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LATE QUATERNARY UPLIFT HISTORY FROM EMERGED REEF TERRACES ON SANTO AND MALEKULA ISLANDS, CENTRAL NEW HEBRIDES ISLAND ARC

C JOUANNIC, F W TAYLOR, A L BLOOM, AND M BERNAT

Currently uplifting reef terraces on Santo and Malekula islands, in the central New Hebrides arc, offer a detailed record of vertical tectonics related to the subduction of the Australian plate beneath the Pacific plate.

Inferred uplift rates on Santo range vary widely from 1 to 7 mm/y, generally increasing from east to west. They define an elliptical zone of maximum uplift, which corresponds to the western mountain belt of Santo. This must be related to the location of western Santo very close to the axis of the New Hebrides trench, which is interrupted in front of Santo. The uplift of southern Santo may be influenced particularly by subduction of the d'Entrecasteaux fracture zone, a major bathymetric feature on the underthrusting Australian plate. The uplifted reef terraces which form the Eastern Plateau Limestones, overlying the eastern half of Santo, are tilted E to ENE in the northeastern and central parts of the island, E to ESE in southeastern Santo and Malo. This is consistent with the apparently elliptical shape of the zone of maximum uplift rate.

Such high uplift rates are not observed on Malekula, which is not on the trench axis, although still abnormally close to the thrust zone. Northern and southern parts of the island behave differently because they are separated by a tilt discontinuity across central Malekula. In northern Malekula, inferred uplift rates range from 0.5 to 4.3 mm/y, with a zone of maximum uplift in the southwestern part of north Malekula and a general tilt to the NE in its main northeastern part. The southern Malekula inferred uplift rates range from a few tenths of a mm to about 1 mm/y, with a zone of maximum uplift near the tilt discontinuity of central Malekula and a general tilt to the SE. Such an uplift pattern on Malekula island is likely to be related to the presence of the southern margin of the d'Entrecasteaux fracture zone which is being underthrust beneath northern Malekula.

The main surface of the Eastern Plateau Limestones in Santo and the main terrace of northern Malekula are believed to correspond to the 125 000 years old paleosea level by comparing the terrace levels of both islands with the paleosea levels as estimated for the last 140 000 years in the Huon peninsula area (New Guinea). This correspondence of terraces with paleosea levels is supported by uranium-series dates for a few of the lower terraces on Malekula and Santo. If the inferred ages of the higher terraces are correct, then the uplift rates of both Santo and Malekula may have increased significantly some time between about 40 000 y.b.p. and the Holocene epoch. In any case, it is clear that much of Santo and north Malekula emerged quite recently.

INTRODUCTION

The New Hebrides island arc extends NNW–SSE between latitudes 11° and 22°S, from the Solomons island arc to the Hunter fracture zone (Fig. 1). It is related to the subduction of the Australian plate beneath the Pacific plate. The Australian plate is thrusting steeply in a N75± 11°E direction (Pascal *et al.* 1978) at about 12 cm/y (Dubois *et al.* 1977).

The corresponding New Hebrides trench is interrupted between latitudes 14° 30′ and 17° 30′S, where the rugged relief of the d'Entrecasteaux fracture zone on the Australian plate is being thrust beneath the islands of Santo and Malekula (Fig. 2). These two islands would occupy the position of the inner trench slope if the New Hebrides trench were continuous: this unusual relationship places Santo and Malekula on the very thin western edge of the Pacific plate and therefore very close to the thrust zone. Despite the lack of a trench west of Santo and Malekula, seismicity associated with the Benioff zone is comparable to that to the north and south where a trench exists (Pascal *et al.* 1978).

North of Efate, the New Hebrides can be divided into three belts, corresponding to three main phases of volcanism (Carney and Macfarlane 1976): (1) a western belt, containing the oldest volcanic rocks (Oligocene

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to Middle Miocene), includes Santo, Malekula and the Torres islands; (2) an eastern belt, related to an Upper Miocene to Lower Pliocene volcanism, is represented by Maewo and Pentecost; and (3) between lies a modern volcanic chain consisting of Lower Pliocene to modern volcanic islands. The western belt is the focus of this report because of its unusual position close to the trench and away from the modern volcanic chain and therefore from possible interference by volcanic activity.

Coral-reef terraces have developed widely upon a substrate of volcanic and sedimentary rocks during the Quaternary and have been uplifted throughout much of the New Hebrides. These reef terraces represent paleosea levels (Mesolella *et al.* 1969, Bloom *et al.* 1974), and they record an absolute chronology of uplift history and deformation patterns, because the fossil corals they contain can be radiometrically dated by uranium-series methods and radiocarbon.

Two surveys were done in 1976 and 1977 on Efate, Malekula, Santo and the Torres islands. Data concerning Efate are published elsewhere (Bloom *et al.* 1978), and the Torres islands study is still in progress. In this paper, geomorphological observations and age determinations on Santo and Malekula are first presented and then interpreted.

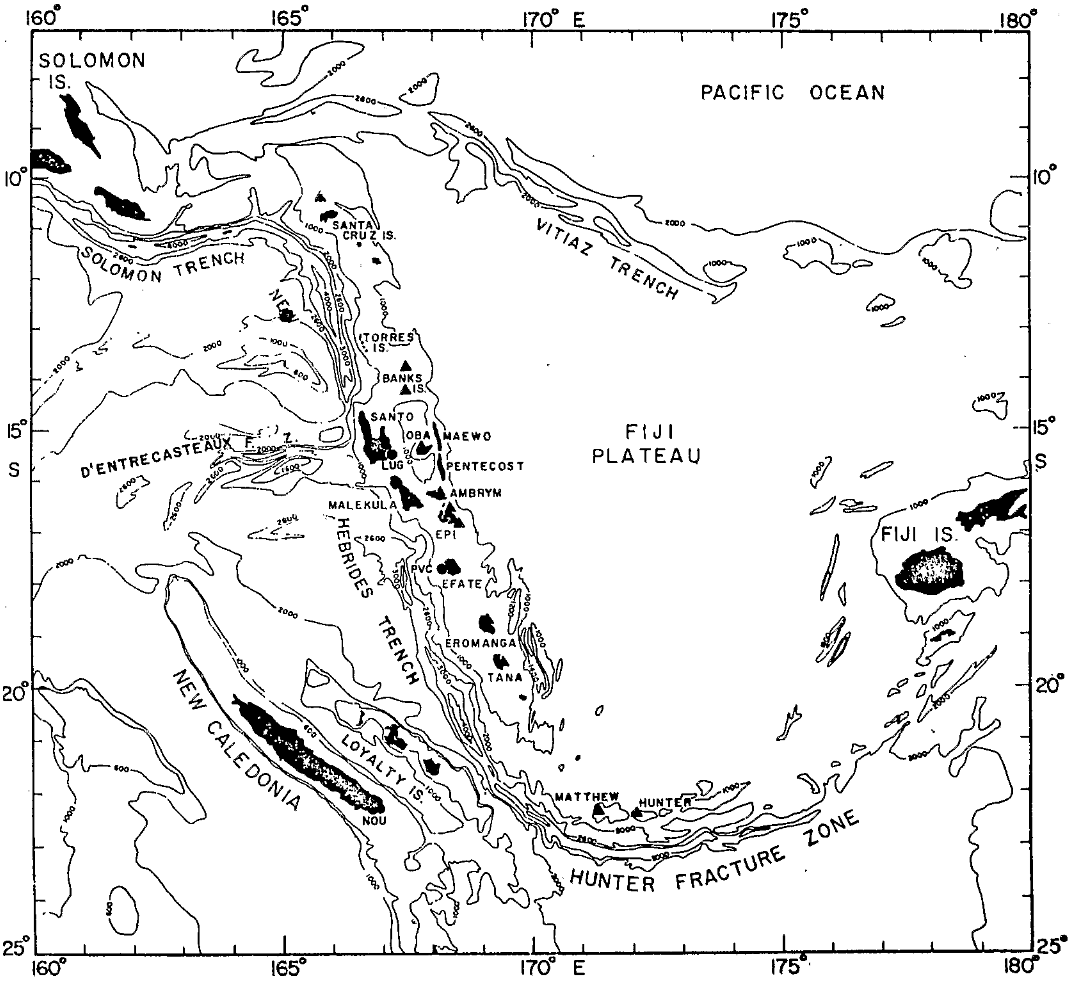

Figure 1. The New Hebrides island arc, bathymetric setting.

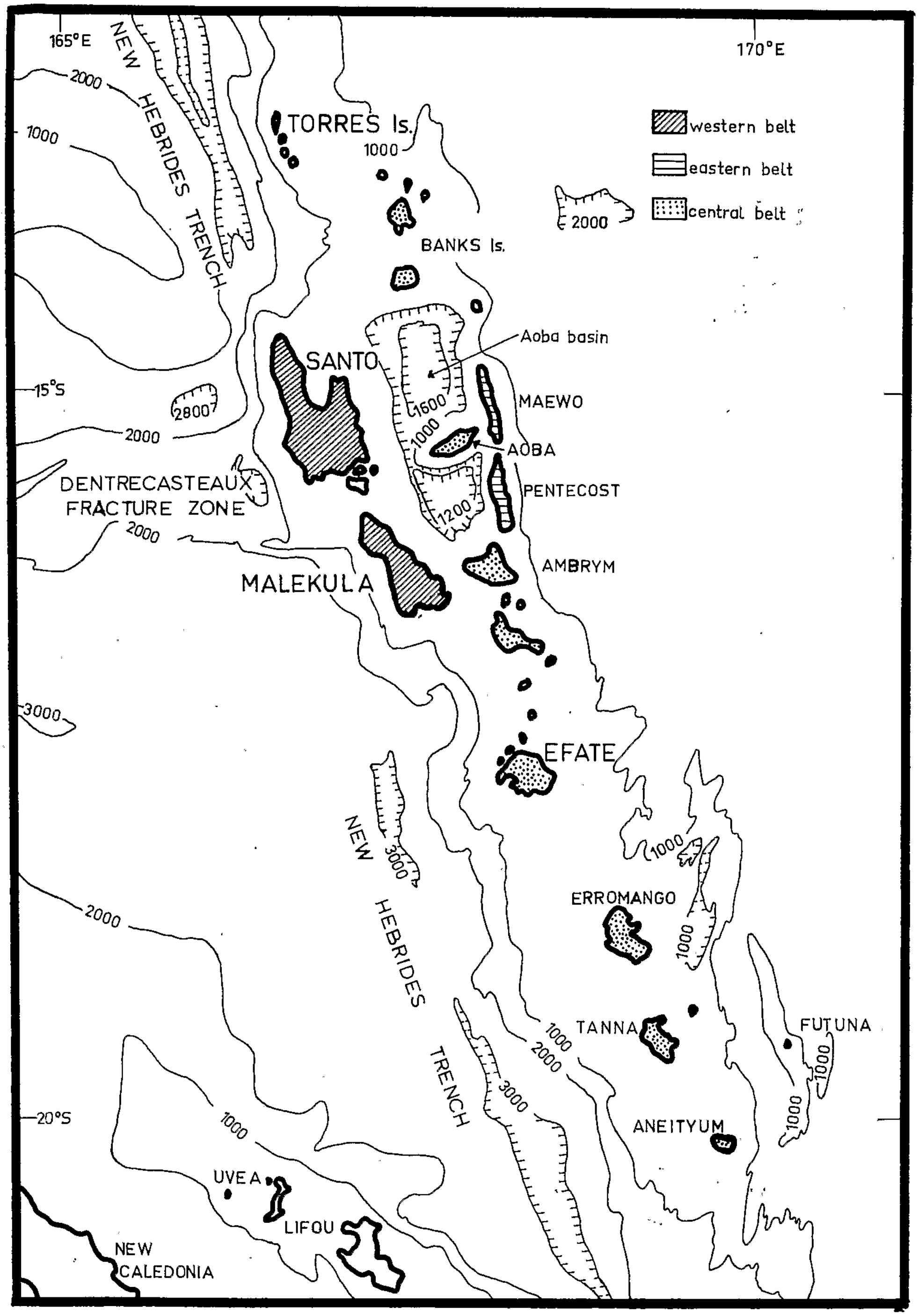

Figure 2. The New Hebrides archipelago.

METHOD

An important part of this paper is represented by the calculations of uplift rates based on the altitudes of emerged reef terraces and the radiometric ages of fossil corals from the terraces. A third factor is the paleosea level at the time each dated coral lived. The higher paleosea levels of the past 140 000 years are reasonably well known (Mesolella *et al.* 1969; Bloom *et al.* 1974; Bender *et al.* 1979). For the older terraces, slight errors in age, altitude and paleosea level are not very important because the large amount of uplift of Santo and Malekula overwhelms other errors. But, for the very young Holocene terraces, close to present sea level, small errors in age, height and paleosea level are more important. For comparison, both a generalized Holocene sea-level-rise curve (Clark *et al.* 1978) and specific Holocene sealevel-rise curves (Bloom 1977) are used to correct the amount of uplift undergone by a coral of a given age. For example, a coral at 14 m altitude is 7000 years old: it must have undergone at least 20 m of uplift because sea level 7000 years ago was about 6 m lower than present. Because this correction assumes that the coral was growing at low-tide level, it gives a minimum amount of uplift.

When two corals from a Holocene terrace give different uplift rates, the higher rate is probably correct; and the coral giving the lower rate lived well beneath the surface.

SANTO ISLAND

The two fundamental geomorphological divisions of Santo are a western chain of volcanic and sedimentary rocks and an eastern limestone plateau zone (Robinson 1969; Mallick and Greenbaum 1977). The western belt is made up of semi-independent uplifted or depressed blocks, in which rocks are steeply tilted and intensely faulted: major faults are mostly parallel to the western Santo coastline or trend NE–SW. In the east, extensive, massive reef limestones rest almost undisturbed over nearly the entire eastern half of Santo: overlying Pliocene sediments and probably Oligo-Miocene volcanic rocks, they form a series of step-edged plateaux which have been uplifted during the late Quaternary. Photogeological interpretation indicates that these plateaux are tilted down slightly E to ENE in the northeastern and central parts of the island, E to ESE in southeastern Santo and in Malo (Mallick and Greenbaum 1977): the angle of tilt is in the order of 1° but reaches 5° (in the higher and older Boutmas plateau, for instance). Thus, there appears to be a sudden change in tectonic style from eastern to western Santo. However, this may be due in part to the lack of a coral limestone carapace on western Santo combined with a gradual increase in uplift rate and faulting from east to west.

The coastal reef-terrace complex of Santo

A continuous coastal fringe of slightly uplifted reef terraces can be observed all along the eastern coast of Santo, much of the southern coast (except where terrigenous sediments are dominant), and the southern islands (Toutouba, Aore, Malo, etc.). Except in the southeast corner of Santo, including islands such as Aore or Toutouba, where it occupies a few square kilometers, the low coastal platform is rather narrow relative to the extent of the high plateaux; its width ranges from a few tens of meters up to a kilometer, generally in the order of a few hundred meters.

The coastal platform, when narrow, consists of uplifted fringing reefs, with a subhorizontal surface inland and a gentle slope seawards, usually edged by a small modern sea cliff and a fringing reef. Where the coastal terrace is wider, its consists mostly of lagoon-type deposits (friable, coarse calcarenite, with many sticks of *Acropora* sp. and numerous *Porites* coral heads).

Queiros peninsula

An uplifted fringing reef surrounds the Queiros peninsula. It is usually edged on its seaward margin by a high modern sea cliff, 3 to 6 m high (Lotoror, Ekar, Bilion, Dolphin island, Areb bay, etc.). In some places, the sea cliff is replaced by a low, sandy shore (Dr Keller's estate, Port Olry mission, Hog Harbour bay). One or two subsidiary terraces sometimes occur between the main terrace and the sea:

(1) The lowest terrace, not well developed, is seen in Dr Keller's estate at 3 m above low-tide level (ALT).

(2) The second one, more obvious, though narrow, is seen between 5 and 8 m ALT in Dr Keller's estate, near Mar hill and at Hog Harbour bay.

Two radiometric dates were obtained from the Queiros peninsula:

(1) A coral head (S-N-1, see Fig. 3), found in growth position close to the surface of the main terrace (13 m ALT in that place), gave a date of 7460 ± 230 y b.p. (Table 1b). If the 7500 y.b.p. sea level was 9 m lower than present (Bloom 1977, Clark *et al.* 1978), a total uplift of 22 m and an uplift rate of 3 mm/y are inferred.

(2) A 2650 ± 100 y b.p. date has been reported previously by Launay and Recy (1972), collected 0.5 m from the top of a 3 m high sea cliff near Hog Harbour: an uplift rate of about 1.1 mm/y is inferred.

SE Santo

The southeastern corner of Santo is characterized by a wide coastal platform and a number of reef-terraced islands offshore. The backreef calcarenite facies dominates the coastal terrace surface. This is illustrated by the terraces of Turtle bay (8–11 m ALT) and Matewulu airfield (9 m ALT). One sample (S-AC-1) from Matewulu terrace is dated at 5940 ± 190 y b.p.: at that time, sea level had not quite reached its present height (Bloom 1977; Clark *et al.* 1978) and a total uplift of 11.5 m is inferred, yielding an uplift rate of 1.9 mm/y.

For a coral from the lowest terrace on western Malo, at 4.5 m ALT, Neef and Veeh (1977) reported a date of 4000 ± 500 y b.p. An uplift rate of 1.1 mm/y is inferred. It is suspected that at least part of a broad terrace levelled at 8–18 m ALT on western Malo may also be Holocene in age.

Southern Santo

From Rose point westwards to Tangoa mission, along the southern coast of Santo, are many emerged paleo-patchreefs on the Holocene terrace. Such a morphology of modern patchreefs exists immediately offshore.

Two of these paleo-patchreefs have been dated (sites S-A and S-B close to Navota Farm School). The top of the first one is 18 m ALT, and dates are 5000 ± 600 and 6500 ± 700 y b.p.: uplift rates of 3.6 and 3.3 mm/y are inferred, after correction of 4 m for 6500 y paleosea level (Bloom 1977; Clark *et al.* 1978). The second fossil patchreef culminates at 13 m ALT: a date of 4180 ± 130 y b.p. (S-B-1) leads to an uplift rate of 3.1 mm/y.

Two other corals from a lower terrace, 2 m ALT, below Navota Farm School (site S-C) have been dated at 1055 ± 80 and 1415 ± 100 y b.p.: the inferred uplift rates, 1.4 and 1.9 mm/y, are not used further in regard to the higher 3.1 and 3.6 mm/y from former sites S-A and S-B, quite close to S-C (see method).

In the vicinity of South Santo lies the small island of Araki, entirely capped by reef terraces. Two samples from the first main terrace, 27 m ALT, are dated consistently at 5430 ± 200 and 5470 ± 160 y b.p.: a high uplift rate of 5.2 mm/y is therefore inferred.

SW and NW Santo

Uplifted fringing reefs form coastal terraces at 6 and 14 m ALT near Tasmaloum, 6 and 10 m ALT at Cape Sinotarip, and 3 and 8 m ALT near Wounpouko, in the area of Cape Cumberland. Older Holocene reefs probably occur at higher altitudes in each of these areas. Instead of being limited by small sea cliffs on their outer edges, the lower terraces are usually bounded by fairly steep slopes without well formed notches. Furthermore, evidence of relatively recent emergence of unknown age occurs along the coast of SW and NW Santo, similar to the 1965 uplifted reef platform visible in NW Malekula (Taylor *et al.* in press).

A coral sample from the 10 m high terrace of Cape Sinotarip (S-Z-5) gives an age of 3200 ± 350 y b.p.: a minimum uplift rate of 3 mm/y is inferred, which is not higher than in the Queiros peninsula or close to Navota Farm School. However, it is possible that this coral was living at some meters depth, or has been downthrown along one of the local faults cutting the coast near Cape Sinotarip.

Six dates come so far from NW Santo. Ranging from 545 ± 90 to 6700 ± 150 y b.p. (Tables 1a and 1b), they indicate uplift rates from 2.1 to 5.5 mm/y. As previously noted (see method), the rate of 5.5 mm/y is selected and is used further in the interpretation.

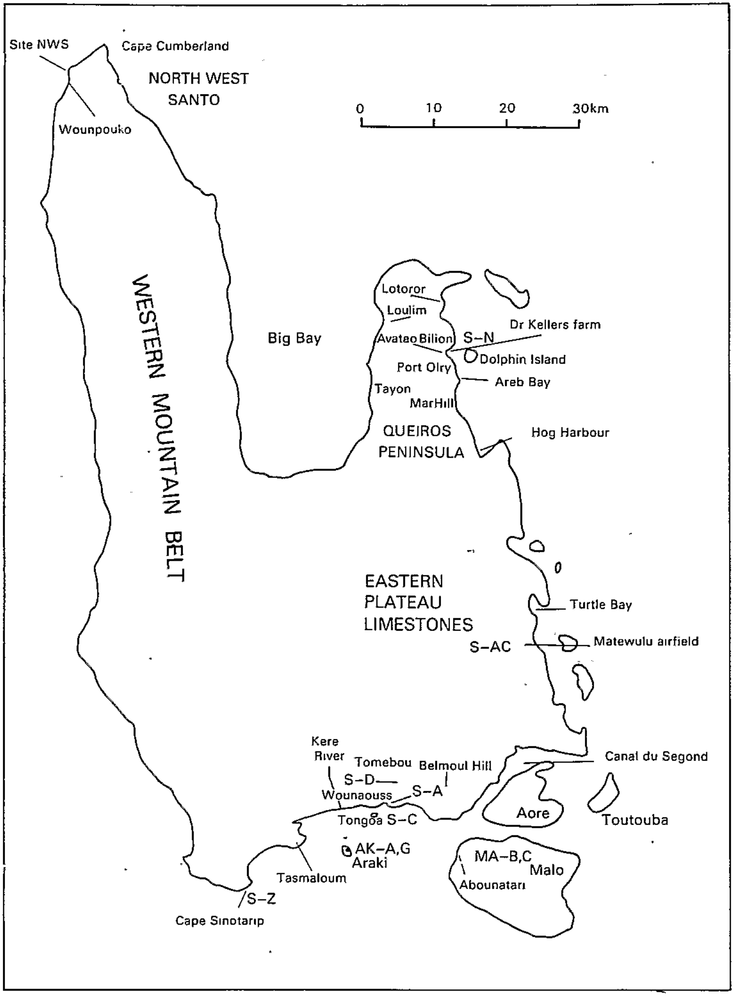

Figure 3. Santo island toponymy and sample locations.

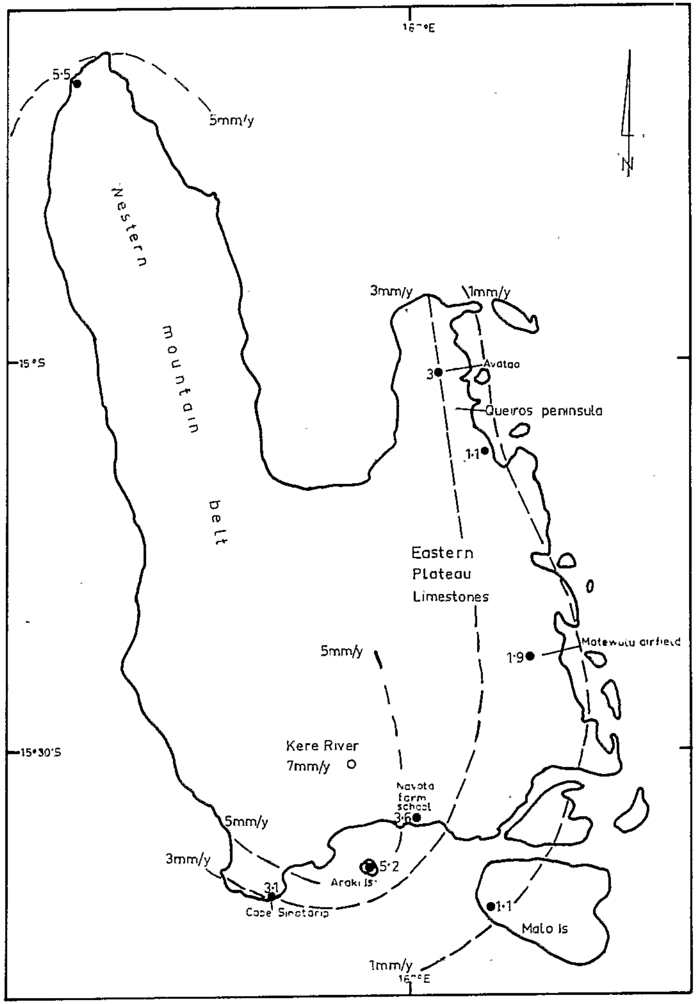

Figure 4. Holocene uplift rates on Santo island.

Interpretation

An emerged Holocene reef platform occurs all along the east coast, most of the south coast and on the end of the northwest point of Santo. It seems to consist of as many as three terraces, the uppermost one usually very broad and sloping gently down towards the sea. The variation in maximum height of the Holocene terrace is probably due, at least in part, to differences in distance from the tilt axis, which is thought to trend N–S or NNW–SSE.

The Holocene uplift rates range from 1 to 5.5 mm/y. The rates of 3 to 4 mm/y on the Queiros peninsula and in southern Santo, and of 5.2 mm/y for Araki island, are high. However, on a map of Santo (Fig. 4), the Holocene uplift rates tend to define an elliptical zone of maximum uplift rates, which corresponds topographically to the high western part of Santo. This is consistent with the structural pattern of Santo, if one assumes that the high topography of western Santo occurs because that area has been uplifted most.

The high reef terraces of Santo

Geomorphology

The higher reef terraces are well developed along the northeast, east and southeast coasts of Santo. They occur as steps on the edges of the high wide plateaux that form the extensive Eastern Limestone Plateau Zone of Santo (Robinson 1969, Mallick and Greenbaum 1977).

Most altitudes of the terraces were measured with two Wallace and Tiernon altimeters (one of them recording changes in barometric pressure at the shore) and are compiled in Table 2. The traverses back to the base station show that the instrumental shift can sometimes reach the equivalent of 3 m: but this drift in most cases is not higher than the altitude inaccuracy in estimating the right place to be measured on the terrace. A mean accuracy of ± 3 m is adopted in this report for altitudes of high-reef terraces.

Nine altimetry traverses were made on Queiros peninsula, including one previously reported by Mallick (1970) on Walraoul plateau. The principal traverse is near Avatao (on the 1 : 100 000 IGN map of Santo), where the terraces are visible under the coconut trees of the plantation. In most other cases, dense vegetation partly conceals the morphology, leading to confusion, as between a simple slope break and a sloping, but definite, terrace.

As many as eight different terrace surfaces above the Holocene platform were seen on the Queiros peninsula. Among these high levels, the second one from sea level (39–46 m), the seventh one (182–190 m) and the upper one (218–253 m) are morphologically the most definite terraces. Particularly, the upper one forms most of the top surface of the Queiros plateaux.

In southern Santo, two altimetry traverses have been made. On Tomebou hill, a former island that is now part of the emerged mainland, the altitudes presented here are quite consistent with those previously reported by Mallick (1970) on the same hill. No correlations are obvious among the southern Santo altimetry traverses and another one previously reported on Malo island by Neef and Veeh (1977). This must be due to the fact that the hill behind Belmoul plantation, Tomebou hill and Malo island have been uplifted at different rates. However, the Tomebou terraces correspond well to the main terraces of the Queiros peninsula, particularly with the terraces observed at Avatao: there appears to be a close relation between the uplift rates of both areas.

Radiometric dates

Four new Th^{230}/U^{234} dates come from the high reef terraces of Santo and Malo (Tables 1a and 1b). Two of them date the 41 m high terrace of Tomebou and are quite consistent with one another: they are 38 ± 2 and 37± 2 ka.

Two more dates of 55 ± 4 ka and 223 ± 44 ka have been obtained from corals in terraces on Malo Island at 43 and 53 m respectively, although the higher terrace seems much younger than the lower one. The older terrace may correspond to an older reef exposed by erosion. These two dates must be added to two other dates previously reported by Neef and Veeh (1977) on the same part of Malo: 60 ± 4 and 130 ± 10 ka, dating two terraces, at 49–55 m and 94–98 m, respectively.

TABLE 1a

U/Th radiometric datings and inferred uplift rates on Santo

Sample No. and Locality (see Fig. 3)	Coral Species	Aragonite (%)	U (p.p.m.)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	Age (× 1000y)	Terrace Altitude (m ALT)	Correction Altitude (m) for Paleosea Level	Inferred Uplift Rate (mm/y)
S-A-1*	*Oulophyllia crispa*	100	2.52±0.07	1.12±0.03	0.045±0.005	5.0±0.6	18	..	3.6
S-A-3†	*Diploastrea heliopora*	99	..	1.14	0.04	6.5±0.7	18	+4	3.3
S-D-1*	*Acropora humilis*	100	3.44±0.07	1.13±0.02	0.30±0.01	38 ±2	41	+38	2.0
S-D-2*	*Montipora* sp.	100	3.58±0.09	1.13±0.02	0.29±0.01	37 ±2	41	+38	2.0
									see text
S-N-1*	*Porites lutea*	100	2.75±0.06	1.15±0.02	0.063±0.003	7.1±0.4	13	+6	see ^{14}C
S-Z-5†	*P. lutea*	100	..	1.17	0.03	3.2±0.3	10	..	3.1
S-AC-1*	*P. lutea*	100	2.73±0.05	1.14±0.02	0.051±0.004	5.7±0.5	9	+2	see ^{14}C
NWS-C-1†	*Porites* sp.	99	2.78±0.05	1.10±0.02	0.04	4.5±0.3	10	..	2.2
NWS-D-1†	*Porites* sp.	100	2.52±0.05	1.13±0.03	0.03	3.5±0.3	16	..	4.6
MA-B-2†	*P. lutea*	100	2.72±0.05	1.07±0.02	0.89	223±44	53	?	?
MA-C-3†	*P. lutea*	100	2.85±0.05	1.15±0.02	0.40	55 ±4	43	+28	1.2

* Dates from Broecker W S and Goddard J G, Lamont-Doherty Geol. Obs., N.Y., USA

† Dates from Bernat M and Gaven C, Géol. Struct., Univ. Nice, France

TABLE 1b

Radiocarbon datings on Santo, with inferred uplift rates

Sample No. and Locality (see Fig. 3)	Coral Species	Aragonite %	Age	Terrace Altitude (m ALT)	Correction Altitude for Paleosea Level (m)	Inferred Uplift Rate (mm/y)
S-B-1*	*Diploastrea heliopora*	100	4180±130	13	..	3.1
S-C-2†	*Platygyra sinensis*	100	1415±100	2	..	1.4
S-C-4†	*Favites virens*	100	1055±80	2	...	1.9
S-N-1*	*Porites lutea*	100	7460±230	13	+9	3.0
S-AC-1*	*P. lutea*	100	5940±190	9	+2.5	1.9
NWS-A-1†	*P. lutea*	100	6700±150	10	+5	2.2
NWS-A-5†	*P. lutea*	100	5745±200	10	+2	2.1
NWS-B-1†	*Pavona clavus*	100	545±90	3	..	5.5
NWS-B-2†	*Acropora* sp.	100	650±95	3	..	4.6
AK-A-1†	*Acropora* sp.	99	5470±160	27	+1	5.2
AK-G-2†	*Acropora* sp.	100	5430±200	27	+1	5.2

* Dates from Broecker W S, and Goddard J G, Lamont-Doherty Geol. Obs. N.Y., USA

† Dates from Fontes J-Ch, Hydrol. et Géoch. Isot., Univ. Paris Sud, France

TABLE 2

High-terrace altitudes measured on Santo

	Altitude in metres ALT*																															
Traverse Locations	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310
NE SANTO																																
Lotoror		11											127	133			161							232								
Bilion	9	18		32	40																											
Dr Keller's farm		14	24		39	(53)																										
Avatao		13			42		(60)			(92)			121		145				185			218			240		260					
Walraoul plateau	7			30				70									160			190						253						
(Mallick 1970)																																317
W. Queiros (Loulim)		19			46		63									154			189													
W. Queiros (Tayon)		15												136					182													
Dolphin island		10	(21)															173														
Mar hill		13			42								128																			
SOUTH SANTO																																
Belmoul hill			(29)								106			136			164															
Tomebou		14			41		(64)			90						154		170							240							
Tomebou (Mallick 1970)			27	35					85							153									240							

*ALT = above mean low tide. Altitudes in ( ) mark a less distinct terrace, rather corresponding to a break in slope.

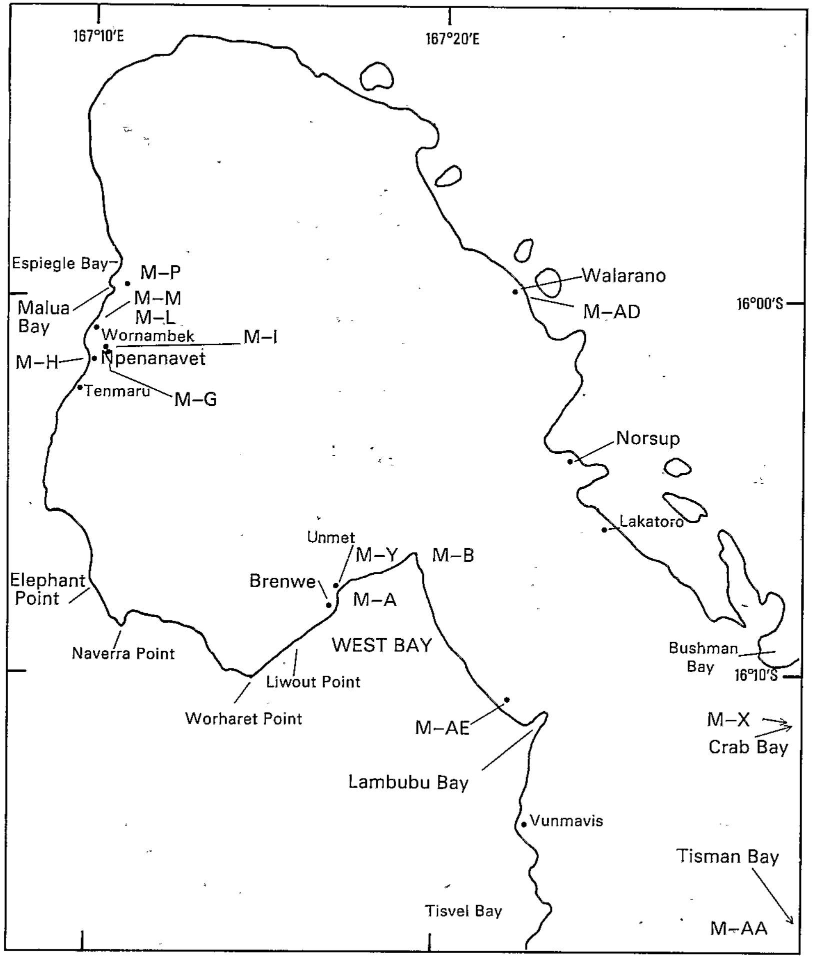

Figure 5. Malekula island: toponymy, sample locations.

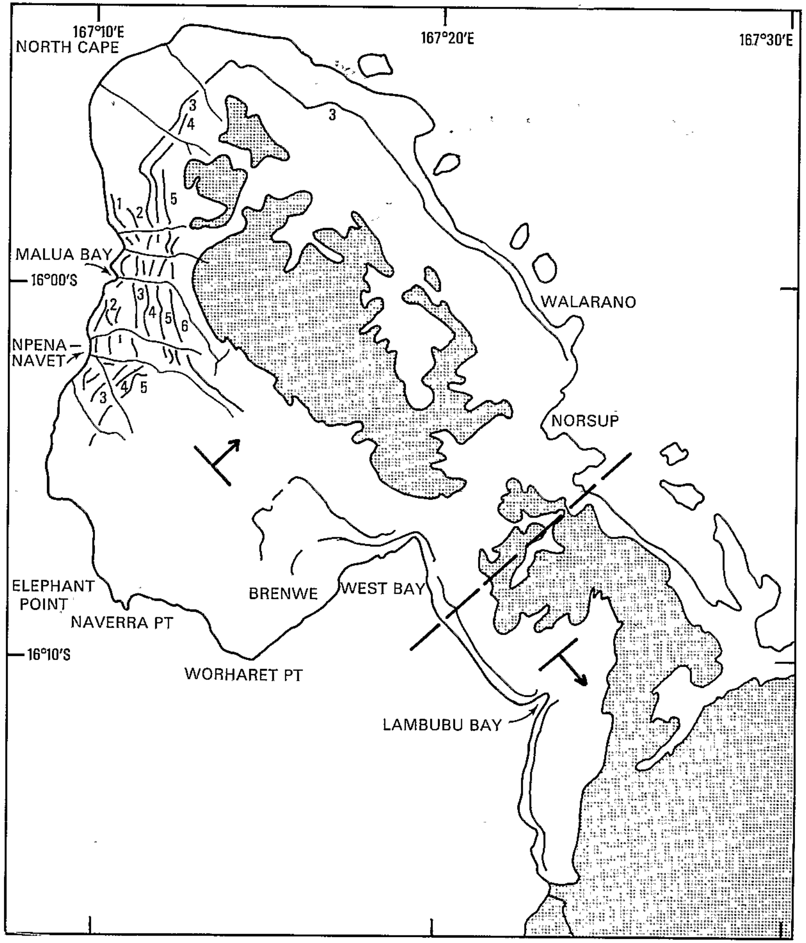

Figure 6. Malekula island: location of uplifted reef terraces (after Mitchell 1971) and tilt features. Stippled areas pre-Pliocene igneous rocks; clear areas Plio-Quaternary.

Finally, one well preserved solitary coral collected in a richly fossiliferous deposit located about 70 m above sea level on the Kere river (south Santo), about 5 km inland, is reported by Ladd (1976) to give a radiocarbon age of 25 280 ± 460y. From faunal analyses (especially from molluscs), the deposits appear to represent an offshore bed laid down at a depth in excess of 50 m.

Inferred uplift rates

It has been clearly demonstrated (Mesolella *et al.* 1969, Bloom *et al.* 1974) that uplifted reef terraces record a succession of high sea levels and represent an interaction between glacio-eustatic sea-level oscillations and regional vertical movements. A sea-level curve for the last 140 000 years has been established from uplifted reef terraces of the Huon peninsula, New Guinea (Bloom *et al.* 1974), and of Barbados, West Indies (Mesolella *et al.* 1969; Bender *et al.* 1979).

Uplift rates of the high reef terraces of Santo can thus be inferred on the basis of the radiometric dates, terrace altitudes and sea-level history:

(1) The 41 m high terrace of Tomebou, dated at 37 and 38 ±2 ka, is likely to correspond to the 40 ka Huon paleosea level, which is assumed to have been 38 m below present sea level (Bloom *et al.* 1974). Thus, a total uplift of 79 m and an uplift rate of about 2 mm/y are inferred for this Tomebou terrace.

(2) In Malo, the 43 m high terrace and Neef and Veeh's (1977) 49–55 m high terrace, respectively dated at 55 ± 4 and 60 ± 4 ka, can be considered equivalent to the 60 ka Huon terrace. The 60 ka paleosea level is supposed to have been 28 m below present sea level (Bloom *et al.* 1974). A total uplift of 71 m and therefore an uplift rate of about 1.2 mm/y are inferred for this terrace. The older dates (223 ± 44 ka and 134 ± 10 ka) are not consistent with one another and are to be confirmed by additional work on older terraces of Malo.

(3) If the 25 280 y coral from the Kere river is contemporaneous with the sediments in which it was collected, then it was deposited at a depth of more than 50 m when sea level is estimated to have been around 50 m below present sea level (Bloom *et al.* 1974). Given the present altitude of the fossiliferous outcrop (70 m above sea level), a minimum uplift of 170 m and a very high uplift rate of 7 mm/y are inferred for this area.

MALEKULA

Malekula consists of a mountainous, deeply dissected core of Miocene volcaniclastic sediments and igneous rocks surrounded mostly in its northern part by a cap of terraced coral limestones, the Tenmaru Reef Limestones (Mitchell 1969, 1971), which reaches a maximum altitude of 614 m. As in Santo, there is a nearly continuous low terrace along most of the north Malekula coast. At the inland border of the modern reef, much of north Malekula is fringed by dead corals killed by earthquake-related emergence in 1965. A detailed comparison of the 1965 uplift pattern and that recorded by the older reef terraces is presented elsewhere (Taylor *et al.* in press).

The coastal terrace complex of northern Malekula

From Vunmavis (south of Lambubu bay) around north Malekula to Tisman bay, on the eastern coast, the low coastal reef terrace disappears for only about 3 km between Naverra and Elephant points (western coast). In the west, from Lambubu bay to Malua bay, it usually does not exceed a few hundred meters wide. It widens to a maximum of about 2 km around the northern coast. On the eastern coast, its width is more variable, ranging from a few meters up to several hundred meters.

The reef terraces edging this low platform along the western coast are uplifted fringing reefs. However, lagoonal deposits are present along the northeastern coast, where former embayments have emerged (e.g. Norsup, Sarmet).

Geomorphologically, in the West bay area the low coastal platform is formed by

(1) the 1965 reef platform, up to about the present high tide level (e.g. Lambubu bay, site M-B, Brenwe, Liwout point, Worharet point);
(2) the remains of an apparently slightly older reef, 1 m higher than the 1965 platform (e.g. Lambubu bay, Brenwe, Liwout point);

TABLE 3a

U/Th radiometric datings and inferred uplift rates on Malekula

Sample No. and Locality (see Fig. 3)	Coral Species	Aragonite %	U (p.p.m.)	$^{234}U/^{238}U$	$^{230}U/^{234}U$	Age (× 1000 y)	Terrace Altitude (m ALT)	Correction Altitude for Paleosea Level (m)	Inferred Uplift Rate (mm/y)
M-G-3*	*Platygyra lamellina*	100	2.76±0.08	1.12±0.03	0.40±0.02	55±4	68	+28	1.6 (see text)
M-G-4*	*Leptoria phrygia*	100	2.73	1.11	0.41	57±2	68	+28	1.6 (see text)
M-I-2*	*Platygyra sinensis*	100	2.60±0.06	1.12±0.02	0.016±0.004	1.7±0.5	57	aberrant	aberrant
M-I-3*	*Acropora* sp.	100	3.35	1.13	0.35	47±2	57	see text	see text
M-L-1*	*Plesiastrea curta*	99	2.89±0.07	1.14±0.03	0.035±0.004	3.9±0.5	11	..	2.8
M-L-2†	*Favia stelligera*	99	..	1.14	0.03	5.8±0.3	11	+2	2.2
M-M-1†	*Acropora humilis*	100	..	1.13	0.03	9.5±0.6	11	see text	see text
M-M-2*	*Favia stelligera*	100	2.34	1.13	0.036	4.0±0.25	11	..	2.75
M-P-3*	*F. stelligera*	100	2.37±0.05	1.13±0.02	0.43±0.02	60±4	37	+28	1.1 (see text)
M-Y-2*	*F. stelligera*	100	2.64±0.07	1.13±0.02	0.050±0.004	5.6±0.5	19.5	+1	3.6
M-AA-2†	*Acropora* sp.	100	3.19±0.09	1.08±0.03	0.60	98±14	30	+15	0.45 (see text)
M-AD-4†	*Acropora* sp.	100	3.16±0.05	1.13±0.02	0.49	72.5±5	30	+13	see text
M-AE-1*	*Porites lutea*	100	2.97±0.09	1.11±0.02	0.50±0.015	75±4	60	+13	see text

* Dates from Broecker W S and Goddard J G, Lamont-Doherty Geol. Obs., N.Y., USA
† Dates from Bernat M and Gaven C, Géol. Struct., Univ. Nice, France

TABLE 3b

Radiocarbon datings on Malekula, with inferred uplift rates

Sample No. and Locality (see Fig. 5)	Coral Species	Aragonite %	Age	Terrace Altitude (m ALT)	Correction Altitude for Paleosea Level (m)	Inferred Uplift Rate (mm/y)
M-A-6†	*Favites pallida*	100	1250±80	5	..	4
M-A-7†	*Favia stelligera*	100	1155±90	5	..	4.3
M-A-8†	*Porites lutea*	100	2530±100	5	..	2
M-H-1†	*P. lutea*	100	6900±180	3	+5	1.2
M-H-4†	*Platygyra lamellina*	100	2475±100	3	..	1.2
M-H-5†	*Porites lutea*	100	2865±130	7.5	..	2.6
M-M-2*	*Favia stelligera*	100	3810±140	11	..	2.9
M-X-2†	*Platygyra sinensis*	100	2970±200	1	..	0.3

* Dates from Broecker W S and Goddard J G, Lamont-Doherty Geol. Obs., N.Y., USA
† Dates from Fontes J-Ch, Hydrol. et Géoch. Isot., Univ. Paris Sud, France

(3) the edge of next terrace, 4–6 m ALT, which is continuous in the West bay area;
(4) the edge of a yet higher terrace, 12 m ALT (site M-B, Brenwe);
(5) a wide terrace, 19.5 m ALT at Unmet.

Along the western coast, between Tenmaru and Espiegle bay, are observed

(1) the 1965 reef, about 0.8 m ALT (Taylor *et al.* in press);
(2) a reef, about 3 m ALT (e.g. Npenanavet, Wornambek, southern bank of Malua bay);
(3) a main terrace, the seaward edge of which is 7.5 m ALT at Npenanavet, 8 m at Malua bay, perhaps 6 m at Wornambek (not obvious in this locality); this terrace rises gently inland up to 12 m at Npenanavet, 11 m at Wornambek and Malua bay;
(4) the remains of a terrace (or huge tumbled blocks from the next high terrace), 23 m ALT near Wornambek.

On the northeastern coast, between Norsup and Lakatoro, a 2–3 m ALT terrace is formed mainly of lagoonal calcarenites. It is bounded landwards by an ancient sea cliff about 10 m ALT corresponding to the outer edge of a higher terrace. At Walarano mission (north of Norsup), two terraces occur at 8 and 30 m ALT.

Thirteen dates have been obtained thus far (see Table 3) for the low platform of north Malekula (they do not include the last recent uplifts: for these, see Taylor *et al.* in press). In West bay area, samples M-A-6, 7 and 8 (Brenwe) represent the lower part of the Holocene terrace from 2.5 m to 4 m ALT seaward of, and within, a sea cliff that reaches 5 m ALT (Table 3b; Fig. 5). Nearby, at Unmet, a coral from the uppermost scarp of the 19.5 m ALT Holocene terrace (M-Y-2) is 5.6 ± 0.5 ka. Across north Malekula, at Npenanavet and Wornambek (sites M-H, M-L and M-M), corals from 3 to 11 m ALT give ages ranging from 2.5 to 9.5 ka.

Maximum uplift rates on the basis of these dates are 4.3 mm/y at M-A, 3.6 mm/y at M-Y, and 2.9 mm/y at M-H, M-L and M-M. The date of 9.5 ka (M-M-1) is considered suspect because it disagrees with the age of M-M-2 and M-L-1 and 2 on corals from a few meters away. Possibly, this older age is from a coral that was transported from a presently submerged part of the Holocene reef as sea level rose from about −30 m to about present sea level between 9.5 ka and 5.8 ka.

Sample M-X-2 is from 1 m ALT at Crab bay on the east coast of Malekula and gives an age of 2970 ± 200 y b.p. This coral was flat-topped and presumably had grown to about low tide level when it died. It indicates a low uplift rate of 0.3 mm/y.

The high reef terraces

The high reef terraces of north Malekula have been described by Mitchell (1969, 1971). They consist of a flight of six major reef-capped terraces, with up to four additional terraces locally (Fig. 6). These terraces extend well to the north and around the northeast coast in the case of the terrace No. 3 of Mitchell. They are untraceable 10 km south of Tenmaru, where they are intersected by a series of northwest-trending faults (Elephant point area). The terraces can be seen again in West bay area and southwards further than Lambubu bay. The terraces on north Malekula are very consistently tilted to the northeast, with an axis of maximum uplift trending northwest from Tenmaru to Brenwe. South from a tilt discontinuity across central Malekula (which runs from West bay to Norsup area), the terraces on south Malekula tilt slightly to the southeast (Taylor *et al.* in press) (Fig. 6).

Altimetry of the reef terraces from two localities above Npenanavet and Malua bay (north Malekula) is presented in Table 4, with a third traverse previously reported by Mitchell (1969) near Malua bay. The N-S component of tilting is obvious when terrace altitudes between the two new traverses are compared.

The first major terrace is at 37 m ALT at Malua bay (site M-P). A minor, lower terrace occurs on its seaward edge above Npenanavet. Here, the crest of the high cliff above the coastal platform is 57 m ALT, but a few tens of meters landwards is a second small sea cliff, 68 m ALT, forming the outer edge of a quite wide flat terrace (site M-G). Air photograph interpretation indicates that the 37 m terrace at Malua bay and the upper terrace at Npenanavet (68 m ALT) correlate. The 57 m terrace at Npenanavet occurs for only a short interval along the coast.

Several age determinations on corals from this first high terrace were obtained at these two localities:

(1) A coral sample from the 37 m terrace at Malua bay (M-P-3) is dated at 60 ± 4 ka.
(2) Two corals from the upper of the two terraces (68 m ALT) at Npenanavet (M-G-3 and 4) are dated at 55 ± 4 and 57 ± 2 ka respectively.
(3) A coral from the minor terrace on the seaward edge of the wide terrace at Npenanavet (M-1-3) gave an age of 47 ± 2 ka.

Although the ages of 55 and 57 ka are young compared to the 60 ka paleosea level as inferred in the Huon peninsula (Bloom *et al.* 1974), and although the morphology of this high reef terrace appears to be unusually well developed for a 60 ka paleosea level, the two dates seem relatively consistent with one another and strongly suggest that this first high terrace corresponds to the 60 ka paleosea level.

The 60 ka paleosea level is estimated to have been at 28 km below present sea level (Bloom *et al.* 1974). Total uplifts of 65 m above Malua bay and 96 m above Npenanavet are inferred, yielding uplift rates of respectively 1.1 and 1.6 mm/y, which are significantly lower than the Holocene uplift rate of 2.7 mm/y, calculated from coral samples collected nearby at localities M-H, M-L and M-M.

An age determination comes from the locality of Walarano, on the northeastern coast of Malekula: a coral (M-AD-4) sampled in the 30 m high terrace gives an age of 72.5 ± 5 ka. By assuming the terrace corresponds to the 82 ka paleosea level, this leads to an uplift rate of 0.6 mm/y. Such a low uplift rate on the eastern coast of Malekula is in agreement with the general tilting of the northern part of the island towards the northeast.

South from the tilt discontinuity across central Malekula, two dates have been obtained on high terraces:

(1) A coral from the terraces above Lambubu bay (M-AE-1) gives an age of 75 ± 4 ka for a terrace altitude of 60 m. The terrace is

TABLE 4

High-terrace altitudes measured on north Malekula

Terrace Nos (Mitchell 1971)	Mitchell's Traverse (1969) (m)	Malua Bay Traverse (m)	Npenanavet Traverse (m)
6	240	223-240	353
5	215	204	(289)*
4	180	160	231
3	120	122	173
2a	..	(89)*	154
2	75	71	(113)*
1	45	37	57, 68

* Altitudes in parentheses mark a less distinct terrace, usually corresponding to a break in slope

TABLE 5

Comparison of the Tomebou terraces with Huon paleosea-level changes
(assumption, steady uplift rate of 2 mm/y)

Paleosea-Level Ages (ka)	Calculated Uplift (m)	Position of Paleosea Levels from Present Sea Level* (m)	Terrace Heights Calculated (m)	Terrace Heights Measured (m)
28	+56	−41	+15	+14
40	80	−38	42	41
60	120	−28	92	(64), 90
82	164	−13	151	154
103	206	−15	191	170 (to 190)
125	250	+6	256	240

* As determined in Huon peninsula (Bloom *et al.* 1974)

assimilated as in the case of Walarano to the 82 ka paleosea level. An uplift rate of 0.9 mm/y is inferred.

(2) A coral (M-AA-2) from Tisman bay locality (southeast Malekula) gives an age of 98 ± 11 ka for a terrace altitude of 30 m. The terrace is assumed to correspond to the 103 ka paleosea level. An uplift rate of 0.45 mm/y is inferred.

DISCUSSION AND INTERPRETATION

Santo Island

When plotted on the map of Santo, the uplift rates based on the high terraces agree somewhat with the Holocene data. The Kere river uplift rate, particularly, if confirmed, is quite consistent with the presence of a zone of maximum uplift coinciding with the high spine running the length of western Santo (Fig. 4).

Nevertheless, the 2 mm/y uplift rate in Tomebou is lower than the 3.6 mm/y uplift rate of site S-A (very close to Tomebou). This may mean that the uplift rate in this area has increased in the Holocene epoch. Both uplift rates are based on only two samples each. Additional age determinations would be useful to confirm the difference in late Pleistocene and Holocene uplift rates in this area. It is possible that the reef terrace from which corals gave dates of 37 and 38 ka was not deposited during the maximum sea level near 40 ka, but, instead, during a pause during the fall of sea level after the 40 ka high sea stand.

It is interesting to compare the terrace flight of Tomebou with the paleosea levels changes as inferred from Huon peninsula for the last 140 ka (Bloom *et al.* 1974). A similar method was used by Konishi *et al.* (1970) for the Ryu-Kyu islands. The basis of the calculation rests on the assumption of a constant 2 mm/y uplift rate, which has been previously inferred for the supposed 40 ka terrace on Tomebou (see Table 5).

The correspondence between the calculated and measured heights of Tomebou appears to be consistent. A 64 m level is reported in Table 2 but was not reported by Mallick, 1970: it does not correspond to an obvious geomorphic terrace, but rather to a break in the steep slope.

This comparison is based on the assumption of a uniform uplift rate, which is not in full agreement with the former observation about the possible increase of the uplift rate in the Holocene. Yet, it can be suggested that the summit of the Tomebou records the 125 ka paleosea level and that, consequently, the 90, 154 and 170 m terraces represent the 60, 82 and 103 ka paleosea levels.

Two remarks must be made:

(1) In the case of the assumed 82 ka terrace, the observed measure, on the chosen traverse, 170 km, does not quite fit with the height as calculated, 190 m. But this terrace is effectively 190 m high on the northern edge of Tomebou.

(2) The 28 ka terrace, which is predicted to be at 15 m ALT in this sequence, presents an interesting theoretical problem. This altitude corresponds to much of the Holocene platform. Holocene coral reefs may have developed as a veneer upon a 28 ka old reef that was inundated as sea level rose in the Holocene.

Previously, it has been pointed out, from Table 2, that the terraces of Tomebou and Queiros peninsula, particularly the terraces of Avatao, are nearly accordant in altitude. Therefore, the terraces at Avatao can also be considered as consistent with the paleosea level history of the past 125 000 years and a constant uplift rate of 2 mm/y. If one compares the terrace heights as measured at Avatao and as calculated for a constant uplift rate of 2 mm/y, one can observe the correlation set out below.

TABLE 6

Comparison of the Queiros terraces (Avatao) with the Huon paleosea-level changes

Paleosea-Level Ages (ka)	Terrace Heights Calculated (see Table 5) (m)	Terrace Heights Measured (m)
28	+15	+12
40	+42	+42
		(60)
60	92	92
		(121)
82	151	145
103	191	185
125	256	218

This observation, however, requires two qualifications:

(1) Two levels, 60 and 121 m high, are observed at Avatao, but do not seem to corres-

pond to any main paleosea level recognized in Huon peninsula. In fact, they are only minor geomorphic terraces at Avatao and they may record minor events. There is, however, a correspondence of the 60 m level of Avatao with the 64 m level of Tomebou. The two may correspond to one of the several terraces in the 40–50 ka time range on the Huon peninsula. (2) The highest terrace altitude, as measured at Avatao (218 m), seems rather low in comparison to its calculated altitude (256 m). But it must be emphasized that the measurement was made on the low eastern edge of the uppermost terrace of the Walraoul plateau. The 1:50 000 IGN map of Santo indicates that near Avatao the terrace is between 240 and 260 m. The eastern edge of Walraoul plateau is at about the correct altitude to have formed during the 125 ka plaeosea level.

It has been stated that the surface of the Walraoul plateau corresponds to the main surface of the other eastern limestone plateaux of Santo: all of these plateaux are therefore likely to be 125 000 years old.

Nevertheless, the calculations of Table 5 rest on the assumption of a constant uplift rate of 2 mm/y for the eastern edge of the Walraoul plateau. This is not consistent with the uplift rate of 3 mm/y inferred from the Holocene platform, at site S-N, very close to Avatao. Calculations for the terrace altitudes of Avatao were made with the assumption of a constant uplift rate of 3 mm/y instead of 2 mm/y: 3 mm/y give calculated terrace heights (43, 82, 152, 233, 294 and 381 m) which cannot be correlated with the measured terrace heights (Table 3). Thus, the uplift rate appears to have increased in the Queiros peninsula in the Holocene, as in the case of the Tomebou area.

North Malekula

Based on the assumption of constant uplift rates as inferred in north Malekula (1.1 mm/y at Malua bay, 1.6 mm/y at Npenanavet), the same calculations as on Santo can be made for the terraces of Malua bay and Npenanavet (Tables 7 and 8).

TABLE 7
Comparison of the Malua Bay terraces with Huon paleosea-level changes (assumption, constant uplift rate of 1.1 mm/y)

Paleosea-Level Ages (ka)	Calculated Uplift (m)	Position of Paleosea Levels from Present Sea Level (m)	Terrace Heights	
			Calculated (m)	Measured (m)
28	+31	−41	−10	..
40	44	−38	+6	+3; 8-11
60	66	−28	38	37
82	90	−13	77	71
103	113	−15	98	89
125	137	+6	143	122

TABLE 8
Comparison of the Npenanavet terraces with Huon paleosea-level changes (assumption, constant uplift rate of 1.6 mm/y)

Paleosea-Level Ages (ka)	Calculated Uplift (m)	Position of Paleosea Levels from Present Sea Level (m)	Terrace Heights	
			Calculated (m)	Measured (m)
28	+45	−41	+4	3; 7.5-12
40	64	−38	26	(23 at Wornambek)
60	96	−28	68	68
82	131	−13	118	113
103	165	−15	150	154
125	200	+6	206	173

As on Santo, there is a similarity between calculated and measured terraces heights in north Malekula. Thus, terraces No. 2, 2a and 3 (Mitchell's numbering, 1971; see Fig. 6) are assumed to correspond to the 82, 103 and 125 ka paleosea levels. Such a correlation between the terrace No. 3 and the 125 ka paleosea level is consistent with the great extent of this terrace on north Malekula (Fig. 6).

In both traverses, the presumed 125 ka terrace is rather low relative to its calculated position: without neglecting the possible effects of erosion, this may indicate that the uplift rate slightly increased during the last 100 000 years.

As in Santo, calculations show that the Holocene and 28 ka reef may interfere in north Malekula.

CONCLUSION

Uplifted Quaternary reef terraces on Santo and north Malekula give evidence of uplift continuing into the present on both islands. The main surface of the eastern limestone plateaux of Santo is assumed to correspond to the 125 000-year-old paleosea level, by comparing the terraces levels of Santo with the paleosea levels as estimated for the last 140 000 years in the Huon peninsula area (New Guinea). The emergence of a large part of eastern Santo thus appears to be quite recent. A similar conclusion is inferred for north Malekula.

The second clear implication of these early results is that the uplift rates for both Santo and Malekula have increased dramatically in the Holocene. Pre-Holocene paleosea level history is sufficiently well known that if our terrace ages from radiometric dates and inferences are correct our pre-Holocene uplift rates must also be correct. They appear to have been relatively constant until the Holocene. There are certainly errors in our assumed Holocene sea-level history, but the errors must be small compared to the amount of Holocene emergence which was measured, and our Holocene uplift rates must be essentially correct. They are significantly higher than the inferred late-Pleistocene uplift rates.

The cause for the increase in uplift rates, which, if confirmed by further studies, constitutes the main conclusion of this paper, may be a change in convergence rate between the Australian and Pacific plates, or a change in ruggedness of topography of the descending plate (particularly in regard to the d'Entrecasteaux ridge). The latter explanation seems, however, inadequate because the present convergence rate of 1.2 cm/y (Dubois *et al.* 1977) allows subduction of only 1.2 km of Australian plate in 10 000 years. The inferred average late-Pleistocene uplift rates seem constant enough through time for a long-term change in average uplift rates to be unlikely. Possibly, we have merely discovered a short-term increase in uplift rates that will not significantly affect the long-term average rates.

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C Jouannic
ORSTOM
Port Vila, New Hebrides

F W Taylor, A L Bloom
Department of Geological Sciences
Cornell University
Ithaca, N.Y., U.S.A.

M Bernat
Laboratoire de Géologie Structurale
Université de Nice
Nice, France