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Uplift History along the Clermont Nose Traverse on the West Coast of Barbados during the Last 500,000 Years—Implications for Paleo–Sea Level Reconstructions

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ABSTRACT

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Barbados is one of the few localities in the world with uplifted fossil coral reef tracts that provide detailed insights into interglacial sea level change during the Late and Middle Pleistocene. Since the late 1960s, several sea level reconstructions have been established, each contributing to the "Barbados Model" of sea level change. Considering the global importance of paleo–sea level research in Barbados, it is important to note that substantial issues are still unresolved regarding the results obtained thus far. In this paper, we deal with one of the major problems of paleo–sea level reconstruction on Barbados—the assumption of constant uplift—which we test along the Clermont Nose traverse on the southern part of the west coast of Barbados. We demonstrate that uplift along this transect was not, in fact, constant over the last 500,000 years. The data from Clermont Nose strongly support the argument that anticlinal warped areas might have complex tectonic histories and are therefore not necessarily suitable for Pleistocene sea level reconstructions.

ADDITIONAL INDEX WORDS: *Quaternary sea level reconstruction, Barbados, electron spin resonance dating, neotectonics.*

INTRODUCTION

Today's models of past sea level changes are complex. Although our knowledge has increased enormously over the last 40 years, many problems concerning the concepts of sea level change still exist or have only recently been recognized. This particularly applies to the reconstruction of Middle Pleistocene sea level variations, which have been derived from fossil coral-reef terraces or deep-sea oxygen isotope records from benthic foraminifera. Fossil reefs can theoretically reveal sea level history for the whole Quaternary. In contrast, isotope methods provide a detailed continuous sea level record for the past 140,000 years (*e.g.,* SHACKLETON, 1987) that is calibrated with fossil reef data, but for which the uncertainties in the sea level estimates are still relatively high (±20 m).

The Barbados coral reef terraces sequence is one of the few type localities in the world that provides insights into interglacial sea level changes during the Late and Middle Pleistocene. Since the late 1960s, several sea level curves have been reconstructed, and each has contributed to the "Barbados Model" of sea level change. During this interval, a large number of dating results have been measured (for references see, *e.g.,* GALLUP *et al.,*, 2002; SCHELLMANN and RADTKE, 2004a, 2004b) which have helped to generate a dense geochronologic framework for the Barbadian fossil reef tracts. However, the accuracy of the data becomes more and more questionable as sample age increases, and substantial unresolved problems remain that could invalidate results obtained so far.

A fundamental assumption when reconstructing paleo sea levels from elevated marine terraces or coral reef tracts is that long-term tectonic uplift has been constant for all coastal terraces. In addition, in Barbados, the elevation of the Last Interglacial sea level high stand is assumed to be 6 ± 2 m (*e.g.,* RADTKE, 1989). This paper deals with the first of these assumptions—constant uplift—through a detailed consideration of newly acquired paleo–sea level data from the famous Clermont Nose traverse on the southern part of the west coast of Barbados (Figure 1).

Clermont Nose Traverse: Previous Research

Coral reef terraces stretch roughly south to north along the west coast of Barbados between Batts Rock Bay and Speightstown. They run parallel to the modern shoreline and are up to several hundred meters wide (Figure 1). Terrace distributions, sediment facies structures, and absolute dating results have been published by, among others, MESOLELLA (1968) for different sites along the west coast; STEINEN, HARRISON, and MATTHEWS (1973) and BLANCHON AND EISENHOWER (2001) for the vicinity of Holetown; RADTKE, GRÜN,

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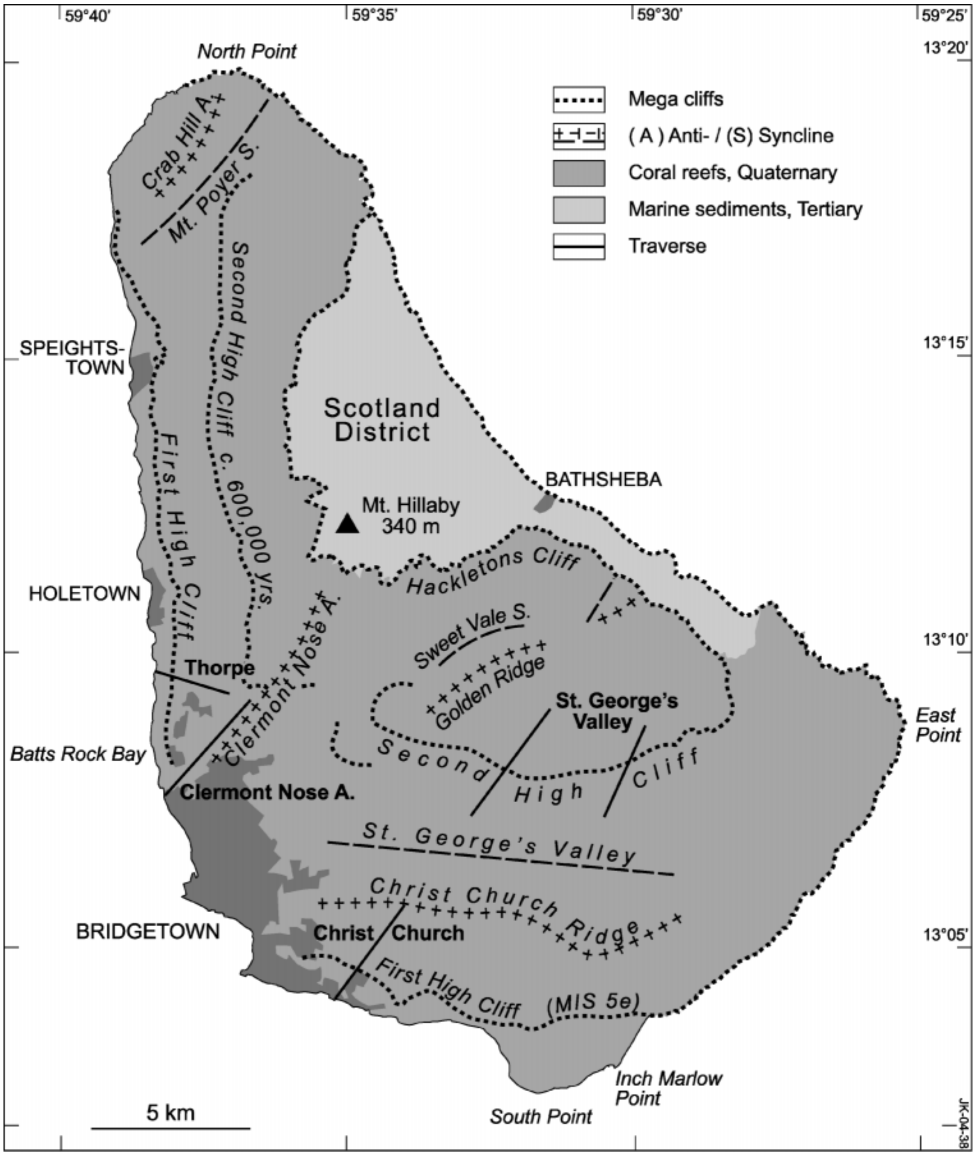

Figure 1. Site map and location of the Clermont traverse on the west coast of Barbados.

and SCHWARCZ (1988) and RADTKE (1989) for the Thorpe and Clermont Nose traverses; GALLUP, EDWARDS, and JOHNSON (1994) for Clermont Nose and Holders Hill; and MESOLELLA *et al.* (1969), BENDER *et al.* (1979), EDWARDS *et al.* (1997), BARD, HAMELIN, and FAIRBANKS (1990), KU *et al.* (1990), GALLUP *et al.* (2002), SCHELLMANN and RADTKE (2002), and SPEED and CHENG (2004) for the Clermont Nose area. The results of the research mentioned above is presented and discussed in detail in SCHELLMANN and RADTKE (2004b).

The Clermont Nose area has the highest average uplift rate on Barbados, at least since the Last Interglacial maximum, with estimates ranging from approximately 0.44 to 0.49 m per 1000 years (RADTKE and SCHELLMANN, 2002) to a maximum of 0.53 m per 1000 years (SPEED and CHENG, 2004). The marine isotope stage (MIS) 5e coral reef terrace, which is commonly referred to as the first high cliff (or Rendezvous Hill terrace), has a maximum elevation of 61 m above sea level (asl) on the Clermont Nose traverse and drops to less than 40 m asl to the north and south. This warping indicates an anticlinal deformation of the coral reef terraces in this area. It is commonly referred to as the Clermont Nose or Clermont–Mount Hillaby anticline (BENDER *et al.,* 1979; TAYLOR and MANN, 1991). Thus, this area has the best potential for observing preserved uplifted coral reef terraces that developed during interglacial sea level submaxima.

Many researchers have previously described and dated a sequence of constructional coral reef terraces in the Clermont Nose area (*e.g.,* BENDER *et al.* 1979; BROECKER *et al.,* 1968; EDWARDS *et al.,* 1997; GALLUP, EDWARDS, and JOHNSON, 1994; GALLUP *et al.,* 2002; MESOLELLA *et al.,* 1969; RADTKE, 1989; Radtke, Grün, and Schwarcz, 1988; Radtke and Grün, 1990). This lower part of the sequence includes:

- Worthing terrace, 20 m asl, approximately 83,000 years (MIS 5a);
- Ventnor terrace, 30 m asl, approximately 104,000 years (MIS 5c);
- Rendezvous Hill terrace, 61 m asl, approximately 121,000–127,000 years (MIS 5e);
- Durants terrace, 67 m asl, approximately 206,000 years (MIS 7).

For the more elevated older terraces, ages were reported by Mesolella *et al.*(1969) on the basis of α-spectrometric U-series dating; Bender *et al.* (1979) on α-spectrometric Th/U and He/U dating, Gallup, Edwards, and Johnson (1994) on thermal ionization mass spectrometry (TIMS) ^{230}Th dating, and Radtke, Grün, and Schwarcz (1988) and Radtke (1989) on electron spin resonance (ESR) dating. These studies provided the basis for the following commonly used subdivision of the upper coral reef terraces on the Clermont traverse:

- Cave Hill terrace, 78–85 m asl, approximately 227,000 years (ESR), corresponding to MIS 7;
- WAN-B outcrop, 91 m asl, approximately 204,000 years (MIS 7) (Gallup, Edwards, and Johnson, 1994);
- Thorpe terrace, 94–100 m asl, approximately 220,000–300,000 years (Th/U), and 307,000 years (ESR), thus corresponding to MIS 9;
- Husband or Lodge terrace, 107–113 m asl, estimated at 360,000 or 380,000 years on the basis of He/U and ESR dating, corresponding to MIS 11;
- So-called Unnamed terrace, 122 m asl, age unknown.

METHODS

Field Studies and ESR Dating

Our investigations of coral reef terraces on Barbados began in 1990 and were stimulated by a belief that the existing morphologic and stratigraphic model for the island did not reflect the complex evolutionary history of the Barbados coral reef terraces. In particular, no research had challenged the established morpho- and chronostratigraphic model first proposed by Mesolella (1968) and Bender *et al.* (1979). No studies had detailed morphostratigraphic investigations that exceeded the generally preferred local descriptions or included the dating of reef terraces only along traverses. Therefore, it was necessary for us to conduct extensive field investigations focusing on the distribution and elevation of coral reef terraces and to combine morphostratigraphic with geochronologic research by dating a large number of sample sites.

The morphostratigraphy described herein includes a differentiation of coral reef terraces, wave-cut platforms, and other erosive features, such as notches and cliffs, and an examination of various sedimentary features, such as coral reef facies types and discontinuities. The study of these morphostratigraphic features combined with geochronologic analyses (ESR, Th/U) allowed us to estimate the tectonic uplift rates and to identify areas in which tectonic movements have varied over time. These investigations were especially important for precise sea level reconstructions.

Electron spin resonance dating was conducted as described by Schellmann and Radtke (2001a). The accuracy of ESR dating significantly improved with the use of the new D_E-D_{max} plot procedure for D_E determination (Schellmann and Radtke, 2001a; Schellmann *et al.,* 2004), such that this new methodology is sufficiently precise to allow for a differentiation between MIS 5a, 5c, and 5e, as well as MIS 7 and 9 or 11. Last Interglacial samples can now be classified into the main isotope stages as well as their substages $5a_1$ and $5a_2$, 5c, and 5e (Schellmann and Radtke, 2004a). Accurate differentiation between stages 9, 11, and older stages remains a challenge because of considerable alterations and recrystallization processes that can occur within coral samples. The problem of fading, a natural "ESR rejuvenation" characterized by the recombination of electrons that increases until steady state is achieved, also needs to be considered. Physically, the upper dating limit of the ESR method is defined by the steady state, although age underestimations progressively occur before reaching this limit. Progressive underestimation of ESR ages, which occurred especially with the dating of coral samples from Middle Pleistocene terraces, could not be avoided, and further research is needed to develop a method that recognizes such diagenetic recrystallization and fading effects.

We reduced the tendency to underestimate the ESR age of Middle Pleistocene coral samples by (1) dating numerous samples from one locality, (2) sampling more than one locality in one coral reef terrace, and (3) using only the oldest ESR dating results for chronostratigraphic interpretations. In the past, the extent of fading and other age "rejuvenation effects" were underestimated, and it was assumed that these effects did not exceed more than a few thousand years. However, we have shown that this age underestimation can be much larger. Despite the problem of fading of Middle Pleistocene samples, the new ESR dating results nevertheless provide a detailed picture of Late and Middle Pleistocene reef formation for Barbados (reported herein), which challenges existing chronostratigraphies on the basis of α-spectrometric and TIMS U-series dating methods. These methods are also not without their own problems, including isotope mobilization and varying $^{234}U/^{238}U$ composition of the ocean water (Bard, Hamelin, and Fairbanks, 1990).

Mapping and sampling along the Clermont Nose standard traverse was conducted mainly during our field trips of 1999 and 2000. Samples were collected for ESR dating and for TIMS Th/U dating by E.K. Potter, T. Ezat, and M. McCulloch (Australian National University, Canberra). The ESR dating results are presented in Figure 2. The TIMS data will be published elsewhere (*e.g.,* Potter *et al.,* 2004; Schellmann *et al.,* 2004). Figure 2 also shows a field map of sample sites and different terrace levels (n = Niveau). A correlation of the terraces to the commonly used terminology is also illustrated in the legend of Figure 2.

RESULTS

The lowest coastal terrace in the study area is the beach sand terrace at up to 2 m asl, assumed to be of mid-Holocene age. A partly destroyed beach rock is preserved along the

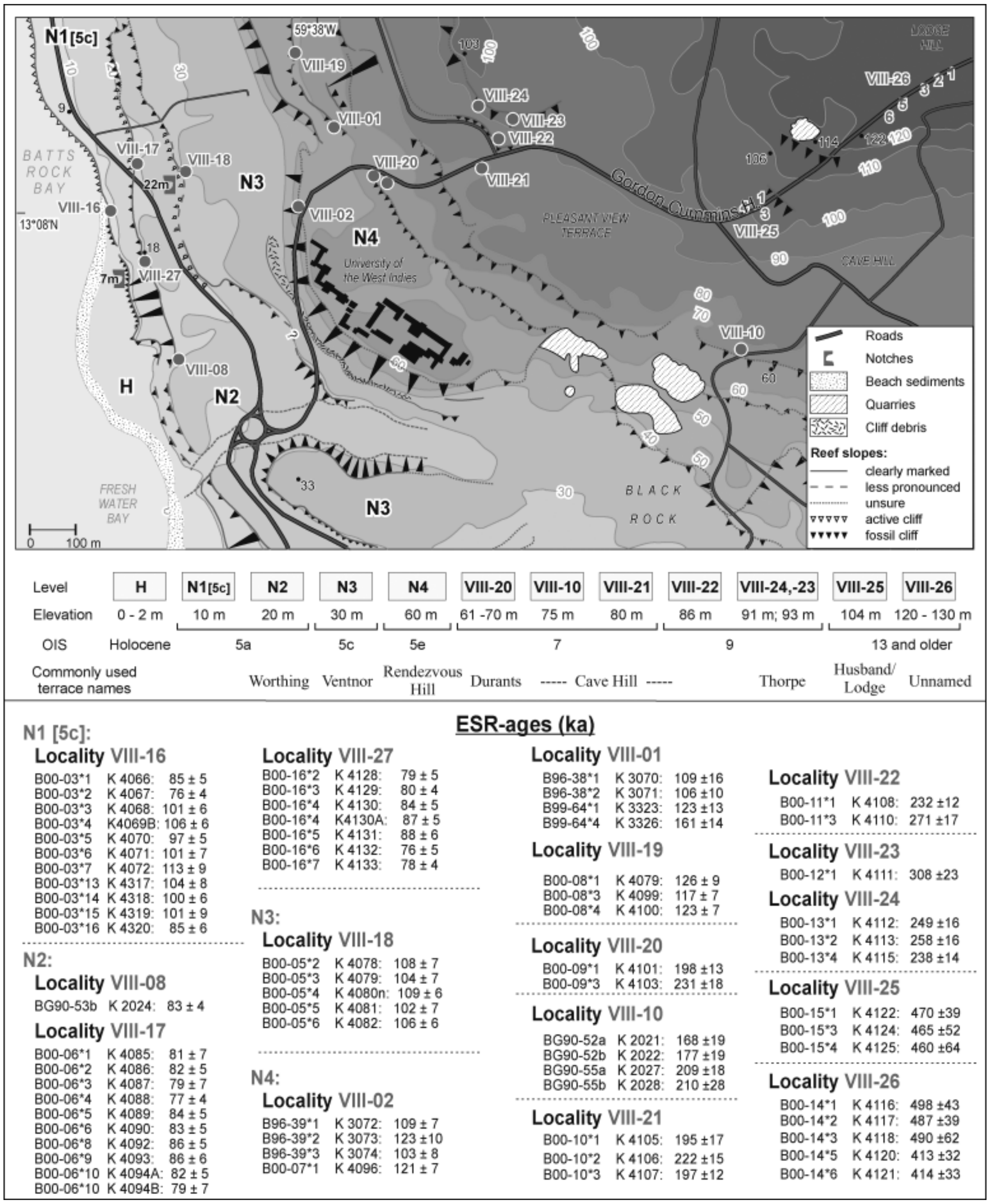

Figure 2. Clermont Nose traverse area with distribution of coral reef terraces and ESR ages of dated localities along the traverse. For color version of this figure, see page 357.

sandy beach of this terrace, and a deep MIS 5a notch at *ca.* 7 m asl is cut into MIS 5c coral limestone of the $N1_{[5c]}$ wave-cut platform at the proximal landward margin of the former mid-Holocene cliff line. The $N1_{[5c]}$ wave-cut platform is approximately 10 m asl. It is well developed northeast of Batts Rock Bay, where it reaches a width of up to 180 m. The abrasion terrace is cut into a deeper forereef coral facies, which is approximately 106,000 ± 8000 years (MIS 5c). The younger ESR ages of 76,000 ± 4000 and 85,000 ± 5000 years (MIS 5a), derived from samples embedded in the uppermost 1 m of the profile, indicate that the uppermost layer consists of reworked coral fragments, which were deposited during the abrasion process. However, dense vegetation and the height of the profile have precluded confirmation of the existence of an unconformity at the base of the presumed upper MIS 5a layer. Nevertheless, the morphostratigraphic context implies that the platform was formed during late MIS 5a.

The $N1_{[5c]}$ wave-cut platform is younger than the MIS 5a coral reef formation of the N2 (Worthing) terrace at 18 to 20 m asl. The seaward part of the N2 terrace consists of an *Acropora palmata* reef crest facies that is at least 2–3 m thick. A deep notch has developed at the base of the former N2 cliff line at the proximal landward side of the N2 terrace. The notch was cut into the *A. palmata* reef crest facies of the N3 or Ventnor terrace during the growth of the N2 coral reef. The N2 terrace was ESR dated at three localities: VIII-17, VIII-27, and VIII-08 (Figure 2). The ESR ages range between 76,000 ± 5000 years and 88,000 ± 6000 years, with a mean age of 82,000 ± 5000 years; the mean of the upper 10% of all ages is 88,000 ± 7000 years. As described above (see SCHELLMANN and RADTKE, 2004b, for details), because of the "rejuvenation" of the ESR ages, only the maximum ESR ages should be used for dating here, and these indicate an early MIS 5a age for the N2 terrace. This terrace correlates to the T-1a$_2$ terrace at the south coast of Barbados, which was ESR dated at 85,000 ± 7000 years (SCHELLMANN and RADTKE, 2004b). A late MIS 5a terrace with an ESR age of 74,000 ± 5000 years is preserved at the southern coast of Barbados (SCHELLMANN and RADTKE, 2004b). The N1$_{[5c]}$ wave-cut platform at approximately 10 m asl might correlate to this late MIS 5a terrace if a stronger uplift rate is considered for the Clermont Nose area (*ca.* 0.44–0.49 m per 1000 years).

The N3 terrace at approximately 30 m asl is located landward of N2. An *A. palmata* reef crest is preserved on the seaward part of N3, which is approximately 100 m wide and more than 3 m thick. East of sample site VIII-18, a broad lagoon developed behind the N3 reef crest and is filled with sand and coral rubble. Five ESR ages were determined for sample site VIII-18. They range between 102,000 ± 6000 years and 109,000 ± 6000 years, with a mean age of 106,000 ± 7000 years. Therefore, N3 formed during MIS 5c and correlates to one of the three MIS 5c terraces at the south coast of Barbados.

The Rendezvous Hill (N4) terrace, located at 60–61 m asl, is the next oldest coral reef terrace east of Batts Rock Bay. The University of the West Indies is largely situated on this terrace, and the N4 coral reef facies are exposed along Gordon Cummins Highway below the University. The uppermost 3.5 m comprise a compact *A. palmata* reef crest facies, which is underlain by an *Acropora cervicornis* reef slope deposit, at least 6–8 m thick, with some rounded boulders of *A. palmata, Siderastrea* sp. and *Montastrea* sp. Pebbles of rounded *A. cervicornis* predominate in its basal part. This continuous reef facies sequence overlies a second *A. palmata* reef crest facies at 45 asl, which is more than 4 m thick and mixed with different species of head coral. The precise age of this sequence is still unknown. ESR ages of four *A. palmata* samples from the uppermost reef crest facies range between 103,000 ± 8000 years and 123,000 ± 10,000 years. The mean of the two oldest ages is 122,000 ± 9000 years, indicating that N4 (including *A. palmata* reef crest and underlying *A. cervicornis* reef slope facies) was formed during late MIS 5e.

North of University Road, a higher sublevel of N4 is preserved at 61–62 m asl. It was ESR dated at sample sites VIII-01 and VIII-19 (Figure 2). Neglecting the extreme age value of sample B99-64*4, which might have been a reworked sample, the maximum ESR ages are similar to those determined for sample site VIII-02, located at University Road, and indicate an MIS 5e age for this small terrace rim.

As already stated, mapping of the higher and older terraces in this area of the island is still in progress. However, the ESR dating results presented in Figure 2 indicate an MIS 7 age for both of the coral reef terraces located east of the university: the first at 61–70 m asl (Figure 2, sample site VIII-20) and the second at approximately 75–80 m asl (Figure 2, sample sites VIII-10 and VIII-21). These results agree well with former penultimate interglacial U-series and ESR dating results (see Clermont Nose Traverse: Previous Research) from Durant Terrace (67 m asl) and Cave Hill Terrace (78 to 85 m asl). Two higher coral reef tracts were most probably formed during MIS 9 and appear at approximately 86 m asl (Figure 2, sample site VIII-22) and 91–93 m asl (Figure 2, sample sites VIII-23 and VIII-24). Sample sites VIII-23 and VIII-24 correspond to the Thorpe terrace, dated to approximately 307,000 years (ESR) by RADTKE, GRÜN, and SCHWARCZ (1988) and RADTKE (1989).

Remarkably, the highest coral reef terraces, located at "only" 104 and 122 m asl, seem to be as old as 470,000 and 500,000 years, respectively (Figure 2, sample sites VIII-25 and VIII-26). The lower sample site VIII-25 at 104 m asl corresponds to the Husband or Lodge terraces, for which BENDER *et al.* (1979) and RADTKE (1989) estimated an age of 360,000 years or 380,000 years on the basis of He/U and ESR dating. Sample site VIII-26 at 122 m asl might correlate to the so-called Unnamed terrace level, which has not been dated as yet. Reef terraces of sea level highstand MIS 11 are to be investigated in more detail in the future.

DISCUSSION

Many scientists who base their research on the classical Barbados Model assume a 6 ± 2 m higher sea level during the Last Interglacial *ca.* 130,000 years ago (MIS 5e) and a constant rate of uplift for all coastal terraces (see RADTKE, 1989, for discussion). On the basis of this assumption, various models suggest that sea level alternated between 10 and 20 m below present sea level during subsequent MIS 5c and MIS 5a approximately 105,000 years ago (MIS 5c) and approximately 80,000 years ago (MIS 5a$_1$ and 5a$_2$). Both assumptions require critical evaluation. Reef stages from the last interglacial transgression maximum (MIS 5e) are located between about 20 and 60 m asl on Barbados. Assuming that these reef stages record the same sea level highstand, it is an unavoidable conclusion that uplift rates have varied spatially and, most probably, temporally. In southern Barbados, for example, the region located to the east of South Point is not suited for paleo–sea level estimates because this region has experienced differentiated tectonic uplift (SCHELLMANN and RADTKE, 2001b, 2002, 2004a, 2004b). The reef terraces in the vicinity of the Christ Church traverse, which was generally used for sea level calculations in the past, are warped anticlines. In contrast, the reef terraces preserved to the east of the Christ Church standard traverse are not affected by the Christ Church anticline, and their reef crests maintain a constant elevation above present sea level in the area to the west of South Point. This suggests that a spatially uniform uplift has affected this coastal area, but not necessarily that the rate of uplift has been constant over time.

The relatively low elevations of the coral reefs MIS 9 to MIS 13 situated in the Clermont Nose traverse area provide strong evidence for a much greater uplift of the Clermont Nose area since the Last Interglacial maximum compared

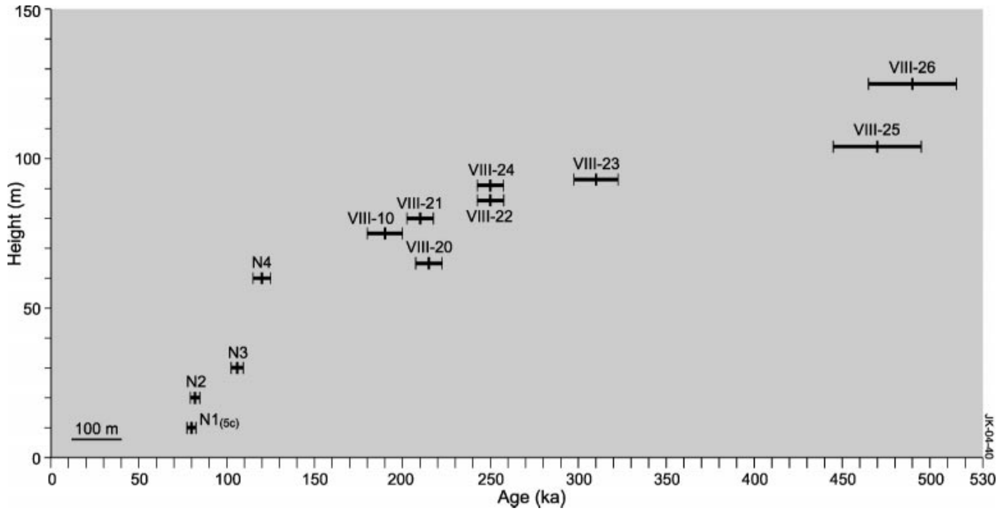

Figure 3. Ages (ESR) of the different terraces (see Figure 2) plotted against the altitude of the terraces along the Clermont Nose traverse. Note that the uplift rate increased after 200,000 y.

with the preceding period (Figure 3). For example, if we assume a constant uplift at the rate calculated from the present height of the Last Interglacial terrace at 61 m asl (*ca.* 0.47 m per 1000 years), the oldest MIS 13 coral reef tract, which is preserved at sample site VIII-26 (122 m asl), should have an elevation of approximately 220 to 245 m asl, whereas, in fact, its present height is only 120 to 125 m asl. Even if one assumes that denudation has lowered the original reef surface, that sea level was somewhat lower than present at 500,000 years ago, it follows that uplift has not been constant over the period of the last 500,000 and 200,000 years. This could be a result of discontinuous local mud diapirism (SPEED, 1990; *Speed and Larue,* 1982; TORRINI AND SPEED, 1989). The latter might have caused the anomalous elevation of Barbados above the Barbados Accretionary Prism and is probably still active. However, *direct* evidence is lacking to suggest that the uplift rate has not been constant over the last 130,000 years, so the sea level calculations made by others (see, *e.g.,* GALLUP *et al.,* 2002) might still be valid. Nevertheless, we believe that the data from Clermont Nose *strongly supports* the argument presented by SCHELLMANN and RADTKE (2004b) that anticlinal warped areas have a complex tectonic history and are not necessarily suitable for Pleistocene sea level reconstruction.

CONCLUSIONS

Geomorphologic and geochronologic investigations along the "classical" Clermont Nose traverse at the west coast of Barbados clearly demonstrate that the assumption of a constant uplift is not valid for at least the period between 500,000 and 200,000 years. This finding implies that this anticlinal warped area is not suitable for paleo–sea level reconstructions in general. Unfortunately, this means that both standard traverses on Barbados (Clermont Nose and Christ Church, see Discussion), which were generally used for paleo–sea level reconstructions in the past, are affected by differentiated tectonic uplift. Therefore earlier attempts to calculate paleo–sea level values on the basis of studies from this part of Barbados, including those deep-sea foraminfera-based reconstructions that use data from here for calibration, must be considered with caution. Although it is impossible to prove that the uplift rate has switched to a constant uplift mode between *ca.* 200,000 years and present, it might be dangerous to base far-reaching theories on such an assumption. Thus, our results can be seen as a contribution to a more critical and careful look at the widely applied Barbados Model and the paleo–sea level data obtained on Barbados, which were commonly derived from the discontinuously uplifted Clermont Nose and Christ Church areas.

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