# QUATERNARY UPLIFT OF THE TORRES ISLANDS, NORTHERN NEW HEBRIDES FRONTAL ARC: COMPARISON WITH SANTO AND MALEKULA ISLANDS, CENTRAL NEW HEBRIDES FRONTAL ARC[1]

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## ABSTRACT

Coral reef terraces on the Torres Islands have recorded the Quaternary uplift of part of the northern New Hebrides frontal arc. These isles lie about midway between the volcanic chain and trench axis, where the Indian plate underthrusts the arc from the west. $^{14}$C and $^{230}$Th/$^{234}$U ages for Torres fossil corals indicate that for approximately the past 100,000 years the islands uplifted at a constant rate ranging geographically from 0.7 to 0.9 mm/yr. The occurrence of similar uplift rates and eastward-tilting directions and the absence of major crosscutting structures or rupture zone boundaries suggest that the islands may be part of a single tectonic block or arc segment. The frontal arc morphology in the Torres area is typical of frontal arcs. Farther south, the central New Hebrides frontal arc has no physiographic trench at the plate boundary west of Santo and Malekula Islands, and the axes of the maximum uplift rate are at the seaward edge of the plate. The d'Entrecasteaux Ridge (DR), a massive E-W trending bathymetric feature on the Indian plate, is underthrusting Santo and Malekula. The eastern parts of Santo and Malekula are physiographically equivalent to the Torres Islands and seem to have been on a former axis of maximum uplift rate. However, in response to subduction of the DR, the uplift axes of Santo and Malekula may have shifted westward. In a few hundred thousand years the new uplift axes caused the western parts of these islands to achieve their present topographic dominance over the earlier uplift axes. Holocene uplift rates on southern Santo and northern Malekula are about twice the average rates of the previous 100,000 years. The accelerated Holocene uplift could be explained if a particularly prominent part of the DR has recently underthrust Santo and Malekula.

## INTRODUCTION

Vertical deformation patterns at convergent plate boundaries allow us to infer important information about interactions between plates and the earthquake generation process. Over times of 100 years or less, precise leveling, tiltmeters, tide gauges, and gravity measurements are valuable for documenting vertical deformation (e.g., Fitch and Scholz 1971; Yonekura 1975; Bevis and Isacks 1981; Mogi 1981). However, over longer periods of time only geological methods can determine the net deformation pattern resulting from the coseismic and aseismic vertical motions (see Sieh 1981 for review). On tropical coasts, emerged marine and coral reef terraces have proven to be valuable geological recorders of net vertical deformation on the time scale

from 10 to 1,000,000 years (Chappell 1974; Konishi et al. 1974; Taylor and Bloom 1977; Plafker and Rubin 1978; Taylor et al. 1980). In the New Hebrides island arc we have used instrumental methods to measure short term vertical movements (Marthelot et al. 1980; Bevis and Isacks 1981; Isacks et al. 1981). To interpret the significance of these results, we have used reef terraces to establish the long term rates and patterns of net vertical deformation on the islands of Santo, Malekula, Efate and, now, the Torres Islands (Bloom et al. 1978; Taylor et al. 1980, 1981; Jouannic et al. 1980, 1982; Gilpin 1982; Lecolle et al. in prep.).

At convergent margins, uplift rates provide a measure of the intensity of interaction between the subducting and overthrusting plates. In the classification of Uyeda and Kanamori (1979), when the subducting and overthrusting plates are strongly coupled the arc system is called the Chilean-type. In this case, the arc is in a state of compression, much of the interplate motion occurs as seismic slip, and uplift rates tend to be rapid (Dewey 1980; Yonekura 1983). Where inter-
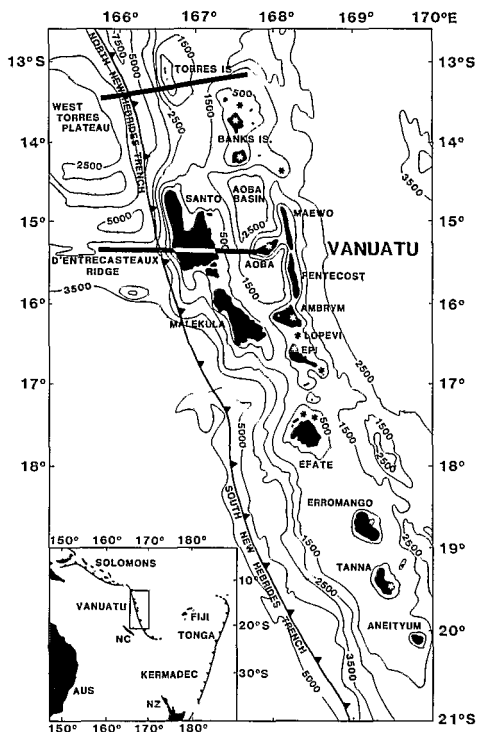
FIG. 1.—Bathymetry (meters) of the Vanuatu (New Hebrides) arc (after Kroenke et al. 1983). Asterisks indicate the locations of volcanoes. Note the trends of the d'Entrecasteaux Ridge and the West Torres Plateau on the Indian plate which is thrusting eastward beneath the New Hebrides arc. The New Hebrides trench does not exist west of Santo and Malekula. The lines across the Torres Islands and Santo indicate the locations of topographic profiles in figure 8.

plate coupling is weak and an arc is classified as Mariana-type (Uyeda and Kanamori 1979), virtually all underthrusting is aseismic. In this classification, the New Hebrides arc probably represents an intermediate case where interplate coupling is somewhat strong and frequent shallow-thrusting earthquakes indicate that a significant proportion of the interplate motion is seismic (Pascal et al. 1978; Isacks et al. 1981). However, the New Hebrides has an actively opening back-arc basin (Chase 1971; Falvey 1975; Malahoff et al. 1982) as well as Quaternary rifting in the immediate back-arc (Karig and Mammerickx 1972; Ravenne et al. 1977). These features suggest relatively weak interplate coupling (Uyeda and Kanamori 1979).

Other explanations for vertical arc tecto-

nism attribute a major role to subduction of sediment (Cloos 1982) or bathymetric features (McCann and Habermann in prep.). In these models, increased strength of interplate coupling is not a cause of uplift, but only a symptom of the nature of the material being subducted.

The main purpose of this paper is to describe the uplift of the Torres Islands sector of the New Hebrides frontal arc, where subducting topography apparently has had little influence on upper plate tectonics (fig. 1). This research is the result of a rare opportunity to visit the remote Torres Islands and presents the only existing isotopic ages of fossil corals from the uplifted Torres Island reefs.

In terms of arc geometry and seismicity, the Torres Islands frontal arc is reasonably typical. However, the fact that the islands are emerged makes them a somewhat unusual part of the frontal arc. The Torres Islands parallel the arc trend and lie along the Torres Ridge at the edge of the inner trench slope (fig. 1). The volcanic axis is about 80 km east of the Torres Islands, and the trench axis lies 50 to 60 km west of the isles.

After describing the Torres Islands we will compare their uplift history with that of Santo and Malekula Islands (Neef and Veeh 1977; Taylor et al. 1980; Jouannic et al. 1980, 1982; Gilpin 1982). A comparison is valuable because Santo and Malekula are underthrust by the d'Entrecasteaux Ridge (DR), a major topographic feature on the Indian plate (fig. 1). The detailed morphology of this ridge and its intersection with the New Hebrides arc are described by Collot et al. (1985). Subduction of the DR has profoundly influenced the arc geomorphology, uplift history, and seismicity of the Santo and Malekula area (e.g., Ravenne et al. 1977; Pascal et al. 1978; Chung and Kanamori 1978a, 1978b, Taylor et al. 1980, 1981; Isacks et al. 1981; Daniel and Katz 1981; Collot et al. 1985). Vertical tectonism has greatly modified the geometry of this part of the arc. Due to so much uplift of the extreme western edge of the frontal arc, its morphology is very unusual. Large stress drops accompany earthquakes here, but we do not know if increased coupling or other effects are the causes for the rapid uplift and other phenomena at Santo and Malekula. In contrast with the Torres Islands, there is no

geomorphic trench along the plate boundary west of Santo and Malekula Islands. In fact, the western parts of Santo and Malekula are where the inner trench slope would be if the northern and southern segments of the trench were continuous along a straight line (fig. 1).

By comparing the Torres Islands and the Santo-Malekula area, we identify some peculiar effects of subduction of the DR on the Santo-Malekula frontal arc. This is important because subduction of large aseismic ridges is common (e.g., Kelleher and McCann 1976; Vogt et al. 1976; Dupont 1979, 1982; McCann and Habermann in prep.), but the extent of their influence is poorly understood. For example, the Louisville Ridge may have influenced development of the Tonga frontal arc (Vogt et al. 1976, p. 23; Dupont 1982). McCann and Habermann (in prep.) proposed that nearly all frontal arc uplift not related to sediment accretion is due to ridge subduction.

## METHODS

Uplifted reef terraces record an interaction between sea level oscillations, tectonic uplift, and reef growth (e.g., Mesolella et al. 1969; Bloom et al. 1974). Constructional reef terraces have formed by reef growth during interglacial or interstadial high paleosea levels. Consequently, series of reef terraces around the world have similar ages because eustatic sea-level history is similar everywhere reefs grow (Clark et al. 1978; Clark and Lingle 1979).

In this paper we use paleosea-level history to interpret island arc tectonism rather than using the Torres Islands reefs to modify the sea-level history. The paleosea-level history that we use (Bloom et al. 1974) was derived where emerged reefs are better exposed and have been very thoroughly documented.

In September 1977, Jouannic and Taylor studied the Torres Islands reef terraces during a 10-day visit aboard the French ORSTOM research vessel "Vauban." Although the time available for our visit was short, this rare visit to the Torres group allowed us to examine briefly each of the four larger isles (Toga, Loh, Tegua, and Hiu). We mapped the reef terraces with aerial photographs (scale: 1:25,000) and a topographic map (c.i. = 20 m; scale: 1:50,000). We collected coral samples from the lower reef terraces as we made altimeter traverses to measure altitudes. For altimetry measurements we used two Wallace-Tiernan FA-181 surveying altimeters with one altimeter based at sea level giving altitude measurements that were reproducible within ±2 m when stations were reoccupied. Before and after our work on the Torres Islands, the altimeters were checked relative to surveyed altitudes on other islands, where we found them to be quite accurate.

The altimeters consistently indicated altitudes significantly lower than those indicated by the topographic map of the Torres Islands. For example, where the contour lines show altitudes of 50 to 200 m above sea level (ASL), we measured altitudes between 30 and 160 m ASL. The map indicates that no inland surveyed altitudes were used to plot the topographic contours. Therefore, sea level was the only constraint determining the contour lines, which are decreasingly accurate away from the coasts. We used altimeter measurements to correct map altitudes for locations near altimeter traverses. In the figures, map altitudes are indicated by small numbers and symbols and altimeter altitudes are indicated by underlined bolder symbols and numbers.

We obtained four $^{14}$C and 12 $^{230}$Th/$^{234}$U ages for fossil coral samples from Hiu, Tegua, Loh, and Toga. We selected the samples using the criteria of Taylor (1974) and Bloom et al. (1974) and eliminated samples containing less than 98% aragonite by X-ray diffraction analysis. All isotope values (table 1) fell within ranges consistent with the hypothesis that the corals have been closed systems with respect to thorium and uranium (Bender et al. 1979). J. C. Fontes of the Universite of Paris-Sud prepared the $^{14}$C ages and W. S. Broecker, John Goddard, and Ursula Middel of Lamont-Doherty Geological Observatory prepared the $^{230}$Th/$^{234}$U ages.

## GEOMORPHOLOGY OF THE TORRES REEF TERRACES

Each of the five larger Torres Islands has one or more flat-topped coral limestone peaks built by coral reefs around an emerging frontal arc topographic high (figs. 2, 3, 4, 5, and 6). Sea level oscillations on the slowly emerging isles must have caused superposition of reefs built during high sea levels over reefs built

## TABLE 1

### Radiometric Dates

| | | | Radiocarbon Dates[a] | | |
|---|---|---|---|---|---|
| Field Sample | Coral Species[c] | Aragonite % | Alt. Above Living Coral (m) | | Age (yr B.P.) |
| HI-H-2 | Not identified | 99 | 3 | | 3405 ± 95 |
| TEG-C-1 | Not identified | 100 | 3 | | 2720 ± 100 |
| LO-A-2 | Not identified | 100 | 3 | | 3850 ± 300 |
| TO-A-3 | Not identified | 100 | 3 | | 3780 ± 160 |

| | | | | $^{230}$Th/$^{234}$U Dates[b] | | | |
|---|---|---|---|---|---|---|---|
| LDGO No. | Field Sample | Coral Species[c] | Aragonite % | U (ppm) | $^{234}$U/$^{238}$U | $^{230}$Th/$^{234}$U | Alt. Above Living Coral (m) | Age (×10³ yr B.P.) |
| 1543F | HI-F-1 | *Plesiastrea curta* | 100 | 2.84 ± .09 | 1.075 ± .03 | 0.79 ± .03 | 30 | 164 ± 2 |
| 1526G | HI-D-1 | *Acropora sp.* | 100 | 3.00 ± .08 | 1.09 ± .02 | 0.67 ± .02 | 80 | 118 ± 6 |
| 1543A | HI-D-3 | *Platygyra sinensis* | 98 | 2.57 ± .09 | 1.12 ± .03 | 0.655 ± .029 | 80 | 112 ± 9 |
| 1543G | HI-G-2 | *Platygyra sinensis* | 100 | 2.40 ± .07 | 1.16 ± .03 | 0.62 ± .02 | 62 | 102 ± 6 |
| 1526F | TEG-B-5 | *Cyphastrea serailia* | 100 | 2.33 ± .07 | 1.09 ± .02 | 0.73 ± .02 | 53 | 137 ± 8 |
| 1543E | TEG-B-2 | *Plesiastrea curta* | 99 | 2.40 ± .10 | 1.14 ± .04 | 0.83 ± .04 | 53 | 180 ± 20 |
| 1526E | LO-B-2 | *Porites sp.* | 100 | 2.60 ± .07 | 1.07 ± .02 | 0.68 ± .02 | 85 | 122 ± 7 |
| 1543H | LO-B-3 | *Leptoria phrygia* | 98 | 2.54 ± .08 | 1.11 ± .03 | 0.725 ± .027 | 85 | 135 ± 11 |
| 1543B | LO-C-4 | *Porites sp.* | 100 | 2.47 ± .07 | 1.105 ± .026 | 0.74 ± .03 | 69 | 141 ± 12 |
| 1543D | TO-B-1 | *Symphyllia sp.* | 99 | 2.97 ± .10 | 1.12 ± .03 | 0.53 ± .02 | 53 | 80 ± 5 |
| 1526H | TO-C-1 | *Favia stelligera* | 100 | 2.39 ± .06 | 1.11 ± .02 | 0.65 ± .02 | 77 | 112 ± 6 |
| 1543C | TO-C-3 | *Goniastrea retiformis* | 100 | 2.74 ± .08 | 1.095 ± .026 | 0.62 ± .02 | 77 | 103 ± 6 |

[a] Radiocarbon dates were prepared by J.-C. Fontes, Laboratoire D'Hydrologie et de Geochimie Isotopique, Universite de Paris-Sud, Batiment 504, 91405 ORSAY CEDEX, FRANCE.

[b] $^{230}$Th/$^{234}$U dates were prepared by W. S. Broecker and his associates John Goddard and Ursula Middel, Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964, USA.
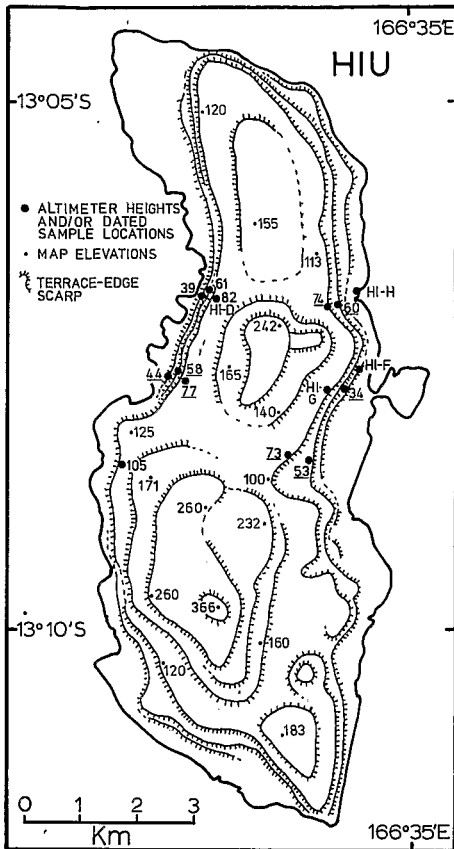
[c] Corals identified by J. W. Wells.

FIG. 2.—Hiu Island has three plateaus. The middle plateau is separated from the others by NW-SE striking faults along which it is downdropped relative to the N and S plateaus (fig. 6). Measured altitudes are underlined. Some map elevations are included because we made few altimeter measurements, but the topographic map heights are approximately 20% higher than equivalent altimeter measurements. The sources of samples for which isotopic ages were determined are indicated (e.g., HI-D: table 1B). These comments apply to figures 3, 4, and 5 as well.

topographic relief of the islands indicate that a substrate having considerable relief lies beneath the coral limestone capping the Torres Islands. Only narrow reef terraces could develop on steep slopes and, upon emergence, their fore reefs underwent intense wave erosion during subsequent high sea-level stands.

The similarity of the terrace altitudes and relative development from isle to isle implies that the islands have similar uplift histories. Hiu, Toga, Tegua, Loh, Metoma, and Linua have coastal terraces 5 to 8 m ASL that range in width from a few meters to about a kilometer (figs. 2, 3, 4, and 5). The seaward edge of this terrace often has a low emerged sea cliff. A supratidal terrace often lies between this low sea cliff and the sea. At the inland edge of the 5 to 8 m ASL coastal terrace is a steep slope with up to three narrow terraces between altitudes of 10 and 90 m ASL. These narrow reef terraces often are locally eroded. A very prominent terrace at 90 to 120 m ASL ranging from tens to hundreds of meters wide is comparable in development to the low coastal terrace at 5 to 8 m ASL. This terrace is the highest on Loh Island and comprises its two flat-topped peaks (fig. 4). Toga, Tegua, and Hiu have a higher terrace at about 180 m, 140 m, and 160 m ASL, respectively, according to the map altitudes (figs. 2, 3, and 5). Hiu has another major level at about 260 m and a peak at 366 m ASL on the map (fig. 2). As mentioned earlier, however, the map altitudes for these higher terraces are probably at least 20% too great. Because our stay in the Torres Islands was limited by the ship schedule we could not measure the higher terrace altitudes.

ISOTOPIC AGES FOR FOSSIL CORALS

*[14]C Ages from the Low Coastal Reef Terrace*.—We obtained one ^{14}C age from about 3 m ASL on the low coastal terrace of each of the four larger islands (tables 1, 2, 3, 4, and 5). The four ^{14}C ages range from 2720 ± 100 to 3850 ± 300 yr B.P. and show that the low coastal reef terraces are Holocene in age. The samples came from the seaward edge of the Holocene terrace and not the higher parts, which are usually too heavily vegetated for sampling. Therefore, the Holocene reefs probably contain older fossils at higher levels and began to emerge earlier than indicated by our oldest ^{14}C age.

grown during lower sea levels. In the upper seaward edge of many of the terraces, abundant shallow-water corals indicate a predominantly constructional origin for the terraces. However, as noted by Greenbaum et al. (1975), locally severe marine erosion created sheer cliffs at the seaward edge of many terrace segments and deep solution notches in emerged sea cliffs. This is particularly apparent on the southern and eastern coasts, which are exposed to the southeast trade winds. Outcrops of volcanic rocks and marine sediments at high and low altitudes and the steep
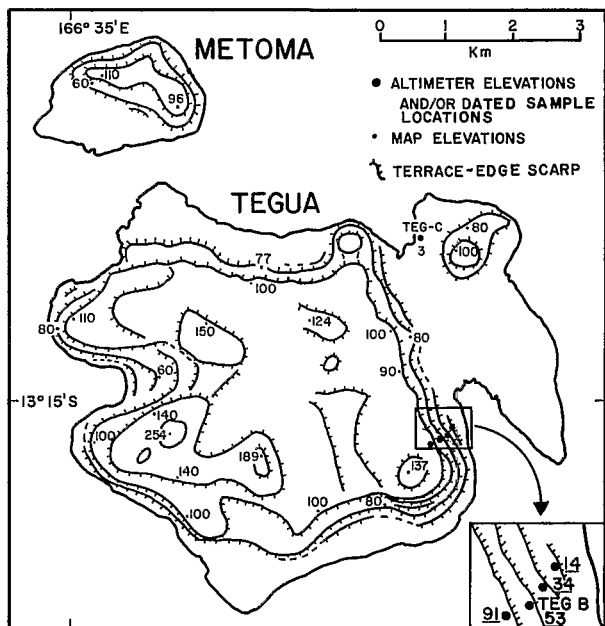
FIG. 3.—Tegua and Metoma Islands. Since Tegua began emerging, a narrow E-W trending block has been down-dropped relative to the rest of the isle (fig. 6). Details of the reef terraces from which we collected samples are shown in the lower right.
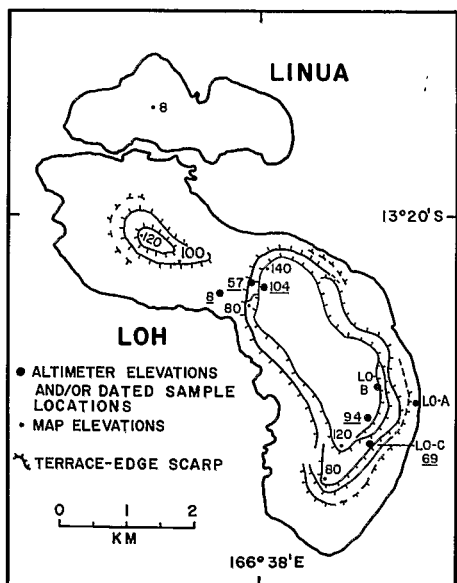


FIG. 4.—Loh and Linua Islands. No obvious faulting has displaced the isles since they emerged although they appear to have inherited a form imposed by faulting prior to emergence (fig. 6).
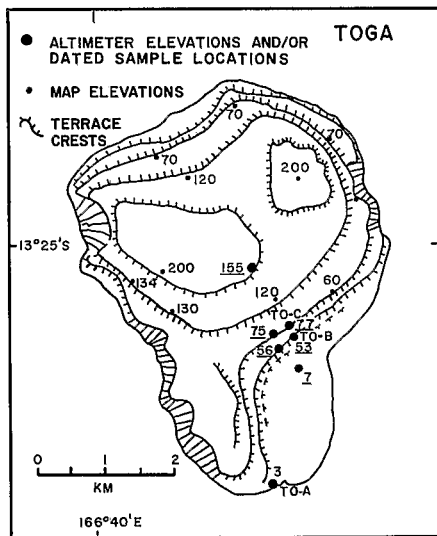


FIG. 5.—Toga Island. Two flat-topped peaks occupy the main part of the island. The heavy lineament in figure 6 causes a sag in altitudes of the reef terraces where it intersects their trends.
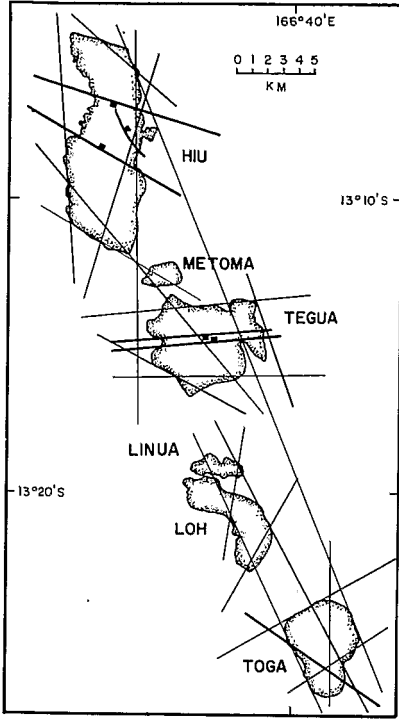
Fig. 6.—Map of lineaments based on aerial photograph interpretation and topography of the islands. Greenbaum et al. (1975) interpreted the existence of additional photolineaments and many small faults that we did not detect. However, some of them may be visible on aerial photographs not available to us. The long lineaments extending from isle to isle in this figure suggest that some faults may extend the length of the Torres archipelago. To appreciate the interpretation, compare with the figures for each island.

The ages and altitudes of the coral samples imply average late Holocene uplift rates of approximately 1 mm/yr for all of the isles. Extrapolation of the 1 mm/yr Holocene uplift rate implies specific greater ages for the higher reef terraces. Based on the New Guinea sea level history (Bloom et al. 1974) and a 1 mm/yr uplift rate, we predict the following sequence of reef ages from sea level up to about 130 m altitude on the Torres Islands: Holocene, 60,000 yr B.P., 80,000 yr B.P., 103,000 yr B.P., and 125,000 yr B.P. At 1 mm/yr, the 28,000 and 40,000 yr B.P. New Guinea reefs, which grew when sea level was 41 and 38 m lower than present, would have been drowned by the Holocene transgression which reached at least its present level by about 6,000 yr B.P. in the southwest Pacific (e.g., Baltzer 1970; Thom and Chappell 1975). As in the New Guinea and other terrace sequences, the Holocene and presumed last interglacial (125,000 yr B.P.) reefs should be developed best and the intermediate reefs markedly less well developed.

$^{230}Th/^{234}U$ *Ages for the Higher Reef Terraces.*—We obtained dates for two samples from the prominent terrace that occurs at an altitude of about 90 to 120 m ASL on Loh Island (fig. 4; table 1B). These samples gave ages of 122,000 ± 7,000 and 135,000 ± 11,000 yr B.P. (tables 1B and 4). However, a sample from the next lower terrace at 69 m ASL had an age of 141,000 ± 12,000 yr B.P. If our assumption that the terraces increase in

TABLE 2

HIU TERRACES

| Paleosea Level ($\times 10^3$ yr B.P.) | Actual Terrace Altitudes[a] (m) | | Uplift Rate (mm/yr) | Predicted Terrace Altitudes (m) | Radiometric Age ($\times 10^3$ yr B.P.) |
|---|---|---|---|---|---|
| | E. Coast | W. Coast | | | |
| 125 | 120 | 120 | .91 | 120 | |
| 103 | 74 | 82 | | 79 | 102 ± 6 |
| | | | | | 112 ± 9 |
| | | | | | 118 ± 6 |
| 80 | 57 | 59 | | 60 | |
| 60 | 34 | 42 | | 27 | 164 ± 12 |
| Holocene | 7 | 7 | | 7 | 3.405 ± .095 |

[a] Greenbaum et al. (1975) reported terraces for which they gave parallax-bar altitudes from aerial photographs of 5 m, 70 m, 85 m, 105 m, and 152 m. They did not report terraces equivalent to our 34 to 42 m terrace. All of our terrace altitudes were measured by altimeter except for the 120 m terrace for which the height was estimated by using nearby altimeter heights as a guide to correcting map altitudes.

## TABLE 3

### TEGUA TERRACES

| Paleosea Level ($\times 10^3$ yr B.P.) | Actual Terrace Altitudes[a] (m) | Uplift Rate (mm/yr) | Predicted Terrace Altitudes (m) | Radiometric Age ($\times 10^3$ yr B.P.) |
|---|---|---|---|---|
| 125 | 91 | 0.68 | 91 | |
| 103 | 53 | | 55 | 137 ± 8 |
| | | | | 180 ± 20 |
| 80 | 34 | | 41 | |
| 60 | 14 | | 13 | |
| Holocene | 6 | | 5 | 2.720 ± .100 |

[a] Greenbaum et al. (1975) reported terraces for which they gave parallax-bar altitudes from aerial photographs of 5 m, 26 m, 56 m, 83 m, and 130 m. All of our terrace altitudes were measured by altimeter.


## TABLE 4

### LOH TERRACES

| Paleosea Level ($\times 10^3$ yr B.P.) | Actual Terrace Altitudes[a] (m) | Uplift Rate (mm/yr) | Predicted Terrace Altitudes (m) | Radiometric Age ($\times 10^3$ yr B.P.) |
|---|---|---|---|---|
| 125 | 99 | .74 | 99 | 135 ± 11 |
| | | | | 122 ± 7 |
| 103 | 69 | | 61 | 141 ± 12 |
| 80 | 57 | | 46 | |
| 60 | Not Measured | | 16 | |
| Holocene | 8 | | 6 | 3.85 ± .3 |

[a] Greenbaum et al. (1975) reported terraces for which they gave parallax-bar altitudes from aerial photographs of 44 to 47 m, 37 m, 25 m, 11 to 12 m, and 5 m. All of our terrace heights were measured by altimeter.


## TABLE 5

### TOGA ISLAND TERRACES

| Paleosea Level ($\times 10^3$ yr B.P.) | Actual Terrace Altitudes[a] (m) | Uplift Rate (mm/yr) | Predicted Terrace Altitudes (m) | Radiometric Age ($\times 10^3$ yr B.P.) |
|---|---|---|---|---|
| 125,000 | 110 | .83 | 110 | |
| 103,000 | 76 | | 70 | 103 ± 6 |
| | | | | 112 ± 6 |
| 80,000 | 55 | | 53 | 80 ± 5 |
| 60,000 | Not Measured | | 22 | |
| Holocene | 7 | | 6 | 3.780 ± .160 |

[a] Greenbaum et al. (1975) reported terraces for which they gave parallax-bar altitudes from aerial photographs of 5 m, 50 m, 95 m, and 135 m. Our terrace heights were measured by altimeter except for the 110 m terrace which was estimated on the basis of altimeter heights as a guide to correcting map altitudes.

age uphill is correct, the lower terrace represents a younger paleosea level than that of the lower terrace, even though the $^{230}Th/^{234}U$ ages do not support this inference.

On Toga, a sample from the narrow terrace at 55 m ASL gave an age of 80,000 ± 5,000 yr B.P. (tables 1 and 5; fig. 5). The next higher narrow terrace at 76 m ASL gave ages of 103,000 ± 6,000 and 112,000 ± 6,000 yr B.P. These reefs probably correspond, respectively, to the 80,000 and 103,000 yr B.P. reefs on New Guinea and Barbados and imply that the very wide terrace at about 100 m ASL on Toga formed during the last interglacial (about 125,000 yr B.P.).

Two samples from a narrow reef terrace at 53 m ASL on Tegua gave ages of 137,000 ± 8,000 and 180,000 ± 20,000 yr B.P. (fig. 3; tables 1 and 3). These ages contradict each other, and also the proposition that the 90 m ASL terrace is last interglacial and the 53 m ASL terrace is 103,000 yr B.P. in age (table 3). It is likely that the terrace at 53 m was eroded into older reefs than the paleosea level in which it formed.

On Hiu, the prominent major terrace lies near 120 m ASL and the next lower terrace is at 82 m ASL on the west coast and 74 m ASL on the east coast (tables 1 and 2). Ages of 102,000 ± 6,000, 112,000 ± 6,000, and 118,000 ± 6,000 yr B.P. on coral samples (HI-G-2, HI-D-1 and HI-D-3) from the 74 to 82 m ASL terrace indicate that it corresponds to the 103,000 yr B.P. New Guinea reef (Bloom et al. 1974). However, a coral sample collected from the east coast terrace at 34 m ASL gave the anomalous age of 164,000 ± 12,000 yr B.P. (HI-F-1; tables 1 and 2). We found this coral adjacent to an outcrop of Torres volcanics (Greenbaum et al. 1975), indicating that severe local erosion cut through the coral cap and exposed older underlying reefs.

EVALUATION OF THE TORRES REEF TERRACES

*Ages of the Torres Islands Reef Terraces.*—Overall, the isotopic ages indicate that the reef terraces from the coast up to 90–120 m ASL are Holocene to last interglacial (~125,000 yr B.P.) in age. Apparently, these reef terraces are equivalent to the late Quaternary reef terraces documented on Barbados (Mesolella et al. 1969; Matthews 1973), the Ryukyu Islands (Konishi et al. 1970,

1974), New Guinea (Bloom et al. 1974), Timor and Atauro (Chappell and Veeh 1978), Efate (Neef and Veeh 1977; Bloom et al. 1978), Santo and Malekula (Jouannic et al. 1980, 1982) and on other reef terraced coasts. By comparing the Torres reef terraces with those of New Guinea we can test the validity of our isotopic age determinations and infer the uplift history of the Torres Islands.

The 164,000 yr B.P. age on Hiu, the 180,000 yr B.P. and 137,000 yr B.P. ages from Tegua, and the 141,000 yr B.P. age from Loh are inconsistent with the other 12 isotopic ages from the Torres Islands. Each age is from a reef terrace that should be younger than the last interglacial (~125,000 yr B.P.) according to the other dates, sea-level history, and the assumption of constant uplift. These ages are from shallow-water corals, but may represent reefs deposited during lower sea levels that were exhumed when erosion cut terraces during much younger paleosea levels. Some of the minor terraces seem to have been eroded into the steep last interglacial age fore reef or even older buried reefs. Consequently, these narrow terraces on steep slopes may vary along their trends from largely constructional to largely erosional in origin. However, the majority of isotopic ages support our proposed morphostratigraphic sequence of reef terraces ranging in age from Holocene to last interglacial.

*Comparison of the Torres Islands' and Huon, New Guinea, Reef Terraces.*—With knowledge of paleosea-level history for the past 125,000 years, we can predict the heights at which terraces should occur on the Torres Islands if we assume a constant uplift rate. Comparison of the heights of observed and predicted terraces on the Torres Islands should reveal any major variations in uplift rate of the Torres Ridge. A comparison will also test our conclusions about the ages of the Torres reef terraces and their relationship to paleosea-level oscillations.

For comparison we choose the Huon, New Guinea, paleosea-level history of Bloom et al. (1974) which we consider representative of paleosea-level records from reef-terraced islands. Due to hydro-isostatic effects, sea level during Holocene time may have reached about 1 m higher than present a few thousand years ago in the New Hebrides region (Clark et al. 1978; Clark and Lingle 1979). However,

this amount of emergence is not significant to this study because local Holocene tectonic uplift of the Torres Islands has been much greater than 1 m.

Our primary assumption is that the prominent terrace level at 90 to 120 m ASL on the Torres Islands corresponds to the last interglacial age (125,000 yr B.P.) reef terraces on Barbados, New Guinea, and other coasts. This assumption is reasonable because fossil corals from this reef terrace at 100 m altitude on Loh gave ages of 122,000 and 135,000 yr B.P. (tables 1 and 4). We assume that these ages are correct and that the equivalent terraces on the other islands are the same age, although they were not dated directly. Sea level was about 6 m higher than present during the last interglacial (see Bloom et al. 1974 for discussion). We can derive an uplift rate R for each island from the height H of the last interglacial-age reef terraces, an assumed age T of 125,000 yr B.P., and a paleosea level SL of +6 m:

$$R = \frac{H - SL}{T}$$

Tables 2, 3, 4, and 5 give the resulting uplift rates for each of the four larger islands derived by this method.

From the Torres Islands' uplift rates derived above and the New Guinea ages and paleosea levels, we can predict the height at which terraces should occur between sea level and the assumed 125,000 yr B.P. reefs on the Torres Islands. To do this we transpose the above equation to:

$$H = (R \times T) + SL$$

Bloom et al. (1974) determined the following ages and paleosea levels from the uplifted reef terraces on Huon Peninsula, New Guinea: 28,000 yr B.P. = −41 m; 40,000 yr B.P. = −38 m; 60,000 yr B.P. = −28 m; 80,000 yr B.P. = −13 m, and 103,000 yr B.P. = −15 m. These ages and paleosea levels are combined with the uplift rates to produce the predicted terrace levels for each island. The results in tables 2, 3, 4, and 5 show that the predicted and actual terrace altitudes from the Torres Islands compare quite well. Most of the terrace altitudes are remarkably similar to the predicted altitudes. These results support our proposed age sequence for the Torres reef terraces and our assumption of uniform late Quaternary uplift rates. Likewise, the relative development of each of the terraces compares well with its proposed counterparts on reef-terraced coasts on New Guinea, Barbados, and elsewhere. No extra terraces are left over and no predicted ones are missing.

Uphill from the last interglacial age reefs on Hiu (120 m ASL), Tegua (90 m ASL), and Toga (110 m ASL), other major reef terraces up to as high as about 360 m ASL (map altitude) on Hiu probably represent older interglacial paleosea levels. No fossil corals suitable for isotopic dating were found in these higher reefs. However, at an average uplift rate of 1 mm/yr, the Torres Ridge would have begun to emerge during low paleosea levels about 400,000 yr B.P. Uplift may have begun long before emergence began.

### UPLIFT PATTERNS, FAULTS, AND LINEAMENTS ON THE TORRES ISLANDS

The pattern of lineaments and faults on the Torres Islands suggests that their morphology and alignment are largely a product of major steeply dipping faults. Because the coral carapaces are thin veneers relative to the dimensions of the isles, the sub-reef morphology can be inferred. In agreement with Greenbaum et al. (1975), we found that the faults and lineaments mapped from aerial photographs of the isles trend predominantly NW-SE, approximately parallel to the trend of the island chain (fig. 6). Many of the lineaments affecting the islands' orientation and coasts appear to continue from isle to isle. For example, a projection of the NW-SE graben-like structure on eastern Tegua is tangent to straight segments of steep coastline on both Hiu and Toga.

Several faults on the Torres Islands are sufficiently young to displace reef terraces (fig. 6). Two of these faults cross central Hiu. The resulting central block is about 30 m lower than the adjacent northern and southern blocks. The reef terrace at 74 m to 82 m ASL (~103,000 yr B.P.) is the youngest one clearly displaced by the two faults. However, the modern reef is indented on both the east and west coasts where the faults intersect the shore (figs. 2 and 6). This indentation proba-

bly reflects the morphology of the surface on which the modern reef grew. Two similar closely spaced parallel faults on Tegua displace the 100 m ASL terrace, and one fault on Toga displaces the 76 m (103,000 yr B.P.) and 55 m ASL (80,000 yr B.P.) reefs.

From end to end, the Torres chain has had quite uniform average uplift rates in Quaternary time. The reef terrace heights and their ages show that Hiu, westernmost of the Torres Islands, has been most rapidly uplifted at a rate of 0.9 mm/yr (table 2). Southwest Hiu appears to have uplifted even faster according to the map elevations and our terrace correlations. The slowest rate inferred was 0.7 mm/yr for southeastern Tegua (table 3), which is one of the areas farthest from the trench axis.

As noted by Greenbaum et al. (1975) we find that each of the larger islands is tilted eastward. For example, altimetry shows that on Hiu, terraces at 80 m, 59 m, and 42 m ASL on the west coast are at 74 m, 57 m, and 34 m ASL on the east coast (fig. 2). The map is not accurate for absolute elevations, but it systematically indicates eastward tilting of the higher terraces and plateaus on the four larger islands.

The altitudes of the lowest reef terraces and their ^{14}C ages indicate average uplift rates of about 1 mm/yr for the past few thousand years. Thus, there is no evidence that the uplift rates in Holocene time are significantly different from the average uplift rates for the past 100,000 years.

We discovered no evidence in 1977 to indicate that any uplift of the Torres Islands has occurred in recent decades. In contrast, we found recently emerged corals on Malekula, Santo, and other islands that allowed us to determine the timing, amount, and distribution of recent coseismic uplifts (Taylor et al. 1980, 1981). Therefore, we presently lack evidence as to whether uplift of the Torres Islands occurs during earthquakes or as a gradual aseismic process. Since 1977, however, large shallow earthquakes have occurred near the Torres Islands (Habermann 1984), and the islands should be re-examined for evidence of vertical deformation.

## DISCUSSION

This is the first study devoted to understanding the late Quaternary tectonic history of the Torres Islands. Our results are significant because the Torres Islands represent an area where the frontal arc morphology is much more normal than that of Santo and Malekula. Knowledge of the Torres Islands uplift provides a basis for comparison with the morphology and uplift pattern of the Santo-Malekula frontal arc, where the arc morphology is extremely unusual due, at least in part, to subduction of the DR.

*Uplift of the Torres Islands.*—The topographic relief and gross morphology of the Torres Islands are principally a product of faulting, although Greenbaum et al. (1975) suggested that the islands are emerging extinct volcanoes. The islands are veneered with coral reef terraces that do not effectively mask their underlying fault-block morphology. Recently active faults on seismic reflection profiles taken normal to the arc trend less than 20 km north and 10 km south of the island chain (Luyendyk et al. 1974; Ravenne et al. 1977), strongly support our conclusion that the isles are fault blocks at the crest of a broad up-arching frontal arc. Santo and Malekula represent a broad uplifted frontal arc that is subdivided into tilt blocks. Each block has a significantly different uplift history, and each is internally faulted (Taylor et al. 1980; Gilpin 1982).

The Torres Islands either occupy a non-rigid block or perhaps several blocks that shift slightly relative to one another. Uplift rates vary slightly among the isles. Along the axis of the chain, uplift rates increase and decrease slightly from isle to isle with no obvious pattern. For example, the uplift rate averages 0.7 mm/yr on Tegua, which lies directly between Hiu and Toga, where the uplift rates are about 0.9 and 0.8 mm/yr, respectively.

The Torres Islands chain is too narrow in an east-west direction to determine whether the islands are located on the present axis of maximum uplift rate. The topography and structure of the Torres Ridge suggest that the most rapid uplift rates occur along the island trend, but it is possible that submarine areas have uplifted faster than the islands themselves in late Quaternary time.

*Seismic Rupture Zones and Upper Plate Segmentation of the Torres Frontal Arc.*—The similar uplift histories among the Torres Islands suggests that, despite some internal
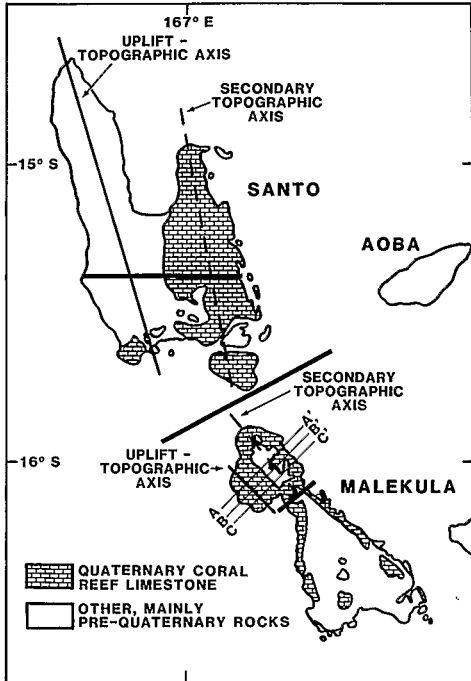
FIG. 7.—Location of Quaternary coral limestone on Santo and Malekula. The uplift and topographic axes are the areas of fastest late Quaternary uplift and they are the highest parts of the islands. The secondary topographic axes show the trends of topographic highs on the eastern parts of Santo and northern Malekula. Heavy bars crossing Santo and Malekula and one between Santo and Malekula are tectonic discontinuities identified with reef terraces and seismicity (Taylor et al. 1980; Gilpin 1982).

deformation, the islands are behaving as a loosely defined unit or block. Perhaps they share a rupture zone, as does each of the four blocks of Santo and Malekula (Taylor et al. 1980, 1981). The 45-km length of the Torres chain is similar in size to the Santo and Malekula blocks each of which is about 50 km long (fig. 7). The Torres Ridge is bathymetrically distinct from areas immediately north and south where the sea floor slopes to depths of more than 1500 m on the crest of the frontal arc (fig. 1).

Seismicity patterns support the proposition that the Torres Islands occupy a single tectonic block or arc segment. Rupture zones inferred for large shallow earthquakes in December 1966 and July 1980 indicate an asperity immediately north (~13.25°S) of the Torres chain (Wyss et al. 1983; Habermann 1984). Wyss et al. (1983) and Habermann

(1984) proposed another asperity of 13.5°S just south of the island chain where very high seismic stress drops have occurred. This suggests the possibility that a topographic feature has been subducted, because the highest stress drops in the arc are beneath Santo and Malekula where the DR is subducting. These proposed asperities bracket the Torres Islands and suggest an arc segment about 50 km long. However, these possible asperities were located on the basis of teleseismic data and their absolute locations could be incorrect by tens of kilometers.

*Topographic Features Underthrusting the New Hebrides Arc.*—The Indian plate underthrusts the New Hebrides arc in approximately a N76°E ± 11° direction (Pascal et al. 1978; Isacks et al. 1981). Part of the back-arc spreading rate of 7 cm/yr (Malahoff et al. 1983) to 9.6 cm/yr (Falvey 1975) on the Fiji plateau should be added to the INDI/PACF convergence rate of 11 cm/yr (Dubois et al. 1977) for a convergence rate between 11 and 20 cm/yr for the central to northern New Hebrides arc. The Eocene to Late Cretaceous lithosphere underthrusting the New Hebrides arc (Lapouille 1982; Weissel et al. 1982; Maillet et al. 1983) is generally quite rugged, but the DR and the West Torres Plateau (WTP) are particularly prominent features. The DR is a 100 km-wide, east-west trending feature on the Indian plate having up to about 4 km of relief. It intersects the arc at a right angle west of Santo and Malekula Islands (fig. 1). The DR is usually termed a fracture zone, but it probably was either a transform fault at the end of an island arc (Daniel et al. 1977; Maillet et al. 1983) or a south-dipping subduction zone (Collot et al. 1985) that is isostatically compensated (Chung and Kanamori 1978a).

The West Torres Plateau (WTP) is a much broader bathymetric high trending NW-SE that obliquely intersects the arc near the northwestern tip of Santo and has about 3 km of relief above the surrounding ocean floor (fig. 1; Mammerickx et al. 1971; Kroenke et al. 1983). It is not isostatically compensated (Luyendyk et al. 1974). The area of potential interaction of the WTP with the arc is difficult to define and its areas of influence may migrate rapidly northward along the arc. McCann (1980), Wyss et al. (1983), and McCann and Habermann (in prep.) have

mentioned the possibility that the WTP has influenced the Torres Islands. This is quite possible, but the bathymetry of the Indian plate (fig. 1; Mammerickx et al. 1974; Kroenke et al. 1983) does not clearly require that a bathymetric feature such as the DR has underthrust the Torres Islands. The NW-SE trend of the WTP suggests that it may have been thrust beneath northern Santo as well as areas farther north. This could account for the absence of a trench west of northern Santo and for the rapid uplift of the western peninsula of northern Santo.

*Comparison between the Torres Islands and Santo-Malekula.*—Uplift of the Torres Ridge on the New Hebrides frontal arc occurs in an arc setting that is morphologically normal. The Wadati-Benioff zone lies approximately 40 km beneath the Torres Islands (Chinn and Isacks 1983). Santo and Malekula also lie above the zone of shallow thrusting earthquakes, but in a morphologically unusual part of the frontal arc where there is no physiographic trench. The main thrust zone slopes from approximately 10 km deep under western Santo to 30 km beneath eastern Santo (Isacks et al. 1981; Chinn and Isacks 1983). Efate and other uplifting isles in the New Hebrides arc lie on or even behind the volcanic chain where the Wadati-Benioff zone is much deeper and where mechanisms causing uplift may differ from those operating at the plate edge. The Torres Islands offer the best frontal arc setting available for comparison with Santo and Malekula.

There are major geomorphic and tectonic differences between the Santo-Malekula and Torres frontal arcs. However, most differences are attributable to subduction of the DR and WTP. The eastern halves of Santo and Malekula seem geologically and physiographically equivalent to the Torres Islands (e.g., Luyendyk et al. 1974; Ravenne et al. 1977; Carney and Macfarlane 1982; Collot et al. 1985). Eastern Santo and Malekula are about the same distance as the Torres Islands from the plate boundary and the volcanic axis (fig. 1). The eastern coral limestone plateaus of Santo are geomorphically very similar to the Torres Islands. Each of the plateaus was formerly a separate isle. Emergence joined the string of islands to form the northeastern peninsula of Santo. During approximately the past 100,000 years, however, Santo's eastern

plateaus have been uplifted about twice as fast (~2 mm/yr) as the Torres Islands (~1 mm/yr) (Jouannic et al. 1980; Gilpin 1982). Gilpin (1982) demonstrated that the terraces surrounding each of the eastern plateaus of Santo has tilted in a slightly different direction. This is quite similar to the Torres Islands, which also have slightly different uplift and tilt histories.

*Relationships between Geomorphology and Uplift History of Santo and Malekula.*— Both Santo and northern Malekula have two topographic axes subparallel to the arc trend. The western topographic axes are higher and coincide with the axes of maximum late Quaternary uplift rate (Taylor et al. 1980, 1981; Jouannic et al. 1980, 1982; Gilpin 1982) (figs. 1, 7, 8, and 9). Western Santo and Malekula have late Quaternary uplift rates of about 3–4 mm/yr and 2 mm/yr, respectively, and Holocene rates of at least 3.6 and 6 mm/ yr, respectively (Taylor et al. 1980; Jouannic et al. 1980, 1982; Gilpin 1982). Linear topographic lows separate the two topographic axes on both Santo and Malekula. The central trough between the eastern and western topographic axes of Santo is pronounced and extends offshore north and south as a bathymetric trough (Gilpin 1982; map: Kroenke et al. 1983). The linear topographic low on Northern Malekula is less developed because uplift rates have been slower. The correlation between topographic relief and uplift rate on Santo and Malekula is the direct result of the late Quaternary geographic pattern of uplift persisting for at least several hundred thousand years once it was established.

The reef terraces on northern Malekula show that the eastern peaks and ridges of pre-Quaternary rocks actually emerged before the western reef-capped plateau (Taylor et al. 1980; figs. 7 and 9). The western area became the topographic axis because it began to uplift faster than any other area. Western north Malekula clearly uplifted at least 600 m because Quaternary coral limestone occurs as a continuous cover to a height of 614 m (Mitchell 1971).

Western Santo probably emerged before eastern Santo, but the uplift rate of the western axis has been so much greater that the great height difference between the east and west could have accumulated in only a few hundred thousand years. The maximum al-
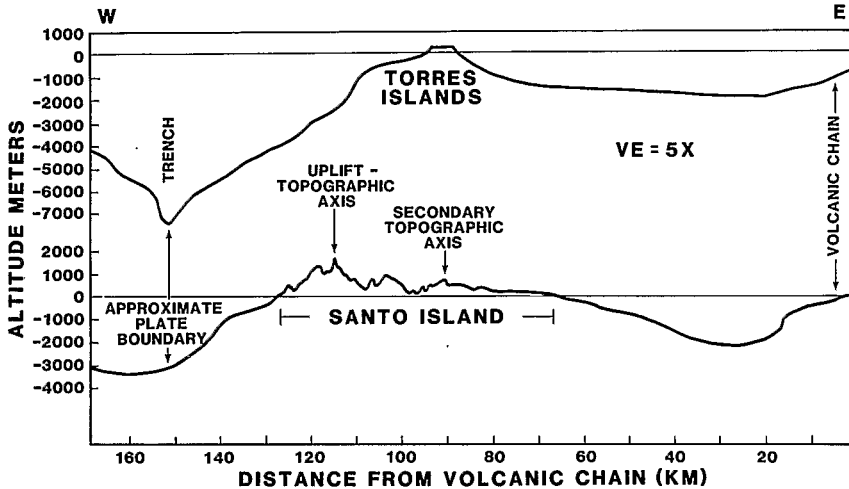
FIG. 8.—Topographic profiles across the Torres frontal arc and across southern Santo. See figure 1 for locations. Bathymetry is from Kroenke et al. (1983) and topography is from topographic maps of Institut Geographique National, Paris. The submarine profiles are much more generalized than the profiles across Santo because they are based on a bathymetric contour interval of 500 m while the maps of the islands have a 40 m contour interval.

titude of coral limestone on eastern Santo is nearly 800 m. This represents only about 400,000 years of uplift at 2 mm/yr, the rate for easternmost Santo for the past 100,000 years. At the 6 mm/yr or greater Holocene uplift rate of western Santo, the sea floor could have emerged to form the high western topographic axis in less than a million years. Alternatively, the present uplift pattern could

have begun by superimposition on pre-existing topography within the past few hundred thousand years. This alternative implies either that the DR began to influence tectonics and uplift of Santo and Malekula only very recently, or that the pattern of its tectonic effects changed in late Quaternary time.

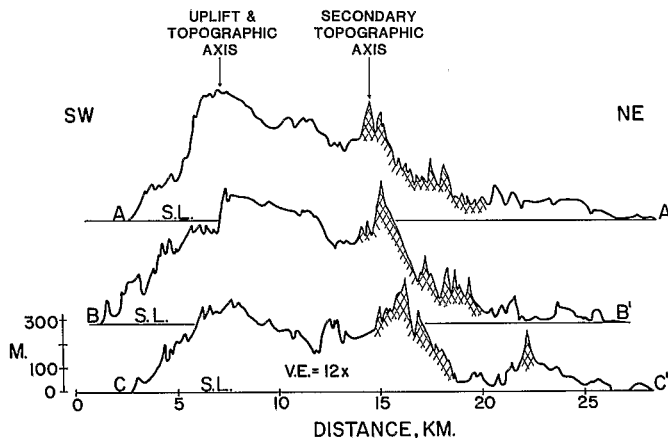Western Santo has probably uplifted much more in Quaternary time than is indicated by



FIG. 9.—Topographic profiles oriented SW-NE across northern Malekula (from Taylor et al. 1980). See figure 7 for locations. The vertical exaggeration is greater than in figure 8 because Malekula is a smaller, lower island. The profiles cross Quaternary coral limestone except on the cross-hatched area where Miocene rocks underlying the coral limestone are exposed. Reef terraces increase in altitude to the west and show that the lower eastern topographic axis emerged before the more rapidly uplifting western axis. (Taylor et al. 1980; Jouannic et al. 1980, 1982).

the maximum height of occurrence of coral limestone at about 300 m. The scarcity of emerged coral limestone on western Santo is probably due to: (1) large amounts of terrigenous sediments shed from the island; (2) the steep coastline and submarine slopes requiring any coral reef that develops to be very narrow; and (3) extremely rapid uplift.

Both emerged fossil and living reefs on western Santo occur only at the north and south ends of the island where sedimentation does not greatly inhibit reef growth, the slopes are more gentle providing a wider reef substrate, and uplift rates are slower allowing thicker reefs to accumulate. Where uplift rates are rapid and slopes are steep, reefs cannot thicken significantly. For example, where the uplift rate is 5 mm/yr, the past 125,000 years of reef deposition would be spread across a surface reaching from below present sea level to 630 m ASL. Significant reef accumulations develop only when uplift and sea-level rise rates are nearly equal. Even then, as today, sedimentation probably inhibits reef growth in all but ideal locations.

However, the stratigraphy of Santo suggests that shallow-water conditions prevailed from late Pliocene time (Robinson 1969; Mallick and Greenbaum 1977; Carney and Macfarlane 1980). This implies that uplift acted upon a slightly submerged area of sea floor that pre-existed the latest phase of uplift rather than upon an uplifted trench slope. Likewise, sedimentary rocks beneath northern Malekula's coral cap (Mitchell 1971) suggest uplift from fairly shallow rather than abyssal depths.

Western Santo and western Malekula are not uplifted accretionary prisms. Instead, except for superficial sediments, they appear to represent an ancient east-facing Miocene volcanic island arc that existed before the New Hebrides arc reversed to face westward in late Miocene time (Mitchell and Warden 1971; Karig and Mammerickx 1972; Carney and Macfarlane 1977, 1980, 1982; Falvey 1975, 1978). K/Ar ages of 36.7 and 39 m.y. indicate a similar origin for the Torres Islands (Greenbaum et al. 1975).

*Model for the Uplift of Santo and Malekula.*—The similarity of the Torres Islands and eastern Santo suggests an explanation for the geomorphic development of Santo and Malekula. In the past, the eastern limestone plateaus of Santo and eastern peaks of northern Malekula occupied the uplift and topographic axes of the frontal arc. A change in uplift patterns in the frontal arc caused axes of more rapid uplift rate to originate at the western edge of the upper plate. The western axes began to uplift at least twice as fast as the eastern axes, and rapidly became topographically dominant. At average uplift rates of 4 mm/yr, a surface originally 1000 m below sea level would be 1000 m ASL in only 500,000 years. Most of the western Santo peaks are now about 1000 m ASL, although the highest peak is 1879 m ASL and is aligned with the northern flank of the DR. Western Santo would probably be considerably higher were it not for the high erosion rates caused by the steep topography and humid tropical climate.

*Underthrusting of the DR as the Most Likely Cause for Establishment of a New Axis of Maximum Uplift Rate at the Western Edge of the Upper Plate.*—Many studies have considered the effects of subduction of the DR on the central New Hebrides arc (e.g., Karig and Mammerickx 1972; Pascal et al. 1978; Chung and Kanamori 1978a, 1978b; Taylor et al. 1980; Daniel and Katz 1981; Isacks et al. 1981; Louat et al. 1982; Carney and Macfarlane 1982; Collot et al. 1985). Taylor et al. (1980) used emerged reef terraces to show that at least four blocks or upper plate arc segments make up the Santo and Malekula frontal arc (fig. 7). Boundaries between the tilt blocks also act as rupture zone boundaries or asperities during major interplate earthquakes (Taylor et al. 1980, 1981; Ebel 1980; Wyss et al. 1983; Habermann 1984). Two of the boundaries between arc segments correspond to the north and south flanks of the DR, respectively (Pascal et al. 1978; Taylor et al. 1980). Collot et al. (1985) present evidence that the plate boundary on the sea floor west of Santo is farther west than a straight line connecting the northern and southern New Hebrides trenches (fig. 1) because of subduction of the DR. Perhaps underthrusting started in Quaternary time, or the topographic relief of the part being underthrust increased. A change in convergence rates is unlikely to be the cause of a westward shift in the axis of maximum uplift rate because the change in uplift rates did not affect other parts of the arc.

The large amount of Quaternary uplift of western Santo and Malekula does not require that they represent the uplifted inner trench slope, although the scenario we propose strongly suggests that possibility. The distribution of late Quaternary uplift is clearly a major cause for the anomalous morphology of the Malekula-Santo frontal arc even if it is not the only cause.

We know of no other study that demonstrates the details of such a shift in uplift pattern related to aseismic ridge subduction beneath frontal arcs. However, Vogt et al. (1976) and McCann and Habermann (in prep.) reviewed the effects of aseismic ridge subduction. The effects predicted by McCann and Habermann (in prep.) are similar to those we describe when they suggested that subduction of topographic features can have profound effects on the upper plate including increased vertical tectonism. The detailed uplift history of most other frontal arcs is less well known than on Santo and Malekula because few emerged islands are located so close to plate boundaries. Moreover, the DR is underthrusting nearly normal to the arc trend so that its effects accumulate in one place over a long period. Subducting linear ridges are more likely to be oriented obliquely and migrate more rapidly along the arc trend than the DR as they underthrust.

*Holocene versus Pre-Holocene Uplift Rates.*—On Santo and Malekula the uplift rates in Holocene time are about double the average rates of the past 125,000 years. In contrast, there has been no observed temporal change in uplift rates on the Torres Islands or on Efate Island near the volcanic axis (Bloom et al. 1978). In the New Hebrides arc the increased Holocene uplift rates apparently are limited to Santo and Malekula. However, changes in uplift rates have been observed elsewhere. In Japan, Ota and Yoshikawa (1979) found significantly greater uplift rates in Holocene time as compared with the past 100,000 years. Koba et al. (1982) also reported significant differences between late Pleistocene and Holocene uplift rates for several Ryukyu forearc isles. Perhaps the New Hebrides example of accelerated uplift rate shows that the assumption of constant uplift rates is not valid when shorter time intervals are considered. Nevertheless, the increased rates must have an underlying cause.

An explanation for the increased Holocene uplift rates of Santo and Malekula must account for two observations. First, the uplift rate increase occurred rather suddenly between about 28,000 yr B.P. and the time of Holocene reef deposition. If the rate had increased before 28,000 yr B.P., then according to the sea-level history of Bloom et al. (1974), there should be a 28,000 yr B.P. reef terrace where uplift rates exceed about 2 mm/yr. If a 28,000 yr B.P. reef grew in a paleosea level of −41 m, then it would not be exposed if it was uplifted at the slower pre-Holocene rate because it would have been drowned by the Holocene transgression. Second, the accelerated uplift rates affect hundreds of square km of the upper plate above the DR, but north of the DR eastern Santo is apparently unaffected (Gilpin 1982; Jouannic et al. 1980, 1982). A convergence rate of about 15 cm/yr consumes only 1.5 km of the Indian plate since 10,000 yr B.P. Yet the above observations indicate that the uplift rates of a broad area increased nearly simultaneously.

Gilpin (1982) suggested several possible explanations: (1) parts of the downgoing plate are underplated or accreted to the upper plate; (2) there have been changes in the kinematics of the plates involved; (3) faulting began within the upper plate; and (4) the topographic relief of the DR increased suddenly. Accretion or underplating would probably be slow and unlikely to influence such a large area in so short a time. Faulting within the upper plate also seems unlikely to influence such a large area. Changes in plate dynamics should have caused increased uplift rates for the Torres Islands as well. Of the four possible explanations, the third or fourth seems most likely. In the case of a rapid increase in relief on the DR, simple displacement of the upper plate due to subduction of a particularly prominent part of the DR cannot explain increased Holocene uplift rates over an area of hundreds of square km. For the same reason we eliminate any change in amounts of sediment being subducted (Cloos 1982) as a cause for this change in uplift rates. However, perhaps an increase in topographic relief on the DR could produce a change in faulting along the interplate thrust or other faults. Collot et al. (1985) suggested that an increase in the strength of coupling has resulted in an increase in horizontal compressive stress. Although this explanation does

not adequately specify a mechanism, it seems possible that increased horizontal stress could result in more rapid vertical deformation. Unfortunately, we cannot specify a mechanism to account for the increased Holocene uplift rates although we can eliminate some possible causes. We can say that circumstantial evidence indicates that the increased rates are related to subduction of the DR.

### CONCLUSIONS

1) The Torres Islands have uplifted at rates of about 1 mm/yr for at least the past 125,000 years. Gentle eastward tilting accompanied uplift. Emergence of the Torres Ridge began approximately 400,000 years ago.

2) Steeply dipping faults control the Torres Islands' morphology and apparently displaced the frontal arc before the islands began to emerge. Some faults continued to move after the islands emerged in late Quaternary time.

3) Because uplift rates for all of the Torres Islands are between 0.7 and 0.9 mm/yr and because there are no known tectonic discontinuities or asperities crossing the island chain, the Torres Islands probably share an arc-segment block or set of blocks that behave as a unit. Young faults and slight variations in uplift rates occur, but such faults also occur within the largely coherent arc-segment blocks of Santo and Malekula.

4) In contrast to the emerged Holocene reefs of Santo and Malekula, the Holocene reefs on the Torres Islands do not indicate a Holocene uplift rate faster than that of the past 125,000 years. This suggests that the accelerated Holocene uplift is limited to Santo and Malekula. Thus the accelerated Holocene uplift rates probably are related to subduction of the DR.

5) The Santo and Malekula area may have formerly had a more typical arc geometry, similar to that of the Torres Islands. Initiation of a new axis of more rapid uplift at the western edge of the plate could account for emergence of the area normally occupied by the inner trench slope and for the dual topographic axes of Santo and Malekula. We propose that the westward shift of the uplift axis is related to subduction of the DR, and accounts for the anomalous morphology of the Santo-Malekula frontal arc.

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