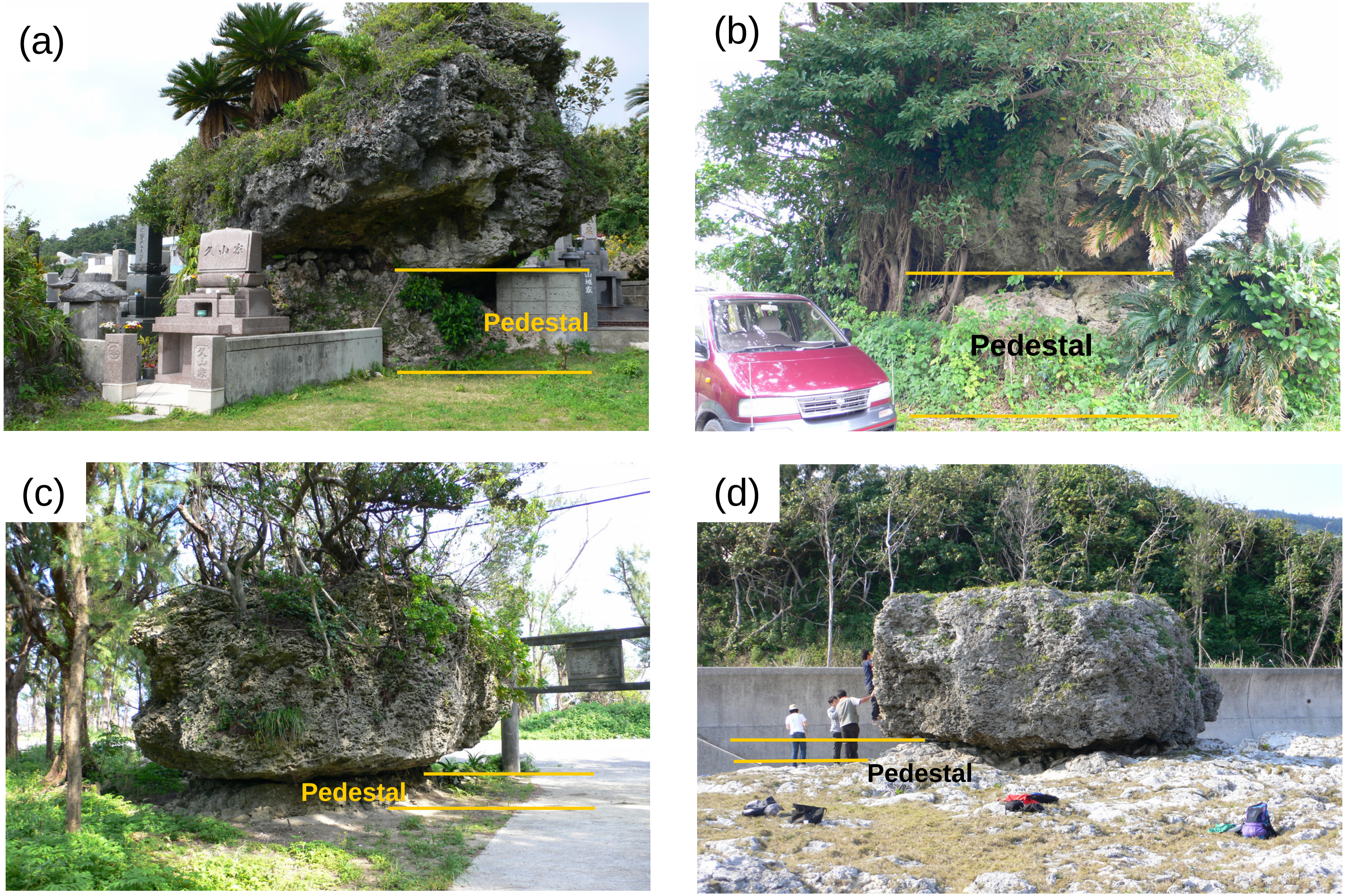
Figure 3. Relation between the height of pedestals and formative age, i.e., pedestal growth as a function of time.

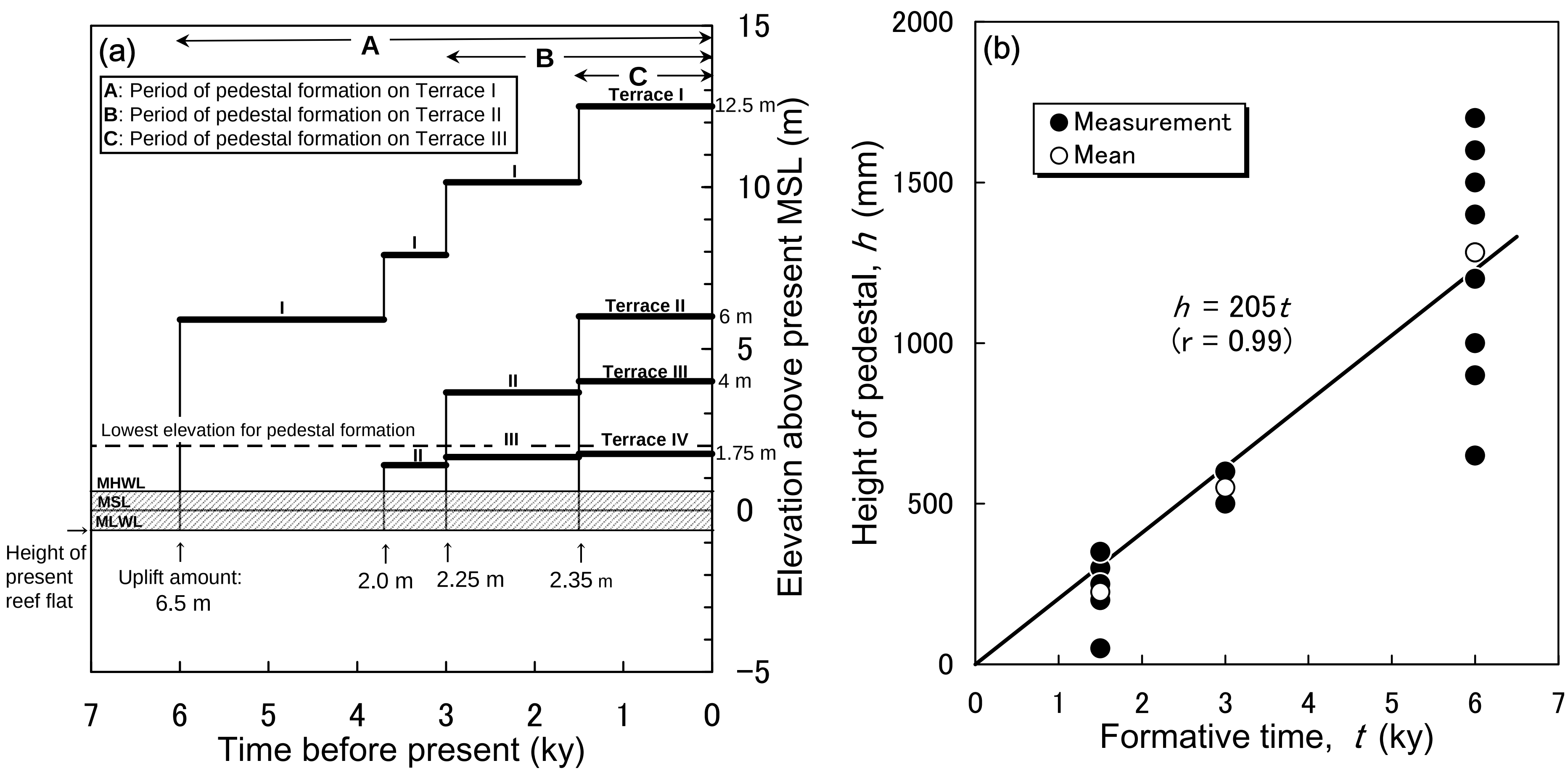
Table I Physiographical setting of study sites for field measurements. D_l, D_s and D_d are three dimensions of boulder, i.e., long axis, short axis and height, respectively.

Site No.	Location	Altitude H (m)	Terrace	Height of pedestal h (cm)	Boulder on the pedestal D_l (m)	D_s (m)	D_d (m)
1	Shitooke	7.5	I	100	6.5	3.6	2.1
2	Shitooke	7.1	I	120	9.2	6.1	3.1
3	Shitooke	6.8	I	65	3.3	2.3	1.4
4	Shitooke	5.9	I	160	10.4	4.5	6.2
5	Keraji	9.7	I	160	11.3	6.5	4.0
6	Keraji	9.7	I	150	14.0	9.6	7.6
7	Keraji	7.2	I	170	9.1	4.8	4.0
8	Keraji	7.3	I	150	8.3	6.7	4.3
9	Keraji	7.8	I	100	4.3	3.1	1.5
10	Keraji	7.5	I	150	11.6	7.9	9.2
11	Keraji	7.5	I	90	4.3	3.5	2.5
12	Keraji	7.5	I	140	4.4	3.1	2.6
13	Keraji	7.5	I	120	30.8	12.2	11.1
14	Kami-katetsu	10.0	I	120	9.5	4.8	5.3
15	Sueyoshi Shrine	6.4	II	50	6.8	5.4	3.2
16	Sueyoshi Shrine	6.4	II	60	8.0	5.2	2.6
17	Aden	3.0	III	30	9.3	7.0	3.3
18	Aden	2.1	III	35	5.1	3.9	2.7
19	Aden	2.2	III	5	3.7	2.9	3.2
20	Aden	1.9	III	25	9.7	7.0	2.9
21	Aden	2.1	III	20	3.7	3.0	1.4
22	Aden	2.1	III	20	3.8	1.8	1.1



129°55'E
130°E
Terrace I
Terrace II
Terrace III
Terrace IV
High cliff
1–22 Study site
Kikai-jima
1–4
Shitooke
28°20'N
Seiwa sugar-mill
40 m
80
120
160
200
Sueyoshi Shrine
15,16
Aden
17–22
Keraji
5,6
14
7–9
10–13
Kami-katetsu
0 1 2 km
N
34°N
Kyushu
32°N
30°N
Northern limit of coral reef
Amami-oshima
Kikai-jima
Naze
28°N
Iheya-jima
Okinawa-jima
Ryukyu Islands
26°N
Irabu-jima
Miyako-jima
Tarama-jima
Ishigaki-jima
0 100 200 km
24°N
124°E
126°E
128°E
130°E
132°E


(a)
Pedestal
(b)
Pedestal
(c)
Pedestal
(d)
Pedestal


(a)
A
B
C
A: Period of pedestal formation on Terrace I
B: Period of pedestal formation on Terrace II
C: Period of pedestal formation on Terrace III
Terrace I
Terrace II
Terrace III
Terrace IV
12.5 m
6 m
4 m
1.75 m
Lowest elevation for pedestal formation
MHWL
MSL
MLWL
Height of present reef flat
Uplift amount: 6.5 m
2.0 m
2.25 m
2.35 m
Time before present (ky)
Elevation above present MSL (m)
(b)
Measurement
Mean
h = 205t
(r = 0.99)
Height of pedestal, h (mm)
Formative time, t (ky)