Pleistocene Sea Levels from Raised Coral Reefs of Haiti

Abstract. *The elevations and ages of a sequence of three uplifted Pleistocene coral reefs on the Northwest Peninsula of Haiti have been determined. With the assignment of a sea level of +6 meters (relative to the present day) at 130,000 years before present and constant uplift of the reefs, the data indicate that sea level stood −10 and −13 meters at 108,000 and 81,000 years before present, respectively. These results are in substantial agreement with those reported for Barbados and New Guinea and support the hypothesis of constant uplift for each area. Sea level data from raised reefs indicate that the interglacial marine oxygen isotope oscillations during oxygen isotope stage 5 are a result of 30 percent ice volume effects and 70 percent temperature effects.*

Woodring *et al.* (*1*) conducted a reconnaissance geological study of Haiti in the early 1920's and reported that "marine Pleistocene deposits, consisting principally of coral reef rock and coralliferous limestone . . ., are most extensive in the western part of the Northwest Peninsula, where they cover the Bombardopolis Plateau and the magnificent emerged terraces that lead down to the sea like gigantic stairs" (*2*, p. 122). Butterlin (*3*) later confirmed these observations. Horsfield (*4*), on the basis of the number of terraces in Haiti and other nearby islands, postulated that a region located over the Windward Passage is the site of most rapid uplift in the Greater Antilles area and probably in the Caribbean as a whole. In view of the disparate estimates of the magnitude of Pleistocene sea level oscillations (*5, 6*) and the importance of calibrating eustatic sea level and the marine oxygen isotope record (*7, 8*), we conducted a detailed mapping and dating study in Haiti.

The most impressive and well-defined series of Haitian marine terraces are located on the Northwest Peninsula (Fig. 1a). From air photographs, topographic maps, field inspections, and plane table and alidade mapping we have determined that at least seven terraces rise to an elevation of over 200 m and continue eastward from the town of Mole St. Nicolas. These are linearly continuous, show little evidence of warping or differential uplift for more than 10 km, extend at least 60 km eastward to Port de Paix, and are exposed on the Island of Tortue. At least seven older terraces are present at an elevation of from 200 to 600 m around the area of Mare Rouge. To the west of Mole St. Nicolas a similar flight of terraces is present around the extreme portion of the Northwest Peninsula at Cap St. Nicolas.

Vegetation and soil cover is sparse in this arid peninsula, and from inspection of stream cuts, cliff faces, and differentially eroded surfaces we determined that each major terrace is a constructional fossil coral reef (*9*). Virtually all contain a massive reef crest facies composed primarily of *Acropora palmata* corals. A beach facies is often located landward of the *A. palmata* crest. Below the crest are located facies dominated by the coral species *A. cervicornis* or head corals dominated by *Montastrea annularis*, or both. In areas of extensive erosion of the seaward portion of a terrace, facies of forereef sand and rubble are sometimes revealed. Because of a general lack of exposure landward of the reef crests and the close fringing nature of Haitian reefs, we did not observe lagoonal deposits.

We carried out detailed fieldwork at two locations on the terrace sequence eastward of Mole St. Nicolas, which was restricted to the three lowest reefs (Fig. 1b). Reef crest elevations were determined as the highest exposure of the *A. palmata* facies. The seaward portion of the lowest terrace, designated by the name "Mole," typically forms a modern sea cliff. Its crest is 16 ± 3 m in elevation (plane table and alidade surveys). The next higher terrace, "Saint," crests at 28 ± 3 m. A beach facies is usually present landward a few meters higher. The cliff face of the next higher reef, "Nicolas," is as much as 15 m in height and is analogous to the Barbados major raised reef feature "first high cliff," also named Rendezvous Hill (*8, 10*). The *A. palmata* facies of Nicolas extends to an elevation of 52 m at the lip of the cliff face. Its upper surface forms a relatively flat plain extending over 500 m laterally to the next higher terrace (*11*).

In the Caribbean, living *A. palmata* typically dominate modern reef crests in water depths of 0 to 5 m. When found in fossil deposits, it therefore indicates that sea level was closer than 5 m during the time of reef formation. We sampled *A. palmata* fossils in growth position from the crest regions of each of the three terraces for uranium series dating. We screened these fossils for diagenetic alteration, using the established criteria (*12*). Age estimates based on methods

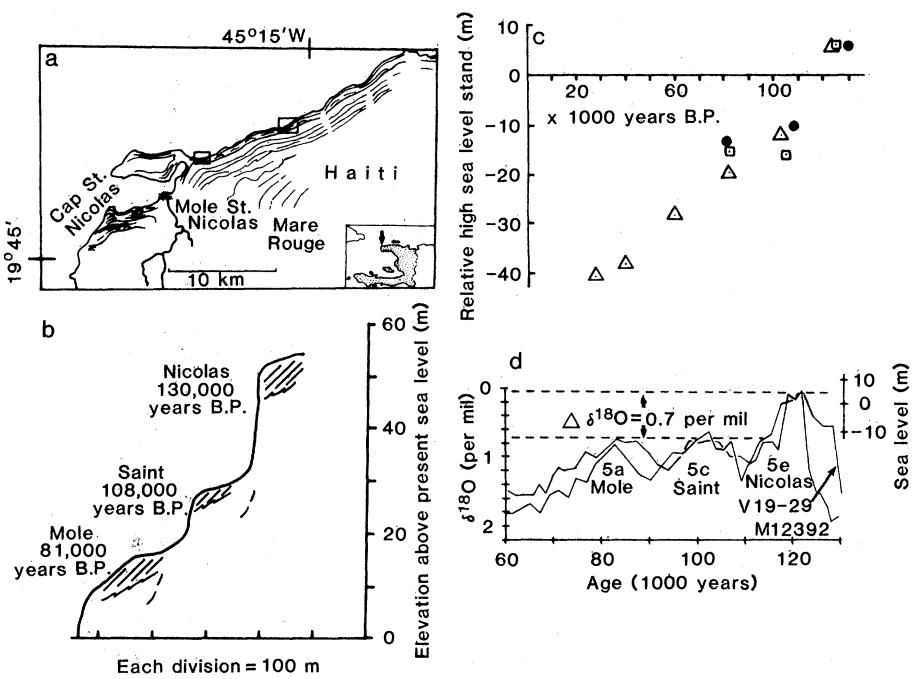

Fig. 1. (a) Sketch map of the Northwest Peninsula of Haiti. Lines paralleling the coast are traces of the crests of raised reefs. Small rectangles on the coast indicate the locations of detailed transects and collections. The inset shows the Haiti portion of the island of Hispaniola, and the arrow designates the area expanded in the larger map. (b) Generalized cross section of the three lower Haitian raised reefs. Slashes indicate the *A. palmata* facies. (c) The elevation of high sea level (relative to the present day) as derived from raised reef data from Haiti (circles), Barbados (squares) (*16*), and New Guinea (triangles) (*6*). (d) The benthic foraminiferal oxygen isotope records for isotope stage 5 from cores V19-29 (*19*) and Meteor 12392 (*20*). The records are stacked so that the minimum $\delta^{18}O$ values in substage 5e are coincident. The $\delta^{18}O$ axis is relative. The records are stretched on the age axis so that substages 5a, 5c, and 5e correspond to $^{230}Th/^{234}U$ age estimates from Barbados (*10*). The sea level axis is based on the constant uplift assumption for Haiti and Barbados.

Table 1. Uranium series ages for *Acropora palmata* corals. The errors assigned to individual dates are counting statistics standard deviations. The errors assigned to means are the largest of individual errors. The half-lives used for ^{234}U and ^{230}Th were 2.48×10^5 and 7.52×10^4 years, respectively. The initial $^{234}U/^{238}U$ ratio is assumed to be equal to 1.15 (*28*).

Sample	^{238}U (dpm/g)	$^{234}U/^{238}U$†	^{232}Th (dpm/g)	^{230}Th (dpm/g)	$^{230}Th/^{234}U$†	Age (10^5 years)
Mole (average age, 81,000 ± 3000 years B.P.; crest elevation, 16 m)						
E12	2.275 ± 0.032	1.101 ± 0.015	< 0.011 ± 0.002	1.318 ± 0.023	0.526 ± 0.012	0.80 ± 0.03
G1*	2.815 ± 0.048	1.086 ± 0.018	< 0.011 ± 0.002	2.145 ± 0.041	0.702 ± 0.018	1.28 ± 0.06
O2	2.516 ± 0.040	1.121 ± 0.016	< 0.007 ± 0.001	1.515 ± 0.025	0.537 ± 0.012	0.82 ± 0.03
K1	2.483 ± 0.040	1.104 ± 0.016	< 0.004 ± 0.001	1.402 ± 0.025	0.512 ± 0.012	0.77 ± 0.03
P3	2.508 ± 0.038	1.102 ± 0.015	< 0.008 ± 0.001	1.491 ± 0.029	0.540 ± 0.013	0.83 ± 0.03
Saint (age, 108,000 ± 5000 years B.P.; crest elevation, 28 m)						
D4*	2.314 ± 0.038	1.161 ± 0.019	< 0.007 ± 0.001	1.906 ± 0.038	0.710 ± 0.018	1.30 ± 0.06
Q5	2.237 ± 0.029	1.105 ± 0.014	< 0.006 ± 0.001	1.581 ± 0.030	0.640 ± 0.015	1.08 ± 0.05
Nicolas (average age, 130,000 ± 6000 years B.P.; crest elevation, 52 m)						
B2	2.736 ± 0.045	1.104 ± 0.018	< 0.008 ± 0.002	2.142 ± 0.040	0.709 ± 0.018	1.30 ± 0.06
B11	2.512 ± 0.034	1.124 ± 0.017	< 0.019 ± 0.002	2.016 ± 0.033	0.714 ± 0.012	1.32 ± 0.05
C1	2.345 ± 0.038	1.121 ± 0.017	< 0.007 ± 0.001	1.865 ± 0.025	0.709 ± 0.015	1.30 ± 0.06
C4	2.230 ± 0.031	1.115 ± 0.015	< 0.009 ± 0.001	1.735 ± 0.031	0.698 ± 0.016	1.26 ± 0.06

*Date not included in the mean because of stratigraphic anomalies. †Activity ratio.

described in (*13*) are presented in Table 1.

Four Nicolas samples gave an average age of 130,000 years before present (B.P.). One sample from the Saint terrace gave an age of 108,000 years B.P. Four samples from Mole reef gave an average age of 81,000 years B.P. The ages of one sample from Saint and one from Mole (the latter collected below the crest in the sea-spray zone) are stratigraphically anomalous. The reason for these two high ages is unknown as all sample screening criteria were passed. If we ignore these two samples, the age-height relationships of the first three terraces can provide an indication of the tectonic uplift history of this part of Haiti and, if we assume constant uplift rates, an indication of the height of sea level during reef formation time. A sea level of +2 to +6 m above present-day level has been well documented (*14*) at about 125,000 years B.P. Under the assumption that the sea level stood 6 m higher than at present during the peak of Nicolas reef formation, an uplift rate of 0.35 m per 1000 years can be calculated (52-m minimum crest elevation less 6-m difference between sea level 130,000 years B.P. and today = 46 m per 130,000 years). Assuming constant uplift, the sea level during formation of the Saint reef stood at −10 m relative to the present (elevation of 28 m less uplift of 108,000 years multiplied by 0.35 m per 1000 years) and −13 m during the final formation of Mole reef (present elevation of 16 m less uplift of 81,000 years multiplied by 0.35 m per 1000 years).

The relative heights and absolute ages of the Haitian terraces are in close agreement with results reported for the lower three reefs on Barbados (*10, 15*). Matthews (*16*) has calculated past sea level heights from the Barbados data under the assumption of constant uplift along transects perpendicular to the reef trends. The averages, assuming +6 ± 2 m for Rendezvous Hill–Barbados III (125,000 years B.P.), are −16 ± 3 m for Ventnor–Barbados II (105,000 years B.P.) and −15 ± 3 m for Worthing–Barbados I (82,000 years B.P.) and are in general agreement with the Haitian results. Figure 1c presents the age and position of former sea level as determined from the Haitian data set. Also plotted are results from Barbados and from another sequence of raised reefs on New Guinea. The New Guinea (*6, 17*) average sea level heights from transects, assuming +6 m for 124,000 years B.P., are as follows: −12 ± 6 m for 103,000 years B.P.; −19 ± 6 m for 82,000 years B.P.; −28 ± 1 m for 60,000 years B.P.; −38 ± 5 m for 40,000 years B.P.; and −41 ± 1 m for 28,000 years B.P.

The presence of confirming data sets from three areas widely separated geographically and tectonically indicates that the constant uplift assumption is reasonable for these locations and provides a strong stratigraphic argument for our paleosea level estimates approximately 108,000 and 81,000 years ago. The additional evidence from Haiti demonstrates that dated sequences of raised reefs can provide sea level estimates available in no other way. Studies in New Guinea (*6*) have demonstrated that high uplift areas may record more raised reefs and more sea level information (*18*).

On the basis of oxygen isotope measurements of *A. palmata* from the raised reefs on Barbados, Fairbanks and Matthews (*8*) assigned Emiliani's oxygen isotope substages 5a, 5c, and 5e to the 82,000-year B.P. Worthing terrace, the 105,000 year B.P. Ventnor terrace, and the 125,000 year B.P. Rendezvous Hill terrace, respectively. We correlate the Haitian sequence of raised reefs (Mole, Saint, and Nicolas) to those of Barbados (Fig. 1d). The benthic foraminiferal oxygen isotope records of cores V19-29 (equatorial Pacific) (*19*) and Meteor 12392 (subtropical Atlantic) (*20*) are the best and most detailed available for isotope stage 5 (Fig. 1d). It has been suggested that such isotope records are controlled primarily by temperature (*21*), primarily by continental ice volume (*7, 22*), and by the combination of ice volume, temperature, and floating ice caps in the Arctic Ocean (*23, 24*). For control by continental ice volume alone, a maximum calibration of 0.11 per mil per 10 m (*8*) has been measured. The benthic isotope record (Fig. 1d) shows a 0.7 per mil difference between substage 5e (Nicolas) and substages 5a or 5c (Mole or Saint), which corresponds to a sea level difference of 70 to 77 m. The physical stratigraphic evidence from Haiti and Barbados, however, allows less than 20 m. Clearly, sea level approximations based on assumptions of constant temperature during interstadials (*8*) provide gross overestimations when compared to the congruent data from a variety of emergent islands.

Growth of continental ice changes the $\delta^{18}O$ (*25*) composition of seawater as well as sea level by moving isotopically light water onto the land as glaciers. Temperature change alters the isotopic composition of benthic foraminifera by 0.22 per mil per degree Celsius. Thick floating ice caps which grow from atmospheric precipitation rather than frozen seawater also alter the oceanic isotopic composition but do not affect sea level. If limits can be put on floating ice-cap effects during the last interglacial, then we can calculate ocean temperature changes by using our measured sea level changes from the raised reef data. Earlier workers (*23, 24*) have overestimated isotopic effects from a floating ice cap because they used an incorrect volume for the Arctic Ocean. Menard and Smith (*26*) have given a more reliable value of 12.6×10^6 km^3. Calculations based on the use of their depth and area distribution reveal that a floating ice cap to a depth of 1 km would occupy 5.4×10^6 km^3. This is equivalent to a change of only 0.14 per mil in mean oceanic $\delta^{18}O$ composition [if we assign a value of -35 per mil (*23*) for the ice].

Williams *et al.* (*24*) assumed that a floating Arctic ice cap 1 km thick formed during glacial substage 5d and remained until the present interglacial. If so, 0.14 per mil must be subtracted from the 0.7 per mil $\Delta\delta^{18}O$ between interglacial Nicolas and Mole or Saint. From the known sea level change of 18 m, a bottom temperature change of 1.6°C can be calculated (*27*). If, more reasonably, no floating ice cap accumulated during these interstadials, the full 0.7 per mil benthic $\Delta\delta^{18}O$ is used and the temperature change is 2.2°C. In the latter case temperature accounts for 70 percent and continental ice volume for 30 percent of the effects.

RICHARD E. DODGE
Oceanographic Center, Nova University, Dania, Florida 33004
RICHARD G. FAIRBANKS
Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York 10964
LARRY K. BENNINGER
Department of Geology, University of North Carolina, Chapel Hill 27514
FLORENTIN MAURRASSE
Department of Physical Science, Florida International University, Miami 33199

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$$(\delta^{18}O_{glacial\ ice})(\Delta SL) + (\Delta\delta^{18}O_{benthic\ foram} - 0.22\ \Delta T)(MOD - \Delta SL) = 0$$
28. We have used these parameters to be consistent with the dating of other reef material. There is a large uncertainty for the half-life of ^{230}Th; a value of 8.03×10^4 years has also been reported in *Table of Isotopes* [C. M. Lederer and V. S. Shirley, Eds. (Wiley, New York, ed. 7, 1978)].
29. This project was funded by NSF grants EAR-7919721 (R.E.D. and L.K.B.) and OCE 8200717 (R.G.F.) and the ARCO Foundation (R.G.F.). We thank R. K. Matthews and A. L. Bloom for reviewing the report, the Haiti Department of Mines and Mineral Resources for field support, C. J. Poix for field assistance, R. Free for laboratory assistance, and P. McCoy for drafting. This is contribution No. 3399 from Lamont-Doherty Geological Observatory of Columbia University and a contribution from Nova University Oceanographic Center.

7 April 1982; revised 18 June 1982

Residential Firewood Use in the United States

Abstract. *An empirical relation between residential firewood use and population density was developed from survey data for 64 counties in New England and was corroborated by data from other states. The results indicate that usage is concentrated in urbanized areas of the Northeast and north central states and that about 9.0 to 11.0 percent of U.S. space heating input is from firewood. No constraints due to the supply of wood were apparent in 1978–1979. These findings have implications for effects on air quality.*

Uncertain oil supplies and steep price increases for petroleum and natural gas have led to increased use of alternative fuels for home heating. Sales of wood stoves and efficient fireplaces are estimated to be about 1 million units per year (*1*). Although wood smoke is generally regarded as benign by the public, there is concern about effects on ambient air quality and health that might result from widespread use of wood fuel (*2*) and about accidents from harvesting the wood (*3*). To assess these effects data on firewood usage, and in particular, estimates of the spatial density of wood use (cords per square mile or kilograms per hectare) are needed.

Most surveys of the use of firewood for space heating have reported data for states, with occasional breakdowns to regions of a state. The New England Fuelwood Survey (*4*), however, provided data for counties in New England for the 1978–1979 heating season. These survey data were used to develop the following equation for the 64 mainland counties, excluding islands.

$$\text{Cords used per household per } 10^4 \text{ degree days} = 3.087 \pm 0.25 - (0.322 \pm 0.05)\ \ln(\text{population density}) \quad (1)$$

where population density is expressed as persons per square mile with the 95 percent confidence interval shown (*5*). Equation 1 was then applied to all counties in the conterminous United States to develop estimates of wood usage based on the number of households in the county (1970 census) and the 30-year average heating degree days (*6*). Spatial patterns of usage throughout the country on the basis of Air Quality Control Regions (*7*) (Fig. 1) show concentrations in