Evolution of marine terraces and sea level in the last interglacial, Cave Hill, Barbados

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ABSTRACT

The uplifted marine terrace of last interglacial (stage 5e) age at Cave Hill, Barbados, has been investigated with views toward terrace architecture, developmental processes, and sea level history. Methods include stratigraphic analysis of new deep exposures, precise ^{230}Th geochronology, and geomorphic mapping. Cave Hill was central to earlier studies that led to important ideas on reef and terrace evolution but with which we find significant disagreement. We present a new model of terrace evolution that emphasizes the role of marine erosion, deposition of carbonate cover during the full eustatic cycle rather than only at highstand, and principal reef development during transgression rather than at highstand by keep-up rather than catch-up growth. The new model and geochronology contribute to an improved understanding of surficial processes during emergence of uplifting coral coasts and of global sea level changes in the last interglacial.

Transgression in stage 5e at Cave Hill was accompanied by progressive marine erosion of a terrace floor and receding seacliff and deposition of a seaward-thickening reefal wedge on the floor and above limestones of stage 6 and 7 ages. The wedge contains a diachronous basal *Acropora palmata* fringe reef. This is overlain by an in-place *A. cervicornis* reef that aggraded progressively during sea level rise. The transgressive phase took place between 136 ka (or earlier) and ca. 128 ka. During highstand between ca. 127 and 120 ka, the floor and seacliff continued to recede landward. Regression began at or after ca. 120 ka, and sea level fell ≥37 m below the highstand level by ca. 115 ka. In stage 5c, the seaward front of the last interglacial terrace was eroded landward an uncertain distance. The sea level record at Cave Hill has implications for timing and constituent events of the penultimate glacial, the last interglacial highstand, and the fall in sea level at the transition from stage 5e to stage 5d.

Shoreline angles, which are isochronous linear geomorphic features, are the most accurate markers of sustained highstand levels. Highstand levels and uplift rates interpreted from *A. palmata* in Barbados are less accurate and lower because the coral grew mainly in transgression. The coral-derived data therefore include uncertainties of depths of growth and collapse.

Keywords: marine terraces, last interglacial, sea level history, reefal facies, past highstand levels.

INTRODUCTION

Barbados is an actively rising island capped by thin limestone whose deposition records the island's progressive emergence through the tropical littoral zone (Fig. 1A). The surface of the limestone cap includes locally preserved marine terraces that have been linked to past high sea levels and successfully dated as far back as stage 7, ca. 200 ka (Broecker et al., 1968; Mesolella et al., 1969; Edwards et al., 1987; Gallup et al., 1994). Early studies of Barbadian terraces led to a widely accepted hypothesis of terrace and reef development (Mesolella, 1967, 1968; Mesolella et al., 1970).

We reexamined Barbadian terraces with views toward their architecture, developmental processes, and records of sea level and tectonics. The conclusions of earlier authors that ages of successive terraces increase upslope and that terraces contain shallow-water coral are undoubted. Our findings disagree, however, with the definition of terraces by Mesolella et al. (1969, 1970) as spaced narrow belts of *Acropora palmata*, the principal shallow-water reef-framework coral of the Caribbean, and their strictly constructional origin of terrace relief. We define terraces on a geomorphic basis as a succession of contiguous broad belts, each having had marine erosion as a prime formative process, together with reefal and carbonate clastic deposition. Such differences are critical to hypotheses of terrace formation and to correct assessment of past sea levels and uplift rate.

Our interpretations of Barbadian terrace evolution are based on island-wide study of the geomorphology, stratigraphy, and structure of the limestone cap (Speed, 2001) and new and existing mass spectrometric ^{230}Th coral dates. We focus here on the last interglacial Rendezvous Hill terrace at Cave Hill (Fig. 1B) to illustrate field and age data that underpin a new model of terrace evolution. Cave Hill is the focus because it contains a new roadcut that cuts deeply across the seaward half of the Rendezvous Hill terrace and exposes the terrace floor and a basal *A. palmata* fringe reef. With a new model of terrace development and dating, we constrain sea level history during the last interglacial at Cave Hill and compare it to sea level histories interpreted from other reefal coasts and the deep-sea benthic foram record. We also point out problems in choice of terrace features and markers with which to identify sea level at eustatic highstand and ar-

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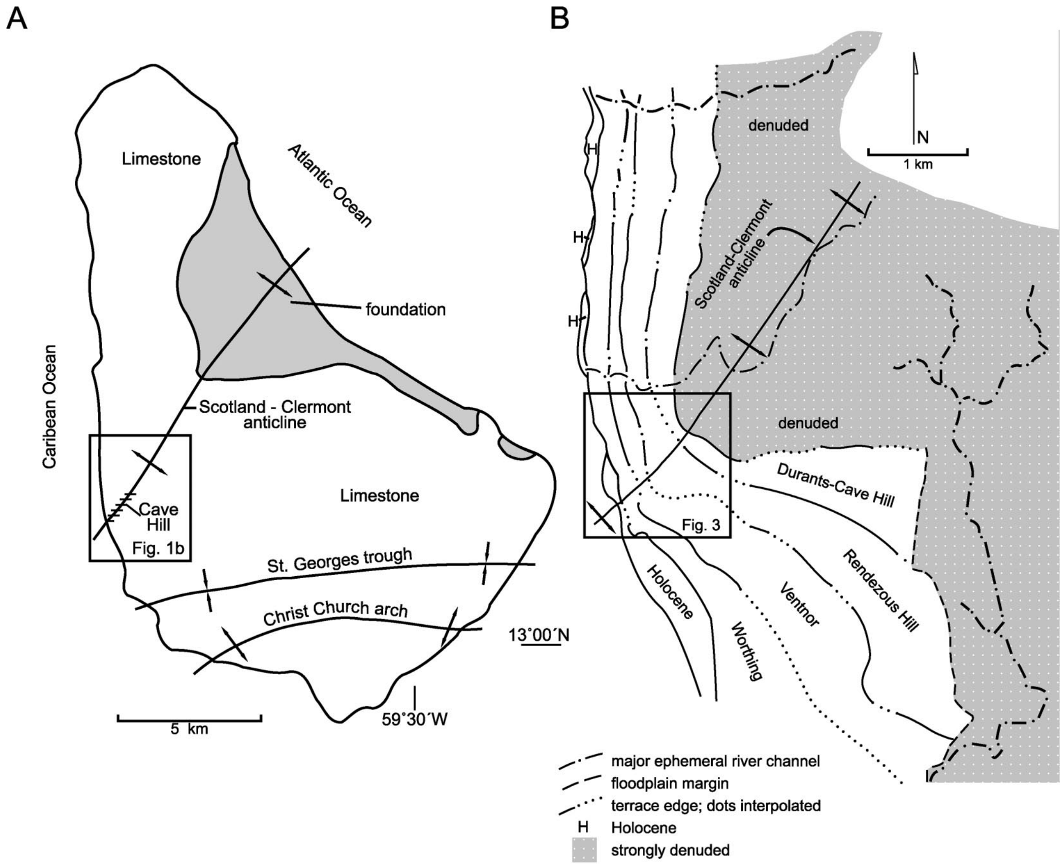

Figure 1. (A) Barbados island. Map shows areas underlain by Pleistocene limestone (no pattern) and Paleogene siliciclastic foundation (shaded) and axial traces of active major folds. (B) Map of marine terraces in region of Cave Hill. Terrace edges are marine cliffs with preserved (solid line) and denuded (dotted line) increments. Terrace areas are restored to eliminate local post–terrace denudation. In region east of terraces (shaded), marine geomorphic features have been totally denuded by subaerial agents.

gue that the terrace shoreline angle is the most apt.

GEOLOGIC BACKGROUND

The Cave Hill area extends from the modern shoreline upslope to ~100 m elevation. Farther inland, marine terraces are totally eroded (Fig. 1B). Cave Hill is underlain by island-capping littoral limestone, which is 30–60 m thick above a Paleogene siliciclastic foundation (Fig. 1A). The stratigraphy of outcropping limestone at Cave Hill is presented below. The stratigraphy of subsurface limestone is unknown. Active major folds control the rates of uplift, which vary island-wide from about zero to >0.6 m/k.y. (Speed, 2001). Cave Hill occupies the crest of the broad Scotland-Clermont anticline (Fig. 1A) whose width is ~4 km. Normal faults of small displacement (<1–5 m) locally cut the limestone cap on fold flanks and imply stretching downslope.

MARINE TERRACES AT CAVE HILL

Landforms

The surface morphology at Cave Hill includes four types of landforms: treads of marine terraces, cliffs of marine origin, features of post–terrace denudation, and a depression probably related to normal faults. The terrace treads are subplanar, shallowly seaward–dipping surfaces between marine cliffs. Marine cliffs are 5–15 m high and have generally coast-parallel strikes. Features of post–terrace denudation are gullies, bluffs, and hummocks, which are products of dissection and degradation of the marine landforms by runoff and spring sapping. The word ''denudation'' is used to distinguish subaerial from marine erosional processes. Denudation varies from slight degradation to complete effacement of marine landforms and has occurred episodically through the >200 k.y. history of Cave Hill.

Terrace Definition and Components

Terrace surfaces are defined by preserved or slightly denuded treads (Fig. 2). They extend upslope either to the base of a marine cliff, called a ''backcliff,'' or to a domain of post–terrace denudation. Downslope, treads are bound either by a marine cliff, called a ''forecliff,'' or a denudation domain. A backcliff is the forecliff of the next older terrace landward. In the absence of post–terrace denudation, the surface of Cave Hill would be a continuous succession of terrace treads and cliffs. The tread is underlain by contemporary carbonate deposits called terrace cover. Below the cover is the terrace floor, an unconformity on older limestone. Owing to denudation, the tread may be below its initial level, which is indicated by the highest horizon of cover. The intersection of the terrace floor and backcliff, also termed the base of the backcliff, is the shoreline angle, a linear

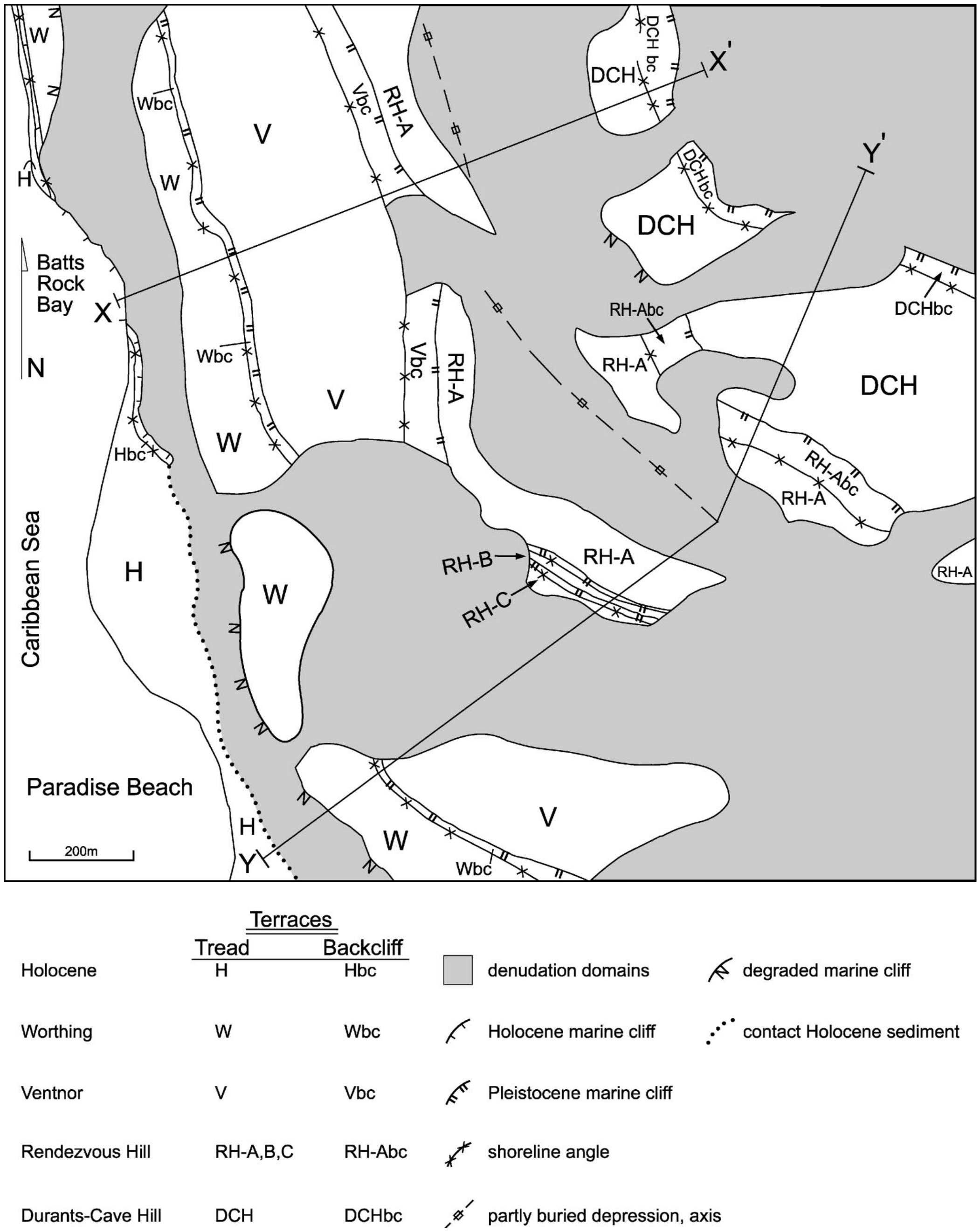

Figure 2. Geomorphic map of Cave Hill. Area location shown in Figure 1B. Moderately- to well-preserved marine terrace treads and backcliffs (bc) are differentiated from domains of strong post–terrace denudation (shaded).

geomorphic feature (Lajoie, 1986). Each terrace has an age range, which may be constrained by dating its cover.

With these definitions, we divided Cave Hill among four terraces and intervening cliffs. Terrace names are those used by Bender et al. (1979) for three of Mesolella's (1968) reef crests, and ages are from Gallup et al. (1994): Worthing (stage 5a), Ventnor (stage 5c), and Rendezvous Hill (stage 5e). Our fourth terrace, Durants–Cave Hill, of late stage 7 age, is newly defined. Figure 1B shows the regional distribution of the four terraces as contiguous belts interpolated through denuded tracts and lying seaward of a totally denuded region. Figures 2 and 3 illustrate at greater resolution the four terraces, denuded tracts, and other geomorphic features of the Cave Hill area. Properties of the four terraces are summarized in Table 1; the last interglacial Rendezvous Hill terrace is further discussed in the text.

Erosional Origin of Terrace Floors and Cliffs

Evidence that terrace floors are erosional is the truncation of underlying strata, as seen in roadcuts and denudation domains (Fig. 3). An erosional origin of backcliffs and forecliffs is

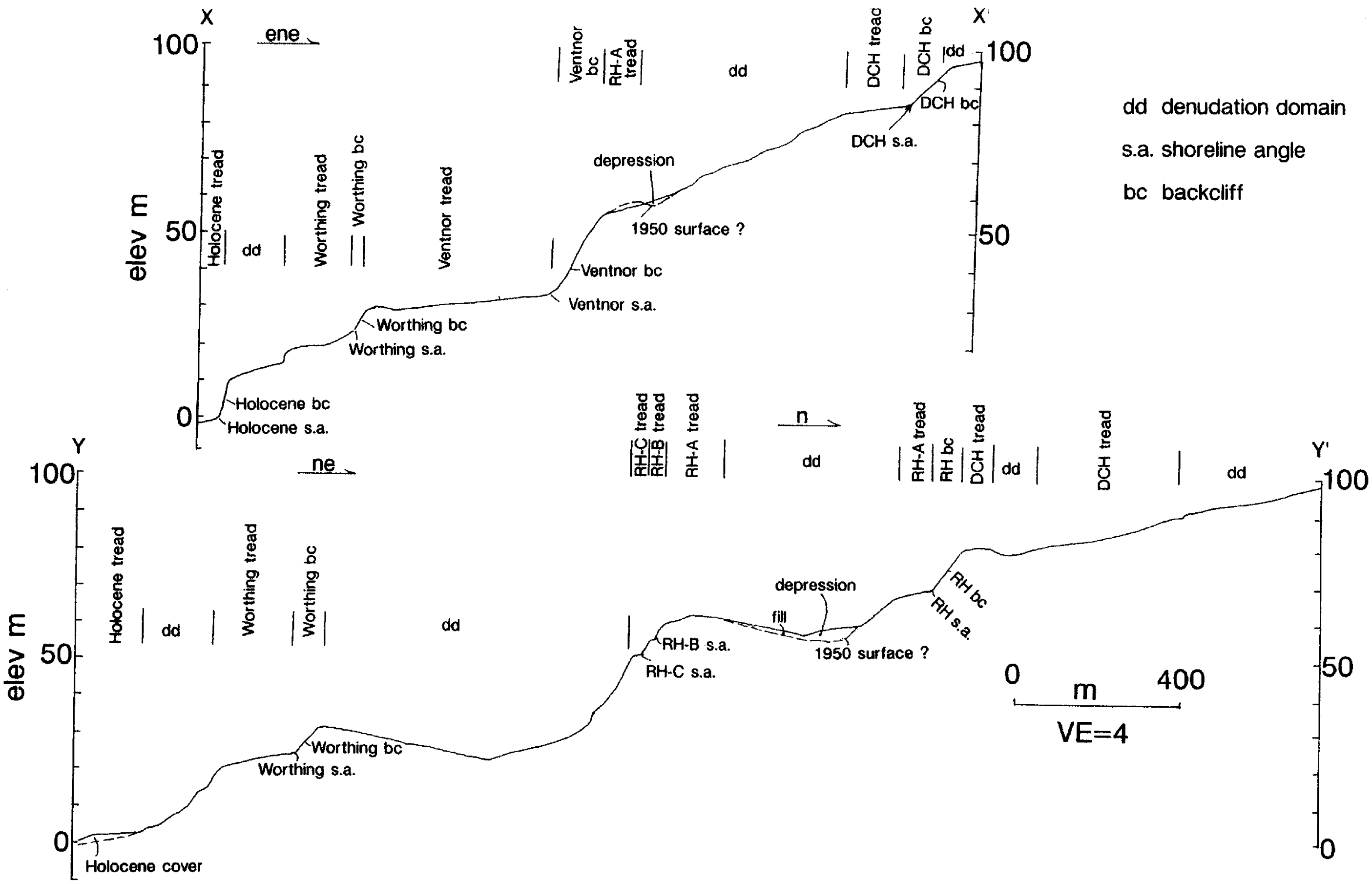

Figure 3. Geomorphic profiles at Cave Hill. Profile traces in Figure 2, which also gives a key to the unit abbreviations. Base of surface depression in Y–Y′ is inferred from 1950 aerial photographs. Domains dd are affected by post–terrace denudation.

indicated by the following: (1) the forecliff faces that cut down through terrace cover into older limestone; (2) the arbitrary truncation of limestone facies and clasts by cliff faces; (3) the general absence on Barbadian marine cliff faces of features and coral zonations that indicate cliffs developed by reefal or depositional construction (Speed, 2001); and (4) the assumption that ancient and modern seacliffs of Barbados formed by the same mechanism and the observation that modern cliffs on both leeward and windward coasts undergo erosional recession at rates of >10 m/k.y. (Speed, 2001).

Terrace floors are interpreted as diachronous surfaces of marine erosion that lengthened landward, following a recessing backcliff. Deposition of cover on the floor progressively followed the floor's erosion. The shoreline angle represents the most landward and youngest locus of the floor and the position at which further floor development was abandoned by regression. During the succeeding eustatic cycle and recession of a new seacliff, an unknown width and volume of the preceding terrace were excised before the final forecliff evolved. Thus, present-day terraces are only the landward remnants of their initial widths.

The depth of erosion of the floor is assumed proportional to the duration of sea surface at a given elevation during a eustatic cycle. During rapid transgression and regression, downcutting was probably small, whereas at a stillstand, downcutting was greater, perhaps down to some limiting depth of effective erosion by breakers (perhaps 10–12 m; Sunamura, 1994).

Conflict with Earlier Terrace Models

Mesolella (1968), Mesolella et al. (1969, 1970), and Bender et al. (1979) equated terraces with narrow belts drawn to connect discrete outcrops containing *Acropora palmata*. Where such belts occur, they are along the forecliffs of our terraces. The belts were interpreted as crests of coast-parallel, ridged barrier-like reefs that had grown up from a deep seafloor to shoal when rising sea level reached highstand for a sustained period. The Mesolella model considered the seaward-facing cliffs that border reef crests to have been constructed by reefal upward growth. In contrast, our terrace definition, based on landforms, accounts for the full width of tread between each cliff. Our backcliff is considered a product of synterrace erosion, not one of reef growth in the preceding highstand, and our forecliff is interpreted as the product of marine erosion in the development of the next younger terrace. In our view, terrace treads initially extended well seaward of their current seaward limits, which are the result of younger phases of seacliff recession by wave erosion.

Johnson (2001) has identified features at and near Cave Hill that he called notches: small, local, meter-high bluffs and slope changes. He interpreted them as products of shoreline erosion at stillstands. Only one of Johnson's many notches corresponds to a shoreline angle of one of our terraces (Rendezvous Hill subterrace B). None has the morphology of a true notch with indented profile

TABLE 1. MARINE TERRACES AT CAVE HILL

Terrace name	Age; elevation of s.a.	Morphology	Limestone cover	^{230}Th dates (ka)
Worthing	Stage 5a; 22 ± 1 m	Tread up to 300 m wide between Worthing backcliff and Holocene backcliff. Worthing backcliff cut into Ventnor unit.	Worthing unit. Max thickness ≥9 m. Clastic facies near s.a. Two reefal facies downslope: w1: mixed Ap + head framework at midslope; w2: Ac framework + clastic sediment farthest downslope.	Reefal facies w1: FS3, 83.3 ± 0.3 and FS 8, 87.2 ± 0.5 from G94; OC 26, 82 ± 2 from M69. Reefal facies w2: FA 3, 76.49 ± 0.34 from G02.
Ventnor	Stage 5c; 38 ± 1 m	Tread as wide as 350 m between Ventnor backcliff and Worthing backcliff. Ventnor backcliff and floor cut in Rendezvous Hill and Lazaretto units.	Ventnor unit. Max thickness ≥10 m. Subunit v1 is basal coarse clastic transgressive surf deposit; pebbles both coeval coral and reworked from subunit rh5. Subunit v2 is mixed reef above v1; cells of Ap + h and of Ac; it is a transgressive fringe reef. Subunit v3 is clastic wedge between s.a. and v1 + v2 section; a highstand beach.	Subunit v1: OC 1–5 = five coral pebbles between 105.3 ± 0.6 and 116.7 ± 0.7 (G02). Subunit v2: FT1 (Ap) 104.3 ± 0.4 (G94) and AFK 1 (Ac) 104 ± 6 (M69).
Rendezvous Hill	Stages 5e and 5d; 70 ± 2 m	Tread between Rendezvous Hill backcliff and Ventnor backcliff. Terrace comprises large subterrace RH-A and small subterraces RH-B and RH-C. Tread much denuded. RH-A includes linear depression, interpreted as a graben.	Rendezvous Hill unit. Max thickness 19 m. Unit comprises five subunits: rh1–rh5. Rendezvous Hill unit overlies two exhumed units: Lazaretto unit (lz, stage 6) and Wanstead unit (wa, early stage 7). Full description in text.	18 dated corals, discussed in text
Durants–Cave Hill (DCH)	Stages 7.1 and 7.2 (?); 92 ± 2 m	Highest-preserved marine terrace at Cave Hill. Tread up to 400 m wide between DCH backcliff, which cuts old limestone (dated 302 ± 6 ka, WAN A1 by G94), and RH backcliff. Tread much denuded.	DCH unit. Subunit dch1 is coarse clastic at and near s.a. Subunit dch 2, downslope from dch1, is mixed reefal, contains cells of Ap and of Ac. DCH unit overlies early stage 7 Wanstead unit (exhumed) on RH backcliff.	Subunit dch1: at s.a., WAN B, six cobbles of Ap between 190.8 ± 0.7 and 203.6 ± 1.7, all with δ^{234}Ui < 181 from G94. Subunit dch2: WAN E1 (Ap) 209.2 ± 1.7; WAN C1 (P), 203.4 ± 4, G94.

Notes: Sites of dated coral in Figure 4. References: M69, Mesolella et al. (1969); G94, Gallup et al. (1994); G02, Gallup et al. (2002), and website. Abbreviations: s.a.—shoreline angle; Ap—*Acropora palmata;* Ac—*Acropora cervicornis;* h—head coral.

on or at the base of a marine cliff (for example, Neumann and Hearty, 1996). We doubt that Johnson's notches are markers of past shoreline erosion because they are essentially point features and are unrelated to the laterally extensive and continuous major features that express terrace geomorphology.

GEOCHRONOLOGY

Ages are assigned to terraces and event histories through the use of 31 new mass spectrometric ^{230}Th dates of coral (Table 2, Fig. 4), together with existing dates from Gallup et al. (1994) (Fig. 4). Dates are from *A. palmata* and head corals (montastrids and siderastrids). Samples were prepared by repeated crushing, ultrasonic cleaning, and handpicking under a microscope. The NU samples (as designated in Table 2) were aragonitic to the detection level of X-ray diffraction. The accuracy of coral dates is best judged by the concordance of ^{230}Th and ^{231}Pa dates from the same specimen (Edwards et al., 1997); ^{231}Pa dates of some of our specimens are in Gallup et al. (2002, Web site). Concordance of ^{230}Th dates from in-place corals at the same stratigraphic level is another good test. An implication of accuracy is afforded by δ^{234}Ui, the initial ^{234}U/^{238}U content at time of coral growth (Table 2) within some range of the value of modern sea water, ~148. Edwards et al. (1997) found concordant ^{231}Pa and ^{230}Th dates for corals with δ^{234}Ui up to 166, and Stirling et al. (1998) detected no inaccuracy in a large and stratigraphically controlled set of dates with δ^{234}Ui up to 164. Of our stage 5 dates, 74% are in the range $144 \leq \delta^{234}\text{Ui} \leq 166$. For limestone older than stage 5, the proportion of dates with $\delta^{234}\text{Ui} \geq 166$ is greater.

Terrace age assignments also require that dated corals grew contemporaneously with terrace formation and were not resedimented or sampled from exhumed older limestone. Multiple dates, unconformities, and evidence for in-place growth are used to address this criterion. The time divisions of stage 5 are well resolved by our dating. Resolution in stage 7 is limited to early and late intervals, which are probably separated by stage 7.2. Coral older than stage 7 is known only as "old" (i.e., >300 ka), owing to large changes of the uranium-system composition during diagenesis.

LIMESTONE

The Cave Hill surface is underlain by limestone of two types: terrace cover, which exists between a terrace floor and tread, and exhumed limestone, which is preterrace and exposed by denudation or human excavation below terrace floors. Named divisions of limestone cover and exhumed limestone exposed at Cave Hill together with their ^{230}Th dates are in Figure 4 and Tables 1 and 2.

Most limestone units contain both clastic and reefal carbonate. Reefal facies are either a species framework, built dominantly of *A. palmata* or *A. cervicornis*, or a mixed framework of two or more species. Small (<10-m-diameter) bodies side-by-side of different frameworks are called cells. There is a continuous spectrum between clastic and reefal limestones, between laterally transported sediment and coral wholly at the place it grew. Acroporids are rarely preserved in growth position, and it is important to judge by rounding and sorting whether their deposits represent in-place collapse or lateral transport. Head coral, in contrast, is commonly preserved in growth position and, if so, provides evidence that companion acroporids have collapsed in place. Our usage of clastic means there is evidence of transport of all particles of the deposit. Unsorted sand of local biogenic origin (benthic foram and algal particles) exists as infill in most reefal bodies but does not indicate that the body is clastic.

Profiles of cover units are wedge shaped, thickening seaward from a tip at the shoreline angle. The thickest cover identified is 19 m. Clastic facies generally prevail in the upslope terrace reaches, and reefal facies are downslope.

TABLE 2. NEW MASS SPECTROMETRIC ^{230}Th DATES OF CORALS FROM CAVE HILL AREA, BARBADOS

Sample number	Limestone unit	Elevation (m)	Coral	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U (meas.)	^{230}Th/^{238}U (activity)	^{230}Th age (ka)	δ^{234}Ui (initial)
NU 1509	rh5	51	Ap	3150 ± 4	71 ± 8	123.7 ± 1.4	0.7567 ± 0.0020	118.5 ± 0.6	173.0 ± 1.9
NU 1510	rh5	51	C:Ap	3115 ± 4	53 ± 9	120.3 ± 1.2	0.7446 ± 0.0019	115.9 ± 0.6	167.0 ± 1.7
UWI 104 (1)	rh5	57	Ap	3226 ± 4	134 ± 4	104.3 ± 1.2	0.7313 ± 0.0022	115.6 ± 0.7	144.6 ± 1.7
104 (2)				3215 ± 3	134 ± 7	107.7 ± 1.2	0.7356 ± 0.0023	116.1 ± 0.7	149.5 ± 1.7
UWI 105	rh5	57	Ap	3136 ± 3	60 ± 7	107.9 ± 1.2	0.7373 ± 0.0023	116.5 ± 0.7	149.9 ± 1.7
UWI 19 (1)	rh5	43	Ap	3654 ± 4	307 ± 10	98.7 ± 1.2	0.7054 ± 0.0024	109.7 ± 0.7	134.6 ± 1.6
19 (2)				3763 ± 3	338 ± 10	98.0 ± 1.2	0.7046 ± 0.0021	109.7 ± 0.6	133.6 ± 1.6
UWI 17	rh5	42	Ss	3071 ± 4	44 ± 7	103.6 ± 1.1	0.7351 ± 0.0026	116.8 ± 0.8	144.1 ± 1.6
SSS 93	rh5	33	AP	3160 ± 4	117 ± 15	115.9 ± 1.5	0.7521 ± 0.0032	118.4 ± 1.0	162.2 ± 2.2
NU 1473	rh5	41	C:Ap	3265 ± 3	42 ± 13	107.3 ± 1.0	0.7963 ± 0.0024	134.2 ± 0.8	156.7 ± 1.6
UWI 101 (1)	rh1	32	Ap	3095 ± 5	95 ± 8	103.3 ± 2.0	0.7788 ± 0.0021	129.7 ± 0.8	149.0 ± 2.9
101 (2)				3182 ± 4	77 ± 14	104.7 ± 1.2	0.7768 ± 0.0024	128.7 ± 0.8	150.6 ± 1.7
101 (3)				3232 ± 3	70 ± 13	104.6 ± 1.0	0.7768 ± 0.0023	128.8 ± 0.8	150.5 ± 1.5
UWI 107	rh1	32	Ma	2592 ± 3	194 ± 13	91.2 ± 1.2	0.8768 ± 0.0027	170.3 ± 1.3	147.6 ± 2.0
NU 1471	rh2	39	Ma	2689 ± 2	38 ± 16	102.4 ± 1.1	0.7970 ± 0.0024	135.8 ± 0.8	150.3 ± 1.7
NU 1472	rh2	39	Ap	3212 ± 3	20 ± 11	111.5 ± 1.0	0.8056 ± 0.0024	136.1 ± 0.8	163.7 ± 1.6
UWI 26	rh3	54	Ap	3459 ± 3	4100 ± 19	119.2 ± 1.2	0.7985 ± 0.0043	131.3 ± 1.4	172.9 ± 1.8
UWI 23	rh3	53	Ap	2992 ± 6	486 ± 10	144.0 ± 3.3	0.8495 ± 0.0031	141.5 ± 1.4	214.8 ± 5.1
PH 93-2	rh4	60	Ap	3188 ± 6	63 ± 11	108.5 ± 2.5	0.7739 ± 0.0031	126.9 ± 0.8	155.3 ± 3.7
PH 93-3(1)	rh4	61	Ap	3207 ± 3	44 ± 9	111.7 ± 0.9	0.7829 ± 0.0018	128.9 ± 0.6	160.7 ± 1.4
93-3(2)				3296 ± 4	82 ± 12	110.5 ± 1.1	0.7876 ± 0.0024	130.6 ± 0.8	159.8 ± 1.7
UWI W93-1	rh4	62	Ap	3308 ± 5	408 ± 10	109.2 ± 1.6	0.7758 ± 0.0021	127.3 ± 0.7	156.6 ± 2.3
UWI W93-2	rh4	62	Ap	3242 ± 4	31 ± 26	105.3 ± 1.7	0.7806 ± 0.0088	129.8 ± 2.8	151.9 ± 2.7
NU 1511	Lz	35	Ap	3359 ± 4	25 ± 8	109.3 ± 1.0	0.8872 ± 0.0022	167.3 ± 1.0	175.4 ± 1.7
NU 1467	Lz	35	Ap	2401 ± 2	221 ± 20	91.0 ± 1.1	0.9027 ± 0.0027	182.7 ± 1.5	152.6 ± 2.0
NU 1463	Lz	36	Ma	2765 ± 4	688 ± 13	103.2 ± 1.3	0.9567 ± 0.0030	205.8 ± 2.0	184.5 ± 2.8
NU 1129	Lz	36	Ap	3244 ± 4	1330 ± 14	102.1 ± 1.9	0.8996 ± 0.0023	176.0 ± 1.4	167.9 ± 3.2
NU 1464	Lz	37	Ap	3598 ± 5	50 ± 13	95.7 ± 1.2	0.8780 ± 0.0028	168.0 ± 1.3	153.8 ± 2.1
NU 1465b	Lz	34	Ap	3191 ± 4	53 ± 18	112.2 ± 1.2	0.9494 ± 0.0029	196.1 ± 1.8	195.3 ± 2.4
NU 1466	Lz	35	Ap	3403 ± 4	27 ± 14	95.8 ± 1.3	0.8838 ± 0.0027	171.5 ± 1.3	155.5 ± 2.2
NU 1468	Lz	34	Ap	3190 ± 3	164 ± 13	96.1 ± 1.2	0.9008 ± 0.0027	179.3 ± 1.4	159.8 ± 2.1
NU 1507	wa	68	Ap	3382 ± 4	33 ± 18	103.9 ± 1.1	0.9872 ± 0.0024	225.3 ± 1.9	196.4 ± 2.4
NU 1508	wa	68	Ma	2227 ± 3	43 ± 10	89.2 ± 1.1	0.9682 ± 0.0024	223.3 ± 1.9	167.7 ± 2.3
WAN 2-93-1 (1)	wa	68	Ap	3741 ± 4	125 ± 7	91.7 ± 0.9	0.9870 ± 0.0024	235.5 ± 2.1	178.4 ± 2.3
2-93-1 (2)				3168 ± 4	144 ± 17	94.5 ± 1.6	0.9904 ± 0.0030	235.7 ± 2.8	184.0 ± 2.2
WAN 2-93-2	wa	68	Ap	3568 ± 4	37 ± 14	69 ± 1.2	0.9048 ± 0.0028	195.6 ± 1.8	121.2 ± 2.3

Notes: Sample numbers with (1), (2), and (3) are different fragments of same sample. Coral: Ap—*Acropora palmata*; Ma—*Montastrea annularis*; Ss—*Siderastrea sidarea*; C—cobble. Limestone unit nomenclature explained in Figure 4 key. NU specimens prepared by repeated crushing, ultrasonic cleaning, and handpicking; samples wholly aragonitic according to X-ray diffraction. Elevations by leveling relative to benchmarks. The initial ^{234}U/^{238}U content at time of coral growth is represented by $\delta^{234}U_i = \delta^{234}U_{meas}\exp(\lambda_{234}t)$, $\delta^{234}U_{meas} = ([^{234}U/^{238}U]_{activity} - 1) \times 1000$, $\lambda_{234} = 2.8263 \times 10^{-6}$ yr^{-1}, and t = age; other constants and equations used are from Gallup et al. (2002). Errors are 2σ.

RENDEZVOUS HILL TERRACE AT CAVE HILL

Geomorphology

The last interglacial Rendezvous Hill terrace at Cave Hill lies between the Rendezvous Hill backcliff, which is the first marine cliff upslope from dated Rendezvous Hill terrace cover, and a forecliff, which is the stage 5c Ventnor backcliff (Figs. 2, 3). The Rendezvous Hill backcliff cuts the late-stage 7 DCH (Durants–Cave Hill) terrace cover unit and the exhumed early-stage 7 Wanstead limestone unit (Table 1, Figs. 2–4). The shoreline angle at the backcliff's base is at 70 ± 2 m elevation. The tread, locally much denuded, defines three subterraces, RH-A, RH-B, and RH-C (Fig. 2). RH-A is the highest and broadest; RH-B and RH-C are narrow benches in a stair step downslope from RH-A but higher than the Ventnor shoreline angle.

Tread of subterrace RH-A is preserved in several discrete remnants, which are separated by denudation domains (Figs. 2, 3). A linear depression, now much filled, lies between two remnants of subterrace RH-A (Figs. 2, 3). Its original locus and width, ~100 m, are identified on preurbanization (1950) aerial photographs and by present-day local drainage. The depression is interpreted as a half graben.[1]

The treads of subterraces RH-B and RH-C each reach back over 20 m to a shoreline angle and backcliff (Y–Y′ in Fig. 3). Both subterraces are cut out laterally by denudation (Fig. 2).

The floor of subterrace RH-A lies close to the base of section of the University Drive roadcut, as known from several sites of exposure (for details, see footnote 1). The floor is shallowly concave up, diminishing in dip downslope or southwest from ~7° to 3.5°

[1]GSA Data Repository item 2004030, details of two important features of the Rendezvous Hill terrace at Cave Hill, is available on the Web at http://www.geosociety.org/pubs/ft2004.htm. Requests may also be sent to editing@geosociety.org.

Limestone Stratigraphy

Limestone below the preserved tread and denuded surfaces of the Rendezvous Hill terrace is divided among the Rendezvous Hill unit, which was deposited in stage 5e, and two exhumed units: Lazaretto of stage 6 age and Wanstead of early stage 7 age (Figs. 4, 5). Dated outcrops of the Rendezvous Hill unit are subdivided among five subunits (rh1–rh5) (Figs. 4, 5). In general, subunits rh2–rh4 compose a seaward-thickening wedge that makes up subterrace RH-A. Subunit rh5 is associated with subterraces RH-B and RH-C. Subunit rh1 is an outlier downslope from the Rendezvous Hill terrace. The main features of these units and subunits are summarized below. Details concerning the RH-A floor and bedding and normal faulting in subunit rh3 are available (see footnote 1).

Rendezvous Hill Subunit rh2

Subunit rh2 is a tabular reef of 5 m exposed thickness below subunit rh3 and above a bur-

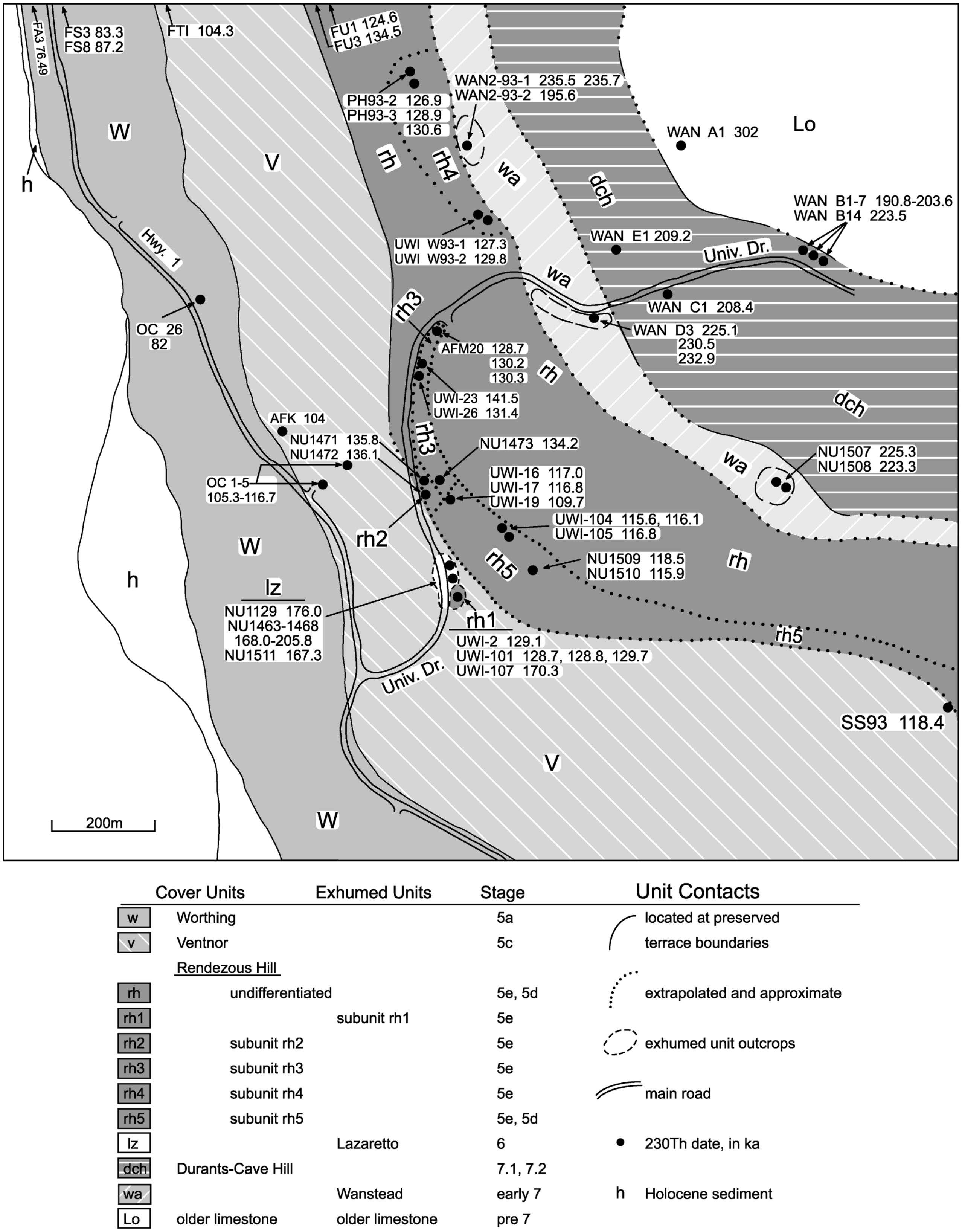

Figure 4. Map of limestone units and Rendezvous Hill subunits and sites of coral dated by ^{230}Th at Cave Hill. Rendezvous Hill subunit boundaries delineate areas of dated outcrops; remainder of Rendezvous Hill cover is undifferentiated. Outcrop areas of exhumed Lazaretto and Wanstead units indicated. New geochronologic data in Table 2; preexisting dates referenced in text. Sites with arrows at northern edge of map are 1 km north, at Holders Hill.

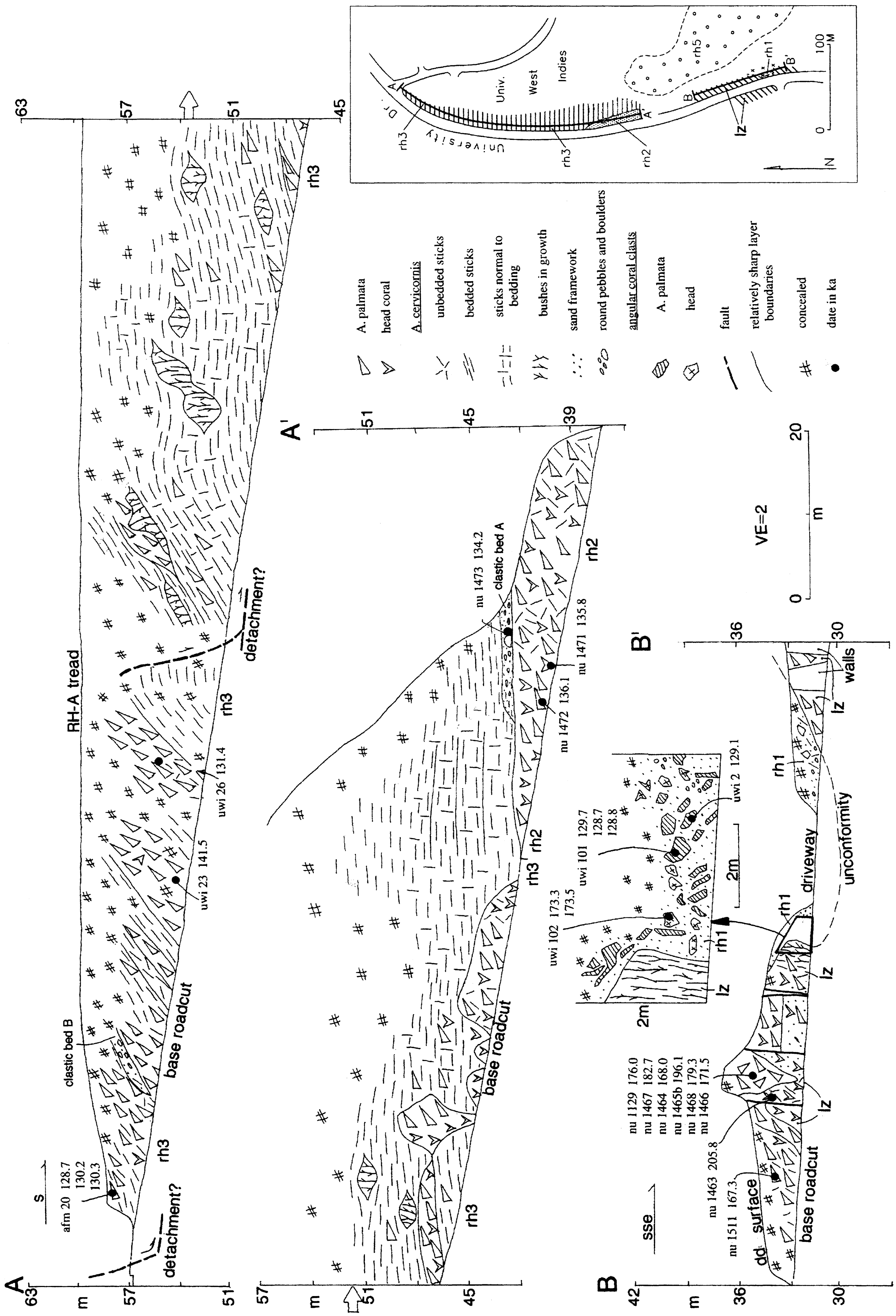

Figure 5. Sections of University Drive roadcut in two segments, A–A′ and B–B′; section traces on inset map. Denuded surfaces constitute the denudation domain (dd). Vertical axes are elevation in m.

ied base that is within 1 m of the floor of subterrace RH-A. Subunit rh2 contains cells of large *A. palmata* plus head coral and of *A. cervicornis* with minor *A. palmata* and head coral with no vertical zonation (Fig. 5). Head corals are in growth orientation, implying that associated acroporids collapsed in place. From subunit rh2, we dated a head coral at 135.8 ± 0.8 ka (NU 1471) and an *A. palmata* at 136.1 ± 0.8 ka (NU 1472) (Figs. 4, 5; Table 2). For NU 1471, a concordant ^{231}Pa date (Gallup et al., 2002), δ^{234}Ui = 150, stratigraphic and temporal concordance with the NU 1472 date, and evidence of growth in place imply that the date accurately records deposition at the site at ca. 136 ka.

Rendezvous Hill Subunit rh3

Rendezvous Hill subunit rh3 is an extensive reefal wedge that laps upslope across subunit rh2 and extends well landward of rh2 on the seaward-dipping floor of subterrace RH-A. The subunit continues up to the subterrace tread with thickness as great as 17 m. Subunit rh3 contains two coral facies and two thin clastic interbeds. The *A. palmata* facies occupies the seaward-dipping basal zone of the wedge and is the upslope continuation of subunit rh2. The *A. cervicornis* facies lies above and seaward of the *A. palmata* facies, not as shown in the undocumented section of Gallup et al. (2002). The two facies join at a seaward-dipping interdigitating contact. The *A. cervicornis* facies is well bedded; fabrics and particle properties indicate bedding is due to progressive vertical collapse of in-place *A. cervicornis* colonies (see footnote 1).

Coral dates in the *A. palmata* facies are as follows. Site AFM 20 is just below the subterrace RH-A tread and at the highest outcrop of subunit rh3 (Figs. 4, 5). A triplicate analysis of an *A. palmata* gave 128.7 ± 0.7, 130.2 ± 0.7, and 130.3 ± 0.7 ka, all with δ^{234}Ui ≤ 169 (Gallup et al., 1994). Sites UWI 23 and 26, downslope from AFM 20, gave *A. palmata* dates of 141.5 ± 1.4 and 131.4 ± 1.4 ka, respectively (Table 2, Figs. 4, 5). The UWI 23 date is rejected because δ^{234}Ui = 215, whereas the UWI 26 date with δ^{234}Ui = 173 is considered because the date fits concordantly between the 136 ka date below and the 129 ka date above.

The two clastic beds, each tabular and ~1 m thick, provide the only indications of breaks of reefal deposition in subunit rh3 (Fig. 5). Clastic bed A occurs locally at the base of subunit rh3 over a 15 m dip length above rh2. The bed pinches out landward, beyond which the rh2-rh3 contact is apparently gradational to rh2. Clastic bed A contains well-bedded, rounded coral gravel as coarse as 10 cm, exceptionally 25 cm, mixed with angular *A. cervicornis* sticks. The bed fines upward and landward. We dated the largest clast in clastic bed A, a 25 cm *A. palmata* cobble at the bed's base, at 134.2 ± 0.8 ka with δ^{234}Ui = 157 (Table 2; Figs 4, 5). This coral is younger than corals dated in the underlying rh2. Clastic bed B is ~10 m below the highest exposure of subunit rh3 (Fig. 5). There is no evidence for downcutting of subjacent reef below either clastic bed.

The age range of subunit rh3 is delimited by the 136 ka age of the underlying subunit rh2 and ca. 129 ka, an average of the AFM 20 values, within 1 m of the subunit's highest exposure. The age of clastic bed A is between ca. 134 and ca. 131 ka, and that of clastic bed B is between ca. 131 and 129 ka.

Rendezvous Hill Subunit rh4

Rendezvous Hill subunit rh4 contains the most landward and highest limestone, as high as 64 m elevation, of preserved Rendezvous Hill unit. It occurs in a discrete remnant of subterrace RH-A that is isolated from that containing rh3 by denuded ground (Fig. 4). Upslope from the subterrace RH-A remnant, subunit rh4 outcrops continue into a higher denuded tract (Figs. 2, 4). Limestone of subunit rh4 is an unzoned mixed reef, comprising cells of *A. palmata* and head corals, the latter in growth orientation, and of *A. cervicornis* and head coral. Acroporids show no reworking or sorting and are judged to have collapsed in place.

Four *A. palmata* were dated from subunit rh4 (Fig. 4; Table 2): 126.9 ± 0.8 ka (PH 93-2), 128.9 ± 0.6 and 130.6 ± 0.8 ka (PH 93-3), 127.3 ± 0.7 ka (W93-1), and 129.8 ± 0.8 ka (W93-2). Their δ^{234}Ui range is 152–161. A ^{231}Pa date of PH 93-3 from Gallup et al. (2002) indicates that the older ^{230}Th value is inaccurate. The other four dates average 128.2 ka, which may be close to the true age. Limestone of subunit rh4 is similar to that at the landward end of subunit rh3, and its dates are probably only slightly younger. The two subunits probably were continuous below the tread of subterrace RH-A before denudation.

Rendezvous Hill Subunit rh 5

Rendezvous Hill subunit rh5 is a mainly clastic limestone that covers all or parts of the south-facing slope below the southern edge of the subterrace RH-A tread (Figs. 2, 3). This slope includes subterraces RH-B and RH-C. Exposures of subunit rh5 at subterrace RH-C show a stratified coarse clastic deposit that includes layers of round-pebble calcarenite and layers of slightly worked and sorted, large *A. palmata* and *A. cervicornis* fragments that imply a local source. From RH-C, we dated *A. palmata* in a large subangular fragment at 118.5 ± 0.6 ka (NU 1509; δ^{234}Ui = 173) and in a round pebble at 115.6 ± 0.6 ka (NU 1510; δ^{234}Ui = 167) (Fig. 4, Table 2). Other outcrops of rh5 near RH-B and RH-C include *A. palmata* dated at 115.6 ± 0.7 and 116.1 ± 0.7 ka (UWI 104) and 116.5 ± 0.7 ka (UWI 105) (Table 2, Fig. 4), both of which have δ^{234}Ui = 149. At the base of the rh5 slope at site SSS 93 at 33 m elevation, *A. palmata* was dated at 118.4 ± 1.0 ka with δ^{234}Ui = 162 (Table 2, Fig. 4). Three specimens from rh5 on the western side of the south-facing slope were dated (Fig. 4): UWI 16, a rounded cobble of *A. palmata*, 117.0 ± 1.0 ka and δ^{234}Ui = 158 from Gallup et al. (1994); UWI 17, a head coral, 116.8 ± 0.8 ka and δ^{234}Ui = 144 (Table 2); and UWI 19, an *A. palmata*, 109.7 ± 0.7 and 109.7 ± 0.6 ka (Table 2). UWI 19 is dismissed because δ^{234}Ui = 134. The seven specimens with acceptable dates thus indicate that subunit rh5 has an age range between 119 and 115 ka.

Rendezvous Hill Subunit rh1

Rendezvous Hill subunit rh1 is seen in a single outcrop just seaward of the base of the Rendezvous Hill forecliff where it is exhumed below the Ventnor unit. It is a resedimented clastic limestone composed of unsorted sand, rounded granules, and floating angular coral cobbles without stratification except for the parallelism of platy *A. palmata* and head coral clasts in a 30°–40° south-dipping imbrication. The subunit lies above an erosional unconformity on the stage 6 Lazaretto unit (Figs. 4, 5).

Three coral clasts from rh1 yielded the following ages (Figs. 4, 5): 129 ± 0.8 ka (UWI 2, *A. palmata*, from Gallup et al., 1994); 128.7 ± 0.8 and 129.6 ± 0.6 ka (UWI 101, *A. palmata*, Table 2), and 170 ± 1.3 ka (UWI 107, head coral, Table 2). All have δ^{234}Ui between 147 and 151. The angularity, large size, and concordance of age of the dated *A. palmata* clasts implies that they were derived from coral that grew penecontemporaneously with the deposition of subunit rh1, at ca. 129 ka. The 170 ka head coral is coeval with the subjacent Lazaretto unit, implying derivation from the eroded substrate.

Lazaretto Unit

The Lazaretto unit, which is exhumed on and below the Rendezvous Hill forecliff, lies below the floor of subterrace RH-A, and farther downslope, underlies subunit rh1 (Figs. 4, 5). The Lazaretto unit almost certainly continues landward in the subsurface of its roadcut exposure and underlies subunits rh2 and rh3. Its reefal cells are unzoned and predominantly either *A. palmata*, *A. cervicornis*, or head coral (Fig. 5). Six of eight coral dates from the Lazaretto unit are between 167.3 and 182.7 ka and have δ^{234}Ui < 175 (Figs. 4, 5). We infer that this range includes the true age span of deposition. The other two dates, 196.1 and 205.8 ka, are dismissed because δ^{234}Ui > 184. The acceptable dates indicate an early stage 6 age, between ca. 167 and 183 ka.

Wanstead Unit

This exhumed limestone unit is exposed in a belt of denuded ground that cuts through the upper reaches of subterrace RH-A and the Rendezvous Hill backcliff and DCH terrace (Fig. 2). It contains mixed reefal deposits, comprising unzoned cells of predominantly *A. cervicornis* and of *A. palmata*. Dates from the Wanstead unit are 223 ± 1.9 ka (in-place head coral, NU 1508); 225.3 ± 1.9 ka (*A. palmata*, NU 1507); 235.5 ± 2.1 and 235.7 ± 2.8 ka (*A. palmata*, WAN 2-93-1); and 195.6 ± 1.8 ka (*A. palmata*, WAN 93.2) (Fig. 4, Table 2). Preexisting dates from Gallup et al. (1994) are 225.1 ± 5.5, 230 ± 3.7, and 232.9 ± 7.6 ka (*A. palmata*, WAN-D3). Except for WAN 93-2, the dates occupy a narrow 223–235 ka interval; their δ^{234}Ui is between 167 and 195. The WAN 93-2 date has δ^{234}Ui = 121 and is dismissed. The Wanstead unit is considered an early stage 7 limestone that underlies the Rendezvous Hill, Lazaretto, and DCH units.

EVOLUTION OF THE RENDEZVOUS HILL TERRACE

We now interpret the architecture and conditions of deposition of the limestone subunits of the Rendezvous Hill terrace at Cave Hill and propose an evolutionary model.

Facies Architecture

The reefal subunit rh2 was deposited on or within 1 m of the seaward-dipping floor, and its large *A. palmata* branches indicate growth in shallow water, probably, <5 m depth (Adey, 1978). Thus, subunit rh2 is a fringe reef. Its stratigraphic level at 25 m below and 8–10 k.y. older than subunit rh4, the highest preserved Rendezvous Hill limestone, indicates that subunit rh2 was deposited during transgression, not at a sustained highstand.

Subunit rh3 is in depositional continuity with rh2 by virtue of its partially gradational contact and younger dates. Its framework facies zonation, *A. palmata* to landward and *A. cervicornis* to seaward, indicates a lateral change in conditions of coral growth at each stratigraphic level (Fig. 5). This change may represent deepening of the seabed and/or diminishing water circulation seaward. Because the *A. palmata* facies of subunit rh3 is on or close to the terrace floor, it must be a fringe reef and the upslope continuation of the subunit rh2 reef. This diachronous transgressive fringe reef reached the present-day elevation of 59 m at ca. 129 ka. As the *A. palmata* fringe-reef blanket migrated landward with rising sea level, the space seaward of it was filled by vertically aggrading *A. cervicornis* and minor, small *A. palmata*.

The two clastic interbeds in subunit rh3 record deposition of sediment of upslope provenance on local flats of the growing reefal body. This origin is implied by the conformable planar bases of the interbeds and by their lateral pinchouts. The sediment in these beds may have come from the breaker zone and been transported down chutes through the reef. The two beds do not indicate large sea level fluctuations during rh3 deposition.

Subunit rh4 is inferred to be the upslope continuation to at least 64 m elevation of the floor-carpeting fringe reef of subunits rh2 and rh3 because of its similar facies, proximity to the floor, and slightly younger age—ca. 128 ka—compared to rh3.

A major unknown consists of the facies and age of the Rendezvous Hill unit that lay initially between subunit rh4 and the Rendezvous Hill backcliff, on the denuded tract underlain by the exhumed Wanstead unit (Fig. 4). The Rendezvous Hill cover is there apparently completely stripped even though the Rendezvous Hill backcliff is moderately preserved. The missing cover must have been especially erodible, probably a thin clastic layer that was little lithified at the time of stripping. We propose that the fringe reef of subunit rh4 graded upslope to beach clastic sediments, which continued landward to the backcliff.

Subunit rh1 was deposited at ca. 129 ka, evidently in a channel cut through older subunits rh2 and rh3 and into the Lazaretto unit. The massive nature of subunit rh1 and its content of angular coral fragments mixed with rounded fine gravel and sand imply that it is a sediment-gravity flow. The steep dip of its large clasts is attributed to progradation in the sand matrix downslope from the overhang in the unconformity (Fig. 5). The source of clastic sediment in rh1 is likely to have included reefs of subunit rh3, which had transgressed to a present-day elevation of >50 m by 129 ka, and a beach farther landward. We suggest that the channel may have been initiated by local sliding at the front of the subterrace RH-A wedge and that subunit rh1 contains the most rearward part of the subsequent sediment-gravity flow. The more headward, presumably *A. cervicornis*–rich, part of the flow is or was seaward of the rh1 outcrop.

Subterraces RH-B and RH-C, the youngest preserved geomorphic features of the Rendezvous Hill terrace, evolved by stepwise erosion of the downslope reach of subterrace RH-A. Subunit rh5 was deposited concurrently, between 115 and 119 ka. Because their elevations are lower than the tread of subterrace RH-A and their rh5 cover is discretely younger than rh1–rh4, subterraces RH-B and RH-C formed during regression from the higher sea levels of subterrace RH-A. The prevalence of coarse clastic sediments in subunit rh5 and its geometry as slope cover indicate that rh5 is a shoreline facies that migrated with contemporaneous coral growth down the slope during regression. The stair step of subterraces implies either nonsteady rates of regression or uplift or both.

Sea Level History

A time series of sea levels at Cave Hill between 140 and 100 ka based on dated coral and shoreline angles is compiled in Figure 6. Elevations are adjusted for uplift over the 40 k.y. span by using a steady rate of 0.53 m/k.y. (see below). A sea level curve is sketched to pass a few meters above coral elevations to account for depth of growth and collapse and to intersect shoreline angles.

The curve begins at 140 ka with a transgressive first leg at the erosional unconformity on the stage 6 Lazaretto unit. It continues to the transgressive fringe reef of subunit rh2 at 136 ka and elevates through subunits rh3 and rh4, whose dates are between ca. 131 and 128 ka. This first leg indicates mean rates of transgression from 136 to 128 ka, corrected for uplift, of 3.4 m/k.y. Subunits rh2 and 3, however, have probably been displaced down by normal faulting (see footnote 1) relative to rh4. If so, the transgression rate would have been less.

The second leg of the curve begins when sea level reached the Rendezvous Hill shoreline angle, the terrace's highstand marker. The leg has an uncertain duration owing to the absence of dates between 127 and 119 ka. At least three alternative sea level paths are permitted (Fig. 6). Path a depicts constant sea level between 127 and 119 ka. In this case, the rate of recession of the wave-cut cliff was great enough to keep the shoreline angle at constant elevation during uplift. In path b, a slowed transgression between 127 and 119 ka

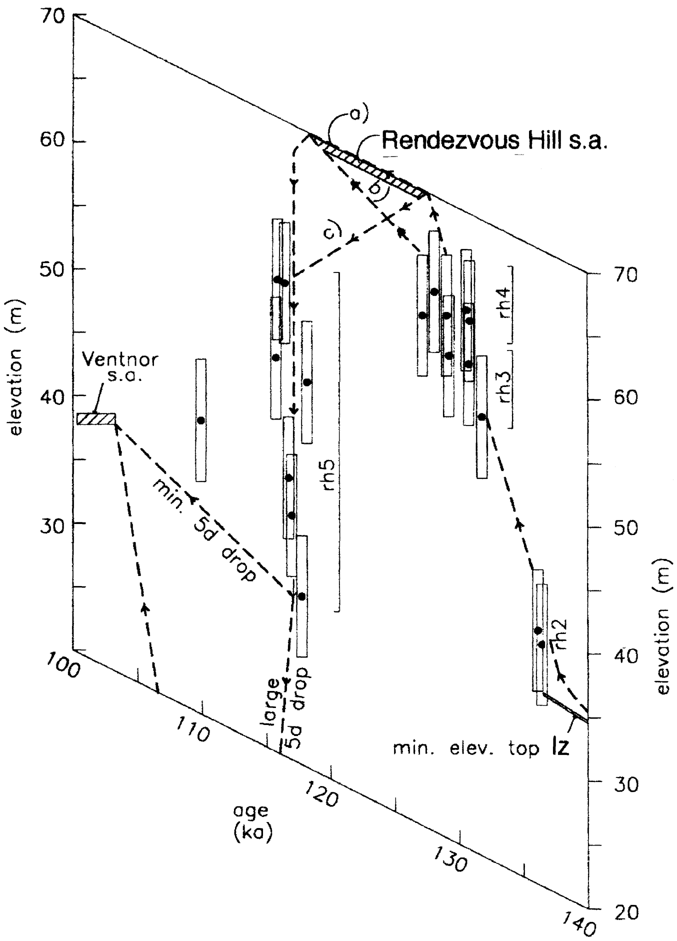

Figure 6. Plot of age vs. elevations for dated corals of Rendezvous Hill subunits rh2–rh5 and shoreline angles in the age range 100–140 ka. Elevations adjusted for uplift at a constant rate of 0.53 m/k.y. Dashed line indicates approximate sea level curve. Curve includes alternative paths a, b, and c for last interglacial highstand and for two cases of sea level drop in stage 5d: minimum and large. Alternatives explained in text. Age uncertainty for coral is analytic (2σ). Elevation error assigned to corals includes ±1 m uncertainty of measurement and ±5 m uncertainty of depth at time of coral growth and at time of coral collapse. Head corals are used when they are in growth orientation and in a mixed reef with *A. palmata*. Cobbles are used where evidence implies that the coral they contain is coeval with a local shoreline. Abbreviations: s.a.—shoreline angle; lz—Lazaretto unit.

is followed by a cusp and rapid regression. In path c, a cusp at 127 ka occurs between the transgressive first leg and an 8 k.y. interval of slow regression. Of the alternatives for the second leg, path a is most likely because a sustained highstand level is needed to erode the >100 m width of the terrace landward of subunit rh4. Moreover, data of Stirling et al. (1998) indicate an onset of principal regression in stable Western Australia not before ca. 120 ka, casting doubt on path c. Thus, our best estimate of the duration of the last interglacial highstand is 127 to 120 ka. The age of the Rendezvous Hill shoreline angle, which marks the highstand to regression transition, is ca. 120 ka via either path a or b. Brief excursions of sea level during highstand are possible but not resolved in Figure 6.

In the third leg of Figure 6, between ca. 119 and 115 ka, sea level falls rapidly, recording regression in stages 5e and 5d. Regression began at the cusp of path a at 120 ka, and sea level fell >37 m. The descent of the third leg below 33 m current elevation is irresolvable because the base of subunit rh5 is buried. The data of Stirling et al. (1998), however, suggest the beginning of very gradual regression of no more than a few meters between 120 and 119 ka, continuing to 116.1 ± 0.3 ka or younger. Taking their 116 ka age as a limit to slow regression, the third leg of Figure 6 represents a major acceleration in regression at ca. 116–115 ka to ≤33 m elevation, apparently exceeding −20 m/k.y.

The fourth leg is the rise of sea level from an unidentified stage 5d minimum to the stage 5c Ventnor highstand at 38 m current elevation. Under the assumption that the age of the Ventnor shoreline angle is 102 ka, a minimum rate of transgression is 0.8 m/k.y. from the minimum possible drop of the stage 5d low at 33 m (Fig. 6). Alternatively, a larger 5d drop or older Ventnor age would yield more rapid transgression to stage 5c.

Uplift Rate

A time-averaged uplift rate of 0.53 ± 0.04 m/k.y. is calculated for the Rendezvous Hill shoreline angle at 70 ± 2 m present-day elevation and an age of 120 ± 2 ka, as deduced above. An elevation of sea level at 120 ka is taken to be 6 ± 2 m on the basis of the highest elevations of dated corals of stage 5e age at stable coasts: 3–4 m in Western Australia (Stirling et al., 1998) and 3 m in the Bahamas (Chen et al., 1991) plus modest water depth.

The shoreline angle is the only certain marker of the level of a sustained highstand at Cave Hill. Under the assumption that our deduction of its age is valid, the shoreline angle provides an accurate value of mean uplift rate. Coral, which has been used as markers in previous studies of uplift rates at Cave Hill (Matthews, 1973; Bender et al., 1979), grew in transgression and at lower sea level than existed at highstand. The elevation of sea level at the age of the transgressive coral above or below present-day sea level is unknown, and the depths of water during growth and at collapse upon death are uncertain. In general, an uplift rate determined from coral grown in transgression will be less than that determined from the shoreline angle of the same terrace. For example, an uplift rate of 0.44 ± 0.03 m/k.y. is calculated with the highest dated *A. palmata* of stage 5e age (128 ka, UWI W93-1, Table 2), assuming that sea level elevation at 128 ka was 6 ± 2 m.

Model of Facies Architecture

A model architecture of the Rendezvous Hill terrace and its cover is depicted at two times of its evolution: ca. 120 ka, the end of stage 5e highstand (Fig. 7A), and ca. 115 ka, after or during the stage 5e–5d regression but before the stage 5c highstand (Fig. 7B). The model is sectional and normal to coastal trend;

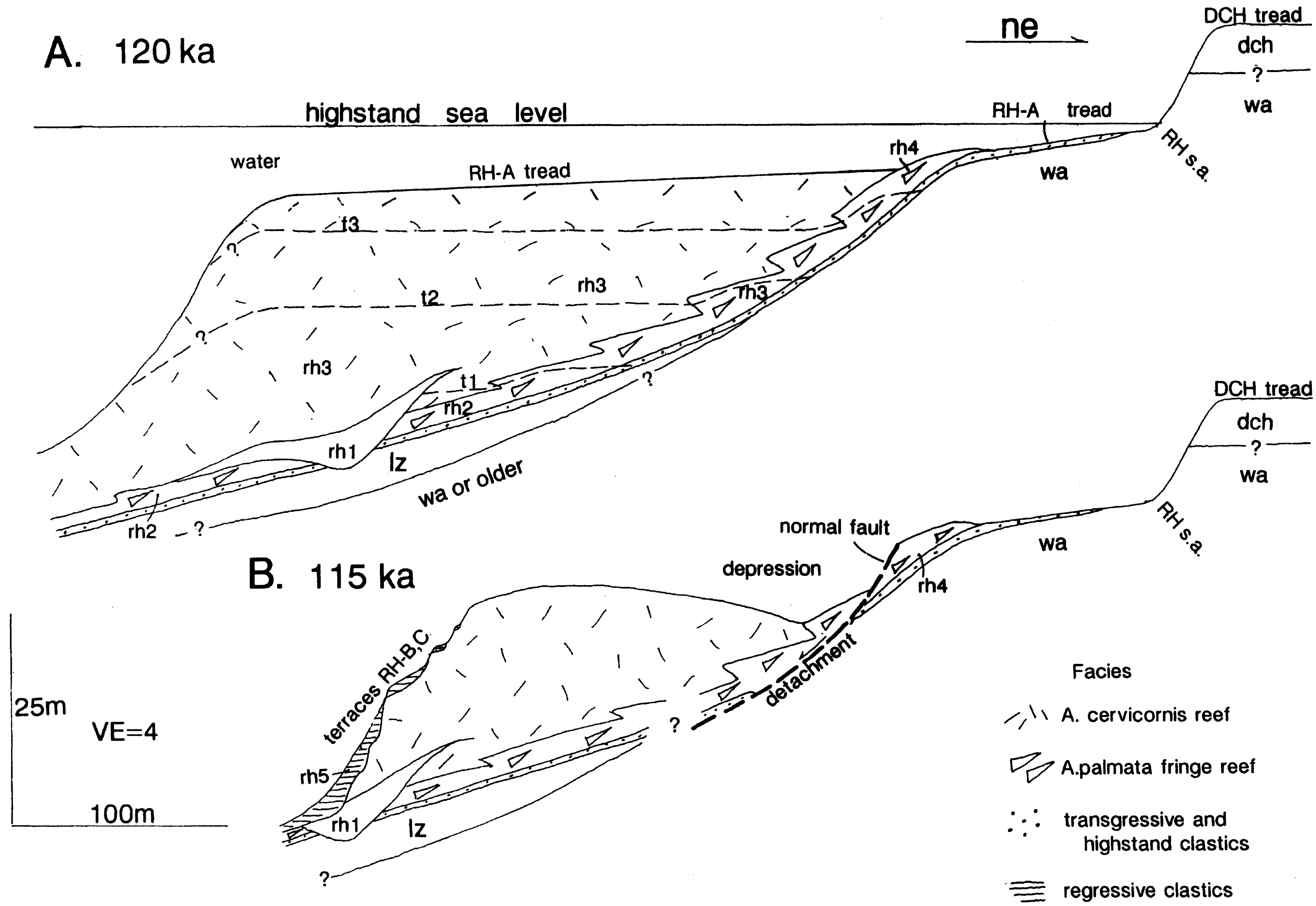

Figure 7. Model architecture of Rendezvous Hill terrace in two stages: (A) at the end of the last interglacial highstand, ca. 120 ka, and (B) after regression to below 33 m modern elevation at ca. 115 ka and after normal faulting and post–terrace denudation. Terrace and limestone unit codes from Figures 3 and 5; s.a.—shoreline angle.

it makes no adjustment for the differential uplift, ~10 m, over the duration of deposition.

A hypothetical thin basal clastic facies is shown above the floor. Although the generation of such clastic sediments as the surf zone transgressed across the floor is probable, their preservation as a continuous layer is uncertain.

Above the basal clastic layer is a transgressive fringe reef, the *A. palmata* facies of Rendezvous Hill subunits rh2–rh4. The fringe reef tracked rising sea level between 136 ka (or earlier) and ca. 128 ka. The reef probably grew below and just seaward of the breaker zone and above sandy and pebbly surf and beach zones. The fringe reef migrated landward above the clastic sediments as transgression continued. At each isochron, the fringe reef graded seaward and downslope to the *A. cervicornis* facies, which aggraded behind the transgressive fringe reef and followed the fringe reef upslope. This facies reflects decreasing wave motion and slight increase in depth, conditions where *A. cervicornis* could outcompete *A. palmata* (Macintyre, 1988). It evolved from forests of *A. cervicornis*, which episodically grew up into increasingly turbulent water, were broken up, and were reestablished as sea level rose. The product is a thick, well-bedded framework of sticks, stems, and bushes. The continuing aggradation of *A. cervicornis* across the full width of subterrace RH-A caused the cover as a whole to become a seaward-thickening wedge (Fig. 7A).

The scattered individuals and lenses of small *A. palmata* in the *A. cervicornis* facies may represent stunted strays and the tips of progradational increments of fringe reef, both possibly reaching water depths as great as 10–15 m (Adey, 1978). The boundary between the two reefal facies is shown to zigzag through the section, reflecting small variations in the rates of transgression and of growth and progradation of the fringe reef (Fig. 7A). The sediment-gravity flow deposit of subunit rh1 is portrayed as a discordant lens emplaced in a crosscutting chute through the older part of the wedge. Succeeding aggradation of the *A. cervicornis* facies buried rh1.

Between the reefal wedge and the Rendezvous Hill backcliff, subterrace RH-A is a wave-cut platform eroded at highstand and covered by clastic sediments (Fig. 7A). The fringe reef either did not migrate onto this highstand platform, or if it did, it was repeatedly broken up and became a source of clastic sediments. The fringe reef may have prograded at highstand a small distance seaward from the break in slope above the *A. cervicornis* facies (not shown in Fig. 7), as seen at a few Barbadian sites but not at Cave Hill.

Figure 7A depicts the normal fault system as a breakaway ramp and related half graben, the linear depression of subterrace RH-A. The ramp is placed above the landward tip of a seaward-dipping detachment. The model leaves the downslope locus of the fault system in question. We suggest that faulting occurred between 120 and 115 ka and was due to the loss of lateral support during sea level fall and erosion of the front of the RH-A subterrace in stage 5d.

At ca. 120 ka, regression of the sea commenced, leading to the terrace architecture shown in Figure 7B at ca. 115 ka. Regression from the Rendezvous Hill shoreline angle began slowly and stripped the stage 5e clastic cover from the highstand platform. The south-facing slope of subterrace RH-A and subterraces RH-B and RH-C were eroded during the fall of sea level before ca. 115 ka. The slope cover, subunit rh5, deposited during regression probably exists mainly below the subterrace treads but may form a continuous apron (Fig. 7B).

Our field study of Barbados as a whole indicates that the model components of transgressive fringe reef and highstand clastic facies at Cave Hill exist widely, both in the stage 5e terrace and in terraces of other ages. The subterraces and cover formed during the regression, however, are apparently preserved only at Cave Hill. *A. cervicornis* reefs that are contemporaneous with and seaward of the fringe reef are either more thickly developed or preserved in stage 5e terraces than in terraces of other ages.

Comparison of Evolutionary Models

Mesolella (1968), Mesolella et al. (1970), and Bender et al. (1979) identified the Rendezvous Hill terrace at Cave Hill as a narrow belt of discontinuous outcrops of *A. palmata*. Their belt coincides with our forecliff of subterrace RH-A. They interpreted the belt to be the crest of a coast-parallel, ridged, barrier-like reef and the cliff at the seaward front of this reef to be a product of upward coral growth. In their view, corals of the ridged reef are vertically zoned, succeeding upward from head coral to *A. cervicornis* to *A. palmata*, and had grown up from an initially deeply submerged floor to shoal (the catch-up mode of Neumann and Macintyre, 1985). They inferred that aggradation along this linear locus began when transgression slowed to highstand and that the reefal ridge blocked off a lagoon on the landward side and shed debris down a forereef slope on the seaward side.

We argue that *A. palmata* outcrops do not form a belt as they mapped it and do not occupy the crest of a ridged reef. Further, the seaward slope of their ridge is not a constructional reef front but a younger wave-cut cliff. Their forereef, our *A. cervicornis* facies, is not a product of downslope transport of sediment from a reef crest but a thick, in-place reef. The vertical coral zonation of their model, implying catch-up reef growth, differs from our zonation where *A. palmata* is succeeded upward by *A. cervicornis*. We interpret the reef as having kept up but with a succession in the principal acroporids. In our model, the terrace limestone cover is not a narrow ridge but a broad, seaward-thickening wedge whose deposition occurred in transgression and regression as well as highstand.

Our study indicates that outcrops of *A. palmata* on subterrace RH-A are the basal fringe reef, either where exposed by the erosional forecliff or on the tread well upslope from the subterrace margin. The difference in the perceived coral zonations of Mesolella's and our study may be explained by the lack of deep exposure required to detect the basal *A. palmata* fringe reef during earlier investigations. Typical Barbadian roadcuts are shallow and cross terrace fronts at a low vertical angle; they do not directly show that one acroporid layer is above another. The Mesolella coral succession may have come from horizontal projection in such roadcuts of seaward-dipping transgressive facies in which *A. cervicornis* is topographically lower than but is actually stratigraphically above *A. palmata*.

GLOBAL IMPLICATIONS

The timing and causes of climatic changes of the last interglacial (stage 5e) are of major scientific interest because this interval could be the most apt predictor of the future of the present-day interglacial (e.g., Broecker, 1998). A principal phenomenon of interglacial periods is high sea levels, and these have been widely investigated at coral-bearing coastal marine terraces (Bloom et al., 1974; Chen et al., 1991; Chappell et al., 1996; Muhs et al., 2002), as well as by the oxygen isotope composition of benthic foraminifera in deep-sea sediments (Martinson et al., 1987). Here, we compare the sea level history deduced for the last interglacial at Cave Hill with earlier findings.

Our temporal record of the Rendezvous Hill terrace ranges from ca. 136 to 115 ka. The record may exclude older parts of the terrace that exist buried downslope of exposures or were eroded away in stage 5c, but is likely to contain the terrace's youngest elements. It begins some 8 ka before the 128 ka beginning of stage 5e interpreted in the benthic record. In fact, the age of 136 ka is placed in the benthic record at about the stage 6 glacial lowstand (Martinson et al., 1987). The correct age of the stage 6 glacial maximum must be significantly older than 136 ka.

Our sea level curve suggests a structure to the stage 5e high that is little resolved in the benthic record: an apparently discrete highstand with sharp or narrowly gradual transitions from a transgressive leg at 127 ka to a regressional leg between 120 and 115 ka (Fig. 6). The highstand duration is thus between ~7 and 12 k.y. Nonetheless, this structure is generalized and does not resolve whether brief excursions occurred during the highstand. The record of such excursions, if any, was probably destroyed by post–terrace denudation. However, the absence of a notch on the Rendezvous Hill backcliff implies that a very late (e.g., 120 ka) positive excursion like that documented by Neumann and Hearty (1996) in the Bahamas left no record if it occurred.

Our finding that the Rendezvous Hill subunit rh2–rh4 fringe reef migrated diachronously landward toward highstand level from 136 to 128 ka implies that transgression was generally monotonic over 8 k.y. Thus, proposals of a second sea level peak early in stage 5e (Bloom et al., 1974; Sherman et al., 1993; Johnson, 2001) are either denied, or the second peak is required to have been earlier than 136 ka. Further, the suggestion by Esat et al. (1999) that a major sea level regression occurred at 130 ka is doubtful at Cave Hill because there is no throughgoing unconformity that cuts through the Rendezvous Hill subunit rh2–rh3 section. Rendezvous Hill subunit rh1 is not likely to be a product of such a regression because it is not a shoreline deposit. Conclusions that a single or principal highstand was attained by ca. 127 ka (Edwards et al., 1987; Chen et al., 1991; Stirling et al., 1998) are supported by our model.

As noted, the data of Stirling et al. (1998) in stable Western Australia indicate that regression in stage 5e may have begun between 120 and 119 ka but that sea level fell no more than a few meters until after 116.1 $\pm$ 0.3 ka. This constraint is accommodated by the regression leg at Cave Hill (Fig. 6). It implies that the rate of sea level fall must have increased greatly to >20 m/k.y. after 116.1 ka to reach >37 m below highstand by 115 ka. Such timing supports the view of rapidly increasing ice volume upon entering stage 5d. Our data, however, disagree with the proposal by Szabo et al. (1994) that the stage 5e highstand persisted until 114 ka or younger.

CONCLUSIONS

Our model of the evolution of the last interglacial Rendezvous Hill terrace at Cave Hill, Barbados, emphasizes the role of erosion as well as deposition and in terrace development during transgression and regression as well as highstand, in contrast to earlier ideas. We find that the terrace overlies a floor that is eroded into limestones of stage 6 and 7 ages and extends upslope to an erosional backcliff. The floor is covered by a basal fringe-reef blanket of *Acropora palmata*, which tracked the breaker zone in transgression between 136 (or earlier) and ca. 128 ka. Above and laterally gradational to the fringe reef is an in-place *A. cervicornis* reef with the geometry of a seaward-thickening wedge. The wedge aggraded progressively during transgression, recording keep-up growth of acroporids. Landward of the fringe reef, the floor is a platform that eroded landward following a receding wave-cut cliff during highstand, between ca. 127 and 120 ka, and was probably covered by clastic sediments. Regression began at ca. 120 ka and produced subsidiary terraces with contemporaneous reefs but mainly clastic deposits on the earlier terrace wedge between ca. 120 and 115 ka. The Rendezvous Hill terrace was trimmed landward during the ensuing highstand of stage 5c.

Relative to global sea level history, the Rendezvous Hill terrace at Cave Hill indicates the following: The stage 6 glacial maximum was older than the 136 ka age suggested by the deep-sea benthic record. Stage 5e contained an early monotonic transgression to highstand at ca. 127 ka and did not include two principal highstand maxima. The highstand of stage 5e had a duration of between ~7 and 12 k.y. Finally, the stage 5e–5d transition at ca. 115 ka was accompanied by rapid and large sea level drop.

The most accurate marker of levels of past highstands is the shoreline angle, an isochronous linear geomorphic feature that records the shoreline at the transition from highstand to regression. Used as the highstand marker, the last interglacial shoreline angle gives an average uplift rate of 0.53 ± 0.03 m/k.y. at Cave Hill. Corals provide a less accurate measure of highstand level because, at least in Barbados, most grew in transgression.

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