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REPORT

Holocene uplifted coral reefs in Lanyu and Lutao Islands to the southeast of Taiwan

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Abstract Lanyu and Lutao Islands to the southeast of Taiwan are located in the northern extension of the Luzon Arc. Crustal deformation of these islands provides a key to understand the collision of the Luzon Arc against Taiwan. To clarify the style and the rate of vertical movement during the Holocene, uplifted coral reefs fringing these two islands were investigated. Living corals were also investigated for comparison with fossil corals. It was found that *Isopora palifera* lives dominantly in the upper slope of the present-day fringing coral reefs in Lanyu Island at an average depth of 101 ± 46 cm (one standard deviation) below mean sea level. Using *I. palifera* as an accurate indicator of paleo-sea levels, Holocene relative sea-level changes were reconstructed. Lanyu Island has been uplifted continuously at a rate of 2.0 mm yr^{-1}, at least during the late Holocene from 2,269 cal. yr BP to the present. Lutao Island has been uplifted at an average rate of 1.2 mm yr^{-1}, since at least 5,749 cal. yr BP, although it is unclear whether the uplift was continuous. The present observations, combined with the GPS displacement field and deep crustal structure, suggest that the continuous uplift is related to aseismic slip on the Longitudinal Valley Fault.

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Abbreviations
MSL Mean sea level
LVF Longitudinal Valley Fault

Introduction

This paper reports geological evidence for gradual uplift caused by aseismic slip on a plate boundary fault. Previous studies on Holocene relative sea-level changes in tectonically active regions have either placed emphasis on episodic (and in most cases coseismic) changes in sea level or ignored the distinction between episodic and gradual (and aseismic) changes altogether (Liew et al. 1993; Yamaguchi and Ota 2004). However, recent works by Zachariasen et al. (1999) and Natawidjaja et al. (2004) have shown that continuous records of sea-level change registered in coral microatolls are useful in understanding the process of strain build-up and release at subduction zones. These records show the recurrence of coseismic uplift events associated with sudden slip on a plate boundary fault, followed by gradual subsidence associated with strain build-up during interseismic periods. On the other hand, the coral reef data set of the present study revealed gradual uplift that has continued without interruption during the Late Holocene and probably since the Middle Holocene, and it is suggested that the gradual uplift is due to aseismic slip on a plate boundary fault.

In the present study, the study areas are Lanyu and Lutao Islands, located off the southeast coast of Taiwan. Taiwan is located along a convergent plate boundary, where the Luzon Arc on the Philippine Sea Plate is colliding with the Eurasian continental margin. Global positioning system (GPS) observations (Yu et al. 1997) indicate that the Philippine Sea Plate is moving to the northwest at a rate of about 80 mm yr^{-1} relative to the Chinese continental margin; the relative plate motion is accommodated mainly along the Longitudinal Valley Fault (LVF) to the east, and the fold-and-thrust belt on the west, of the Central Range. A marked discontinuity in the GPS displacement field implies that the LVF is creeping at a convergence rate about 30 mm yr^{-1} (Yu et al. 1997). Lanyu and Lutao Islands, as well as the Coastal Range of Taiwan, constitute the northern part of the Luzon volcanic arc, which is bounded to the west by the east-dipping LVF and its southern extension (Fig. 1). The Coastal Range has been uplifted at very high rates on both geodetic and geologic time scales. Leveling measurements undertaken at two stations across the LVF reveal that the Coastal Range side of the fault has been uplifted at a rate as high as 24 mm yr^{-1} (Yu and Kuo 2001). On a longer time scale, a maximum uplift rate of 15 mm yr^{-1} has been estimated for the east coast of the Coastal Range based on Holocene marine terraces and related deposits, including coral reefs (Ota and Yamaguchi 2004). Ota and Yamaguchi (2004) attributed this high rate to coseismic (episodic) changes, based on the existence of multiple steps of marine terraces. However, the geodetically observed uplift rate is high enough that the Holocene uplift can be attributed solely to aseismic creep on the LVF.

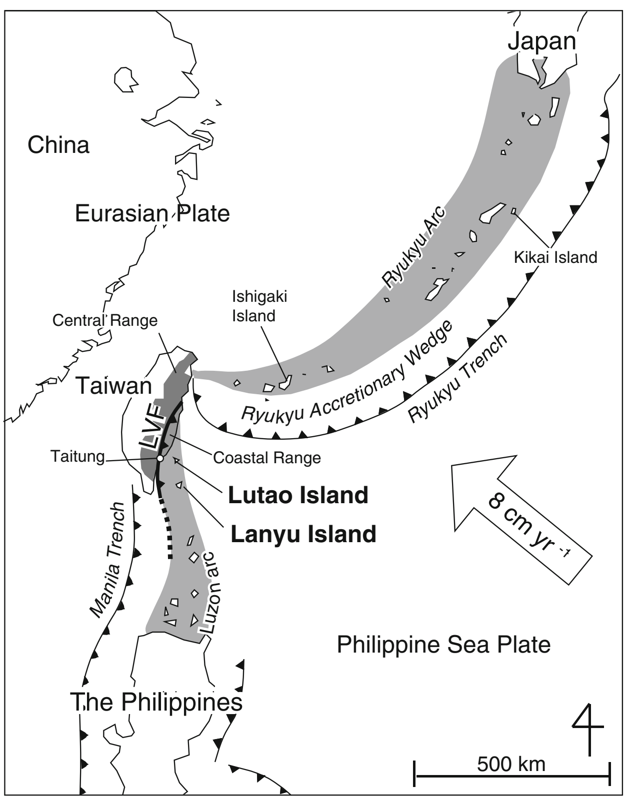

Fig. 1 The tectonic setting of Taiwan and location of Lanyu and Lutao Islands. The *open arrow* shows the current motion of the Philippine Sea Plate relative to the Chinese continental margin based on GPS data (Yu et al. 1997). *LVF* Longitudinal Valley Fault

There exists little information on the uplift style and rate at Lanyu and Lutao Islands. These islands may provide important constraints on the nature of collision tectonics in Taiwan (Fig. 1). Chen and Liu (1992) estimated the long-term uplift rate of Lutao Island to be 3.4 mm yr^{-1}, based on the heights of Pleistocene (about 80 kyr BP) marine terraces, comparing with eustatic sea-level change. Chen and Liu (1992) also estimated the uplift rate during the Holocene from radiocarbon ages and the elevations of various coastal deposits (beach clastic sediments, algal limestones, and corals) and concluded that Lutao Island has been uplifted, at a higher uplift rate in the Holocene than in the Pleistocene. However, the samples in this earlier study included detrital sediments, which did not yield paleo-sea level or age data, making it difficult to precisely discuss the nature of Holocene uplift. Considering Lanyu and Lutao Islands together as a single tectonic block, Wang and Burnett (1990) estimated a spatially averaged uplift rate of 1.6–2.2 mm yr^{-1} based on radiocarbon ages and the elevations of fossil corals. However, the living depths of the corals were not considered in their study; thus, their uplift estimate represents a minimum value because corals live within a depth range of several meters below mean sea level (MSL).

Uplifted fossil corals have been used widely in reconstructing paleo-sea level. Previous studies have used coral facies to reconstruct paleo-sea level (Chappell et al. 1996; Ota and Chappell 1999). Recently, Sugihara et al. (2003) precisely estimated paleo-sea levels in Kikai Island (Fig. 1) based on a coral species, *Pocillopora verrucosa*, which lives in a narrow depth range with a peak abundance at 1.5 m below mean seal level (MSL). Precise indicators of paleo-sea level are necessary to reconstruct the Holocene uplift history and uplift rates for these two islands. In the present study, depth distribution of living corals in Lanyu was examined and used to reconstruct the Holocene uplift history and uplift rate for Lanyu and Lutao Islands.

Study sites and methods

Study sites

Lanyu and Lutao Islands are located about 98 and 33 km east of Taitung, a city on the east coast of Taiwan, respectively, and are apart from each other about 70 km north and south (Fig. 1). Both islands are underlain by andesitic rocks and are rimmed by coral reef terraces at

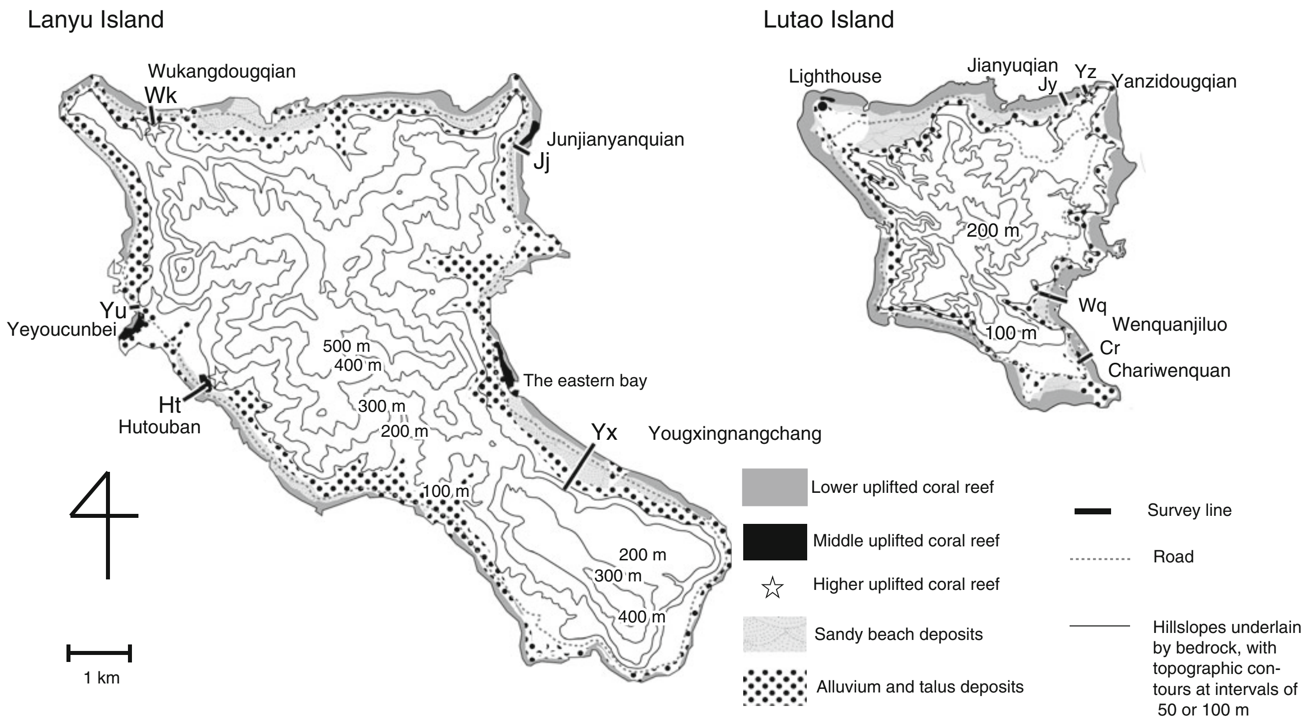

Fig. 2 Geomorphic maps of Holocene uplifted coral reefs on Lutao and Lanyu Islands, showing the locations of survey lines. The lower uplifted coral reefs fringe almost of the both islands, while the middle and the higher uplifted coral reefs distribute in limited area near the cliff of basement

several elevations developed from the Pleistocene to the Holocene (Chen and Liu 1992). The tidal range around the study sites is about 1.1 m, based on data for Taitung provided by XTide software. These islands contain modern fringing reefs with a relatively high species diversity of corals. The estimated number of stony coral species in these two islands is about 300 (Dai et al. 2004).

Present reef and depth distribution of living corals

A line transect method was used to record the distribution of corals along a single transect at Hutouban on the southwest coast of Lanyu Island (Ht in Fig. 2) on October 19, 2008. The line was 35 m long, starting from the shoreline and extending seaward in a direction perpendicular to the coastline, connecting to the Ht line across uplifted coral reefs on land. A measuring tape was set along the transect line, enabling a record to be made of the positions, depths, and species or genera of all the coral colonies encountered along the transect line. To construct the section showing the landform of coral reefs, water depth was measured using a staff every 5 m and at points of landform change. In water depths >5 m, depth was gauged using a diving computer (Dive Beans Neo, Bism Corporation, Japan). Those corals along the deeper transect, not only on the line but also in the area 5 m wide of both sides of the transect line, were examined because there were only a few corals. Recorded were the genera, living depths, and diameters of corals located there.

Uplifted reefs and fossil corals

The distribution of all Holocene uplifted coral reefs was mapped based on aerial photographs with a scale of 1:5,000 and based on field observations conducted between October 16 and October 22, 2008. Along selected survey lines oriented perpendicular to the coastline, starting from the shoreline (five lines at Lanyu Island and four lines at Lutao Island), cross-sections were made using an auto-level and a staff. Elevation was measured relative to sea level along each line during the survey and was converted to elevation relative to mean sea level (MSL) by correcting for the tide level at Taitung using XTide software.

A 1-m-wide zone along each land survey line (Ht line at Lanyu Island and Jy and Cr-lines at Lutao Island) was sketched at a scale of 1:20 in order to record the genus and species of the corals. The coverage area of each genus of coral was measured using ImageJ software.

Ten fossil corals from Lanyu Island and six from Lutao Island were dated by radiocarbon method at Beta Analytic Inc. (Miami, USA). The samples were firstly analyzed for mineralogy by X-ray diffraction (XRD) with a PANalytical X'Pert diffraction system; only these samples that contained less than 2% calcite were selected for dating. Calendar year correction was performed using the Marine09 dataset (Reimer et al. 2009) and the calibration curve was smoothed following Talma and Vogel (1993), using the online calibration program and documentation CALIB Rev. 6.0.1 (Stuiver et al. 2010). A local reservoir correction was applied for water of the Kuroshio Current in the southern part ($\Delta R = 73 \pm 17$), as in the southern part of the East China Sea, following Yoneda et al. (2007).

Results

Living corals

Along the Ht line in the western part of Lanyu Island, the present shore is fringed by a gentle slope of about 35 m in width (Fig. 3), with a spur-and-groove structure. The slope extends down to a water depth of 3 m and then steepens abruptly without any shoreline angles. A platform extends farther seaward for more than 100 m, at a constant depth of about 7 m. The depth of this platform decreases to 2–3 m at the landward cut into the present reefs. The floor of the abrasion platform is covered with platy pebbles and cobbles of 5–50 cm in diameter.

An encrusting form of *I. palifera* (Fig. 4) lives at high densities at an average depth below MSL of 101 ± 46 cm (average ± SD, $n = 86$ colonies) (Fig. 5). No other corals live shallower than *I. palifera*. A variety of coral genera, including *Acropora*, *Pocillopora*, and *Heliopora*, live at

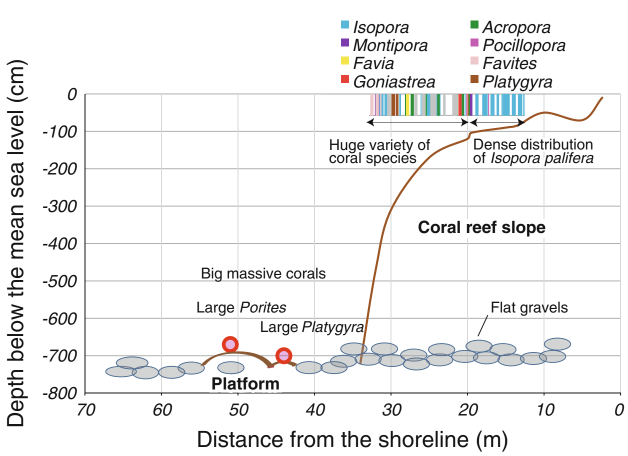

Fig. 3 Cross-section under the sea of the present coral reef along the seaward transect of Ht line on the west coast in Lanyu Island (Fig. 2). The distribution of living corals, according to genera, is plotted at the *top*. *Isopora palifera* live densely on the upper side on reef slope and massive big corals live in deeper on platform. Flat gravels were paved on the platform and big massive corals stand on the basement. *Arrows* show the general areas occupied by *I. palifera* and the huge variety of coral species

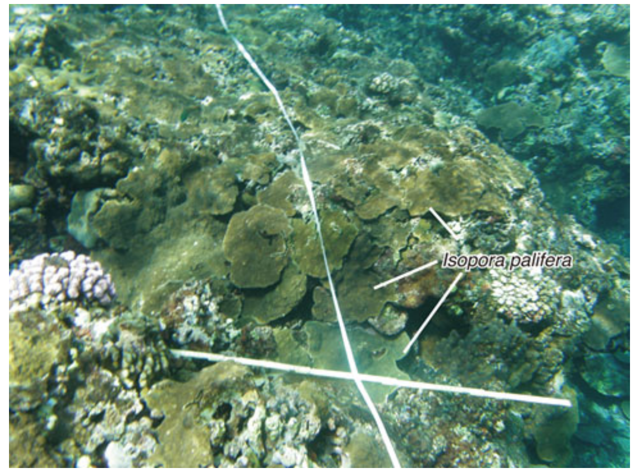

Fig. 4 *Photograph* of *I. palifera* densely encrusting the upper part of the reef slope at 19.5 m from the shore along the seaward transect of the Ht line (Fig. 2a) on Lanyu Island. The *bar* lying is 1 m long

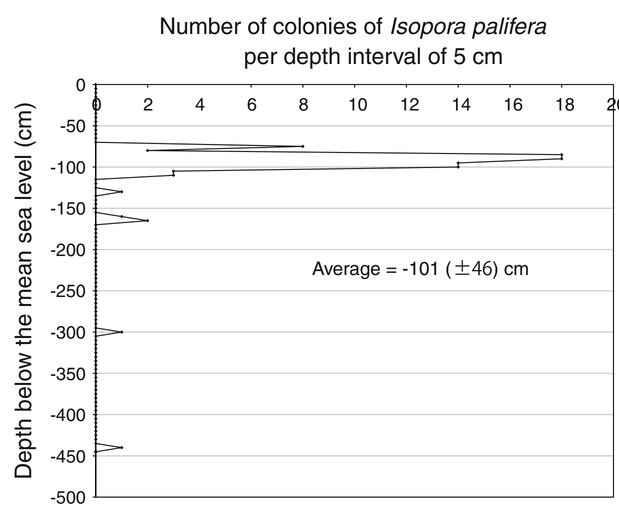

Fig. 5 Depth distribution of *I. palifera* on Ht line, Lanyu Island. The average of living depth is 101 ± 46 cm (mean ± 1σ)

depths from 100 to 500 cm on the gentle slope. Large massive corals such as *Porites* and *Platygyra*, with diameters of about 2 m, live on convex parts on the abrasion platform that are not covered with gravel.

Uplifted coral reefs

At both islands, uplifted coral reefs are divided into three levels (lower, middle, and higher) based on their elevation and plan-view patterns. The middle and higher uplifted coral reefs occurred in limited parts of the two islands (Fig. 2).

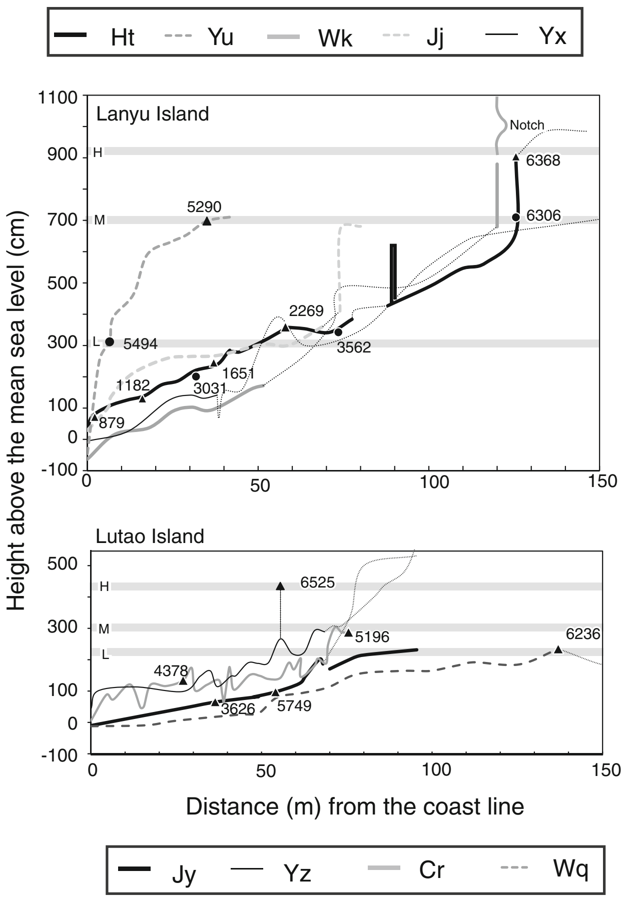

Fig. 6 Topographic profiles and locations of samples for radiocarbon dating (*triangles* encrusting type, *circles* big massive type), shown with calibrated age (yr BP). These *gray bars* with L, M, and H correspond to the elevations of the lower, middle, and higher uplifted coral reefs, respectively. Sandy beach deposits were drawn with *dot lines*

Fig. 7 Middle uplifted coral reefs about 7 m above MSL, the eastern bay, Lanyu Island (Fig. 2)

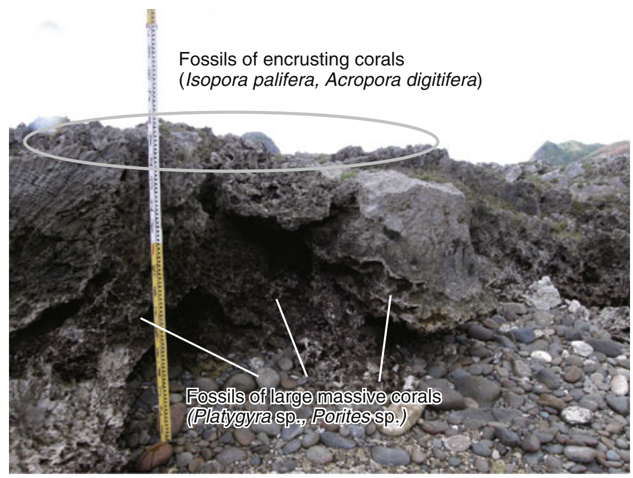

Fig. 8 Outcrop of the lower uplifted coral along the Ht line. Well-preserved fossils of encrusting corals occur on top of large massive corals such as *Porites* sp. and *Platygyra* sp.

Lanyu Island

At Lanyu Island, uplifted coral reefs are at a higher elevation than those at Lutao Island. They form discontinuous surface and the levels are consistent at different places (Fig. 6). A transect survey was conducted along five lines (the Ht, Yu, Wk, Jj, and Yx lines, in clockwise order around the island from the Ht line on the southwest coast). The lower uplifted coral reefs occur at the heights up to about 4 m above MSL and rim almost the entire coastline. The middle uplifted coral reefs occur at the heights of about 7 m above MSL and were found only at the Ht, Jj, and Yu lines, and at the eastern bay (Figs. 2, 7) where basement rock is exposed. The higher uplifted coral reefs occur at about 9 m above MSL and are found at two sites: the wall of a marine cave on the Wk line in the northwest of the island and on an outcrop along the Ht line (Fig. 2).

The Ht line was set at Hutouban on the west coast and surveyed in detail. The lower uplifted coral reef was less than 3.5 m above MSL and slope seaward gently (Fig. 6). On the flat surface of beach deposits of basalt gravels and sands 5 m above MSL, there are some mounds of middle uplifted coral reefs (about 1–4 m wide and 0.3–2 m high). Landward of the middle uplifted coral reef, there occurs an outcrop with a flat upper surface. It is defined the higher uplifted coral reef. The top of the outcrop is about 9 m above MSL.

Isopora palifera predominantly covers the surface of the lower uplifted coral reefs. In addition to *I. palifera*, there are other encrusting corals such as *A. digitifera* and *A. gemmifera*. Such encrusting corals overlie large massive corals such as *Porites* and *Platygyra* (Fig. 8). On the surface of the lower uplifted coral reefs, fresh fossil corals (including *I. palifera*, *A. digitifera*, and *A. gemmifera*) are identified from among weathered corals, some of which are so worn that they possess no anatomic structure.

Isolated mounds of middle uplifted coral reefs that occur along the Ht line are dominated by the genera *Pocillopora*, *Goniastrea*, and *Millepora,* but the tops of these middle coral reefs are covered with vegetation, and therefore, it is not clarified what corals are on the upper surface. The outcrop of the higher uplifted coral reef consists of encrusting *I. palifera* and *Favites chinensis* on the top and large massive *Porites* sp. on the bottom.

The Yu line was set at Yeyoucunbei on the northwest coast, near a cliff of bedrock. The transect line includes narrow lower and middle uplifted coral reefs whose top elevation is about 7 m. The surface of the middle uplifted coral reef contains large massive corals that exceed 1 m in diameter and that consists of *Porites* sp. and *Diploastrea heliopora* overlain by *I. palifera.* The internal structure of these massive corals is the same as that at the outcrop of the lower uplifted coral reef along the Ht line (Fig. 8). Also observed were *Goniastrea retiformis* and *Favites* species, but no *Acropora* species.

The Wk line was set at Wukangdougqian on the northern coast, where lower and higher uplifted coral reefs are found. The lower uplifted coral reef about 2 m above MSL forms a gentle slope that dips seaward (Fig. 6). Only encrusting fossil corals (e.g., *I. palifera*, *A. digitifera*, and *A. gemmifera*) were observed on the lower reef. Landward, the lower uplifted coral reef is covered with beach deposits of flat gravels and sands and they form flat surface about 5 m above MSL. The higher uplifted coral reef is found on the wall of a marine cave located 9 m above MSL. The reef is about 2 m wide and 1.5 m high; a diphycercal notch at 1.5 m above the top of the reef (10.5 m above MSL) indicates the paleo-mean sea level.

The Jj line was set at Junjianyanquian on the northeast coast. Lower and middle uplifted coral reefs occur along the survey line. The lower uplifted coral reef 3.5 m above MSL slopes seaward. The lower reef is covered with beach sands about 0.5 m thick on its landward part >4 m above MSL. In the area of the lower uplifted coral reef, some mounds of the middle uplifted coral reefs distribute at around 7 m above MSL, the top of which are flat surfaces about 3 m in diameter (Fig. 6). A continuous surface of uplifted coral reef occurs at about 10 m north from the survey line, at a similar elevation to the mounds. It was difficult to survey the reef because of bush cover. In addition to encrusting corals, branching *Acropora* species and *G. retiformis* are seen on the lower and middle uplifted coral reefs.

The Yx line was set at Yougxingnangchang on the east coast. The transect line includes a lower uplifted coral reef about 2 m above MSL and beach deposits on it (Fig. 6). There is also an alluvial fan landward. Fossil corals on this line are similar to those on the lower reef on the Wk line. Only encrusting fossil corals of *I. palifera*, *A. digitifera*, *and A. gemmifera* are seen and the surface is very smooth.

Lutao Island

At Lutao Island, uplifted coral reefs are lower than those in Lanyu Island (Fig. 6). Transect surveys were conducted along four lines (the Jy, Yz, Wq, and Cr lines, in clockwise order around the island from the Jy line on the northeast coast) (Fig. 2). Lower uplifted coral reefs occur at less than 2.5 m above MSL and form continuous gentle slopes. These reefs fringe the entire coastline of the island. Middle and higher uplifted coral reefs do not form wide flat surface as a whole. Middle uplifted coral reefs occur at about 3 m above MSL and are found only at the Cr and Yz lines and near the lighthouse at the northwest of the island, where basement is exposed (Fig. 2). The higher uplifted coral reef is found only at one site near the Yz line, where it is attached to basement rock and is at an elevation of 4.5 m above MSL.

The Jy line was set at Jianyuqian on the northeast coast. The line contains an uplifted coral reef of the lower level and the alluvial lowland. The uplifted coral reef is covered with beach sands. The highest uplifted coral reef is seen at 2.5 m above MSL, and about 3 m thick of sand accumulates on the coral. The surface of the uplifted coral reef was so ablated that it was difficult to identify the genera of constituent corals from the surface; however, observations of a section cut through the fossil corals by hammer revealed the dominance of *I. palifera*.

The Yz line was set at Yanzidougqian on the northeast coast near a cliff of bedrock. The line includes the uplifted coral reef of the lower level at 2 m and the middle level at 3 m above MSL, and the uplifted coral reef of the higher level at about 4.5 m above MSL is present about 7 m east of the line. The higher uplifted coral reef has a horizontal flat upper surface of 1×1.5 m in size and is attached to a bedrock boulder. The reef includes *I. palifera* lain alongside by *G. retiformis.*

The Wq line was set at Wenquanjiluo on the east coast. The transect line includes an uplifted coral reef of the lower level 2.5 m above MSL. The landward surface of the reef is covered with beach deposits of gravels and sands, and scattered boulders of basement were found at the foot of the cliff and near the shoreline. The uplifted coral reef consists almost of encrusting *I. palifera*, which live at shallow depth on the present reef.

The Cr line was set at Chariwenquan on the southeast coast, near a cliff of bedrock. The transect line includes uplifted coral reefs of the lower and middle levels 2 and 3 m above MSL, respectively. Boulder gravel covers the reef near the cliff. The lower and the middle uplifted coral reef largely consisted of encrusting corals of *I. palifera*, *A. digitifera*, and *A. gemmifera*.

Radiocarbon ages of fossil corals

Table 1 lists the results of radiocarbon dating; the elevations of the dated samples are plotted in Fig. 6.

Lanyu Island

The highest coral (Ht-17, 9.0 m above MSL) has an age of 6,368 cal. yr BP. The higher-level encrusting fossil corals of *I. palifera*, *A. digitifera*, and *A. gemmifera* yield the older dates. However, this age–height relation is not found for large massive corals in the lower uplifted coral reef. Even though they are at lower elevations, big massive corals yield older ages than fossils of encrusting *I. palifera*. The radiocarbon ages of large massive corals at 3.4 (Ht-7) and 2 m (Ht-19) above MSL are 3,562 and 3,031 cal. yr BP, respectively, whereas those of encrusting *I. palifera* at 3.6 m (Ht-8) and 2.5 m (Ht-2) are 2,269 and 1,652 cal. yr BP, respectively (Fig. 6 and Table 1).

Lutao Island

The highest coral on Lutao Island (Yz-1, 4.4 m above MSL) has an age of 6,525 cal. yr BP. The elevation of this coral is just half that of the highest coral in Lanyu Island though the ages are similar.

Discussion

I. palifera as an indicator of paleo-sea level

Coral reefs and corals have been widely used as an indicator of paleo-sea level. For example, in a study at Kikai Island in the Ryukyu Islands, Japan, changes in Holocene relative sea level were reconstructed based on the assumption that the flat surfaces of uplifted coral reefs

Table 1 Radiocarbon ages of fossil corals

Sample no.	Species	Colony type[a]	Elev. (cm)[b]	Calcite cont. (%)	^{14}C age (yr BP)[c]	Lab. no[d]	Cal. ^{14}C age(cal. yr BP)[e]	2σ Ranges
Lanyu								
Ht-9	*A. digitifera*	E	71	0	1,410 ± 40	Beta-254577	879	764–972
Ht-10	*I. palifera*	E	130	0	1,690 ± 40	Beta-253565	1,182	1,067–1,269
Ht-19	*Porites* sp.	BM	201	0	3,290 ± 40	Beta-253567	3,031	2,887–3,179
Ht-2	*I. palifera*	E	245	0	2,150 ± 40	Beta-253563	1,651	1,531–1,776
Yu-1	*D. heliopora*	BM	311	0	5,200 ± 50	Beta-253568	5,494	5,330–5,584
Ht-7	*P. sinensis*	BM	342	0	3,730 ± 50	Beta-253564	3,562	3,417–3,702
Ht-8	*I. palifera*	E	359	0.6	2,670 ± 50	Beta-254576	2,269	2,121–2,406
Yu-2	*I. palifera*	E	697	1.8	5,020 ± 50	Beta-254579	5,290	5,111–5,441
Ht-15	*Porites* sp.	BM	709	0	5,960 ± 50	Beta-254578	6,306	6,192–6,413
Ht-17	*F. chinensis*	M	904	0	6,030 ± 50	Beta-253566	6,368	6,265–6,489
Lutao								
Jy-1	*A. gemmifera*	E	65	0	3,780 ± 50	Beta-253571	3,626	3,473–3,780
Jy-3	*I. palifera*	E	97	0	5,450 ± 60	Beta-254580	5,749	5,606–5,886
Cr-1	*A. gemmifera*	E	134	0	4,340 ± 50	Beta-253569	4,378	4,216–4,524
Wq-1	*A. digitifera*	E	234	0	5,890 ± 60	Beta-254581	6,236	6,091–6,385
Cr-4	*I. palifera*	E	288	0	4,960 ± 50	Beta-253570	5,196	4,999–5,325
Yz-1	*G. retiformis*	M	435	0	6,170 ± 50	Beta-253572	6,525	6,395–6,652

Alphabets before the numbers in "Sample No." mean the sample site

[a] *E* Encrusting type, which lives shallower on the upper of reef slope; *BM* Big massive, which lives deeper on abrasion platform; *M* Massive, which lives on reef slope

[b] Elevation above mean sea level

[c] Conventional ^{14}C age (yr BP $\pm$ 1σ error)

[d] Sample number assigned at dating laboratory, BETA ANALYTIC INC

[e] Calibrated with (Talma and Vogel 1993) and the data set of Marine 09 (Reimer et al. 2009), using the online calibration program and documentation, CALIB Rev. 6.0.1 (Stuiver et al. 2010). Local reservoir correction of water belonging to Kuroshio Current in the southern part, ($\Delta R = 73 \pm 17$) reported by Yoneda et al. (2007), is applied

represent paleo-sea water level of low tide (Nakata et al. 1978; Ota et al. 1978). Subsequently, Webster et al. (1998) developed a model of coral reef formation in relation to sea level changes at Kikai Island, based on observations of outcrops containing three modes of coral reef formation: keep-up, catch-up, and give-up. Sugihara et al. (2003) reported that *P. verrucosa* showed a peak abundance at a depth of 1.5 m on the reef slope of fringing reefs in the Ryukyu Islands and used this species to precisely reconstruct sea-level changes at Kikai Island.

The present results indicate that *I. palifera* is an excellent indicator species on the Ht line where revealed the peak abundance of *I. palifera*. Live encrusting *I. palifera* on the reef slope of fringing reefs at Ht is densely distributed on the upper slope of the coral reef at an average elevation of 101 $\pm$ 46 cm (average $\pm$ SD) below present MSL. According to Nishihira and Veron (1995), *I. palifera* lives predominantly on upper reef slopes in areas with strong wave energy; it is rarely observed in other environments. Therefore, the peak abundance of its distribution, in the case of fossil specimens, indicates the location of the upper reef slope. The cross-sections surveyed on uplifted coral reefs at the Ht and Yu lines—which were both located on the lee side of the island, on which samples of fossil corals were dated—indicate an environment similar to that of the present reef slope along the Ht line: an upper reef slope facing the ocean, without a reef crest to block the ocean swell. In addition, several Holocene paleo-sea surface temperatures in low and mid-latitudes of the northwestern Pacific are similar to the present mean SST (Shen et al. 2005). Therefore, in the present study, the relation between *I. palifera* and mean sea level is applied to reconstruct the paleo-mean sea level at the Ht and Yu lines. However, the reconstructed paleo-sea level at Lutao Island is less accurate, as we have not examined the depth range of *I. palifera* or other corals for this island.

The distributions of fossil corals of other species or genera (i.e., other than *I. palifera)* also provide information on the paleo-sea level. In the present study, fossils of encrusting *Acropora* species were observed on both islands. The main species of *Acropora* found as encrusting fossils were *A. digitifera* and *A. gemmifera.* These species usually form colonies of corymbose type, but they change to encrusting type where exposed to strong waves (Nishihira and Veron 1995).

Regarding the living depth of fossil corals at the highest level upon both islands, *F. chinensis* was uppermost on Lanyu Island (Table 1, Ht-17) and *G. retiformis* was uppermost on Lutao Island (Table 1, Yz-1). These species generally have a wide range of living depths; however, it is inferred that the fossil corals at the highest levels lived at depths as shallow as those for *I. palifera* because fossils of *I. palifera* were found adjacent to the highest fossil corals. In addition, both fossil corals of *F. chinensis* and *G. retiformis* were found on the upper part of a flat, horizontal surface, similar to the upper part of the present coral reef. These observations indicate that the fossils Ht-17 and Yz-1 lived at a shallow depth, similar to that for *I. palifera*.

Large massive corals (e.g., *Porites* and *Platygyra*) grow well at greater water depths than those preferred by other corals. Large massive corals were not observed on the shallower reef slope, but were found on platforms at a depth of about 7 m. This finding indicates that they had occupied a zone located deeper than the reef slope, although it is difficult to estimate their time of death. Therefore, massive corals do not provide effective paleo-depth indicators, though it is known that the large massive corals cannot live at depths shallower than those occupied by *I. palifera.* It is because they yield an older age than that of *I. palifera* at higher elevations (Fig. 6 and Table 1). For example, Yu-1 (*D. heliopora*) obtained from the lower uplifted coral reef, but it was dated as 5,494 cal. yr BP.

Holocene reconstructed relative sea level

To accurately reconstruct changes in relative sea level at Lanyu and Lutao islands, *I. palifera* is used as a precise depth indicator. Holocene relative paleo-mean sea level is estimated by adding the average peak abundance depth (101 $\pm$ 46 cm below the present-day MSL) obtained along the Ht line at Lanyu Island and the observed elevations of fossils of this species (filled triangles in Fig. 9). As an additional guide, corals of other species (*A. digitifera, A. gemmifera, F. chinensis*, and *G. retiformis*) are used as secondary indicators (open triangles in Fig. 9).

The elevations of notches and the surface elevations of uplifted coral reefs are also considered in the reconstruction. The presence of massive corals only indicates the minimum elevation of sea level (open circles). Also plotted in Fig. 9 are the heights and ages of in situ algal (filled square) and coral samples (open squares) at Lutao Island, as reported by Chen and Liu (1992). Previously published conventional ages are converted to cal. yr BP using the procedure described above.

Along the Ht section, fossils of *I. palifera* in the lower uplifted coral reefs become progressively older with increasing relative paleo-sea level, as reconstructed from their elevations, taking account of their living depth (Fig. 9). The sea level curves for lower uplifted coral reefs at Lanyu Island show a smooth, continuous slope (Fig. 6). These findings suggest that sea level at Lanyu Island has dropped continuously, rather than episodically, at least during the late Holocene from 2,269 cal. yr BP to the present. Just as a reference, in the similar way, the Holocene relative sea-level curve for Lutao Island is reconstructed. The sea-level curve shows a drop rise from 5,749

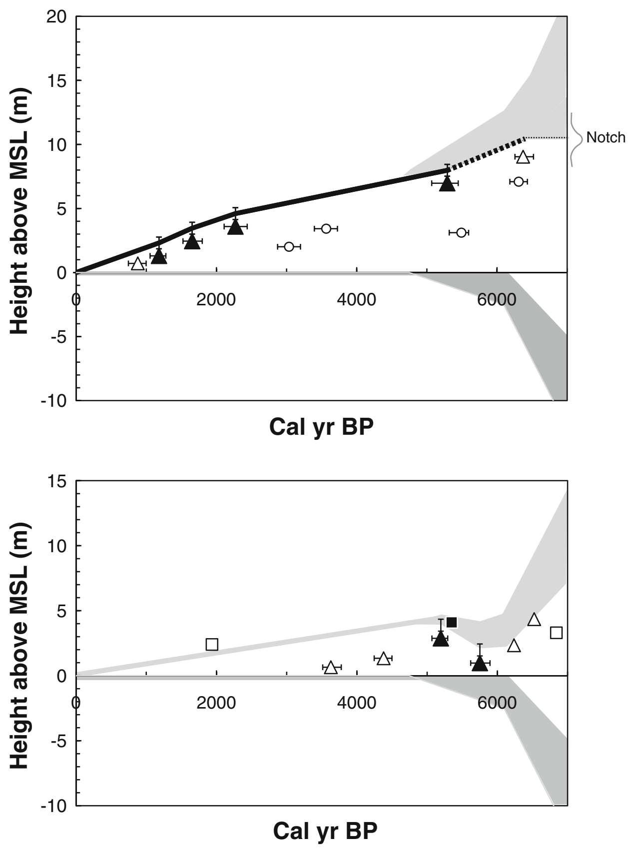

Fig. 9 Reconstructed Holocene relative sea level at Lanyu (**a**) and Lutao (**b**) Islands. In Lanyu Island, relative sea level change is drawn in *solid line-curve*. Paleo-mean sea level is reconstructed from the elevations and the ages of *I. palifera* (*filled triangles* with *vertical error bar* of 1σ and *horizon bar* of 2σ). The average living depth of 101 $\pm$ 46 cm (mean $\pm$ 1σ) below MSL of present-day *I. palifera* was used for the calibration (see Fig. 5). Elevations and ages (with error bar of 2σ) of encrusting corals (*open triangles*), and massive corals (*open circles*) are also plotted. An age datum reported by Chen and Liu (1992) is plotted as a *filled square*; encrusting algal limestone, which indicates the exact sea level is plotted as an *open square*; coral indicates levels below sea level. *Dark grey area*: reference eustatic sea-level range (Yokoyama et al. 1996; Hongo and Kayanne 2010; Bard et al. 1996; Nakada 1986). *Light gray area* Range of vertical displacement of each island obtained subtracting the eustatic sea-level range

to 5,196 cal. yr BP, based on data from *I. palifera*. The data from Chen and Liu (1992) are well consistent with the relative sea-level curve reconstructed in the present study.

The highest sea level is indicated with the oldest corals on each island. *Favites chinensis* (Ht-17) at an elevation of 9.0 m on Lanyu Island yielded an age of 6,368 cal. yr BP. The surface elevation of upper reefs (9.0 m) and the elevation of the notch at the Wk line (10.5 m) indicate that the highest sea level reached an elevation of 10.5 m in the mid-Holocene, because the reef surface and notch correspond to low water level and mean sea level, respectively. At Lutao Island, there is relatively little evidence regarding the highest sea level. *G. retiformis* (Yz-1) at an elevation of 4.4 m yields an age of 6,525 cal. yr BP. This fossil co-occurred with *I. palifera,* and the highest sea level is tentatively estimated to have been 5.5 m. Further research is necessary in this regard.

Changes in relative sea level during the Holocene have been influenced by changes in seawater volume, the glacio- and hydroisostatic redistribution of earth mass, and vertical tectonic displacement. At islands located far from ice sheets and continental margins, the timing of an inflection in sea level, representing a change from an increase to stabilization or to a slight fall, differs with the location and size of the island. In Fig. 9, dark gray area indicates the range of reconstructed sea level curves during the Holocene near or similar this study site. It includes these sea level curves in Ishigaki island (Hongo and Kayanne 2010, Fig. 1), around western Japan (Yokoyama et al. 1996), in Tahiti (Bard et al. 1996), and in far field model island less than 10 km in diameter (Nakada 1986). Hongo and Kayanne (2010) reconstructed the sea level curve for Ishigaki Island, revealing a mid-Holocene highstand of 3 m at 4,700 cal. yr BP. The occurrence of a highstand is controlled by the size of the island: larger islands experience a higher stand of sea level due to hydroisostatic emergence (Nakada 1986; Grossman et al. 1998). Lanyu and Lutao islands are small (radii of 10 and 4 km, respectively) relative to Ishigaki Island (radius, 30 km); thus, minimal hydroisostatic emergence is inferred for these islands. Here, a stabilized sea level is applied after 4,700 cal. yr BP as an approximate reference curve in grey area in Fig. 9. By subtracting the reference sea-level curve before 4,700 cal. yr BP, the history of vertical displacement is obtained for the two islands (light gray area in Fig. 9). After 4,700 cal. yr BP, the history of vertical displacement is represented by the relative sea-level curve. There is no accurate indicator of paleo-sea level at Lutao Island for the period after 4,700 cal. yr BP; consequently, a linear decline in sea level is tentatively shown for the period from 5,749 to 5,196 cal. yr BP. The vertical distribution of *A. digitifera* and the data reported by Chen and Liu (1992) after 4,700 cal. yr BP are consistent with a continuous fall in sea level.

Continuous uplift during the late Holocene

Continuous uplift at Lanyu Island since 2,269 cal. yr BP is strongly constrained by the age–elevation relation of *I. palifera* on the smooth continuous slope of the lower uplifted coral reefs (Fig. 9). Lanyu Island has been uplifted continuously, rather than episodically, at least during the late Holocene from about 2,269 cal. yr BP to the present. The rate of continuous uplift at Lanyu Island is 2.0 mm yr^{-1}, which is an order of magnitude less than that along the Coastal Range of Taiwan. The amount of uplift

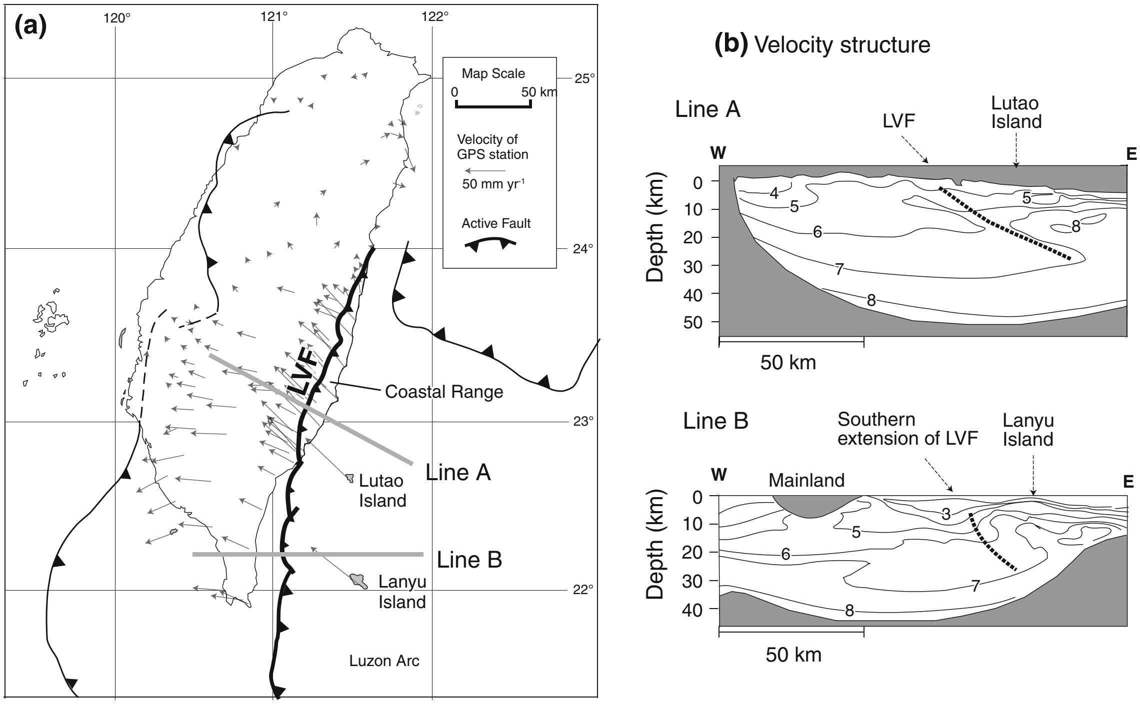

Fig. 10 **a** Major tectonic elements of Taiwan and its vicinity (modified from Malavielle and Trullenque 2009). *Arrows* show horizontal displacement field measured by GPS (data from Yu et al. 1997). The Longitudinal Valley Fault (LVF) forms a major boundary between the Luzon Arc and the Central Range of Taiwan. Note that the northern extension of Luzon Arc, including the Coastal Range, Lanyu and Lutao Islands, is moving northwestward at rates as high as 56–82 mm yr^{-1} almost as a seamless block with respect to the Central Range of Taiwan. **b** *P* wave velocity structure revealed by wide-angle seismic experiments (data from McIntosh et al. 2005). Survey *lines* are located in Fig. 10a. Contours indicate *P* wave velocity (contour values are in km/s). *Grey shadows* indicate areas where velocity structure is poorly resolved. *Thick dashed lines* indicate the deep extension of the LVF as interpreted by McIntosh et al. (2005). Note that the dip angle of the LVF, which is sensitive to surface uplift rates, is possibly higher beneath Lanyu Island than beneath Lutao Island

reconstructed from *I. palifera* (Yu-2) with an age of 5,290 cal. yr BP, on the middle uplifted coral reef, is in good agreement with the amount obtained by extrapolating the late Holocene uplift rate (Fig. 9). It indicates continuous uplift has been occurred from 5,290 cal. yr BP previously. There is no clear evidence regarding whether Lutao Island also has been uplifted continuously. The slight rise from 5,196 to 5,740 cal. yr BP, as indicated by *I. palifera*, appears to correspond to the sea level rise during this period, and the reconstructed tectonic displacement curve indicates continuous uplift. The average uplift rate at Lutao Island since 5,749 cal. yr BP is tentatively estimated as approximately 1.2 mm yr^{-1}.

The following lines of evidence suggest that the continuous uplift at Lanyu Island was caused by aseismic slip on the LVF and its southward extension. Recent GPS observations by Yu et al. (1997) reveal that the northern extension of the Luzon Arc, including the Coastal Range, and Lanyu and Lutao Islands, is moving northwestward, possibly as a single block, with respect to the Central Range of Taiwan (Fig. 10a). Yu et al. (1997) also reported a marked discontinuity (dominantly contractive) in the horizontal velocity field across the LVF and attributed the discontinuity to aseismic slip (up to 30 mm yr^{-1}) on the LVF. In addition, McIntosh et al. (2005) examined the deep velocity structure of Taiwan based on onshore and offshore wide-angle seismic datasets (Fig. 10b). According to their results, the LVF marks an east-dipping boundary between a higher-velocity body beneath the Luzon arc (east of the fault) and a lower-velocity body beneath the Central Range (west of the fault). These two lines of evidence indicate that the LVF is an east-dipping fault on which the rate of aseismic thrust slip is about 30 mm yr^{-1}. This rapid aseismic slip is associated with vertical movement on its hanging-wall side, with a higher rate of uplift with decreasing distance from the fault. Thus, it is interpreted that the continuous uplift of Lanyu Island (and possibly also Lutao Island) is caused by aseismic slip on the LVF.

The average uplift rate at Lanyu Island during the late Holocene is higher than that at Lutao Island, despite the fact that Lutao Island is located closer to the surface trace of the LVF. The difference in uplift rates between the islands is tentatively attributed to lateral variations in fault geometry: the dip of the LVF, as deduced from the velocity structure, is much higher beneath Lanyu Island than beneath Lutao Island (McIntosh et al. 2005; Fig. 10b).

In summary, the use of *I. palifera* as an accurate indicator of paleo-sea levels revealed that gradual uplift—caused by aseismic slip on a plate boundary fault—has continued without interruption during the Late Holocene and probably since the Middle Holocene.

Formation of uplifted coral reefs at different levels

At Lanyu Island, uplifted coral reefs occur at three different elevations and each reef has a wide surface. Holocene sea-level change reconstructed with *I. palifera* indicates that Lanyu Island has been uplifted continuously since 5,290 cal. yr BP, which is when the middle uplifted coral reef formed, i.e., the separation of the lower uplifted coral reef from the middle one was due to continuous rather than episodic uplift.

The separation of the two reefs occurred because of the existence of an original geomorphological gap of marine platform. In the present sea, there is a wide platform with basalt gravels and massive corals on the seaward side of the reef, separated from the reef by a low scarp (Fig. 3). Middle uplifted coral reef has a typical reef flat, whereas the lower uplifted coral reef slopes seaward. The latter is formed of massive corals and coral gravels covered by encrusting corals and probably formed as a platform on the seaward side of the middle uplifted coral reef. The scarp between the middle and lower coral reefs corresponds to the scarp between the reef and the platform; the continuous decline of sea level resulted in the platform rising to shallower depths, along with encrusting corals attached to it.

In previous studies, separated terraces of coral reefs have generally been explained by episodic uplift (Liew et al. 1993; Yamaguchi and Ota 2004). However, our results indicate that separate landforms may form during a continuous decline in sea level. In this study, the use of *I. palifera* as a paleo-depth indicator showed continuous uplift for the first time. The present movement of the LVF, as determined in geodetic studies, involves aseismic slip. The rate of aseismic slip is concordant with the long-term uplift rate obtained through geomorphological analysis, which is explained as the accumulation of episodic uplift evident as coral reef terraces. Our results show that continuous slip has occurred for at least the past 5,000 years, which is concordant with geodetic observations.

The higher uplifted coral reefs have a patchy distribution, but the presence of notches at the levels of these reefs indicates a short period of sea level stability during their formation. This observation may indicate that Holocene sea level reached a stable position. However, the reference sea-level curves are variable for observations before 4,700 yr cal. BP, and the details of the sea level change, which separated the middle coral reefs from the higher coral reefs, are unknown.

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