MEMOIR OF THE GEOLOGICAL SOCIETY OF CHINA
NO. 2, PP. 57-69, 6 FIGS., 2 TABS., OCTOBER 1977

TECTONIC UPLIFT RATES OF THE TAIWAN ISLAND SINCE THE EARLY HOLOCENE[1]

TSUNG-HUNG PENG,[2] YUAN-HUI LI,[2] and FRANCIS T. WU[3]

ABSTRACT

In contrast with Konishi *et al.* and Bonilla's estimates, the average uplift rates of the Hengchun Peninsula, the Tainan area, and the Coastal Range of Taiwan for the last 9000 years all fall on a narrow range of 5.0 ± 0.7 mm/yr. The rate of uplift in the northern coastal area, on the other hand, was very small, ~ 2mm/yr at maximum, from about 1500 BP to 5500 BP but was 5.3 mm/yr from 5500 BP to 8500 BP. These rates of northern Taiwan are similar to those of the Ryukyu Islands. The striking similarity of the uplift history between northern Taiwan and the Ryukyu Islands indicates their affinity in geotectonics. The high uplift rate of the Taiwan Island is consistent with the observation that Taiwan is in the collision zone between the Asian plate and the Philippine Sea plate. The frequency of seismicity seems to relate to the rate of uplift.

INTRODUCTION

The Taiwan Island is a part of the Ryukyu-Taiwan-Philippine island-arc system but presently, unlike the Ryukyu and Philippine arcs, it lacks many features of active arc tectonics (e.g., intermediate and deep-focus earthquakes, active volcanism, strong negative Bouguer anomalies, and a well-developed foredeep). Thus, Biq (1971) is of the opinion that the Taiwan Island has entered its stage of block tectonics (Richter, 1960) or, in plate-tectonics parlance, a collision of plates is taking place there (Wu and Lu, 1976). According to Biq (1971), the Taiwan Island consists of four main blocks (Coastal Range, Central Range, Hsüeshan Range, and Foot Hills Zone plus Western Coastal Plain and Terrace) and each block moves relative to other blocks by upthrusting as well as by strike-slip faulting (Fig. 1). As a consequence, one would expect a strong differential vertical movement among the blocks, if the upthrusting is still very active.

Using (1) the radiocarbon dates (t) of raised coral reefs, (2) their present altitude (A) relative to the mean high-tide sea-level, (3) estimations of eustatic sea-level (E) relative to the present sea-level, and (4) the depositional depth of corals (D) relative to the eustatic sea-level, Konishi *et al.* (1968) estimated average uplift rate $(=[A+E+D]/t)$ of many raised coral reefs from Taiwan. The raised coral reefs from the Hualien area (the northern tip of the Coastal Range) give an uplift rate of 6-9.7 mm/yr as compared to 1.8-4.8 mm/yr for the other raised coral reefs from the northern and southern coasts of Taiwan. They concluded that the Coastal Range must be tectonically more active than the other areas of Taiwan.

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1 Lamont-Doherty Geological Observatory contribution no. 2619

2 Lamont-Doherty Geological Observatory, Palisades, N.Y. 10964, U.S.A.

3 Department of Geology, State University of New York at Binghamton, Binghamton, N.Y. 13901, U.S.A.

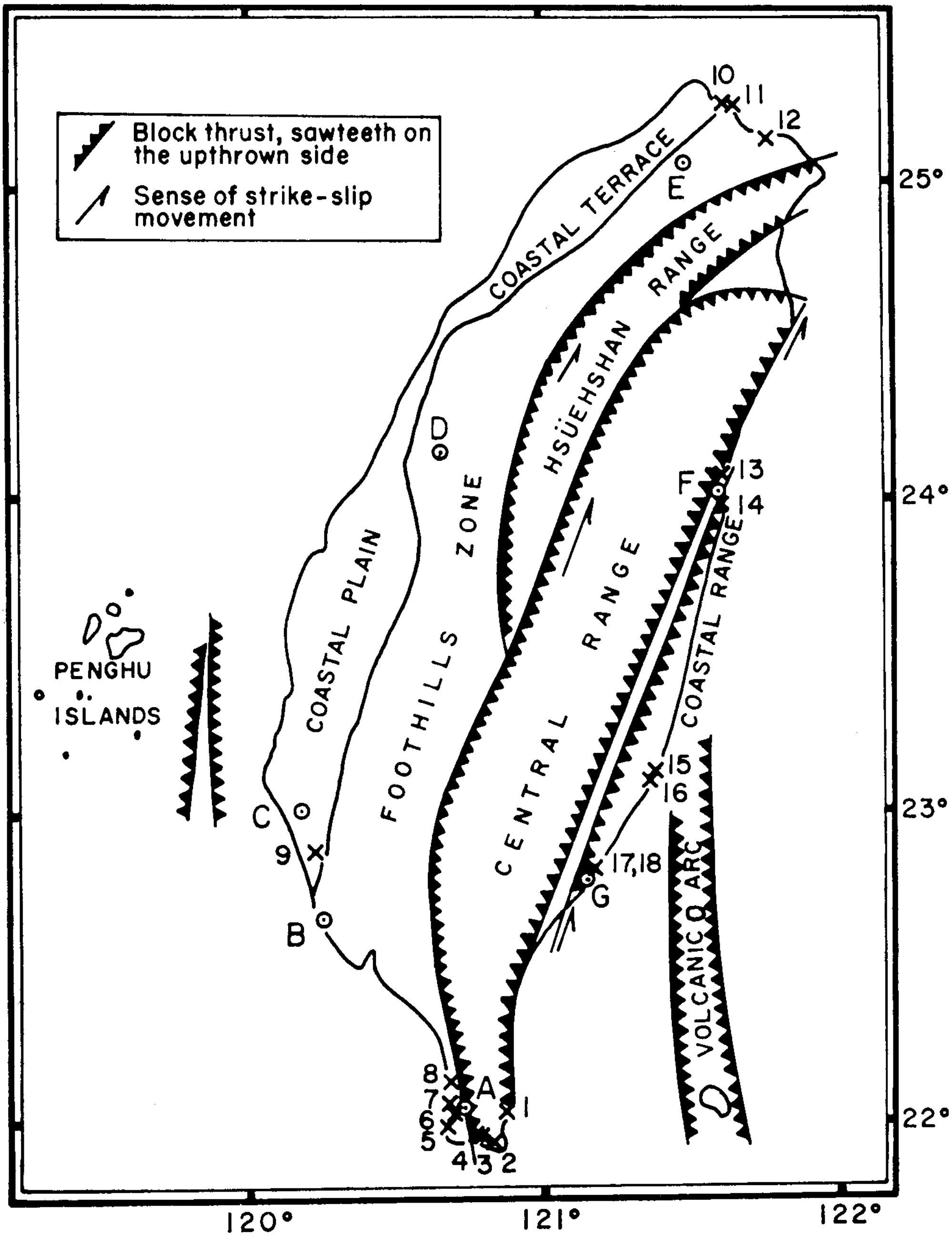

Fig. 1. The distribution of the upthrust blocks in Taiwan (Biq, 1971) and the locations of the raised coral reef samples (X). Names of numbered localities are given in Table 1. A=Hengchun, B=Kaohsiung, C=Tainan, D=Taichung, E=Taipei, F=Hualien, G=Taitung.

Recently Bonilla (1975) summarized all available radiocarbon dates (<9000 years) of raised coral reefs, marine shells, and drift woods from Taiwan and estimated a "minimum uplift rate" (=[A+E]/t) for each sample locality. His estimated rates range from 0.3 mm/yr to 8.7 mm/yr (the highest value is from the Hualien area). These values imply that the minimum uplift rate of land changes drastically from place to place even within a short distance. However, since the depositional depths of marine shells and drift woods are usually very poorly defined, one cannot directly compare the minimum uplift rates obtained from different kinds of fossil materials without knowing the depositional depths.

In order to firmly establish whether the Coastal Range has an exceptionally high uplift rate (Konishi *et al.*, 1968), we collected and dated additional samples of raised coral reefs from the Coastal Range and a few from the Hengchun Peninsula. To check the variability of the uplift rates from place to place, we have summarized only the published ^{14}C dates of raised coral reefs younger than 10,000 years from Taiwan and the Ryukyu Islands and present here our interpretation of the data.

RADIOCARBON DATING METHOD

To eliminate the possible contamination of coral samples by modern carbon, the weathered outer section of coral was removed. The sample was then acidified by phosphoric acid and the released CO_2 gas was purified through a Cu-Ag purification tube. The radiocarbon activity of the purified CO_2 was counted by a low background anti-coincident proportional counter for 17 hours or more. The NBS oxalic acid was used as the standard. We adopted 5730±30 years as the half-life of ^{14}C instead of 5570±30 years as recommended by the Fifth Radiocarbon Dating Conference in Cambridge (1962) since all existing radiocarbon dates from Taiwan are based on the half-life of 5730 years. One can easily convert the age based on the ^{14}C half-life of 5730 years into the age based on the 5570-year half-life by multiplying a factor of 0.972.

RESULTS AND DISCUSSION

The radiocarbon dates and the altitudes of raised coral reef samples, as obtained by the present study and by others (Ma, 1967; Konishi *et al.*, 1968; Lin, 1969; Hashimoto *et al.*, 1970, 1972; Hashimoto, 1972; Taira, 1975, 1976) are summarized in Table 1 and are plotted in Fig. 2. The sample locations are indicated in Fig. 1 by the same numbers as designated in Table 1. Two estimates of the eustatic sea-level relative to the present sea-level for each sample in Table 1 are based on Shepard's (1963) average eustatic sea-level curve obtained from tectonically relatively stable areas and on Mörner's (1971) eustatic sea-level curve from southern Scandinavia (in parenthesis). As summarized by Mörner (1971), most of the eustatic sea-level curves derived by other authors in various areas fall roughly between Shepard's and Mörner's curves (one exception is Fairbridge's curve which gives at least four periods of high sea stand relative to the present sea-level for the last 6000 years). According to Mörner (1976), the minor differences among the various eustatic sea-level curves from different areas may be real, due to the change of geoid's surface in time and in space. Since the general trend of various eustatic sea-level curves is similar, the average uplift rate of an area estimated by a linear regression analysis of data is fortunately not sensitive to the choice of different eustatic sea-levels as shown in the following.

Table 1. The radiocarbon dates and altitudes of raised coral reef samples from Taiwan

Sample Locality*	Sample number	C^{14}-age (t) yr. B.P.	Altitude (A) +m	Eustatic sea-level (E)** −m	Minimum uplift (A+|E|)**	Reference
Hengchun Peninsula						
(1) Yakouhai	NTU44	3700±250	10	3 (0)	13 (10)	a
(2) Fantzeliao	1434H	1300±120	1	0.6(0)	1.6(1)	This study
(3) Kenting	1434K	1580±120	1	0.8(0)	1.8(1)	This study
	N620	4310±120	12	4 (2)	16 (14)	f
	N400	3900±125	14	3 (1)	17 (15)	f
	N399	4040±120	14	3 (0.5)	17 (15)	d
	NTU17	4600±400	14	4 (2)	18 (16)	e
	N1645	5200±95	20	5 (3)	25 (23)	c
	NTU-	7530±480	20	14 (17)	34 (37)	b
	N1636	7810±115	22	15 (20)	37 (42)	c
	N621	8140±155	20	17 (20)	37 (40)	f
	N627	8660±155	20	20 (19)	40 (39)	f
(4) Shihniuchiao	N403	1710±110	1.5	0.8(0)	2.3(1.5)	d
	N447	1780±115	1.5	0.9(0)	2.4(1.5)	d
	NTU41	5000±300	15	5 (2)	20 (17)	a
	N401	5670±140	15	7 (3)	22 (18)	d
	N402	7050±145	15	12 (11)	27 (26)	d
(5) Shanhaili	N406	4950±125	12	5 (2)	17 (14)	d
(6) Ssukou	N762	7240±760	20	13 (14)	33 (34)	e
(7) Haikou	N575	1470±105	1	0.8(0)	1.8(1)	f
	N606	5390±130	10	6 (4)	16 (14)	f
	N605	4210±120	15	3 (2)	18 (17)	f
(8) Fengkang	N404	5190±130	20	5 (3)	25 (23)	d
	N405	5260±140	20	5 (3)	25 (23)	d
Tainan Area						
(9) Akungtien	NTU4	7530±480	10	14 (17)	24 (27)	f
	N570	5900±135	10.8	7 (4)	18 (15)	f
	N569	5700±130	11.9	6 (3)	18 (15)	f
	N563	6000±130	12	7 (6)	19 (18)	f
	N580	5570±135	13	6 (3)	19 (16)	f

Table 1 (*Continued*)

Sample Locality*	Sample number	C^{14}–age (t) yr. B.P.	Altitude (A) +m	Eustatic sea-level (E)** −m	Minimum uplift (A+|E|)**	Reference
	NTU9	6700±400	13	10 (11)	23 (24)	e
	N578	6010±135	14	7 (6)	21 (20)	f
	N574	5670±130	14.3	6 (3)	20 (17)	f
Northern Coastal Area						
(10) Kuoshenpu	N1631	5410±95	2	5.8(3.5)	8 (6)	c
(11) Yehlieu	NTU18	8020±410	4.5	16.5(20)	21 (24)	a
(12) Kengtzuliao	N1583	5290±95	2	5.5(3)	7.5 (5)	c
	N1581	5550±100	2	6 (3.5)	8 (5.5)	c
Eastern Coastal Area (Coastal Range)						
(13) Milun	NTU13	3200±300	14	2 (0)	16 (14)	a
	NTU5	3900±270	20	3 (1)	23 (21)	a
	N407	2880±120	25	2 (0)	27 (25)	d
(14) Hualien	1434A	1440±120	2	0.7(0)	2.7(2)	This study
(15) Shihyusan	1434B	840±160	1	0.4(0)	1.4(1)	This study
(16) Sanhsientai	1434C	1600±170	2	0.8(0)	2.8(2)	This study
(17) Fukang	1434D	1110±120	3	0.5(0)	3.5(3)	This study
	1434E	2450±130	9	1 (0)	10 (9)	This study
	1434F	7100±215	20	11 (12)	31 (32)	This study
(18) Taitung	N445	6480±145	20	9 (6)	29 (26)	d

Note:

* Sample locality is shown by the corresponding number in Fig. 1.

** The eustatic sea-level relative to the present sea-level (E) and the minimum uplift (A+|E|) are based on Shepard's (1963) eustatic curve and Morner's (1971) (in the parenthesis).

a Lin (1969).
b Ma (1967).
c Taira (1975, 1976).
d Konishi *et al.* (1968).
e Hashimoto (1972).
f Hashimoto *et al.* (1970, 1972).
g Konishi *et al.* (1970).

Hengchun Peninsula

A linear least-square fitting of radiocarbon dates versus the minimum uplift (=A+E) of samples in the area (Fig. 3) gives a slope (=average uplift rate) of 5.3 ±0.2 mm/yr, a zero age interception of −5.9 ± 1.2 m based on Shepard's curve, and a slope of 5.7 ± 0.3 mm/yr, a zero age interception of −8.8 ± 1.7 m based on Mörner's curve. It is also clear from Fig. 3 that there is no significant differential

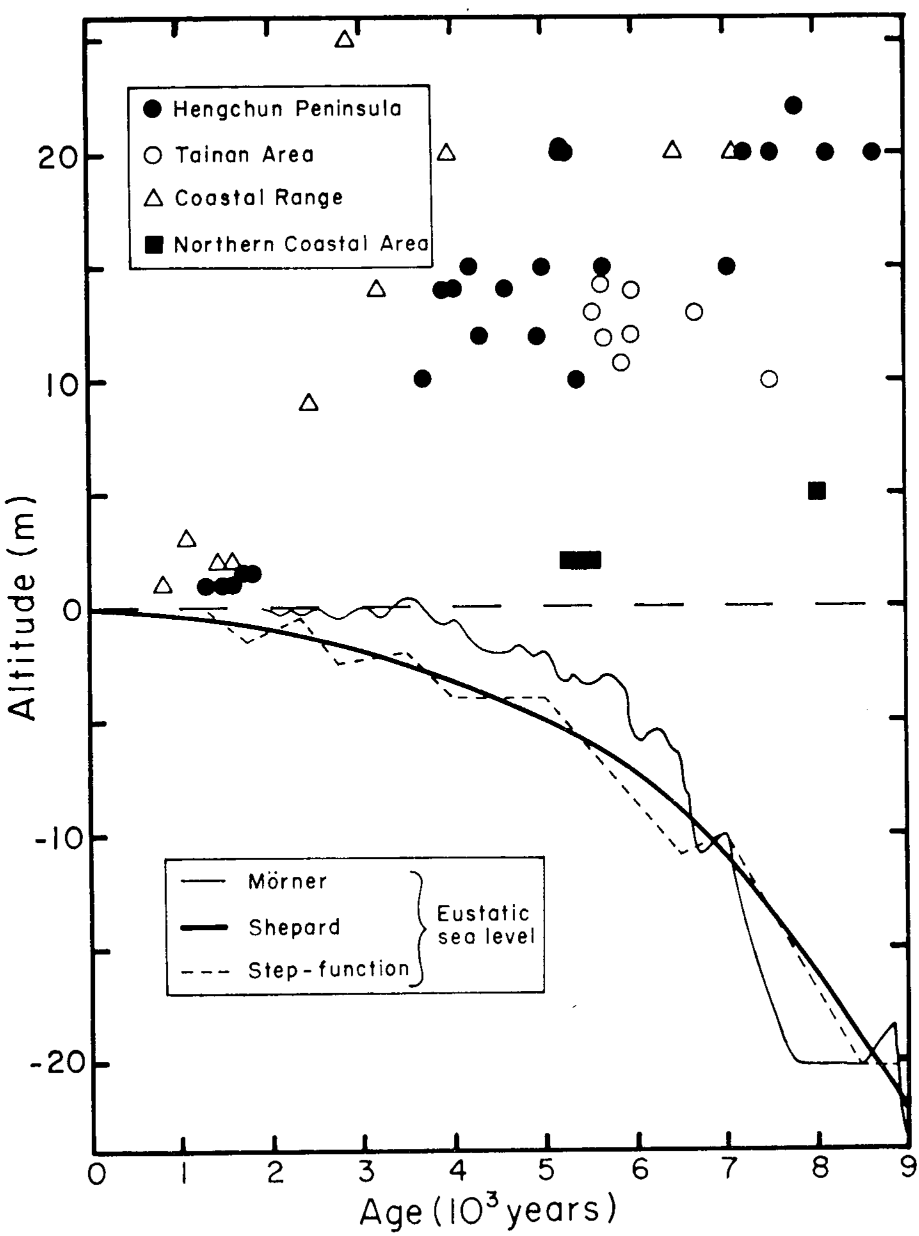

Fig. 2. Upper part of the figure: the radiocarbon dates and altitudes of the raised coral reef samples. Lower part of the figure: eustatic sea-levels given by Shepard (1963) and Mörner (1971). The dashed line represents the proposed stepwise eustatic sea-level of Shepard's original curve.

movement between the Foot Hill block and the Central Range block in the Hengchun Peninsula for the last 9000 years, as already noted by Bonilla (1975), implying that the Chaochou fault has not been very active in recent times.

The zero age interception of −5.9 m (or −8.8 m) is far deeper than the optimal growth depth of coral reefs, i.e., about 2–3 m below the mean high-tide sea-level (the average tidal amplitude is about 1 m along the Pacific coast of Taiwan). The most probable explanation is as follows: Our uplift rate obtained from the linear least-square fitting of data is an overall average for the last 9000 years but, in reality, the mode of uplift may well have been a multiple step function (Taira, 1975) as schematically drawn in Fig. 3. Therefore, the Hengchun Peninsula may have been rising relatively slowly (~2.5 mm/yr) for the last 2000 years. Those raised coral reefs less

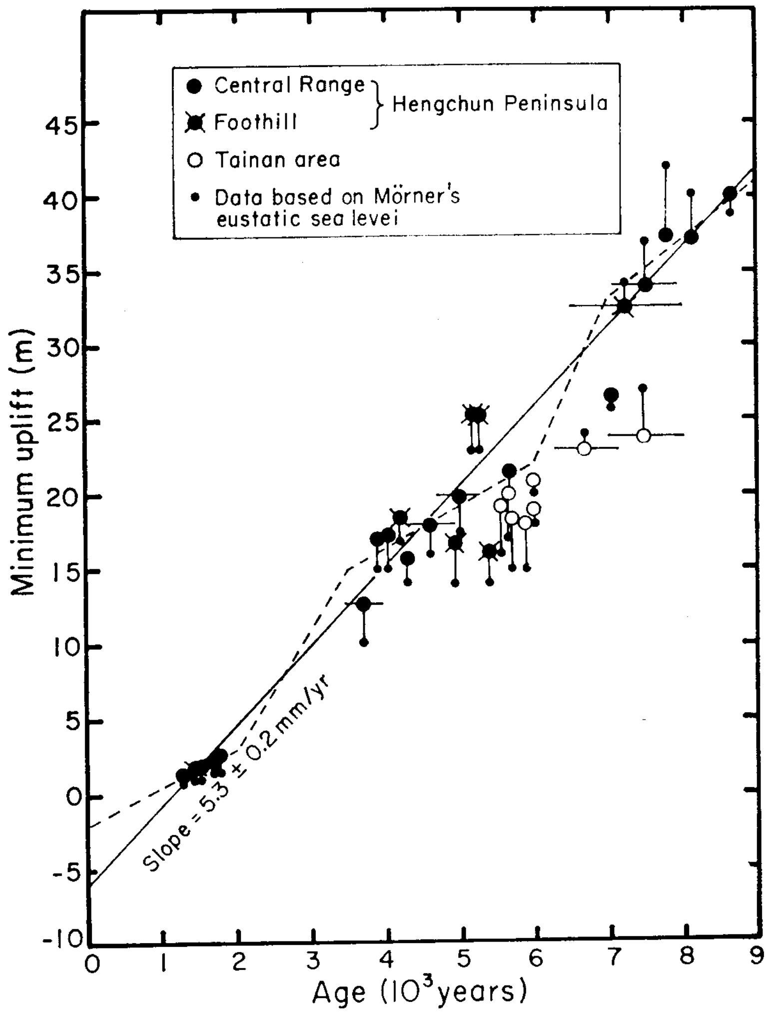

Fig. 3. The plot of the minimum uplift (= altitude of the raised coral reef sample + the eustatic sea-level relative to the present sea-level) vs. the age of samples from the Hengchung Peninsula and Tainan area. The dashed line represents a proposed stepwise rise of the Hengchun Peninsula.

than 2000 years old are actually the extended part of the presently living coral reefs which are growing at a depth between ~2 and 10 m below the high-tide sea-level.

According to Lin (1969), there have been several transgression-regression events on Taiwan since the early Holocene. In order to have a transgression of the sea over a land, the rising rate of the eustatic sea-level should be higher than the tectonic uplift rate of the land. But, as shown in Fig. 4, the rising rate of the eustatic sea-level based on Shepard's curve (thin dashed curve in Fig. 4) is always lower than either the constant uplift rate of 5.3 mm/yr (thick dashed line in Fig. 4) or the variable uplift rates (thick solid line in Fig. 4) calculated from the proposed stepwise uplifting curve of the area (Fig. 3) (one exception is one transgression between 7000 and 8500 B.P.). Therefore, the only way to have several transgressions is to have the Shepard's smooth eustatic curve transformed into zigzag curve as shown schematically in Fig. 2 (dashed curve). The geochronology of the proposed zigzag curve follows closely Lin's (1969) transgression-regression chronology. Interestingly, the proposed zigzag curve resembles more Mörner's (1971) eustatic sea-level curve. The rising rate of sea level for the proposed zigzag curve is shown in Fig. 4 (thin solid curve) for comparison. It is

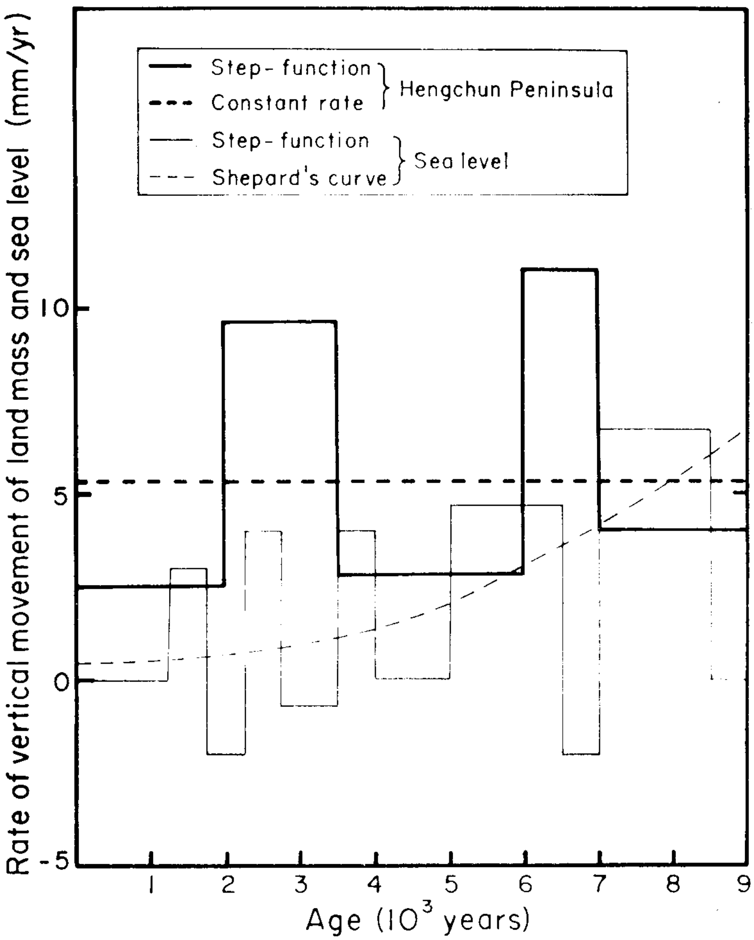

Fig. 4. The inferred approximate rising rates of landmass and sea-level as a function of age.

clear that only the combination of the intermittent rise of land and the intermittent fluctuation of the rising sea-level can produce several transgression-regression cycles. Also, only the earlier two transgressions in the periods of 7000 to 8500 B.P. and of 5000 to 6000 B.P. could have deposited substantially thick marine sediments on Taiwan as exemplified by the Lungkang Formation (10–18 m) and the Tainan Formation ($>$ 6 m), respectively (Lin, 1963).

Tainan Area

As shown in Fig. 3, the uplift rate of the Tainan area may have been slightly slower than that of the Hengchun Peninsula. There are not enough data to make a meaningful linear least-square fitting of data. If one adopts the zero age interception of the Hengchun Peninsula, then the average uplift rate of the area would be about 4.3 ± 0.4 mm/yr based on Shepard's curve and 4.7 ± 0.4 mm/yr based on Mörner's.

Eastern Coastal Area (Coastal Range)

The linear least-square fitting of data in the area (exclusive of sample number N407 in Fig. 5) gives the average uplift rate of 5.0 ± 0.4 mm/yr, zero age interception

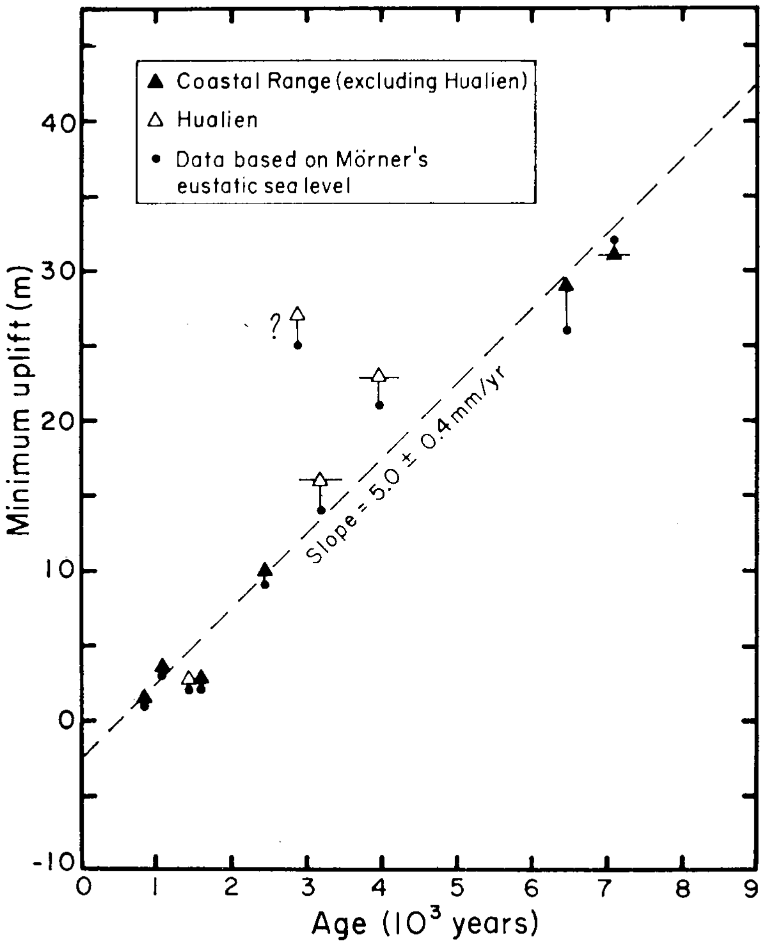

Fig. 5. The plot of the minimum uplift vs. age of the raised coral reef samples from east coast of Taiwan.

of −2.5 ± 1.6 m based on Shepard's curve and 5.0±0.4 mm/yr and −3.3 ± 1.4 m based on Mörner's. Sample number N407 may have been contaminated by modern carbon. The uplift rate of the Hualien area may be slightly higher than the average (Fig. 5) but the data are still too few to come to a definite conclusion.

Northern Coastal Area

The average uplift rate of the northern coastal area between 5000 and 8000 B.P. was the same as that of the Hengchun Peninsula, i.e., about 5.3 ± 0.2 mm/yr (or 5.7 ± 0.3 based on Mörner's curve). There are no raised coral reef samples younger than 5000 years in the area, but the radiocarbon dates of marine shells obtained from the raised sand beach in the area (Table 2 and Fig. 6) show that there was almost no uplift of the area between 2000 and 5000 B.P. (at most ~2 mm/yr). Furthermore, the raised coral reefs of the Ryukyu Islands and the northern coastal area of Taiwan have shown a very similar uplift history (Table 2 and Fig. 6) indicating their affinity in geotectonics. It is quite probable that the period of uplift (or no appreciable uplift) of the Ryukyu Islands and the northern Taiwan corresponded to the period of no subduction (or subduction) of the Philippine plate under the Ryukyu trench. We also suspect that there was a long period of stability before 8000 B.P. when no appreciable uplift occurred so that the rising of sea level (~80 m) due to the rapid melting of the last glacial ices between 8000 to 18,000 B.P. caused the formation of a typical submerged shoreline topography observed today in this area (Lin, 1957).

Table 2. The radiocarbon dates of marine shells from the northern coast of Taiwan and of raised coral reefs from the Ryukyu Islands

Sample Locality*	Sample number	C^{14}-age (t) yr. B.P.	Altitude (A) +m	Eustatic sea-level (E)** −m	Minimum uplift (A+|E|)**	Reference
Northern Coast of Taiwan						
(10) Kuoshepu	N1630	1810±80	3	0.9(0)	3.9(3)	c
	NTU-	2710±120	5	1.7(0.5)	6.7(5.5)	b
(12) Kengtzuliao	N1582	2860±100	2.5	1.8(0.4)	4.3(3)	c
	N1580	3620±85	2.5	2.8(0)	5.3(2.5)	c
	NTU40	6200±400	−2.5	8 (5.5)	5.5(3)	a
Ryukyu Islands						
Okinawa-Shima	N625	5140±125	0	5.2(3)	5.2(3)	c
Kikai-Jima	Gak453	2740±100	3	1.7(0.5)	5 (3.5)	c
	Gak454	6630±150	7	9.7(10)	17 (17)	c
Okierabu	N545a	5000±150	−6	5 (2)	−1 (−4)	g
	N545b	4700±140	−6	4.4(2)	−1.6(−4)	g
	N545c	4600±140	−6	4.2(2)	−1.8(−4)	g

Note:
See Table 1.

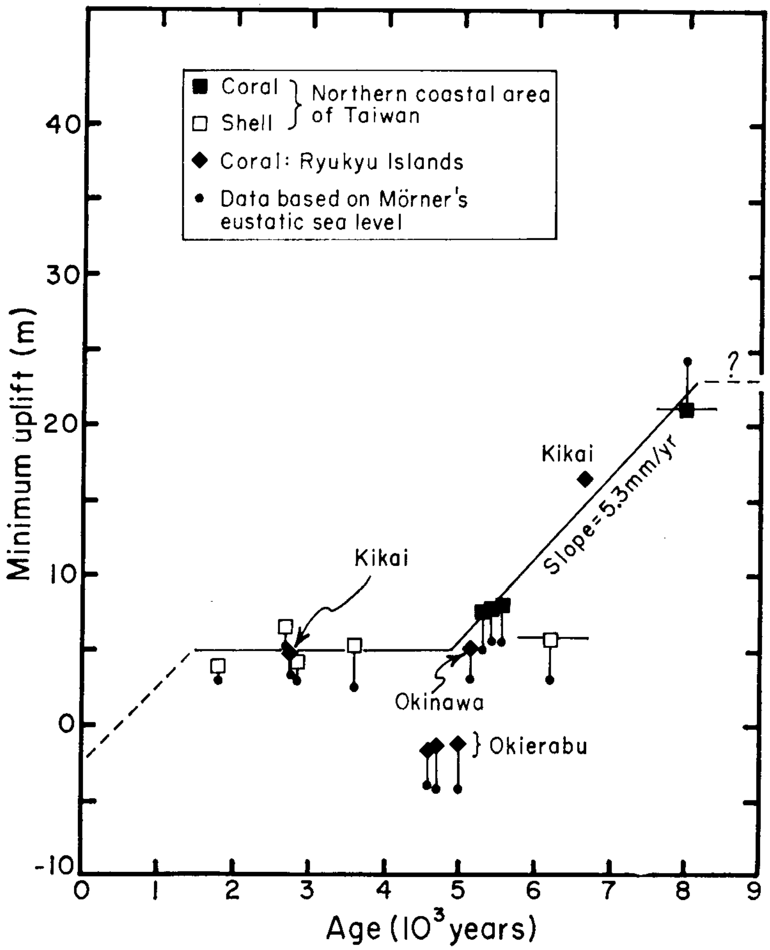

Fig. 6. The plot of the minimum uplift vs. age for the samples from the northern coastal area of Taiwan and the Ryukyu Islands (Kikai, Okinawa, and Okierabu).

SUMMARY AND CONCLUSIONS

(1) The average uplift rates of the Hengchun Peninsula (5.3 ± 0.2 mm/yr), the Tainan area (4.3 ± 0.4 mm/yr), and the Coastal Range (5.0 ± 0.4 mm/yr) do not differ greatly from one another for the last 9000 years, in contrast with Konishi *et al.* (1968) and Bonilla's (1975) estimates. The average uplift rates of the areas mentioned above are comparable to the present uplift rate of the Himalayan Mountains, i.e., about 4 to 5 mm/yr (Chugh, 1974), but much higher than that of the nearby Ryukyu Islands or the northern coastal area of Taiwan. This is consistent with the observation that Taiwan is in a continent-arc collision zone between the Asian plate and the Philippine Sea plate.

(2) If the uplift rate of 5.0 ± 0.7 mm/yr applies to the Central Range of Taiwan, the height of the Central Range would not change much, since the average denudation rate of the Central Range is also about 5.5 ± 0.5 mm/yr (Li, 1976).

(3) Only the intermittent fluctuation of the rising sea-level combined with the intermittent rise of land can produce several transgression-regression cycles along the sea-land boundary of Taiwan during the Holocene.

(4) The similar uplift history of northern Taiwan and the Ryukyu Islands indicates that both areas may belong to the same tectonic unit, i.e., the Ryukyu arc.

(5) The intermittent change in the uplift rate of the northern coastal area of Taiwan and the Ryukyu Islands may be related to the intermittent nature of the subduction in the region.

(6) The high rate of uplift is closely related to the high frequency of seismicity of the eastern Taiwan, Hengchun, and Tainan areas. The low rate of uplift of northern Taiwan, on the other hand, is reflected by the fewer earthquake occurrences in recent decades.

ACKNOWLEDGEMENTS

We wish to thank Professors Biq Chingchang, C. C. Lin, and T. L. Hsu for their encouragement and their help in obtaining the coral samples. The manuscript was reviewed by Drs. M. G. Bonilla and Y. F. Wang.

This paper is partially supported by ONR Grant N00014-75CO 210, NSF Grant OCE 75-19627 (a/c 24211), and NSF Grant EAR 76-14457.

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全新世以來臺灣島的上升率

彭宗宏　李遠輝　吳大銘

節　要

恒春半島、臺南一帶、及海岸山脈的平均上升率自 9000 年前以來大約都是每年 5.0 ± 0.7 公釐。這與小西健二等 (1968) 及柏尼剌 (Bonilla) (1975) 所估計的顯然不同。至於臺灣北部海岸一帶，在1500年至5500年前的上升率却非常小，不大於每年 2 公釐；但在5500年至8500年前，上升率也高達每年 5.3 公釐。因此臺灣北部時大時小的上升率與琉球羣島的上升率近似。這表明了這兩處在大地構造上彼此關聯。臺灣之有頗高的上升率與其居於亞洲地塊和非律賓海地塊的碰撞帶上有密切關係。在臺灣島內，一個地區的地震頻率與這個地區的上升率成正比。