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QUATERNARY REEF RECORD OF DIFFERENTIAL UPLIFT AT LUWUK, SULAWESI EAST ARM, INDONESIA.

P.A. SUMOSUSASTRO[1], H.D. TJIA[2], A.R. FORTUIN[3] and J. VAN DER PLICHT[4]

[1]*Marine Geological Institute, Ministry of Mines and Energy, Jalan Dr. Junjunan 236, Ministry of Mines and Energy, Bandung 40174, Indonesia*
[2]*Department of Geology, University Kebangsaan Malaysia, 43600 Bangi, Malaysia*
[3]*Geomarine Centre Amsterdam, Institute of Earth Sciences, Free University, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands*
[4]*Centre for Isotope Research, University of Groningen, Westersingel 34, 9718 CM Groningen, The Netherlands*

ABSTRACT

The coastal morphology of Luwuk (Sulawesi) is dominated by raised coral reef terraces, reaching elevations of over 400 m. A lower group of 6 to 10 terraces reach maximum heights varying between 30 and 100 m. A middle group, elevated up to 250 m, forms an 18° to 22° seaward sloping surface that is bordered by coast-parallel faults. The upper group of terraces is more than 400 m above sea level. Four reef terraces at 410, 62, 19 and 6.6 m above high tide have U/Th ages ranging from 350 ka to 67 ka and, except for the oldest terrace, can be correlated with several stages of interglacial reef growth at Huon Peninsula, New Guinea. Using the sea level curve established for the Huon reefs, uplift rates for the Luwuk area can be calculated. The highest terrace has risen at an average rate of 184 cm·ka^{-1}. The 3 dated terraces of the lower group also indicate net uplift, but at a much lower rate, which is partially due to subsidence at 53 cm·ka^{-1} between 101 ka and 67 ka. Intermittent subsidence could be due to isostatic compensation and/or drag by the downthrown parts during periods of crustal relaxation in the fault zone.

INTRODUCTION

Eastern Indonesia (Fig. 1) is a region of convergence between three major lithospheric plates, *viz.* the Australian Plate, the Pacific Plate and the Eurasian Plate. Consequently its geology is complex and dominated by many active and completed collision zones. One of the active zones is the east arm of Sulawesi. Here collision has been taking place since the Late Cenozoic between the eastern Sulawesi island arc and the Sula Platform, a detached fragment of continental crust (KLOMPÉ, 1956; HAMILTON, 1979; MCCAFFREY *et al.*, 1981; PIGRAM *et al., 1985*).

Luwuk is a coastal town near the eastern tip of Sulawesi's east arm (Fig. 1). The terrace morphology of the Luwuk area was studied during the Snellius-II Expedition, to determine timing, rate and magnitude of Quaternary uplift known to be taking place in this region of suturing crustal elements.

The east arm of Sulawesi comprises a highly complex belt, consisting of disrupted and tectonized ophiolites, associated with Palaeozoic and Mesozoic oceanic sediments. This belt is flanked by a cover of Neogene clastics (dominantly Pliocene sands and gravels), known as the Sulawesi Molasse. The ophiolites and associated sediments are telescoped into northwest-dipping imbricate thrust slices (Fig. 2). The thrust zone, called the Batui Thrust (SILVER & MCCAFFREY, 1983), separates the ophiolites from the molasse-like deposits formed along the leading edge of the Sula Platform and continues further eastward offshore. Folding and thrusting continued into the Quaternary, as the Pliocene east of the ophiolite complex also underwent similar, but gentler, deformation. According to KÜNDIG (1956) the youngest movements are characterized by pronounced block faulting, gentle folding and arching of the Luwuk area.

The Luwuk area is situated in the central portion of the arcuate thrustbelt where Quaternary reefs show maximal elevation. The elevation gradually decreases towards the east tip of the peninsula and towards the southwest (Batui area). Beyond Batui the Quaternary coastal development is governed by subsidence with regard to the present sea-level, as demonstrated by the presence of a vast, swampy coastal plain and large, drowned reef platforms offshore. Recent uplift therefore seems closely related to a rather narrow zone at the front of the Sula Platform.

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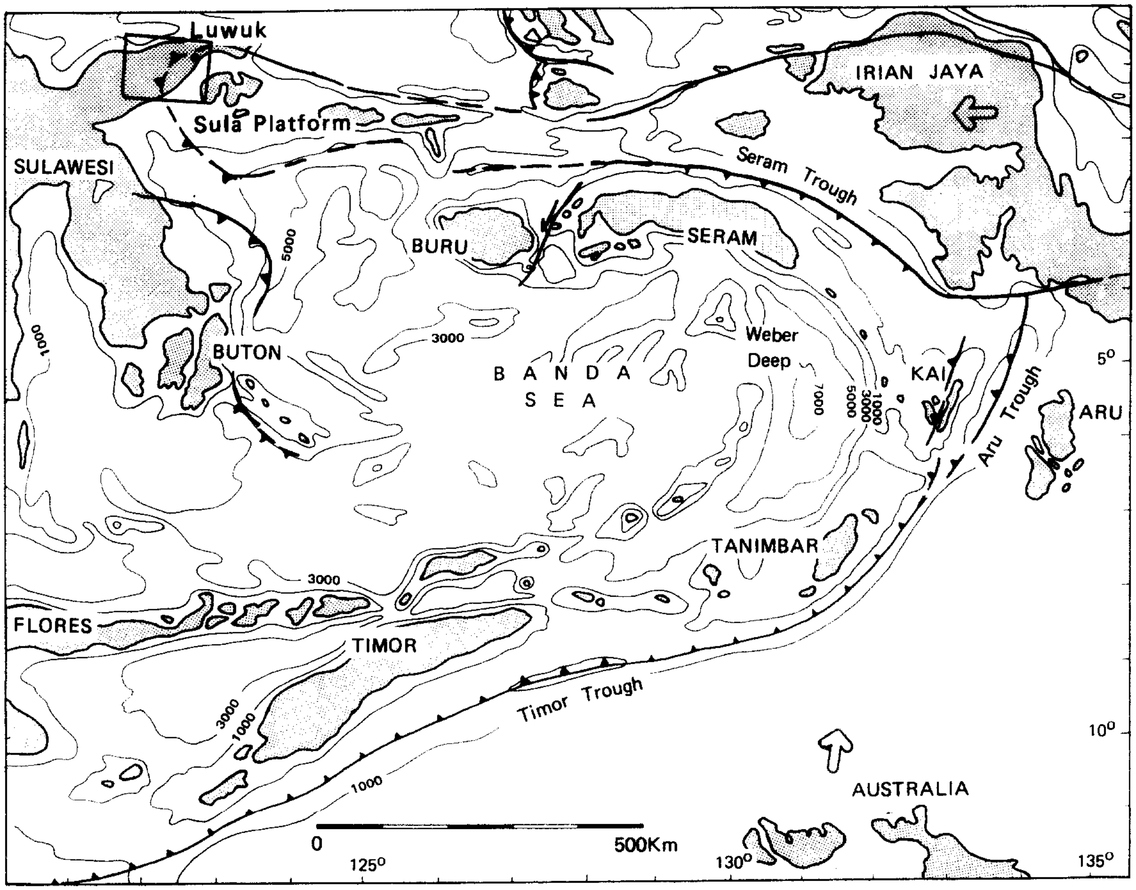

Fig. 1. Index map of eastern Indonesia, Banda Arc area and location of Luwuk in Sulawesi's east arm. Box shows outline of Fig. 2, the main topographic and tectonic features are indicated. The open arrows indicate the relative plate motions of Australia and Irian Jaya with respect to Eurasia.

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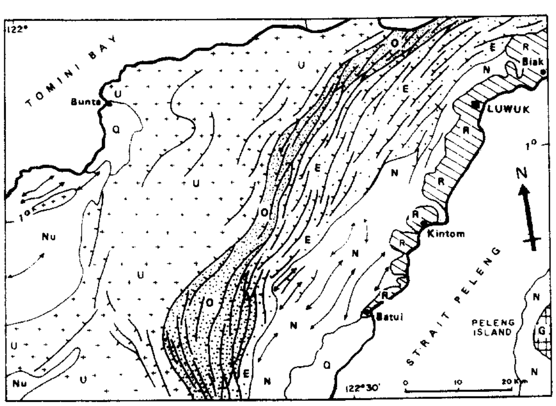

Fig. 2. Geological sketch map of Sulawesi's east arm in the Vicinity of Luwuk, after HAMILTON (1979). Q=Quaternary Coastal alluvium R=Raised Quaternary coral reefs; N=neogene clastic sediments (Sulawesi Molasse); O=imbricated complex of ophiolite fragments and Mesozoic-Palaeogene deep- and shallow-water sediments; U=ultramafic rocks with slices of Mesozoic sediments; Nu=upper Neogene clastic beds; G=Upper Palaeozoic granitoids on Peleng Island. Heavy lines indicate surface trace of reverse faults (dashes on the overriding part); double headed arrows and lines denote fold axes.

ing the value of the radiocarbon ages, stressing application of UTD dating. Prof. J.E. Van Hinte (Amsterdam) kindly read the manuscript. Discussion with O. van de Plassche (Amsterdam) was highly appreciated.

2. GEOMORPHOLOGY

The Luwuk coast consists of coralline reef terraces rising stepwise from the present sea level to heights exceeding 400 m (Fig. 3). The terraces may be divided into three groups: a lower, a middle and an upper group. In the vicinity of Luwuk the lower group consists of 6 distinct terraces that dip gently seaward (dip under 5°). Their faces are less than 5 m high. The uppermost of these terraces rises 30 m above sea level (Fig. 4B). Elsewhere this lower group consists of two subgroups of level to gently, seaward sloping terraces: first, a lowermost subgroup, consisting of the 6 terraces similar to those described from the neighbourhood of Luwuk town and, secondly, an upper subgroup consisting of 3 or 4 terraces. A distinct step of about 15 m height separates these two subgroups. The highest of these terraces rises approximately 100 m above sea level (Fig. 4A).

Near Luwuk the middle group is represented by an 18° to 22° seaward sloping surface. At one locality, northeast of Luwuk, an outcrop shows that the sloping reef surface is underlain by well-bedded sand and gravel layers belonging to the Late Neogene Sulawesi Molasse. These strata are dipping 25° S. At the same locality the slope break between the lower group and the middle group of terraces is masked by coral debris (Fig. 4B). Eastward of Luwuk town, this sloping surface remains a distinct morphologic element over the next 8 km. Its seaward tilt, however, becomes gentler.

Just north of Luwuk town, the sloping surface of the middle group (the triangular patch on Fig. 3) is separated by a 73 m high scarp from the lower group. The abrupt change in elevation of the lower edge of this sloping surface is most probably caused by differential vertical movements along interpreted north-south oriented faults, which are indicated by deep ravines. Some hundreds of metres more to the west of these ravines, the sloping surface of the middle group abuts against yet another north-south striking fault. A left-lateral displacement is suggested by the abrupt change in the position of the shoreline. West of this fault, the middle group consists of at least 4 prominent, gently seaward sloping terraces. The terrace steps are a few tens of metres high. North of the Luwuk airfield the uppermost terrace of the middle group is very extensive (Fig. 4D) and is estimated to slope over 170 m to 200 m.

The upper group is composed of two or more levels, the most extensive being at 410 to 418 m above sea level. The surface of this latter platform (called T410) is gently undulating and may become 200 m wide. It is bordered to the north by a 20 to 30 m high slope, which delimits a still higher undulating

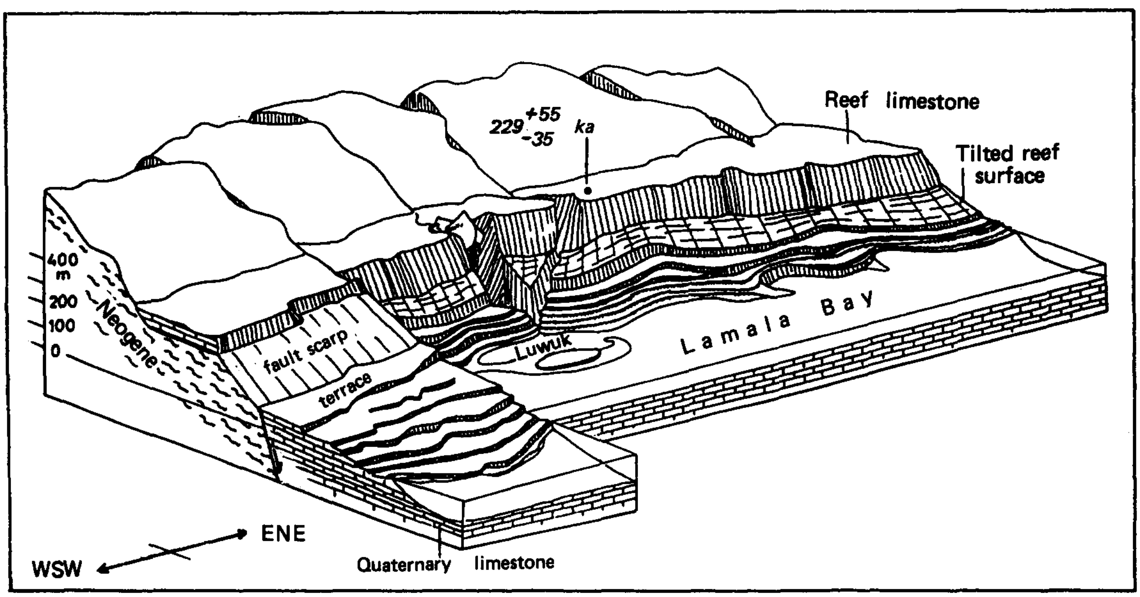

Fig. 3. Geomorphologic block diagram of the Luwuk area. Three groups of terraces comprise a middle series, that near Luwuk town consists of moderately seaward slanting surfaces and an upper group. The low terrace offshore Luwuk town is attached by a recurved spit to the Mainland. Vertical exaggeration is approximately x 2.

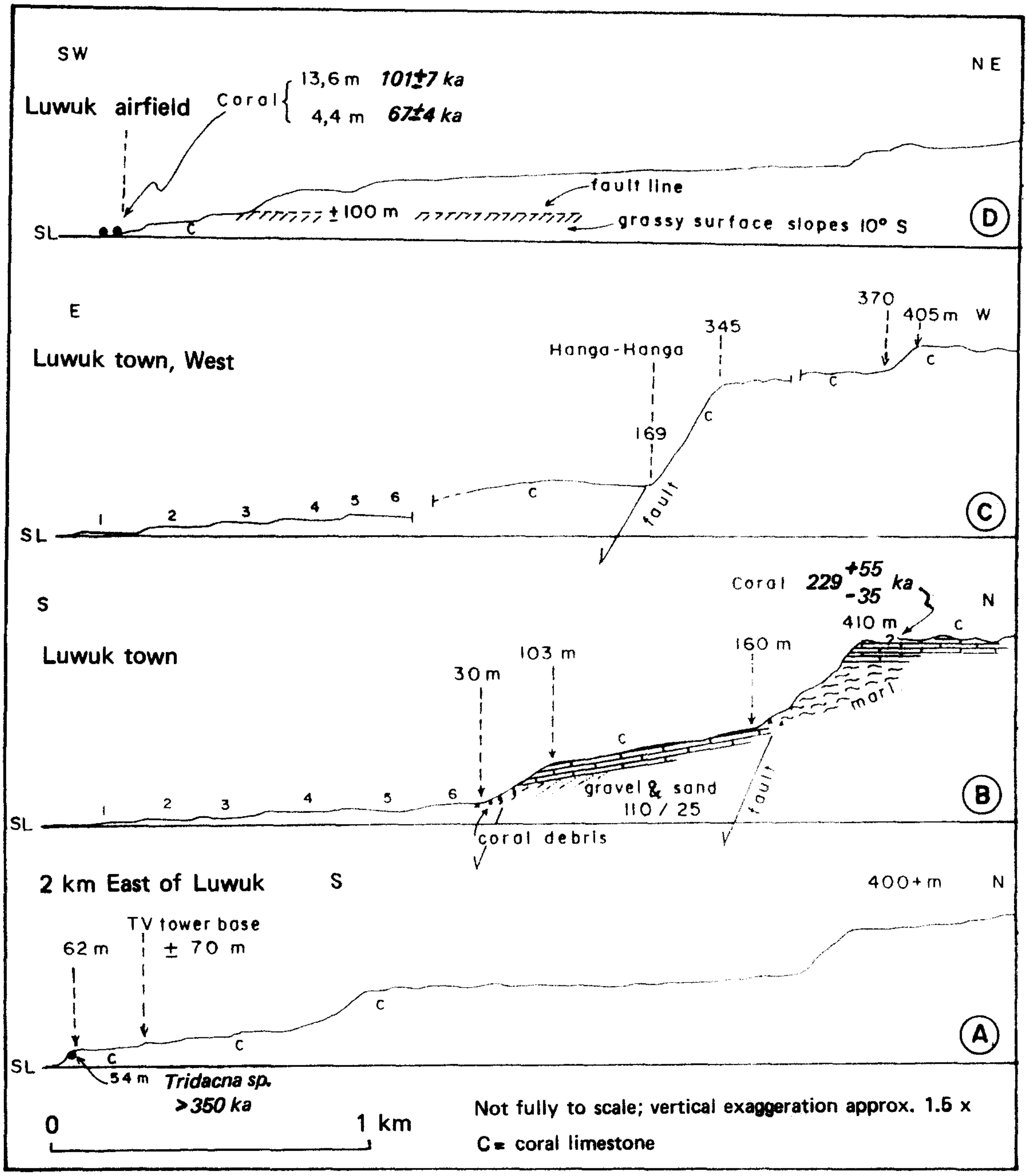

Fig. 4. Profiles showing the morphology of the Luwuk area sample Localities. The radiocarbon ages are indicated.

surface (Fig. 4C). Seen from the air, the upper group appears to form a low-relief, hummocky karst surface. In the Luwuk area the upper group forms a distinctly level highland (Fig. 3).

The steep scarp between the upper and middle group of terraces is due to faulting. Along our traverses we observed Neogene marl underlying the upper group. At its lower end, the middle group is most probably also bordered by a normal fault. In other words, normal faults striking parallel to the coastline apparently delimit the middle terrace group (Fig. 4B) and drag along these faults most probably caused its moderate seaward tilt between Luwuk and Biak.

3. RADIOMETRIC AGES

Initially, three samples of coralline limestone and one of the clam *Tridacna* sp. in growth position were collected from four different terraces (Fig. 4) and radiocarbon dated. Parts of the same coral colony from the T410 terrace were independently dated at the N.W.G. Macintosh Centre for Quaternary dating (New South Wales, Australia) and the Centre for Isotope Research, University of Groningen, The Netherlands. Both analyses arrived at almost identical ages of around 36 000 yr BP (Table 1). These ages would imply very rapid uplift for the T410 terrace, which interpretation was rejected (Bloom, written comm.) because radiocarbon ages near the upper limit of the conventional technique have proved unreliable (see also VEEH & BURNETT, 1982; MOOK & WATERBOLK, 1985). Subsequently U/Th dating (UTD) was carried out at Groningen, the results of which are quite different indeed (Table 1). In the analysis we also incorporated a Holocene coral sample from the nearby island of Peleng, in order to be able to compare the resulting ages where both methods should give good results.

Samples G-88141 and G-88143 are from terraces at the airstrip of Luwuk (Fig. 4D). The latter is from 4.4 m above high tide (AHT). The sample is located in the terrace face that slopes up landward between 4.7 and 6.6 m AHT and is therefore named T6.6. Sample G-88141 is from the rise of a wide terrace that over a distance of about 100 m grades westward from about 14 m to 22 m AHT. The Luwuk airstrip is built upon this terrace at an average elevation of 19 m AHT, hence the designation T19.

Recently formed corals contain Uranium, with a concentration of several ppm, but no Thorium (IVANOVICH & HARMON, 1982). This can be explained by observing that U, occurring in soluble form in seawater, is easily incorporated in the $CaCO_3$ matrix, while Th, due to its much lower solubility, is not available in ionic form.

The increase of $^{230}Th/^{234}U$ activity should show an increasing trend with presumed older stratigraphy because of the radioactive ingrowth of ^{230}Th with increasing age. Provided the corals are closed with respect to U and Th, the ^{230}Th and ^{234}U activity ratios then can be used for age determinations (Uranium Series Disequilibrium Dating, or UTD). The ^{232}Th concentration is an indication of contamination with environmental Th.

UTD dating is based on the decay of natural uranium (^{238}U) and its radioactive daughter nuclei. One of the decay products is ^{234}U, which decays with a half life of 75 ka. This decay is the only source for ^{230}Th (the natural Th isotope is ^{232}Th). Thus, as long as the production of ^{230}Th exceeds its radioactive decay, $^{230}Th/^{234}U$ activity ratio is a measure of the age, provided the system is chemically closed. After approximately 300 ka an equilibrium situation is reached where the decay of ^{230}Th balances its production. From this moment on the $^{230}Th/^{234}U$ activity ratio is approximately unity, independent of time. In addition, the relative contribution of ^{232}Th in the sample is an indication of the amount of contamination with detrital inorganic material. For more details concerning the physical background and the mathematical equations involved, we refer to IVANOVICH (1982).

In order to extract U and Th from the samples, these were dissolved in HCl (36%) over night. The remaining solids (not more than a few weight percent) were removed by centrifugation. A known quantity of

TABLE 1

Result of ^{14}C and UTD datings in the Luwuk area, Sulawesi. *The field code of the samples and the terrace (L= Luwuk; P= Peleng) to which they belong.

*Sample**	*UTD code*	*[U](ppm)*	*$^{234}U/^{238}U$*	*$^{230}Th/^{234}U$*	*$^{230}Th/^{232}Th$*	*UTD age(ka)*	*^{14}C code*	*^{14}C age (BP)*
01-TP-07(L) (T19)	G-88141	2.44±0.05	1.10±0.02	0.61±0.02	102±26	101± 7	GrN 13889	36700 $^{+1500}_{-1300}$
							SUA 2399	35000±4000
02-TP-11(L) (T62)	G-88142	0.32±0.02	1.2±0.1	1.18±0.09	24± 5	>350	GrN 13890	>42000
04-TP-08(L) (T6.6)	G-88143	3.07±0.05	1.13±0.02	0.47±0.02	104±25	67± 4	GrN 13891	42500 $^{+4900}_{-3000}$
04-TP-08(P)	G-88149	2.36±0.05	1.08±0.02	0.024±0.002	9± 3	2.6±0.2	GrN 13892	2310±60
6 (L) (T410)	G-88144	2.08±0.06	1.03±0.03	0.89±0.04	56±12	229 $^{+55}_{-35}$	GrN 14191	35600±1300

$^{232}U/^{228}Th$ spike activity was added for calibration purposes. From the solutions, U and Th were coprecipitated with $Fe(OH)_3$. The precipitate was redissolved and U, Th and Fe were separated and purified on an ion-exchange column. By electroplating on a stainless steel planchette, thin α-sources were prepared, one for U and one for Th per sample. The radioactivity of the sources was measured by means of silicon semiconductor detectors, mounted in an α-spectrometer, as described by VAN DER WIJK (1987).

Table 1 shows the results of the UTD dates, together with the independently obtained radiocarbon dates. Some general conclusions can be drawn. First, the U-concentrations in the corals are rather low, especially for G-88142, which is close to the detection limit. This sample appears to be older than 350 ka and had also shown to be too old for radiocarbon dating. All corals dated by UTD are older than we found by means of radiocarbon, except for the sample from Peleng island, G- 88149/GrN-13892, which ages agree very well indeed, giving positive evidence concerning the reliability of the UTD ages.

4. INTERPRETATION

The UTD ages of the lower group of terraces range from over 350 ka to 67 ka, while that of the high terraces is around 229 ka. Reef crests will approximately represent the peaks of periods of transgression (CHAPPELL, 1974). The UTD ages for the three coral samples of Luwuk agree fairly well with UTD ages obtained from certain interglacial reef crests developed along the tectonically rising northeast coast of Huon Peninsula, New Guinea, which serves as a standard for the interpretation of sea level changes over the past 300 ka (BLOOM *ET AL.* 1974; AHARON, 1983; CHAPPELL, 1983; BLOOM & YONEKURA, 1985; CHAPPELL & SHACKLETON, 1986; SHACKLETON 1987; PILLANS, 1987). The age of around 67 ka for the sample from T6.6 probably indicates coral growth during reef stage IV (age centred around 60 ka). The age of around 101 ka for the sample from T19 corresponds with the age given for reef VIa (around 100 ka), and the age of around 229 ka for the sample from T410 probably indicates formation during reef stage IXb (ages around 218 ka), although the wide range may also cover the ages indicated for IXa and Xc.

We have no information on the geoids during the times the Luwuk terraces developed. Presently, the geoid for the region, which includes East Sulawesi and Irian-New Guinea (Huon), is between +60 to slightly over +70 m (RAPP, 1974). It is reasonable to assume that during the past 300 ka the geoid has changed several times, since the cyclical orbital changes of the earth have much shorter periodicities. These external factors are believed to also affect the core-mantle coupling (YE & YOKOYAMA, 1987), hence resulting in mass redistributions that may also change the geoid. Lack of information concerning these possible changes has forced us to assume that the geoids during the time of formation of the Luwuk terraces were similar to that of today. The past sea levels used here as a reference to calculate rates of uplift are those recently recalculated from the reef terraces at Huon Peninsula, after detailed correlation with the ^{18}O deep-sea record (CHAPPELL & SHACKLETON, 1986). The present geoid shows that sea level is approximately 10 m lower at Luwuk, but in view of the uncertainties concerning the past geoidal changes, it serves no purpose to estimate what the geoidal differences with the Huon Peninsula might have been during the various stages of development of the Luwuk terraces.

Sea level during formation of T410 is hard to establish. First, the wide range of possible ages, in between 194 and 280 ka, may indicate growth during the sea level highs that formed terrace stages IXb, IXa and Xc of Huon. Second, ages in this range may be overestimated (CHAPPELL & SHACKLETON, 1986) and for sea level estimates relatively few data are available for calibration with the oceanic oxygen isotope curve. Sea level during these 3 terrace stages, however, is interpreted to have been more or less equal, ranging between 0 and −25 m. Using the minimal age of 196 ka, and a lowest sea level position of −25 m, this results in an average rate of highest uplift of 222 $cm{\cdot}ka^{-1}$. Lowest rate of uplift, using the maximum age of 280 ka and zero sea level, has been 146 $cm{\cdot}ka^{-1}$. This gives an average rate of 184 $cm{\cdot}ka^{-1}$, which is within the range of uplift rates calculated for reefs of the Huon Peninsula (between 90 and 350 $cm{\cdot}ka^{-1}$ (CHAPPELL, 1974)). This rate also is similar to uplift rates calculated for Late Cenozoic uplift in Buton (175 $cm{\cdot}ka^{-1}$; FORTUIN *et al.*, 1989) and Seram (250 $cm{\cdot}ka^{-1}$; DE SMET *et al.*, 1989a), using the geohistory technique (DE SMET *et al.*, 1989b).

The rate of uplift for T6.6 is calculated as follows (Fig. 5): the sample is from a level at 4.4 m AHT, whereas the reef crest is at 6.6 m and the platform slopes over a distance of 32 m reach up to 12 m elevation at the base of the crest that contains sample G-88141 of T19. This position below the reef top suggests that the sampled coral grew before the culmination of the transgression, which would explain its somewhat older age than reef IVa. Sea level at 59 ka (adjusted age for Huon reef IVa) was at −28 m ± 3 m), so that for that time interval average uplift was around 66 $cm{\cdot}ka^{-1}$. Extrapolating this uplift rate towards 67 ka, sea level then may have been around −34 m.

The age of 101 ka for T19, which corresponds very well with the age for terrace VIa, that had an inter-

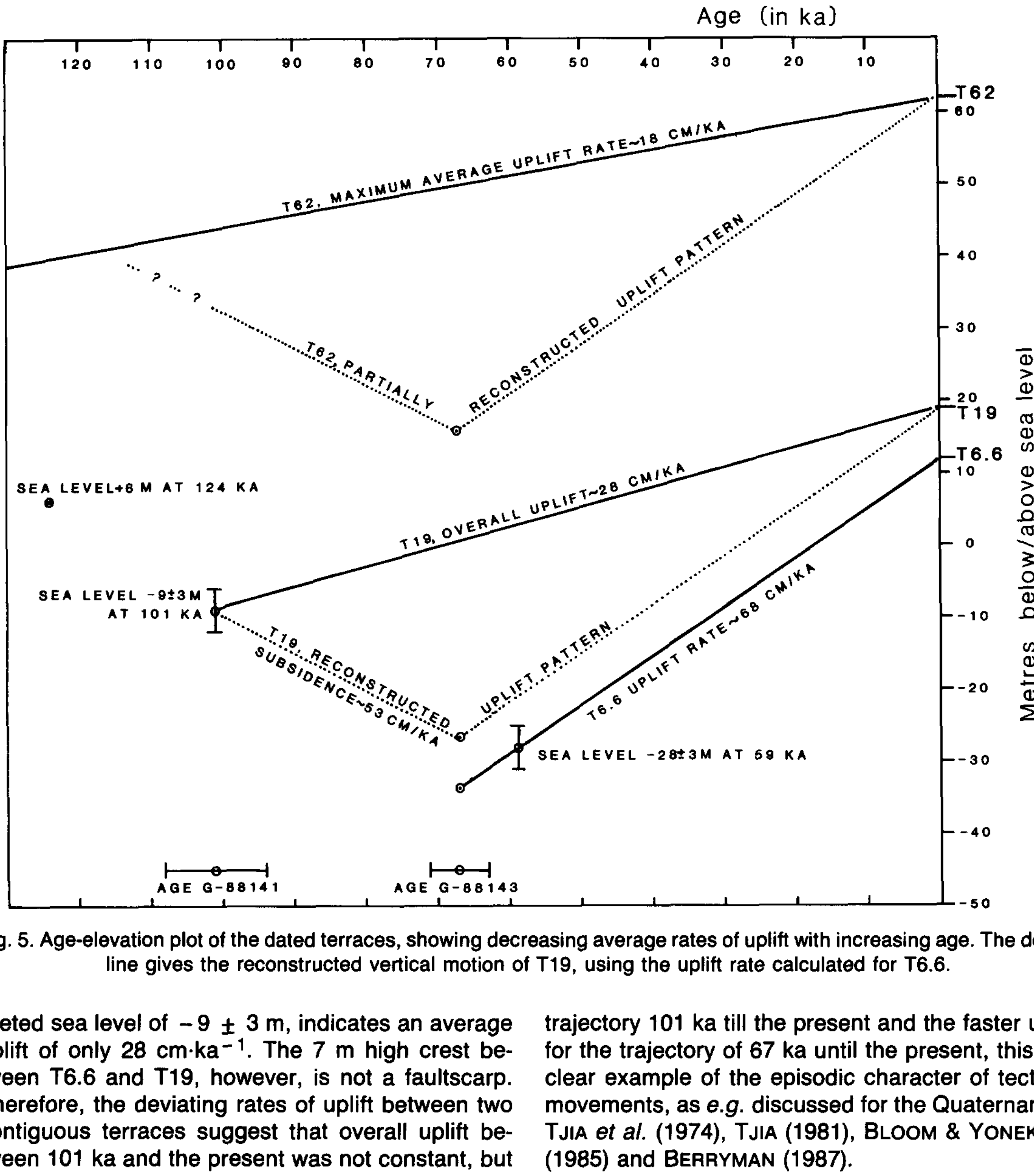

Fig. 5. Age-elevation plot of the dated terraces, showing decreasing average rates of uplift with increasing age. The dotted line gives the reconstructed vertical motion of T19, using the uplift rate calculated for T6.6.

preted sea level of -9 ± 3 m, indicates an average uplift of only 28 cm·ka^{-1}. The 7 m high crest between T6.6 and T19, however, is not a faultscarp. Therefore, the deviating rates of uplift between two contiguous terraces suggest that overall uplift between 101 ka and the present was not constant, but that subsidence took place between 67 ka and 101 ka, at a rate of 53 cm·ka^{-1} (Fig. 5).

T62, together with T6.6 and T19, belongs to the same group of terraces and no major faults have been mapped between T62 and the other terraces of this group. Applying the reconstructed curve of vertical motion from the present to 101 ka, it follows that T62 was well above sea level. We therefore suppose that since its formation T62 remained above sea level, because otherwise it should have been covered by younger overgrowth. The minimum age of T62 of 350 ka versus its moderate elevation indicates a maximum average rate of uplift of only 18 cm·ka^{-1} (not corrected for sea level changes). Compared with the faster average uplift calculated for the trajectory 101 ka till the present and the faster uplift for the trajectory of 67 ka until the present, this is a clear example of the episodic character of tectonic movements, as *e.g.* discussed for the Quaternary by TJIA *et al.* (1974), TJIA (1981), BLOOM & YONEKURA (1985) and BERRYMAN (1987).

Usually the reefs formed around the interglacial sea level rise between 129 and 122 ka are well developed. Sea level at Huon then was about 6 m above the present level. It is tempting to speculate which non-dated terrace was formed then. Extrapolation, using the average rate of uplift of 28 cm·ka^{-1} obtained for the reef of 101 ka, indicates a position around 41 m AHT. Extrapolation of the subsiding trend that existed between 67 and 101 ka towards 124 ka would, however, result in a position no more than a few metres above T19. This possibility then might indicate that the wider platform of the Luwuk airstrip is a compound platform. It is clear that more age data are needed.

5. DISCUSSION

Detailed sampling and mapping of the Luwuk terraces should furnish sufficient information for unravelling the Quaternary tectonic movements of the region. The limited data presented here already indicate that considerable differential uplift is taking place between a rapidly rising hinterland (as exemplified by T410) and a probably subsiding Peleng Strait. The decreasing average uplift rates with increasing age calculated for the lower terrace group indicate that on the time scale of 10^4 years tectonic movements in orogenic areas may still show a very 'jerky' pattern (see discussion by BLOOM & YONEKURA, 1985).

The temporal reversal (on a scale of 10^4 years) of overall uplift of the lower terrace group into subsidence is very remarkable. It is perhaps related to its particular setting in the hinge zone between a rapidly rising hinterland and Peleng Strait. Pulses of uplift in the centre of uplift probably also had a positive effect along the fault blocks bordering it (the lower terrace group), but isostatic compensation during intervals of crustal relaxation, perhaps further accentuated by drag from the downthrown block, may have caused intermittent subsidence. For Holocene tectonics, *i.e.* on a scale of 10^3 years, it has been shown that upheaval of fault blocks may be followed by intervals of sinking (THOMMERET *et al*, 1981).

The average differential motion of 184 - 68 $cm \cdot ka^{-1}$ between terrace T410 and T6.6 suggests that during the last 67 ka, in the order of 78 m of differential uplift has taken place. Because of the episodic character of uplift, this is only an approximation. The 18 to 22° slant of the middle group of terraces is interpreted as drag resulting from older movement on the upper normal fault, while the fault separating the inclined middle group and lower group was probably active in more recent times.

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