Pacific Science (1990), vol. 44, no. 4: 348–365

Coastal Geomorphology of Beqa and Yanuca Islands, South Pacific Ocean, and Its Significance for the Tectonic History of the Vatulele-Beqa Ridge[1]

PATRICK D. NUNN[2]

ABSTRACT: Data referring to elevations of emerged shoreline indicators along the coasts of Beqa and Yanuca islands in southern Fiji were collected and indicate the presence of former mean sea levels at elevations (and shoreline names) of 0.96 m (MUA1), 1.93 m (BUL1), 2.63 m (MUA2), 4.32 m (MUA3), 5.94 m (MUA4), and 7.79 m (MUA5) above present mean sea level. No dates for shoreline formation or emergence are available directly although age is believed to increase with increasing elevation. Investigations of the Beqa lagoon floor and comparison of shoreline levels between eastern Beqa, western Beqa, Yanuca, and Vatulele island (at the western end of the Vatulele-Beqa Ridge) suggest that downfaulting along faults and grabens trending a little west of north has occurred both during and since the time of shoreline emergence. Uplift related perhaps to either compression of the area between the Kadavu Trench (Hunter Fracture Zone) to the south and the Fiji Fracture Zone to the north or the renewal of northward underplating along the Kadavu Trench is believed to be responsible for shoreline emergence, which was probably contemporary along the whole Vatulele-Beqa Ridge and occurred during the middle and late Quaternary.

THE ISLANDS OF BEQA (Mbengga) and Yanuca (Yanutha) rise from the eastern end of the Vatulele-Beqa Ridge (lineament), an abandoned island arc that is a discrete structural unit in southern Fiji (Kroenke 1984, Brocher and Holmes 1985). Investigations on Vatulele Island, at the western end of the ridge, allowed a detailed tectonic history of that island to be worked out principally from analysis of emerged shoreline elevations and the pattern of faulting in the limestone of which most of the island surface consists (Nunn 1988*a*; in press). The purpose of the study on the volcanic islands of Beqa and Yanuca, reported in this paper, was to examine evidence for emergence and therefore to assess the tectonic history of the whole Vatulele-Beqa Ridge.

Beqa is wholly the product of subaerial volcanism. The old volcanic center lies near the southwest corner of Malumu Bay, which effectively divides Beqa in two (Figure 1). A parasitic volcanic center was established on the flanks of the main volcano just north of Vaga Bay. Although most of the island is formed from volcaniclastics, the dates of the main eruptive activity have been obtained from an andesite flow in the northwest, dated to 3.07 ± 0.08 million yr ago (Ma), and a basalt on offshore Ugaga (Unganga or Stuart) Island, dated to 4.21 ± 0.06 Ma (Whelan et al. 1985). The interior of Beqa, in which rock dips closely follow ground-surface dips, is only moderately dissected. The nine settlements are located on a narrow discontinuous coastal plain. Beqa is 36.30 km^2 in area and rises to 440 m.

Yanuca (Figure 1) represents a volcano separate from that of Beqa and is of submarine origin, as testified to by pillow lavas and derived lithified sandstones. Dates of eruptive activity range from 5.0 ± 0.2 Ma (quoted by

---

[1] Much of this work was funded by University of the South Pacific grant 0703-0054. Manuscript accepted 15 January 1990.

[2] Department of Geography, University of the South Pacific, P.O. Box 1168, Suva, Fiji.

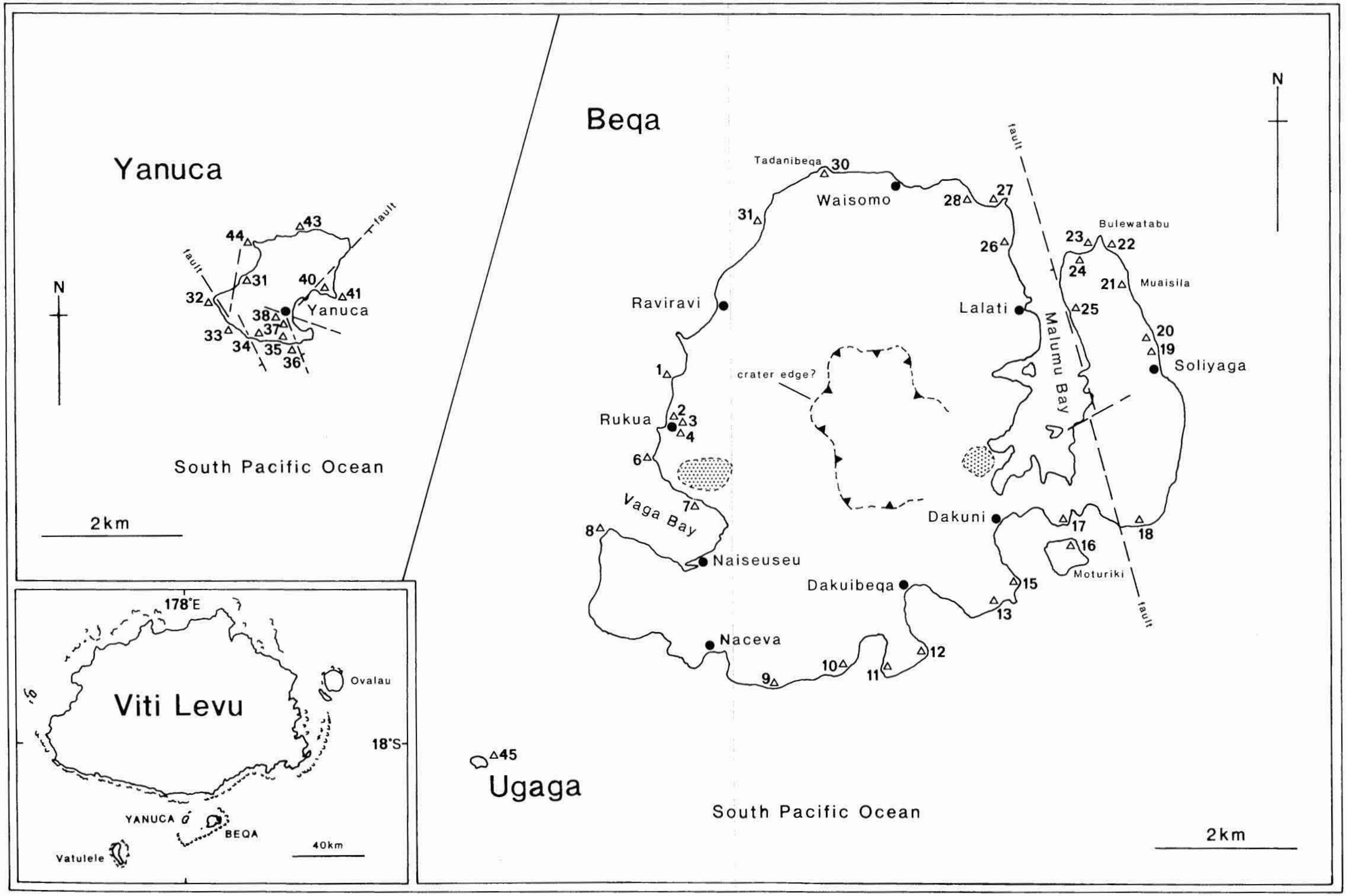

FIGURE 1. Outline of the geology and geomorphology of Beqa and Yanuca showing field sites (1–45) to which data in Table 2 refer. No reef is shown. Dot shading is hornblende-augite andesite, which fills old volcanic centers on Beqa. Mapping of this and the faults shown was by Band (1968). Location of these islands relative to Viti Levu is shown in the inset in which the fluted lines represent major reefs.

Kroenke 1984) to 4.00 ± 0.05 Ma (Whelan et al. 1985). Yanuca is 1.5 km^2 in area and reaches just over 100 m in height.

Both Beqa and Yanuca are enclosed within a single barrier reef up to 1.3 km wide, which marks the edge of an undulating platform up to 45 m deep. The islands are subject to southeast tradewinds all year round. Mean annual temperature is 25° C , varying only slightly throughout the year; precipitation ranges from a maximum of 300 cm annually in Beqa's southeast quadrant to around 220 cm on the northwest side (Rajotte and Bigay 1981).

Despite being the closest inhabited islands to Suva (the capital of Fiji), Beqa and Yanuca have received little attention compared to many other, more remote islands of similar size in Fiji.

Some of the earliest interest was shown by those seeking to ascertain the relationship between coral-reef configuration and island tectonics. Contrary to the then-prevailing view that fringing reefs were converted to barrier reefs through volcanic island subsidence, Foye (1918: 81) argued that on Beqa (Mbengha) the evidence did "not warrant the assumption that the island has subsided to any great extent." Davis (1928) disagreed with Foye's views, regarding the evidence for subsidence as plentiful. Davis' argument hinged on a belief in a causal relationship between coastal embayments and island subsidence, which has since been rendered largely academic owing to the recognition that the Holocene transgression drowned all coasts, creating embayments that are not necessarily indicative of subsidence.

A reconnaissance survey of the geology of Beqa (J. M. Romanu, unpublished Fiji Geological Survey Note 86, 1961), which reported emerged notches at Rukua village, paved the way for that of Band (1968), which remains the most detailed geological survey of Beqa and Yanuca to date.

K. Berryman (unpublished New Zealand Geological Survey Report 70, 1979) reported data referring to possible displaced shoreline levels on Beqa that contributed to his seismotectonic zoning of Fiji. Expressed relative to mean sea level, those data are as follows: on Ugaga Island, notch lips and terraces at 1.35 m, 2.85 m, and 6.85 m; at Rukua village, notch lips and terraces at 1.35 m, 6.85 m, and 18.85 m; at Soliyaga (Suliyanga) village, a notch lip at 0.85 m and a terrace at 8.85 m; along the sides of Malumu Bay, terraces at 1.35 m, 2.35 m, and 9.35 m. The highest terraces at Rukua, Soliyaga, and around Malumu Bay were not found during my survey in 1988.

More recent investigations have concentrated on the Beqa lagoon, which is of interest in petroleum exploration (R. A. Eden and R. Smith, unpublished Fiji Mineral Resources Department Note BP34/5, 1984). Metalliferous mineralization associated with the center of the old Beqa volcano has also been investigated recently.

Coastal Types

Most of the coastline of Beqa and Yanuca alternates between coral-sand beaches fringing coastal plains, composed of alluvium, colluvium, and marine-derived materials, and cliffs at the foot of which a narrow beach is often found in association with a well-developed wave-cut platform at low tide level. This basic division of coastal types corresponds to the aggradational and erosional alternation that would be expected along such a comparatively steep, indented coastline. Less common coastal types include barrier beaches with standing water on their landward sides, confined to the northwest-facing shores of Beqa, which receive the waves with the longest fetch in the area, and mangrove-colonized intertidal mud flats around the mouths of large rivers, especially at the heads of Malumu and Vaga bays.

Holocene Coastline Development

Following its early Holocene rise, sea level in most parts of the Southwest Pacific reached its present level between 4500 and 6000 yr B.P. (Thom and Chappell 1975, Marshall and Jacobson 1985, Nunn 1989*a*) and, in many places, including the area with which this paper is concerned, exceeded that level subsequently (Buddemeier et al. 1975, Easton and Ku 1980, Roy, in press). In southern Fiji, sea level reached 1.0–1.6 m above its present level around 3500 years B.P. and has since fallen reasonably uniformly (Shepherd 1988, Sugimura et al. 1988, Nunn 1989*a*). This series of events, combined with the initial settlement of Beqa and Yanuca, probably 3000–2000 years B.P. (earliest settlement date from a Lapita site just off the Viti Levu mainland to the northwest of the Beqa group is 2980 ± 80 yr B.P. [Green 1979]), provides the background to late Holocene coastline development that is described in three stages with approximate dates below.

(1) 10,000–6000/4000 yr B.P.

During the relatively low sea level at the beginning of the Holocene, islands such as Beqa and Yanuca would have had a fortress-like appearance, with steep walls of Pleistocene reef fringing the volcanic core (Gibbons 1984). Sea-level rise in the early Holocene would have occurred on these steep faces, but vertical reef growth would not have begun until sea level exceeded the level of the subaerially reduced surface of the Pleistocene reef.

Sea level rose at an average rate of 3.5 m/1000 yr between 8000 and 4000 yr B.P. (Nunn 1989*a*), and although such rates are known to have been matched by those of vertical reef growth on the mid-Pacific atoll of Tarawa (Marshall and Jacobson 1985), they exceed those from elsewhere in the Pacific (Labeyrie et al. 1969, Tracey and Ladd 1974). In such a situation, it is generally believed that reef growth would have lagged behind sea-level rise (Neumann and MacIntyre 1985, Davies et al. 1985).

On Beqa and Yanuca, this lag may have given rise to a "Holocene high energy window," a period of higher-than-present wave energy that preceded the development of protective reefs (Neumann 1972, Hopley 1984). The effects of the mid-Holocene high-energy window described by Hopley (1984) and others are believed to account most satisfactorily for the contemporary coastal landforms in southern Fiji.

(2) 6000/4000–3000 yr B.P.

This was a time of relative stability of sea level in the area, the first for about 14,000 yr. The principal consequence of this stability was a marked increase in the rate of lateral shoreline erosion, a rate that would have significantly exceeded modern rates for as long as the high-energy window remained open. Extensive shore platforms were cut in places at this time, mostly at low tide level. These shore platforms were backed by wide-mouthed notches, especially along shorelines composed of easily erodible or unstratified rocks, which include the volcaniclastic coasts of Beqa and Yanuca and the limestones of Vatulele Island.

Once the Holocene high-energy window was closed, coastal processes became comparatively subdued. The reefs had reached sea level and had begun to develop reef flats. It is possible that sea level had begun falling from its Holocene high stage before the accreting reef surface reached that level.

(3) 3000–0 yr B.P.

Sea level fell during this period at an average rate of 0.5 m/1000 years (Nunn 1989*a*), a process that exposed the shorelines formed at the higher level. In parts of Fiji, it has been demonstrated that the exposed shore platforms became covered with aeolian deposits and colluvium at this time (Nunn 1988*a*; in press). Subsequent alluviation, soil development, and vegetation colonization transformed these old shorelines on many Pacific islands into comparatively attractive environments for settlement, which may partly explain the rapid settlement of the South Pacific at this time (Schofield 1977, Nunn 1988*b*). Sea-level rise in many parts of this region has been recorded over the last 70–90 yr (P.D. Nunn, unpublished report to the South Pacific Commission, 1989).

Shoreline Formation and Displacement

Emerged shorelines have been used in many parts of the world to make authoritative statements about the past, especially the tectonic and eustatic changes experienced at particular times in particular places. Although the most cogent and precise reconstructions come from emerged aggradational and biogenic shoreline indicators (e.g., Chappell 1983, Taylor et al.

1987), emerged erosional shorelines have been used in many places, especially midocean islands, to infer details of past history (e.g., Stearns 1961, Pirazzoli 1978, Yonekura 1983, Nunn 1984*a*,*b*, 1989*a*). Of particular interest has been the recognition of coseismic uplift that occurs during repeated large-magnitude earthquakes and produces series of regularly spaced emerged shorelines (Taylor et al. 1980, Chappell 1983; Nunn, in press). Compilations of such information have proven to be important to seismotectonic zoning and large-magnitude earthquake prediction in parts of the Pacific (K. Berryman, unpublished New Zealand Geological Survey Report 70, 1979; Nunn 1989*b*).

On tropical limestone coasts, one of the most common types of emerged erosional shoreline indicators used in such reconstructions has been notches, the classification and formation of which were discussed by Pirazzoli (1986). Many volcanic-rock coastlines display sequences of emerged notches that are morphologically similar to those found on limestone coasts. Discussions of the formation and significance of coastal notches cut in volcanic rocks have been few; I have identified only three studies (Emery and Foster 1956, Guilcher et al. 1962, Guilcher and Bodere 1975).

From viewing notches in limestones and volcaniclastics on island coasts in close proximity, I contend that notches in certain volcanic materials have origins similar to those in limestones and can, therefore, where these notches are emerged, be assigned a comparable significance as indicators of tectonic and eustatic history. This is true of Vatulele Island, where four emerged notches cut in limestone have been documented (Ladd 1930, Nunn 1988*a*, in press), and of the nearby Beqa group, which I visited for the first time shortly after having completed fieldwork on Vatulele.

The notches being formed at present on the islands of the Vatulele-Beqa Ridge (Beqa, Vatulele, Yanuca [see Figure 1, inset]) are all the result of marine erosion, primarily solution and bioerosion, which is known to affect certain volcanic rocks in a fashion similar to its effect on limestones (Pirazzoli 1986). The reason for favoring corrosion rather than abrasion as the dominant notch-forming process on Beqa and Yanuca is that the coasts of these islands are presently reef-fringed and characterized by low wave energy except during storm surges. The inside surfaces of the notches are irregular and pitted rather than smooth and polished. Further, with a few exceptions, the mouths of the modern notches do not exceed present tidal range (1 m), as has been observed in abrasion notches. Using Pirazzoli's (1986) classification, I believe the notches of Beqa, Vatulele, and Yanuca to be midlittoral tidal notches that formed in moderately to very sheltered environments; these are the most precise indicators of sea level among the range of erosional shoreline landforms. Numerous field studies (e.g., Hodgkin 1964, Gill 1973, Montaggioni 1979, Kawana and Pirazzoli 1985) have shown that mean sea level corresponds to the retreat (innermost) point of such notches and that the roof and floor levels mark approximate mean high and low tide levels, respectively. These relationships have also been applied to emerged notches to calculate precise magnitudes of emergence by measuring between similar datum levels. Such studies have been useful contributions to an understanding of past sea-level and tectonic changes in many parts of the world, including the Southwest Pacific (e.g., Stoddart 1969, Taylor 1978, K. Berryman [unpublished New Zealand Geological Survey Report 70] 1979, Miyata et al. 1988).

MATERIALS AND METHODS

Collection of Field Data

The clearest evidence for shoreline displacement on Beqa and Yanuca is confined to cliffed coasts and is represented by emerged erosional landforms (Figure 2). Fieldwork involved measuring the elevations and dimensions of indicators of shoreline displacement around the coasts of Beqa and Yanuca. When the high tide level was apparent, indicated by the upper limit of vermetid growth, for example, it was used as the field measurement base; otherwise, sea level at the time of measurement was used. Data relative to both these

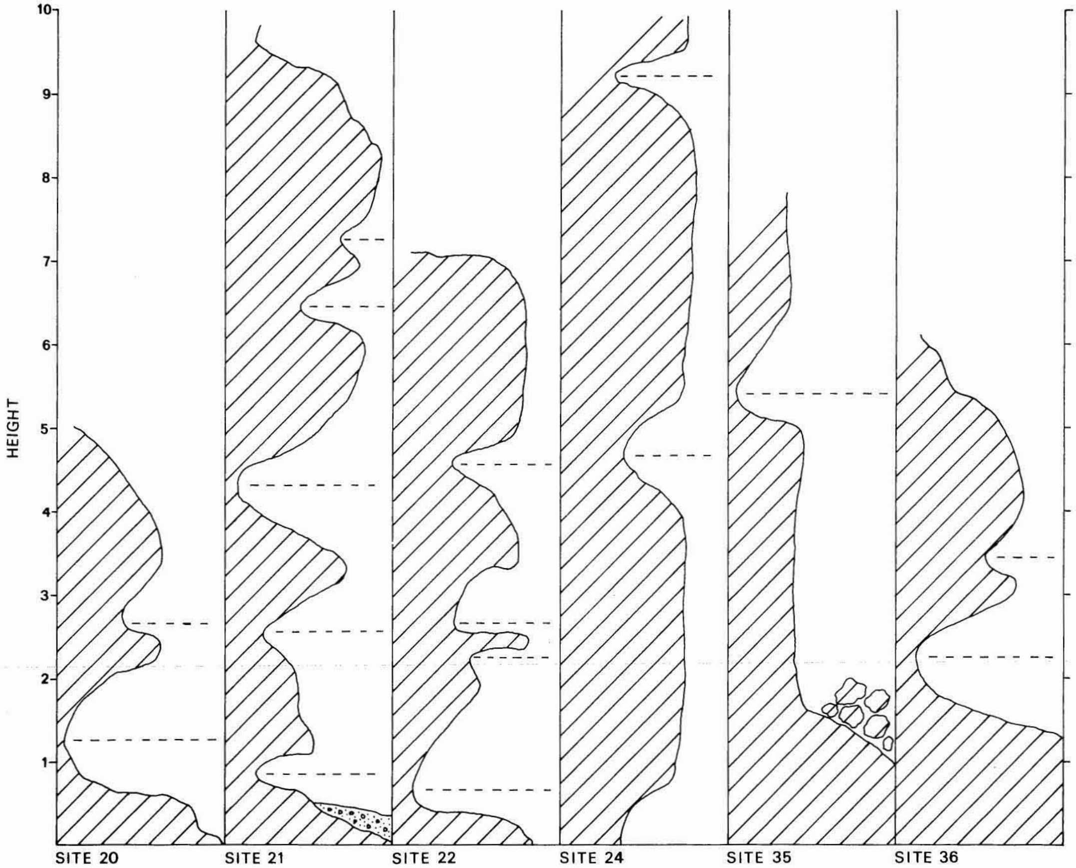

FIGURE 2. Cliff profiles and former mean sea levels (broken lines) to which emerged notches can be related. All elevations are in meters above present mean sea level. Vertical exaggeration is ca. zero.

bases were subsequently calculated relative to present mean sea level (Table 1) using daily tide tables (Anonymous 1988). All data in this paper are expressed relative to mean sea level. Maximum measurement errors for most data are around 0.2 m.

Data referring to shoreline displacement are listed in Table 2 by site number (shown in Figure 1). In Table 2, data in parentheses refer to elevations of features measured. (e.g., notch retreat points, shore platform surfaces); those data not in parentheses refer to the heights of the mean sea level bases represented by the features measured above present mean sea level. The latter data are thus the closest possible approximations of the net change in (mean) sea level represented by the emerged landforms.

TABLE 1

TIDAL LEVELS AT RUKUA VILLAGE, BEQA

TIDAL LEVEL	RELATIVE TO MEAN SEA LEVEL	RELATIVE TO FIJI DATUM*
Mean high water spring	+0.55 m	+1.70 m
Mean high water neap	+0.45 m	+1.60 m
Mean sea level	0.00	+1.15 m
Mean low water neap	−0.45 m	+0.70 m
Mean low water spring	−0.55 m	+0.60 m

NOTE: From Anonymous (1988).
* Lowest Astronomical Tide level at Suva, Fiji.

No absolute ages are available to help date the shorelines of which the notches are part, although altitudinal comparison with the Vatulele sequence does allow some inference to be made about shoreline age in the context of the whole Vatulele-Beqa Ridge (see below). The relative ages of the shorelines cannot be determined with complete certainty although consideration of the likely cause of shoreline uplift suggests, as does the decrease in morphological clarity and continuity with increasing elevation, that shoreline age increases with increasing elevation. The small elevation range and similarity in shoreline elevation interval to dated Pacific coastline sequences elsewhere (e.g., Neef and Veeh 1977, Chappell 1983, Pillans 1983) are also observations that support an increase in age with increasing elevation. In the absence of contrary evidence, I assume this to be the case.

TABLE 2

SHORELINE DISPLACEMENT DATA FROM BEQA AND YANUCA

SITE NUMBER (NAME)	DATA
Beqa	
1	(2.15) 2.15
2 (Rukua)	(1.75) 2.25
3 (Rukua)	(1.75) 1.75; (1.95–2.25) 2.10; (4.35) 4.35
4 (Rukua)	(2.35–2.55) 2.45; (6.00) 6.00
6	(2.45–2.55) 2.50
7	(2.40) 2.40
8	(1.75) 1.75; (2.15) 2.15
9	(6.05) 6.05
10	(1.45) 1.45
11	(5.80–6.10) 5.95
12	(0.95–1.35) 1.15
13	(3.30) 3.30
15	(2.05) 2.05
16 (Moturiki)	(1.65–2.25) 1.95
17	(1.85) 1.85
18	(1.75) 1.75
19	(1.35–1.65) 1.50
20	(1.25) 1.25; (2.65) 2.65
21 (Muaisila)	(0.85) 0.85; (2.55) 2.55; (4.15–4.45) 4.30; (6.45) 6.45; (7.25) 7.25
22 (Bulewatabu)	(0.65) 0.65; (2.25) 2.25; (2.65) 2.65; (4.55) 4.55
23 (Bulewatabu)	(8.10–8.30) 8.20
24	(4.65) 4.65; (9.20) 9.20
25 (Vatuvakawa)	(6.20) 6.20
26	(0.65) 0.65
27	(1.75–1.85) 1.80
28	(1.75–1.85) 1.80; (2.75) 2.75
29 (Tadanibeqa)	(0.95) 0.95
30	(0.65) 0.65; (3.55) 3.55
Yanuca	
31	(2.45) 2.45
32	(1.25) 1.25
33	(2.65) 2.65; (4.55) 4.55
34	(0.95) 0.95
35	(5.40) 5.40
36	(2.25) 2.25; (3.45) 3.45
37	(5.80) 5.80; (6.30) 6.30
38	(2.85) 2.85
40	(2.05) 2.05
41	(2.85) 2.85
43	(5.25) 5.25
44	(3.25) 3.25
Ugaga	
45*	(2.50) 1.85; (4.00) 3.35; (8.00) 7.35

NOTE: Field sites are shown in Figure 1. Data in parentheses are original data relative to mean sea level; data not in parentheses are the differences between present mean sea level and the mean sea level at which the displaced shoreline was formed. The latter data are those used in data analysis.

* Ugaga data from K. Berryman (unpublished New Zealand Geological Survey Report 70, 1979).

RESULTS AND INTERPRETATION

Histograms (Figure 3) were constructed using half tide (0.5 m) as interval width for all data, which were subsequently divided into those from eastern Beqa (sites 18–25), western Beqa (sites 1–17 and 26–30) including Ugaga Island (site 45), and Yanuca (sites 31–44). Beqa is divided along the line of the Malumu Bay fault (Figure 1). Analysis proceeded on the assumption that the five emerged notches at Muaisila (site 21) represent discrete shorelines (MUA1 to MUA5 from lowest to highest) that find expression elsewhere in the area.

Although analysis of the relative levels of shoreline groups across the area does allow statements about relative tectonics to be made, the question as to how the whole area has been displaced relative to the modern shoreline is more difficult to resolve. Although the Muaisila (site 21) sequence includes five emerged shorelines, each of which is represented elsewhere, albeit at slightly different levels, there is another shoreline, which is clearly represented at sites 3, 8, and 22 (at levels of 1.75 m, 1.75 m, and 2.25 m, respectively) yet is not visible at Muaisila. Because this shoreline (BUL1 after Bulewatabu [site 22]) exhibits the same amount of displacement between eastern and western Beqa (0.5 m) calculated for the other emerged shorelines, it is considered to be a discrete entity.

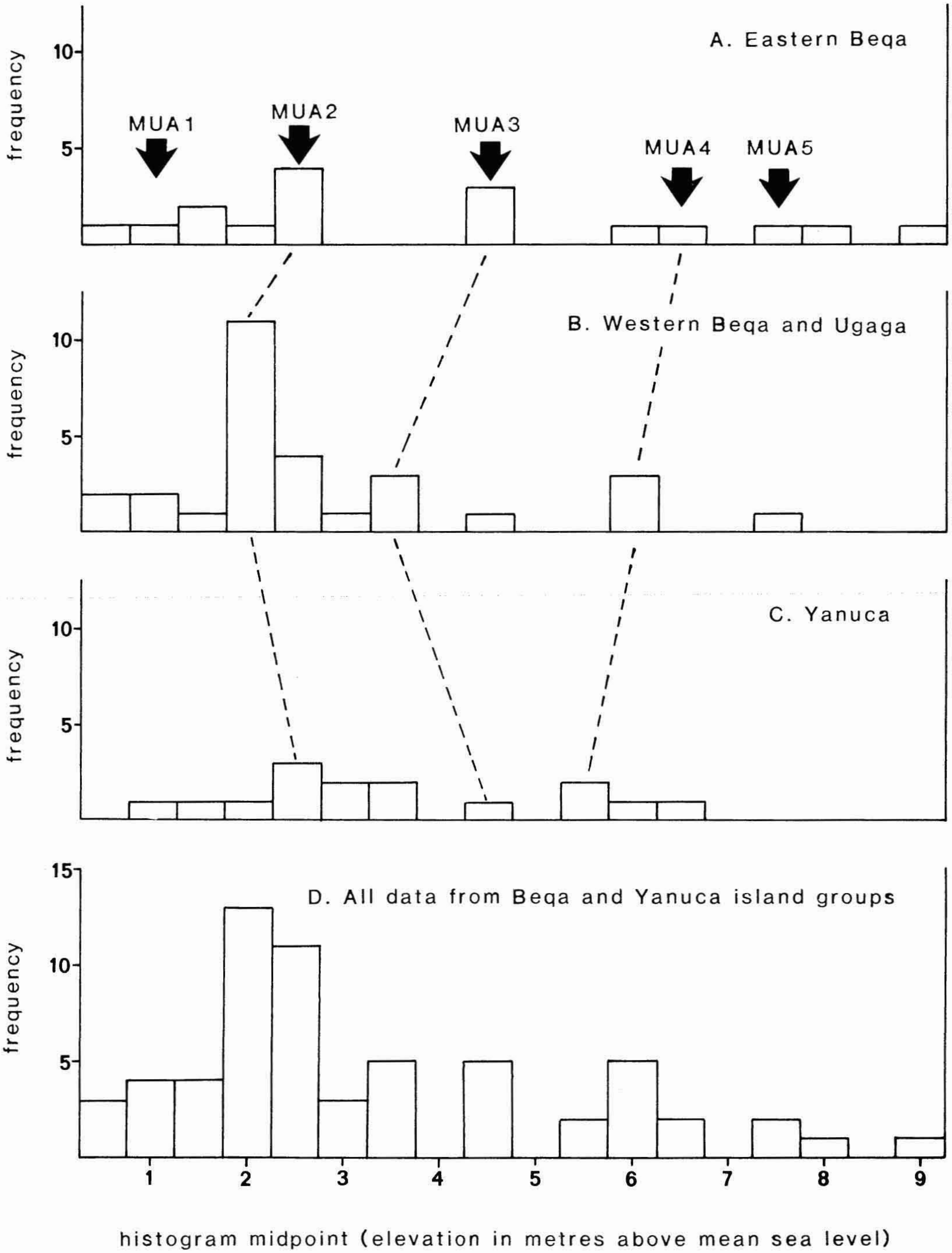

FIGURE 3. Histograms of shoreline displacement data. Shorelines MUA1 to MUA5 are traced graphically through the constituent groups; owing to the histogram intervals used, shoreline BUL1 is not distinguishable in this figure.

TABLE 3

SUMMARY OF DATA ANALYSIS ON SHORELINE GROUPS

SHORELINE NAME	MEAN SHORELINE LEVEL (NUMBER OF DATA)				
	EASTERN BEQA	WESTERN BEQA	YANUCA	WHOLE AREA*	VATULELE†
MUA1	0.92(3)	0.85(4)	1.10(2)	0.96(9)	0.70(2)
BUL1	1.83(3)	1.81(9)	2.15(2)	1.93(14)	2.20(29)
MUA2	2.62(3)	2.34(8)	2.92(6)	2.63(17)	—
MUA3	4.50(3)	3.64(4)	4.55(1)	4.23(8)	4.06(15)
MUA4	6.33(2)	6.00(3)	5.48(3)	5.94(8)	6.20(4)
MUA5	8.22(3)	7.35(1)	6.30(1)‡	7.79(4)	7.85(3)

NOTE: All data are in meters relative to present mean sea level.

* This refers to the Beqa and Yanuca group only.

† Data given for comparative purposes, from Nunn (1988*a*).

‡ Considered a rogue measurement because of local faulting at site 37, this is not used in calculation of MUA5 group mean.

TABLE 4

INTERVALS BETWEEN MEAN SEA LEVELS REPRESENTED BY DISPLACED SHORELINES

SHORELINE PAIR	INTERVALS				
	EASTERN BEQA	WESTERN BEQA	YANUCA	WHOLE AREA*	VATULELE†
MUA1/BUL1	0.91	0.96	1.05	0.97	1.50
BUL1/MUA2	0.79	0.53	0.77	0.70	—
MUA2/MUA3	1.88	1.30	1.63	1.60	1.86§
MUA3/MUA4	1.83	2.36	0.93	1.71	2.14
MUA4/MUA5	1.89	1.35	0.82‡	1.62	1.65

NOTE: All data are in meters. Note that no interval is less than the maximum measurement errors of 0.5 m for higher notches and 0.2 m for the rest, which implies that the identification of the six shorelines is valid.

* This refers to the Beqa and Yanuca group only.

† Data given for comparative purposes, from Nunn (1988*a*).

‡ The MUA5 value here is not considered reliable (see Table 3) and is not used in the calculation of the value in column 5.

§ Actually the figure between BUL1 and MUA3; MUA2 is absent on Vatulele.

Six emerged shorelines are therefore recognized in the area, the type site for five (MUA1–MUA5) is at Muaisila (site 21), and that for the other (BUL1) is at nearby Bulewatabu (site 22). Because it is not certain what the actual direction of displacement has been in the area, the mean elevations of emerged shorelines in each group are used to classify the shoreline. The data analysis involved is summarized in Table 3, where values from Vatulele Island are also shown. The correspondence between mean (whole area) values from the Beqa and Yanuca group and those from Vatulele is remarkable and has implications for the tectonic history of the Vatulele-Beqa Ridge.

Some confirmation of the identification of these six shoreline groups can be gained by calculation of the intervals between them in different places. As shown in Table 4, the intervals between the mean sea levels represented by the six shorelines never fall below the maximum measurement errors and are similar from place to place within the Beqa and Yanuca group. Similarity to the intervals between the Vatulele shorelines is also apparent. Were the shorelines not continuous throughout the area, discrepancies would be

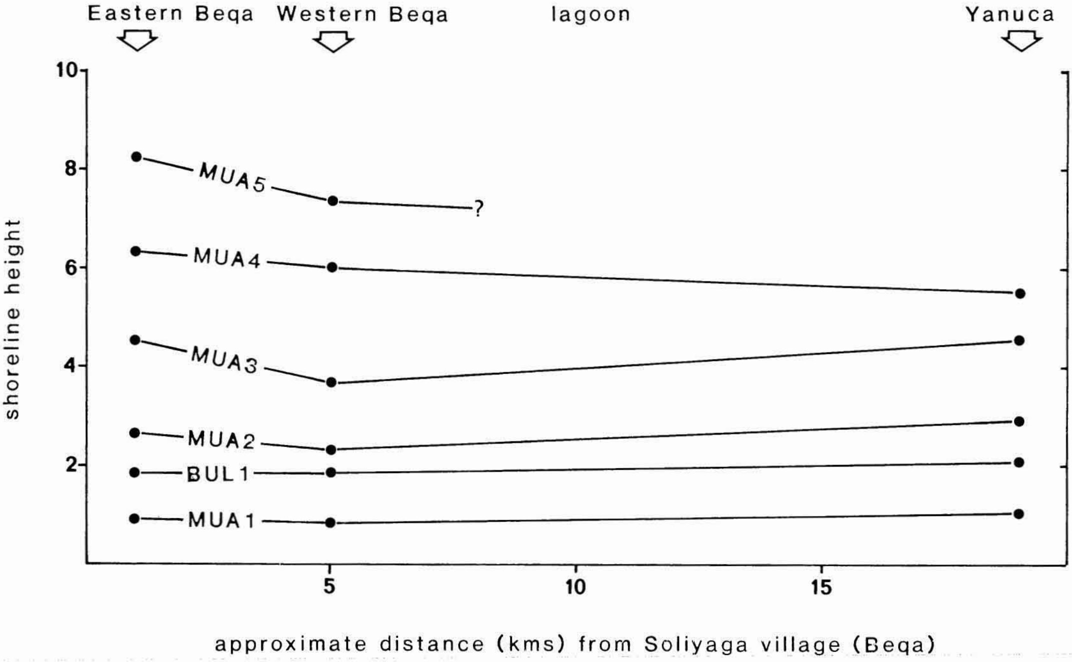

FIGURE 4. Comparative average levels of shorelines in the Beqa and Yanuca group in meters above mean sea level; vertical exaggeration is × 1000.

expected both in the intervals between individual shorelines in particular places and in the vertical sequence of intervals across the area.

The relative levels of shorelines in the Beqa-Yanuca area are depicted graphically in Figure 4 using data from Table 3. It is clear from this diagram that relative downfaulting to the west has occurred along the Malumu Bay fault since the formation of at least the three lower shorelines (MUA1–MUA3).

The other important observation is that shorelines MUA1–MUA3 are lower in western Beqa than on Yanuca, and this may also be the result of downfaulting. It is therefore concluded that that part of the Vatulele-Beqa Ridge occupied by the main part of Beqa (west Beqa) has been displaced downward relative to parts to the east and west by an average of 0.41 m (MUA1–MUA3 only), ranging from 0.02 m for BUL1 between eastern and western Beqa to 0.91 m for MUA3 between Yanuca and western Beqa.

The amount of displacement between vertically adjacent shorelines (MUA1–MUA3 only) increases uniformly with increasing elevation between Yanuca and western Beqa; this relationship is also manifest along the Malumu Bay fault between eastern and western Beqa (Figure 5). Such relationships mean that displacement between these areas did not occur in a single event, which would have caused all shorelines to have been displaced an equal amount, but was continuous or occurred in a series of discrete events from the time of the relative emergence of MUA3 until at least the time of that of MUA1. This conclusion, which assumes that shoreline age increases with increasing elevation, has important implications for the understanding of the tectonic history of the area.

The relative levels of shorelines from islands along the whole Vatulele-Beqa Ridge have been plotted (Figure 6); the data used are listed in Table 3. The absence of a displacement of consistent direction between Vatulele and Yanuca, and indeed between Vatulele and the whole area mean (Table 3), suggests that the Vatulele-Yanuca ridge segment has remained undeformed relative to present sea level since

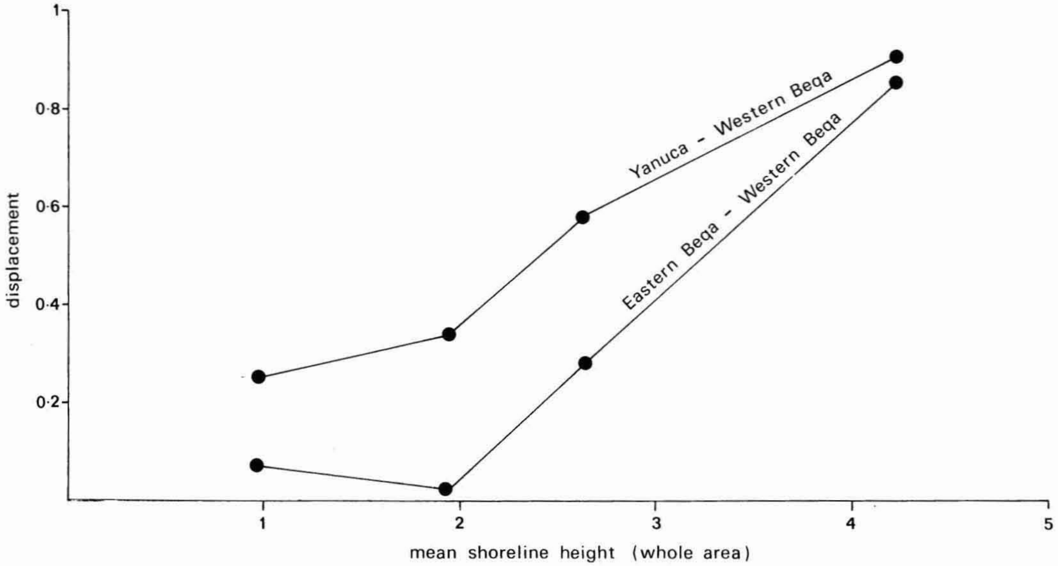

FIGURE 5. Variation in the amount of displacement of shorelines MUA1–MUA3 in the Beqa and Yanuca group.

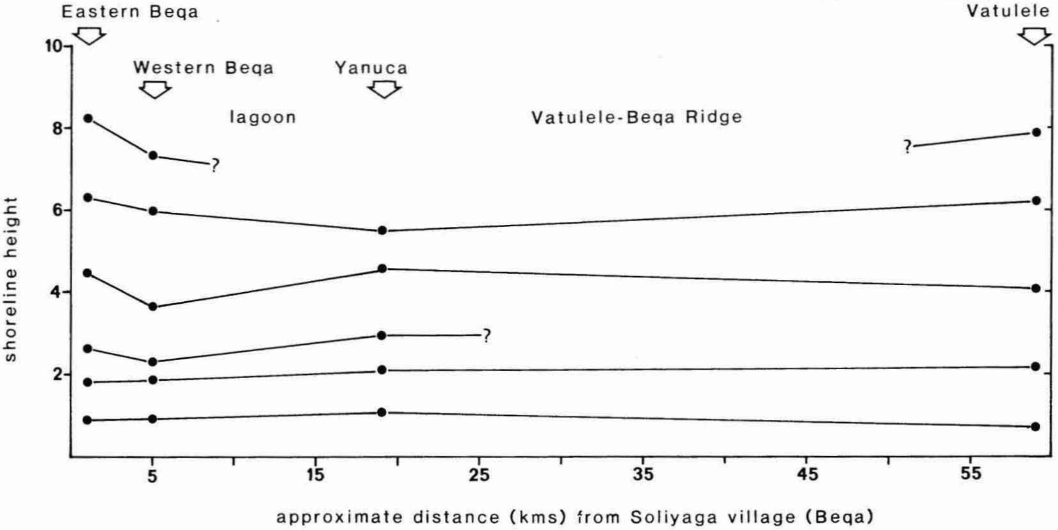

FIGURE 6. Relative levels of shorelines along the Vatulele-Beqa Ridge; additional information from Nunn (1988*a*). Vertical exaggeration is × 2500.

the time of formation of the oldest shoreline. This conclusion agrees with that of Nunn (1988*a*; in press), who argued, contrary to the views of many earlier writers, that Vatulele had not been tilted eastward. However, Nunn found that Vatulele Island was divisible into a number of fault-bounded blocks that had been downfaulted in a broadly eastward direction. This observation suggests, as does the regional bathymetry, that the area between Yanuca and Vatulele may be relatively downfaulted. If this is so, then the close correspon-

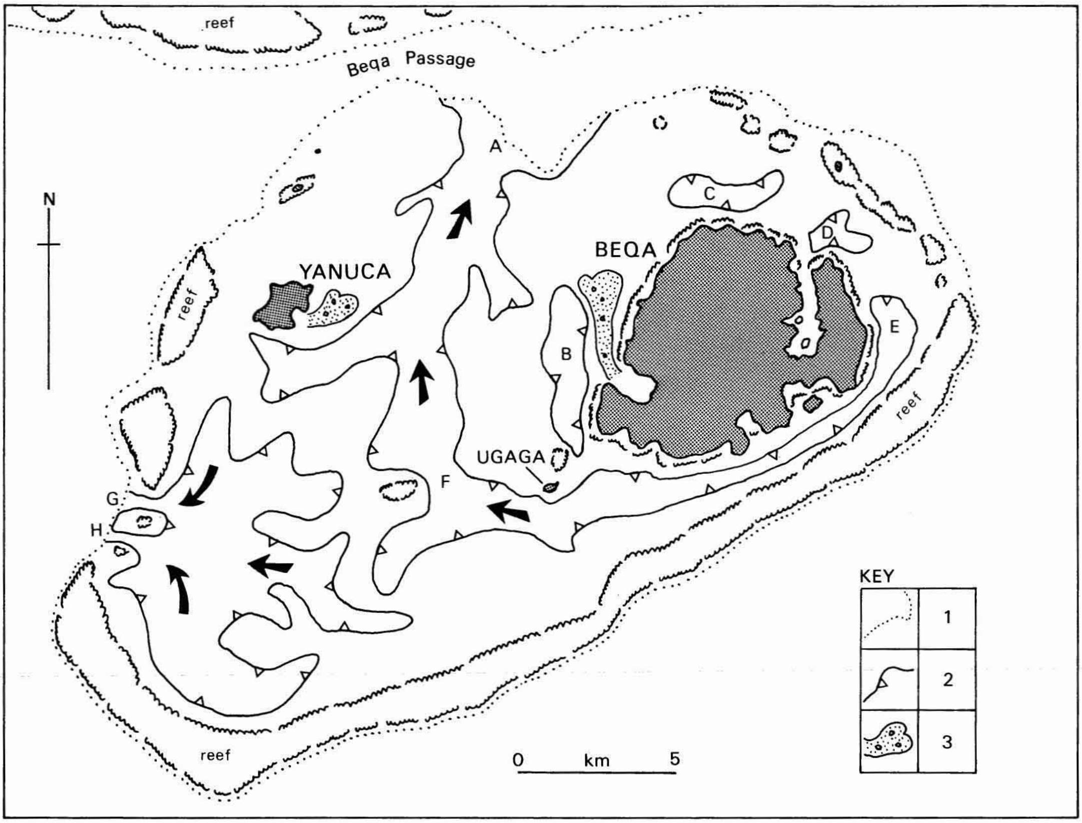

FIGURE 7. Submarine geomorphology of the floor of the Beqa lagoon. Key: 1, 180-m isobath marking the edge of the Beqa-Yanuca island platform and that surrounding Viti Levu to the north; 2, 30-m isobath, believed to coincide with a slope break, defining paleodrainage or scour channels and enclosed depressions; 3, major areas of bedded sediment, possibly terrigenous. Bathymetry constructed from soundings shown on admiralty chart 167; sediment pattern interpreted from seismic line data reported by R. A. Eden and R. Smith (unpublished Fiji Mineral Resources Department Note BP34/5, 1984). Large arrows indicate channel slope direction.

dence between emerged shoreline elevations on (western) Vatulele, Yanuca, and eastern Beqa (Table 3) can be explained only by supposing that they are the sole in situ remnants of an original Vatulele-Beqa Ridge surface. Those parts of the Vatulele-Beqa Ridge in western Beqa and between Yanuca and Vatulele are therefore explained as grabens trending normal to the ridge axis within which sections of the ridge have been downfaulted.

The outlines of the geomorphology of the floor of the Beqa lagoon (Figure 7) are of considerable relevance to questions about the structure of this part of the Vatulele-Beqa Ridge. Two major paleodrainage systems can be clearly identified. The first and largest comprises a north-south trough (AF) in its lower reaches; the other is confined to the southwest of the platform, from which it exits at points G and H. In addition to these channels, there are several enclosed depressions, one off Beqa's west coast (B) and two off the north coast (C and D). The western border of depression B was mapped as a 20-m scarp by R. A. Eden and R. Smith (unpublished Fiji Mineral Resources Department Note BP34/5, 1984) with a vertical flexure of similar amplitude just to its west. Depression B's eastern border is well marked in the sounding data, and its clarity despite the sediment lobe emanating from Vaga Bay suggests that a similar scarp may exist here.

The western side of channel AF and the eastern border of depression B are both aligned with prominent changes in the aerial form of the reef that fringes the southern side of the island platform (Figure 7). This observation, combined with those about the nature of channel AF and depression B described above, suggests that these features are grabens, trending parallel to Malumu Bay, which account satisfactorily for the variation in shoreline levels between western Beqa and Yanuca.

Tectonic History of the Vatulele-Beqa Ridge

A series of north-south faults, some forming grabens, occurs between eastern Beqa and Yanuca. Similarly aligned faults account for the apparent eastward tilt of Vatulele (Nunn 1988*a*; in press) and probably also for the relative downfaulting of that section of the Vatulele-Beqa Ridge between Yanuca and Vatulele. A diagrammatic representation of the pattern of faulting along the whole Vatulele-Beqa Ridge is shown in Figure 8.

The Vatulele-Beqa Ridge is believed to be an abandoned island arc, linked to approximately northward subduction during the late Tertiary (Nunn 1989*b*). The parallelism between the axial trend of this arc and the ridges and basins of the Kadavu Trench complex to the south (Figure 9) suggests that volcanism on Vatulele, Beqa, and Yanuca occurred as the result of proximal subduction along an ancestral Kadavu Trench, possibly one located farther north than the present one.

Although the nature of modern activity along the Kadavu Trench is not agreed upon, it is clear that it accommodated plate convergence throughout most of the Quaternary and probably also during the late Tertiary (Malahoff et al. 1982, Gill et al. 1984, Hamburger 1986). Late Miocene uplift of the predominantly limestone island of Vatulele was proposed by Nunn (1988*a*; in press) to be the result of initial underplating along the Kadavu Trench, and this would most likely have affected the whole Vatulele-Beqa Ridge. Subsequent abandonment of this island arc, perhaps the result of southward migration of the Kadavu Trench, would have been accompanied by lithospheric cooling that would have led to contraction and rifting. I believe these processes to have been responsible for the development of the cross-ridge faults and grabens on the Vatulele-Beqa Ridge described above.

Nunn (1988*a*; in press) argued that Pleistocene uplift of Vatulele Island caused the emergence of at least three shorelines and was either related to compression of the area between the Kadavu Trench (Hunter Fracture Zone of earlier writers) and the Fiji Fracture Zone (north of Viti Levu) or was the consequence of renewed subduction along the Kadavu Trench, which was associated with underplating and thermal uplift. Either explanation, additional evidence for each of which was discussed by Nunn (1988*a*; in press), is equally tenable for shorelines in the Beqa and Yanuca group.

Mainly on account of its continuity, the 2.20-m shoreline on Vatulele, which is believed to be coeval with shoreline BUL1 on Beqa and Yanuca (Table 3), was considered by Nunn (1988*a*: in press) to have been the last Interglacial shoreline, the relative emergence of which was due solely to the net sea-level fall since that time. This conclusion is also transferable to shoreline BUL1 on Beqa and Yanuca although there, unlike on most of Vatulele, it has been disrupted by faulting since its emergence.

The lowest shoreline on Vatulele, equivalent to shoreline MUA1 on Beqa and Yanuca, was dated to 1375 ± 65 yr B.P. (Matsushima et al. 1984) and was interpreted as the product of a late Holocene high sea level. If its age is assumed to be transferable from Vatulele to Beqa and Yanuca, then I conclude that, although sea level has fallen a minimum of 0.96 m since that time, displacement along faults of 0.07 m and 0.25 m has occurred between eastern and western Beqa and between western Beqa and Yanuca, respectively, since that time. This suggests that the north-south faults along at least the eastern part of the Vatulele-Beqa Ridge are still active, a conclusion also suggested by the pattern of historical seismicity (Houtz 1962, I. B. Everingham 1983; unpublished Fiji Mineral Resources Department Note BP33/8, 1984).

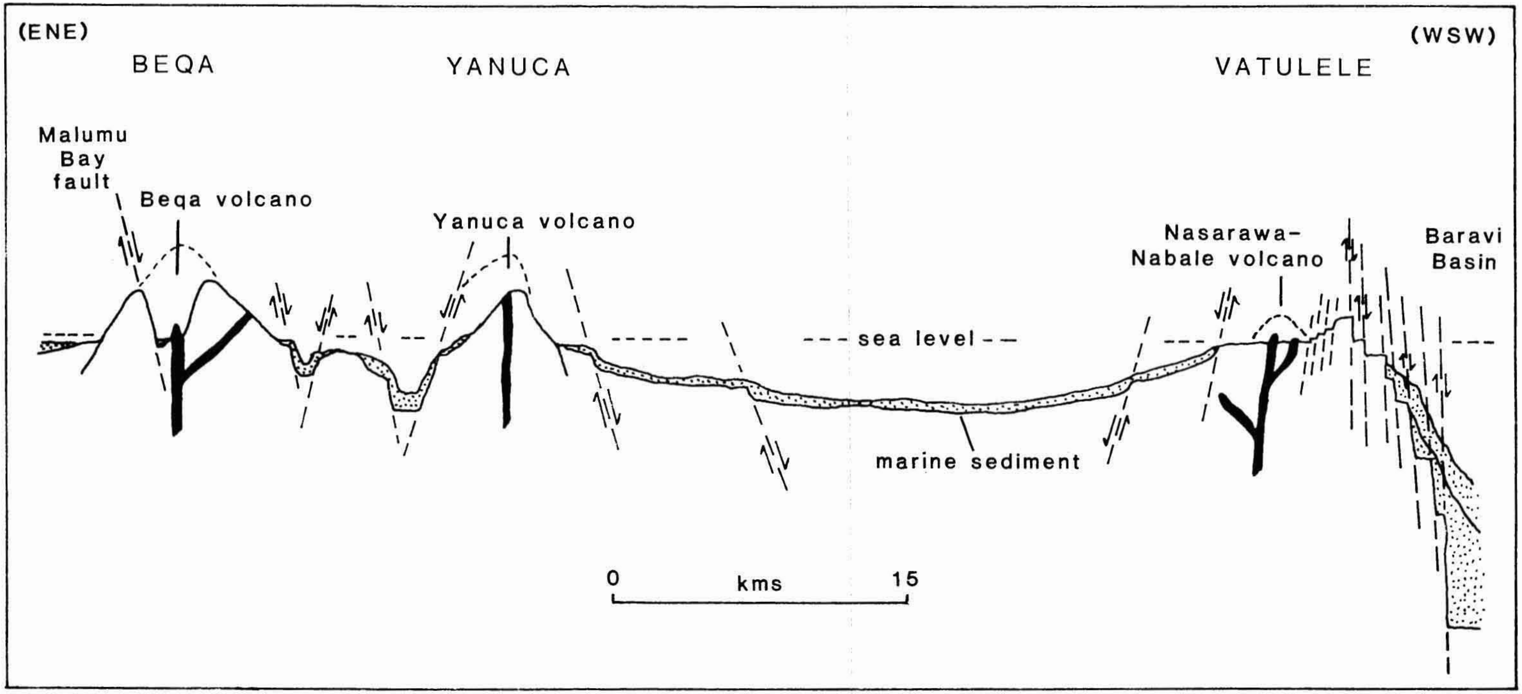

FIGURE 8. Diagrammatic structural interpretation of the Vatulele-Beqa Ridge (not to scale). Additional structural information from Larue et al. (1980) and R. A. Eden and R. Smith (unpublished Fiji Mineral Resources Department Note BP34/5, 1984).

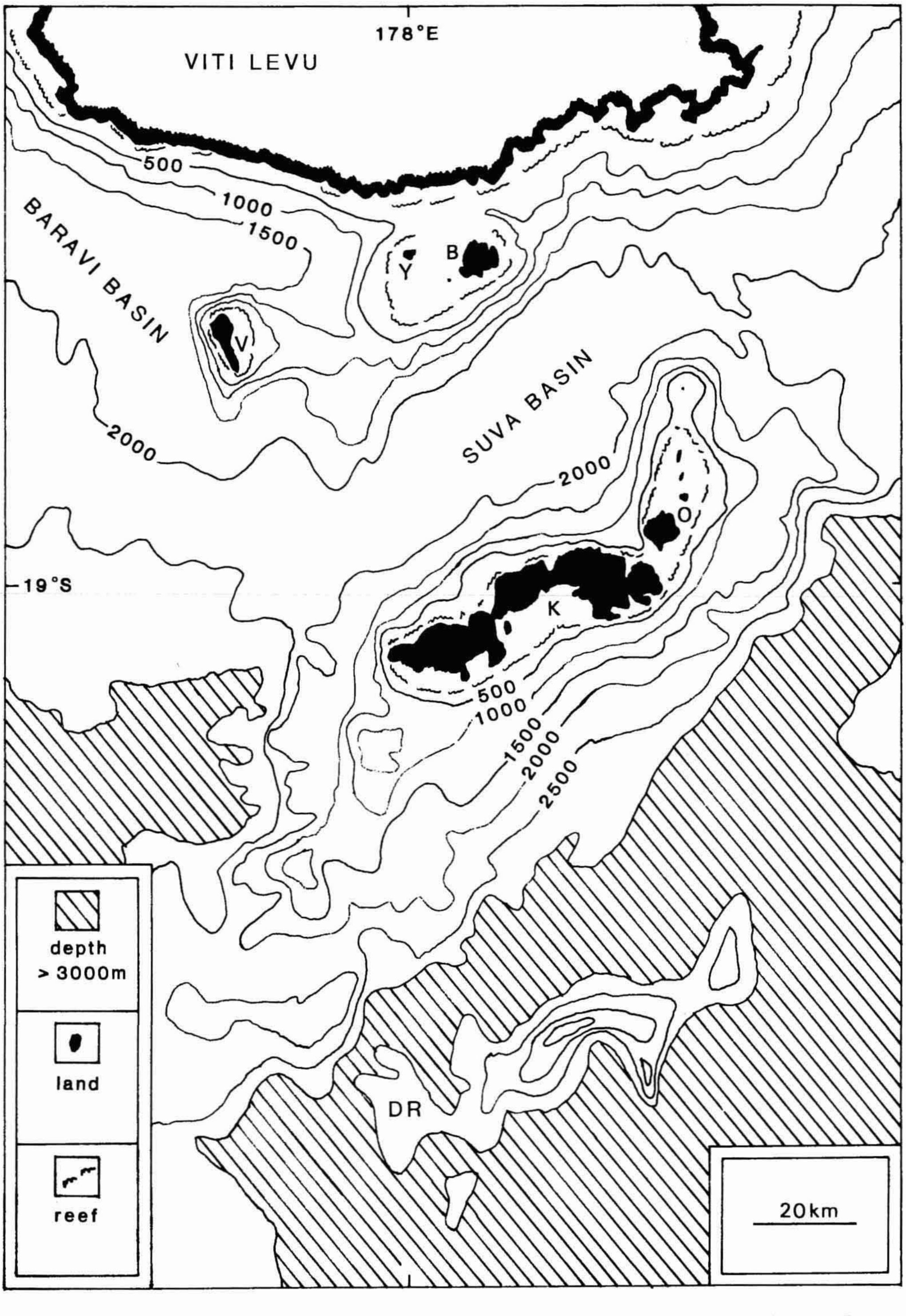

FIGURE 9. Bathymetry of the South Fiji region (after Smith and Raicebe 1984). Abbreviations: B, Beqa; DR, Denham Ridge; K, Kadavu; O, Ono; V, Vatulele; Y, Yanuca.

Although the outlines of the present geotectonic character of the Southwest Pacific and its Cenozoic development are fairly widely agreed upon, much remains unknown or disputed locally. In the last two decades, increasing interest has been shown by resource exploration companies and international cooperative agencies in the geological history of the region, but their activities have been hampered by the difficulties involved in applying the regional geotectonic framework to local situations. More exchange of information between land-based and marine geologists is needed in the region, but, most especially, more attention must be given to the small islands (Nunn 1987*a*, 1988*c*).

The use of geomorphological information, in this case the levels of displaced shoreline indicators, to aid the understanding of local tectonic history is underused, but clearly has great potential, as some other studies in the Southwest Pacific have also shown (e.g., Taylor 1987, Nunn 1987*b*). It is hoped that this trend will continue.

ACKNOWLEDGMENTS

The hospitality of the *mataqali ko Tonobo* is gratefully appreciated; field assistance from Setareki Delana and Tevita Moce was invaluable.

LITERATURE CITED

ANONYMOUS. 1988. Nautical almanac 1988. Fiji Marine Department, Suva, Fiji.

BAND, R. B. 1968. The geology of southern Viti Levu and Mbengga. Fiji Geol. Surv. Dep. Bull. 15.

BROCHER, T. M., and R. HOLMES. 1985. The marine geology of sedimentary basins south of Viti Levu, Fiji. Pages 122–137 *in* T. M. Brocher, ed. Geological investigations of the Northern Melanesian Borderland. Circum-Pacific Council for Energy and Mineral Resources, Tulsa, Oklahoma.

BUDDEMEIER, R. W., S. T. SMITH, and R. A. KINZIE. 1975. Holocene windward reef-flat history, Enewetak Atoll. Geol. Soc. Am. Bull. 86:1881–1884.

CHAPPELL, J. 1983. A revised sea-level record for the last 300,000 years from Papua New Guinea. Search 14:99–101.

DAVIES, P. J., J. F. MARSHALL, and D. HOPLEY. 1985. Relationships between reef growth and sea level in the Great Barrier Reef. Proc. 5th Int. Coral Reef Cong. 3:95–103.

DAVIS, W. M. 1928. The coral reef problem. American Geographical Society, Special Publication 9.

EASTON, W. H., and T. L. KU, 1980. Holocene sea-level changes in Palau, West Caroline Islands. Quat. Res. (N.Y.) 14:199–209.

EMERY, K. O., and H. L. FOSTER. 1956. Shoreline nips in tuff at Matsushima, Japan. Am. J. Sci. 254:380–385.

EVERINGHAM, I. B. 1983. Reports of earthquakes felt in Fiji, 1850–1940. Fiji Miner. Resour. Dep. Rep. 48.

FOYE, W. G. 1918. Geological observations in Fiji. Proc. Am. Acad. Arts Sci. 54. 145 pp.

GIBBONS, J. 1984. A brief environmental history of Fiji. I: The situation before human habitation. Domodomo (Fiji Mus. Q.) 2: 23–33.

GILL, E. D. 1973. Rate and mode of retrogradation on rocky coasts in Victoria, Australia, and their relationship to sea-level changes. Boreas 2:143–171.

GILL, J. B., A. L. STORK, and P. M. WHELAN. 1984. Volcanism accompanying back-arc basin development in the southwest Pacific. Tectonophysics 102:207–224.

GREEN, R. C. 1979. Lapita. Pages 27–60 *in* J. D. Jennings, ed. The prehistory of Polynesia. Australian National University Press, Canberra.

GUILCHER, A., and J. C. BODERE. 1975. Formes de corrosion littorale dans les roches volcaniques aux moyennes et hautes latitudes dans l'Atlantique. Bull. Asso. Geogr. Fr. 426:179–185.

GUILCHER, A., L. BERTHOIS, and R. BATTISTINI. 1962. Formes de corrosion litorale dans les roches volcaniques, particulièrement à Madagascar et au Cap-Vert (Sénégal). Cah. Oceanogr. 14:208–240.

HAMBURGER, M. W. 1986. Seismicity of the

Fiji Islands. Ph.D. diss., Cornell University, Ithaca, New York.

HODGKIN, E. P. 1964. Rate of erosion of intertidal limestone. Z. Geomorphol. NF 8: 385–392.

HOPLEY, D. 1984. The Holocene "high energy window" on the central Great Barrier Reef. Pages 135–150 *in* B. G. Thom, ed. Coastal geomorphology in Australia. Academic Press, London.

HOUTZ, R. E. 1962. The 1953 Suva earthquake and tsunami. Bull. Seismol. Soc. Am. 52:1–12.

KAWANA, T., and P. A. PIRAZZOLI. 1985. Holocene coastline changes and seismic uplift in Okinawa Island, the Ryukyus, Japan. Z. Geomorphol. Suppl. 57:11–31.

KROENKE, L. W. 1984. Cenozoic tectonic development of the southwest Pacific. U. N. ESCAP, CCOP/SOPAC Tech. Bull. 6. 126 pp.

LABEYRIE, J., C. LALOU, and G. DELIBRIAS. 1969. Etude des transgressions marines sur l'atoll de Mururoa par la datation des differents niveaux de corail. Cah. Pac. 3:59–68.

LADD, H. S. 1930. Vatu Lele, an elevated submarine bank. Am. J. Sci. 5:435–450.

LARUE, B. M., J. Y. COLLOT, and A. MALAHOFF. 1980. A sedimentary structure southwest of Viti Levu, Fiji: The Baravi Basin. U. N. ESCAP, CCOP/SOPAC Tech. Bull. 3:77–83.

MALAHOFF, A., R. H. FEDEN, and H. F. FLEMING. 1982. Magnetic anomalies and tectonic fabric of marginal basins north of New Zealand. J. Geophys. Res. 87(B5): 4109–4125.

MARSHALL, J. F., and G. JACOBSON. 1985. Holocene growth of a mid-Pacific atoll: Tarawa, Kiribati. Coral Reefs 4:11–17.

MATSUSHIMA, Y., A. SUGIMURA, K. BERRYMAN, T. ISHII, Y. MAEDA, E. MATSUMOTO, and N. YONEKURA. 1984. Holocene sea-level changes in Fiji and Western Samoa. Pages 137–185 *in* A. Sugimura, ed. Sea-level changes and tectonics in the middle Pacific: Report of the HIPAC Project in 1981, 1982 and 1983. Kobe University, Japan.

MIYATA, T., Y. MAEDA, E. MATSUMOTO, Y. MATSUSHIMA, P. RODDA, and A. SUGIMURA. 1988. Emerged notches and microatolls on Vanua Levu, Fiji. Pages 67–76 *in* N. Yonekura, ed. Sea-level changes and tectonics in the middle Pacific: Report of the HIPAC Project in 1986 and 1987. Tokyo University, Japan.

MONTAGGIONI, L. F. 1979. Le probleme de l'absence de hauts stationnements marins d'age holocene dans l'archipel des Mascareignes, Ocean Indien occidental. C. R. Acad. Sci. Ser. D 288:1591–1594.

NEEF, G., and H. H. VEEH. 1977. Uranium series ages and late Quaternary uplift in the New Hebrides. Nature (London) 269:682–683.

NEUMANN, A. C. 1972. Quaternary sea level history of Bermuda and the Bahamas. Pages 41–44 *in* American Quaternary Association, Second National Conference, Abstracts.

NEUMANN, A. C., and I. MACINTYRE. 1985. Reef response to sea level rise: Keep-up, catch-up or give-up. Proc. 5th Int. Coral Reef Cong. 3:105–110.

NUNN, P. D. 1984*a*. Occurrence and ages of low-level platforms and associated deposits on South Atlantic coasts: Appraisal of evidence for regional Holocene high sea level. Prog. Phys. Geogr. 8:32–60.

———. 1984*b*. Review of evidence for late Tertiary shorelines occurring on South Atlantic coasts. Earth-Sci. Rev. 20:185–210.

———. 1987*a*. Small islands and geomorphology: Review and prospect in the context of historical geomorphology. Trans. Inst. Br. Geogr. 12:227–239.

———. 1987*b*. Late Cenozoic tectonic history of Lau Ridge, Southwest Pacific, and associated shoreline displacements: Review and analysis. N. Z. J. Geol. Geophy. 30:241–260.

———. 1988*a*. Studies in the tectonics and structure of southern Fiji. University of the South Pacific, School of Social and Economic Development, Working Paper 10. 54 pp.

———. 1988*b*. Recent environmental changes along Southwest Pacific coasts and the prehistory of Oceania: Developments of the work of the late John Gibbons. J. Pac. Stud. 14:42–58.

———. 1988*c*. Plate boundary tectonics and oceanic island geomorphology. Z. Geomorphol. Suppl. 69:39–53.

———. 1989*a*. Sealevel changes during the last 6000 years in Fiji, Tonga and Western Samoa: Implications for future coastline development. U. N. ESCAP, CCOP/SOPAC Tech. Bull. 7.

———. 1989*b*. Tectonic environments of Fiji. U. N. ESCAP, CCOP/SOPAC Tech. Bull. 7.

———. (in press). Vatulele: A study in the geomorphological development of a Fiji island. Fiji Miner. Resour. Dep. Mem. 2. 99 pp.

PILLANS, B. J. 1983. Upper Quaternary marine terrace chronology and deformation, South Taranaki, New Zealand. Geology 11:292–297.

PIRAZZOLI, P. A. 1987. High stands of Holocene sea levels in the northwest Pacific. Quat. Res. (N.Y.) 10:1–29.

———. 1986. Marine notches. Pages 361–400 *in* O. van der Plassche, ed. Sea-level research: A manual for the collection and evaluation of data. Geo Books, Norwich, U.K.

RAJOTTE, F., and J. BIGAY, eds. 1981. Beqa—island of firewalkers. Institute of Pacific Studies, University of the South Pacific, Suva, Fiji.

ROY, P. S. (in press). The morphology and surface geology of the islands of Tongatapu and Vava'u, Kingdom of Tonga. U. N. ESCAP, CCOP/SOPAC Tech. Rep. 62.

SCHOFIELD, J. C. 1977. Effect of late Holocene sea-level fall on atoll development. N. Z. J. Geol. Geophys. 20:531–536.

SHEPHERD, M. J. 1988. The higher-energy coasts of southern Viti Levu, Fiji, with particular reference to the geomorphology of the Deuba coast. J. Pac. Stud. 14:1–19.

SMITH, R., and T. RAICEBE, comps. 1984. Bathymetric map of Fiji. Mineral Resources Department, Suva, Fiji.

STEARNS, H. T. 1961. Eustatic shorelines on Pacific islands. Z. Geomorphol. Suppl. 3: 3–16.

STODDART, D. R. 1969. Geomorphology of Marovo elevated barrier reef, New Georgia. Philos. Trans. R. Soc. London, Ser. B 355:199–218.

SUGIMURA, A., Y. MAEDA, Y. MATSUSHIMA, P. RODDA, and E. MATSUMOTO. 1988. Lobau lowland, Viti Levu, Fiji. Pages 59–65 in N. Yonekura, ed. Sea-level changes and tectonics in the middle Pacific: Report of the HIPAC Project in 1986 and 1987. Tokyo University, Japan.

TAYLOR, F. W. 1978. Quaternary tectonic and sea-level history, Tonga and Fiji, southwest Pacific. Ph.D. diss., Cornell University, Ithaca, New York.

TAYLOR, F. W., C. FROHLICH, J. LECOLLE, and M. STRECKER. 1987. Analysis of partially emerged corals and reef terraces in the central Vanuatu arc: Comparison of contemporary coseismic and nonseismic with Quaternary vertical movements. J. Geophys. Res. 92:4905–4933.

TAYLOR, F. W., B. L. ISACKS, C. JOUANNIC, A. L. BLOOM, and J. DUBOIS. 1980. Coseismic and Quaternary vertical tectonic movements, Santo and Malekula islands, central New Hebrides island arc. J. Geophys. Res. 85:5367–5381.

THOM, B. G., and J. CHAPPELL. 1975. Holocene sea levels relative to Australia. Search 6:90–93.

TRACEY, J. I., and H. S. LADD. 1974. Quaternary history of Eniwetok and Bikini atolls, Marshall Islands. Proc. 2nd Int. Coral Reef Symp. 2:537–550.

WHELAN, P. W., J. B. GILL, E. KOLLMAN, R. DUNCAN, and R. DRAKE. 1985. Radiometric dating of magmatic stages in Fiji. Pages 415–440 *in* D. W. Scholl and T. L. Vallier, eds. Geology and offshore resources of Pacific Island arcs—Tonga Region. American Association of Petroleum Geologists, Special Report 2.

YONEKURA, N. 1983. Late Quaternary vertical crustal movements in and around the Pacific as deduced from former shoreline data. Pages 41–50 *in* Geodynamics of the Western Pacific—Indonesian Region. American Geophysical Union, Geodynamics Series 11.