

QUATERNARY STRATIGRAPHY OF BERMUDA: A HIGH-RESOLUTION PRE-SANGAMONIAN ROCK RECORD

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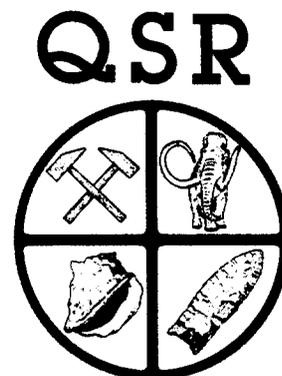
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Abstract — Carbonate islands such as Bermuda are created by climatic change. Warm climates and high sea levels stimulate carbonate sediment production that may ultimately result in island growth, while cold glacials expose the platforms to weathering, dissolution and soil formation. Of great importance in Quaternary studies is the ability to decipher this climatic history. Mapping and geochronologic studies have established that Bermuda may have one of the most continuous and detailed Quaternary interglacial depositional records on a carbonate platform. Advances in racemization dating (AAR) have offered a means of deciphering this climatic history and generating a high-resolution stratigraphic and age framework for the Quaternary.

Bermudian interglacial units consist predominantly of eolianites, with less voluminous occurrences of beach deposits and calcarenite protosols (Entisols). Glacial or stadial-age *terra rossa* (aluminous laterite) paleosols, whose degree of development is a function of time of exposure, form boundaries between interglacial units. D-alloiso-leucine/L-isoleucine (A/I) ratios have been determined on marine pelecypods, land snails and whole-rock samples from mapped sections; aminozones have been defined for two Sangamonian and at least five pre-Sangamonian depositional intervals. From kinetic models based on calibration with previously published U-series coral dates, estimated ages of middle Pleistocene and older aminozones are: F = 190,000–265,000 years; G = 300,000–400,000 years; H = 400,000–500,000 years; J = >700,000 years; and K = > 900,000 years.

Aminozone G, which is correlated with the upper Town Hill Formation and Isotope Stage 9, is volumetrically the most important depositional event of the middle Pleistocene. The great mass of sediment deposited during this period suggests an interglacial of significant duration and prolonged shelf submergence, during which the island grew to over half its present size. Only the Sangamonian (*sensu lato*) rivals Stage 9 in volume of eolianite deposited on the island. Sea-level amplitude, as determined from dated outcrops, appears to correlate well with amplitudinal variations in the oxygen isotope record.



INTRODUCTION

The middle Pleistocene encompasses the period from the end of the penultimate glacial period (~140,000 years) to the Brunhes–Matuyama Boundary (~750,000 years). This interval of time includes seven to eight glacial–interglacial cycles (Shackleton and Opdyke, 1973; Shackleton *et al.*, 1984, 1988). Unlike the familiar early Sangamonian (Substage 5e) which provides a ‘golden spike’ along most of the world’s coastlines, little is known of the sea-level history, duration of interglacials, details of the physical stratigraphy and paleoclimates of the pre-Sangamonian. This dearth of information is due, in part, to limitations of radiometric methods including their short effective ranges, the lack of pristine materials for dating, and the absence of significant criteria for recognition of lithologic differences among units.

Recent studies in Bermuda (Vacher and Hearty, 1989; Hearty *et al.*, 1992; Vacher *et al.*, *in press*) and the Bahamas (Hearty and Kindler, 1993a) have shown that

aminostratigraphic methods, coupled with field geology, can be used effectively to establish a pre-Sangamonian chronostratigraphy. In Bermuda, Vacher *et al.* (1989) and Hearty *et al.* (1992) have demonstrated that a significant and detailed middle and early Pleistocene section is present below the Sangamonian.

Given that large eolianitic limestone ridges define the landward shoreline facies of ancient coastlines (Bretz, 1960; Land *et al.*, 1967), it is thus possible through stratigraphy and dating of these deposits to identify the number of occurrences of near-present sea-level events throughout the Quaternary period. It is also reasonable to assume that the volume of sediments deposited during each interglacial event is directly proportional to the duration of the platform flooding event. Paleo sea levels are determined from low-angle bedding, intertidal sedimentary structures and trace fossils.

The goals of this paper are to focus specifically on the physical stratigraphy and ages of pre-Sangamonian deposits in Bermuda. The purpose is three-fold: (1) to

investigate the number, timing and stratigraphic detail of interglacials recorded by this mid-ocean tide gauge for Pleistocene sea levels (Harmon *et al.*, 1983); (2) to inquire about the early accretionary history of Bermuda's carbonate bank; and (3) to discuss regional correlations and some of the implications for climate history during the Quaternary.

PHYSICAL STRATIGRAPHY

Facies

Bermuda's exposed rock column consists of an alternation of limestones and paleosols (Sayles, 1931). Most of the limestones are eolianite that formed as coastal dunes when the platform surrounding Bermuda was submerged during interglacials (Bretz, 1960). Intervening glacials and prolonged stadials are represented by *terra rossa* paleosols (Land *et al.*, 1967; Vacher *et al.*, *in press*) whose degree of pedogenesis (mineralogy; clays) is proportional to the time of platform exposure.

A recurring facies package is a coastal sequence of beach limestones overlain by eolianite (Vacher and Harmon, 1987; Hearty *et al.*, 1992). Common between beach and eolian limestones are white, lenticular calcarenite protosols (or Entisols), representing backbeach environments where vegetative cover trapped additional sand (Vacher, 1973). Calcarenite protosols also occur in lenticular forms at the base of foresets in distal dune environments. In some cases, these protosols represent local, brief pauses in eolianite sedimentation, while in other cases, the extensive protosols must represent intervals of island-wide non-deposition of eolianite brought on by minor regressions or periods of ecological stability within interglacial stages (Hearty *et al.*, 1992).

Stratigraphic Nomenclature

Sayles (1931) recognized and named Bermuda's two geomorphic provinces: Younger and Older Bermuda. Younger Bermuda consists of high-standing lithified dunes of the outer coastline; these dune forms retain their depositional morphology (Bretz, 1990; Vacher, 1973). Older Bermuda consists of subdued, partially submerged dune forms within and alongside the interior sounds and marshes; these areas have been significantly altered by dissolution and erosion (Bretz, 1960; Vacher, 1978). To Sayles (1931), Older Bermuda was the core around which the dunes of Younger Bermuda accreted during later sea-level fluctuations.

Sayles (1931) also defined the stratigraphic column that has led to the stratigraphic classifications in Bermuda. Sayles' original column consisted of 5 eolian units, 2 marine units and 5 paleosols (see Vacher *et al.*, *in press*). The units have been recombined and redefined. The upper 5 units (three eolianites and two protosols) became the Southampton Formation (Land *et al.*, 1967). The intermediate three units (Devonshire, Harrington, Pembroke) were redefined by relocation of the type areas by Land *et al.* (1967) and are recognized as a facies succession within the Rocky Bay Formation (Hearty *et al.*, 1992). From U-series dates (Harmon *et al.*, 1983), the

Rocky Bay and Southampton Formations are known to correlate with the last interglacial (*sensu lato*; Isotope Stage 5; the Sangamonian Interglacial). They also correspond to the Younger Bermuda of Sayles (1931). Thus, in terms of the columns of Sayles (1931), Bretz (1960) and Land *et al.* (1967), only the two lowest units (Belmont and Walsingham) are left to represent the pre-Sangamonian, Older Bermuda.

Geologic mapping of Older Bermuda has led to the recognition of a complex section between the Rocky Bay and Walsingham Formations (Vacher *et al.*, 1989, *in press*; Rowe, 1990). The mapped units of both Younger and Older Bermuda are listed in Table 1 together with correlations, type and reference areas. The Town Hill Formation is named from Bermuda's highest hill (70+ m), which is the site of Bierman's Quarry (Table 1). The lower Town Hill includes a weak, discontinuous *terra rossa* that is present at a few localities. The lower Town Hill is distinguished from the upper Town Hill by another prominent *terra rossa* paleosol (Harbour Road Geosol). The lower Town Hill is interrupted by at least one major paleosol (Vacher *et al.*, 1989) and multiple protosols. The Town Hill members were not initially defined as separate formations (Vacher *et al.*, 1989, *in press*) because of difficulties in distinguishing their similar lithologies, but are unambiguously resolved by AAR ratios (Hearty *et al.*, 1992) and ESR dates (this study). The Belmont Formation, as defined by Land *et al.* (1967), is separated from the Town Hill formation by a prominent *terra rossa* paleosol (Ord Road Geosol). Therefore, there are at least 5 *terra rossas* in Bermuda below the Sangamonian Rocky Bay Formation. From oldest to youngest they are: the Castle Harbour Geosol (Vacher *et al.*, 1989), the intra-lower Town Hill paleosol, the Harbour Road Geosol, the Ord Road Geosol and the Shore Hills Geosol (Land *et al.*, 1967).

FIELD RELATIONS WITHIN OLDER BERMUDA

The distribution of the Town Hill and Belmont Formations in the central parishes of Bermuda is shown in Fig. 1. The overall pattern is one of lateral accretion of younger limestone units on the seaward margin of older units and exposure of older units along the shoreline of interior sounds and reaches. Thus, in the eastern part (Devonshire and Smiths Parishes) of Fig. 1, the interior of the island consists of a large axial ridge of upper Town Hill eolianite. Lower Town Hill, which occurs in the subsurface, crops out further east along Harrington Sound. This large axial mass of Town Hill is overlapped by younger eolianites on both its northern (Devonshire Parish) and southern (Devonshire-Smiths) flanks.

In the western part of the map area, the lower Town Hill is exposed within and along both shores of Hamilton Harbour. To the south (Paget Parish), a complete section of upper Town Hill, Belmont, Rocky Bay and Southampton occurs sequentially in a series of ridges in which foresets dip northward. To the north (Pembroke Parish), there is a similar succession of upper Town Hill,

TABLE 1. Type and reference localities related to the stratigraphic column of Bermuda

Formation (stage*)	Type locality	Reference locality
Recent (1)	—	Elbow Beach, Warick Long Bay, Horseshoe Bay, Southampton
Weak paleosol (2-4) Southampton (5a)	Southampton Parish, South Shore	Astwood Park, Ft. St. Catherine
Weak reddish paleosol Rocky Bay (5e)	Rocky Bay, Devonshire	Devonshire Bay, Blackwatch Pass
Shore Hills Geosol (6) Belmont (7)	Rocky Bay (Land <i>et al.</i> , 1967); lowest unit in section	Harvey Road Quarry Eolianite below the Shore Hills Geosol
Ord Road Geosol (8)	Intersection of Ord Road and Harvey Road	South Road at entrance to Watch Hill Park
U. Town Hill (9)	Bierman Quarry Town Hill, Smiths Par.	Cobbs Hill Road from Ord Road to Harbour Road
Harbour Rd. Geosol (10)	Harbour Road and Cobbs Hill Road	Bierman Quarry, big red soil
L. Town Hill (11)	Bierman Quarry Town Hill, Smiths Par.	Harbour Rd. and shore, Cobbs Hill Rd. to Belmont Wharf
Castle Harbour Geosol (13-21?)	Entrance to Castle Harbour Hotel, main bldg.	Wilkinson's Quarry
Unnamed (25?)	Government Quarry	+22 m marine deposit (removed)
Walsingham (35-37?)	Government Quarry	Dockyard, Ireland Island

*Correlations with isotopic stages are based on U-series ages (Harmon *et al.* 1983), AAR age estimates (Hearty *et al.*, 1992), ESR dates (this study) and stratigraphic age.

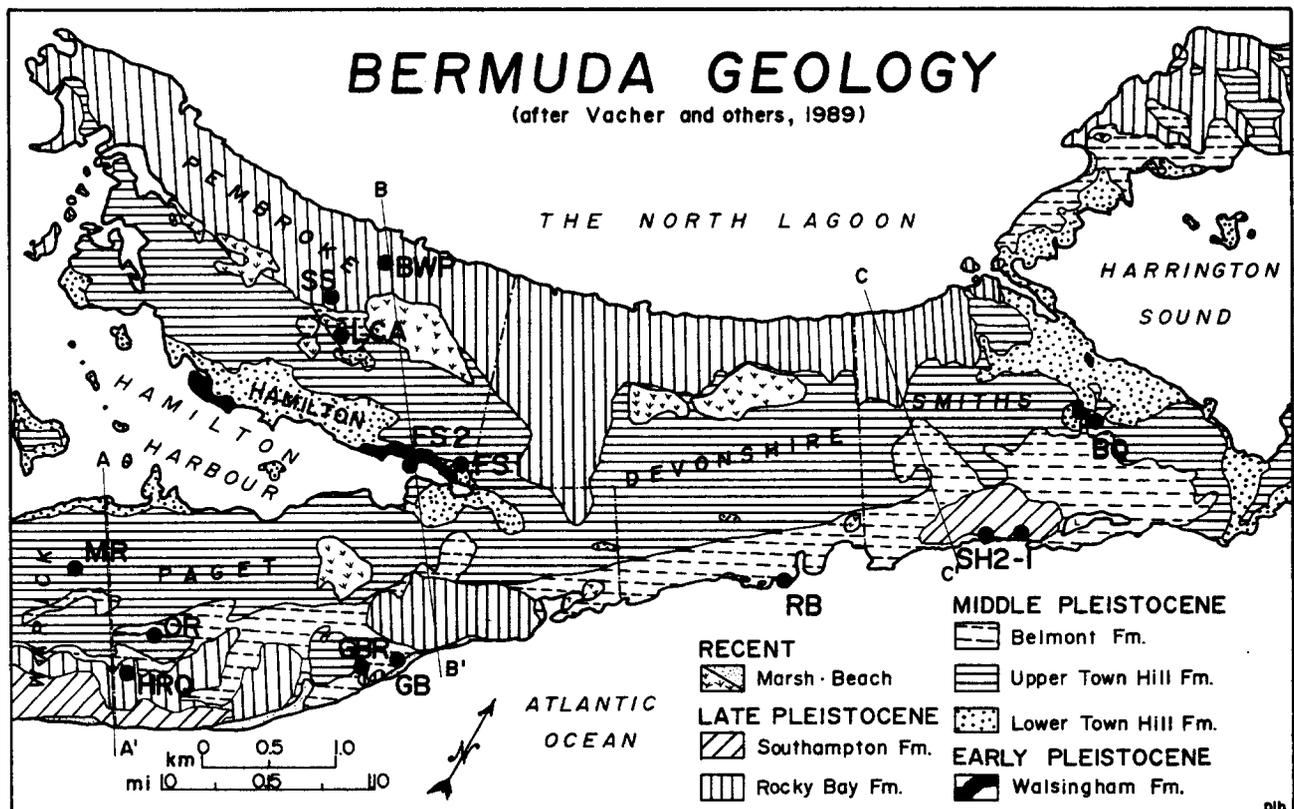


FIG. 1. Geology of Bermuda with sites and cross-sections. This map has been modified from the Geological Map of Bermuda (Vacher *et al.*, 1989).

minor Belmont and Rocky Bay in a series of eolianite ridges in which foresets dip southward. The upper Town Hill of the three areas (Pembroke, Paget and Devonshire-Smiths) is connected in an extremely large, Y-shaped body. All the other units are discontinuous, either as windows beneath the upper Town Hill, or disjunct younger bodies onlapping its flanks.

In terms of previous studies (Sayles, 1931; Bretz, 1960; Land *et al.*, 1967; Vacher, 1973), a classic area is the South Shore from Grape Bay to Harrington Sound (Fig. 1). As mapped by Vacher *et al.* (1989), the present shoreline exposes an along-strike section of a Belmont marine and eolian facies that is overlain at several places by younger deposits. At most places, the Belmont complex consists of an interdigitation of beach and eolian deposits without an intervening protosol; at Saucos Hill (SH1 and SH2; Fig. 2), however, the beach and eolian facies are separated by a prominent protosol. At Watch Hill Park, the Belmont beach deposits end at a paleo-cliff cut in the upper Town Hill eolianite. Younger deposits along this stretch of coastline are scattered and, in general, small: marine facies of the Rocky Bay Formation (Devonshire Member) in discontinuous patches of conglomerate; eolian facies of the Rocky Bay Formation (Pembroke Member) in small hillocks at Rocky Bay (RB; Fig. 2) and a large eolianite ridge from Grape Bay (GB) to Hungry Bay; and eolianite of the Southampton Formation in large mounds at Saucos Hill.

Eolianites of the Belmont Formation of Smiths Parish onlap the southern flank of the large ridge of eolianites forming the interior of Smiths Parish. The Ord Road Geosol beneath the Belmont is exposed at several localities near Verdmont, Harrington Hundreds, and, most notably, along South Road just landward of the paleo-cliff contact between Belmont beach deposits and Town Hill eolianite at Watch Hill Park. The large inland ridge is deeply incised by Bierman's Quarry (BQ) (recently renamed Rocky Heights Quarry and again DeSilva Quarry). During the early 1980s, this quarry exposed three *terra rossa* soils, the upper one of which was overlain by eolianite of the Belmont Formation, and the lower one of which was underlain by eolianite of the Walsingham Formation. The intervening section (Fig. 2) of two eolianites separated by a *terra rossa* was mapped by Vacher *et al.* (1989) as the Town Hill Formation and Harbour Road Geosol. Continued quarrying (since 1989) has removed the Belmont and its underlying *terra rossa* and has exposed two weakly developed red paleosols within the lower Town Hill.

The section of Town Hill and Belmont beneath the Rocky Bay Formation is duplicated in a section along the boundary between Paget and Warwick Parishes, where the units occur in a straightforward, laterally accreted succession (Figs 1 and 2). Eolianite of the Southampton Formation occurs along the south and west coastlines, and is particularly well exposed at Astwood Park. Inland,

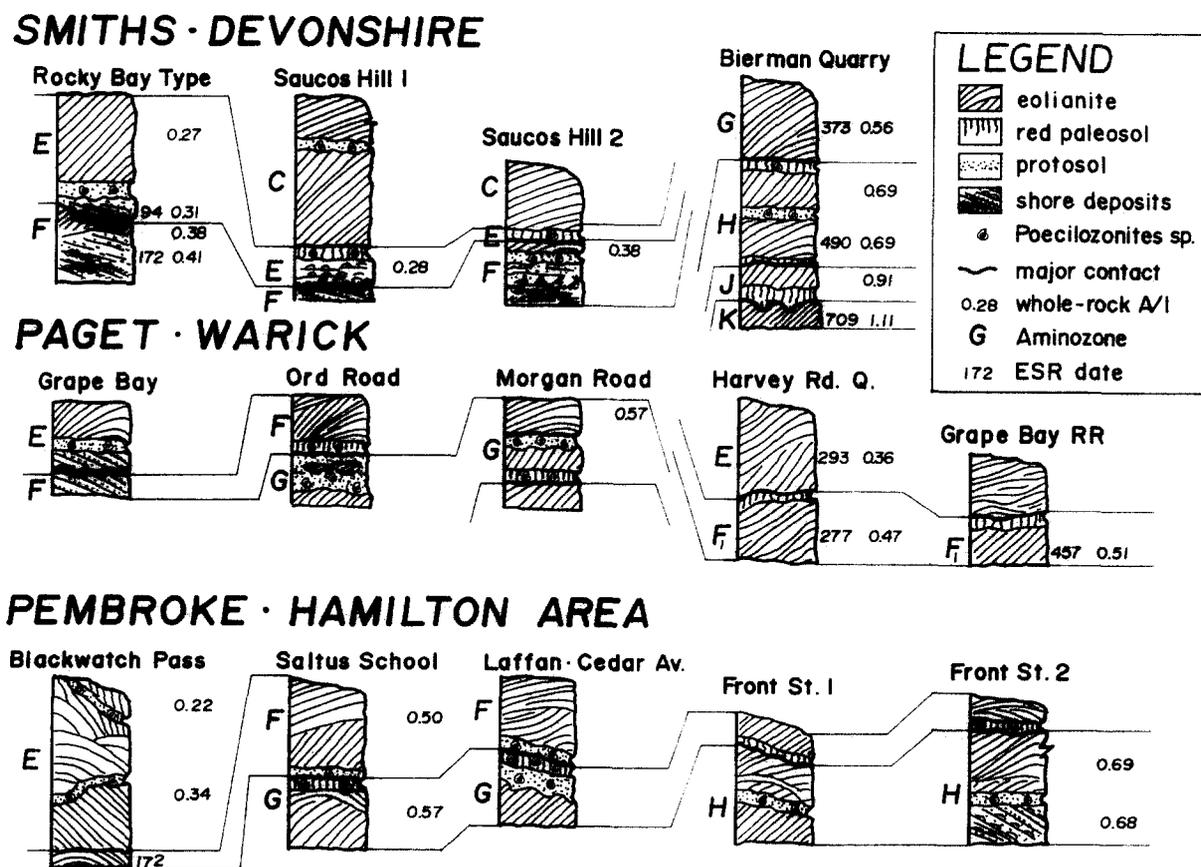


FIG. 2. Stratigraphic sections representing the Pleistocene of Bermuda with special emphasis on the middle Pleistocene. Whole-rock amino acid ratios and electron spin resonance dates are also noted.

between South and Ord Roads, high quarried hills are composed mostly of Rocky Bay eolianite. Two *terra rossa* soils occur within these hills: the Shore Hills is easily seen high in the quarries, such as at Harvey Road (HQ or HQR); the Ord Road (OR; Fig. 2) Geosol is further north and lower in elevation, generally near the base of the ridge. North of this contact lies the main axial ridge of Older Bermuda: upper Town Hill is exposed on the surface from Ord Road northward; lower Town Hill is exposed along the northern shoreline; and a *terra rossa* (Harbour Road Geosol) occurs between them. Outliers of Belmont occur on the southern side of the upper Town Hill ridge. These outliers, which are in line with similar bodies on the north side of South Road in Smiths Parish (Fig. 1), may well represent an earlier Belmont than that represented by the beach-ridge complex along the coastline.

AMINOSTRATIGRAPHY OF PRE-SANGAMONIAN DEPOSITS IN BERMUDA

Sample Provenance

Samples were collected from 14 sections in the central parishes for AAR analysis (solid dots and capital letter abbreviations in Figs 1 and 2). In addition, for the completeness of the chronostratigraphic section, data from Government Quarry (GQ), which lies to the east of the main study area of this paper, and from Fort St. Catherine (FSC) which lies on the northeasternmost point of the island, have been incorporated into the dataset. In the 1960s, a marine conglomerate was exposed at +22 m on a platform cut in the Walsingham Formation (Land *et al.*, 1967). The conglomerate was later removed by quarry expansion; however, archive samples of it were provided by F. T. Mackenzie for this study.

The different sample materials for this study include land snails of the genus *Poecilozonites*, and whole-rock samples from the bioclastic eolianites. The marine shell *Glycymeris* sp. (the bittersweet clam) from Sangomonian deposits and fragments of *Brachidontes exustus* (the scorched mussel) from both Sangamonian and middle Pleistocene marine and eolian deposits have also been analyzed (Table 2). *Poecilozonites* occur in protosols in most of the mapped units and are desirable for AAR analysis because they are typically rapidly buried in the eolian environment and represent discrete intervals of time within the interglacial. Their rapid burial increases the preservation potential of the land snails because bioturbation and chemical activity of vadose water and plants are reduced. Excellent preservation (primary color, pearly luster and hardness) of land snails is common among the youngest deposits, while poorer preservation (loss of color, chalkiness, etched, etc.) occurs more frequently among older deposits. This diagenetic alteration is apparently due to leaching of the carbonate by organic acids which also selectively remove and deposit various amino acids.

In contrast to the protosols, the *terra rossa* soils are

thin, exposed and vulnerable to a variety of physical, biological and chemical processes. It appears that the *terra rossa* soils accumulated mainly during glacial periods, with their accumulation being diluted and overwhelmed, rather than turned off, by the episodic deposition of eolianites during interglacials. Thus, these paleosols may indeed represent either prolonged exposure during intra-interglacial regressions (e.g. 30,000 years), entire glacial maxima exceeding 100,000 years, or even longer periods if their accumulation in distal environments is not interrupted by coastal deposition. These relatively long periods of exposure to chemical and biological processes result in a relatively low preservation potential of *Poecilozonites*. The land snails are occasionally chalky, sometimes leached and often have lower *A/I* ratios; since there are only rare examples of diagenetic effects increasing the *A/I* ratio, it is assumed that heating effects are overwhelmed by chemical diagenesis (leaching). Ages calculated from ratios on the shells from *terra rossa* soils, therefore, are used as *minimum* ages in this study.

Whole-rock samples are collected mainly from the massive eolianites exposed in fresh roadcuts or quarries. Some whole-rock marine deposits along the coast have also been collected for calibration with U-series-dated units. Although more patchy among older formations, whole-rock samples are generally well preserved throughout the geologic record of Bermuda.

The whole-rock method is possible because skeletal eolianites, because of their biogenesis, contain abundant amino acids. The whole-rock samples represent a mix (or average) of the *A/I* ratios of the constituent particles (fragments of calcareous algae, corals, mollusks, echinoderms, forams, etc.) that racemize at different rates. Despite some compositional variation, and some apparent potential for error, the whole rock *A/I* ratios are internally consistent with Bermuda stratigraphy (Hearty *et al.*, 1992), and like their molluscan counterparts, reliably represent the ages of discrete interglacial periods, as well as subunits within those interglacials.

Reworking of lithoclast sand grains into the eolianites is not considered significant because deposition of the large eolianite ridges occurred at a time of a positive sediment budget along the affected coastlines. The inference is that more sediments were being manufactured on the shelf than could be effectively redistributed on the island, or off the shelf margin. The presence of a surplus of 'new' sediments on the coast implies a slower rate of erosion of older units. Even so, if a fraction of sediments of older interglacials is incorporated into the sample, theoretically, the 'average' *A/I* ratio would not be significantly affected. Allochems that are one or two interglacials older generally possess exponentially reduced concentrations of amino acids (Corrado *et al.*, 1986), and thus their presence in the sample, even at significant levels, would have little influence on the ultimate whole-rock *A/I* ratio.

For preparation, whole-rock samples are gently milled with a mortar and pestle to separate the grains. A majority of the cements are removed when the samples are sieved to obtain the 250–1000 μm fraction. Samples are

TABLE 2. AAR mean values, standard deviation (1σ) and number of samples analyzed (parentheses) (after Hearty *et al.*, 1992)

Site #	Marine <i>All</i>	<i>Poecilozonites All</i>	Whole-rock <i>All</i>	A-Zone
SH1-2	<i>Gl</i> 0.55 (1)	0.36 ± 0.06 (4)	0.28 ± 0.02	C
		0.46 ± 0.02 (2)		E
		0.61 ± 0.05 (10)	0.38 ± 0.01 (2)	F2
RB	<i>Be</i> 0.66 ± 0.01 (2)	0.52 ± 0.01 (3)	0.27 ± 0.02 (12)	E
			0.42 ± 0.00 (2)	E
			0.31 ± 0.01 (5)	E
			0.38 ± 0.01 (2)	F2
			0.41 ± 0.01 (2)	F2
GB	<i>Gl</i> 0.70 <i>Gl</i> 0.57 ± 0.07 (4) <i>Be</i> 0.75 ± 0.02 (2)	0.50 (1)		E
				F
BWP		0.50 ± 0.01 (4) 0.57 ± 0.02 (6)	0.22 ± 0.01 (9)	E
				E
GBR			0.51 ± 0.06 (3)	F1
HRQ			0.36 ± 0.02 (2)	E
			0.47 ± 0.01 (6)	F1
SS		0.47 ± 0.04 (3)	0.50 (1)	F1
				F
OR		0.73 (1)	0.57 ± 0.02 (2)	G
				0.57 (1)
LCA		0.59 (1) 0.81 (1) 0.83 ± 0.00 (3)		F
				G
				G
MR		0.80 ± 0.02 (3) 0.82 (1) 0.65 (1)	0.57	G
				G
				G
FS1-2	<i>Be</i> 1.09 ± 0.02 (2) <i>Be</i> 1.13 ± 0.03 (2)	0.89 ± 0.06 (2)	0.69 ± 0.01 (3)	H
				H
BQ		0.88 (1) 0.92 ± 0.02 (7) 0.82 ± 0.05 (3)	0.68 (1)	H
			0.56 ± 0.02 (8)	G
			0.69 (1)	H
			0.68 (1)	H
				H
				?
GQ		0.82 ± 0.03 (2)	0.91 (1)	H
				?
			0.92 ± 0.03 (4) 1.11 ± 0.02 (3)	J K

Gl = *Glycymeris* sp.; *Be* = *Brachidontes exustus*. Site Abbreviations: SH1-2 = Saucos Hill; RB = Rocky Bay (Type Section); Gb = Grape Bay; BWP = Blackwatch Pass; GBR = Grape Bay Railroad; HRQ = Harvey Road Quarry; SS = Saltus School; OR = Ord Road (Type Section); LCA = Laffan St./Cedar Ave.; MR = Morgan Road; BQ = Bierman Quarry (Type Section of Town Hill); and GQ = Government Quarry (Type Section of Walsingham).

then weighed out and prepared in the same manner as molluscan samples (Hearty *et al.*, 1986, 1992).

Aminozones

Hearty *et al.* (1992) defined Aminozones C, E, F₂, F₁, G, H, J and K for Bermuda. These aminozones agree with stratigraphic order and the mapped stratigraphy in 97% of the 257 analyzed samples. Figure 3 illustrates the mapped stratigraphic cross-sections of Vacher *et al.* (1989) compared to average whole-rock ratios. Aminozone E and C are correlated to high sea levels of the Sangamonian (last) Interglacial and Isotope Stage 5. Aminozone E mean ratios (*Glycymeris* = 0.57; *Poecilozonites* = 0.49; whole-rock = 0.30) are calibrated to an age of ca. 125,000 years by U-series dates of Harmon *et al.* (1983) indicating correlation with Isotope

Substage 5e. Aminozone C sediments are younger, demonstrated by U-series coral dates of 85,000 years; these dates and the AAR ratios (*Glycymeris* = 0.42; *Poecilozonites* = 0.40; whole-rock = 0.23) correlate Aminozone C with Isotope Substage 5a (Vacher and Hearty, 1989). Marine shell, *Poecilozonites* and whole-rock ratios are listed in Table 2. Only whole rock-ratios (from Table 2) are used in the sections in Figs 2 and 3.

Aminozone F is represented at Saucos Hill by an *All* ratio of 0.61 for *Poecilozonites cupula* (a species extirpated previous to the Sangamonian (S.J. Gould, *pers. commun.*)) from the younger part of the Belmont Formation. The sampled protosol is from the most seaward part of the formation and overlies the marine deposits. The larger error from *Poecilozonites cupula* at Saucos Hill suggests that some of the samples (exposed to the open sea) are slightly leached and that the higher of the ratios

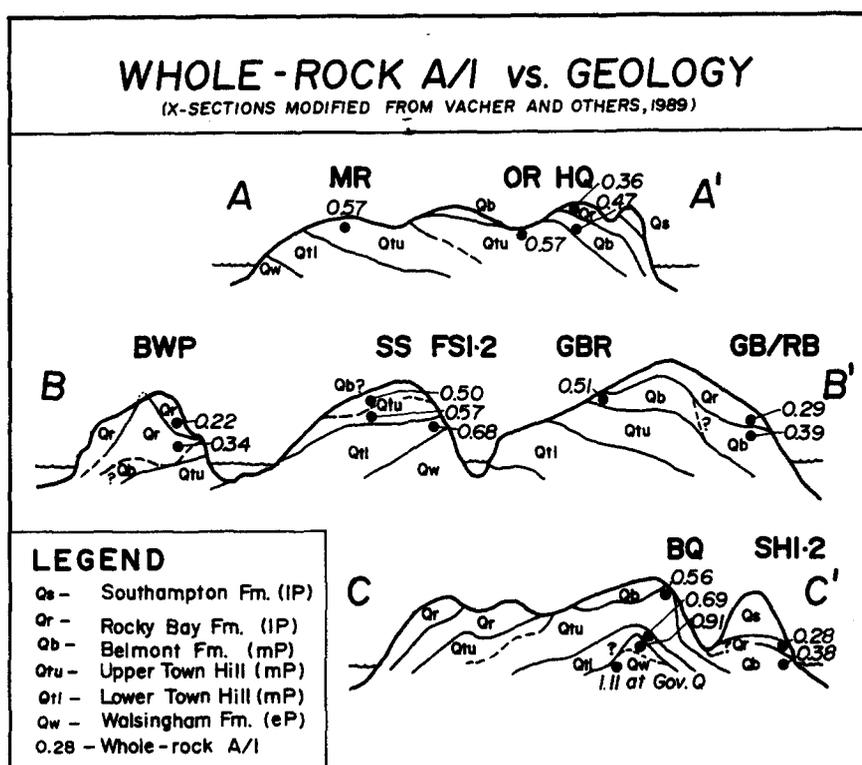


FIG. 3. A comparison of the geologic cross-sections from the Geologic Map of Bermuda (Vacher *et al.*, 1989) with whole-rock amino acid ratios. The legend identifies the mapped formations and their suspected age (eP = early Pleistocene; mP = middle Pleistocene; IP = late Pleistocene). Capitalized abbreviations (e.g. GB) refer to sites and sections in Fig. 2 and Table 2. Some sites are projected along strike onto the cross-sections where clear stratigraphic correlations exist. Possible changes in the existing stratigraphy, in light of amino acid data, are indicated in the figure by queries (?).

(e.g. 0.65) are nearer the correct value. Whole-rock ratios for Aminozone F are bimodal (Table 2), with values averaging 0.39 for F₂ and 0.49 for F₁. The 'younger' whole-rock values are directly associated with the Belmont marine deposits on the south shore (RB and GB) and overlying protosol that yield the *Poecilozonites* samples. The 'older' 0.49 group is from a Belmont eolianite positioned further inland (HRQ, GBR and SS).

Aminozone G correlates with the upper Town Hill deposits. *Poecilozonites A/I* ratios for this aminozone cluster around 0.78 and whole-rock *A/I* of 0.56.

Aminozone H (at Front Street (FS1 and FS2) and Bierman Quarry (BQ)) occurs within the Lower Town Hill. At 0.92 on the average, ratios on *Poecilozonites cupula* from protosols at Corkscrew Hill (Old Bus Station on Front St (FS1)) and in Bierman Quarry are the greatest thus far obtained for Bermuda land snails. Large whole-rock *A/I* ratios (averaging 0.69) from the same deposits and large ratios from *Brachidontes exustus* (1.11) from upper shoreface deposits at the Texaco Station on Front Street (FS2), parallel the 'old' ratios obtained from *Poecilozonites* of 0.89, supporting a much greater age of the lower Town Hill deposits, compared to other middle Pleistocene units.

Aminozones J and K are, thus far, identified only by whole-rock ratios. Aminozone J is present at two localities separated by several kilometers. These include the lowermost non-Walsingham deposits in Bierman Quarry (Figs 2 and 3) and marine deposits from a +22 m bench,

now removed from Government Quarry ('Belmont conglomerate' of Land *et al.* (1967)). The Walsingham in Government Quarry has produced significantly older whole-rock ratios (1.08 and 1.13) than middle Pleistocene units.

AGES OF INTERGLACIAL DEPOSITS

The amino acid age estimates from Hearty *et al.* (1992) are presented in Table 3. These ages were calculated independently from AAR marine shells, land snails and whole-rock ratios using a model of apparent parabolic kinetics (APK) developed by Mitterer and Kriausakul (1989), and by a species-dependent extrapolation of U-series-calibrated kinetic curve (explained in Hearty *et al.*, 1992). The estimated ages of aminozones C, E and F are concordant with U-series ages of Harmon *et al.* (1983). Aminozones G and H are generally in agreement with ca. 300,000 and 400,000 year age estimates, respectively, by their stratigraphic positions one and two interglacials older than the U-series dated Stage 7 deposits. Table 3 also compares APK ages with new electron spin resonance (ESR) data from replicate whole-rock samples (Hearty and Radtke, *unpublished*). About 80% of the ESR dates are in stratigraphic order and agree with AAR age estimates in their ability to discern successive interglacial stages. The best APK/ESR correlation is found at Bierman Quarry (Fig. 2). Early Pleistocene AAR ratios provide an age estimate of > 880,000 years for the

TABLE 3. A comparison of apparent parabolic kinetic (APK) ages calculated from whole-rock (W) and *Poecilozonites* (P) amino acid ratios with electron spin resonance (ESR) dates from whole-rock samples

Site (FM)	Facies	W A/I	P A/I	APK (ka)	ESR (ka)	Sample #
Elbow Beach (mod)	M	0.11		29	56	1675
St. Catherine (S)	E	0.25		81	103	1637
	M*	0.21		57	127	1638
Astwood Park (S)	E		0.36	66	87	1677
(S)	E	0.26	0.43	94	110	1678
Rocky Bay (RB)	E	0.27		—	230	1639
(RB)	M†	0.31		—	94	1679
(B)	E‡	0.38		190	172	1682
Blackwatch (RB)	E		0.57§	175	172	1680
Harvey Rd Q. (RB)	E	0.36		—	293	1640
(B)	E	0.47		—	277	1641
Grape Bay RR (B)	E	0.51		240	457	1642
Bierman Q (UTH)	E	0.56		340	373	1643
(LTH)	E	0.69	0.92	450	490	1644
Government Q (W)	M	0.91		> 700	—	—
	E	1.11		> 880	709	1685

ESR samples were analyzed at the Geographisches Institut, University of Düsseldorf, Germany (Professor U. Radtke) by PJH. APK = apparent parabolic kinetics (Mitterer and Kriasakul, 1989). Associated U-series dates from Harmon *et al.* (1983) of *85,000 years; †125,000 years; ‡205,000 years on underlying marine deposits with whole-rock ratios of 0.41. §The A/I ratio has been obtained from an overlying protosol and it thus reflects minimum age of the lower whole-rock sample.

Walsingham Formation. This age is supported by an electron spin resonance age of > 709,000 years, and confirmed by the reversed magnetic polarity of the rocks (Hearty and Kindler, 1993b; Hearty and McNeill, unpublished data). Future tests of the ESR whole-rock method will seek to determine why the remaining 20% of the dates disagree (e.g. upper unit Rocky Bay; upper unit Harvey Road Quarry; and lower unit Grape Bay RR in Fig. 2) with the presumed ages and stratigraphic order of the limestone deposits.

THE HISTORY OF ACCRETION OF BERMUDA

The combination of geologic mapping and aminostratigraphic studies (Vacher *et al.*, 1989; Hearty *et al.*, 1992; this paper) enable a reconstruction of the build-up of Bermuda during the Quaternary. 'Snapshot' sketches illustrate the progressive growth of the island, and outline the successive, major depositional episodes during the Quaternary (Fig. 4). Naturally, the preserved volume of older rocks is less; however, despite loss of volume by dissolution, sufficient geological evidence remains to document how this carbonate island took shape through a sequence of (1) early shoaling, (2) dune-building, (3) catenary growth on older anchors, (4) vertical growth, and (5) lateral accretion.

At some time between approximately 1.1 Ma and 800,000 years the Walsingham Formation was deposited (Fig. 4.1) around Castle Harbour and along two arcs stretching to the west. The Walsingham is complex and most likely represents multiple early Pleistocene interglacials. Support for this complexity is derived from predictions of at least four flooding events between the Brunhes/Matuyama Boundary (~750,000 years) and about 1.5 Ma ago (Quinn and Matthews, 1990). The warmest of early Pleistocene isotopic excursions

occurred during Stages 25 (~0.88 Ma), 31 (~0.99 Ma), 35 (~1.07 Ma) and 37 (~1.10 Ma) (Shackleton *et al.*, 1984, 1988; Ruddiman *et al.*, 1986). Late in the early Pleistocene (900,000 to 750,000 years ago), probably centered around Stage 25, a major marine transgression apparently inundated the entire landscape, and deposited a marine conglomerate on a high (+22 m) platform cut in Walsingham eolianites at Government Quarry. Blackwelder (1981) similarly recognized a +25 m sea level associated with the early Pleistocene Waccamaw Formation on the southeast U.S. Coastal Plain (see also Hollin and Hearty, 1990). Two Aminozones, J and K, have been defined for the early Pleistocene.

The next several hundred thousand years passed apparently leaving no carbonates but only deeply karstified and *terra rossa*-mantled surfaces. A significant early-middle Pleistocene hiatus is also recognized on the southeast U.S. Coastal Plain (Blackwelder, 1981), and in Italy (Hearty *et al.*, 1986; Hearty and Dai Pra, 1992). Renewed platform flooding and sedimentation resumed on Bermuda during deposition of the lower Town Hill. These sediments nucleated on early Pleistocene ridges, resulting in emergence and growth of the island (Fig. 4.2). AAR dates on these sediments center around 450,000 years, and indicate a correlation with Isotope Stage 11 or (less likely) Stage 13. The lower Town Hill consists of at least three ridges: two that accumulated from the north, and one that accumulated from the south. These ridges, which are grouped under Aminozone H, together with weak paleosols and protosols, suggest that at least two positive sea-level oscillations occurred during this interval. The orientation of dune foresets indicate both north and south source-to-sink vectors (Fig. 4.2).

The upper Town Hill records the most important depositional event of the Bermuda Pleistocene (Fig. 4.3). The voluminous deposits associated with Aminozone G sug-

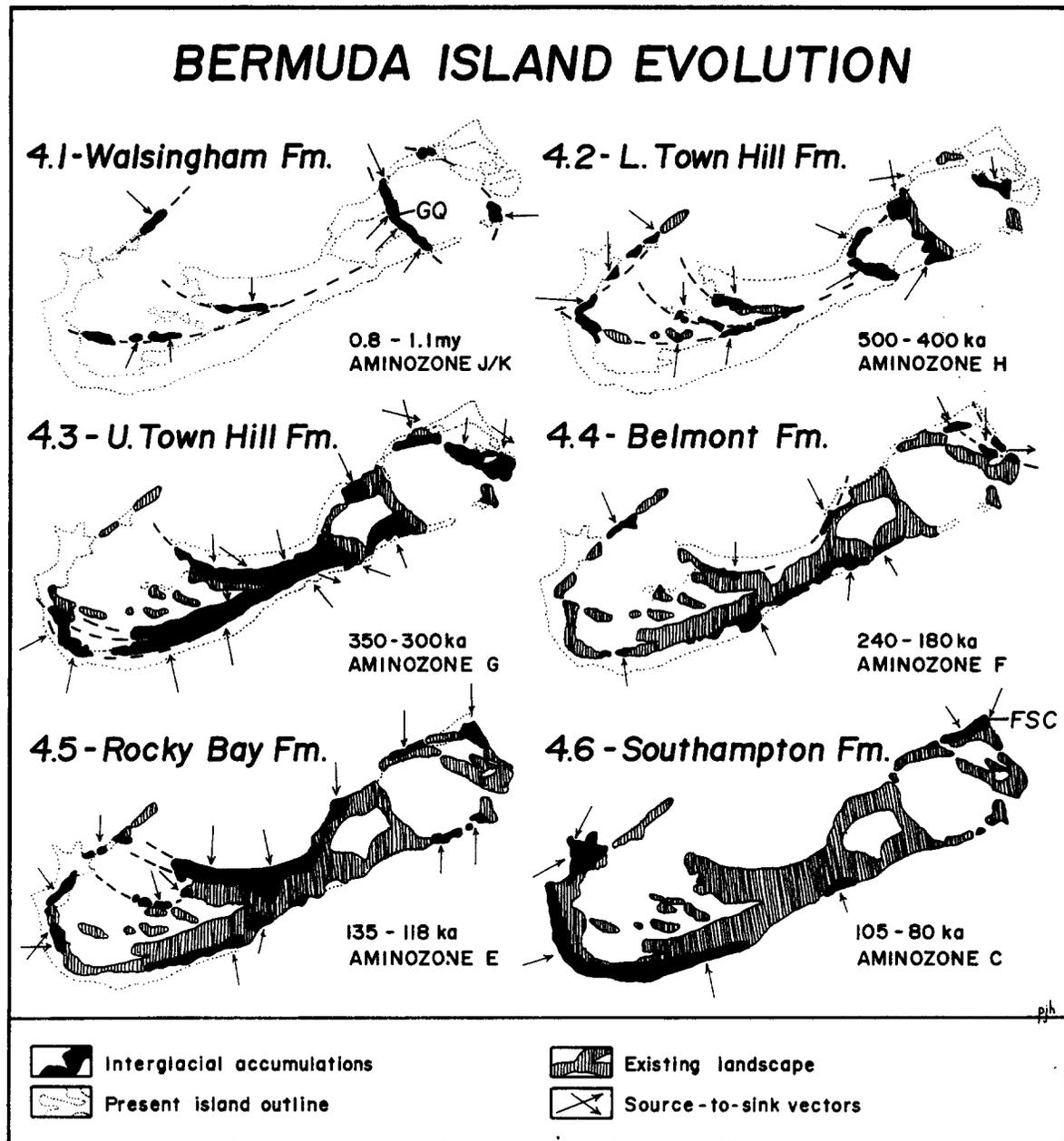


FIG. 4. A sequence of 'snapshots' of depositional phases on the Bermuda Platform. Multiple ridge systems (dashed lines) indicate minor oscillations of sea level within each major depositional phase. (GQ = location of Government Quarry; FSC = location of Fort St. Catherine.)

gest platform flooding of considerable magnitude and duration. AAR and ESR dates center around 300,000 to 350,000 years and correlate with Stage 9. This body of rock is also complex, having multiple beach ridges and internal protosols associated with numerous depositional pulses. Like the lower Town Hill, the upper Town Hill has source-to-sink vectors from both north and south.

A transition from vertical island growth to lateral accretion occurred during the upper Town Hill: as the island widened and heightened, eolianites of later interglacials could not overtop the eolianites of the upper Town Hill, and therefore accreted laterally.

In agreement with most deep-sea isotopic records, the Belmont (190,000 and 265,000 years) formed during an interglacial of lesser importance (Fig. 4.4). Two separate ridges are observed, and judging from their relative vol-

umes, both flooding episodes were probably short-lived in comparison to bracketing interglacial stages. The eolianite ridges accumulated generally on a northwest-southeast axis, with the younger event being of somewhat greater importance (Fig. 4.4). Meischner and others (*in press*) concur with two Belmont phases, but assign much higher sea levels (+2 m and +7.5 m) to the respective early and late events.

Together, the late Pleistocene Rocky Bay and Southampton Formations (Figs 4.5 and 4.6) are similarly voluminous and complex compared to Stage 9. This complexity is expressed by at least two Rocky Bay and two Southampton eolianite ridges. As with the early Sangamonian (Substage 5e) of the Bahamas (Hearty and Kindler, 1993a, c), the Rocky Bay Formation was deposited during at least two (probably three) pulses over

a 10,000 to 15,000 year period. The source-to-sink vectors are mainly from the north, and less so from the south. The greater sediment volume transported across the shallow (now sediment choked) North Lagoon would require much higher energy levels (brought about by higher sea levels?) than exist there today.

A case can be made for the presence of the Substage 5c deposits (105,000 years ago) based on UNIBOOM and vibracore data (Vollbrecht, 1990). Large submerged eolianite ridges capped by modern reefs are indicated by subsurface profiling in the North Lagoon; cores have yielded U-series ages from 99,000 to 106,000 years at a depth between -15 and -20 m. Large notches have also been found at between -12 and -16 m in blue holes off Eleuthera Island, Bahamas (*pers. observations*) that could possibly be attributed to this event.

The Southampton Formation was deposited mainly on steep, higher-energy, open-ocean, southern and western margins of the island. The lagoon-side ridges reflect a lower energy setting and lower sea level for the period. Deposition of multiple eolianite ridges took place around 85,000 years ago (Vacher and Hearty, 1989). At several localities (e.g. Astwood Park, Warick parish), as many as five protosols interrupted by dune deposits are found in vertical section, suggesting that the eolian deposition occurred episodically, while protosol formation was the dominant distal process. It appears from this setting and stratigraphy that only the greatest of storms 'heaved' coarse sediments up the ramp onto the shore, where wind-dominated processes took over, carrying the sediments further inland, burying the protosols.

IMPLICATIONS FOR CLIMATE AND SEA-LEVEL HISTORY

The limestone rocks and soils of Bermuda record the details of climate change and sea-level oscillations throughout the Quaternary. Not only have several broad interglacials of varying amplitude been resolved, but also the minor pulses of deposition that occurred within the interglacials are expressed in the form of separate eolianite ridges and extensive protosols. Bermuda geology thus provides a tangible, high-resolution dataset of environmental change that is not available in deep sea cores or from tectonic coastline studies.

At least six pre-Holocene major positive sea-level cycles, individually bracketed by *terra rossa* paleosols, are recorded in marine and eolian sequences (Fig. 5). During each cycle, sea level rose to near, or above the present level. Significantly lower sea levels would deposit dune ridges seaward of the present coast (like Substage 5c), while higher ones would flood the interior of the island. At least two important interglacials of early to early-middle Pleistocene age were followed by a hiatus encompassing around 300,000 to 400,000 years, after which interglacial flooding of the platform resumed with the Town Hill and subsequent formations.

Figure 5 offers a proposed correlation of paleo sea levels with the isotope stages of Shackleton and others (1984, 1988), while Table 4 offers a correlation between the known units of Bermuda, with those from the Bahamas (Hearty and Kindler, 1993b, c).

The Walsingham Formation preserves marine facies

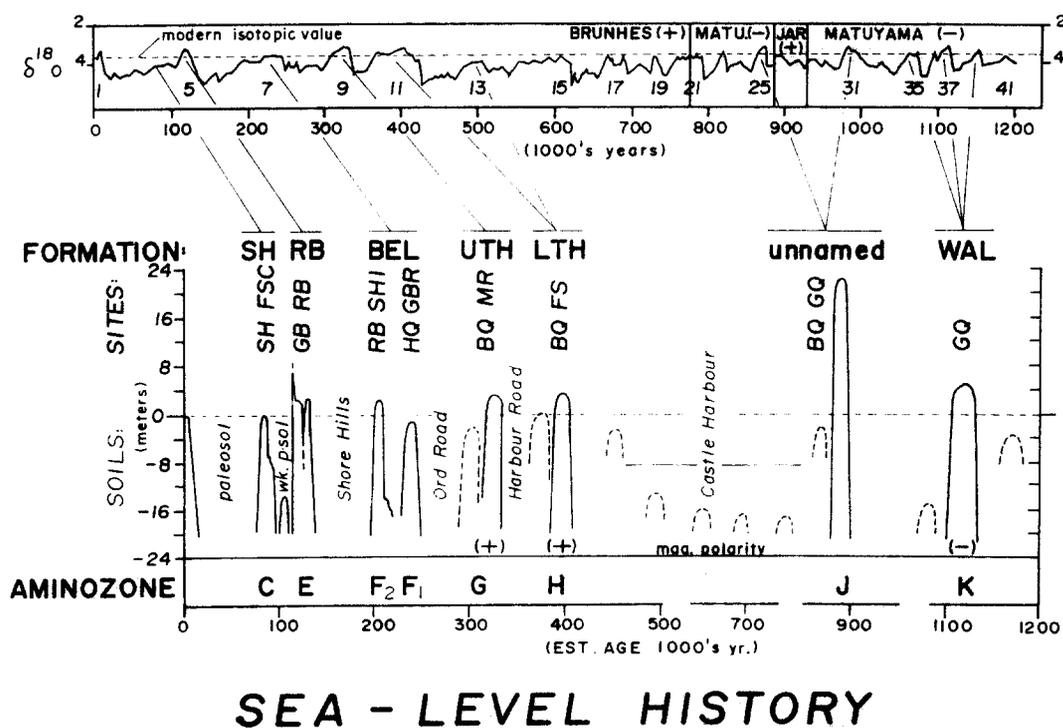


FIG. 5. A proposed correlation between the sea-level history from Bermuda and the isotopic curve from DSDP 552A (Shackleton *et al.*, 1988).

TABLE 4. Proposed correlation of Bermudian formations with formations and sites in the Bahamas

Stage	A-zone	Bermuda* formation	Bahamas formations/sites
Holocene			
1	A	Recent	Rice Bay Fm†
Late Pleistocene			
5a	C	Southampton	Almgreen Cay Fm‡
5e	E	Rocky Bay	Grotto Beach Fm†
Middle Pleistocene			
7	F ₂	Belmont Fm	Fortune Hill Fm‡
7	F ₁		Owl's Hole Fm†
9	G	U. Town Hill Fm	Hunt's Cave Quarry, NPI§ Goulding Cay East, ELU
11	H	L. Town Hill Fm	Goulding Cay East, ELU
Early Pleistocene			
25?	J	Unnamed	no record
37?	K	Walsingham	no record

*After Vacher *et al.* (1989); †Carew and Mylroie (1987); ‡Hearty and Kindler (1993a, c); §Hearty and Kindler, 1993c; ||Hearty *et al.* (*in progress*).

up to about +5 m on St. George's Island, and in now-removed caves at Government Quarry. An unnamed +22 m marine deposit, with rounded volcanic clasts up to 3 cm in diameter, has been determined to be much older than previously thought at > 700,000 years.

The Castle Harbour Geosol rests upon a highly weathered and karstified surface of Walsingham eolianites. Deep solution pits filled with *terra rossa* soil indicate that this surface was exposed for a much greater duration than all other *terra rossa* soils on the island. It is suggested that this soil indeed represents hundreds of thousands of years (a minimum of 220,000 years as indicated by AAR ages) during a period of persistently lower-than-present sea levels of the early-middle Pleistocene. The isotopic records from several deep sea cores including DSDP 552A (Fig. 5) indicate that values were less than present between Stages 13 and 23 (500,000 to 800,000 years ago).

Both the lower and the upper Town Hill Formations were important and complex flooding events with sea levels exceeding the present level by a few meters (Vacher *et al.*, 1989; Hearty and Kindler, 1994). Both events contributed enormous amounts of sediment, with the upper Town Hill comprising a large percentage of the island's current volume. These deposits constitute the 'backbone' of modern Bermuda.

The Belmont occurred in two phases (Hearty *et al.*, 1992) but was less significant than the Town Hill in terms of sediment volume. During the late Belmont, sea level rose to about +2.3 m. Meischner *et al.* (*in press*), however, maintain that sea level rose well above present during both the early and the late Belmont times.

Previous studies (Harmon *et al.*, 1983) suggest that Bermuda lacks the complex stratigraphic record of Substage 5e, as seen in the Bahamas (Hearty and Kindler, 1993a, c; Hearty *et al.*, 1993), the southeast U.S. Coastal Plain (Hollin and Hearty, 1990), the Mediterranean (Hearty, 1986) and more recently, in Hawaii (Sherman *et*

al., 1993). In contrast to this view, deposits at Blackwatch Pass (BWP in Fig. 2) clearly reveal such complexity, showing at least three phases of eolian deposition bracketed by protosols and paleosols. The youngest of these exposes regressive marine deposits at < +3 m. These North Shore marine deposits may indeed represent a different 5e oscillation than the somewhat higher deposits (> +5 m) on the South Shore at Grape Bay and Hungry Bay (Hearty and Kindler, 1994). Deposits at +9.2 m, represented by the now obsolete name 'Spencer's Point Formation', present an interesting prospect for Antarctic ice surge theory (Mercer, 1978; Hollin, 1980). Moreover, it is possible that these rocks are tied to the catastrophic movements of sea level at the close of the early Sangamonian as proposed by Neumann and Hearty (1993, *in review*). Thus, from an assortment of evidence, it is clear that the last interglacial of Bermuda is indeed complex, with several oscillations represented within the broad eustatic curve.

After an apparent rise to ca. -15 m during Substage 5c, sea-level movements during the Southampton time appear to have been confined to sub-modern levels; except at the close of the period when sea level rose to the actual datum (Vacher and Hearty, 1989).

CONCLUSIONS

Despite Bermuda's small relative size compared to the Bahamas, the former has provided globally relevant data on carbonate sedimentary processes, sea-level change and geochronology. Certainly, Bermuda preserves one of the most detailed and extensive early and middle Pleistocene depositional records known from carbonate islands (Vacher *et al.*, 1989, *in press*; Hearty *et al.*, 1992). The composite section of the Bahamas is comparable to that of Bermuda back to the Town Hill Formation (Table 4), but thus far, early Pleistocene rocks are lacking from the surficial geology of the Bahamas. In learning from

Bermuda's rich geological heritage, our perspectives on Bahamian island geology are also enhanced by the availability of new strategies and concepts (Vacher *et al.*, in press) with which to investigate their formation (Hearty and Kindler, 1993a, b, c).

Six pre-Holocene aminozones are recognized by aminostratigraphy (three of which are in stratigraphic superposition in Bierman Quarry). The youngest Sangamonian aminozones E and C are fixed by U-series dates to the beginning and the end of the Sangamonian. The youngest three pre-Sangamonian aminozones, F, G and H, are centered around ages of 200,000, 330,000 and 450,000 years and correlated with Isotope Stages 7, 9 and 11. Two older aminozones, J and K, are estimated to date from > 700,000 to 1,100,000 years. The AAR method provides one of the only means of correlation and dating of carbonate deposits during a period in which traditional radiometric techniques are not effective.

Bermuda geology also provides a global model for the accumulation of sediments on a carbonate bank. Although the history of growth of Bermuda is complex, it appears that three processes were of greatest importance in the formation of the island: (1) the 'initial' shoaling during deposition of the Walsingham Formation; (2) the vertical growth of the island by deposition of the enormous volumes comprising the upper Town Hill Formation; and (3) the lateral accretion of the island to near its present form during the late-middle and late Pleistocene. Sea-level studies from Bermuda have generated a model of eustasy that is applicable to sediment dynamics, neotectonics and global climate change.

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