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Revised Reconstruction of Middle and Late Pleistocene Sea-Level Changes Based on New Chronologic and Morphologic Investigations in Barbados, West Indies

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ABSTRACT

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In an application of the relatively new technique of ESR (Electron Spin Resonance) dating, an extensive chronological and morphometric study has been carried out on coral reef tracts in Barbados. These sequences have been used in previous studies (Bender *et al.*, 1979) to reconstruct paleo-sea-level elevations for the middle and upper Pleistocene, concluding in the so called "Barbados-Model." The new data set implies that this model is subject to a far larger uncertainty than previously claimed due to geochronological problems and local variation in the uplift rate.

ADDITIONAL INDEX WORDS: *Paleo-sea-level, chronostratigraphy, ESR-dating, U-series dating, marine Quaternary, uplift-rate.*

INTRODUCTION

Barbados is situated along the axis of the submerged Barbados ridge, about 160 km east of the island arc of the Lesser Antilles. The island is located between 13°02′ and 13°20′N and 59°25′ and 59°39′W and covers an area of about 430 km^2 (Figure 2). Its maximum north-south and east-west lengths are 32 km and 24 km, respectively. The highest point of the island is Mt. Hillaby, at 339 m. From a distance the island appears as a broad dome, terraced on its slopes by Pleistocene reef tracts. Most of the island (86%) is covered by fossil reefs which attain a maximum thickness of more than 130 m in the south-eastern part. On the remaining 14% of the island, Tertiary strata are exposed in the so called "Scotland District" (Figure 1). Two major reef complexes dominate the geomorphology of Barbados: the "2nd High Cliff" (*ca.* 500,000 yrs) and the "1st High Cliff" (Barbados III, 125,000 yrs) as described by MESOLELLA (1968). Holocene reef formation occurs exclusively on the western margin.

The tectonic setting of the islands of the Lesser Antilles has been discussed by JORDAN (1975) and WESTBROOK *et al.* (1984). Barbados is the highest point of the Barbados ridge and lies between the Barbados and Tobago trenches. The uplift of the island is a result of the migrating subduction zone on the east, but is also affected by an interaction near the junction of the three lithospheric plates in the area (North American, South American and Caribbean Plates). The subduction of the oceanic lithosphere has resulted in "en enchelon" thrust faulting at the foot of Barbados ridge and is largely responsible for the tectonic instability of the island. On the south-west part of the island coral rock formation took place during the Pleistocene emergence of the Barbados coastline with only minor evidence of faulting of the coral rock formation.

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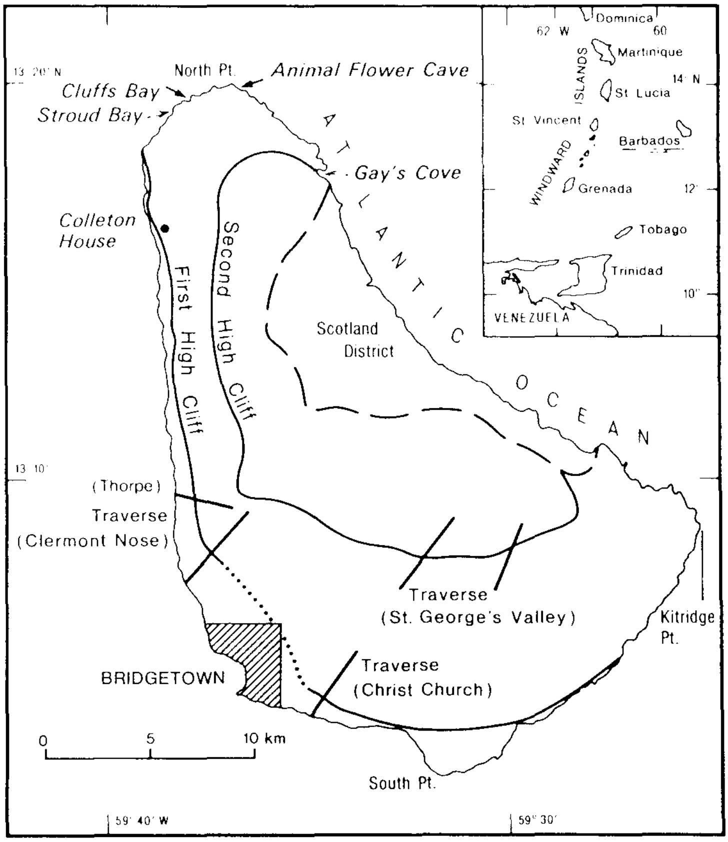

Figure 1. General map of Barbados with location of the investigated traverses.

PREVIOUS STUDIES OF REEF CHRONOLOGY AND SEA-LEVEL HISTORY

MESOLELLA (1968) demonstrated that the reef tracts were a result of accumulation of fringing reefs during eustatic sea-level changes along a tectonically rising coast. He demonstrated the zonation of reef facies and indicated superposition of several individual reefs. Several events were identified by U-series dating of corals: the youngest deposits are formed at the lowest position and near the present coast; the older ones are found today at successively higher elevations. Based on the reconstruction of the reef facies, MESOLELLA concluded that the terrace topography was a product of relatively continuous emergence. BROECKER *et al.* (1968) and MESOLELLA *et al.* (1969) assigned ages to the three youngest reef complexes (Barbados I, II and III) of 82,000, 105,000 and 125,000 yrs, respectively, which independently verified the progressive emergence of the island. The rate of tectonic uplift (in m/1,000 yrs), necessary for the determination of paleo-sea-level, has been calculated along each traverse. The estimation follows the equation: uplift rate equals present height of reef crest of Barbados III (less 6 m original elevation) divided by 125,000 yrs. From an assumed Barbados III original sea-level elevation of +6 m, BROECKER *et al.* (1968) calculated Barbados I sea-level positions from three profiles on the west coast and from one on the south coast of −14 m (profile A), −16 m (profile B), −13 m (profile C) +and −13 m (profile D) and Barbados II sea-level elevations of −10 m (profile B) and −13 m (profile C).

BROECKER *et al.* (1968) and MESOLELLA *et al.* (1969) suggest a glacio-eustatic origin of the sea-levels defined by coral reefs, imprinted on a tectonically emergent coast. The terraces were thus correlated with the astronomical cycles as defined by MILANKOVITCH (1941). MESOLELLA (1968) extended this concept by assigning all reef complexes to this curve. By extrapolating the uplift rates of the younger reefs, Mesolella deduced that the oldest reef complex must be about 600,000 yrs old. In contrast to subsequent workers on Barbados, Mesolella employed a generally falling eustatic sea-level model for the Quaternary (ZEUNER, 1958; FAIRBRIDGE, 1961, 1971; discussed in RADTKE, 1989). Based on an original elevation (35 m) of the 484,000 yr BP sea-level position (2[nd] High cliff, age astronomically deduced) and the 127,000 yr BP stand (Barbados III, 1[st] High Cliff, 6–7 m, age radiometrically determined), Mesolella calculated an average eustatic fall of sea-level of 7.6 m/100,000 yrs. He also calculated sea-levels for other events during the Pleistocene along several traverses using the following equation: $L = E - (R \times T)$ (here L is the sea-level of the high stand when the terrace was formed relative to present sea-level, E is the present day elevation of the terrace, R is the respective average tectonic uplift rate and T is the age of the terrace).

For many years research continued to concentrate on the same traverses (*i.e.*, west coast, south coast and south-central area). Based on the original dates, MATTHEWS (1973) attempted to provide further evidence for a constant uplift model during the last 130,000 yrs and provided the following estimates of eustatic paleo-sea-levels:

Table 1. *Estimates of paleo-solvents.*

	Clermont Traverse	Christ Church Traverse
Barbados I	−15 m a.s.l.	16m
II	−15m	18m
III	+6m	+7m

Assumed uplift rate for Clermont: 0.43 m/1,000 yrs; Christ Church; 0.23 m/1,000 yrs (MATTHEWS 1973).

Among the (few) criticisms of this model, STEARNS (1976) questioned the validity of constant uplift between 125,000 and 80,000 yr BP. He considered this "Barbados Model" as only a first approximation of Quaternary paleo-sea-level positions. Later, by dating non-recrystallized, fossil corals with He/U method (methodological discussion in RADTKE and GRÜN, 1988), BENDER *et al.* (1979) were able to establish a chronology for the middle Pleistocene and to extend the models of BROECKER *et al.* (1968) and of MATTHEWS (1973) (Figure 2).

BENDER *et al.* (1979) concluded the following:

(1) The model for determining Pleistocene paleo-sea-level positions by assuming constant uplift is generally applicable, although in the case of the Christ Church traverse a greater uplift rate before 125,000 yr BP is apparent.

(2) There is a clustering of paleo-sea-level elevations near the present datum (particularly St. George's Valley traverse, see Figure 2) which suggests that the volume of the global ice masses during interglacial periods has remained relatively constant for at least the last 700,000 yrs. This implies that no general fall of sea-level (*vis à vis* ZEUNER, 1958) has taken place since the early mid-Pleistocene; and that in areas of relative tectonic stability, only the highstands around 125,000, 300,000 and 500,000 yr BP would rise slightly above present.

RE-EVALUATION OF PALEO-SEA-LEVEL ELEVATIONS

In order to validate the relatively new technique of ESR (Electron Spin Resonance) dating, we decided to work on Barbados, with its well-investigated and dated framework. In the course of our study we also remeasured the altitudes of the reef tracts. It was possible to obtain ≥ 500,000 yrs ESR dates on non-recrystallized corals (RADTKE *et al.*, 1988; RADTKE & GRÜN, 1988; ESR methodology in GRÜN, 1989).

In the following, this new data set from the "classic" Barbados traverses is used to present new calculations of paleo-sea-level elevations. The basic assumption of constant uplift is made for the sake of comparison with the previous results. ESR dates presented in the figures are generally the means of several samples. For details, *e.g.*, sites, number of samples, methodological considerations, *etc.*, see RADTKE (1989).

Unfortunately, it is not possible at this time

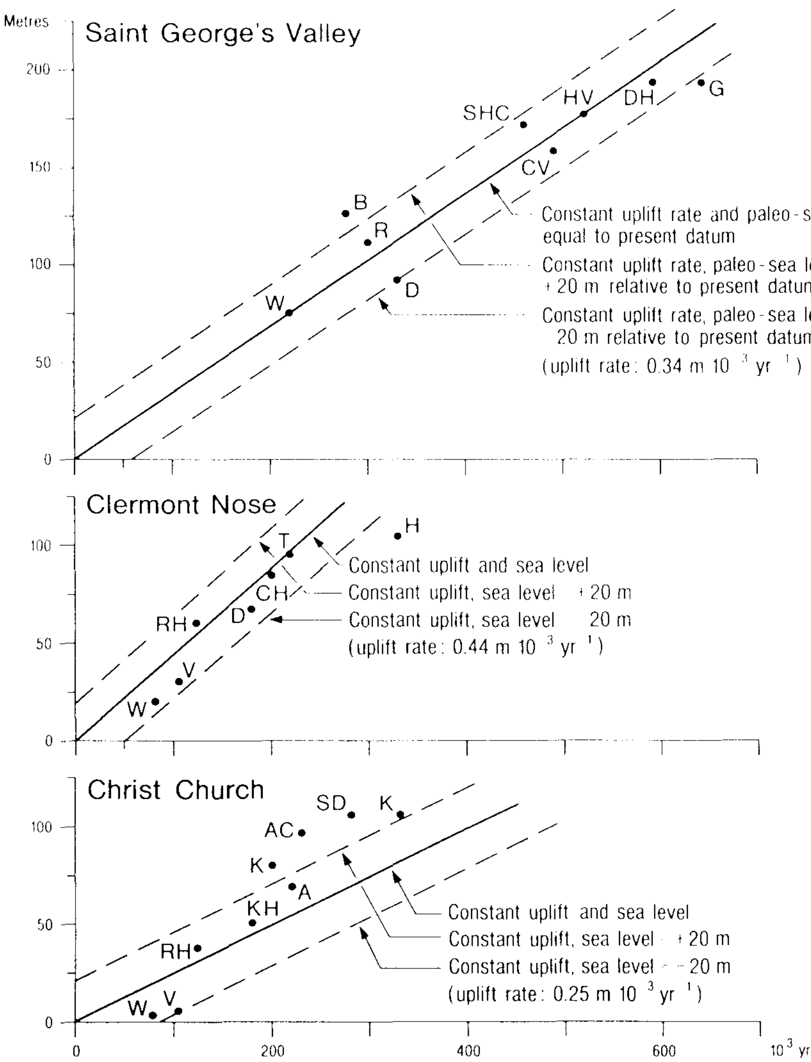

Figure 2. Plot of reef-tract elevation along Saint George's Valley, Clermont Nose and Christ Church Traverse versus He/U ages. Superimposed lines show where points would fall for three uplift models: (1) constant uplift rate and paleo-sea-level equal to present datum; (2) constant uplift rate, paleo-sea level +20 m relative to present datum; (3) constant uplift rate, paleo-sea level −20 m relative to present datum. Initials given for terrace names in Figures 3 and 6 and Bender *et al.*, 1979 (after Bender *et al.*, 1979).

to compare the results from the St. George's Valley traverse due to an insufficient ESR data-base (future studies are aimed at this area to supplement the current data set).

There was generally no difficulty in confirming the chronologic and topographic position of the Stage 5e reef complex of Barbados III (Rendezvous-Hill). However, some uncertainty seems to exist in the topographic data of the height of Barbados I and II (Worthing and Ventnor) which were used for the reconstruction of the original sea-level elevations (MESOLELLA, 1968, BROECKER *et al.*, 1968; MESOLELLA *et al.*, 1969; MATTHEWS, 1973; and BENDER *et al.*, 1979). This problem is discussed in more detail in RADTKE (1989).

As in the former studies, the Kendal Hill and Kingsland/Aberdare I reef tracts in the Christ

Church Traverse (Figure 3) have been assigned to penultimate interglacial (Stage 7) around 200,000 yr BP with ESR dating. Our results indicate the Kingsland/Aberdare II and Adams Castle sites have clearly older ages than the ones previously published, and are probably of an age corresponding to Stage 8/9. ESR has provided a higher precision in this age range than He/U ages (see RADTKE & GRÜN, 1989; RADTKE, 1989). A similar discrepancy can be seen for Kent Terrace which previously had been assigned to Stage 9. It now appears more likely to correspond to Stage 11. This allocation, however, is based on single ESR and Th/U dates which certainly require further verification. A single ESR date of the St. David's Terrace indicates that this highest terrace is probably older than previously suggested.

These revisions of the chronostratigraphy of the Christ Church Traverse have important consequences on the reconstruction of the sea-level history (Figure 4). The conclusion of BENDER *et al.* (1979) that a stronger uplift took place before the last interglacial was based on "positive anomalies" (unfilled circles in Figure 4) of paleo-sea-level elevation (*e.g.* +39 m for St. David's (SD); see Figure 2). Our data (filled circles in Figure 4) support a constant Pleistocene sea-level hypothesis (*i.e.* interglacial sea-levels generally with maxima near the present datum as proposed by BENDER *et al.* 1979), without the necessity of postulating these anomalies.

Geomorphic correlation, particularly of Barbados I, II and III, is more straightforward on the Clermont and Thorpe Traverses (Figures 5 and 6) along the west coast, owing to the greater uplift rates which more clearly separate the reef tracts.

The ESR dates of 296,000, 318,000 and 350,000 yr BP for the Thorpe terrace favor a correlation with Stage 9 rather than Stage 7 as proposed by BENDER *et al.* (1979) based on He/U dates of 210,000 and 220,000 yr BP. Furthermore, the reef complexes of Husband and Lodge are probably one interglacial older than indicated in BENDER *et al.* 1979. This one-interglacial-shift in age has the effect of creating a more negative trend (below present sea-level) in the paleo-sea-level values (Figures 2, 7 and 8).

The data from the Christ Church Traverse generally result in more positive trends (sea-level positions above the present datum), and more negative ones along the Thorpe and Clermont Traverses. This suggests that constant uplift throughout Barbados is rather unlikely, and that the island has been variably affected by tectonic influences during the Pleistocene.

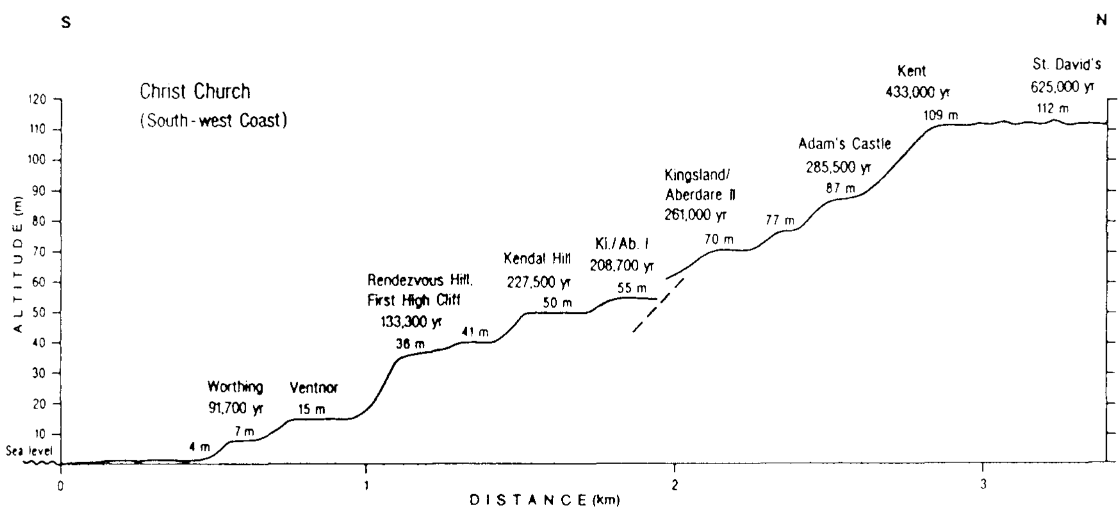

Figure 3. Christ Church Traverse at southwest coast (after Radtke *et al.*, 1988).

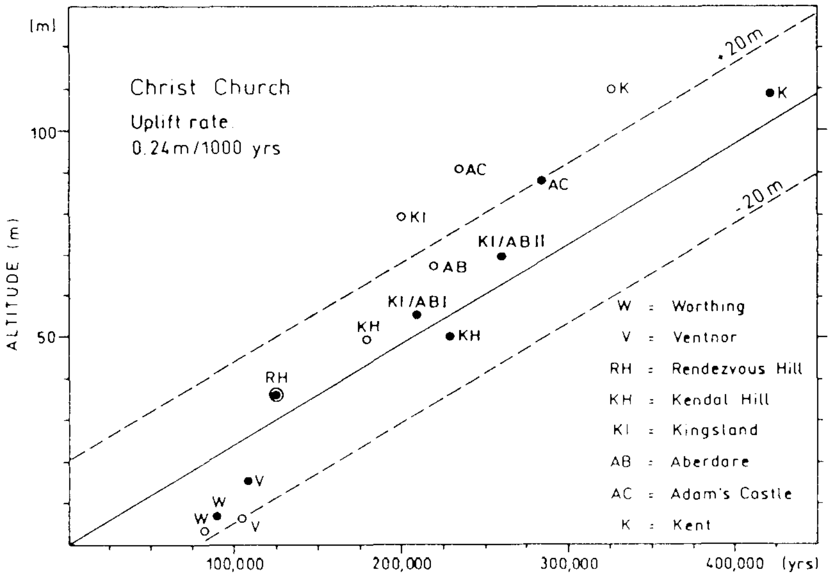

Figure 4. Plot of reef-tract elevation of Christ Church Traverse versus ESR ages (Unfilled circles: Bender *et al.*, 1979, compare Figure 2; Filled circles: Radtke, 1989).

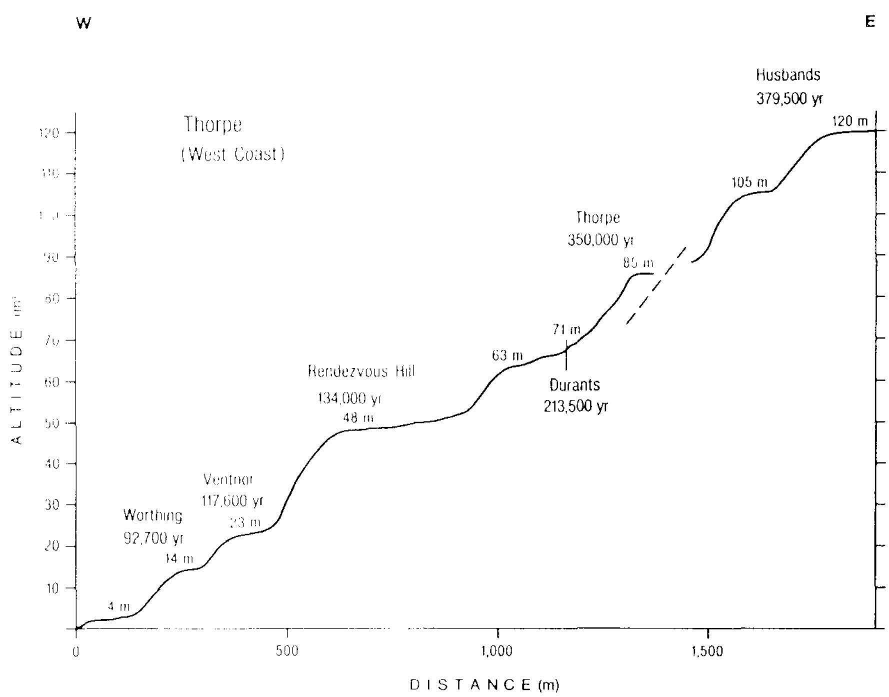

Figure 5. Thorpe Traverse at west coast (after Radtke *et al.*, 1988).

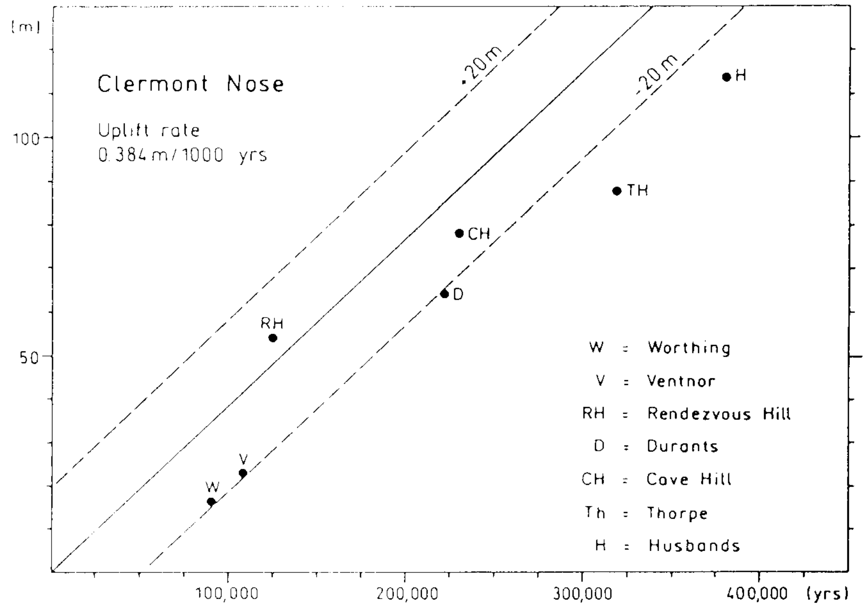

Figure 6. Clermont Nose traverse at west coast (after Radtke *et al.*, 1988).

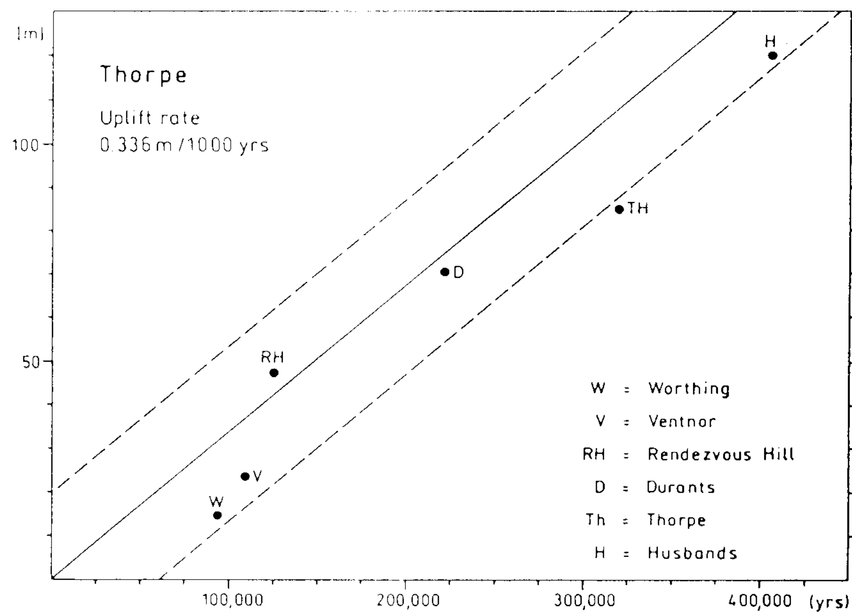

Figure 7. Plot of reef-tract elevation of Thorpe Traverse versus ESR ages (after Radtke, 1989).

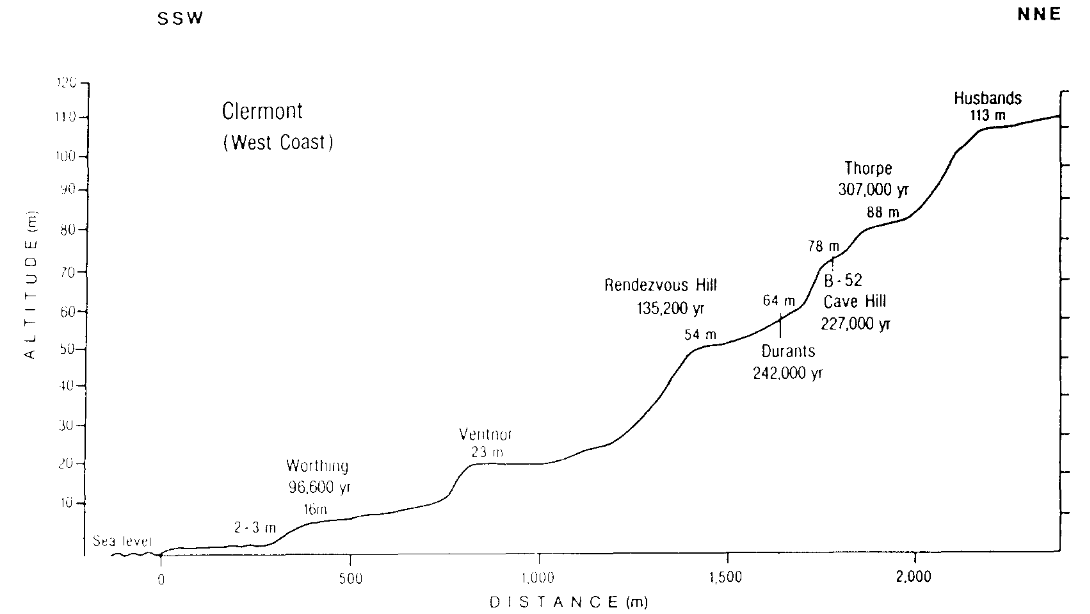

Figure 8. Plot of reef-tract elevation of Clermont Nose Traverse versus ESR ages (after Radtke, 1989).

THE "BARBADOS MODEL" AND ITS CONSEQUENCES FOR PLEISTOCENE SEA-LEVEL RECONSTRUCTION

Even the preliminary results of the "Barbados Project" initiated by Matthews were an impressive contribution to the late Quaternary marine chronostratigraphy. The identification and dating of the three last interglacial high stands indicated by raised coral reefs of Barbados I, II and III at ages of 82,000, 105,000 and 125,000 yr BP provided the global foundation for all future studies. Together with investigations from Papua New Guinea (CHAPPELL, 1974; BLOOM *et al.*, 1974) and Bermuda (HARMON *et al.*, 1983) the so called "Barbados Model" represents one of the most-cited studies in investigations of sea-level change in the Quaternary. The original "Model" identified the three stages of the last interglacial period, and later incorporated the older middle Pleistocene stages. Subsequently, Barbados I, II and III were correlated to isotope Stages 5a, 5c, and 5e, respectively (SHACKLETON & MATTHEWS, 1977) and were assigned paleo-sea-level elevations of −15.5 ±3 m (82,000 yr BP), −16.5 ±3 m (105,000 yr BP) and +6.5 ±2 m (125,000 yr BP).

The remapping of the Worthing (Barbados I) and Ventnor (Barbados II) fossil cliffs along the Christ Church traverse required re-definition of this last interglacial sequence. Given the same assumptions as MATTHEWS (1973), the new data result in paleo-sea level elevations of −13 and −10 m for Barbados I and II, respectively.

The dating of the type localities in Barbados by mass spectrometric method (Th/U) (EDWARDS *et al.*, 1987a,b) produced results similar to those obtained by ESR dating, although with a much smaller uncertainty of about ± 2% (see Table 2). Compared to the Barbados III level at 125,000 yrs BP, the ages of the 5a and 5c high stand in Barbados (and particularly at other localities around the world) are not as clearly defined. This has important implications for the paleo-sea-level elevations of these events.

The most critical point of this investigation is that a precision of ±2 m as claimed by previous studies (*e.g.* MATTHEWS, 1973; BENDER *et al.*, 1979) is implausible (given the inadequacies of dating and morphometric control, and even assuming constant uplift, which is doubt-

Table 2. *Ages of selected stratigraphic units.*

Stratigraphic unit	Mesolella *et al.*, 1969, Th/U	Edwards *et al.*, 1987a, MS–Th/U	Radtke *et al.*, 1988, Radtke and Grün 1988, ESR
Barbados I	82,000 yr BP	87,700 yr BP	92,000 yr BP
Barbados II	105,000 yr BP	112,000 yr BP	110,000 yr BP
Barbados III	125,000 yr BP	125,000 yr BP	136,000 yr BP

ful). It is obvious that sea-level positions of Stages 5a and 5c have been below the level of the last interglacial maximum 5e. However, as a result of our investigation on Barbados, the determination of the sea-level elevations of the two submaxima—based on the (hypothetical) assumptions of (1) sea-level at 125,000 was +6 m and (2) constant uplift of Barbados—cannot be determined (with precision) better than -15 ± 5 m.

The discussion becomes more complex for determining the accuracy of paleo-sea-level calculations because former interglacial periods up to 700,000 yr BP is involved. BENDER *et al.* (1979) assigned an error of $\pm$ 25m for the 300,000 yr reef and $\pm$ 50 m for the 640,000 yr reef. These values have been calculated from the St. George's Valley traverse; the uncertainty in the uplift rate of the entire St. George's Valley sequence is $\pm 10\%$, an additional uncertainty of $\pm 10\%$ is introduced by uncertainty in the terrace age (dating errors), and the uncertainty of present reef-crest elevation is ± 5 m (BENDER *et al.*, 1979). Their errors for the other traverses ought to be somewhat smaller. However, as we have shown in this work, the older reef systems of the Thorpe, Clermont and Christ Church Traverses seem to be one isotope stage older, resulting in a shift of paleo-sea level towards "lower" values (see Figures 4, 7, 8).

The assumption that each reef represents a (relatively) high stand of the sea in the Quaternary is probably correct, but the correlation of the Barbados reef tracts with these interglacial events by He/U dating appear hypothetical. A revised view seems necessary through further research. The statement by BENDER *et al.* (1979) that: "We believe the correlations are reliable to plus or minus one interglacial isotope stage" is apparently too optimistic. The implication, that the elevation of the sea during the interglacial maxima over the last 700,000 years has not changed very much, is certainly fascinating. However, this deduction cannot be proven by the Barbados results—even if future results, particularly for the last 400,000 years, may strengthen this impression. However, without a larger number of comparable investigations on other coastlines of the world, it seems hazardous to construct a general model of sea-level change from this singular data set.

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RÉSUMÉ

Ce papier présente une application de la datation par électro résonnance magnétique pour une chronologie et une étude morphométrique des coraux aux Barbades. Ces séquences avaient été déjà utilisées antérieurement (Bender et al., 1979) pour une reconstitution des paléo-élévations du niveau de la mer au Pléistocène moyen et supérieur et avait abouti au "modèle des Barbades". Ces nouvelles données impliquent que ce modèle est beaucoup plus incertain que celle présumée ultérieurement. Cela est du à des problèmes de chronologie, comme à la variation locale de la montée du niveau.—*Catherine Bressolier (Géomorphologie EPHE, Montrouge, France).*

RESUMEN

Se ha realizado un estudio cronológico y morfométrico en los rastros coralinos de Barbados aplicando una técnica de datación relativamente nueva, la ESR (Electron Spin Resonance). Estas secuencias has sido utilizadas en estudios previos (BENDER et al., 1979) para reconstruir los paleo-niveles del mar en el Pleistoceno Medio y Superior, concluyéndose en el lamado "Modelo Barbados". El nuevo juego de datos demuestra que este modelo está sometido a un mayor grado de incertidumbre del obtenido previamente debido a problemas geocronológicos y a variaciones locales de la velocidad de ascenso del fondo.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

ZUSAMENFASSUNG

Mit Hilfe der vergleichsweise neuen ESR-Altersbestimmungsmethode wurde die Chronostratigraphie der fossilen quartären Korallenriffe auf Barbados untersucht. Darüber hinaus wurde versucht, die bisher durchgeführten Paläomeeresspiegelberechnungen von BENDER et al. (1979) zu überprüfen. Durch eine intensive Datierung und eine neue morphologische Aufnahme der Riffsequenzen, die z.B. dem "Barbados-Modell" zur Berechnung der letztinterglazialen sowie später auch der älteren pleistozänen Hochstände dienten, konnte festgestellt werden, daß eine z.T. beträchtlich höhere Unsicherheit hinsichtlich der Genauigkeit der Höhenlagen der Paläomeeresspiegel existiert, als bisher angenommen wurde.