LATE QUATERNARY UPLIFT RATE AND PALEOSEA-LEVELS IN THE HUON PENINSULA, NEW GUINEA

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Abstract A mathematical method to estimate uplift rate of marine terraces and paleosea-levels during the late Quaternary is interpreted, which has been previously proposed by the author in Japanese (Kikuchi, 1988). The data of height and age adopted for the re-examination in this time are presented by Chappell and Shackleton (1986) who studied the raised coral reefs of the Huon Peninsula, New Guinea. First in the method, we obtain theoretically regression equations $H_n = a_nH_0 + b_n$ on the several values of height of some couples of terraces, which are a higher standard terrace and some lower comparative ones. The regression coefficients (a_n) take various values according to the age of comparative terrace (T_n) and the age and ratio of change of uplift rate. The graphic relation of T_n to a_n called "T-RC diagram" shows the rising process of these terraces. The T-RC diagram based on the Huon data clears that uplift rate of this district decreased to approximately 80 percent about 80,000 years ago. The equation to estimate paleosea-levels $L_n = a_nL_0 + b_n$ is also obtained from the regression equation. Using the method, the elevation of paleosea-levels after the standard terrace (raised reef VIIa) formation were caluculated.

Key words: Pleistocene, paleosea-level, marine terrace, Time-Regression Coefficient diagram, Huon Peninsula

1. Introduction

In recent years, radiometric datings of raised coral reefs by Uranium series method have made the detailed paleosea-levels clear during the Middle to Late Pleistocene (Broecker *et al.*, 1968; Matthews, 1973; Konishi *et al.*, 1974; Ku *et al.*, 1974; Bloom *et al.*, 1974; Chappell and Veeh, 1978), and the studies for the paleosea-levels have been continued by many authors. A more correct height of paleosea-level is obtained by right understanding of the process of marine terrace uplift since the height of paleosea-level is that of terrace subtracted by amounts of uplift. In most previous papers, the paleosea-levels were estimated on the basis of the assumption that the uplift rate of coral reef terraces was constant during the late Quaternary. Nevertheless, there is no evidence that the said terrace has risen in constant rate.

Some authors described that uplift rate was not constant during the formation of a flight of terraces. Stearns (1976), for example, pointed out that uplift of coral reefs in the Barbados Island was not uniform between 124,000 and 82,000 years ago. Chappell (1974) expressed the detailed sea-level curve for the late Quaternary in the Huon Peninsula and suggested that uplift rate went down about 80,000 years ago. I also published in the previous paper in Japanese that uplift rate of the peninsula decreased to 75 percent of the preceding rate about 90,000 years ago on the basis of my original method (Kikuchi, 1988).

In this paper, I would like to express my opinion about the process of tectonic uplift in the Huon Peninsula using the data published by Chappell and Shackleton (1986). According to the re-examination, it is certain that the uplift rate of the peninsula was decreased about 80,000 years ago. The correct elevations of paleosea-level, therefore, cannot be estimated by the previous simple method based on the assumption uniform uplift rate. Moreover, I will propose the paleosea-levels for the late Quaternary estimated by the method (Kikuchi, 1988). It is characteristic of the method that we can obtain the paleosea-level from the height of terraces even affected by the change of uplift rate although it needs some applicable conditions.

2. Mathematical Method to Estimate Uplift Rate of Marine Terraces and Paleosea-levels

Precondition

Many data of radiometric age and height of the raised coral reefs in the Huon Peninsula have been published by several authors. Chappell and Shackleton (1986) exhibits many data which are very available for the present mathematical method to estimate uplift rate of marine terraces and paleosea-levels. I make refer to the data in this paper since I have not known such available ones. Moreover, before going into the main argument, the two major preconditions for the examination must be expressed;*i.e.* the uplift pattern of terraces and the process of uplift.

Uplift pattern of terraces

Three models of marine terrace deformation are deduced on the basis of components of three dimensions: they are the transverse, the longitudinal and the regional components (Fig. 1). The first component runs across coastline and inclines a flight of marine terraces seaward or scarcely landward. The second one runs parallel to coastline and tilts a flight longitudinally along the coast. Folding deformation model whose axis runs across coastline may correspond to this type. The last one trends vertically, and a flight of terraces belonging to this type is suffered extensively regional deformation which may be continuous extending over a long term.

In the actual case, it seems that the coral terraces at the Huon Peninsula is due to the second type because the tilting of the terraces trends clearly along the coast as Chappell (1974) suggested previously (Fig. 2). In other words, not the transverse component but the longitudinal one must be taken account of in this district. The regional component will be described later in detail.

Process of uplift

Although it is understood that a flight of marine terraces was undergone uplift during

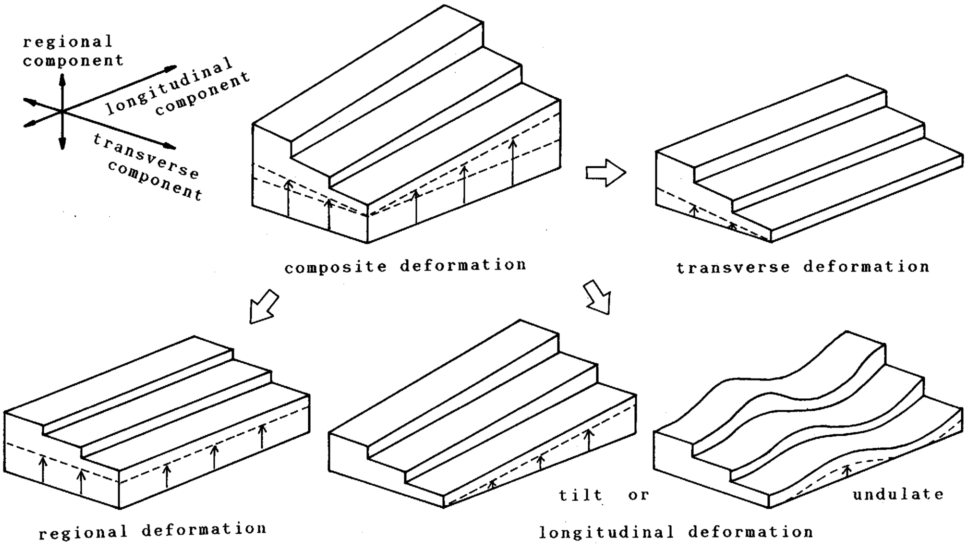

Fig. 1 Components of three dimensions in marine terraces deformation

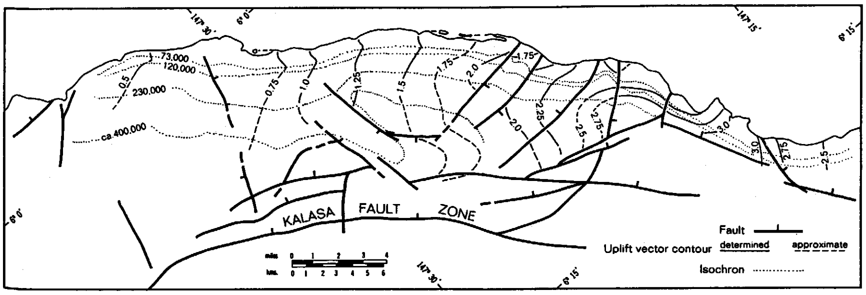

Fig. 2 Map showing uplift pattern of raised coral reef terraces in Huon Peninsula, New Guinea (after Chappell, 1974)
The terraces generally incline along the coastline.

the late Quaternary, the process of uplift is generally unknown. Uniform rate of uplift is an easy but uncertain approximation, which several authors have adopted previously in estimating paleosea-levels. Comparison between an actual flight of terraces and some models based on hypothetical processes of uplift, however, is one of the most available ways in order to answer the question. Following several cases on the uplift process of terraces in a relatively extensive district are deduced for the comparison:

1) continuous uplift at uniform rate extending all of the district
2) uplift gained/lost simultaneously the same rate in the district
3) uplift increased/decreased simultaneously at the same ratio of each rate at each point

4) uplift accelerated/decelerated gradually at the same ratio of each rate at each point
5) uplift changed at separate rate with each other point

Among them, the fifth one must come out of the district where the each point belongs to different tectonic block, and the others must come a single block.

The suggestive study by Chappell (1974) on the tectonic movements in the Huon Peninsula indicates that the third one is the most applicable to the district, because the uplift rate at the illustrated six points decreased simultaneously at the nearly same ratio about 80,000 years ago (Fig. 3). The present method adopts the process of uplift mentioned above.

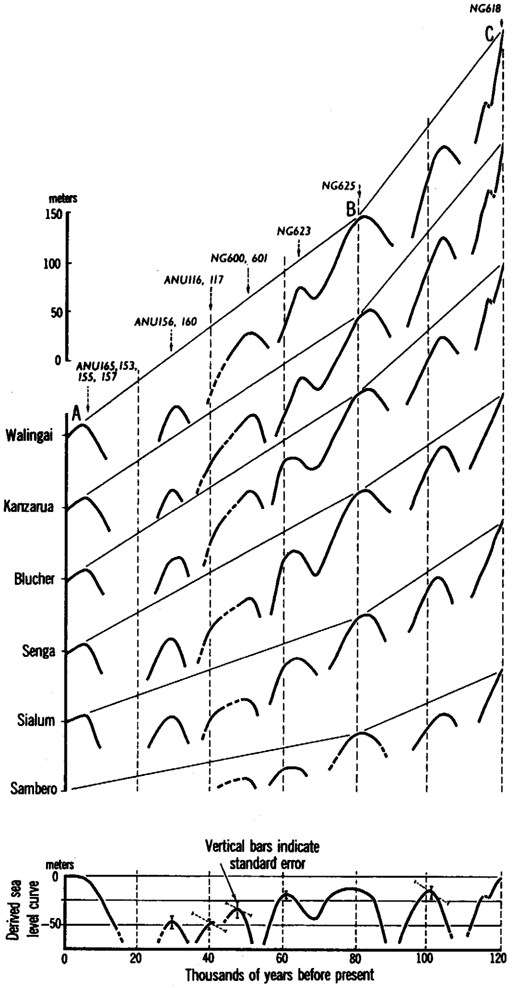

Fig. 3 Relative sea-level changes for six sections across the terraces I to VII in Huon Peninsula and derived sea-level curve
Straight lines joining corrected "fixed point" A, B and C represent preliminary uplift curves (after Chappell, 1974).

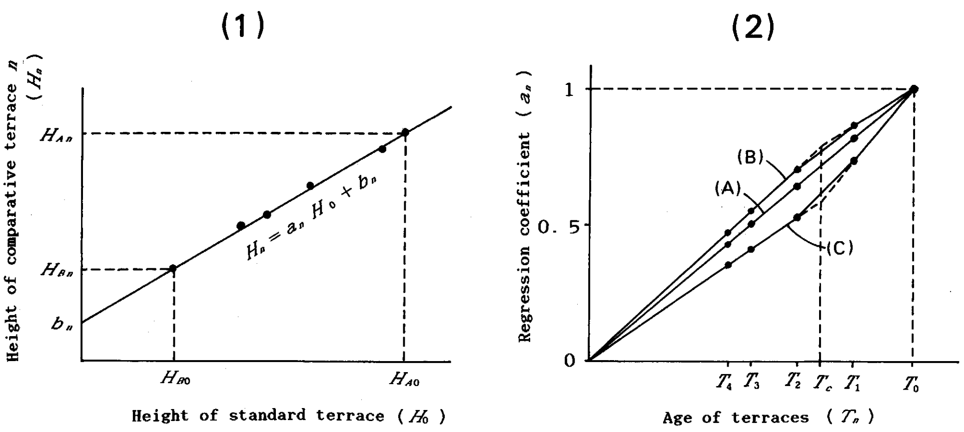

Fig. 4 (1) Regression of height of comparative terrace (H_n) as a function of height of standard terrace (H_0) and (2) T-RC diagram
The line (A) shows constant uplift rate, the line (B) uplift rate increased and the line (C) uplift rate decreased.

Regression equation on height of terraces and tectonic uplift rate

In a coastal region which has been upheaved at locally different rate, a flight of terraces is preserved at different level every transection. If there are sufficient transections including a flight of terraces to take statistical analysis, we can examine the relation between the level of higher terrace and that of lower one. This relationship may be represented by the least squares method (Fig. 4(1)) as

$$H_n = a_n H_0 + b_n \qquad n = 1,\ 2,\ \cdots \tag{1}$$

where H_0 is the height of standard terrace set at higher level and independent variable in the regression equation, H_n is the height of lower comparative terrace n and subordinate one, a_n is the regression coefficient, and b_n is the intercept. The equation is precisely equivalent to that shown by Bloom and Yonekura (1985) and bears a slight resemblance to that indicated by Sugimura and Naruse (1954) and discussed previously by Ota *et al.* (1968).

If uplift rate had been constant at every district, the regression coefficient a_n ought to be in proportion to the age of the comparative terrace, then

$$a_n = \frac{T_n}{T_0} \tag{2}$$

where T_0 is the age of standard terrace and T_n is that of comparative terrace n. The interpretation is as follows:

In two selected transections A and B, each height of standard terrace (H_{A0} and H_{B0}) and each comparative terrace (H_{An} and H_{Bn}) are given by

$$H_{A0}=L_0+R_{A(0,p)}T_0$$
$$H_{B0}=L_0+R_{B(0,p)}T_0$$
$$H_{An}=L_n+R_{A(n,p)}T_n$$
$$H_{Bn}=L_n+R_{B(n,p)}T_n$$

where L_0 and L_n are original paleosea-levels at T_0 and T_n, $R_{A(0,p)}$ and $R_{B(0,p)}$ are the uplift rate since the formation of the standard terrace to the present in both transections, respectively, and $R_{A(n,p)}$ and $R_{B(n,p)}$ are that of the comparative terrace. The coefficient a_n, accordingly, is expressed by

$$a_n=\frac{H_{An}-H_{Bn}}{H_{A0}-H_{B0}}=\frac{(R_{A(n,p)}-R_{B(n,p)})T_n}{(R_{A(0,p)}-R_{B(0,p)})T_0} \qquad (3)$$

As both transections have been constantly uplifted, $R_{A(0,p)}$ and $R_{B(0,p)}$ are equal to $R_{A(n,p)}$ and $R_{B(n,p)}$, respectively. Thus, equation (2) is get from equation (3).

By the way, a_n can be represented every following three cases in the district which the uplift rate was decreased or increased in the midst of several terraces formation such as that in the Huon Peninsula. These cases are classified according to the time of change of uplift rate T_c for the age of the comparative terrace T_n, and correspond to that of $T_n > T_c$, $T_n = T_c$, and $T_n < T_c$ (Fig. 5). In the case of $T_n > T_c$, the height of terraces can be expressed as

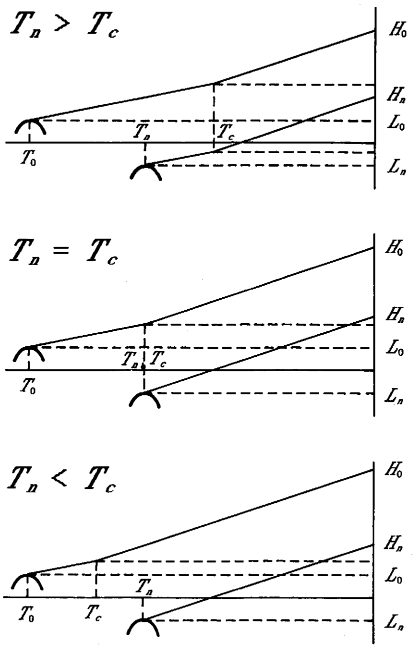

Fig. 5 Schematic illustrations of terrace uplift with different time of change in uplift rate

$$\begin{aligned} H_{A0} &= L_0 + R_{A(0,c)}(T_0 - T_c) + dR_{A(0,c)}T_c \\ &= L_0 + R_{A(0,c)}\{T_0 - (1-d)T_c\} \end{aligned} \tag{4}$$

where d is the ratio of uplift rate after T_c to that before then. In the same way, we can obtain following equations as other cases

$$H_{An} = L_n + R_{A(0,c)}\{T_n - (1-d)T_c\} \tag{5}$$
$$H_{B0} = L_0 + R_{B(0,c)}\{T_0 - (1-d)T_c\} \tag{6}$$
$$H_{Bn} = L_n + R_{B(0,c)}\{T_n - (1-d)T_c\} \tag{7}$$

Using these equations, a_n may be written by

$$\begin{aligned} a_n &= \frac{H_{An} - H_{Bn}}{H_{A0} - H_{B0}} \\ &= \frac{1}{T_0 - (1-d)T_c}\,T_n - \frac{(1-d)T_c}{T_0 - (1-d)T_c} \end{aligned} \tag{8}$$

This equation (8) means a straight line.

In the cases of $T_n = T_c$ and $T_n < T_c$, the coefficient a_n may be also given by

$$a_n = \frac{d}{T_0 - (1-d)T_c}\,T_n \tag{9}$$

As equations (8) and (9) indicate, the relation between a_n and T_n is represented by two lines, whose gradients change at T_c in all cases except the case of $d=1$.

The regression coefficient a_n, as considered above, proved to take various values according to the age of comparative terrace, the time of change of uplift rate and the ratio of the change. The relation of T_n to a_n is diagrammed on the basis of the equations

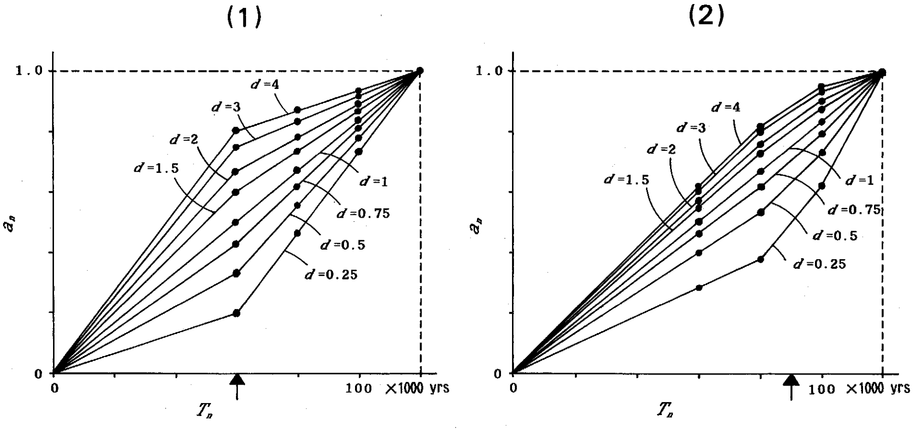

Fig. 6 Calculative T-RC diagram
Regression coefficients were calculated on the assumption that one standard terrace and three comparative ones were formed 120,000, 100,000, 80,000 and 60,000 years ago, respectively, and uplift rate of these terraces was changed 60,000 (1) and 90,000 (2) years ago. Arrow points the time of change of uplift rate.

(8) and (9), and some examples are shown in Fig. 4(2). I named such a diagram "Time - Regression Coefficient diagram", simplifying T-RC diagram (Kikuchi, 1988). In the T-RC diagram, a_n is in direct proportion to T_n (the line (A) in Fig. 4(2)) in the district which was continuing uplift at uniform rate since $d=1$ in the equations (8) and (9). In the case that the uplift rate increased at T_c (*i.e.* $d>1$), the graphical relation shows an upwardly broken line as the line (B). On the contrary, when the uplift rate decreased (*i.e.* $d<1$), the line is broken downwardly as the line (C).

Figure 6 represents some calculative T-RC diagrams using hypothetical values on the height and the age of marine terrace.

Equation for paleosea-levels

In a flight of marine terraces raised continuously in constant rate, an equation for paleosea-levels is expressed simply as

$$\begin{aligned} L_n &= H_n - R_{(n,p)} T_n \\ &= H_n - (H_0 - L_0)\frac{T_n}{T_0} \qquad (10) \end{aligned}$$

where L_0 is the absolute height of paleosea-level at the standard terrace formation, L_n is that at the comparative terrace n formation, and $R_{(n,p)}$ is uplift rate after the comparative one formation to the present and is equivalent to $R_{(0,p)}$ which is the rate after the standard one formation. Equation (10) has been used by many authors for estimating the height of paleosea-level of raised coral reefs and marine terraces (Broecker *et al.*, 1968; Matthews, 1973; Stearns, 1976; Bloom *et al.*, 1974). The equation is very simple and useful if it is clear that the uplift rate has been constant. How is the other case which uplift rate changed in the past as mentioned previous section?

If some pairs of the height of terraces in a district such as the Huon Peninsula have close regressive relations to each other, we may substitute equation (1) and equation (2) for equation (10) and obtain the equation

$$L_n = a_n L_0 + b_n \qquad (11)$$

This is the equation to get the paleosea-level at the comparative terrace formation, although the paleosea-level of the standard terrace must be given an supposed value as equation (10).

Equation (11) has an extremely unique characteristic that is applicable to a region which uplift rate was not only constant but also changed. The reason is explained as follows:

It may be deduced three cases on the process of uplift classified according to the time of change of uplift rate as illustrated in Fig. 5. First examination is on the case of $T_n > T_c$, namely the uplift rate changed after the comparative terrace formation. Equations (4) to (7) are rewritten as

$$H_{A0}-L_0=R_{A(0,c)}\{T_0-(1-d)T_c\} \tag{12}$$
$$H_{An}-L_n=R_{A(0,c)}\{T_n-(1-d)T_c\} \tag{13}$$
$$H_{B0}-L_0=R_{B(0,c)}\{T_0-(1-d)T_c\} \tag{14}$$
$$H_{Bn}-L_n=R_{B(0,c)}\{T_n-(1-d)T_c\} \tag{15}$$

Since the product of right side of equations (12) and (15) is equivalent to that of equations (13) and (14), it becomes also the following equality from left sides of these formulas;

$$(H_{A0}-L_0)(H_{Bn}-L_n)=(H_{B0}-L_0)(H_{An}-L_n) \tag{16}$$

If there is a linear relationship between the height of the standard terrace and the comparative one as shown in Fig. 4(1), the height of comparative terraces in the transections A and B are expressed as

$$H_{An}=a_nH_{A0}+b_n \tag{17}$$
$$H_{Bn}=a_nH_{B0}+b_n \tag{18}$$

Using equations (17) and (18), equation (16) is rearranged as

$$(H_{A0}-L_0)(a_nH_{B0}+b_n-L_n)=(H_{B0}-L_0)(a_nH_{A0}+b_n-L_n)$$
$$L_n(H_{A0}-H_{B0})=(a_nL_0+b_n)(H_{A0}-H_{B0})$$

Since it is an initial condition that H_{A0} is not equal to H_{B0}, dividing both sides of the equation by $(H_{A0}-H_{B0})$, we obtain

$$L_n=a_nL_0+b_n$$

This is precisely equal to equation (11).

In the other cases of $T_n=T_c$ and $T_n<T_c$, namely the uplift rate changed already before the comparative terrace formation, the process proving the equation is almost the same as the case described above except for the equations (13) and (15) which must be expressed as

$$H_{An}-L_n=R_{A(0,c)}dT_n \tag{19}$$
$$H_{Bn}-L_n=R_{B(0,c)}dT_n \tag{20}$$

Thus, equation (11) may be also obtained.

The equation for estimating paleosea-levels is practically equivalent to what was expressed by Bloom and Yonekura (1985), although they approached to it based upon a graphical method differing from the present mathematical one.

Effect of regional component of deformation for T-RC diagram and paleosea-levels

In the case that regional component of deformation superimposed to longitudinal one all over a coastal district, it has been proved that T-RC diagram is never affected by the additional component but the regional uplift is supposed to be uniform because it may be leisurely and extend over a long term (Kikuchi, 1988), as following interpretation.

When two marine terraces, standard terrace and comparative one, are uplifted by only longitudinal component, the regression equation on the height of both terraces is

$$H_n' = a_n' H_0' + b_n' \tag{21}$$

On the other hand, when regional component of uplift participates in addition to longitudinal one, the equation is

$$H_n = a_n H_0 + b_n \tag{22}$$

In the latter case, additional values of uplift to the height of both terraces on the former case are ST_0 and ST_n, where S is rate of uplift owing to the regional component, and then, height of both terraces H_0' and H_n' are represented $(H_0 - ST_0)$ and $(H_n - ST_n)$, respectively. From equation (3), therefore, regression coefficient a_n' in equation (21) is

$$\begin{aligned} a_n' &= \frac{H_{An}' - H_{Bn}'}{H_{A0}' - H_{B0}'} = \frac{(H_{An} - ST_n) - (H_{Bn} - ST_n)}{(H_{A0} - ST_0) - (H_{B0} - ST_0)} \\ &= \frac{H_{An} - H_{Bn}}{H_{A0} - H_{B0}} = a_n \end{aligned}$$

Thus, the coefficient in equation (21) is equal with that in equation (22) and T-RC diagram is available in spite of including regional component or not.

Moreover, the equation for paleosea-levels can be obtained from equation (16), too. Since additional height of both terraces caused by regional component are ST_0 and ST_n, equation (16) is rearranged as

$$(H_{A0} - ST_0 - L_0)(H_{Bn} - ST_n - L_n) = (H_{B0} - ST_0 - L_0)(H_{An} - ST_n - L_n) \tag{23}$$

If equation (23) is rearranged using equations

$$\begin{aligned} H_{An} &= a_n H_{A0} + b_n \\ H_{Bn} &= a_n H_{B0} + b_n \end{aligned}$$

it becomes the following equation

$$(H_{A0} - H_{B0})(L_n - b_n + ST_n) = (H_{A0} - H_{B0})(a_n L_0 + a_n ST_0)$$

thus,

$$L_n = a_n L_0 + b_n + S(a_n T_0 - T_n) \tag{24}$$

As a result of the examinations, it may be explained that the right hand third term of the equation, $S(a_n T_0 - T_n)$, is the correction for regional component of uplift.

3. Paleosea-levels and Uplift Process Estimated from the Huon Data

Paleosea-levels

When we are going to know paleosea-levels, the mathematical method mentioned above is very available. Because it may be applied to the tectonic region whose uplift rate changed clearly in the past but the rate changed simultaneously at the same ratio of each such as the case of Huon Peninsula. The raised coral reef terraces in the Peninsula have

Table 1 Age and height data of the Huon terraces after Chappell and Shackleton (1986) and Bloom *et al.* (1974)

Reef	Age(kyr)	Tewai	Kanzarua	Blucher	Kwanbu	Nama	Sambero	Kambin*1
VIIa	124	440	330	280	220*2	160	150	120
VIa	100	338	250	215	160	115	110	93
VIb	96	312						
Va	81	260	190	155	117	90	80	60
Vb	72	216						
IVa	59	178	125		70	48		28*3
IVb	53	156						
IIIa	45	112						
IIIb	40	98	70	41	28	10	10	
II	28	52	30	18	7			

* 1 The data at Kambin are after Bloom *et al.* (1974)
* 2 Bloom *et al.* (1974) show 215m
* 3 Original value is 28±2m

Table 2 Regression equations and calculated paleosea-levels

Reef	Age (kyr)	Regression equation	R	Paleosea-level(m)* (1)	Paleosea-level(m)* (2)
VIIa	124			5±3	6
VIa	100	$H_{VIa}=0.78\ H_{VIIa}-6.5$	0.999	− 2.6±2.3	−9±3
Va	81	$H_{Va}=0.616H_{VIIa}-13.7$	0.998	−10.6±1.8	−19±5
IVa	59	$H_{IVa}=0.467H_{VIIa}-29.1$	0.999	−26.8±1.4	−28±3
IIIa	40	$H_{IIIa}=0.322H_{VIIa}-42.9$	0.991	−41.3±1.0	−41±4
II	28	$H_{II}=0.206H_{VIIa}-38.9$	0.999	−37.9±0.6	−44±2

* (1) This paper (2) Chappell and Shackleton (1986)

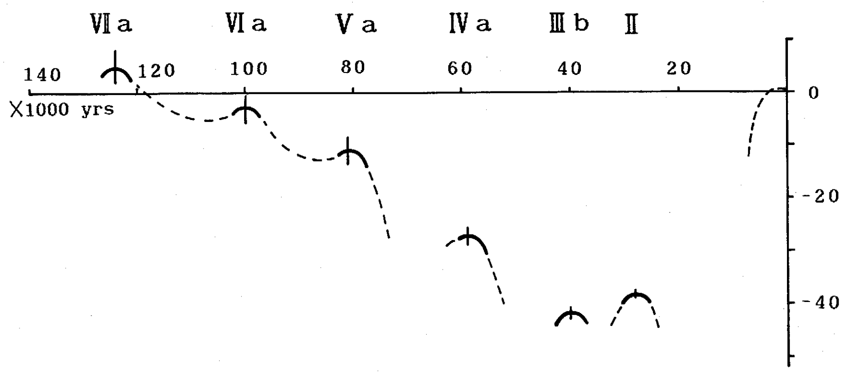

Fig. 7 Estimated sea-level curve
Vertical bars crossing the curve show the range of errors in elevation.

very favourable conditions and offer satisfactory data for the paleosea-level study. Many data of age determined by radiometric method and height of the terraces in this district are reported by many authors; *e.g.* Chappell (1974), Bloom *et al.* (1974), Aharon (1983), Bloom and Yonekura (1985), Chappell and Shackleton (1986) and Pillans (1987). Among them, Chappell and Shackleton (1986) tabulate some detailed data on the height and the age of terraces, which are very useful for this method and shown in Table 1.

The relationships between the height of a couple of terraces, *i.e.* reef VIIa as the standard terrace and other lower reefs as the comparative ones, were calculated by the least squares method. Reef VIIa referred to Chappell and Shackleton (1986) is correspond to reef VIIb by Bloom *et al.* (1974). The regression coefficients and intercepts estimated for every comparative terrace are tabulated in Table 2.

To calculate the paleosea-levels using equation (11), I adopted 5±3 m as the value of the paleosea-level at the reef VIIa formation though the value of +6 m has been adopted by several authors, because I mind that the value has no explicit foundations (Kikuchi, 1988). The paleosea-levels calculated are shown in Table 2 and Fig. 7.

The effect of regional component on terrace deformation must be considered. One of the difficulties is that the rate of regional uplift, S in equation (24), is an unknown quantity. Using some supposed values as S, the corrections for regional component of uplift are calculated tentatively and listed on Table 3. As the result of the examination, it seems that the uplift value of the regional component is so little as to be neglected relatively, because the error on the original sea-level at the standard reef VIIa formation cannot be ignored for the present.

Table 3 Correction of paleosea-level on regional uplift calculated from equation (24)

Reef	a_n	Correction of paleosea-level (m)			
		Rate of regional uplift S			
		0.1m/kyr	0.2m/kyr	0.5m/kyr	1.0m/kyr
VIa	0.78	−0.3	−0.6	−1.6	−3.3
Va	0.616	−0.5	−0.9	−2.3	−4.6
IVa	0.467	−0.1	−0.2	−0.6	−1.1
IIIa	0.322	−0.0	−0.0	−0.0	−0.1
II	0.206	−0.2	−0.5	−1.2	−2.5

The T-RC diagram of Huon terraces and process of uplift

T-RC diagram is a very available graphology to estimate process of terrace uplift but it is in need of many data on height and age of every terrace if possible. The data presented by Chappell and Shackleton (1986) are also used for the diagram and the result is also illustrated in Fig. 8(1). The diagram shows indistinctly but certainly a broken line 80,000 years ago, which represents that the rate of tectonic uplift of the district decreased abruptly at the time that line is broken downwardly. We may be able to regard as the tectonic uplift has been nearly constant, since these values of data contain originally some observational and analytical errors. As Chappell (1974) assumed preliminary,

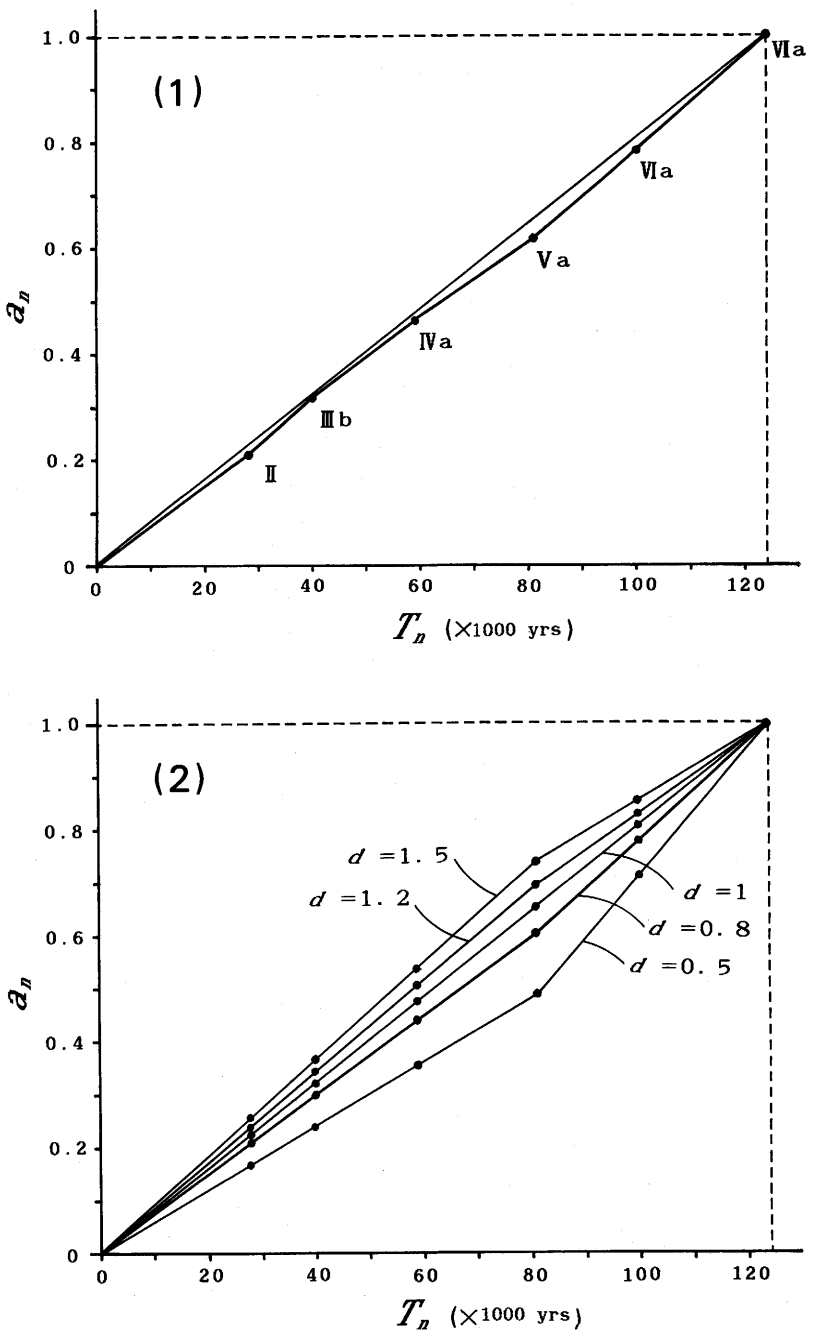

Fig. 8 (1) T-RC diagram of the Huon terraces drawn on the basis of the data by Chappell and Shackleton (1986) and (2) Reconstructed T-RC diagram based on the calculated paleosea-levels
The case that uplift rate decreased to 80 percent about 80,000 years ago is in nearly accord with that of the Huon terraces.

however, it is a reasonable assumption that the rate of uplift must have changed at the time.

By the way, some simulative T-RC diagrams may be drawn on the basis of the peleosea-levels estimated by the present method. Five cases on the change of uplift rate 80,000 years ago were assumed; *i.e.* 1.5, 1.2, 1, 0.8 and 0.5 times as much as rate before the change. Then, each T-RC diagram was figured to compare with the actual diagram of the Huon terraces (Fig. 8(2)). Among them, the case that uplift rate changed 0.8 times at the time is in nearly accord with that of the Huon. Considering above, I conclude that the uplift rate in the Huon Peninsula must decreased to approximately 80 percent about 80,000 years ago extensively.

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I would like to dedicate this paper to Prof. S. Kaizuka on the occasion of his retirement from Tokyo Metropolitan University.

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(*: in Japanese with English abstract)