Uranium-series dating of the Pleistocene reef tracts of Barbados, West Indies

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ABSTRACT

Detailed studies of reef-tract stratigraphy in the southwestern part of Barbados have revealed nine, seven, and ten reef tracts in the Christ Church, Clermont Nose, and Saint George's Valley sections, respectively. The reefs have been projected onto standard traverses, and present elevations are reported for each reef crest.

To date the reef crests by Th^{230}/U and He^4/U methods, the U^{234}/U^{238} and Th^{230}/U^{234} activity ratios and U and He^4 concentrations were determined in about 35 unrecrystallized coral samples. Discordant U^{234}/U^{238}, Th^{230}/U, and He^4/U ages for many samples indicate that both U^{234} and Th^{230} have been diagenetically added to the samples. He^4/U ages are corrected by subtracting the He^4 added due to the presence of "open system" U-series nuclides; the correction ranges from 0% to 10%.

The reef-tract ages and present elevations as projected on the standard traverse show that prior to 125,000 B.P., the uplift rate of the Christ Church section was much greater than the rate after 125,000 B.P. Paleo–sea levels inferred from Saint George's Valley reef tract ages and elevations cluster about the present datum, which suggests that throughout the Brunhes epoch, minimum interglacial continental ice volume was comparable to the present value.

Within the uncertainty of the age and paleo–sea-level estimates, the Brunhes sea-level history inferred from Barbados reef-tract chronostratigraphy is consistent with that inferred by Shackleton and Opdyke from the oxygen isotope record of core V28-238.

INTRODUCTION

The staircase morphology of Barbados, West Indies, is due to construction of coral reefs during times of Pleistocene high sea stands, and subsequent uplift (Mesolella, 1967, 1968). The topography of Barbados is dominated by two especially large terraces, each paralleling the southern and western sides of the island (Mesolella, 1968). The one closest to the sea, First High Cliff, is a single constructional feature, while the landward, higher terrace, Second High Cliff, is partly constructional and partly erosional. There are at least ten less prominent reefs that roughly parallel these two features. It can be documented that most seaward reefs, which are lower in elevation than landward reefs, are younger. Models of reef tract formation were discussed by Mesolella (1968). Tracts form when local sea level is stable for the length of time needed to construct a reef. Reefs are exposed because the island has been uplifted at a rate of about 0.3 m/1,000 yr. Reefs formed during glacial episodes are likely to be covered by reef-tract formation during subsequent events of higher sea level. Tracts formed during interglacials and some interstadials will be uplifted before burial and preserved, if they are not destroyed by erosion.

Suitable Pleistocene corals can be dated by the Th^{230}/U and Pa^{231}/U methods (Sackett, 1958; Sackett and Potratz, 1963; Broecker and Thurber, 1965; Thurber and others, 1965; Veeh, 1966). Application of these methods has revealed that there was a major episode of reef-tract formation at approximately 120,000 to 140,000 B.P., the record of which has been found in Pacific atolls (Sackett, 1958; Sackett and Potratz, 1963; Thurber and others, 1965; Veeh, 1966), Hawaii (Veeh, 1966; Ku and others, 1974), Japan (Komura and Sakanoue, 1967), New Guinea (Veeh and Chappell, 1970; Bloom and others, 1974), Bermuda (Land and others, 1967; Broecker and Thurber, 1965), Jamaica (Moore and Somayajulu, 1974), and the Bahamas (Neumann and Moore, 1975). On Barbados, First High Cliff is the 120,000- to 140,000-yr-old feature (Broecker and others, 1968; Mesolella and others, 1969; Ku, 1968). Less well-developed reef tracts record interstadial periods at 82,000 and 105,000 B.P. (Broecker and others, 1968; Mesolella and others, 1969).

In most areas, the attempt to extend the chronology of high sea stands back in time has been hampered by the paucity of older reef tracts containing unrecrystallized corals for dating studies. While these problems certainly affect Barbados, the record of high sea stands is perhaps more accessible there than at any other place. There is a continuous series of fossil coral reefs extending back to about 700,000 B.P. (Mesolella and others, 1969). While corals are generally recrystallized to calcite, unrecrystallized aragonite corals can be found in most of the major fossil reef tracts in the drier areas of the island.

We have previously reported results on stratigraphic studies and Th^{230}/U and He/U dating studies on First High Cliff and younger reef tracts (Mesolella, 1968; Bender and others, 1973). There were episodes of reef-tract formation at approximately 200,000, 330,000, 500,000 and 560,000 B.P. However, the significance of the results was limited by three factors: the stratigraphy had not

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been completely resolved, Th^{230}/U dates around 200,000 B.P. have a high uncertainty, and He/U dates were based on few samples.

We report here results of further work on the chronostratigraphy of Pleistocene Barbados coral reefs older than First High Cliff (125,000 B.P.). A considerable amount of additional field work has been carried out with the goal of mapping individual reefs. Approximately 35 new Th^{230}/U dates and He/U dates have been determined.

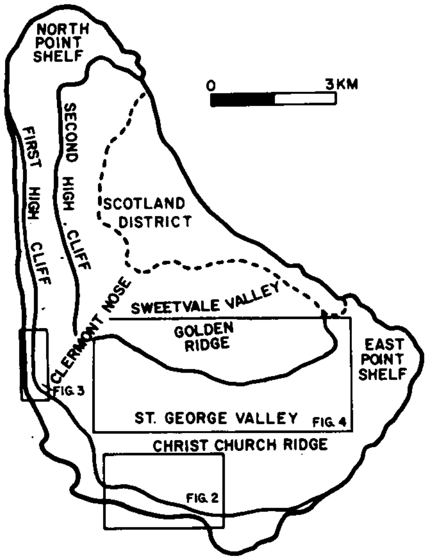

Figure 1. Index map of Barbados, West Indies, showing location of areas selected for detailed study (Figs. 2, 3, 4).

STRATIGRAPHIC METHODS AND SAMPLE SELECTION

We have tried to define morphostratigraphic units that represent the deposition of coral reefs and associated sediments ascribable to discrete stillstands of sea level relative to the emerging island of Barbados. To meet our criteria for such a morphostratigraphic unit, there must be geomorphic continuity and an environmental datum indicating shallow-water conditions in close relationship with the geomorphic feature. Goreau (1959) has shown that *Acropora palmata* is the coral most characteristic of Jamaican coral reef-crest facies. Mesolella (1967) demonstrated that uplifted Pleistocene reef tracts on Barbados have reef facies corresponding to modern Jamaican reef facies. In most cases, we therefore generally use the *A. palmata* reef-crest community as a shallow-water datum; occasionally we rely on beach facies. Without both geomorphic continuity and an environmental datum, we would have no independent cross-check on the relation with respect to sea level of one dated coral sample to another. In view of our experience, we strongly discourage interpretation of random coral dates that cannot be related to morphostratigraphic units as defined above.

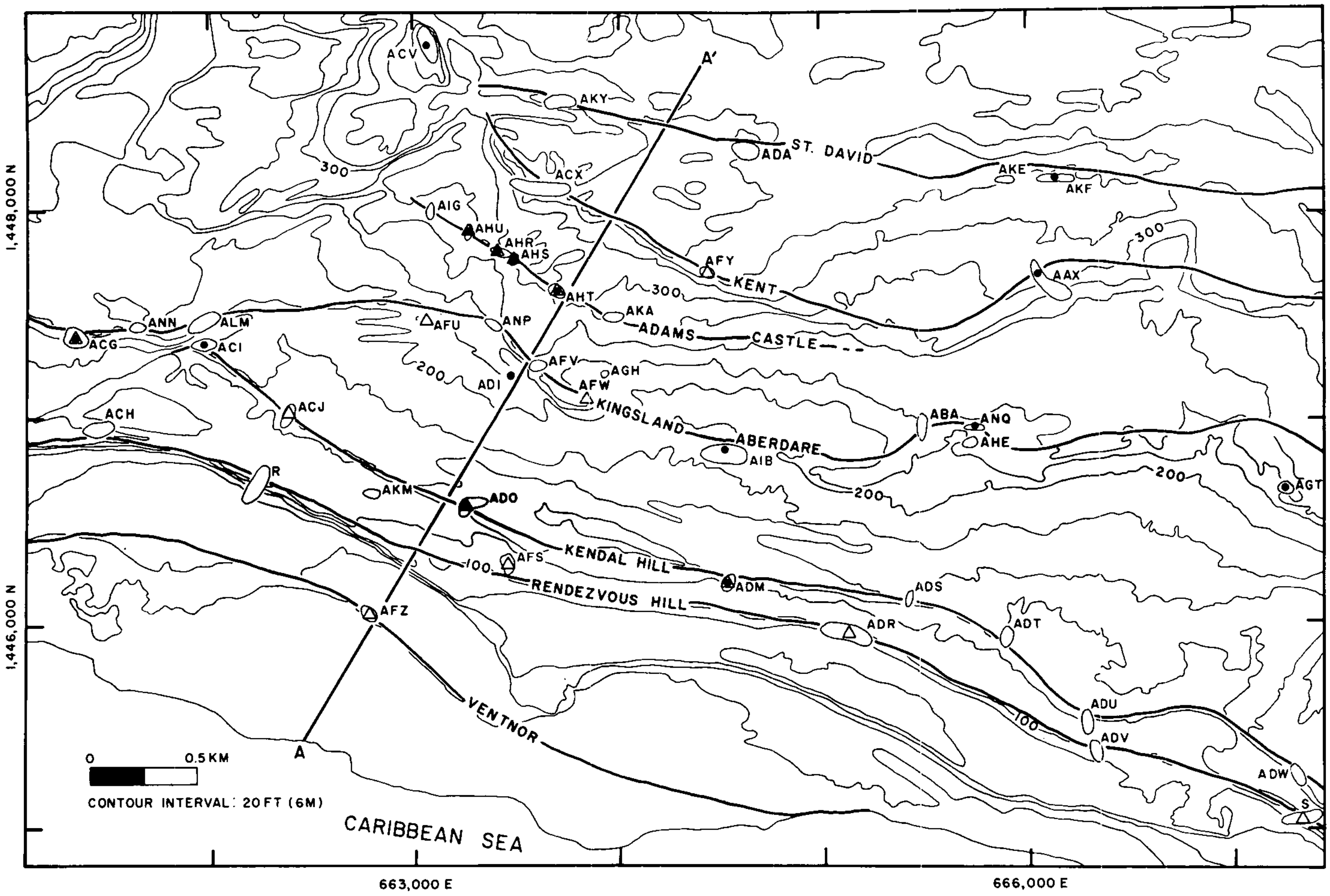

Figure 2. Map of Christ Church Ridge study area. Locations of *A. palmata* reef-crest zone of the various reef-tract terraces are indicated by heavy lines and terrace names. Free-form ovals indicate localities that provide shallow-water environmental datum (predominantly *A. palmata* reef-crest facies). Triangles indicate localities dated by He^4/U method. A–A′ denotes location of Christ Church Ridge standard traverse (see Table 1).

Study Areas

Figure 1 indicates the location of three areas of detailed stratigraphic study. The Christ Church Ridge area (Fig. 2) was studied because it provides well-developed geomorphology in an area of relatively low rainfall (and therefore good preservation of aragonite corals used in dating and isotopic studies). The Clermont Nose area (Fig. 3) was chosen as the area that best allows radiometric dating of the excellent morphostratigraphic sequence that exists along the west coast of Barbados. The central west coast area has been significantly altered by freshwater diagenesis, whereas the Clermont Nose area to the south remains largely unaffected. Further, previous thorium-230 dating (Mesolella and others, 1969) suggests that the Clermont Nose area has the highest uplift rate observed in Barbados. The St. George's Valley area (Fig. 4) was chosen to provide stratigraphic context for the oldest aragonitic corals yet found on Barbados (Bender and others, 1973).

Methods and Mapping Conventions

Preliminary geomorphic mapping of reef terraces was done by stereoscopic examination of air photographs. The reef terraces thus identified were checked in the field by investigating outcrops in roadcuts, gullies, quarries, and so forth. Coral reef facies corresponding to those of modern coral reefs (see Mesolella, 1967) were described and mapped.

Reef crests are represented by the heavy lines in Figures 2, 3, and 4. Each reef crest is characterized by numerous exposures of *A. palmata*. Many additional localities (Mesolella, 1968; Taylor, 1974) not shown in Figures 2, 3, and 4 contain other coral-reef–associated facies. These localities expose various fore-reef and back-reef facies and serve as important guides in mapping coral reef tracts (Mesolella and others, 1970). Reef-crest stratigraphy is summarized in Tables 1, 2, and 3.

Integration of Previous Work

Several previous publications have referred to various Barbados terraces by Roman numeral ("Barbados III"), age ("the 125,000 B.P. terrace"), or descriptive phrases ("the upper St. George's Valley reef terrace"). Such systems have led to a cumbersome terrace nomenclature. Names based on age are subject to continual change with re-evaluation of the absolute age of the terrace. Roman numerals become particularly awkward when additional field work delineates a previously unnumbered morphostratigraphic unit within a series of terraces that have already been assigned Roman numerals. In this paper, we pull together the previous nomenclature for the reef terraces of Barbados, define the terraces more precisely as morphostratigraphic units, and assign them informal geographic names. In doing this, we hope to relieve the literature of the cumbersome system of Roman numerals and absolute dates and to initiate a system that will more conveniently accommodate future refinement of Barbados stratigraphy.

Sample Selection

In order to maintain a high degree of confidence concerning the relation of a dated sample to the morphostratigraphic framework, we have chosen to work almost exclusively with the reef crest coral *A. palmata* (Mesolella, 1967). Laboratory criteria for selecting dat-

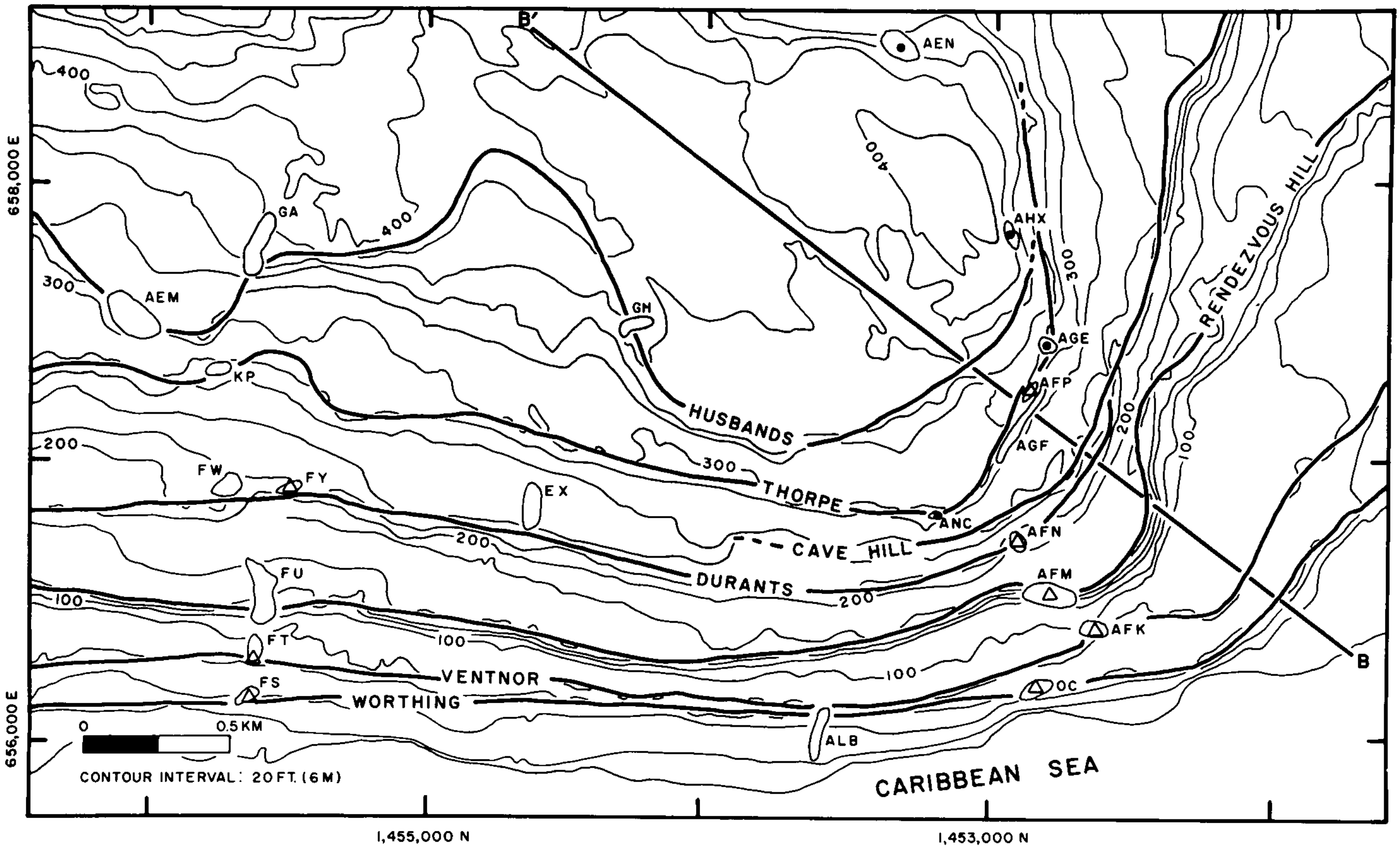

Figure 3. Map of Clermont Nose study area. North is to left. Symbols as in Figure 2. B–B′ denotes location of Clermont Nose standard traverse (see Table 2).

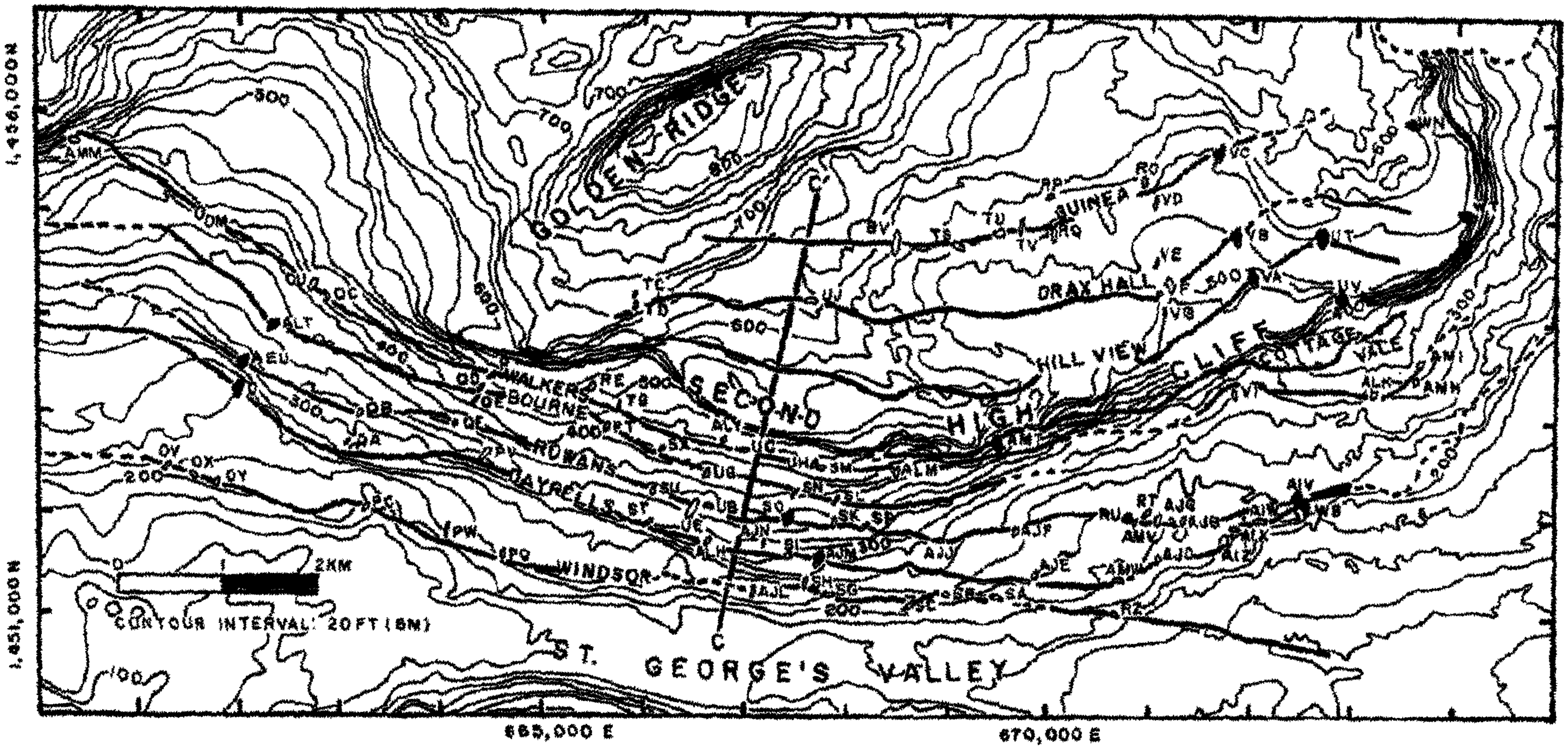

Figure 4. *Map of St. George's Valley study area. Symbols as in Figure 2. C–C' denotes location of St. George's Valley standard traverse* (see Table 3).

able material are described elsewhere (Taylor, 1974; Bloom and others, 1974).

Designation of Standard Traverses

Within each study area we have designated a standard traverse and have estimated uplift of the hypothetical paleo–sea-level marker relative to present mean sea level in the standard traverse for each morphostratigraphic unit (Tables 1, 2, 3). Matthews (1973) subdivided error in uplift estimates into (1) uncertainty in values of altitudes determined from topographic maps and (2) uncertainty in the ecological corrections applied to the altitudes of paleo–sea-level markers.

ANALYTICAL TECHNIQUES

Uranium and thorium concentrations and relative isotopic abundances were determined by alpha spectrometry using the tech-

TABLE 1. TERRACE TERMINOLOGY AND ELEVATION OF TERRACES AND PALEO-SEA-LEVEL SURFACES IN CHRIST CHURCH STANDARD TRAVERSE, BARBADOS

Previous terrace terminology		Morphostratigraphic unit (this paper)	Topographic elevation and estimated paleo-sea-level surface elevation (with uncertainty) in standard traverse (m)
Mesolella (1968) and others	Taylor (1974)		
Barbados I (82,000 B.P.)	Barbados I	Worthing	3^{+1}_{-2}
Barbados II (105,000 B.P.)	Barbados II	Ventnor	6^{+5}_{-1}
Barbados III (127,000 B.P.)	Barbados III	Rendezvous Hill	37±2
198, 220, 242, 268 (10^3 yr B.P.)	Lower 200,000 B.P.	Kendal Hill	49^{+3}_{-2}
X	Upper 200,000 B.P.	Kingsland	79^{+3}_{-2}
X	Middle 200,000 B.P.	Aberdare	67^{+3}_{-2}
XI	Upper 200,000 B.P.	Adams Castle	91^{+3}_{-1}
XII	Lower 300,000 B.P.	Kent	110^{+3}_{-2}
XIII	Upper 300,000 B.P.	St. David	110^{+3}_{-2}
XIII?	Upper 300,000 B.P.	Unnamed	$122^{+??}_{-2}$

TABLE 2. TERRACE TERMINOLOGY AND ELEVATION OF TERRACES AND PALEO-SEA-LEVEL SURFACES IN CLERMONT NOSE STANDARD TRAVERSE, BARBADOS

Previous terrace terminology		Morphostratigraphic unit (this paper)	Topographic elevation and estimated paleo-sea-level surface elevation (with uncertainty) in standard traverse (m)
Mesolella (1968) and others	Taylor (1974)		
Barbados I (82,000 B.P.)	Barbados I (82,000 B.P.)	Worthing	20^{+3}_{-2}
Barbados II (105,000 B.P.)	Barbados II (105,000 B.P.)	Ventnor	30^{+3}_{-2}
Barbados III (127,000 B.P.)	Barbados III (125,000 B.P.)	Rendezvous Hill	61±2
198, 220 (10^3 yr B.P.)	Clermont, lower 200,000 B.P.	Durants	67^{+3}_{-2}
198, 220 (10^3 yr B.P.)	Clermont, lower-middle 200,000 B.P.	Cave Hill	85^{+3}_{-2}
242, 268 (10^3 yr B.P.)	Clermont, upper 200,000 B.P.	Thorpe	94^{+3}_{-2}
XI	Clermont, 300,000 B.P.	Husbands	107^{+3}_{-2}
XII	Unnamed	Unnamed	$122^{+??}_{-2}$

niques of Kaufman and Broecker (1965). Since calculated ages of samples older than 150,000 yr are very sensitive to small changes in the Th^{230}/U^{234} ratio, great care was taken in making the corrections to the integrated alpha spectral peak areas used in calculating this ratio. The validity of the method chosen for making the correction for the tail of the Ra^{224} peak under the Th^{228} peak was verified by counting a Th^{228} sample repeatedly as the Ra^{224} grew in. The Th^{232} content was below the limit of detection for all samples except AIB-2 (0.25 ± 0.03 ppb), AGH-2 (0.10 ± 0.01 ppb), AHR-2 (0.04 ± 0.004 ppb), ALT-1 (0.04 ± 0.004 ppb), and VC-1 (0.025 ± 0.003 ppb).

Uranium concentrations of samples dated by the He/U method were determined independently using the epithermal neutron activation analysis technique of Steinnes (1971). Coral samples weighing 250 mg were sealed in 2-cm^2 plastic bags. The sample bags, along with similar bags packed with a coral standard, were stacked and wrapped in aluminum foil. There was at least one standard adjacent to each sample. The stack was placed in a cadmium container and irradiated for 4 hr at a flux of 4×10^{12} neutrons cm^{-2} s^{-1}. Samples and standards were allowed to cool for two to seven days and then counted using a Ge(Li) detector and pulse-height analyzer. The activity of U^{239} daughter Np^{239} ($t_{\frac{1}{2}}$ = 2.34 days) was estimated from the sum of the 228-keV and 278-keV photopeaks. The U concentrations in the samples were determined by comparing sample and standard activities. The U content of the coral standard itself was determined by epithermal neutron activation analysis using a uranium nitrate standard solution prepared from pure U_3O_8. The precision is ±3%, and the accuracy is ±4%.

Some samples were analyzed for uranium by both alpha spectrometry and epithermal neutron activation. Results are compared in Figure 5. On the average, U concentrations determined by activation are 2% higher than values determined by alpha spectrometry. This difference is not outside the error limits of the standard calibrations. The standard deviation from the mean is ±2%; thus, the results from the different methods are in very good agreement.

Epithermal activation is an attractive technique for routine uranium analyses in sedimentary rocks. Delayed neutron activation, however, is a more desirable technique, because it is equally precise and more rapid. Epithermal neutron activation involves considerably less work for sample preparation than does uranium analysis on powders by fission track counting (Turekian and Chan, 1971). It is far faster and nearly as precise as alpha spectrometry, but of course yields no information on isotopic abundances.

Helium analyses were carried out using the acid dissolution, isotope dilution method of Bender (1970, 1973). Isotopic assays were performed on an AEI-MS 20 mass spectrometer to which the preparation line was attached. Samples were analyzed immediately after preparation. Hydrogen peaks were very small, and no correction was needed for H_3 and HD under the He^3 peak. The He^3 spike was calibrated as described by Bender and others (1973). The precision of spike calibrations was ±1%; accuracy is believed to be as good as precision. The precision of the He^4 analyses on samples is ±2%. Ne^{20} was measured in some samples by comparing the Ne^{20}/He^4 ion current ratio for the coral sample with that for air. The Ne^{20} concentration was then computed from the formula

$$[Ne^{20}]_{sample} = \frac{(Ne^{20}/He^4)_{icr - sample}}{(Ne^{20}/He^4)_{icr - air}} \times \left(\frac{[Ne^{20}]}{[He^4]}\right)_{air} \times [He^4]_{sample} ,$$

where icr indicates ion current ratio. In some samples $[Ne^{20}]$ was not measured because of a small leak in the analyzer tube of the mass spectrometer.

TABLE 3. TERRACE TERMINOLOGY AND ELEVATION OF TERRACES AND PALEO—SEA-LEVEL SURFACES IN ST. GEORGE'S VALLEY STANDARD TRAVERSE, BARBADOS

Previous terrace terminology		Morphostratigraphic unit (this paper)	Topographic elevation and estimated paleo–sea-level surface elevation (with uncertainty) in standard traverse (m)
Mesolella (1968)	Taylor (1974)		
242, 268 (10^3 yr B.P.)	Lower St. George's Valley reef terrace	Windsor	73^{+5}_{-2}
XI	XI	Rowans	110^{+5}_{-2}
X	X	Dayrells	92^{+5}_{-2}
XII	XII	Bourne	125^{+5}_{-2}
XIII	XIII	Walkers	137^{+5}_{-2}
Not recognized	Upper St. George's Valley reef terrace	Cottage Vale	158±6
Second High Cliff	Second High Cliff	Unnamed	171^{+6}_{-2}
XV	XVa	Hill View	177^{+5}_{-2}
XV	XVb	Drax Hall	192^{+5}_{-2}
XVI	XVI	Guinea	192^{+5}_{-2}

There are three components of He^4 — atmospheric, inherited, and radiogenic. The magnitude of the atmospheric component is calculated by multiplying the $[Ne^{20}]$ of the sample by the atmospheric $[Ne^{20}]/[He^4]$ ratio. The total was corrected for atmospheric He^4 assuming that the He^4/Ne^{20} ratio in this fraction is identical to that in air. Where Ne^{20} was not measured, the atmospheric He^4 content was assumed to be 0.6×10^{-8} scc g^{-1} (the mean and standard deviation of measured atmospheric He^4 values of samples in this study is 0.6 ± 0.1 scc g^{-1}). The presence of an inherited component is inferred from the fact that the amount of atmospherically corrected He^4 exceeds the amount generated by U and U daughter decay in 82,000-, 105,000-, and 124,000-yr-old corals by $0.6 \pm 0.4 \times 10^{-8}$ scc g^{-1} (Bender, 1970, 1973). The radiogenic He^4 content is calculated by subtracting the atmospheric He^4 and inherited He^4 components from the total He^4 content. The analytical uncertainty in the He^4/U ratio is ±4%. Where Ne^{20} was determined, the percent total uncertainty in the He^4/U ratio is calculated from the equation

$$\text{Uncertainty} = \sqrt{(4\%)^2 + \left(\frac{0.4 \times 10^{-8}\ \text{scc g}^{-1}}{[\text{He}^4]}\right)^2}.$$

When Ne^{20} was not determined, the uncertainty is calculated from the equation

$$\text{Uncertainty} = \sqrt{(4\%)^2 + \left(\frac{0.4 \times 10^{-8}\ \text{scc g}^{-1}}{[\text{He}^4]}\right)^2 + \left(\frac{0.1 \times 10^{-8}\ \text{scc g}^{-1}}{[\text{He}^4]}\right)^2}.$$

Uncertainties in ages were calculated from uncertainties in the He^4/U ratios. Uncertainties in ages calculated in this way are about 10% for the youngest samples and about 5% for the oldest samples. Note that these estimates do not include any allowance for open-system conditions. Analytical results are summarized in Table 4.

CHRIST CHURCH RIDGE STUDY AREA

Mesolella (1968) reported preliminary morphostratigraphic reconnaissance of the Christ Church Ridge area (Fig. 1). A survey of the mineralogy of the coral cap was reported by Matthews (1968). This work showed that the Christ Church area provides both good morphostratigraphy and exposures yielding aragonitic corals suitable for radiometric dating. The area was therefore chosen for detailed study. Taylor (1974) reported additional morphostratigraphic detail. By incorporating results of a core-drilling program carried out from January to August 1975, along with new observations at key outcrops, Fairbanks further improved the morphostratigraphic determinations.

Geomorphology

Figure 2 shows the location of eight reef terraces recognized in this area. The lowest well-developed reef terrace in the Christ Church Ridge area is the Ventnor terrace (previously dated at 105,000 B.P.; Mesolella and others, 1969). Terrace morphology and *A. palmata* reef-crest facies are particularly well developed near localities ANM and AFZ.

Rendezvous Hill terrace (previously dated at 125,000 B.P.) is a very prominent geomorphic feature. In the western part of the study area the *A. palmata* reef-crest community occupies the seaward margin of the terrace. To the east, the fore-reef slope of the terrace is more gentle, with the slope down to Ventnor terrace dominated by *A. cervicornis* facies.

Kendal Hill terrace has relatively low relief compared to Rendezvous Hill terrace, but it is quite continuous and well punctuated with *A. palmata* occurrences at its seaward margin. To the west, near locality ACI, the Kingsland-Aberdare terrace fore-slope becomes a paleo–sea cliff, owing to erosion associated with the stand of the sea during Kendal Hill time.

Kingsland-Aberdare terrace is a composite terrace in which the *A. palmata* reef-crest facies of the Aberdare sea stand is overlain by *A. palmata* reef-crest facies of the Kingsland sea stand (discussed further below).

Adams Castle terrace has low relief relative to Kingsland. Furthermore, along this tract *A. palmata* reef-crest facies is developed discontinuously, making the seaward margin of the terrace somewhat ill-defined. The unit is considered mappable largely on the basis of geomorphology and *A. palmata* facies distribution in the area between localities AIG and AKA.

Kent terrace is a well-developed geomorphic feature, rising abruptly 12 to 18 m above the shoreward facies of Adams Castle, Kingsland, or Aberdare.

St. David terrace has little topographic separation from Kent terrace. St. David is mapped on the basis of faint air-photo lineations which are consistent with the observed *A. palmata* distribution.

Stratigraphic Relationships

Following the lead of Jukes-Brown and Harrison (1891), we normally consider each successively higher reef tract to be successively older. Indeed, most terraces can be shown to consist of a single reef tract with back-reef, reef-crest, and fore-reef facies corresponding to those of modern Caribbean reef tracts (Mesolella, 1967); good stratigraphic evidence exists for this relationship among the Ventnor, Rendezvous Hill, Kendal Hill, and Aberdare terraces. To date, evidence of this relationship is less than conclusive for Kingsland to Adams Castle and Adams Castle to Kent.

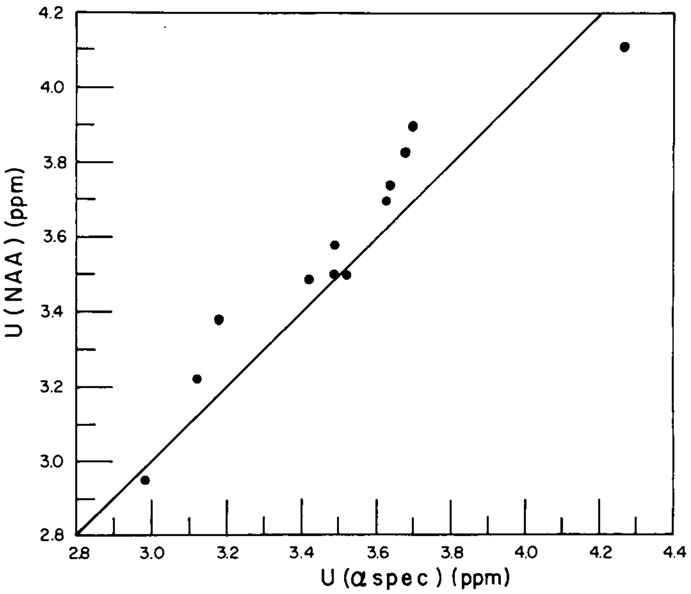

Figure 5. Comparison of [U] determinations by alpha spectrometry and instrumental neutron activation analysis.

TABLE 4. URANIUM AND URANIUM DAUGHTER ABUNDANCES FOR PRE–RENDEZVOUS HILL SAMPLES FROM BARBADOS

Locality, sample	Genus, species	[U] (ppm)	$\frac{U^{234}}{U^{238}}$	$\frac{Th^{230}}{U^{234}}$	$[He^4]$ (10^{-8} scc g^{-1})	$[He^4]$ (atm) (10^{-8} scc g^{-1})	Radiogenic $[He^4]$[*] (10^{-8} scc g^{-1})	Calculated ages (10^3 yr) $\frac{Th^{230}}{U}$	Calculated ages (10^3 yr) $\frac{He^4}{U}$ (uncorrected)	Calculated ages (10^3 yr) $\frac{He^4}{U}$ (continuous diagenesis)[†]
					Durants Terrace, Clermont Nose					
AFN-5	*Acropora*	3.47	1.12	0.88				215		
	palmata	±0.11[‡]	±0.03	±0.03				±25		
FY-5	*Montastrea*	2.76	1.12	0.88				215		
	annularis	±0.07[‡]	±0.02	±0.03				±30		
HG-2	*Siderastrea*	2.66	1.09	0.84				190		
	siderea	±0.03[‡]	±0.01	±0.01				±10		
HG-5	*Acropora*	3.56[**]			3.9	0.6[††]	2.7		110	110
	palmata									
					Thorpe Terrace, Clermont Nose					
AFP-2	*Acropora*	3.44	1.08	0.89				220		
	palmata	±0.06	±0.02	±0.03				±25		
ANC-4	*Acropora*	3.51[**]			7.8	0.6[††]	6.6		210	210
	palmata									
AGE-13	*Acropora*	3.36[**]			8.0	0.6[††]	6.8		220	220
	palmata									
					Lodge Terrace, Clermont Nose					
AEN-1	*Siderastrea*	2.53[**]			10.4	0.6[††]	9.2		380	360
	siderea									
					Kendal Hill Terrace, Christ Church					
ACJ-4	*Acropora*	3.06	1.13	0.89				220		
	palmata	±0.09	±0.03	±0.03				±30		
ADO-7	*Acropora*	3.84	1.14	0.77				154		
	palmata	±0.11[‡]	±0.03	±0.03				±13		
ADM-6	*Acropora*	2.98	1.12	0.86	6.0	0.6[††]	4.8	200	190	190
	palmata	±0.06[‡]	±0.02	±0.03				±17		
		2.95[**]								
ADO-7	*Acropora*	3.54	1.08	0.96	7.0	0.6[††]	5.8	310	180	180
	palmata	±0.07[‡]	±0.02	±0.04				±70		
		3.79[**]								
ACI-2		3.28[**]			5.8	0.6[††]	4.6		170	170
					Kingsland Terrace, Christ Church					
AFU-1	*Siderastrea*	3.07	1.11	0.93				260		
	radians	±0.03[‡]	±0.01	±0.03				±30		
AFW-1	*Siderastrea*	3.06	1.10	0.90				230		
	siderea	±0.06[‡]	±0.01	±0.03				±30		
ACG-5	*Acropora*	3.12	1.14	0.83				180		
	palmata	±0.06[‡]	±0.02	±0.03				±20		
ACG-42	*Acropora*	3.14	1.08	0.94	6.4	0.4	5.4	280	190	190
	palmata	±0.09[‡]	±0.03	±0.04				±50		
		3.22[**]								
AIB-2	*Acropora*	3.16	1.10	0.92				250		
	palmata	±0.07[‡]	±0.02	±0.03				±40		
ADI-2	*Acropora*	3.29[**]			7.3	0.6	6.1		210	210
	palmata									
					Aberdare Terrace, Christ Church					
AGH-2	*Acropora*	4.27	1.10	0.90	9.5	0.7	8.2	230	230	220
	palmata	±0.09[‡]	±0.02	±0.03				±30		
		4.11[**]								
ACG-6	*Acropora*		1.13	0.88				215		
	palmata		±0.02	±0.03				±20		
AGT-2	*Acropora*	3.50[**]			7.9	0.6[††]	6.7		220	
	palmata									

TABLE 4. *(Continued)*

Locality, sample	Genus, species	[U] (ppm)	$\frac{U^{234}}{U^{238}}$	$\frac{Th^{230}}{U^{234}}$	$[He^4]$ (10^{-8} scc g^{-1})	$[He^4]$ (atm) (10^{-8} scc g^{-1})	Radiogenic $[He^4]$* (10^{-8} scc g^{-1})	Calculated ages (10^3 yr)		
								$\frac{Th^{230}}{U}$	$\frac{He^4}{U}$ (uncorrected)	$\frac{He^4}{U}$ (continuous diagenesis)[†]
Adam's Castle Terrace, Christ Church										
AHU-1	*Acropora palmata*	3.18 ±0.10[‡] 3.38[**]	1.23 ±0.03	1.03 ±0.04	8.1	0.6[††]	6.9	>320	230	200
AHS-1	*Acropora palmata*	3.42 ±0.11[‡] 3.49[**]	1.09 ±0.02	1.00 ±0.04	9.3	0.6[††]	8.1	>300	250	240
AHT-1	*Acropora palmata*	3.68 ±0.12[‡] 3.83[**]	1.04 ±0.03	1.00 ±0.04	9.3	0.6[††]	8.1	>320	230	220
AHR-2	*Acropora palmata*	3.70 ±0.07‡ 3.90[**]	1.17 ±0.02	0.83 ±0.03	11.8	0.4	10.8	180 ±15	290	280
Kent Terrace, Christ Church										
AFY-1	*Acropora palmata*	3.71 ±0.01[‡]	1.11 ±0.01	1.00 ±0.03				>350		
AAX[‡‡]	*Montastrea annularis*	2.48[‡‡]					9.0		350	330
AAX[‡‡]	*Acropora palmata*	2.62[‡‡]					8.8		330	310
AAX[‡‡]	*Siderastrea siderea*	2.51[‡‡]					8.8		360	340
Saint David's Terrace, Christ Church										
AKF-1	*Acropora palmata*	3.51[**]			12.1	0.3	11.2		320	310
AKF-2	*Acropora palmata*	3.91[**]			10.0	0.6[††]	8.8		240	230
AMY-1	*Acropora palmata*	3.36[**]			11.9	0.6[††]	10.7		320	310
Rowans Terrace, Saint George's Valley										
AEU-1	*Acropora palmata*	3.49 ±0.07[‡] 3.50[**]	1.10 ±0.02	1.06 ±0.04	12.4	0.6	11.2		320	310
SO-4	*Acropora palmata*	3.85[**]			13.0	0.6[††]	11.8		310	300
RU-1	*Acropora palmata*	3.39[**]			11.3	0.4	10.3		310	300
AIV-3	*Acropora palmata*	3.65[**]			11.8	0.6	10.6		300	290
Dayrells Terrace, Saint George's Valley										
D-14	*Acropora palmata*	3.52 ±0.07[‡] 3.50[**]	1.21 ±0.02	1.07 ±0.04	14.0	0.6[††]	12.8		360	340
AJM-2	*Acropora palmata*	3.51[**]			13.5	0.6[††]	12.3		340	320
Bourne Terrace, Saint George's Valley										
ALT-1	*Acropora palmata*	3.63 ±0.07[‡] 3.70[**]	1.20 ±0.02	0.96 ±0.04	11.8	0.6[††]	10.6	270 ±50	290	280
ALT-2	*Acropora palmata*	3.40 ±0.07[‡]	1.10 ±0.02	0.99 ±0.04				≥300		

(continued on following page)

Clearly, St. David cannot be younger than Kent (on the basis of topography), but they could be of roughly equivalent age.

Within the Kingsland-Aberdare terrace, it can be clearly demonstrated that Kingsland (the higher of the two) is younger than Aberdare. At localities ACG, ANP, AGH, AHE, and AGT, Kingsland *A. palmata* and/or *A. cervicornis* facies overlie a well-developed Aberdare *A. palmata* reef-crest facies. Cored boreholes near localities ACG and ANP encounter subaerial caliche crusts capping the buried Aberdare *A. palmata* facies. Thus, Kingsland is not only younger than Aberdare, but it also appears to be separated from Aberdare by a period of subaerial exposure.

It should be kept in mind that Aberdare sediments have experienced a unique diagenetic history relative to sediments from the other Christ Church terraces. Whereas the general rule is continuous subaerial exposure beginning shortly after deposition on Christ Church Ridge, Aberdare alone is demonstrated to have been inundated once again by a younger stand of the sea. Further, younger Kingsland sediment overlying Aberdare may serve as a source of distinctly younger contamination throughout the vadose history of the terrace complex.

Christ Church Standard Traverse

To facilitate comparison to other data sets, we have designated a Christ Church standard traverse (Matthews, 1973). Its location is indicated in Figure 2. The traverse is chosen as that single line onto which elevation of the *A. palmata* reef-crest community for all reef tracts could be most reliably projected. A summary of terminology and elevation data is given in Table 1.

CLERMONT NOSE STUDY AREA

The Clermont Nose study area (see Fig. 1) appears to have the highest average uplift rate found on Barbados. Rendezvous Hill terrace rises to 60 m here, and the marked change in orientation of older reef tracts suggests that a positive structural element extending from Clermont Nose to Mt. Hillaby has been active throughout the past 700,000 yr. Mesolella (1968) and Taylor (1974) discussed the area. New field observations by two of us (Matthews and Fairbanks), reported here, provide more detailed information concerning pre–Rendezvous Hill terraces.

Geomorphology

Figure 3 shows the location of eight reef terraces recognized in this area. The lowest three reef terraces in the area are Worthing terrace (previously dated at 82,000 B.P.), Ventnor terrace (105,000 B.P.), and Rendezvous Hill terrace (125,000 B.P.). All are prominent geomorphic features and are easily traced throughout the area (Mesolella and others, 1969).

TABLE 4. *(Continued)*

Locality, sample	Genus, species	[U] (ppm)	U^{234}/U^{238}	Th^{230}/U^{234}	[He^4] (10^{-8} scc g^{-1})	[He^4] (atm) (10^{-8} scc g^{-1})	Radiogenic [He^4][*] (10^{-8} scc g^{-1})	Calculated ages (10^3 yr) Th^{230}/U	He^4/U (uncorrected)	He^4/U (continuous diagenesis)[†]
Cottage Vail Terrace, Saint George's Valley										
AMT-2	*Acropora palmata*	3.64 ±0.07 3.74[**]	1.15 ±0.02	1.07 ±0.04	23.5	0.6[††]	22.3		540	490
Second High Cliff, Saint George's Valley										
UV[‡‡]	*Diploria*	2.55[‡‡]					13.9		500	460
WT[‡‡]	*Montastrea annularis*	2.43[‡‡]					12.7		480	440
Hill View Terrace, Saint George's Valley										
VA-1	*Acropora palmata*	3.32[**]			22.9	0.8	21.5		580	520
UT[‡‡]	*Acropora palmata*	3.14[‡‡]					19.5		560	510
Drax Hall Terrace, Saint George's Valley										
VB[‡‡]	*Montastrea annularis*	3.08[‡‡]					22.7		660	590
Guinea Terrace, Saint George's Valley										
VC-1	*Acropora palmata*	3.49 ±0.07 3.58[**]	1.12 ±0.02	1.11 ±0.04	30.7	0.7	29.4		720	640

Note: Tabulated uncertainties in alpha spectrometry data are ±1σ. See text for uncertainties in [U], [He], and He/U ages. [He^4] (atm) is defined as measured [Ne^{20}] of the samples times the atmospheric [He^4]/[Ne^{20}] ratio. Total uncertainty in individual He/U is ±10%.

[*] Equal to [He^4] − [He^4] (atm) − 0.6 × 10^{-8} scc g^{-1}; letter term is "inherited He^4" content not accounted for by atmospheric He^4 correction (see Bender, 1973).

[†] Continuous diagenesis model He^4/U age (see text).

[‡] U determination by alpha spectrometry; errors reflect only statistical uncertainties in count rates.

[**] U determination by neutron activation as described in this paper; uncertainty is ±4%.

[††] Not measured; taken as the average value of measured samples (see text).

[‡‡] Bender and others (1973).

Durants terrace is a well-defined geomorphic feature northward of locality AFN. Cave Hill terrace exhibits good topographic separation from Durants terrace in the vicinity of localities AFN and AGF. To the east, Cave Hill terrace has clear topographic expression; to the north it becomes indistinguishable from the back-reef topography of Durants terrace.

Thorpe terrace and Husbands terrace are easily recognized geomorphic features except in the southeast part of the study area, where terrace convergence, steep relief, and erosion make mapping difficult.

There is a distinct topographic feature above Husbands terrace north of locality AHX and west of locality AEN. Because we cannot clearly assign any *A. palmata* locality to this topographic feature, we leave it unnamed. It should be noted that Mesolella (1968) assigned locality AEN to this feature. Subsequently, we discovered locality AHX. AHX appears best interpreted as a fringing reef developed against the higher topography, *not* a part of it. This interpretation of AHX casts doubt on precise placement of AEN within morphostratigraphic units. Both AEN and AHX are tentatively regarded as part of Husbands terrace. Admittedly this assignment is uncertain; both localities may be pre-Husbands.

Stratigraphic Relationships

As stated above under discussion of Christ Church stratigraphic relationships, we consider each successively higher reef to be successively older. Within the Clermont Nose study area, specific field evidence for this generality exists only in the case of Cave Hill relative to Thorpe and Durants relative to Cave Hill. Locality AGF was an open ditch cut for a water main in 1967. It exposed well-rounded coral rubble (including *A. palmata*) in coarse clean carbonate sand. This locality is interpreted as Cave Hill beach facies lapping onto the fore-reef slope of Thorpe. A similar occurrence of beach facies was noted in the water-main ditch where Durants topography abuts Cave Hill topography. Unfortunately, both of these key outcrops are now covered with cement sidewalks. To the north of the study area, Durants beach facies can be seen lapping onto Thorpe fore reef at localities EH to EI (Winland, 1971, p. 290).

Clermont Nose Standard Traverse

Matthews (1973) designated the Clermont Nose standard traverse to run from 1,451,710 north, 656,330 east, to 1,456,560 north, 659,960 east. The lower part of this traverse is shown as B–B′ in Figure 3. A summary of terminology and elevation data is provided in Table 2.

ST. GEORGE'S VALLEY STUDY AREA

St. George's Valley (see Fig. 1) reflects an east-west–trending low on the folded and faulted marine sedimentary strata underlying the coral cap (Mesolella and others, 1970). Oscillating Pleistocene sea levels repeatedly flooded the valley until uplift gradually carried the valley above the reach of high sea stands about 200,000 yr ago. From the valley floor up the north wall to Second High Cliff, six constructional reef terraces (Fig. 4) are recognized. Immediately above Second High Cliff, the sequence of constructional reef terraces continues up to the highest altitudes on Barbados. The six reef terraces below and the first three above Second High Cliff are included in the St. George's Valley reef-terrace sequence of this paper.

This terrace sequence was chosen for study because (1) the oldest terraces bearing well-preserved aragonite coral are in this area, and (2) the continuous terrace sequence found here minimizes the problems of determining the stratigraphic sequence of the various reef tracts.

Geomorphology

Figure 4 shows the location of the six reef terraces below and the three above Second High Cliff. Each reef tract grew with a nearly level reef-crest surface relative to mean sea level, but with time, variable uplift rates have caused the reef tracts to become ever less parallel to contour lines.

Most of the nine reef terraces on the north flank of St. George's Valley are fairly continuous geomorphic features (Fig. 4). Nearest the floor of St. George's Valley, Windsor terrace can be traced with ease until it disappears in calcarenite facies toward the east. Dayrells and Rowans are easily followed from west to east until they seem to merge in the region of slower uplift in eastern St. George's Valley. Bourne is a more subtle terrace that becomes gradually more indistinct toward the east until it disappears. Walkers terrace is easy to trace except for a short section between 670,000 E and 672,000 E in Figure 4.

Cottage Vale terrace is an indistinct geomorphic feature nestled against the base of Second High Cliff. It is a discontinuous reef terrace and is difficult to correlate from one exposure to the next. In many places, the Cottage Vale sea stand most likely eroded into Second High Cliff with no Cottage Vale reef development. Second High Cliff is the most prominent geomorphic feature on the Barbados coral cap (Figs. 1, 4). In some places, Second High Cliff has a constructional reef morphology and facies, but elsewhere it is clearly the result of massive erosion into the pre-existing reef tracts. This is apparently the case where Second High Cliff cuts across the eastern ends of Guinea and Drax Hall terraces (Fig. 4). Second High Cliff may include one or more *A. palmata* reef crests and associated facies in morphostratigraphic position between Cottage Vale and Hill View terraces. For this reason, Second High Cliff is not equated with the constructional morphostratigraphic units above and below on the valley wall. Localities UV, WN, and WT in Second High Cliff (which do not contain *A. palmata*) are thus not clearly definable as part of any recognizable morphostratigraphic unit.

Immediately above and behind Second High Cliff, three reef terraces were mapped as continuous geomorphic features with facies characteristic of reef crests. Hill View terrace trends subparallel to Second High Cliff. The altitude difference between Hill View and the next higher terrace, Drax Hall, is a reasonably constant 18 m. However, Drax Hall and Guinea terraces have nearly equal altitudes and are separated by a lower troughlike area. Both terraces satisfy the geomorphic and coral facies criteria of reef tracts, but their geomorphic relationship suggests that the two features may be of the same age. Perhaps Drax Hall was a barrier reef and Guinea was the associated fringing reef, with a shallow lagoon separating the two. It is equally possible that these two terraces represent separate stillstands of sea level.

Stratigraphic Relationships

As stated above under discussion of Christ Church stratigraphic relationships, we assume that each successively higher reef terrace is older unless there is field evidence to the contrary. In St. George's Valley we have such evidence for the relationship between Dayrells and Rowans terraces.

Harrison (1974) documented a complex stratigraphic relationship between the two reef tracts forming Dayrells and Rowans terraces. At locality UE, in Rowans terrace, Harrison found a nearly horizontal subaerial caliche crust separating two *A. palmata* depositional units. About 200 m south and 12 to 18 m lower, at locality UD in Dayrells terrace, Harrison documented a depositional break lacking a subaerial caliche crust. However, lithification of the calcarenite just below the break is substantially greater than that above and must have occurred while the pore space was completely occupied by water. Harrison discussed the cementation fabric and proposed that it must have developed in the shallow subtidal or intertidal zone. Calcarenite above the depositional break is less lithified and does not share the cementation fabric and diagenetic history of the calcarenite immediately below the break.

Harrison (1974) interpreted the stratigraphy between reef tracts at localities UE and UD to indicate two high sea levels separated by a minor low stand. The low stand fell below locality UE, but not low enough to subaerially expose locality UD. It is possible that locality UD was subaerially exposed, but either no caliche developed or it was not preserved.

Farther east, localities AJM in Dayrells and AJB in Rowans terrace also expose depositional breaks marked by caliche crusts. Locality AJB exposes *A. palmata* separated by a caliche crust from underlying coral heads in a stratified calcarenite.

Evidence from four localities supports Harrison's (1974) proposal that two high stands separated by a low stand of sea level are recorded by the stratigraphic relationships seen in the limestones of Dayrells and Rowans terraces. The younger high sea level inundated the older reef tract despite any uplift that accumulated between the times of the two sea stands. Thus, either the younger high stand (Rowans) was substantially higher than the older sea-level stand (Dayrells), or the assumption of uniform tectonic uplift is seriously in error for this time interval in St. George's Valley.

Because of the scarcity of satisfactory exposures, it is difficult to precisely define either the younger or the older reef tract relative to the two terraces in which they are expressed. The Dayrells morphostratigraphic unit preceded Rowans and is now, at least in part, veneered by Rowans sediments. Because the uplift rate varies from place to place in St. George's Valley, the precise stratigraphic relationship between the two reef tracts must also vary. Essentially, the amount that the younger unit overlaps the older depends on how much uplift occurred during the time interval between the two sea-level stands.

Where exposures in the Rowans morphostratigraphic trend do not show evidence of the Rowans-Dayrells subaerial exposure surface, it may be assumed that the exposure is simply not deep enough to expose the contact. Alternatively, the overlying reef sediments may be locally missing owing to nondeposition associated with a locally rapid uplift rate.

Because Dayrells terrace was transgressed by a rising sea level that ultimately deposited the limestone of Rowans terrace, the surficial limestone on Dayrells terrace is potentially post-Dayrells in age. This is clearly the case at locality UD (discussed above). At locality D, the relationship between (*A. palmata*) reef-crest and fore-reef facies is so well exposed that it can be stated with certainty that these facies belong to the depositional event responsible for the Dayrells morphostratigraphic unit. Where exposures in the Dayrells morphostratigraphic trend are shallow and facies relationships are obscure, it is possible that the outcrop exposes a veneer of post-Dayrells–age limestone, better correlated with the Rowans transgression. Sample data from exposures having ambiguous relationships with morphostratigraphic units are not subject to a unique interpretation.

Near locality WB, the morphostratigraphic trends of Dayrells and Rowans terraces appear to merge. In addition, the coral cap is very thin, and pre–coral-cap marine sediments crop out in the lower part of locality WB. Because of these irregularities and because the coral assemblage at WB is not diagnostic of near–reef-crest facies, we cannot demonstrate that locality WB belongs to either the Rowans or Dayrells morphostratigraphic unit. In fact, because of the corals present and the relationship of WB to the coral-cap foundation, WB may represent a deep fore-reef facies associated with a reef crest at a much higher altitude and of a much older age. Thus, locality WB does not satisfy the standards we have adopted for a locality from which material for dating may be taken.

St. George's Valley Standard Traverse

The St. George's Valley standard traverse is indicated as C–C′ in Figure 4. A summary of terminology and elevation data is provided in Table 3. In addition to the usual uncertainties of paleo–sea-level estimates described above under Methods, there are other uncertainties unique to Cottage Vale terrace and Second High Cliff. Cottage Vale is given large uncertainty because it is projected into the standard traverse from some distance. Second High Cliff is given no sea-level estimate because we do not consider it to be a morphostratigraphic unit recording a single sea-level event. Bear in mind, however, that we recognize that localities UV, WN, and WT *may* record a post-Hillview stand of the sea.

PHYSICAL CORRELATION AMONG STANDARD TRAVERSES

Rendezvous Hill geomorphic continuity extends between the Christ Church Ridge and Clermont Nose standard traverses. Geomorphic continuity is proposed with reasonable certainty between Clermont Nose and St. George's Valley standard traverses at two levels; Thorpe is equivalent to Windsor and Husbands to Dayrells.

Additional correlations between Christ Church and Clermont standard traverses are reasonable but not based on such firm evidence as geomorphic continuity. Kendal Hill almost certainly correlates with Durants. In Christ Church, Kendal Hill terrace is onlapped by Rendezvous Hill beach facies. In Clermont, Durants onlaps Cave Hill (and, to the north, Thorpe). Thus, there seems little room for error in correlation of Kendal Hill with Durants.

Kingsland terrace may be correlated with Cave Hill on the basis of distinctive absence of a well-developed *A. palmata* reef crest zone and on the basis of uplift considerations. Although Kingsland is the upper reef tract of a composite terrace, Cave Hill shows no evidence of an underlying terrace. The mean thickness of the overlying Kingsland terrace is 5 m. Thus, the difference in elevation between maximum sea level attained by Kingsland versus Aberdare is 5 m plus the vertical uplift of Aberdare before deposition of Kingsland. Matthews (1973) estimated that the average uplift rate of Clermont Nose has exceeded the Christ Church average uplift rate by 0.20 m/yr over the past 125,000 yr. Using this estimate, it would require a minimum of 25,000 yr between deposition of Kingsland and Aberdare in order to avoid producing a composite terrace involving Cave Hill in Clermont Nose. Indeed, if Thorpe is correlated to Aberdare, either the minimum figure of 25,000 yr strongly underestimates the difference in age between the terrace or the assumption of near-constant uplift rates is wrong.

The correlation of Thorpe to Aberdare is only partly substantiated. In addition to their position in the terrace sequence, both terraces are characterized by thick sequences of *A. palmata*. Locality ANC in Clermont Nose is a quarry 7 m deep composed almost exclusively of *A. palmata*. Similarly, locality ACG typifies Aberdare, where a 14-m-thick unit of *A. palmata* is exposed at the base of a deep quarry. Since *A. palmata* generally grows in water shallower than several metres, it is unlikely that these reefs began accreting in water depths as great as 14 or even 7 m with the growth of *A. palmata*. A more reasonable explanation would be the upward growth of *A. palmata* during submergence associated with a eustatic sea-level rise. This model results in a thick sequence of *A. palmata* without invoking unreasonable ecologic assumptions.

Correlation of Christ Church to Clermont Nose above the Kingsland-Aberdare to Cave Hill–Thorpe levels must necessarily imply correlation of upper terraces of Christ Church to the lower terraces of the St. George's Valley standard traverse. We are reluctant to make these correlations solely on the basis of physical stratigraphy. Specifically, we are troubled by the fact that the Rowans-Dayrells composite relationship is not recognized anywhere among Adams Castle, Kent, or St. David terraces of the Christ Church area. Indeed, we cite this problem as further reason to question the constant-uplift assumptions that have dominated the literature on Barbados terrace sea-level history. Two of us (Matthews and Fairbanks) are attempting to use oxygen isotope data from molluscs and corals to develop independent estimates of sea level for the Barbados terraces.

To establish a composite terrace sequence, we equate Aberdare to Thorpe to Windsor and use the lower parts of the Christ Church and Clermont sections in conjunction with the older reefs in the St. George's Valley standard traverse.

ESTIMATION OF AGES FROM URANIUM-SERIES DATA

Ages of samples can be calculated either from Th^{230}/U^{234} and U^{234}/U^{238} ratios (Th^{230}/U dates) or from U^{234}/U^{238} and He^4/U ratios (He^4/U dates). However, in making the calculations one must make a model of the diagenetic history of the samples. The common assumption is that the sample has been a closed system with regard to gain or loss of uranium and uranium daughters. Data on uranium concentrations, U^{234}/U^{238}, Th^{230}/U^{234}, and He^4/U ratios of samples as a function of age give us a basis for ascertaining whether the fossils have, in fact, behaved as closed systems.

In this paper we make four important assumptions concerning helium behavior. The first is that the inherited He^4 content of all samples is $0.6 \pm 0.4 \times 10^{-8}$ scc g^{-1} (Bender, 1970, 1973; and see above). This number is in turn calculated assuming that (1) no inherited helium leaks from corals and (2) corals are closed systems with respect to U^{238} and its daughters during the first 125,000 yr of their history. The second assumption is that the atmospheric He^4 component is associated with atmospheric Ne^{20} and that the ratio of He^4/Ne^{20} ratio in the atmospheric component is equal to that in air. The third assumption is that all He^4 produced by U^{238} or its daughters added to corals from the environment (open system U^{238} and daughters; see below) is retained within the coral. The fourth assumption is that no radiogenic He^4 produced by the alpha emitters in the sample leaks out. The basis for this assumption is that corals from the Caloosahatchee, Pincrest, Chipola, and Gosport formations, ranging in age from early Pliocene to Eocene, gave He^4/U ages in accord with ages independently estimated from stratigraphic relationships (Bender, 1970, 1973). Miocene corals from Eniwetok drill holes were found to give anomalous (although not necessarily young) ages; the anomalies were traced to open-system conditions with respect to U^{238} daughters (Bender, 1970, 1973). More recently, however, M. Bender, J. Hazel, and B. Blackwelder (unpub. data) have found that five corals from the lower Miocene Yorktown formation have He/U ages that are 35% lower than the independently estimated ages, and that a middle Miocene Choptank sample has an age 25% lower than the independently estimated age. We have been unable to trace these anomalies to open-system conditions with respect to U^{238} and its daughters; therefore He^4 loss is implicated. Again, it is assumed that in the samples reported on here, no such loss has occurred.

The possibility of U^{238} and U^{235} gain or loss is considered from the age dependence of U contents. There is no systematic trend in U concentration of the fossils with age (Table 4). While it seems certain that uranium addition or loss in a given sample has not exceeded the variability of U concentrations (about ±0.5 ppm, or ±15%), gain or loss within the range cannot be ruled out. In the remainder of this paper we assume that after possible U addition during early diagenesis (first few thousand years after the coral's death), corals are closed systems for U^{238} and U^{235}.

The U^{234}/U^{238} activity ratio in modern sea water is 1.15 (Turekian and Chan, 1971). When corals grow they assimilate into their skeletons uranium having the same isotopic composition as the U in sea water, and hence initially have a $U^{234}/U^{238} = 1.15$. The U^{234} daughter Th^{230}, which is so insoluble that it has a very low concentration in sea water, is essentially absent in living corals. Upon death, if the coral is a closed system, the U^{234}/U^{238} ratio will decrease toward the value 1.00 with a half-time of 250,000 yr (the U^{234} half-life), while Th^{230} will accumulate and the Th^{230}/U^{234} ratio will approach 1.00 with a half-time of approximately 75,200 yr (the Th^{230} half-life). The closed-system Th^{230}/U^{234} and U^{234}/U^{238} ratios can be calculated as a function of age and plotted against each other. In Figure 6, U^{234}/U^{238} ratios of our samples are plotted versus Th^{230}/U^{234} ratios, along with curves showing the sympathetic variation of U^{234}/U^{238} with Th^{230}/U^{234} for samples with initial U^{234}/U^{238} ratios of 1.15 (the present sea-water value) and 1.25. Samples that follow the closed-system assumption should fall on the line for initial $U^{234}/U^{238} = 1.15$. It is obvious from this plot that samples older than 150,000 yr have not behaved as closed systems with initial U^{234}/U^{238} ratios of 1.15. They either had higher initial U^{234}/U^{238} ratios or had Th^{230} and/or U^{234} added from the environment. Since the mean life of U^{234} is 360,000 yr and the U residence time in sea water is about 4×10^5 yr (Turekian and Chan, 1971), it is unlikely that the U^{234}/U^{238} of sea water was significantly different from the present value when these corals grew. It thus appears that open-system conditions obtained to some extent, and "closed system" ages calculated from the isotope data (hereafter called "apparent ages") will differ from the "true ages." This is true for He^4/U ages as well as Th^{230}/U ages, because in samples having anomalous U^{234} and Th^{230} concentrations, He^4 will be produced at a rate different from that calculated from closed-system assumptions.

Are the open-system conditions a result of Th^{230} addition, U^{234} addition, or both? Our strategy is to use the He^4/U ratios of the samples to answer this question. He^4/U ratios are useful here because ages calculated from the He^4/U ratios are much less sensitive to Th^{230} and U^{234} addition than are ages calculated from Th^{230}/U^{234}

and U^{234}/U^{238} ratios: Th^{230}/U^{234} and U^{234}/U^{238} ratios approach 1.00 asymptotically, whereas He^4/U ratios increase more or less linearly with time. The fact that He^4/U ages are less sensitive to diagenesis than Th^{230}/U ages can be illustrated by a simple model calculation. Consider a coral which, every 10,000 yr, gains an amount of Th^{230} equal to 1% of the Th^{230} the coral would have if it were a closed system. When that sample is truly 200,000 yr old, the apparent Th^{230}/U^{234} age is 255,000 yr and the apparent He^4/U age is 207,000 yr.

In using He^4/U ratios to check for Th^{230} and U^{234} addition, we first compute U^{234}/U^{238} ratios as functions of time, Th^{230}/U^{234} ratios as functions of time, and He^4/U ratios as functions of time for samples following closed-system conditions. We can then construct a plot of the sympathetic variation in U^{234}/U^{238} versus He^4/U for closed-system samples (Fig. 7). Experimental results are also plotted in Figure 7.

With the exception of AHU-1, samples with He^4/U ratios less than 2.5×10^{-8} scc μg^{-1} (corresponding to an age of 280,000 yr) fall close to the line followed by closed-system samples with an initial $U^{234}/U^{238} = 1.15$. Thus, those samples have apparently not suffered U^{234} addition. However, older samples all fall to the left of the concordia line. These samples have obviously endured U^{234} addition, assuming that the U^{234}/U^{238} ratio of sea water has been constant. The sympathetic variation of He^4/U and Th^{230}/U^{234} ratios for hypothetical closed-system samples with initial $U^{234}/U^{238} = 1.15$ is plotted as the solid curve in Figure 8. Data for samples are also plotted. Most sample points fall to the right of the concordia curve. For samples with apparent He^4/U ages less than 250,000 yr this could reflect either He^4 loss or Th^{230} addition. The former explanation is unlikely, however, since it would imply He^4 loss of about 40%. Thus, the discordance is apparently due to Th^{230} addition. In the case of the samples with $Th^{230}/U^{234} > 1.01$, the discordance *must* reflect Th^{230} addition, since closed system samples with an initial U^{234}/U^{238} ratio of 1.15 never attain a Th^{230}/U^{234} ratio greater than 1.01.

The discussion above shows that samples older than 150,000 yr have excess Th^{230} and that samples older than 250,000 yr also have excess U^{234}. The source of the excess U^{234} and Th^{230} is not known. We postulate that the Th^{230} is taken up by corals during their depositional history by scavenging of Th^{230} entering groundwater during dissolution of nearby fossils. U^{234} is more problematic. We doubt that it originates by accumulation of a U^{234}-rich uranium component, since [U] is approximately constant with age. Perhaps there is a surficial U component in exchange equilibrium with U^{234}-rich ground waters. If we knew the diagenetic history of the sample — that is, if we knew when the anomalous addition of U^{234} and Th^{230} occurred — we could correct He/U ages for open-system conditions and back out the true age of the sample. Unfortunately it is impossible, with stratigraphic or geochemical data, to unequivocally unravel the diagenetic history of individual samples. However, we can use information on the presence of anomalous levels of U^{234} and Th^{230} in younger corals to get an idea of the diagenetic history of older samples and use this information to correct He^4/U ages for open-system conditions.

We construct a working model of diagenesis in which we assume that all well-preserved corals on Barbados have been subjected to the same diagenetic processes and that the introduction of environmental U^{234} and Th^{230} has occurred at various times in the history of the sample ("continuing diagenesis model"). All corals of the species *A. palmata* are assumed to undergo the same diagenetic

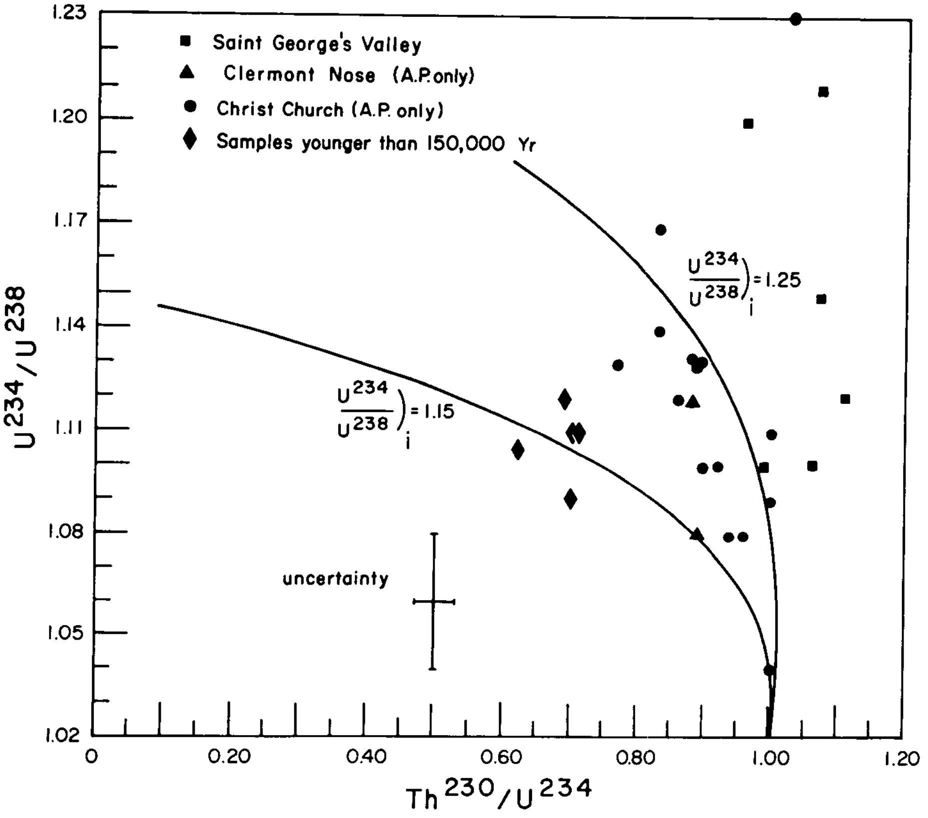

Figure 6. Plot of U^{234}/U^{238} versus Th^{230}/U^{234} activity ratios for corals from this study and Mesolella and others (1969). Uranium daughters development curves, showing sympathetic variation between U^{234}/U^{238} and Th^{230}/U^{234} activity ratios for samples with initial U^{234}/U^{238} ratios of 1.15 and 1.25, are also plotted.

history; thus, their U^{234}/U^{238}, Th^{230}/U^{234}, and He^4/U ratios are a single-valued function of age. From simple assumptions, one can then estimate open-system ages as a function of closed-system ages.

The anomaly in the He^4 production rate is calculated as a function of age; it is then integrated with respect to time to give the total anomalous He^4 production. For a sample with Ra^{226} and Ra^{226} daughters in equilibrium with Th^{230} (age ≥10,000 yr), the He^4 production rate from U^{238} is given by the relation

$$He^4 \text{ production rate from } U^{238} = A_{U^{238}} + A_{U^{234}} + 6A_{Th^{230}}.$$

For a sample with U^{234}/U^{238} ratios higher than the predicted values, anomalous or open-system He^4 is being produced at a rate (that is, the sample has a He^4 production rate anomaly) given by the relation

$$\begin{aligned} He^4 \text{ production rate anomaly} &= [A_{U^{234}} \text{ (observed)} - A_{U^{234}} \text{ (closed system)} \\ &\quad + 6A_{Th^{230}} \text{ (observed)} - 6A_{Th^{230}} \text{ (closed system)}] \\ &= A_{U^{238}}\left[\left(\frac{A_{U^{234}}}{A_{U^{238}}}\right)_{\text{observed}} - \left(\frac{A_{U^{234}}}{A_{U^{238}}}\right)_{\text{closed system}}\right] \\ &\quad + 6A_{U^{238}}\left[\left(\frac{A_{U^{234}}}{A_{U^{238}}}\right)_{\text{observed}} \times \left(\frac{A_{Th^{230}}}{A_{U^{234}}}\right)_{\text{observed}} - \left(\frac{A_{U^{234}}}{A_{U^{238}}}\right)_{\text{closed system}} \right. \\ &\quad \left. \times \left(\frac{A_{Th^{230}}}{A_{U^{234}}}\right)_{\text{closed system}}\right]. \end{aligned}$$

He^4 production rate anomalies were calculated for individual samples assuming that the apparent He^4/U age is equal to the true age (this introduces an uncertainty of only about 1% in the corrected age). The He^4 production rate anomaly (defined in the preceding equation) is plotted versus apparent He^4/U age in Figure 9. Because samples from terraces 130,000 yr old and younger give internally consistent Th^{230}/U ages, have U^{234}/U^{238} ratios concordant with Th^{230}/U^{234} ratios, and have Pa^{231}/U^{235} ratios concordant with Th^{230}/U^{234} ratios (Ku, 1968), the He^4 production rate anomaly is assumed to be zero for samples younger than 150,000 yr.

From the smooth line drawn through the data points we can calculate the integrated excess He^4 production as a function of age. This is calculated from the equation

$$\text{Integrated excess } He^4 = \int_0^t (He^4 \text{ production anomaly}) \times (\text{rate of helium production}) \times dt.$$

This quantity is plotted versus age in Figure 9. The difference between the true age and the apparent He^4/U age due to the He^4 production anomaly is also shown. This term is called the "He^4 production anomaly age correction" (abbreviated as "age error" in Fig. 9). The "corrected age" (Table 4) is equal to the apparent He/U age minus He^4 production anomaly age correction.

Corrected He^4/U ages given in Table 4 represent our best estimates of the "true ages" of the terraces we have studied. The uncertainty in the estimates comes from three main sources: the analytical uncertainty in the He^4/U ratio (±4%), the uncertainty in the inherited helium correction (±6% for the youngest samples to

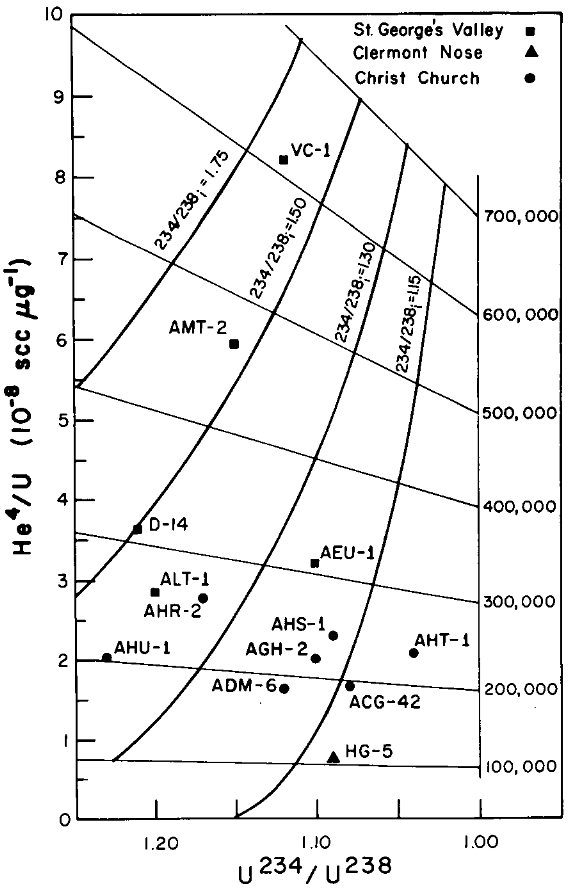

Figure 7. Plot of He^4/U versus U^{234}/U^{238} for samples listed in Table 4. Uranium daughters development curves, showing sympathetic variation between He^4/U and U^{234}/U^{238} ratios for samples with various initial U^{234}/U^{238} ratios, are also plotted.

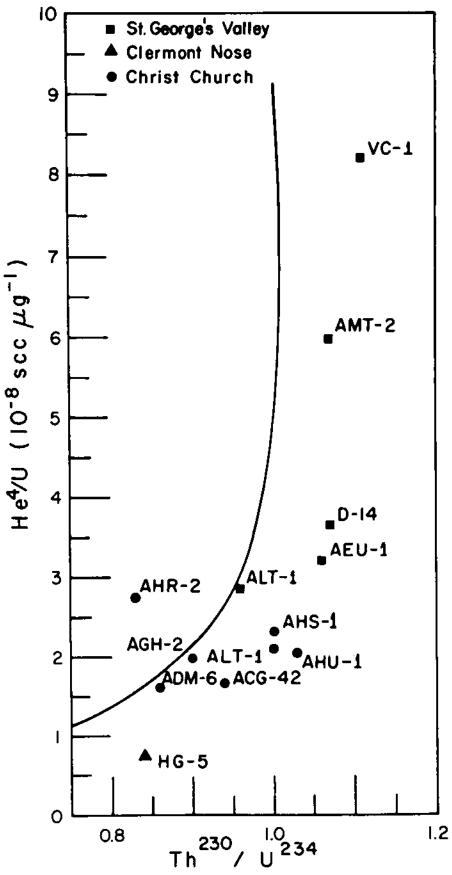

Figure 8. Plot of He^4/U versus Th^{230}/U^{234} for samples listed in Table 4. Uranium daughters development curve showing sympathetic variation between He^4/U and Th^{230}/U^{234} ratios for samples with an initial U^{234}/U^{238} activity ratio of 1.15 is plotted.

±2% for the oldest samples), and the uncertainty in the He^4 production anomaly age correction (assumed to be half the correction, or ±1% for the youngest samples to ±6% for the oldest). We lump these uncertainties together and estimate the uncertainty in each He^4 age as approximately ±10%. Where N samples were dated from one terrace, the accuracy is $\pm 10\%/\sqrt{N}$. This is an informal treatment of errors but should give reasonable error estimates.

We have calculated average ages for Barbados reef tracts using uranium-series results. "Average ages" for the tracts Worthing, Ventnor, and Rendezvous Hill are calculated from Th^{230}/U dates. "Average ages" for all older reefs are taken as the average of continuous diagenesis model corrected He/U ages for corals from a given reef tract. Results are given in Table 5.

UPLIFT AND SEA-LEVEL HISTORY

To interpret Barbados chronostratigraphy in terms of sea-level history, we extend the models of Broecker and others (1968) and subsequent workers. As a first-order model, it is assumed that uplift along each standard traverse has been constant and that sea level during Rendezvous Hill time (approximately 125,000 B.P.) was +6m relative to the present datum (see also Bloom and others, 1974, and Ku and others, 1974). The uplift rate of the Christ Church and Clermont Nose standard traverses calculated in this way are 0.25 and 0.44 m 10^{-3} yr^{-1}, respectively.

Paleo–sea levels for the St. George's Valley sequence cannot be estimated in this way, since the Rendezvous Hill terrace is absent from this area. Here paleoelevations were estimated using as a basis the date of Windsor terrace, its paleo–sea level, and its elevation (both age and paleo–sea level having been computed from its correlative reef, Thorpe, in the Clermont Nose standard traverse). The uplift rate estimated for the St. George's Valley standard traverse is 0.34 m 10^{-3} yr^{-1}.

Paleo–sea levels are calculated from the data for each terrace by subtracting the tectonic uplift (equal to the product of the uplift rate and reef-tract age) from the reef-crest elevation. If uplift has been constant, uncertainties in paleo–sea-level estimates for the individual terraces are the sums of uncertainties in (1) present reef-crest elevation projected along the standard traverse, (2) standard traverse uplift rates, and (3) ages of individual terraces. Uncertainties are greatest in the case of St. George's Valley terraces. An informal analysis of errors based on arguments summarized earlier indicates that the uncertainty in the uplift rate of the entire St. George's Valley sequence is ±10%. An additional uncertainty of ±10% is introduced by the uncertainty in the terrace age that is used, along with uplift rate, to calculate uplift. Adding the uncertainty of present reef-crest elevation (typically ±5m), we calculate that the maximum error in estimated paleo–sea-level values ranges

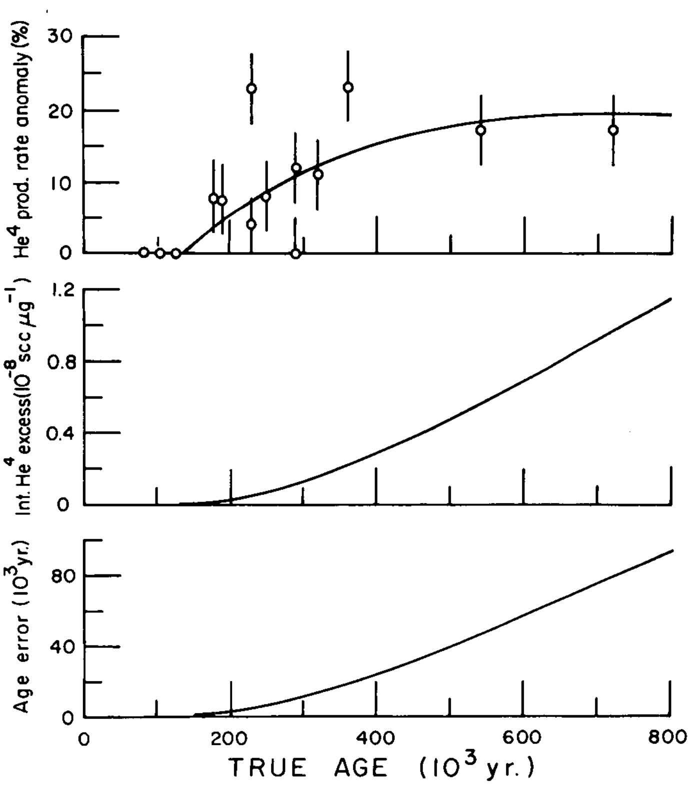

Figure 9. Top: Anomaly in rate of He^4 production (in percent of closed-system rate) for samples versus apparent age of samples. Center: Integrated excess of He^4 (in scc He^4 μg^{-1} U) versus apparent age for samples whose He^4 production rate anomaly varies with time along smooth curve in top graph. Bottom: Error in age (defined as uncorrected age − true age) versus true He^4/U age for samples whose integrated He^4 excess varies with time along curve in central diagram.

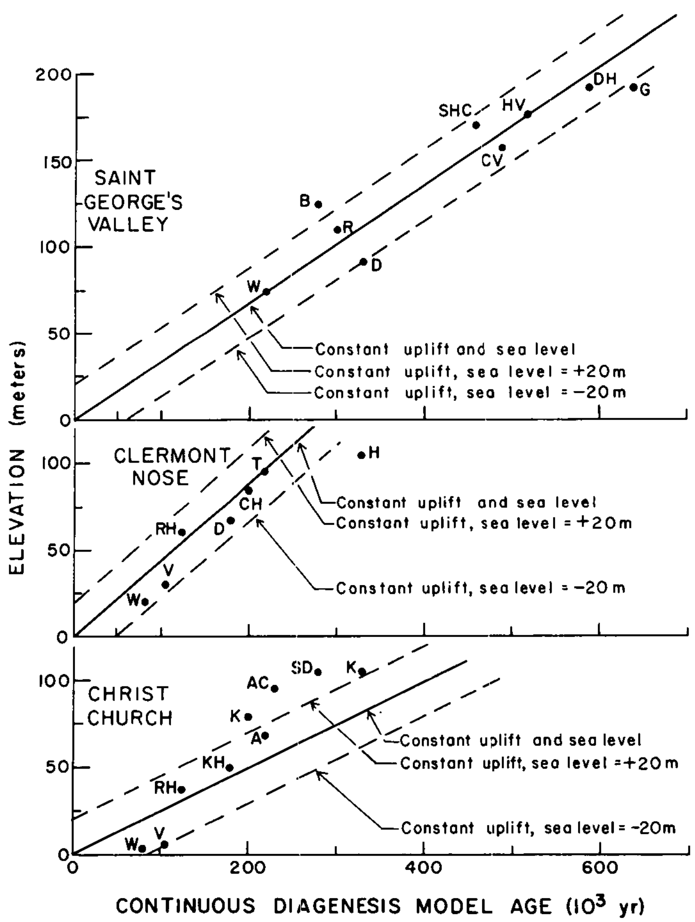

Figure 10. Plot of reef-tract elevation along standard traverse versus continuous diagenesis model He^4/U age for samples from Christ Church, Clermont Nose, and Saint George's Valley sections. Superimposed lines show where points would fall for three uplift models: (1) constant uplift rate and paleo–sea level equal to present datum; (2) constant uplift rate, paleo–sea level +20 m relative to present datum; (3) constant uplift, paleo–sea level −20 m relative to present datum. Initials of terrace names are next to data points.

from ±25 m for 300,000-yr-old terraces to ±50 m for 640,000-yr-old terraces of the St. George's Valley sequence.

The only systematic error in our model paleo–sea-level estimates is due to the error in the uplift rate. Therefore, the maximum systematic bias in paleo–sea-level estimates for St. George's Valley reef tracts is ±10 m at 300,000 yr and ±22 m at 640,000 yr.

The uplift results are all summarized graphically in Figure 10. The three graphs plot reef-crest elevation along the standard traverse versus age of the reef tract. Lines are drawn along which (according to the above model) all points would fall if uplift (for each standard traverse) were constant and if paleo–sea level at the time of reef-tract formation were equal to the present datum. We will discuss the implications of this plot for the uplift history of the Christ Church and Clermont Nose traverses. We will then consider the implications of the St. George's Valley traverse for Brunhes paleo–sea levels.

Model values of paleo–sea levels for 200,000- to 300,000-yr-old Christ Church terraces range from +17 m for Aberdare to +40 m for Saint David. These results are most reasonably ascribed to variable uplift, and they indicate that uplift rates before Rendezvous Hill time were much greater than after that time.

There are two significant observations for the Clermont Nose traverse. First, the model paleo–sea level of Thorpe is +2 m. This provides the basis for the Saint George's Valley uplift model. Second, although the age of Thorpe agrees well with that of Aberdare, its correlative in the Christ Church section, the paleo–sea level computed for Aberdare is 15 m higher than that for Thorpe (of this difference, approximately 3 m is due to the difference in radiometric ages). This is consistent with the notion, outlined in the previous paragraph, that the uplift rate of the Christ Church area was greater before Rendezvous Hill time than since.

The striking feature of the Saint George's Valley sequence is that all the terraces except for Bourne give paleo–sea-level estimates equal to the present datum, taking into account the errors associated with the paleo–sea-level estimates due to uplift. The paleo–sea-level estimate for Bourne (+30 m) is regarded as unrealistic and is believed to reflect either an anomalous He/U age or spurious tectonic activity. The paleo–sea levels estimated for the correlative reefs of Dayrells (Saint George's Valley) and Husbands (Clermont Nose) are −20 m and −51 m, respectively. About 6 m of the 31-m difference is due to the difference in He/U ages for the reef tracts of 30,000 yr. In the context of the model presented here, we would regard the Dayrells-Husbands reef tract as recording a stand of the sea of about −35 m relative to the present datum at about 350,000 B.P. The remainder of the St. George's Valley reef tracts are taken to record a series of high sea stands with sea levels close to the present datum, between 200,000 and 700,000 B.P. In general then, our results are consistent with the notion that during the past 700,000 yr, interglacial ice volumes and sea levels were comparable to the present values.

Barbados reef tracts may be tentatively correlated with interglacial periods inferred from the oxygen isotope record of core V28-238 (Shackleton and Opdyke, 1973). In our proposed correlation, the sedimentation rate of V28-238 is assumed to be constant back to the Brunhes-Matuyama boundary at 700,000 B.P. Our correlations are summarized in Table 5. Generally, the reefs are correlated with the interglacial isotope stages of the same age. The age of Walker reef is estimated from its elevation, assuming constant uplift rate and paleo–sea level equal to the present datum.

It appears that each interglacial isotope stage is represented by at least one Barbados reef tract. The comparison is limited by the uncertainty in the isotope stage ages (due to uncertainties in the age of the Brunhes-Matuyama boundary and possible variability in the sedimentation rate) and the uncertainty in the reef-tract ages. We believe the correlations are reliable to plus or minus one interglacial isotope stage.

SUMMARY AND CONCLUSIONS

We have identified nine Barbados reef tracts in the Christ Church section, seven in the Clermont Nose section, and at least ten in the Saint George's Valley section. The reefs have been projected onto standard traverses, and we have determined present elevations for each reef crest. Uranium and thorium isotope data and helium-uranium ratios were determined for about 35 unrecrystallized samples of the coral *Acropora palmata*. Uranium concentrations

TABLE 5. SUGGESTED TENTATIVE CORRELATION OF BARBADOS REEF AGES WITH 0^{18} RECORD OF CORE V28-238

Christ Church traverse	Clermont Nose traverse	St. George's Valley traverse	Average age (10^3 yr)	Isotope stage
Worthing	Worthing		82[*][†]	5
Ventnor	Ventnor		105[*][†]	5
Rendezvous Hill	Rendezvous Hill		125[*][†]	5
Kendall Hill	Durants		180[*]	7
Kingsland	Cave Hill		200[*]	7
Aberdale	Thorpe	Windsor	220[*][†]	7
		Rowans[‡]	300[**]	9
Adams Castle[‡]	Husbands	Dayrells	320[†][**]	9
Kent[‡]		Bourne	280[**]	9
St. David[‡]		Walker	Undated	11
		Cottage Vail	490[**]	13
		Second High Cliff	460[**]	13
		Hill View	520[**]	13
		Drax Hall	590[**]	15
		Guinea	640[**]	17 or 19

Note: Most reefs older than 300,000 yr are not correlated; dates of reefs older than 300,000 yr are given for St. George's Valley traverse only.

[*] Date for Christ Church reef.

[†] Date for Claremont Nose reef.

[‡] Terrace not correlated with other standard traverses in this paper.

[**] Date for St. George's Valley reef.

were measured by alpha spectrometry and also by instrumental epithermal neutron activation analysis. Results of activation analysis agree well with results of alpha spectrometry.

There are systematic discordances in U^{234}/U^{238} ratios, Th^{230}/U^{234} ratios, and He^4/U ratios in samples older than 125,000 yr. U^{234}/U^{238} and Th^{230}/U^{234} ratios are both anomalously high: this is ascribed to U^{234} addition from an unidentified source and Th^{230} addition by adsorption of Th^{230} freed in the diagenetic dissolution of surrounding rocks. He^4/U ages are corrected for He production by "open-system" (or anomalous) He^4 by assuming that the concentration of anomalous U^{234} and Th^{230} is constant for samples of a given age.

The reef-tract ages and present elevations as projected onto the standard traverses are used to interpret the uplift history of Barbados. The most striking result is that for some interval prior to 125,000 B.P., the uplift rate of the Christ Church section was much greater than the rate after 125,000 B.P. Paleo–sea levels for St. George's Valley reefs as old as 640,000 yr cluster around the present datum. This result suggests that throughout the Brunhes, minimum continental ice volume during relatively deglaciated times was comparable to the present value.

Barbados reef tracts have been tentatively correlated with interglacial oxygen isotope stages as identified by Shackleton and Opdyke (1973). Each interglacial isotope stage back to 640,000 B.P. is represented by at least one Barbados reef tract.

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