Coseismic event of May 15, 1992, Huon Peninsula, Papua New Guinea: Comparison with Quaternary tectonic history

John M. Pandolfi
Australian Institute of Marine Science, P.M.B. No. 3, Townsville M.C., Queensland 4810, Australia
Mairi M. R. Best
Department of Geophysical Sciences, University of Chicago, 5734 South Ellis Avenue, Chicago, Illinois 60637
Stephen P. Murray
Coastal Studies Institute, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, Louisiana 70803

ABSTRACT

The May 15, 1992, earthquake on the Huon Peninsula, Papua New Guinea, resulted in the uplift and large-scale mortality of intertidal fringing coral reefs. Reduction in the highest level of survival of intertidal massive corals was used as a proxy for assessing the amount of coseismic uplift over 45 km of the Huon coastline. Measurements were gathered from three sites one and three months after the earthquake. Sea-level pressure gauges in place in the northern end of Sialum Lagoon showed not uplift, but subsidence, from the earthquake. Uplift ranged from ~7 to 13 cm, and subsidence ranged from 8 to 14 cm. The May 15, 1992, earthquake corroborates the coseismic origin of the raised reef terraces of the Huon Peninsula. Greater uplift of the land in the southeast relative to the northwest is consistent with the regional Quaternary uplift pattern. The close proximity of subsidence (shown by sea-level gauges) to uplift (shown by coral mortality) is a manifestation of the abundant fault blocks in the area. Uplift rates of 3.0–5.2 m/ka calculated from the earthquake are only marginally higher than previous estimates based on radiometric age dates and terrace geomorphology. The first directly observed earthquake uplift event on the Huon Peninsula has yielded only centimetre-scale coseismic uplift. Thus, individual Holocene and Pleistocene terraces thought to have been the result of metre-scale displacement from single earthquakes may rather have been due to successive episodes of centimetre-scale uplift on constructional reef platforms. The clustered history of earthquakes on the Huon Peninsula throughout the past 100 years indicates the complexity involved in assessment of seismic risk throughout the world.

INTRODUCTION

The raised coral-reef terraces of the Huon Peninsula, Papua New Guinea, are a primary source of data on sea level for the late Quaternary (Chappell, 1974, 1983; Bloom et al., 1974; Chappell and Polach, 1991; Chappell and Shackleton, 1986). Formation of the terraces is based on the interaction of sea level and tectonic uplift rate, which increases from northwest to southeast along the coast (the range is 0.5–3.4 m/ka).

Of primary importance in the global sea-level interpretation of the reef terraces is their mode of origin. Ota et al. (1993) interpreted regressive Holocene terraces as the result of 4–6 coseismic events separated in time by ~1 ka. These Holocene coseismic uplift events appear to have occurred at different times on different sectors of the coast. The uplift amplitude per event ranges from 1.5 to 4 m, and increases to the southeast. This paper relates the coseismic vertical displacement caused by the May 15, 1992, earthquake to the mode of origin of the Huon reef terraces and their uplift rates.

The earthquake epicenter was located at lat 6.1°S and long 147.6°E, registered 7.2 on the Richter scale, and was 58 km deep (Table 1, Fig. 1). Large-scale coral mortality involving broad stretches of the fringing reef flat followed the earthquake. Massive corals from the intertidal reef flat either perished or showed a die back on their tops associated with a relative lowering of sea level.

METHODS

Colony Mortality

Intertidal reef corals have great utility in documenting changes in sea level (Scoffin and Stoddart, 1978). The highest level of survival of massive intertidal reef corals served as a datum to compare pre- and postearthquake sea level. The highest level of survival is defined as the uppermost level of living coral tissue within the colony (Taylor et al., 1981, 1987). It is commonly, but not exclusively, at the same level around the entire perimeter of massive coral colonies (Fig. 2).

The reduction in the highest level of survival was measured by subtracting the postearthquake level from the pre-earthquake level (Fig. 2). These observations were made from three sites located on the Huon Peninsula, each separated by ~15 km: Sialum, Pukau, and Hubegong (Fig. 1). At Sialum and Pukau, only colonies that showed previously dead surfaces above the pre-earthquake highest level of survival were measured. We assumed that the upper limit of pre-earthquake survival in these colonies was at or near sea level. In contrast, whole, rounded colonies with pre-earthquake surfaces totally alive may not have been growing at the upper limit of sea level and the amount of reduction in their highest level of survival may underestimate the amount of coseismic uplift. Because of the small number of colonies displaying pre-

TABLE 1. MAJOR EARTHQUAKES, HUON PENINSULA, PAPUA NEW GUINEA

Location (lat, long)	Magnitude	Depth (km)	Year
6.0° S, 147.8° E	7.5	s	1938
6.2° S, 147.7° E	7.2	100	1946
6.1° S, 147.7° E	7.4	55	1987
6.1° S, 147.6° E	7.2	58	1992

Note: Data from Ripper and Letz (1991). s = shallow earthquake.

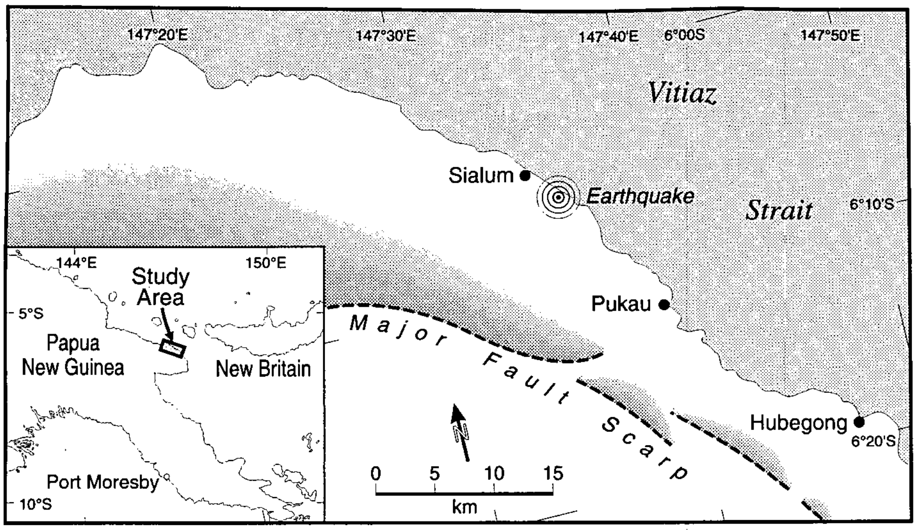

Figure 1. Location map of study area. Epicenter of May 15, 1992, earthquake was located ~4 km southeast of Sialum.

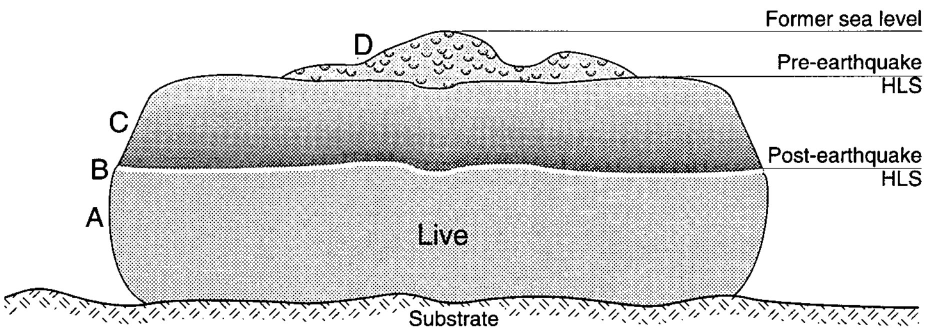

Figure 2. Illustration of reduction in highest level of survival (HLS) of intertidal reef corals. Cartoon shows band of bleached coral (B) separating live coral tissue below (A) from green-algal encrusted dead coral skeleton above (C). Measurements were made from colonies that showed relief above pre-earthquake HLS (D). Layer D was heavily bioeroded with *Echinometra* (sea urchin) and worm borings and was easily distinguished from recently dead layer C.

earthquake dead material above the live colony at Hubegong, it was necessary to measure some of these colonies with totally alive pre-earthquake surfaces. Thus, mean lowering of the highest level of survival is a minimum estimate at Hubegong, whereas at Pukau and Sialum it is a maximum estimate.

Data on the reduction of the highest level of survival were gathered from intertidal colonies of *Goniastrea retiformis*, *G. favulus*, *G. edwardsi*, and *Favites abdita* one month after the earthquake at Sialum and Pukau, and again three months after the earthquake at all three sites. No species effect was detected among the sites. Reduction in survival level was measured at a consistent position on each colony, i.e., in the direction of the sun's rays during the late morning. This orientation provided equal exposure among all sites, thus providing reliable data for regional comparisons of the amount of uplift from the May 15, 1992, earthquake. Colonies shaded on their sun side by other coral colonies were not measured.

Log transformation of the reduction in highest level of survival data resulted in a normal distribution. The generalized linear models procedure in the SAS/STAT User's Guide (1989) was used in the analysis of variance of the log transformed data.

Tidal Measurements

Two pressure gauges to measure sea-level fluctuations were installed on the leg of a pier in Sialum Lagoon (Fig. 1) from February 29 to July 24, 1992. Both the sea data and Sea Bird gauges which were deployed can detect sea-level changes of several millimetres. The pressure gauges were deployed ~200 m northwest of the Sialum site where coral die back was measured.

RESULTS

Colony Mortality

Analysis of variance of the log of the reduction of the highest level of survival showed significant differences between sites [$F_{(2,169)} = 18.59$, $p < 0.001$] and between times after the earthquake [$F_{(1,169)} = 43.61$, $p < 0.001$] but no site × time interaction [$F_{(1,169)} = 1.91$, $p = 0.1689$]. The table of means for the log of the reduction of the highest level of survival shows the differential uplift among sites and between times after earthquake (Table 2).

TABLE 2. MEANS AND STANDARD ERRORS FOR LOG (REDUCTION IN HIGHEST LEVEL OF SURVIVAL) FOR SITES (SIALUM, PUKAU, AND HUBEGONG) AND TIME AFTER EARTHQUAKE (ONE AND THREE MONTHS)

	One Month	Three Months
Sialum	1.39 (0.09)	1.90 (0.10)
Pukau	2.27 (0.05)	2.53 (0.08)
Hubegong		2.51 (0.06)

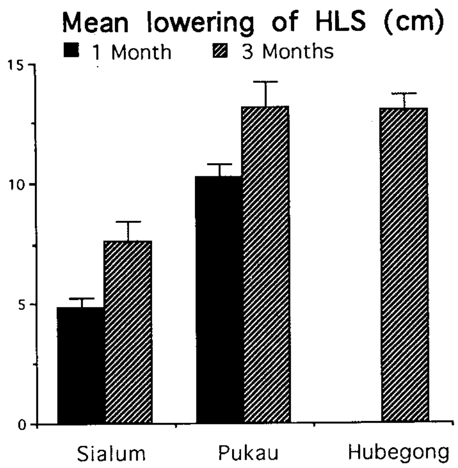

Figure 3. Mean and standard errors for reduction in highest level of survival (HLS) at Sialum, Pukau, and Hubegong one and three months after earthquake.

Sites. One month after the earthquake, die back at Pukau was significantly greater than that at Sialum (Fig. 3). After three months, Hubegong and Pukau were similar (13 cm), but Sialum underwent considerably less mean reduction in highest level of survival (7.6 cm).

Time. At Sialum and Pukau, mean reduction in highest level of survival was significantly greater three months after the earthquake than one month after the event (Fig. 3). It appears that (1) uplift following the earthquake continued for longer than one month, and/or (2) coral mortality increased over a greater than one month interval.

Tidal Measurements

The tidal height variations from the Sialum pressure gauges, after treatment with a Butterworth 10 day low-pass digital filter, clearly display the effect of the May 15, 1992, earthquake (Fig. 4). This analysis removes tidal and other fluctuations with a period of <10 day. The low-pass records from both gauges indicate an initial downdrop of the land of ~8 cm that began on May 15, and

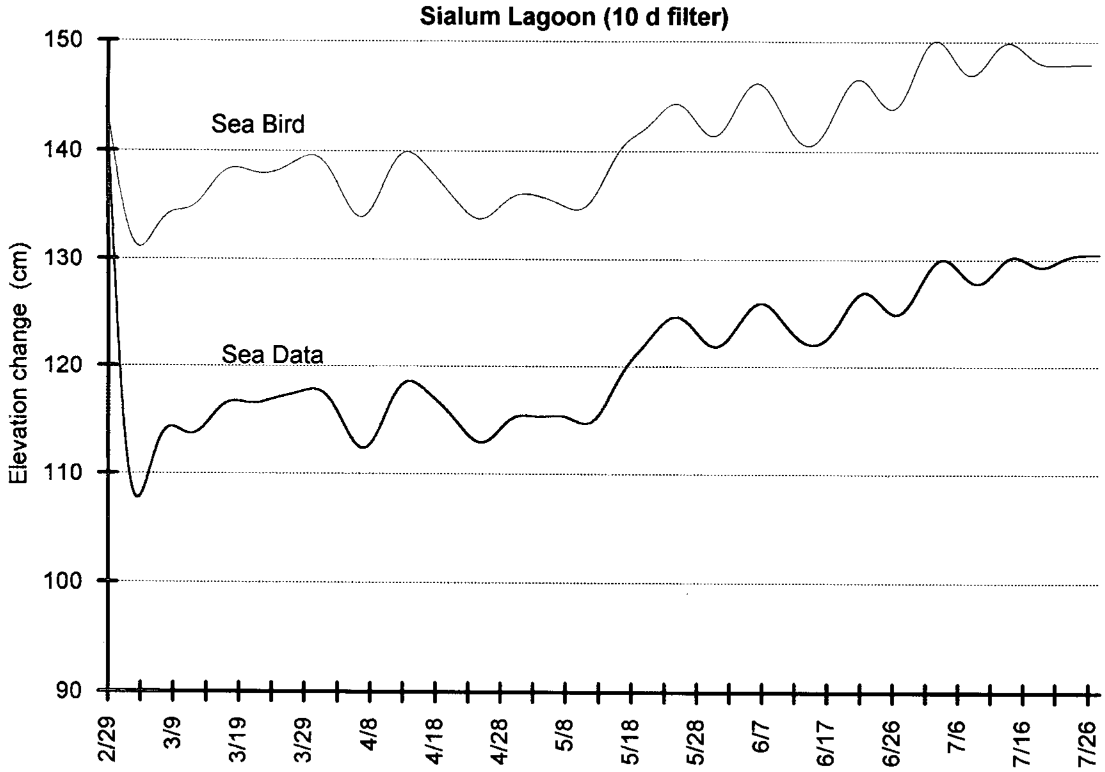

Figure 4. Low-pass sea-level records from two tidal pressure gauges installed in Sialum Lagoon. Initial subsidence event of ~8 cm coincided with earthquake and was followed by additional drop of 6 cm up to July 15, when sea level stabilized.

a continuing increase in water depth of another 6 cm up to July 15, when the sea level stabilized. Thus, during and after the May 15, 1992, seismic event, tidal gauges at Sialum Lagoon measured 8–14 cm of subsidence with respect to sea level. There is no visual evidence that the pier legs failed or subsided with respect to the local sea floor (14 cm slump confined to pier legs would have fractured the pier).

DISCUSSION

Quaternary Patterns

The May 15, 1992, earthquake demonstrated the coseismic origin of Holocene terraces from the Huon Peninsula and yielded southeast to northwest patterns concordant with regional Quaternary uplift. Pleistocene and Holocene reef terraces display higher uplift in the southeast than in the northwest. Thus, the Quaternary history of uplift is related to the differential response to seismicity along the Huon Peninsula coast.

A fundamental question in the sea-level interpretation of the reef terraces relates to the large degree of variability of uplift in Holocene terraces along the Huon Peninsula coastline (Ota et al., 1993). We believe that the answer might in part be the presence of faults distributed along the coast. Uplift of the terraces occurred along a 45 km stretch of coastline, but subsidence occurred at the extreme northwestern end of the study area. The subsidence is consistent with the secular trend of minimum uplift in the northwest region. Because the distance between the subsidence in northern Sialum Lagoon and the uplift just south is <200 m, the subsidence might be an extremely local phenomenon that represents movement of a small block in the Sialum area northwest of the airstrip. The entire region is dominated by a large number of fault scarps (Chappell, 1973, 1974).

An alternative explanation for the presumed tectonic subsidence is compaction. Compaction has been observed after the 1964 Alaskan "Good Friday" earthquake (76 cm; Grantz et al., 1964) and during a one-week interval several weeks after the 1989 Loma Prieta, California, earthquake (4 mm; Bennett, 1990). Because (1) similar material exists below the subsided Sialum pier and the uplifted Sialum reef flat, (2) uplift and subsidence occurred in close proximity (~200 m), and (3) a predominance of faults exist in the Sialum area, we favor a fault block instead of compaction to account for the subsidence at the Sialum pier.

The tidal-gauge data also show regional strain occurring over two months. Thus, the difference in uplift indicated by the coral data over periods of one and three months probably reflects the summation of both the elastic earthquake event and a continuing background of accumulating tectonic strain, rather than a delayed response time of coral die back to relative sea-level lowering.

Uplift Rate on the Huon Peninsula

The results of the May 15, 1992, earthquake invite estimates of Quaternary uplift rate based on the frequency of major modern earthquakes on the Huon Peninsula and the amount of uplift observed during this coseismic event. Four major earthquakes (>7.0 on the Richter scale) have occurred on the Huon Peninsula during the past 92 yr (Ripper and Letz, 1991) (Table 1). By extrapolation, this is equivalent to ~40 major earthquakes per 1 ka. Considering the maximum amount of uplift undergone by intertidal coral colonies at Sialum (7.6 cm) and multiplying by the extrapolated earthquake frequency per 1 ka gives an uplift rate of 3.0 m/ka. At Pukau and Hubegong, a similar calculation results in an uplift rate of 5.2 m/ka. These figures are the same order of magnitude but 33% greater than tectonic uplift rates previously estimated from radiometric age dates and height of terraces at previous sea-level stands (Chappell, 1974; Ota et al., 1993).

These figures corroborate the hypothesis that Holocene terraces are coseismic in origin and substantiate the coseismic uplift rates previously hypothesized for the Huon Peninsula reef terraces (Chappell, 1974; Ota et al., 1993). Four factors could bias estimates of uplift rates from the May 15, 1992, earthquake. (1) The frequency of major earthquakes for the twentieth century is greater than the mean number of major earthquakes per century throughout the Quaternary. (2) Coseismic events are variable in amount of uplift, and not all major earthquakes produce a coseismic uplift event. (3) The mean amount of uplift associated with Quaternary coseismic events is less than that associated with the May 15, 1992, event. (4) Local coseismic or postearthquake subsidence may cause a lowering of the mean uplift rate during the Quaternary (though no evidence for subsidence has been observed in Holocene massive corals on the Huon Peninsula).

The apparent seismic pattern on the Huon Peninsula is one of heightened seismic activity (1938, 1946, 1987, and 1992) followed by periods of low activity (1901–1937; 1947–1986). Such patterns also exist in other places. For example, fault zones in the eastern Mediterranean basin have had periods of dormancy and activity lasting for hundreds of years (Ambraseys, 1971). In addition, large earthquakes on the San Andreas fault are clustered in time (Weldon and Sieh, 1985). These and the Papua New Guinea example illustrate the enormous complexity in assessing seismic risk worldwide.

Terrace Geomorphology

The relation between Quaternary terrace geomorphology and the frequency and intensity of coseismic uplift is complex. Shore-platform development and subsequent terrace formation depend upon the interaction of bedrock characteristics, wave energy, tidal range, erosion, sea-level fluctuations, and tectonic uplift and subsidence (Berryman et al., 1992). All other factors being equal, the height of each individual terrace is taken to be the result of a single coseismic uplift event. Ota et al. (1993) inferred that individual Holocene coseismic events have caused up to 4 m of uplift of the Huon Peninsula.

The centimetre-scale uplift from the May 15, 1992, earthquake indicates that the height of individual terraces on the Huon Peninsula may not necessarily be the result of a single coseismic event. Terraces formed on constructional platforms, such as coral reefs, where material is continually added as it is uplifted (as opposed to eroded), may not show a linear relation between terrace height and amount of coseismic uplift. Erosion of small terraces caused by centimetre-scale uplift may not occur because the new, shallower reef crest grows faster than the erosion of the new small terrace formed landward of the reef crest. Thus, a series of small coseismic uplifts, similar to the May 15, 1992, event, unencumbered by erosion, may accrue at such a rate as to result in the development of a major (metre-scale) cliff.

In erosional platforms, small uplifts will be quickly eroded and not recorded. Thus, high terraces are probably the result of large uplift. However, high terraces in coral-reef environments might result either from a series of small coseismic events or fewer large coseismic events. Thus, the height of individual terraces may not necessarily equate with the magnitude of the coseismic event in reef settings.

CONCLUSIONS

1. Coseismic uplift from the May 15, 1992, earthquake ranged from 7 to 13 cm along the northern coast of the Huon Peninsula, Papua New Guinea. Low uplift in the northwest and higher uplift in the southeast is consistent with previous Pleistocene and Holocene uplift patterns and corroborates the coseismic origin of Holocene terraces proposed by Ota et al. (1993). From 8 to 14 cm of isolated subsidence also occurred as a result of the earthquake.

2. Extrapolation of the frequency of major earthquakes on the Huon Peninsula during the past 100 yr with the amount of uplift from the May 15, 1992, earthquake results in the calculation of marginally higher uplift rates than those based on Holocene and Pleistocene terrace height above sea level and radiometric age. The discrepancy may arise from a difference in major earthquake intensity from the modern back through the Pleistocene, local subsidence, or complex variability in the frequency and intensity of uplift events associated with major earthquakes.

3. The May 15, 1992, earthquake resulted in only centimetre-scale coseismic uplift; thus, the height of some metre-scale Holocene and Pleistocene terraces on the Huon Peninsula may be caused by a succession of coseismic events rather than a single earthquake.

ACKNOWLEDGMENTS

Supported by the Christensen Research Institute, and Australian Research Council grant AD9031784 to Pandolfi, and Monbusho International Scientific Research Program project 04041048 to Yoko Ota. We thank Brian and Jean Pitts-Brown; the people in the villages of Hubegong, Kanomi, and Sialum and Mananoc Gasawe; and Paul Aharon, Kelvin Berryman, Bob Carter, John Chappell, Matthew Jebb, Brad Pillans, Sandy Tudhope, and Yoko Ota for contributing to this study and paper. Australian Institute of Marine Science contribution no. 653 and Christensen Research Institute contribution no. 109.

REFERENCES CITED

Ambraseys, N.N., 1971, Value of historical records of earthquakes: Nature, v. 232, p. 375–379.

Bennett, M.J., 1990, Ground deformation and liquefaction of soil in the Marina District: U.S. Geological Survey Open-File Report 90-253, p. 44–79.

Berryman, K.R., Ota, Y., and Hull, A.G., 1992, Holocene coastal evolution under the influence of episodic tectonic uplift: Examples from New Zealand and Japan: Quaternary International, v. 15/16, p. 31–45.

Bloom, A.L., Broecker, W.S., Chappell, J.M.A., Matthews, R.K., and Mesolella, K.J., 1974, Quaternary sea level fluctuations on a tectonic coast: New $^{230}Th/^{234}U$ dates from the Huon Peninsula, New Guinea: Quaternary Research, v. 4, p. 185–205.

Chappell, J., 1973, Stress field associated with a dense fault pattern in New Guinea: Journal of Geology, v. 81, p. 705–716.

Chappell, J., 1974, Geology of coral terraces, Huon Peninsula, New Guinea: A study of Quaternary tectonic movements and sea level changes: Geological Society of America Bulletin, v. 85, p. 553–570.

Chappell, J., 1983, A revised sea level record for the last 300,000 yrs from Papua New Guinea: Search, v. 4, p. 99–101.

Chappell, J., and Polach, H., 1991, Post-glacial sea-level rise from a coral record at Huon Peninsula, Papua New Guinea: Nature, v. 349, p. 147–149.

Chappell, J., and Shackleton, N.J., 1986, Oxygen isotopes and sea level: Nature, v. 324, p. 137–140.

Grantz, A., Plafker, G., and Kachadoorian, R., 1964, Alaska's Good Friday earthquake, March 27, 1964, A preliminary geologic evaluation: U.S. Geological Survey Circular 491, 35 p.

Ota, Y., Chappell, J., Kelley, R., Yonekura, N., Matsumoto, E., Nishimura, T., and Head, J., 1993, Holocene coral reef terraces and coseismic uplift of Huon Peninsula, Papua New Guinea: Quaternary Research, v. 40, p. 177–188.

Ripper, I.D., and Letz, H., 1991, Distribution and origin of large earthquakes in the Papua New Guinea region, 1900–1989: Papua New Guinea Geological Survey Report 91/5, 75 p.

SAS/STAT User's Guide, 1989, Version 6, Fourth edition, Volume 2: Cary, North Carolina, SAS Institute Inc., 846 p.

Scoffin, T.P., and Stoddart, D.R., 1978, The nature and significance of microatolls: Royal Society of London Philosophical Transactions, ser. B, v. 284, p. 99–122.

Taylor, F.W., Jouannic, C., Gilpin, L., and Bloom, A.L., 1981, Coral colonies as monitors of change in relative level of the land and sea: Applications to vertical tectonism: International Coral Reef Symposium, 4th, Proceedings, v. 1, p. 485–492.

Taylor, F.W., Frohlich, C., LeColle, J., and Strecker, M., 1987, Analysis of partially emerged corals and reef terraces in the central Vanuatu Arc: Comparison of contemporary coseismic and nonseismic with Quaternary vertical movements: Journal of Geophysical Research, v. 92, p. 4905–4933.

Weldon, R.J., and Sieh, K.E., 1985, Holocene rate of slip and tentative recurrence interval for large earthquakes on the San Andreas fault, Cajon Pass, southern California: Geological Society of America Bulletin, v. 96, p. 793–812.

Manuscript received July 26, 1993
Revised manuscript received November 29, 1993
Manuscript accepted December 6, 1993