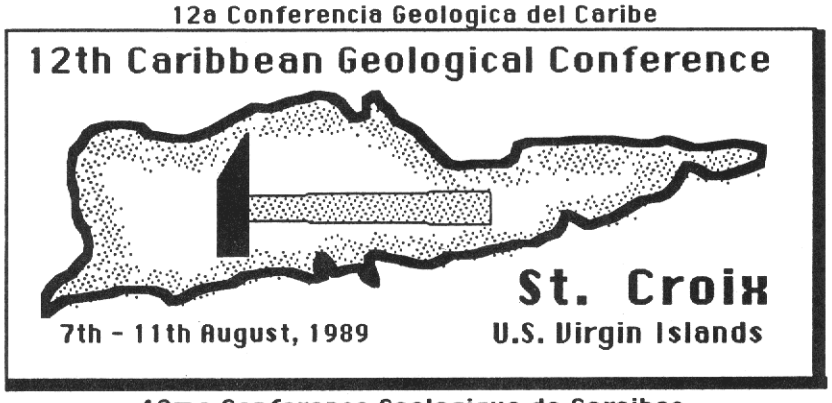
TRANSACTIONS OF THE 12TH CARIBBEAN GEOLOGICAL CONFERENCE

ST. CROIX, U.S. VIRGIN ISLANDS

August 7th - 11th, 1989



Edited by

David K. Larue
Department of Geology, University of Puerto Rico
Mayagüez, PR 00708, Puerto Rico

and

Grenville Draper
Department of Geology, Florida International University
Miami, FL 33199
U.S.A.

Additional copies of this book may be purchased from

Miami Geological Society
P.O. Box 431552
South Miami, FL 33243, U.S.A.

December 1990

RADIOMETRICALLY DATED MARINE TERRACES ON NORTHWESTERN PUERTO RICO

Bruce E. Taggart
Department of Marine Sciences
University of Puerto Rico
Mayagüez, PR, 00709-5000

James Joyce
Department of Geology
University of Puerto Rico
Mayagüez, PR, 00709-5000

ABSTRACT

A detailed study of Pleistocene marine terraces on northwestern Puerto Rico is in progress focusing on the correlation of wave-cut geomorphic features and marine terrace deposit stratigraphy. Stratigraphic control is based on ^{14}C and $^{230}Th/^{234}U$ coral dates from four localities; Rincón, Punta Borinquen, Quebradillas and Palmas Alta.

Radiometric age ranges have been obtained for the 2-3 m and 10 m marine terrace levels. The 10 m marine terrace level has produced $^{230}Th/^{234}U$ ages ranging from 114,000 YBP (± 3,495) to 134,500 YBP (± 2,825). The 2-3 m marine terrace level has produced two groups of radiometric ages. A younger group of ^{14}C ages ranging from 1,460 YBP (± 80) to 2,050 YBP (± 80) and an older group of $^{230}Th/^{234}U$ ages of 115,000 YBP (± 2,955) to 123,000 YBP (± 4,514). The older group of corals were eroded from the 10 m level and subsequently incorporated into the younger 2-3 m level during its formation. Radiometric data and field observations from the Punta Gorda and Punta Borinquen localities, as well as previously published data from northern Puerto Rico and Isla Desecheo, suggest that sea level in northwestern Puerto Rico was 2-3 m higher than present between 1,460 and 3,300 YBP.

Using the data from these marine terrace deposits, a minimum rate of uplift of between 0.03 mm/yr and 0.05 mm/year has been determined for northwestern Puerto Rico during the late Pleistocene. The Pliocene Quebradillas Limestone occurs at elevations of up to 200 m in northwestern Puerto Rico and has marine terrace surfaces developed in it as high as 140 m. These elevations are in agreement with the computed average rate of uplift determined from late Pleistocene marine terrace deposits and suggest that the rate of uplift in northwestern Puerto Rico has been consistent since the mid-Pliocene.

INTRODUCTION

Numerous marine terrace levels and deposits have been observed along all coastal regions of Puerto Rico (Table 1). However, they are most extensively preserved on northwestern Puerto Rico, Isla Desecheo and Isla de Mona (Kaye, 1959a; Kaye, 1959b; Monroe, 1968; Seiders et al., 1972).

In northwestern Puerto Rico marine terrace deposits known to be of Holocene and late Pleistocene age occur at 2-3 m, 10 m, 25-30 m, 36.5 m and 45 m (Kaye, 1959a; Monroe, 1968; Weaver, 1970). The age of the other marine terrace levels shown in Table 1 are not known exactly, but are thought to range from Neogene to early Pleistocene in age. Pleistocene marine terrace deposits occur throughout the northeastern Caribbean Islands (Horsfield, 1975) and have been radiometrically dated on the Cayman Islands (Woodroffe et al., 1985), Jamaica (Cant, 1973), Haiti (Dodge et al., 1983), the Dominican Republic (Schubert and Cowart, 1980) and St. Croix (Hubbard et al., 1989).

We have undertaken a detailed study of marine terraces on northwestern Puerto Rico focusing on correlation of wave-cut geomorphic features and terrace stratigraphy. Stratigraphic control is based on ^{14}C and $^{230}Th/^{234}U$ coral dates. These coral dates indicate the time of deposition on marine terrace surfaces at four localities; Rincón, Borinquen, Quebradillas and Palmas Alta (Figure 1). Table 2 summarizes the radiometric age data determined from coral samples collected at each of the field sites. The elevations of the various deposits and marine terrace surfaces discussed herein were measured from mean sea level using a stadia rod, a tape measure and an inclinometer and are accurate to ± 0.05 m.

The deposits at Rincón, Borinquen and Quebradillas are dominantly calcareous siliciclastic sandstones and conglomerates derived from mixed marine and terrigenous sources. Coral rich layers occur in these deposits immediately above unconformities. Conglomeratic units, especially basal conglomerates, contain numerous corals. The Palmas Alta site consists of an elevated reef tract overlain by lithified beach and eolianite deposits. The Rincón Region contains the best exposures of terrace deposits and has yielded most of the radiometrically dated corals.

These data, along with geomorphic and stratigraphic observations, have been used to correlate deposits and wave-cut features from all other localities to the Rincón deposits. They have then been used to ascertain the amount, and nature, of vertical tectonic movement in northwestern Puerto Rico during the late Quaternary. These data are summarized and discussed for each field site in the following section.

Larue, D.K., and Draper, G., eds.,
Transactions of the 12th Caribbean Conference,
St.Croix U.S.V.I., Miami Geological Society,
P.O. Box 14433, Coral Gables, FL 33114

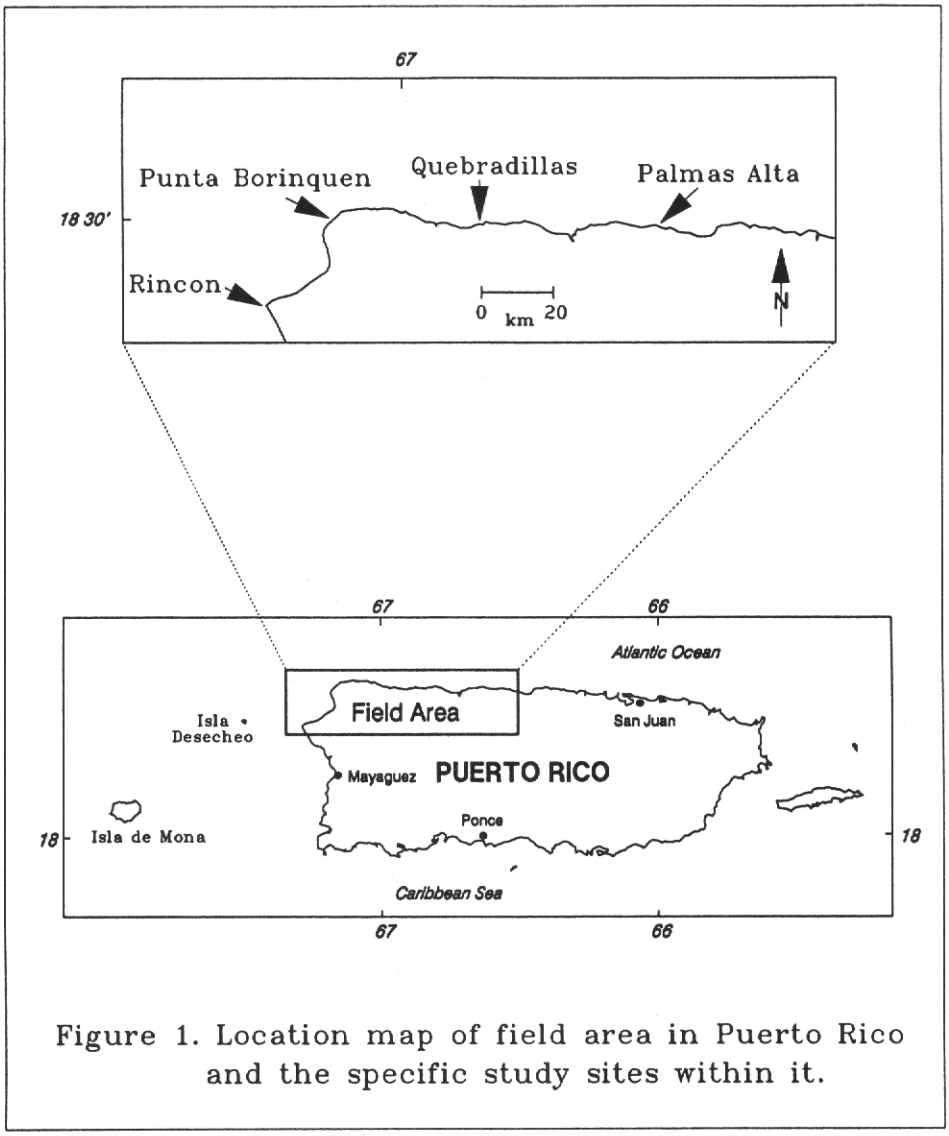


Figure 1. Location map of field area in Puerto Rico and the specific study sites within it.

RESULTS AND DISCUSSION

Rincón Region

The most extensive sequence of Quaternary marine terrace deposits identified are found in the Rincón region. These deposits are best exposed between Punta Ensenada and Punta Gorda (Figure 2). Four marine terrace depositional units are recognized at Rincón: Gorda (Qg), Higüero One (Qh_1), Higüero Two (Qh_2) and Martinica (Qm). Qg is an undifferentiated marine sand and reef rock deposit that is found at elevations ranging from 1 m to 2 m at Punta Gorda. The type section for Qh_1 and Qh_2 is found at Punta Higüero. Qh_1 extends from an elevation of 1 m to 8 m and is a calcareous sandstone containing abundant marine fossil fragments. The upper surface of this unit contains large vertical solution pits that mark the unconformable contact between Qh_1 and the overlying Qh_2 unit. The basal portion of Qh_2 fills the solution pits and grades upwards into a middle zone containing abundant Acropora palmata and other corals in a lithic calcarenite. Above this middle zone, Qh_2 grades into a cross-bedded medium-grained lithic carbonate sand containing granules, pebbles and marine fossil fragments. This unit extends from about 8 m to 10 m elevation. A composite stratigraphic cross-section of these units is presented in Figure 3. Qm consists of small scattered exposures of marine sands and coral fragments unconformably deposited on the Culebrinas Formation of Eocene age. It is found at elevations of up to 25 m along a distinctive slope break throughout the hinterland between Punta Higüero and Punta Ensenada (Figure 4). Weaver (1970) described this unit as a raised beach deposit of Pleistocene age. Based on its location at higher, and more landward, elevations relative to Qh deposits and its association with a distinct break in slope we conclude that Qm constitutes a Pleistocene marine terrace deposit that is older than the Qh deposits. Datable corals have not been recovered from Qm deposits so its exact age

Table 1. Elevated marine terrace (M) and accordant summit levels (A) reported for Puerto Rico. An accordant summit surface consists of summits of equal elevation in a region of high topographic relief that suggest they are remnants of an erosion plain formed in a previous erosion cycle. Kaye (1959a) not only cites his own observations of marine terrace levels but provides an excellent summary of previously reported ones and is cited in their stead for purposes of brevity where appropriate.

Elevation (m)	Surface Type	Reference
760	A	Weaver (1966)
620	A	Weaver (1966)
470	A	Weaver (1966)
330	M	Weaver (1966, 1970)
300	M	Weaver (1966, 1970)
280	M	Weaver (1970)
200	M	Weaver (1970)
190	M	Weaver (1970)
160	M	Weaver (1970)
140	M	Weaver (1970)
120	M	Weaver (1966)
100	M	Weaver (1971)
80	M	Weaver (1971)
50-60	M	Lobeck (1922), Hubbard (1923), Monroe (1968), Weaver (1970, 1971)
36.5	M	Kaye (1959a)
25	M	Weaver (1970)
20	M	Kaye (1959a), Williams (1968)
12	M	Seiders et al. (1972)
8-10	M	Kaye (1959a), Williams (1968)
4-5	M	Kaye (1959a)
2-3	M	Kaye (1959a), Williams (1968), Weaver, (1970), Seiders et al. (1972)

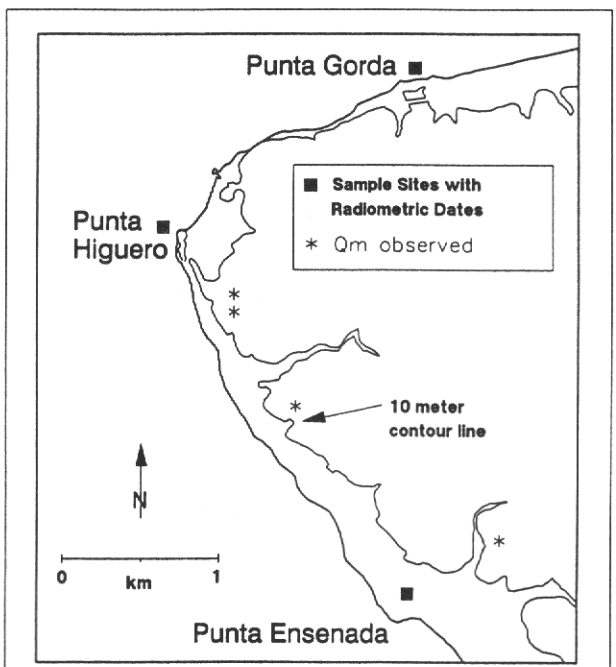


Figure 2. Generalized map of the Rincon Region showing sites of interest discussed in text.

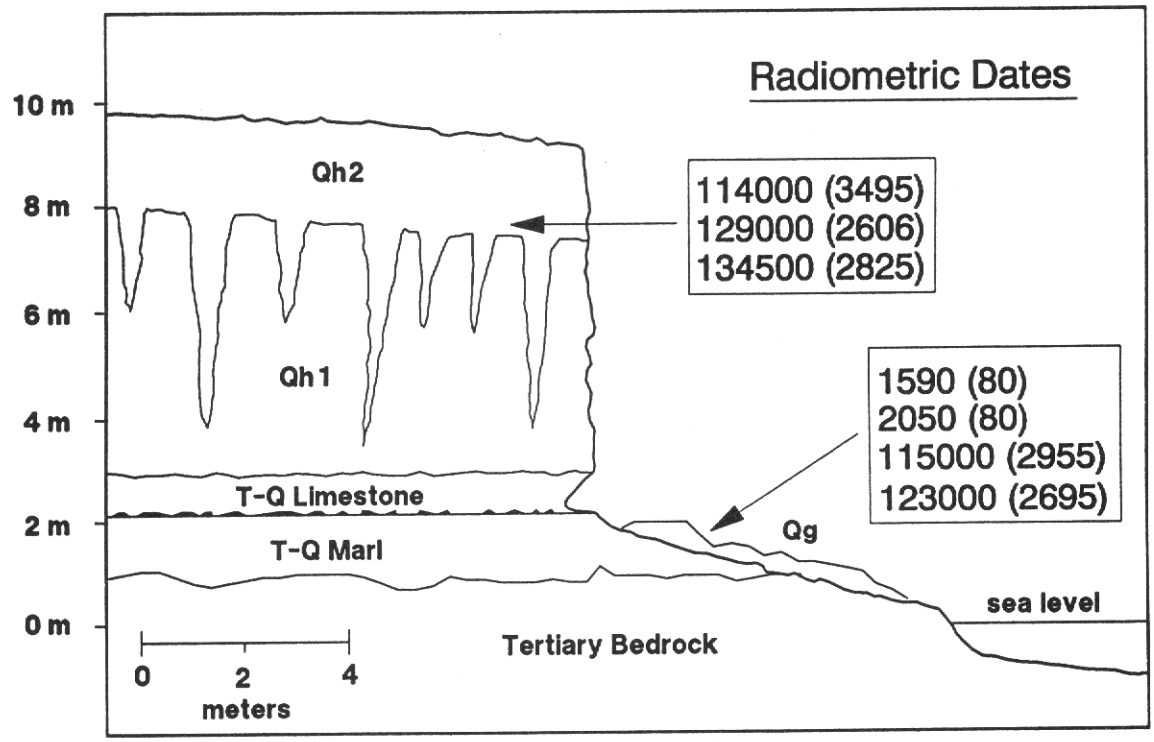


Figure 3. Composite cross-section of the Rincon Region Quaternary deposits on the west coast of Puerto Rico.

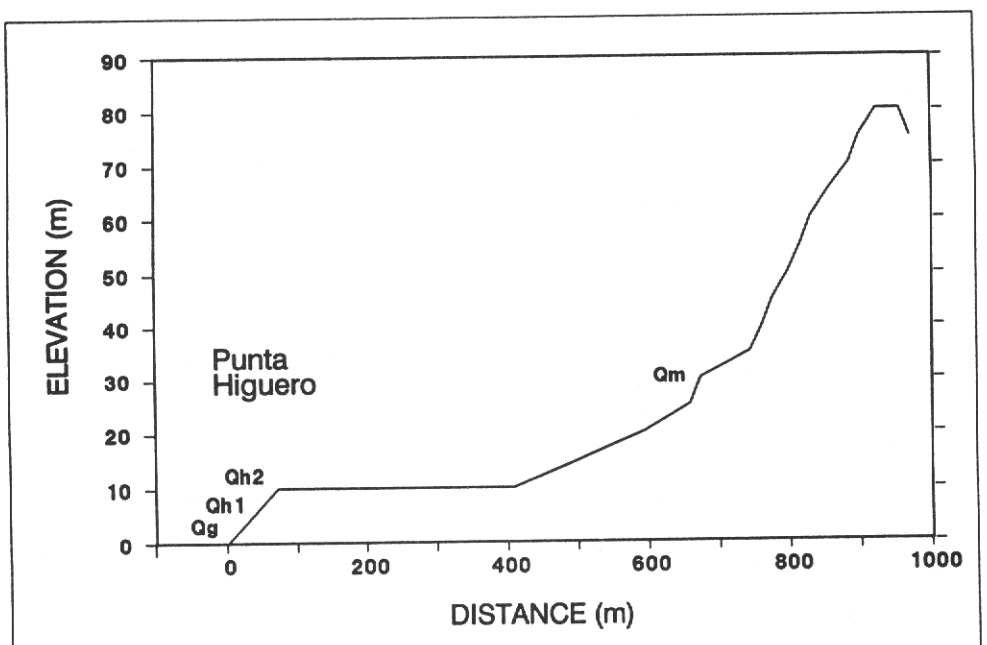


Figure 4. Topographic profile at Punta Higuero, Puerto Rico.

Table 2. Summary of data obtained from corals retrieved from various marine terrace deposits in northwestern Puerto Rico.

Sample Number	Sample Site	Coral Sp.	Sample Elevation (m)	Percent Aragonite	Th-230 (dpm/gm)	Std. Dev.	U-234 (dpm/gm)	Std. Dev.	U-234 / U-238	Std. Dev.	Th-232 / Th-230	Std. Dev.	Th-230 Age	Std. Dev.	C-14 Age	Std. Dev.
1	RH	S	8.8	96.9	1.909	2.53	2.883	1.72	1.13	*	0.662	3.07	114000	3495	33060	670
7	RG	D	1	99.9	0.061	4.90	2.384	1.10	1.15	*	0.026	5.02	3000	150	1590	80
8	RG	Mc	1	99.7	0.054	4.88	2.139	1.10	1.13	*	0.025	5.00	3000	150	2050	80
9	RG	Ap	1	100	1.684	1.73	2.439	1.79	1.12	*	0.690	2.19	123000	2695	35290	1150
10	RG	Ss	1	100	1.444	1.77	2.171	1.87	1.15	*	0.665	2.57	115000	2955	30360	1100
11	PB	Ma	1.4	100	0.146	5.56	2.045	1.93	1.10	*	0.071	5.88	8000	470	1460	80
12	PB	Ap	1.4	100	0.050	5.60	2.637	1.79	1.12	*	0.019	5.88	2000	118	1680	70
13	PH	D	2.7	99.6	1.163	1.80	2.381	1.87	1.09	*	0.677	2.46	120000	2950	33940	800
14	PH	D	2.7	100	1.525	1.77	2.224	1.87	1.09	*	0.680	2.57	120000	3064	39100	1340
25	PB	D	1.4	97.7	1.657	2.31	2.402	2.87	1.08	2.91	0.690	3.68	124000	4563	---	---
28	PA	D	1	100	1.584	2.41	2.215	2.34	1.09	2.53	0.715	3.36	133000	4469	---	---
29	PA	D	1	100	1.525	2.30	2.096	2.95	1.06	3.20	0.728	3.74	138000	5161	---	---
30	PH	D	3.0	100	1.639	1.89	2.291	2.32	1.08	2.50	0.716	2.99	133000	3977	---	---
31	PH	Ma	3.0	100	1.520	1.99	2.130	2.32	1.08	2.56	0.714	3.06	132500	4055	---	---
38	RE	Sr	5.0	98.8	1.896	1.83	2.399	1.42	1.10	1.49	0.790	2.32	162500	3770	---	---
39	RH	Ap	6.7	100	1.745	1.83	2.463	1.19	1.13	1.27	0.709	2.02	129000	2606	---	---
41	RH	Ap	6.7	100	1.744	1.82	2.425	1.34	1.09	1.43	0.719	2.10	134500	2825	---	---

(a) RE = Punta Ensenada RH = Punta Higuero RG = Punta Gorda
PB = Punta Borinquen PH = Puerto Hermina PA = Palmas Altas

* Value not provided with processed data

(b) S = Siderastrea sp. Mc = Montastrea cavernosa Ap = Acropora palmata
Ss = Siderastrea sideria Ma = Montastrea annularis D = Diploria sp.
Sr = Siderastrea radians

is not known.

Coral samples have been retrieved from Qg, Qh_2 and Qm deposits at Punta Higüero and Punta Gorda. However, only samples retrieved from Qg and Qh_2 exposures have proven to be radiometrically datable. At Punta Higüero three corals retrieved from basal Qh_2 deposits have produced $^{230}Th/^{234}U$ ages of 114,000 ± 3,495 YBP, 129,000 ± 2,606 YBP and 134,500 ± 2,825 YBP (Table 2). Sample #1 was also dated by the ^{14}C method and yielded an age of 33,060 ± 670 YBP (Table 2).

At Punta Gorda a wave-cut notch is preserved at an elevation of 1.5 to 2.0 m. The Qg (undifferentiated marine sand and reef rock) deposit lies seaward of, and abuts, this wave-cut notch. Two coral samples retrieved from Qg yielded ^{14}C ages of 1,590 ± 80 YBP and 2,050 ± 80 YBP and $^{230}Th/^{234}U$ ages of 3,000 ± 150 YBP and 3,000 ± 150 YBP. Two additional samples yielded $^{230}Th/^{234}U$ ages of 123,000 ± 2,695 YBP and 115,000 ± 2,955 YBP and ^{14}C ages of 35,290 ± 1,150 YBP and 30,360 ± 1,100 YBP respectively (Table 2). According to Pierce (1986) many ^{14}C dates that fall within the 25-40 YBP range may be the result of contamination of older coral samples (> 50 ka) with between 0.5-2.0 percent young carbon. Therefore, the ages of coral samples retrieved from Punta Gorda that were analysed by both radiometric dating methods appear to be in agreement inasmuch as the young ^{14}C ages are supported by young $^{230}Th/^{234}U$ ages and the older $^{230}Th/^{234}U$ ages are supported by ^{14}C ages in Pierce's (1986) questionable range of 25-40 YBP. These older $^{230}Th/^{234}U$ dates are identical with those determined for Qh deposits at Punta Higüero. The bimodal nature of the dates and the presence of a wave-cut notch at the base of Qh deposits at Punta Gorda suggest reworking of Qh deposits into Qg during the late Holocene.

One coral suitable for radiometric dating was recovered at Punta Ensenada. It was found in a small reef rock exposure located about 200 m inland of Punta Ensenada at an elevation of 5 m. It produced a $^{230}Th/^{234}U$ age of 162,500 ± 3,770 YBP (Table 2). This reef rock exposure contains A. palmata, M. annularis, S. radians and Diploria sp. corals. Based on the elevation of the exposure (lower than Qh_2) and its age (older than Qh_2) we suggest that it is either a Qh_1 deposit or that it represents a pre-Qh deposit. More dates are needed to verify which of these two hypotheses is correct.

Marine terrace deposits on Isla Desecheo, located 21 km west of Punta Higüero, occur at elevations of 2-3 m and 10-12 m (Seiders et al., 1972). These deposits were called the Lower Desecheo Stage (2-3 m)

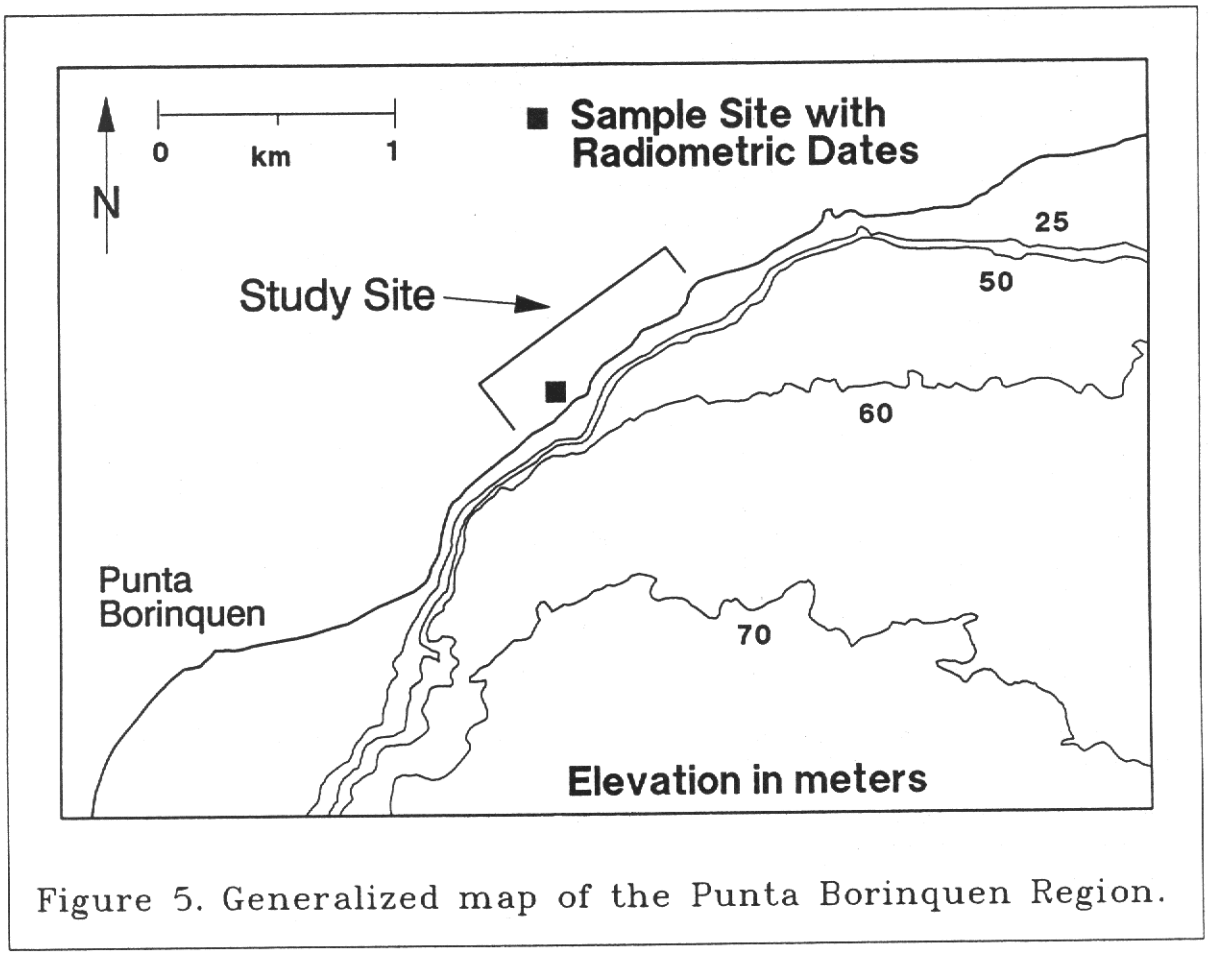


Figure 5. Generalized map of the Punta Borinquen Region.

and the Upper Desecheo Stage (10-12 m) by Hubbard (1923). Seiders et al. (1972) concluded that the Lower Desecheo Stage is Holocene in age and the Upper Desecheo Stage is late Pleistocene in age. They based their conclusion on geomorphic and stratigraphic observations of the deposits and one ^{14}C age of 3,300 ± 300 YBP from a 2 m coastal swamp deposit in north-central Puerto Rico (Seiders et al., 1972; p. 21). We conclude that the Lower Desecheo Stage and the Upper Desecheo Stage correlate with Qg and Qh deposits.

Punta Borinquen Region

Immediately north of Punta Borinquen deposits correlated to Qg are found at elevations of up to 2.7 m within a wave-cut notch that begins at 2.5 m (Figure 5). Marine debris deposits, often overlain by colluvium, are discontinuously exposed in the cliffs throughout this region at an average elevation of 5 m and are correlated to Qh. Two coral samples retrieved from the Qg deposit yielded ^{14}C ages of 1,460 ± 80 YBP and 1,680 ± 70 YBP and $^{230}Th/^{234}U$ ages of 8,000 ± 470 YBP and 2,000 ± 118 YBP. A third sample yielded a $^{230}Th/^{234}U$ age of 124,000 ± 4,563 YBP (Table 2). The distribution of ^{14}C ages here is similar to that found at Punta Gorda and supports correlation with Qg.

At the Punta Gorda and Punta Borinquen sites the radiometric ages fall into two distinct populations on the 2-3 m terrace level. They are late Holocene (1,500 to 2,000 YBP) and late Pleistocene (115,000 to 123,000 YBP) in age. We conclude that the older corals were eroded from the adjacent Pleistocene Qh deposits and subsequently incorporated into the younger surface as it formed during the late Holocene. The presence of a well-developed wave-cut notch at the landward edge of Qg at Punta Gorda and Punta Borinquen, the occurrence of Qh blocks in Qg at Punta Gorda, adjacent Qh deposits and the congruence of coral ages between the two sites support this conclusion. The low average rate of uplift established for northwestern Puerto Rico for the late Pleistocene suggests that this feature must have formed at a higher stand of sea level or been co-seismically uplifted. The lack of surficial features favoring the occurrence of co-seismic movement in this region during the Holocene does not support uplift of 2-3 m during the last 2,000 years. Also, there is no reason to suspect that the average rate of tectonic uplift should increase by two orders of magnitude during the late Holocene. This suggests that local sea-level was locally 2-3 m higher than present between 1,460 YBP and 3,300 YBP.

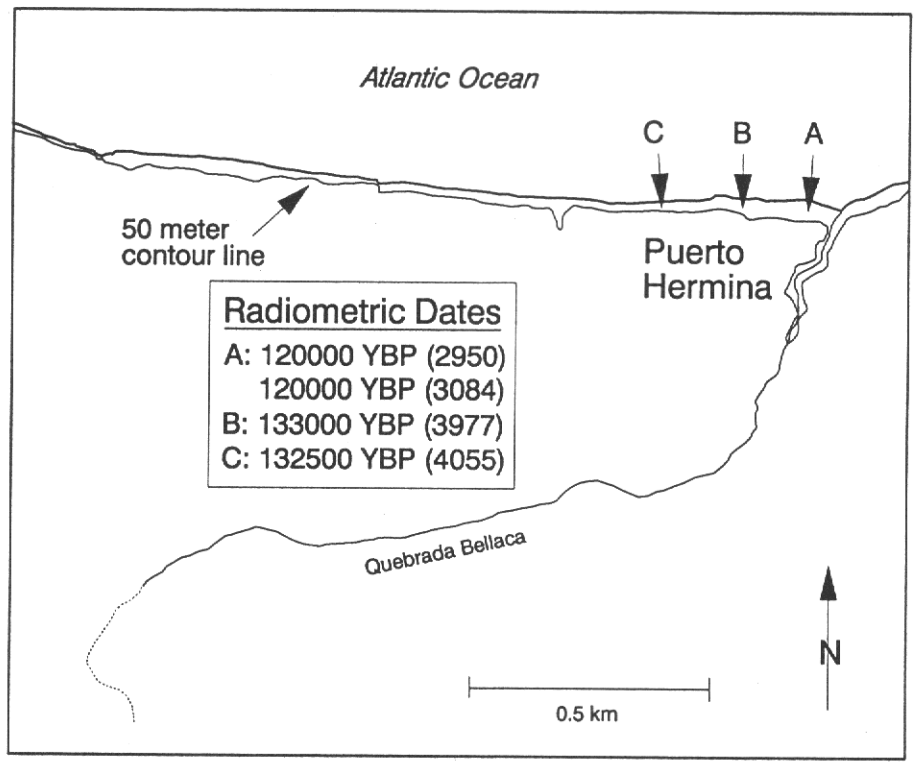


Figure 6. Generalized map of the Puerto Hermina study site in the Quebradillas Region.

Quebradillas Region

On the coast immediately northeast of the town of Quebradillas, at Puerto Hermina, four coral samples suitable for radiometric dating were retrieved from the base of the 10 m marine terrace deposit (Figure 6). $^{230}Th/^{234}U$ ages of 120,000 ± 2,950 YBP, 120,000 ± 3,084 YBP, 133,000 ± 3,977 YBP and 132,500 ± 4,055 YBP were determined for these samples (Table 2). The deposits at Puerto Hermina are correlated with the Qh deposits at Punta Higüero based on radiometric ages of dated corals, the presence of wave-cut notches at 8-10 m elevation and small exposures of marine sand deposits at up to 12 m.

Palmas Alta Region

Palmas Alta differs from the three preceding sites in that it is a reef-rock exposure consisting of large coral heads in a sand matrix rather than marine deposits veneering a wave-cut platform. Corals were collected from the reef tract at Palmas Alta at an elevation of one meter (Figure 7). These samples produced $^{230}Th/^{234}U$ ages of 133,000 ± 4,469 YBP and 138,000 ± 5,161 YBP (Table 2). This reef tract exposure is conformably overlain by lithified Pleistocene beach deposits. The beach deposits are unconformably overlain by late Pleistocene eolianite deposits described by Kaye (1959) that extend along much of the north coast. The radiometric ages effectively establish a maximum age of a late Pleistocene regression and the formation of the overlying eolianite ridge.

The ages available for this deposit indicate that it formed at the same time as Qh deposits at Punta Higüero and Puerto Hermina. The total absence of A. palmata from the deposit suggests that this reef exposure may have formed at depths greater than 5-10 m below the paleosea-level (Lighty et al., 1982). It is also possible that sediment stress and/or the wave-energy environment inhibited the development of A. palmata at this site.

CONCLUSIONS

Elevated marine terraces with deposits 125,000 ± 10,000 YBP occur in northwestern Puerto Rico and on Isla Desecheo at elevations of 10-12 m above present sea level (Seiders et al., 1972). These deposits establish a lower limit constraint on sea level around Puerto Rico 125,000 YBP. Sea level may have been even a few meters higher than the top of the deposits. The age and

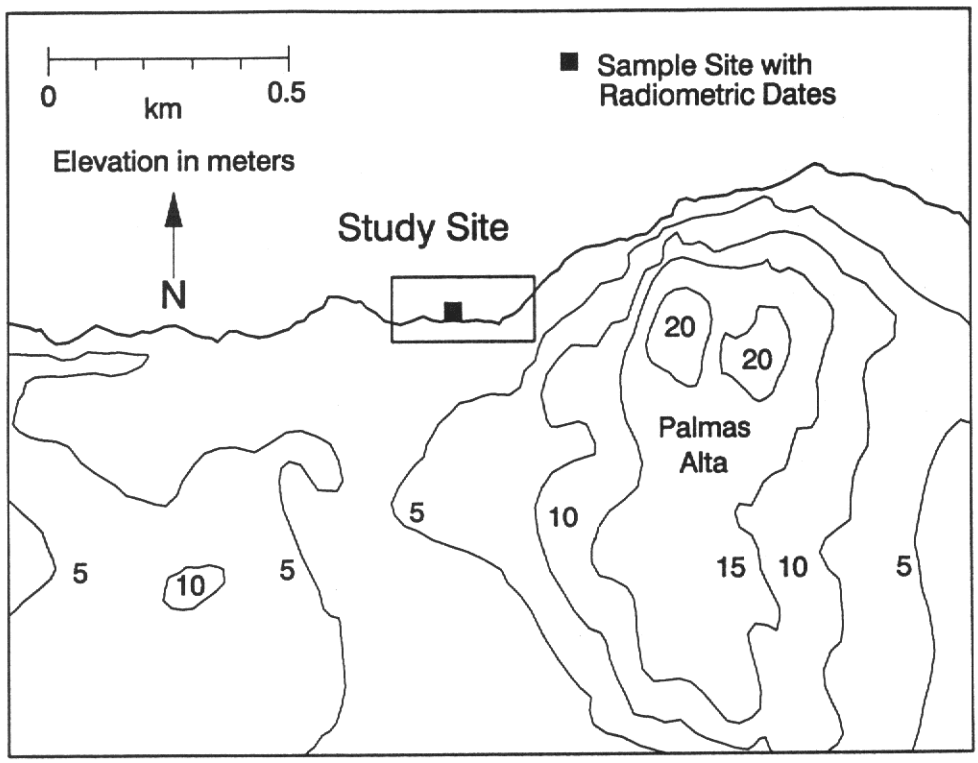


Figure 7. Study site location in the Palmas Alta Region. The hills are composed of Pleistocene eolianite.

elevation of the deposits are compared with the sea-level curve synthesized by Moore (1982) (Figure 8). We have chosen Moore's (1982) sea-level curve, rather than the more recent one published by Chappell and Shackleton (1986), because it incorporates data from both the Pacific and Atlantic Ocean basins and is probably more applicable to Puerto Rico. It is generally accepted that sea level was 6 ± 4 m higher than present approximately 125,000 ± 10,000 YBP (Bloom et al., 1974; Yonekura, 1983; Lajoie, 1986; Edwards et al., 1987) (Figure 8). These data indicate that northwestern Puerto Rico has been uplifted by at least 4 m to 6 m during the last 125,000 years. Performing the calculations on these data produces a minimum rate of uplift of between 0.03 mm/year and 0.05 mm/year during the late Pleistocene. This is a relatively low rate of tectonic uplift when compared to 0.14 mm/year for Jamaica (Cant, 1973) and 0.3 mm/year for Haiti (Dodge et al., 1983). However, it is on the same order of magnitude as the southeastern Dominican Republic (Schubert and Cowart, 1980; F.W. Taylor, personal comm., 1990) and St. Croix (Hubbard et al., 1989) which are in the immediate vicinity of Puerto Rico. This variability of tectonic uplift rates in the northeastern Caribbean is due to the complex tectonic structure of the Northern Caribbean Plate Boundary Zone (Mann et al., in press).

Neritic limestone deposited during the Pliocene (Quebradillas Limestone) is now found at elevations of up to 200 m in northwestern Puerto Rico (Monroe, 1969). The upper member of the Quebradillas Limestone was largely deposited in deep water about 4 million years ago (Moussa et al., 1987). The presence of cross-stratified beach calcarenites and calcareous sandstones and shallow water foramiferal assemblages (10 m to 35 m depths) at the top of the upper member of the Quebradillas Limestone (Seiglie and Moussa, 1984) suggests that it was deposited during a regression. According to Haq et al. (1987) sea level 4 million years ago was approximately 60 m higher than present. All of these data taken together indicate tectonic uplift of at least 130 m, and possibly as much as 200 m, of the Quebradillas Limestone following its deposition and provide a minimum uplift rate of between 0.03 mm/year and 0.05 mm/year. This is in virtual agreement with the minimum rate of uplift range determined for northwestern Puerto Rico during the late Pleistocene. Therefore, we suggest that the rate of tectonic uplift has been slow and consistent in northwestern Puerto Rico during

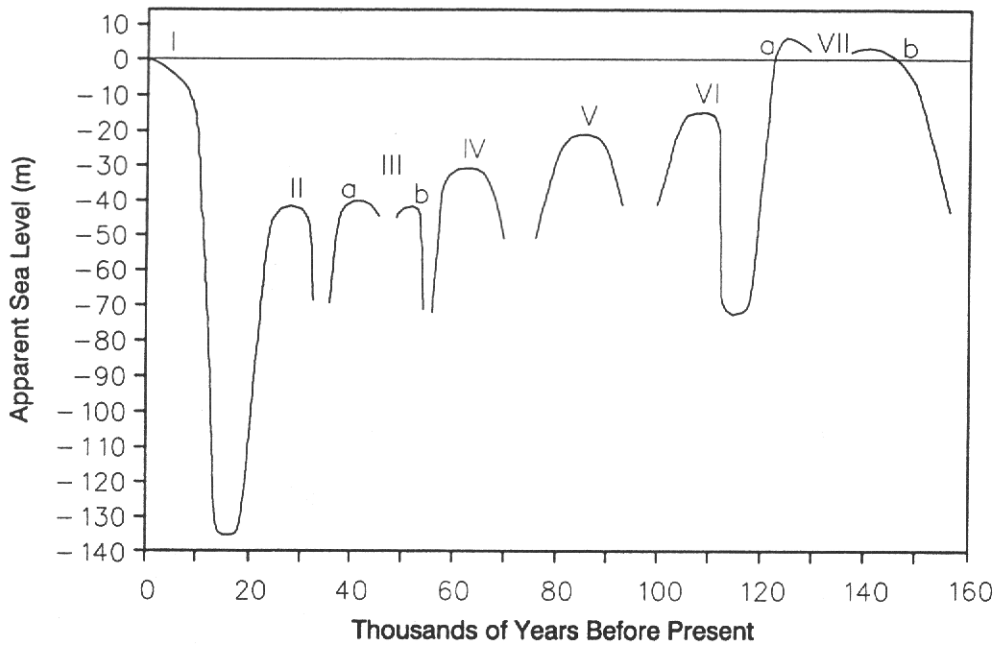


Figure 8. Late Pleistocene sea-level curve relative to present sea level (after Moore, 1982). Roman numerals follow the designations assigned by Chappell (1974) to the Huon, New Guinea terraces. This sea-level curve is used instead of the more recent sea-level curve of Chappell and Shackleton (1986) because it incorporates data from the west-central Atlantic Ocean and Caribbean Sea regions.

the last 4 million years.

Marine terrace deposits, elevated beach deposits and wave-cut notches are found at elevations of 2-3 m throughout the coast of Puerto Rico and on its associated islands (Kaye, 1959a; Williams, 1965; Seiders et al., 1972). As previously discussed, the 2-3 m marine terrace and coastal swamp deposits in northwestern and north-central Puerto Rico have been radiometrically dated and are late Holocene in age. Based on the pervasive presence of this coastal feature around Puerto Rico and the lack of any evidence supporting its co-seismic uplift we conclude that sea level was 2-3 m higher than present between 1,500 and 3,300 YBP.

ACKNOWLEDGEMENTS

Funding for the radiometric dating of coral samples was provided by a National Science Foundation EPSCoR Grant to the Department of Geology at the University of Puerto Rico. ^{14}C dates were determined by Beta Analytic Inc.. $^{230}Th/^{234}U$ dates were determined by Willard S. Moore of the Department of Geological Sciences at the University of South Carolina in Columbia.

REFERENCES

Birch, F.S., 1986, Isostatic, thermal, and flexural models of the subsidence of the north coast of Puerto Rico: Geology, v. 14, p. 427-429.

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.

Cant, R.V., 1973, Jamaica's Pleistocene reef terraces: Geologie en Mijnbouw, v. 52, p. 157-160.

Chappell, J.M.A., 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.

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

Dodge, R.E., Fairbanks, R.G., Benninger, L.K. and Maurrasse, F., 1983, Pleistocene sea levels from raised coral reefs of Haiti: Science, v. 219, p. 1423-1225.

Edwards, R.L., Chen, J.H., Ku, T.-L. and Wasserburg, G.J., 1987, Precise timing of the last interglacial period from mass spectrometric determination of Thorium-230 in corals: Science, v. 236, p. 1547-1553.

Fox, P.J. and Heezen, B.C., 1975, Geology of the Caribbean crust in A.E.M. Nairn and F.G. Stehli (eds.), The ocean basins and margins, v. 3, New York, Plenum Press, 706 p.

Horsfield, W.T., 1975, Quaternary vertical movements in the Greater Antilles: Geological Society of America Bulletin, v. 86, p. 933-938.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156-1167.

Hubbard, B., 1923, The geology of the Lares District: New York, New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, v. 2, part 1, 115 p.

Hubbard, D., Venger, L, Parsons, K. and Stanley, D., 1989, Geologic development of the West End Terrace System on St. Croix, U.S. Virgin islands, in D.K. Hubbard (ed.), Terrestrial and Marine Geology of St. Croix, U.S. Virgin Islands: Teague Bay, St. Croix, Special Pub. No. 8, West Indies Laboratory, p. 73-83.

Kaye, C.A., 1959a, Shoreline features and Quaternary shoreline changes, Puerto Rico: Washington D.C., U.S. Printing Office, U.S. Geological Survey Professional Paper 317-B, p. 49-140.

_____ 1959b, Geology of Isla Mona Puerto Rico, and notes on age of Mona Passage: Washington D.C., U.S. Printing Office, U.S. Geological Survey Professional Paper 317-C, p. 141-178.

Lajoie, K.R., 1986, Coastal tectonics, in R.E. Wallace (ed.), Active Tectonics: Washington D.C., National Academy Press, p. 95-124.

Lighty, R.G., Macintyre, I.G. and Stuckenrath, R., 1982, Acropora palmata reef framework: A reliable indicator of sea level in the Western Atlantic for the past 10,000 years: Coral Reefs, v. 1, p. 125-130.

Lobeck, A.K., 1922, The physiography of Porto Rico: New York, New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, v. 1, part 4, p. 301-384.

Mann, P., Schubert, C. and Burke, K., in press, Review of Caribbean neotectonics, in G. Dengo and J.E. Case (eds.), The Caribbean region: Boulder, Colorado, G.S.A., The Geology of North America, v. H.

McCann, W.R. and Sykes, L.R., 1984, Subduction of aseismic ridges beneath the Caribbean plate; Implications for the tectonics and seismic potential of the northeastern Caribbean: Journal of Geophysical Research, v. 89, p. 4493-4519.

Meyerhoff, A.A., Krieg, E.A., Cloos, J.D., and Taner, I., 1983, Petroleum potential of Puerto Rico: Oil and Gas Journal, p. 113-120.

Monroe, W.H., 1968, High level Quaternary beach deposits in northwestern Puerto Rico: Washington D.C., U.S. Govt Printing Office, U.S.G.S. Prof. Paper 600-C, p. C140-C143.

_____ 1969, Geologic map of the Moca and Isabela Quadrangles Puerto Rico: Washington D.C., U.S. Geological Survey, Miscellaneous Geologic Investigations Map I-565, 1 sheet.

Moore, W.S., 1982, Late Pleistocene sea-level history, in M. Ivanovich and R.S. Harmon (eds.), Uranium Series Disequilibrium: Applications to Environmental Problems: Oxford, Clarendon Press, p. 481-496.

Moussa, M., Seiglie, G.A., Meyerhoff, A.A., and Taner, I., 1987, The Quebradillas Limestone (Miocene-Pliocene), northern Puerto Rico, and tectonics of the northeastern Caribbean margin: GSA Bull., v. 99, p. 427-439.

Perfit, M.R., Heezen, B.C., Rawson, M., and Donnelly, T.W., 1980, Chemistry, origin and tectonic significance of metamorphic rocks from the Puerto Rico trench: Marine Geology, v. 34, p. 125-166.

Pierce, K.L., Dating methods, in R.E. Wallace (ed.), Active Tectonics: Washington D.C., National Academy Press, p. 195-214.

Schneidermann, N., Beckmann, J.P., and Heezen, B.,C., 1972, Shallow water carbonates from the Puerto Rico Trench region: Margarita, Venezuela, Sixth Caribbean Geology Conference, p. 423-425.

Schubert, C. and Cowart, J.B., 1980, Terrazas marinas del Pleistoceno a lo largo de la costa suroriental de la Republica Dominicana; Cronologia preliminar: Transactions of the 9th Caribbean Geological Conference, Santo Domingo, Dominican Republic, p. 681-688.

Seiders, V.M, Briggs, R.P., and Glover, L., III., 1972, Geology of Isla Desecheo, Puerto Rico, with notes on the Great Southern Puerto Rico Fault Zone and Quaternary Stillstands of the sea: Washington D.C., U.S. Printing Office, U.S. Geological Survey Professional Paper 739, 22 p.

Seiglie, G.A. and Moussa, M.T., 1984, Late Oligocene-Pliocene transgressive-regressive cycles of sedimentation in northwestern Puerto Rico, in J.S. Schlee (ed.), Interregional Unconformities and Hydrocarbon Accumulation: Tulsa, Oklahoma, The American Association of Petroleum Geologists, AAPG Memoir 36, p. 89-95.

Sykes, L.R., McCann, W.R., and Kafka, A.L., 1982, Motion of Caribbean plate during last 7 million years and implications for earlier Cenozoic movements: Journal of Geophysical Research, v. 87, p. 10,656-10,676.

Weaver, J.D., 1966, Higher level erosion surfaces in the Caribbean: Third Caribbean Geological Conference, Jamaica Geol. Survey Pub. 95, p. 10-12.

_____ 1970, Terraces in western Puerto Rico: Fourth Caribbean Geology Conference, Port of Spain, Trinidad, p. 243-245.

_____ 1971, Review of geomorphological and Pleistocene research in the Caribbean: Transactions of the Fifth Caribbean Geological Conference, Geol. Bull. No. 5, Queens College Press, p. 201-206.

Williams, R.S., Jr., 1965, Geomorphology of a portion of the northern coastal plain of Puerto Rico: Pennsylvania State University, unpub. Ph.D. dissertation, 191 p.

Woodroffe, C.D., Stoddart, D.R., Harmon, R.S. and Spencer, T., 1983, Coastal morphology and late Quaternary history, Cayman Islands, West Indies: Quaternary Research, v. 19, p. 64-84.

Yonekura, N., 1983, Late Quaternary vertical crustal movements in and around the Pacific as deduced from former shoreline data in Thomas W.C. Hilde and S. Uyeda, (eds.), Geodynamics of the Western Pacific-Indonesian Region: Washington D.C., American Geophysical Union, Geodynamics Series, Volume 11, p. 41-50.