ANOMALOUS PLEISTOCENE PALAEO-SEA-LEVELS AT BERMUDA AND THEIR CONTROL ON LITTORAL DEPOSITIONAL CYCLES WHICH CULMINATE IN THE FORMATION OF LANDWARD-ADVANCING DUNES (EOLIANITES)

Mark P. Rowe
Student # 12608303
Department of Earth and Planetary Sciences
Birkbeck, University of London

Submitted for the degree of Doctor
of Philosophy, September 2015
(minor ammendments made June 2016)

I, Mark P. Rowe confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

1st September 2015

ABSTRACT

The Bermuda islands are constructed predominantly of aeolian dunes, termed eolianites, whose episodic accumulation has been correlated with Pleistocene sea-level oscillations. Despite a long-standing, now disputed, notion of Bermuda as a “tide-gauge” for Pleistocene glacio-eustacy there has never been a consensus on Bermuda’s palaeo-sea-level history. Most recently there has been disagreement over the interpretation of littoral deposits of the Belmont Formation. Based on U-series ages from coral fragments and analyses of sedimentary lithofacies, it is contended here that a sea level of ≥4.5m above present mean sea level at the penultimate interglacial is represented by these Belmont deposits. It is inferred from the anomalously high elevation of this sea-level imprint relative to the estimated global eustatic sea level of the time that glacio-hydro isostatic and possibly, to a lesser extent, tectonic influences have contributed to a composite RSL (relative sea level) signal at Bermuda. This and other interglacial highstands at Bermuda left their imprint in the form of exceptionally well exposed emergent coastal facies assemblages. The most complete assemblages are shown to have developed in two stages, S1 and S2, respectively during a rising RSL and a falling RSL. S1 records beach progradation, barrier construction and back-barrier inundation. S2 begins with emergence of an ultimately wooded backshore, and ends with its burial by advancing dunes sourced on expanding beaches at a highstand termination. Past hypotheses that Bermuda’s dunes were static aggradational structures which accumulated rapidly in storms are tested by analyses of eolianite stratification, wind data and drift potential. It is demonstrated that the eolianites are the remnants of mobile landward-advancing bedforms constructed predominantly when winds above the threshold velocity were directed onshore across source beaches. The model developed for the evolution of beach-dune systems on Pleistocene Bermuda is applicable to present-day clastic coasts which are vulnerable to RSL rise.

TABLE OF CONTENTS

FIGURES

TABLES

APPENDICES

ACKNOWLEDGEMENTS

My supervisor Charlie Bristow provided invaluable guidance throughout the period of research that culminated in this thesis, for which I am very grateful. Gideon Henderson and Karine Wainer are thanked for providing U-series dating resources at Oxford University and for their input on the current state of global glacio-hydro isostatic research. Martin Brewer, Peter Vogt, Angel Gines and Struan Smith are to be thanked for sharing their knowledge, respectively, on Bermuda earthquakes, oceanic volcanism, cave development and fossil identification. Jean Craddock and my mother, Anne Rowe, cheerfully assisted me with the botanical transect and with compilation of foreset-dip azimuth data, respectively. Manuscripts submitted for publication were reviewed by Cristino Dabrio, Leonard Vacher, Dan Muhs, Joel Roskin, Ryan Grimm, Richard Langford, Timothy Lawton and Paul Hearty. Their suggestions ultimately helped improve this thesis and are greatly appreciated.

1. INTRODUCTION

1.1. GEOLOGICAL SETTING OF BERMUDA

Bermuda is a British Overseas Territory located in the North Atlantic at 32° 20' N, 64° 45' W. This places it at 1,015km to the east of the closest landfall, which is North Carolina in the United States (Figure 1.1). The four main islands of Bermuda are connected by short bridges forming an elongate land mass with a combined length of 25km and a maximum width of 2.5 km. They occupy the south-eastern edge of a 35 x 20km reef-rimmed platform, below which is the truncated Bermuda volcanic seamount. Average water depths on the platform are ~15m and depths to the basaltic volcanic rocks average ~45m below sea level, with the intervening interval being occupied by Quaternary and modern carbonates, mostly of marine origin (Vollbrecht, 1990). Given the shallow depth of sub-aqueously erupted volcanic rock (pillow lavas), and a measured age of at least 33 million years (Reynolds and Aumento, 1974), Bermuda does not qualify as a classic Darwinian subsiding atoll.

Bermuda's geology predominantly comprises 5 - 20m thick cross-stratified sets of aeolian bioclastic calcarenite, termed "eolianite" by Sayles (1931), which onlap and sometimes overtop their predecessors from a seaward direction. This has created a topography dominated by 50m to 70m high hummocky ridges the majority of which are aligned approximately parallel to the closest shoreline and to the long-axis of the island chain. This topography qualifies Bermuda as a "high island", as opposed to a "low island", according to the system of categorisation of carbonate islands proposed by Vacher (1997). The dune deposits are intercalated with 0.25 - 1.0m thick fossil soils which range from immature protosols to mature terra rossa palaeosols. The latter represent hiatuses in clastic deposition and have been designated as allostratigraphic boundaries (Vacher et al., 1989). Sayles (1931) first made the correlation between Pleistocene glacio-eustacy and the cyclicity represented by the alternation between eolianites and palaeosols. He reasoned that sub-aerial exposure of marine sediments on the platform, at low or lowering sea levels, was responsible for dune-building; while the intervening periods, particularly at sea-level highstands when the platform was submerged, were recorded by palaeosol formation.

Bermuda's eolianites display a full age-related range of meteoric diagenetic alteration (Land et al., 1967), the most apparent manifestation of which is progressive cementation and concomitant reduction of porosity with age. The Geological Map of Bermuda (Vacher, Rowe and Garrett, 1989) identifies six allostratigraphic limestone formations separated by palaeosols (Figure 1.2.), which were characterised as "solutional unconformities" by Land et al. (1967). Generally, the arrangement of the formations upholds Sayles' (1931) division of the Bermuda islands into a core of older limestones fronted on the seaward sides by ridges of topographically more prominent, younger limestones.

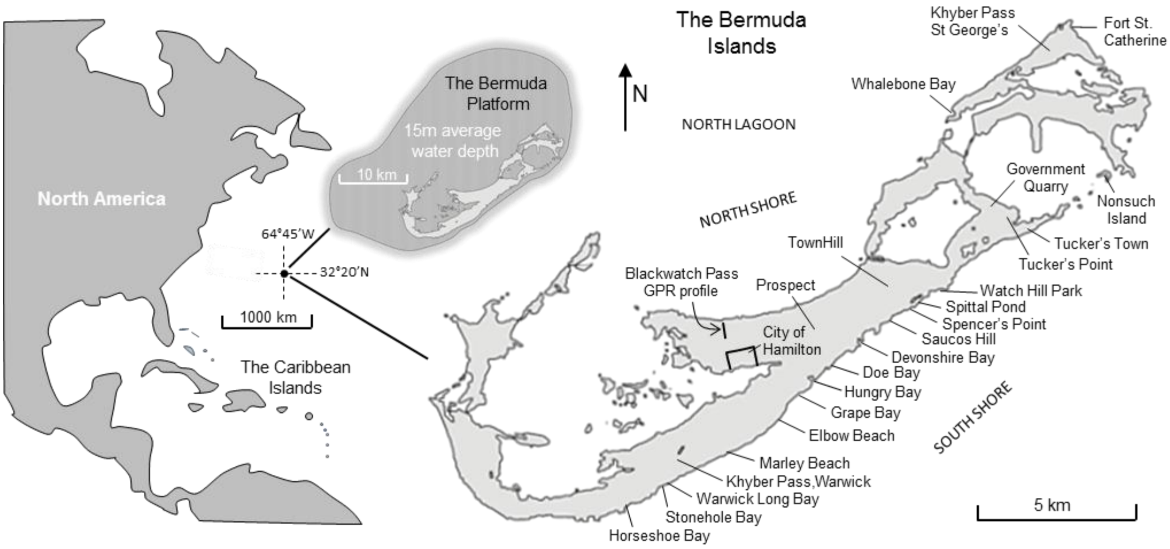


Figure 1.1. Bermuda location map. See Appendix G for better definition of south shore localities.

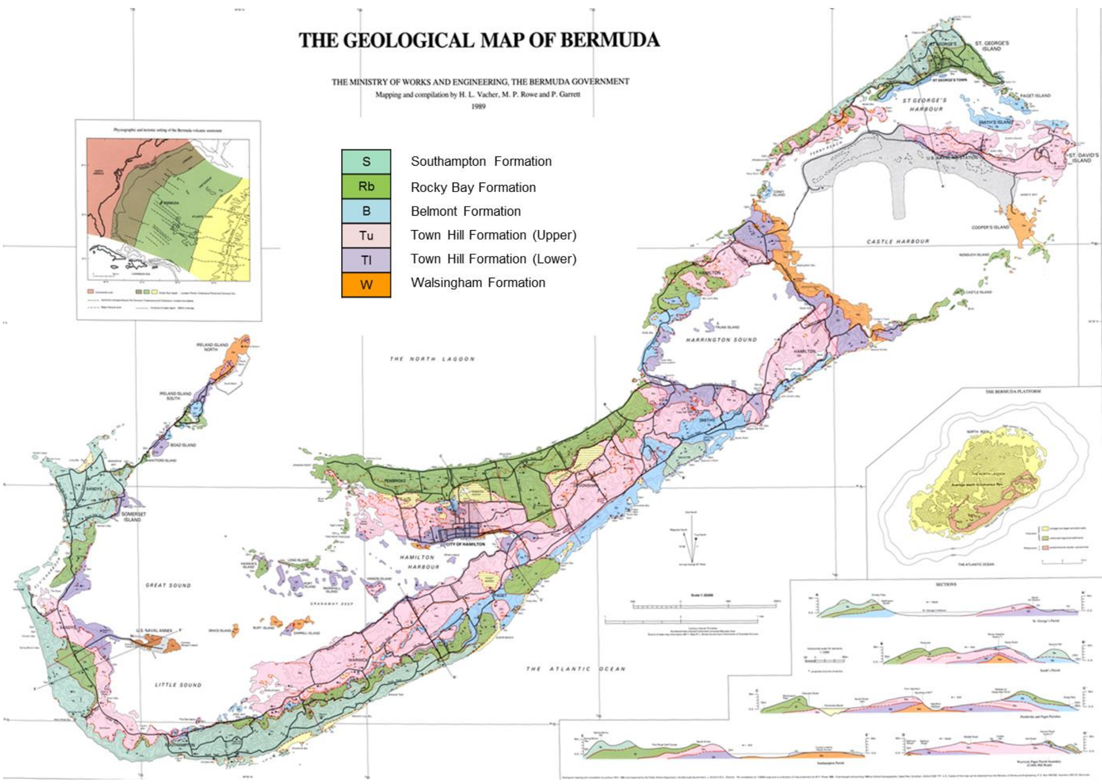


Figure 1.2. The Geological Map of Bermuda (Vacher, Rowe and Garrett, 1989). Six allostratigraphic limestone formations are listed in the stratigraphical column. Formation boundaries are represented by geosols, characterised as "solutional unconformities" by Land et al. (1967). **See Appendix I for full-size original version of the map.**

Emergent marine shoreface and foreshore deposits are restricted to narrow coastal outcrops. Although volumetrically minor, they play a critical role in Bermuda's geological history and its global relevance. This is because, first, they preserve imprints of Pleistocene interglacial highstands from which palaeo-RSL (relative-sea-level) positions can be reliably derived; and second because the facies architecture which is exceptionally well-displayed in shore-normal exposures, facilitates the reconstruction of beach-dune evolution. Despite the clarity of the exposed strata and facies associations, competing models of littoral accretion have been developed. For example, the concept of near-contemporaneity between interglacial sea-level highstands and expansive dune building advocated by Bretz, (1960), Land et al., (1967) and Vacher (1972) contradicts the earlier position taken by Sayles (1931).

1.2 THE IMPORTANCE OF QUATERNARY EVENTS AT BERMUDA IN A GLOBAL CONTEXT

It is inferred from global sea level curves generated from a variety of studies (Shackleton and Pisias, 1985; Martinson et al., 1987; Bintanja et al., 2005; Siddall et al., 2006; Rohling et al., 2009; Dutton et al., 2009) that ice sheet volumes were substantially reduced three times between 250 and 180 ka, during MIS 7, but not to modern levels. Bermuda's pre-eminent status as a global sea-level "tide gauge" (Hearty, 2002) means that the global record should be corroborated by the MIS7 palaeo-RSL (relative sea-level) imprint on the Bermuda islands. The age of Bermuda's Belmont Formation is established in this study as ~200ka which correlates with MIS 7 (Marine Isotope Stage 7). Also, an associated RSL (relative sea level) highstand of at least +4.5 m ASL is inferred from emergent Belmont Formation "sea-level indicator facies' identified in this study. These new data would be considered controversial by those who argue that the palaeo-sea-level signal at Bermuda is overwhelmingly eustatically controlled. However, the importance of Bermuda as a gauge of glacio-hydro-isostacy, as opposed to eustacy, has become increasingly recognised owing to Bermuda's "intermediate field" location relative to major sites of Quaternary ice sheet accumulation in North America. Anomalously high RSLs at MIS 11 and MIS 5a at Bermuda have been successfully modelled by Raymo and Mitrovica (2012), Dutton and Lambeck, (2012) and Creveling et al. (2015) by incorporating isostatic effects such as crustal loading by ice sheets and by ocean-water, alternately. Similar circumstances at the MIS7 interglacial period can be invoked and glacio-hydro-isostatic modellers will no doubt take up the challenge of verifying their models against the latest RSL curve for Bermuda, as presented in this thesis and by Rowe et al. (2014).

The cemented carbonate dunes that dominate Bermuda's geology were recognized early on (Nelson, 1837) as wind-blown deposits. Sayles (1931), in reference to Bermuda's dunes, coined the term "eolianite" which is now applied, globally, to lithified carbonate aeolian dunes (Brooke, 2001). Only short-lived activity has been credited to Bermuda's eolianites between accumulation on the shore and cementation. This is attributable to wide acceptance of Bretz's (1960) hypothesis of rapid stabilisation of eolianites by incipient cementation. Highlighting the importance of dune internal structure as incontrovertible evidence of extended activity, this thesis asserts that Bermuda's dunes were, in fact, mobile and were subject to re-activation. They advanced landward onto and over a pre-existing topography of older dunes. Lithification, predominantly by the effects of infiltrating rain-water within the vadose zone, did serve to preserve the dunes, but only after they had been stabilised by vegetation. The evidence of prolonged mobility has implications for eolianites elsewhere in the world, in terms of their distribution relative to the contemporaneous shoreline and in terms of the position of that shoreline relative to the present one. This, in turn, has repercussions for coastal dune-building models with respect to the timing of maximum dune activity relative to RSL change.

A variety of models from around the world have been developed that correlate states of changing relative sea level (RSL) with stages of the beach-dune evolutionary cycle. Coastal-dune construction models developed in Bermuda are frequently cited as applicable, or not applicable, to other localities (Pye and Tsoar, 1990; Brooke 2001 and Lees, 2006). This thesis challenges the concept of transgressive coastal dunes forming on Bermuda's shores in response to a rising RSL (Bretz, 1960) or autogenic sediment supply (Vacher, 1972). The reversal of Sayles (1931) model by Bretz is questioned; and a two stage model is adopted which involves marine foreshore/shoreface deposition during a RSL transgression and aeolian deposition, sourced from widening beaches (as per Sayles, 1931), during a RSL regression. The new model is grounded on the interpretation of facies assemblage architectures observed in emergent beach and sub-tidal deposits which are exceptionally well exposed along Bermuda's shores. An association of dune-building with platform-flooding at highstands is not denied. However, the differentiation made here between the processes of sediment delivery - being marine on the rising limb and aeolian on the falling limb of the RSL curve - represents a contrast with previous transgressive or sediment-supply models. The conclusions drawn here with respect to chronology is consistent with that of several studies elsewhere which, using OSL (optically stimulated luminescence) dating, have correlated the accumulation of eolianites with post-highstand falling RSLs (Orford et al., 2000; Bateman et al., 2004; Moura et al., 2007; Andreucci et al., 2009). The Bermuda model of two-stage sediment delivery, therefore, has potential for wider application beyond Bermuda's shores, albeit that the quality of exposure of emergent marine facies, elsewhere, is often insufficient to demonstrate exact equivalency.

1.3. OBJECTIVES

Articles on Quaternary global glacio-eustacy, glacio-hydro isostacy and the timing of coastal dune deposition have frequently cited research from Bermuda. Perceived eustatic and isostatic implications of the palaeo-sea-level history at Bermuda have evolved over time. As discussed above, Bermuda data once used to calibrate glacio-eustatic models are now used to calibrate glacio-hydro isostatic models. The various dune-building hypotheses that have been developed for Bermuda (Sayles, 1931; Bretz, 1960; Vacher, 1972) have likewise undergone significant revisions with respect to proposed synchronisations with glacio-eustatic cycles. Convergence of opinions has been confounded by misinterpretation of facies, misidentification of sedimentary structures, unreliable age data and delayed adoption of well-established principles. To a large extent long-standing controversies have remained unresolved, and this reflects an absence of Bermuda-based geological research since the work of Hearty (2002), which in itself introduced new contentious concepts; particularly so with respect to the age of the Belmont Fm and the related palaeo-RSL history at Bermuda during MIS 7.

The objectives of this thesis are to summarise and provide a critical assessment of previous research, and then to bring new data and analyses to bear on controversial or entrenched hypotheses which are deemed overdue for review. New avenues of research which have been identified as important to achieving these objectives are: 1). Reconstruction of the Belmont Formation relative sea-level history using a combination of high resolution lithofacies interpretations and U-series dating; 2). Re-evaluation of Bermuda's Pleistocene dunes with respect to their morphodynamics and to their orientation relative to prevailing winds and the shoreline; and 3). Analyses of facies assemblages architectures to determine the cause and timing of key events in the beach-dune evolutionary cycle, particularly in relation to RSL changes.

Chapters 3, 4 and 5 address the challenges associated with palaeo-RSL (relative sea-level) studies at Bermuda posed by the absence of in-situ corals and potential isostatic/tectonic instability of the seamount. A new approach to reliably establishing palaeo-RSL positions from facies interpretations and field surveys is introduced and its application to the Belmont Fm marine deposits is detailed. This approach is applied with the objective of resolving the controversy over the elevation and age of the RSL event(s) recorded by the Belmont Fm, and to understand the implications with respect to glacio-hydro isostacy and potential tectonism at Bermuda.

Chapter 6 expounds a study of the mobility and orientation of Bermuda's eolianites at the time of their deposition. The prevailing characterisation of these dunes in the literature as fixed structures which accumulated in response to storm winds is tested by analysing cross-stratification geometries as well as foreset-dip azimuths and wind data.

Chapter 7 addresses the effect of RSL changes on littoral accretion on Bermuda, manifested as beach progradation, barrier aggradation and aeolian dune formation. Reconstruction of stages of beach-dune development correlative with RSL change, principally at highstands, is achieved through measurement, analysis and cataloguing of emergent marine facies assemblages of Bermuda's south shore. Also, conflicting versions of the order of events leading up to expansive dune-building on Bermuda's north shore deposits are critically reviewed in the context of new facies interpretations.

An anticipated outcome of this research is a robust mid-late Pleistocene relative sea-level curve for Bermuda along with an understanding of the contributors to sea-level change, which include eustacy, glacio-isostatic adjustment (GIA) and, potentially, tectonic instability. The fact that emergent facies assemblages are a source of information on RSL change as well as beach-dune evolution enables reconstruction of the synchronization between the two. This is critical to evaluating the role of allogenic forcing relative to that of autogenic processes. The well exposed coastal facies assemblages facilitate an understanding of the temporal and spatial relationship between eolianites and beach deposits. This relationship, in conjunction with new insights into dune morphodynamics and orientation, are used here to investigate the processes responsible for triggering, and briefly sustaining, the expansive dune-building that was essentially responsible for the construction of the Bermuda islands. Knowledge of this timing, in turn, enhances the ability to predict the evolution of beach-dune processes elsewhere in the world in response to combinations of local and external factors, principal among which in terms of popular concern is sea level change.

1.4. METHODS

1.4.1 Field mapping and compilation of facies

Geological field studies were commenced at an early stage of the research, with particular attention given to 6km of continuous exposure of the Belmont Fm on the south shore of the central parishes between Grape Bay and Watch Hill Park (Figure 1.1, Appendix G). Localities and descriptions of sedimentary features were recorded on 1:2500 field maps. Vertical sections were sketched in a field notebook showing major bounding surfaces and cross-stratification characteristics. Sedimentary “structural facies” were identified on the basis of the geometry and scale of sedimentary structures and on the spatial associations with other facies (Appendix F). Important conclusions of this thesis are dependent on accurate identification and cataloguing of these littoral facies, several of which had not previously been documented in Bermuda.

Exceptionally well exposed shore-normal emergent successions identified in the process of field mapping are exploited for the purpose of compiling detailed cross-sections of facies assemblages. These are calibrated vertically relative to present mean sea level by accurate elevation measurements (see below). Graphical representations, or panels, of the architecture of facies assemblages are produced from the field data (Appendix H). They are then used to identify progradational, aggradational and retrogradational trends, and for the reconstruction of palaeo-RSL elevations and movements.

1.4.2. Elevation measurements

This research project has relied on the development of an accurate (± 0.2m) method for measurement of the elevation of coastal geological features relative to the sea surface and ultimately mean sea level. In most, if not all, cases of past research on Bermuda it is unclear as to what field techniques were deployed to arrive at the quoted palaeo-sea-level data. The technique described here, incorporates a correction for state of the tides, at the time of measurement, and conversion to an “AOD” value (above ordnance datum) or “ASL” value (above mean sea level). (AOD and ASL are approximately the same). Field datum is taken as the sea surface. Measurements are made only on days when wave action is at a minimum. Using a “builder’s level” for horizontal sightings, a weighted measuring tape and a graduated staff, the elevation of recognisable horizons or surfaces within facies, usually the top, are measured relative to the position of the sea surface (averaged over several minutes). Since all critical exposures are within a narrow strip of coastline, the horizontal length of each survey is invariably less than 10m and the height difference measured is less than 8 m. These short distances minimise cumulative errors. The time of measurement is noted and necessary corrections for astronomical tides calculated by reference to data collected at an automated tide station operated, at Bermuda, by National Oceanographic and Atmospheric Administration (NOAA) of the US Government. For verification purposes, measurements of the same horizon relative to mean sea level (ASL) were repeated at 16 localities at different states of the tide on different days. 75% of these repeated measurements are within ±0.1 m and the remaining 25% are within ±0.2m. An accuracy of ±0.2 m can thus be claimed. A tabulated summary of elevation calculations is provided in Appendix F.

1.4.3. Coral fragment collection for dating

An important component of this research has been the collection of coral fragments from critical outcrops with well-established stratigraphies and unambiguous palaeo-RSL imprints. Only 2 coral fragments, which yielded reliable ages, had previously been recovered from demonstrable Belmont Fm deposits (Muhs et al., 2002). This paucity of data along with questionable provenance of the coral fragments encouraged challenges to the validity of the assumption of a short transport-time between coral death and deposition. In other words claims could be, and have been, made that coral fragment ages (in small numbers) are unreliable because of the potential for reworking from older deposits. A methodical search of facies in which coarse material preferentially accumulates was therefore undertaken and more coral fragments were found. Of the six fragments collected from Belmont Fm deposits three are deemed diagenetically uncompromised. These additional three ages more than doubles the number of reliable Belmont Fm ages and thereby greatly enhances their statistical value. Robust ages of deposits, thus determined, are vital to establishing a credible palaeo-RSL curve for Bermuda. An example of the photographic record that was kept of coral sample-localities along with a tabulation of the location descriptions and the results of age measurements are provided in Appendix A.

1.4.4. Speleothem dating

Dating of speleothem growth layers in samples taken from Bermuda caves proved a valuable tool for palaeo-sea-level research in the hands of Harmon et al. (1983). Analysis of speleothems taken from specific elevations was used to demonstrate whether or not during the period of their growth sea-level exceeded those elevations. This was deduced, respectively, from evidence of either continuous (sub-aerial) growth or of interrupted growth within dated layers. Where there was evidence of a sea-level imprint within the layers, such as marine encrustation, the results were particularly conclusive.

Investigations leading up to this thesis attempted to exploit the aforementioned potential precision of palaeo-sea-level data derived from speleothems. This entailed scouting of many Bermuda caves to identify suitable candidates for sampling. However, due to stringent regulations which have been introduced since the 1980s, requests to remove and export these candidate speleothems were invariably rejected by the Bermuda Government authorities. In the end only those from a single cave were ruled of sufficiently low value that they could be removed. This cave - Wilkinson's Quarry Cave - was considered unstable and compromised due to its location in an active quarry. Five speleothems at 0 to +2m ASL (above present mean sea-level) were selected for sampling on an initial visit; and then on a second expedition, following completion of a survey of their elevation, they were removed using a combination of a cordless sabre-saw and a hammer and chisel. Eventually permission was obtained to export the speleothems to Birkbeck at the University of London where they were sliced and polished. Sub-samples were taken to Oxford University for U-series dating. Initial results, unfortunately suggested that the age ranges represented by the speleothem growth did not span critical periods of the Pleistocene when sea levels are thought to have exceeded present mean sea level. There was no evidence of significant hiatuses or marine overgrowth. It was, therefore, concluded that there was little potential for new palaeo-RSL revelations and this work was given a low priority. There are therefore no data to report from this protracted project although analysis of the samples continues at Oxford University. The work does not form part of this thesis but results may be published in due course. Photographs of the sampling procedures and of the samples as well as a table of speleothem age data prepared at Oxford University are presented in Appendix B.

1.4.5. Wind data and drift potential analyses

Twenty years of hourly wind data collected by the U.S. Navy at the Bermuda Airport between 1975 and 1995 are reduced into a table comprising 10 degree increments in wind direction (36 rows) and 12 wind strength categories ranging up to >55 knots (12 columns; see Appendix C). Wind categories below the threshold velocity, taken as 12 knots (after Fryberger, 1979), are eliminated from the data-set as are those above 40 knots which at Bermuda comprises, over the study period, less than 2% of recorded hourly winds. The percentage of occurrences of winds from given directions within each of the remaining five wind categories are multiplied by Fryberger's (1979) weighting factors. The product, quoted in "vector units", is a measure of the potential amount of sand drift in a given direction (Appendix C). These data can be graphically represented on a circular "sand rose" in which the lengths of arms, or spokes, are proportional to the respective number of vector units. The total of the vector units for all wind categories is known as the "drift potential" (DP) and is unique to Bermuda's wind regime. This represents the power of Bermuda winds to move sand (in the absence of vegetation) without respect to direction. Vector units from different directions are vectorially resolved to a single resultant

“resultant drift direction” (RDD) (Fryberger,1979) which represents the net direction of sand movement over time. The potential of sand to drift in the direction of the RDD, as opposed to general drift (DP), is known as the Resultant Drift Potential. It is calculated using Pythagorean theorem by establishing for each wind direction the component number of vector units that are directed along the RDD and then summing these components. A drift potential analysis, as described here, is a prerequisite to determining controls on dune morphology and orientation discussed in Chapter 6.

1.4.6. Compilation and analyses of slip-face forest azimuth data

As part of this study 3751 slip-face orientations, which had been plotted on field maps in the process of geological mapping (Vacher, Rowe and Garrett, 1989), are segregated into 168 sample areas and entered into an Excel spreadsheet. Because of the long convoluted coastline and large variations in data density (rock exposure), compromises have to be made in the attempt to meet the criteria that sample areas should be of equal size - approximately 0.3 km^2 - and include equal numbers of data points. 168 rose diagrams of foreset dip azimuths are produced (with GEOrient 9.5.0, Holcome, 2011), representing, on average, 22 measurements each (Appendix E). Average dip azimuths for each of the 128 areas are then calculated to enable presentation of a simple yet precise summary of the foreset azimuth data on a single map of Bermuda (Figure 6.8). The scale, alignment and morphology of individual dunes as well as the character of composite structures which form the topography can be established from these compiled dip-azimuth data. Also, when combined with the results of the drift potential analysis, the azimuth data provide fundamental insight into the relative influences of sediment-source and wind regime, respectively, on the direction of dune advance/growth.

1.4.7. Botanical transect of modern dunes

A shore-normal botanical transect of a Bermuda beach-backshore was undertaken in December 2012 at Stonehole Bay on Bermuda’s south shore. It extended 130m in a north-northwesterly direction from the high water mark to the depression at the rear of the foredune ridge. The location was chosen to replicate a survey by Watson et al. (1965). Species identifications were made or confirmed by reference to “Coastal Bermuda” (Pearson, 2008). Where this failed, photos were taken and staff members at the Bermuda Government, Department of Conservation Services were consulted. A complete list of species in the vicinity of the proposed transect was compiled in advance of the survey. Starting on the beach, the presence or absence of species was noted within successive 5m segments extending 1m either side of a 50m tape which was laid along the transect line. The tape was moved end to end as required. Results of the survey are presented in Appendix D. An objective record of historical changes in botanical diversity, contributes to an understanding of the capacity of vegetation cover to adapt to pressures such as climate change. It helps answer the question for example as to whether reduced botanical diversity associated with increasingly harsh conditions at interglacial terminations would necessarily have compromised vegetation cover to the point that dunes became unstable.

1.4.8. GPR survey of sub-surface strata at critical localities

Ground penetrating radar (GPR) surveys led by Charlie Bristow were conducted along three shore-normal road sections in 2014. This was insufficient to be considered anywhere near representative of the study areas on the north and south shores of Bermuda's central parishes. Constraints on the application of GPR were attributable to Bermuda's dense development and low topography relative to the water table which can inhibit resolution at depth. Fortunately, very good rock exposure along the coast combined with numerous man-made rock cuts, inland, means that GPR can be considered an adjunct to field observations. At the three localities where it was employed it had the potential to locally extend facies assemblage interpretations landward from coastal exposures and downward from surface rock cuts. Furthermore, this first deployment of GPR in Bermuda for geological research had the benefit of demonstrating its effectiveness for future studies at well-chosen localities.

The Bermuda GPR studies were conducted using a Pulse Ekko Pro with 250 volt transmitter and 100 MHz antennas. The antennas were deployed in the parallel broadside configuration, spaced 1m apart, with a step size of 0.25m. The position on the ground was determined by 50m tape measures lain along the line of survey. Elevation measurements were made in the field at 5m intervals using a hand held level and staff. The data has been processed using Ekko 42 software and includes: dewow, first pick and first shift, down the trace average of 2 and trace to trace average of 2, AGC gain max 400, and FK migration. The velocity used for migration and depth correction is 0.11 mns-1 which was determined by hyperbolic curve fitting and is a typical velocity for GPR in limestone (Milsom 1996, Reynolds 1997). Corrected GPR profiles accurately represent sub-surface cross-stratification and the position of major bounding surfaces from which facies associations and stratigraphies can be established. The surveys, along roadways at elevations of approximately 10 to 15m ASL (above present mean sea level), also provided structural information from limestone bedrock close to present sea-level where highstand palaeo-sea-level imprints in the form of erosion surfaces might be expected.

2. LITERATURE REVIEW

2.1. QUATERNARY RELATIVE SEA-LEVELS

2.1.1. Development of a stratigraphy for Bermuda and its relationship to sea-level change.

Verrill (1907) produced a stratigraphy for Bermuda which can be considered the foundation of the modern stratigraphy. His three limestone formations amounted to two aeolian facies separated by a marine facies. These were subsequently subdivided by Sayles (1931) into the iconic Walsingham (aeolian), Belmont (marine), and Devonshire (marine) Formations followed by a number of aeolian formations which did not withstand later scrutiny. Of equal importance to the limestone formations were the palaeosols, described and named by Sayles (1931), which were designated as formation boundaries. Sayles (1931) made the first connection between cyclical glacio-eustatic sea level change and the alternation of his "eolianite" deposits with the intervening palaeosols. He attributed the former to falling and low sea-levels and the latter to high sea-levels when, he argued, sand supplies were cut-off by submersion. Bretz (1960) reversed the relationship, citing his observations of physical transitions between emergent marine facies and eolian facies. He, also, "telescoped" the complicated post-Devonshire stratigraphy of Sayles' (1931) into two formations but otherwise made few changes; albeit that marine highstand units by his re-interpretation of events, now necessarily had eolianite counterparts within the same formation. The earlier designation of formations as either marine or aeolian had therefore been abandoned. Land et al. (1967) upheld the Bretz (1960) depositional model for Bermuda. The stratigraphy which they presented was little changed from that of Bretz and comprised the following formations: Walsingham, Belmont, Devonshire, Pembroke, Spencer's Point and Southampton which were separated by named palaeosols. Major new contributions made by Land et al. (1967) were, first, the introduction of a chronostratigraphical framework for Bermuda by assigning ages to the formations based on U-series dating of corals found in marine deposits. Second, Land et al. (1967) introduced the concept of diagenetic grade, which amounted to a measure of changes to mineralogical composition and texture of calcarenites caused, respectively, by conversion of High-Mg calcite and aragonite to Low-Mg calcite, and by an increase in allochthonous cement at the expense of inter-granular porosity.

Detailed geological mapping of the Bermuda islands (Vacher et al. 1989) resulted in the addition of the Town Hill formations (upper and lower) which had previously been parceled into the Belmont Fm and omission of Land et al.'s (1967) Spencer's Point Fm which was found to be an outlier of the Devonshire marine member of the newly established Rocky Bay Fm (approximate equivalent to the Pembroke Fm of Bretz (1960) and Land et al. (1967)).

Land et al. (1967) established that very broad lithological distinctions between deposits of different ages can be made on the basis of diagenetic grade. Harmon et al. (1983) demonstrated that U-series dating of corals collected from marine deposits can be a reliable source of age data. Notwithstanding these developments, the division of Bermuda's calcarenites into mapable formations has been achieved predominantly through allostratigraphic principles rather than those of lithostratigraphy or chronostraphy. Long interruptions of calcarenite accumulation when Quaternary sea levels repeatedly fell below the platform edge are recorded by "solutional unconformities" (Land et al., 1960) which are represented by distinctive palaeosols and erosional surfaces designated as formation boundaries. The ability to trace these boundaries across the islands with an increasing degree of certainty as new man-made exposures were created is what made the geological map of Bermuda (Vacher et al., 1989) possible.

The stratigraphy which was developed as a foundation for the geological map (Vacher et al., 1989) which incorporated recognisable elements dating back to Sayles (1931), was challenged as chronostratigraphically incorrect by Hearty (2002). His objection principally centred on the occurrence of successive low order, mid-late Pleistocene highstands above present RSL, represented in particular by the marine members of the Belmont and Rocky Bay Fms. He argued that the inference of their equal stratigraphical status put the Bermuda record at odds with consensus versions of global eustatic sea level curves which featured only one major higher-than-present highstand over the same time span. Hearty's (2002) revised stratigraphy, which is challenged here, renamed and relegated the Belmont Fm to a member of the Rocky Bay Fm.

2.1.2. Chronostratigraphy of palaeo sea-level imprints on Bermuda

Town Hill Formation - MIS 11 (marine isotope stage 11). Beach-like deposits overlying a conglomerate in small Walsingham Fm caves at +21m ASL (above present sea level) in Government Quarry first documented by Land et al. (1967) were dated to ~400ka (Hearty et al. 1999, McMurtry et al., 2007). McMurtry et al. (2007) controversially attributed their deposition to a mega-tsunami, but the preponderance of evidence (Hearty and Olson, 2008; Olson and Hearty, 2009; van Hengstum et al., 2009) suggests that they do record a >+20m sustained RSL during MIS 11 at Bermuda.

Belmont Formation - MIS 7? A sea-level that reached elevations of +1m to +2.5m ASL during deposition of the Belmont Fm is widely acknowledged (Land et al, 1967, Harmon et al., 1983, Hearty and Kindler 1995, Hearty, 2002, Hearty et al., 2007). What has become contentious is the age of the Belmont Fm and the elevation at which the associated palaeo-RSL peaked. As noted below, the most recent published research on the topic (Hearty, 2002; Hearty et al., 2007) asserts that sea-level did not exceed its present level during MIS 7.

Land et al. (1967) identified phreatic water table cementation and a depositional "strandline" in the Belmont Fm of the south shore at +2m ASL. They believed that this recorded the penultimate interglaciation, i.e. MIS 7. Subsequently, Harmon et al. (1983) concurred that MIS 7 eustatic sea level peaked at ~+2 m ASL at about 200 ka. This conclusion was based on the discovery of an emergent marine deposit within dated cave flowstone layers and on the ages of four coral fragments from coastal deposits. They reported an older age of 262 +35 -27 ka for an *Oculina* coral fragment found at Grape Bay, but they questioned the accuracy of any U-series ages greater 220 ka and did not attribute the 262 ka age to the Belmont Fm or the penultimate interglacial. However, given the ~ 30 ka margin of error, this age could arguably be correlative with a marine transgression at an early sub-stage of MIS 7. Subsequently, Muhs et al. (2002) reported late MIS 7 ages of 199 ±2 and 201 ±2 ka for two *Oculina* fragments collected from sub-tidal Belmont Fm deposits, also, at Grape Bay.

There is no consensus in the literature as to how high RSL rose during deposition of the Belmont Fm. In the process of geological mapping (Vacher et al., 1989) there were new finds of "beach bubble" fenestrae in Belmont foreshore deposits at ~+7 m ASL at Watch Hill Park. Meischner et al. (1995) advanced an hypothesis of two Belmont marine transgressions peaking, respectively at + 1.5m and +≥7.5m ASL based on: 1) separation of two marine units by a vermetid-encrusted surface at Grape Bay; 2) measured elevations of sub-tidal bedding at Grape Bay; and 3) a "marine-eolian transition" at +7.5m ASL at Watch Hill Park. Subsequently, Vollbrecht and Meischner (1996) presented evidence of meteoric phreatic diagenesis and coeval marine cement in the Belmont at Watch Hill Park ranging up to ≥ +8m ASL (at the "beach bubble" locality). They, however, made no assertions with respect to the age of the Belmont Fm as their studies did not include dating.

Hearty and Kindler (1995) found no evidence of the +7.5m ASL Belmont sea-level, reported by Meischner et al. (1995) and Vollbrecht and Meischner (1996). They contended that, based on the interpretation of sedimentological features, combined with Harmon et al.'s (1983) ages and amino acid racemization (AAR) dating of mollusks and land snails (Hearty et al., 1992), Belmont sea-levels peaked at ~0m ASL at ~240ka to ~230 ka, and at +2.3m ASL at ~210 to ~180 ka (Figure 2.1).

Hearty (2002) revised his earlier acceptance of the MIS7 age for the Belmont Fm (Hearty et al., 1992; Hearty and Kindler, 1995) citing a failure: 1) to correct AAR data for the effect of prolonged interglacial warmth, and 2) to take account of potential re-working of corals with old ages (MIS 7) into younger (MIS 5e) deposits. Hearty (2002) now advocated that, consistent with the deep ocean oxygen isotope record (Shackleton and Opdyke, 1973; Bitanja et al. 2005), MIS 7 palaeo-RSLs at Bermuda did not exceed current levels and that emergent marine deposits of the Belmont Fm were, instead, associated with an early MIS 5e highstand. He reasoned, accordingly, that a revision of Bermuda's stratigraphy was in order, which entailed re-assignment of former Belmont Fm deposits, to a member of the Rocky Bay Fm (Table 2.1), which is correlated with MIS 5 (Harmon et al., 1983).

In Hearty's 2002 article entitled "Revision of the late Pleistocene stratigraphy of Bermuda" he observed that "Bermuda's pre-eminent status as a global sea-level "tide gauge" is compromised and paradoxical when global views of MIS 5e and 7 highstands are considered". His concern was that a MIS 7 positive excursion of sea level (to above present level), as had putatively been recorded on Bermuda by the Belmont Fm, was incompatible with evidence of much lower MIS 7 sea levels found elsewhere in the world. By re-interpreting the Belmont Fm as an early MIS 5e deposit (part of a proposed MIS 5e double peak) and merging it into the Rocky Bay Fm, he was able to resolve the "paradox". This was at the cost, however, of dispensing with a central feature of established Bermudian stratigraphy, namely the major allostratigraphic boundary, or solutional unconformity (Land et al., 1967), which separates the Belmont Fm and subsequent MIS 5 Rocky Bay Fm (Vacher et al., 1989). The palaeosol at this boundary, known as the Shore Hills geosol, has been characterised as a "well developed red palaeosol" (Land et al., 1967), or "terra rossa soil" (Bretz 1960) with associated "solution pipes" (Vacher, 1972; Herwitz and Muhs, 1995) and was considered, to represent a "long interval of sub-aerial erosion" (Sayles, 1931) equivalent to a full interglacial period. Hearty's 2002 revision of the stratigraphy (Table 2.1) necessitated compression of the time gap between the Belmont Fm and Rocky Bay Fm into the time span of MIS 5e i.e. from tens of thousands of years to thousands of years.

Rocky Bay Formation - MIS 5e. Ample robust age data has been compiled (Harmon et al., 1983; Hearty and Kindler, 1995; Muhs et al., 2002) to establish correlation of Bermuda's Rocky Bay Fm with MIS 5e (Table 2.1). Seventeen coral fragments collected from emergent Rocky Bay conglomerates yielded an average age of 120ka to 125ka (Harmon et al, 1983; Muhs et al., 2002). The provenance of the host conglomerates is uncertain but they most likely are the product of wave action in shallow shoreface waters. Estimates of a peak Rocky Bay sea level at +5m to +6m (Land et al, 1967, Meischner et al, 1995) seem well-reasoned. An upper constraint on 5e sea level of +6m ASL was adduced by Harmon et al. (1983) from uninterrupted sub-aerial growth of speleothems above +6m ASL over a period that spanned MIS 5e. A higher, but not inconsistent constraint is imposed by state of preservation of the sub-Rocky Bay palaeosol at Rocky Bay Fort and Hungry Bay. At elevations of less than +8m ASL the palaeosol

	Sayles (1931)	Bretz (1960)	Land et al. (1963)	Vacher (1972)	Harmon et al. (1983)	Vacher and Hearty (1989)	Hearty and Kindler (1995)	Hearty (2002)	Rowe et al. (2014)
MIS5a				**S** 80ka	**S** 85ka	**S** 80ka			
MIS5c			**Rb**					**Rb**	
MIS5e	**S**	**Rb**	**Rb** 120ka	**Rb** 130ka	**Rb** 125ka		**Rb** 118ka 133ka	**Rb** 120ka / **Bm** 128ka	**Rb**
MIS7	**Rb**				**Bm** 200ka		**Bm** 195ka 235ka		**Bm** 198ka
MIS9									
MIS11							**Tu** 400ka		
>MIS 11							**W** >700ka		

S – Southampton **Rb** – Rocky Bay **Bm** – Belmont **Tu** – Town Hill Upper **Tl** – Town Hill Lower **W** - Walsingham

Table 2.1. Interpretations of Bermuda's chronostratigraphy. This table presents the correlations that have been proposed between Bermuda's limestone formations and interglacial periods. Also shown are the average ages determined by U-series dating of corals collected from marine members of these formations. Formation names (after Vacher et al.1989) and Marine Isotope Stages that are quoted here were not in usage prior to the 1980s or were defined differently. However, it is known for example that the Pembroke Formation and Sangamon interglacial referred to by Sayles (1931) are equivalents of the Rocky Bay Formation and MIS 5e, respectively. In the case of Sayles (1931), who did not correlate dune building with interglacials, the MIS attributions shown here indicate which highstands preceded deposition of the Rocky Bay and Southampton formation dunes. As such, these were the highstands that generated the requisite sediment for Sayles' subsequent dune-building.

has been removed or displays the effects of intensive marine reworking but at ≥10 m ASL it is completely intact. The case for a double MIS5e sea-level peak, with one close to present sea-level and one at +5m or higher were argued by Bretz (1960) and Vacher (1972); while Hearty and Kindler (1995) and Hearty et al. (1998) cited evidence of 2 peaks above +5m ASL, with second one "surging" to at least +9m ASL. On the north shore, the height and timing of the MIS5e highstand(s) relative to construction of the large dune ridge on that shore (in the central parishes) has repercussions for the relative viability of transgressive versus regressive dune-building models (see Chapter 7).

Southampton Formation - MIS 5c and 5a. A +9m conglomerate at Spencer's Point once thought to represent MIS 5c deposition, upon re-examination (Harmon, 1983) was found to yield coral ages of such a wide age range that is now considered to be a MIS 5e deposit which includes material contributed by subsequent storms (Vacher and Hearty, 1989). MIS 5a, on the other hand, is convincingly represented at Fort St Catherine by a low elevation, rubbly rudite which displays planar swash zone stratification. 1 *Oculina* coral fragment dated by Harmon et al. (1983), 4 dated by Ludwig et al. (1996), and 17 dated by Muhs et al. (2002) from the Fort St. Catherine deposit, yielded ages that ranged from 85 to 77ka (Muhs et al, 2002). These ages fall in a sufficiently narrow range to rule out contamination by storm deposition as had been suggested by Harmon et al., 1983. Assertions of a -1m to +0.5m ASL sea-level during MIS 5a at Bermuda, therefore, appear to be well-founded. Nonetheless, the accumulation of this beach-like unit close to present sea level, indeed any evidence of a post MIS 5e/pre-late Holocene sea level advance that exceeded -15m, is contradicted by Harmon et al.'s (1983) finding that speleothems above this depth experienced uninterrupted growth during that period. This "unresolved contradiction" (Vacher and Rowe, 1997) can be reconciled perhaps by the occurrence of such a brief sea level rise that at the resolution of the Harmon et al. (1983) speleothem sub-sampling, it went undetected.

2.1.3. Interpretation of the relative sea-level history at Bermuda

The first attempts to accurately quantify palaeo-RSL (relative sea level) elevations at Bermuda were made by Land et al. (1967) on the basis of sedimentological or diagenetic evidence of wave action or submergence. A thorough all-encompassing study of Bermuda's palaeo-RSL record was undertaken by Harmon et al. (1983). The principal sources of data were the U-series ages of: 1). marine overgrowths or growth-interruptions within speleothems and 2). coral fragments found within emergent marine deposits. Geological mapping of the island which culminated with publication of the Geological Map of Bermuda (Vacher et al., 1989) identified dozens of previously undocumented exposures of emergent clastic marine deposits. These were concentrated within the Belmont and Rocky Bay Formations, which on the basis of allostratigraphic interpretation were considered representatives of highstands at the penultimate and last interglacial periods, respectively.

The putative tectonic stability of Bermuda is the basis for its past characterization as a palaeo-sea-level “tide gauge” (Land et al., 1967). As a consequence, Pleistocene emergent marine imprints on Bermuda have been accorded global glacio-eustatic significance (Harmon et al., 1978; Harmon et al. 1983; Land et al., 1967; Vacher, 1972; Hearty and Kindler, 1995; Hearty, 2002). However, the tectonic stability of the Bermuda seamount has been questioned in the past (Peckenham et al.,1981; Rowe, 1998; and Bowen, 2010). Furthermore, glacio-isostatic adjustment models indicate the potential for significant vertical movement of the edifice (Dutton and Lambeck, 2012) correlative with continental (North American) ice-sheet loading and un-loading. For these reasons it is no longer considered tenable to refer to changes in sea level at Bermuda, as measured against a datum on the land, other than in terms of relative movement.

Palaeo-RSL curves for Bermuda published by Harmon et al. (1983) and Hearty et al. (1995) are summarised in Figure 2.1. They differ from the global consensus of Pleistocene eustatic sea-level curves (Bintanja et al., 2005; Siddall et al., 2006; Rohling et al., 2009) in that the highstands at Bermuda are for the most part higher than, or at the top of the range of, measurements from elsewhere. This is as predicted by glacio-hydro isostatic models (Raymo and Mitrovica, 2012; Dutton and Lambeck, 2012). The exception is at MIS5e when RSL at Bermuda - an intermediate field site moderately affected by glacial isostatic adjustment (GIA) - is comparable to that at stable far field sites such as Australia (Murray-Wallace, 2002). According to Potter and Lambeck (2004) this discrepancy, at least in the case of the comparison between palaeo RSL at MIS 5e and that at MIS 5a, is a function of differing GIA responses at respective deglaciations, both in terms of amplitude and lag time. This includes the last deglaciation which is still having an isostatic effect on datums against which present and past RSL are measured. Bowen (2010) similarly noted that the GIA response would be affected by the period (wave-length) of climatic of fluctuations, such that long interglacials, for example MIS 11, would produce a more elevated palaeo-RSL imprint than shorter ones.

2.1.4. Assumptions of a tectonically stable Bermuda

Quaternary Bermuda has long been characterised as isostatically (Harmon et al., 1978) and tectonically stable (Vacher, 1972, Harmon et al., 1983, Meischner et al., 1995, Ludwig et al., 1996, Hearty, 2002, Dutton and Lambeck, 2012). Tectonic instability typically is equated to crustal deformation as occurs at tectonic plate boundaries. Land et al. (1967) pointed to` the apparent absence of deformation on Bermuda, such as faulting or tilting, as proof of stability. The majority of researchers spanning Sayles (1931) to Hearty et al. (2007) thus shared the conviction that the Pleistocene sea level imprint on Bermuda was overwhelmingly glacio-eustatically controlled.

Vacher and Rowe (1997) first presented a case for the potential confounding effect of glacio-hydro isostasy on sea-level studies at Bermuda. Muhs et al. (2002) noted apparent evidence of the phenomenon in the form of the anomalously elevated MIS 5a deposits at Fort St. Catherine.

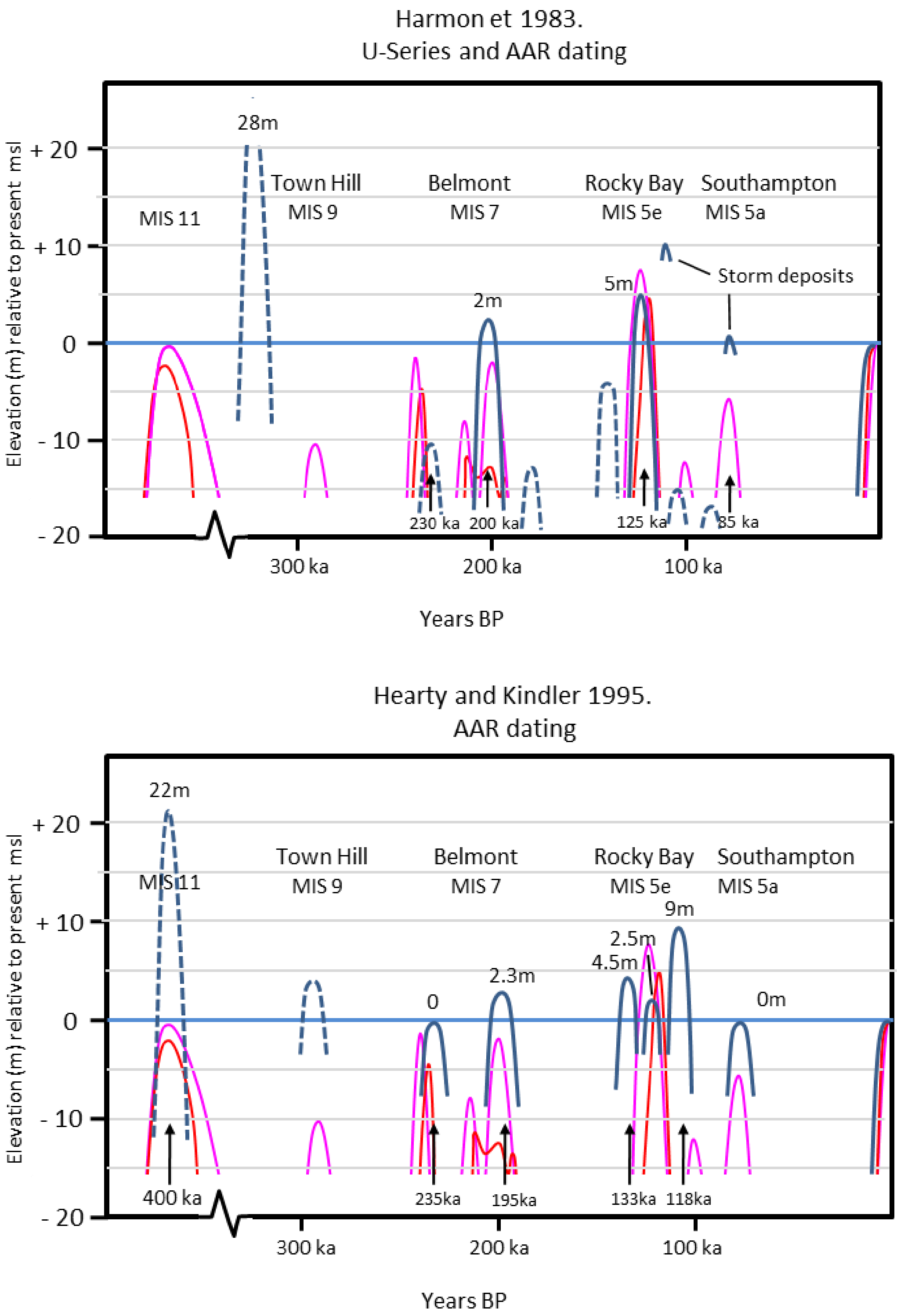


Figure 2.1. Mid to late Pleistocene highstands at Bermuda. The Bermuda sea-level curves (dark blue), reconstructed by Harmon et al. (1983) (top chart) and Hearty and Kindler (1995) (bottom chart), are compared to global eustatic sea-level curves summarised from Bintanja at al. (2005) (red) and Siddall et al. (2006) (purple). Note that other than at ~120ka (marine isotope stage 5e) relative sea-level estimates at Bermuda exceed the elevations that would be expected from a purely eustatic signal. Elevations and ages shown in black pertain to the average heights and ages of highstands at Bermuda attributed by the respective authors. Bermuda formation names and MIS stage numbers are shown.

Even though there has been increasing recognition of the potential for isostatic instability, the precept of "tectonic stability" has continued to be embraced (Dutton and Lambeck, 2012).

The assumption of tectonic stability at Bermuda was questioned by Peckenham et al. (1981), Rowe (1998) and Bowen (2010). Rectilinear fracturing noted by Hartsock et al. (1995) conforms to an orientation consistent with stress trajectories in the North American plate (Scheidegger,1976). Vogt and Jung, (2007) noted that ~30 million year old submarine pillow lavas found in cores at ~30m below present sea-level were at shallow depths where sub-aerial eruptives, or limestones, would typically be expected. This anomalous absence of subsidence of the Bermuda volcanic seamount, implies that the tendency to subside due to cooling and gravitational effects (Clague and Moore, 2006) has been offset by uplift. Furthermore, there is a high seismic activity within the Bermuda Rise (Zoback et al., 1986; Vogt and Jung, 2007) which remains unexplained.

Central to the question of Bermuda's stability, are 1). the inconsistencies between published palaeo-RSL curves reconstructed for Bermuda (e.g. Harmon et al., 1983; Hearty and Kindler, 1995) (Figure 2.1) and palaeo-RSL data from elsewhere and 2). the inconsistencies within the Bermuda palaeo-RSL record. For example, whereas the +4.5 to +6 m ASL early MIS 5e imprint at Bermuda (Harmon et al., 1983; Vollbrecht and Meischner, 1996; Vacher and Rowe, 1997) is comparable with that at the Bahamas and many other intermediate and far field sites (Muhs et al., 2002), the MIS 5a imprint at ~ +1m ASL on Bermuda (Vacher and Hearty, 1989; Muhs et al., 2002) contrasts markedly with that of -15m, or lower, at the Bahamas (Richards et al., 1994) and at most far-field localities (Chappell and Shackleton, 1986; Schellmann and Radtke, 2004). As discussed earlier, a potential explanation for this can be found in the contrasting GIA responses of the Bermuda edifice depending on the duration of interglacials. However, tectonic instability combined with GIA as suggested by Bowen (2010) is a viable if seldom invoked, alternative.

Mallorca is unusual in having a well-documented record of mid-late Pleistocene peak palaeo-RSLs which approximates to those at Bermuda. MIS 7, MIS 5e and MIS 5a sea-levels in the range of ~+1 to ~+5m ASL have been inferred from the ages and heights of phreatic overgrowths on speleothems in Mallorcan caves (Vesica et al., 2000; Dorale et al., 2010). Notably, Dorale et al. (2010) concluded that Mallorca, along with Bermuda, might be at respective pivot points between regions of glacio-isostatic emergence and submergence; and as a consequence, could have experienced sea levels which closely followed the eustatic curve. An alternative explanation is that unrelated sources of instability could have, coincidentally, produced similar relative sea-level curves at both localities.

The occurrence of faults on Bermuda has until now been poorly documented. Their existence and potential causes are discussed in Chapter 5.

2.1.5 The global sea-level record at MIS7.

The elevation of the MIS7 sea level imprint on Bermuda has become contentious. It is thus necessary to review the global consensus on MIS7 sea level(s). A compilation of early deep ocean oxygen isotope records by Porter (1989) (summarised from Shackleton and Pisias, 1985 and Martinson et al., 1987), indicates that ice sheet volumes were substantially reduced three times between 250 and 180 ka, at Marine Isotope Stage 7 (MIS 7), but not to modern levels. By this interpretation, and other interpretations of continuous data, such as that of Bintanja et al. (2005), there were three periods during MIS 7 when eustatic sea level approached the present level, but did not exceed it. Three peaks in global temperature during the time span of MIS 7 are, also, evident from the deuterium profile, measured in the Vostok ice core, which is considered a proxy for Antarctic temperature (Petit et al., 1999). A potential fourth MIS 7 positive sea level oscillation, at ~185 ka, was reported by Henderson et al. (2006) based on U-series dating of sedimentation events on the Bahamas Banks.

Evidence from speleothem growth-records from Argentarola Cave in Italy indicates that relative sea levels at sub-stages 7.5, 7.3 and 7.1 peaked above -18.5m; with the lowest peak, at about -18m at sub-stage 7.3 (Dutton et al., 2009). This general pattern was corroborated by oxygen isotope and other data, which are subject to bathymetric controls, from the Red Sea cores (Rohling et al., 2009). These indicated that sea level at MIS sub-stages 7.5 and 7.1 may have peaked as high as -10 m BSL (below present sea level) but that at MIS 7.3 fell well short. Muhs et al. (2002) provided a good summary of palaeo-RSL data inferred from emergent reef terraces at Barbados, New Guinea and Hawaii (far field sites). He noted that at least two MIS 7 mean sea level oscillations are inferred, which depending on the approach taken to correct for uplift, range from -20m to a few metres above present sea level. Another comprehensive review of MIS 7 global sea level data from a variety of sources including reefs, speleothems and oxygen isotopes led Siddall et al. (2006) to conclude that after correction for uplift or subsidence, as appropriate at respective localities, eustatic relative sea level at each of the MIS 7 sub stages ranged between ~ -15m and ~ -5m.

Higher MIS 7 sea-levels are evidenced in the Mediterranean at Mallorca where “brackish” speleothems record a +4.9 m ASL at 230 ka (Vesica et al., 2000); while at Sardinia, marine deposits dated by the optically stimulated luminescence method (OSL) at 186 ka have been associated with a +2.5 m ASL palaeo-RSL (Andreucci et al., 2009). Correspondingly, Murray-Wallace (2002) and Muhs et al. (2011) and Muhs et al. (2012) described coastal deposits and coral reefs of MIS 7 age, respectively, in southern Australia, southern Florida and the Antilles (Caribbean), which witness palaeo-RSL maxima in the range of +1 m to +4.5m ASL.

The data quoted above are from all parts of the world, not just those that are assumed to be in an equivalent tectonic setting to Bermuda. Nor was any consideration given as to whether they might have experienced comparable isostatic adjustment to Bermuda, attributable to its imputed position on the "peripheral bulge" of a major ice sheet complex (Raymo and Mitrovica, 2012). The data are intended to represent a cross-section of sources from which a wide range of MIS7 eustatic sea levels have been inferred, and with which the relative sea level record at Bermuda can be compared.

2.2. COASTAL DUNES

2.2.1. Eolianite - definition and global distribution.

While Sayles (1931) coined the term "eolianite" to classify the lithified wind-blown sands of Bermuda, it was Lieutenant Richard Nelson (1837) who first called attention to the eolian character of the limestones. Thomson (1873) succinctly depicted the islands as "a bank of blown sand in various stages of consolidation", and "the excellent exposures of the eolian strata" were noted by Agassiz (1895). Much later Vacher et al. (1995) described Bermuda as the "type locality of the carbonate eolianite facies"; while Brooke (2001) considered that the detailed research undertaken into Bermuda's stratigraphy has made it possible to develop important new theories of eolianite evolution.

The meaning of the term "eolianite" has evolved from lithified wind-blown sand (Sayles, 1931) to eolian dunes cemented by calcium carbonate (Gardner, 1983) of Quaternary age (Fairbridge and Johnson, 1978). Some of the best documented continental occurrences of eolianite are known from south and west Australia (Bird, 2007; Short et al, 1986), Brazil (Hesp et al., 2005), South Africa (Bateman et al., 2004) and Israel (Yaalon and Laronne, 1971; Tsoar, 2000); while small island versions analogous to those of Bermuda are found in the Bahamas (Carew and Mylroie, 1995; Caputo, 1995), Lord Howe Island (Woodroffe, 2002) Kangaroo Island, Australia (Milnes et al.,1983) and Rottnest Island, Australia (Playford, 1997). Many other examples have been catalogued by Vacher and Quinn (1997) and by Brooke (2001).

Brooke (2001) identified key criteria for the accumulation and preservation of eolianites as: shallow warm seas with high biogenic carbonate productivity coupled with low terrigenous input; onshore-directed trade winds; and a seasonal water-budget deficit. He attributed an apparent dominance of Quaternary eolianites, over more ancient versions, in the geological record to: 1). difficulties in identifying ancient dune deposits once they have been buried and incorporated into a geological succession; and 2). increased global aridity in the Quaternary, which curtailed fluvial input of terrigenous sediment to many shelf seas. Brooke (2001), additionally, cited the importance of the cyclical movement of Quaternary sea levels to the creation of biologically productive shallow seas during interglacials and to the exposure of "highstand offshore sediment sinks" to reworking, in the littoral zone, when sea levels were in transition. Brooke (2001) did not conclude that eolianite accumulation was predominantly correlative with a particular state of Quaternary sea level - be it high, low, rising or falling. However, Mauz et al. (2013), following a review of published eolianite research at 20 localities around the world, presented data showing that the majority of coastal dune activity was contemporaneous with a peaking or falling relative sea-level.

2.2.2. Classification of coastal dunes – foredunes, transgressive dunes and advancing dunes.

Foredunes develop as the most seaward shore-parallel aeolian dune ridge, which exchanges sediment with the beach (Carter and Wilson, 1993). They typically are fixed in position by vegetation to varying degrees (Hesp,1988), and grow predominantly by vertical accretion (Goldsmith, 1973). Foredunes which develop on shores where there is a positive sediment budget tend to form a series of prograding ridges (Cooper, 1958; Hesp, 2005; Bristow and Pucillo, 2006). Where sea level is rising, however, and/or the sediment budget is negative, but not sufficiently so to destroy the foredunes (including barrier dunes), they can maintain their size, or grow, while retreating landward by a process of sand transfer known as "rollover" (Psuty, 1990). These dunes have been termed "primary transgressive barriers" (Short et al. 1986); while other forms of mobile frontal dunes have been termed "transgressive frontal ridges" (Bird, 2007). However, the consensus is that position and shore-parallelism (Hesp and Thom, 1990; Tsoar, 2000) take precedence over process, and with few exceptions the foremost coastal dune ridge is considered to qualify as a foredune ridge.

The foredune is the only distinctive coastal dune (Bauer and Sherman, 1999). "Unlike desert dunes which advance horizontally …. (foredunes) generally grow upward in place" (Goldsmith, 1989). Unstable mobile coastal dunes which are fed directly from the beach or from degraded foredunes have been termed "transgressive dunes" (Gardner, 1955; Short et al. 1986; Hesp and Thom, 1990; Pye and Tsoar, 1990; Rust and Illenberger, 1996; Helleema, 1998, Tsoar, 2000; Woodroffe, 2002; Lees, 2006; Bird, 2007; Andreucci et al., 2010; Hesp and Walker, 2013, Hesp, 2013). This is because over time their locus of deposition moves progressively landward away from the source-beach. Transverse ridges, barchans, parabolic dunes and precipitation ridges are considered sub-sets of transgressive dunes in a coastal setting (Hesp and Thom, 1990). In contrast to foredunes which exchange sediment with the beach, transgressive dunes are defined by their ability to migrate or expand off the beach onto elevated and vegetated terrain. Mobility is achieved through the lateral transfer of sand from the windward stoss slope of a dune onto its leeward slope. When a dune has grown so high that all of the sand transported across its surface is trapped on the leeward slope, an advancing slip face develops which has a "profound effect" on the behavior of the dune (Bagnold, 1954). This change is reflected in the structural distinction between mobile transgressive coastal dunes and retentive foredunes. The former comprise a high proportion of slip-face strata when compared with retentive dunes, in which low-angle strata dominate (Yaalon and Laronne, 1971). However, use of the term transgressive to describe mobile coastal dunes conflicts with the prevailing definition of "transgressive" deposits as those which accumulated during a rising (transgressive) RSL. The potential for contradiction arises, for example, where transgressive coastal dunes are associated with a falling RSL. Therefore, it is advisable that the term “advancing dune” as proposed by Mauz et al. (2013) be adopted as a substitute for transgressive dune. For the purposes of this thesis, the term “transgressive” shall refer to shallow marine and coastal sediments which have accumulated in response to a rising RSL.

Advancing, or secondary, coastal dunes encroach landward beyond the position of the foredune onto a prior terrain of forest, swamp, marsh, scrub or even into shallow waters (Hesp and Thom, 1990). Advancing dunes are nourished by sand either directly off the beach (Tsoar, 1998, Hesp, 2013); from the degraded remnants of destabilized foredunes (Short and Hesp, 1982; Psuty, 2004); or from a substratum of loose sand (Cooper, 1958). They advance by accretion of sand on the leeside slip-face. They may take the form of transverse dune-fields fronted by precipitation ridges or, when partially stabilised by vegetation, may develop into parabolic dunes (Short et al, 1986; Havholm et al., 2004). Over time advancing dunes can adopt many of the bedforms associated with desert dunes (Hesp, 2013). In coastal regions of extreme aridity dunes migrating across a hard substratum can even take on a barchanoid form (Inmal et al., 1966; Pye and Tsoar, 1990).

2.2.3. The morphodynamics of Bermuda’s Pleistocene dunes.

Formation of the Bermuda islands is commonly attributed, in the literature, to lateral accretion of successive aeolian dune ridges in a seaward direction. Bretz (1960) proposed that Bermuda’s Pleistocene dunes were retentive structures, fixed in position on the proximal backshore. “They did not wander inland” and they were “tied closely to …. the beach” (Bretz, 1960). They advanced laterally only in so far as accretion by the addition of new sand permitted or, in the words of Vacher (1972), “they did not migrate but advanced inland through leeside accretion and upward growth”. Vacher (1972) characterised Bermudian dunes as coalesced accretionary mounds which nucleated on incipient foredunes and which grew upwards and landward as additional sand was delivered from the shoreline. He described their growth by conformable draping and concluded that “They did not advance by reworking of sand in the entire dune body”. It was Bretz’s (1960) contention that this behaviour was consistent with prompt fixation attributable not to vegetation but to incipient cementation by infiltrating rain water. This opinion was endorsed, in reference to Bermuda, by Hearty (2002) in noting “a predisposition (of coastal carbonate dunes) for rapid cementation”.

Mackenzie’s (1964) portrayal of Bermuda dune foresets either transitioning out of or being truncated by windward strata was re-affirmed by Vacher (1972) who described typical Bermudian eolianites as comprising two sedimentary units: a low angle windward topset wedge and a high angle leeward foreset wedge. In the windward parts “the two are superposed (former over latter) with the contact a pronounced seaward dipping sedimentary structural unconformity”. At the leeward extremity he observed that “the two units are intergradational in a “drape-over” or “roll-over” structure in which the beds of the upper wedge merge with the foresets”. In fact, the case made for incipient cementation of Bermuda’s dunes by Bretz (1960) and most that followed (Land et al., 1967; Mackenzie, 1964; Vacher, 1972; Hearty et al., 2002) is contradicted by the presence of the laterally extensive sub-horizontal bounding surfaces or “unconformities” (Vacher, 1972) which invoke reactivation of unconsolidated sand.

Vacher (1972) differentiated between Bermuda’s Pleistocene eolianites and the migratory transverse ridges of Oregon described by Cooper (1958). Features of Bermuda’s dunes which he considered distinctive are the great height and volume of individual dune ridges, the over-steepened foresets and the drape-over structures. A further distinction he made was that Bermudian dunes are characterised by convex-outward slip-faces whereas migratory transverse ridges “tend to be barchanoid”. Citing Bigarella et al. (1969), Vacher (1972) likened Bermudian dunes to certain Brazilian coastal dunes, which he depicted as “a stationary ridge against a vegetation line”, comparable to the large “precipitation ridges” of the forested Oregon coast documented by Cooper (1958).

In point of fact, Cooper’s (1958) precipitation ridges of Oregon are demonstrably advancing-dune forms, which slowly but surely have migrated into, and buried, large tracts of forested terrain (Figure 2.2). The notion that a forested hinterland somehow presents a barrier to dune encroachment is, further, challenged by the observations of Hesp and Thom (1990), who noted that while the height of dune ridges may be increased and their rate of migration slowed, they can continue to advance through a tree-line without any apparent change in their general morphology.

The claim by Vacher (1972) that unlike Bermuda’s dune ridges, “migratory transverse ridges tend to be barchanoid” is incorrect. Barchanoid ridges are specialised forms characteristic of a very low sediment supply, a hard substratum and an absence of vegetation, as observed on the arid coastal plains of Baja, Mexico (Inmal et al, 1966). Advancing transverse ridges and precipitation ridges are typically sinuous and can have convex crests and multiple lobate projections (Cooper, 1958). In short, many of the parallels drawn, by Vacher and Mackenzie, between Bermuda’s dunes and precipitation ridges, defeat the case they attempt to make for rapid stabilisation of the former.

Based on prevailing characterisations of Bermuda’s dune ridges as retentive structures, an architecture similar to that of San Salvadoran (Bahamas) dunes described by White and Curran (1988) and Caputo (1995) might be anticipated. These smaller, distinctly mound-like dune-forms have slip-face dip azimuths which arc through 180 degrees. Their topography reflects their bedforms, the partial preservation of which is characteristic of limited mobility (Figure 2.3.a). The slip-face foresets of Bermudian dunes, on the other hand, are invariably truncated (Figure 2.3.b), which attests to instability and sand recycling from within the bedform. Dip azimuths are directed predominantly onshore, with an average standard deviation for individual dunes of no more than 20 degrees according to Mackenzie (1964). Mackenzie viewed this as evidence that a large proportion of Bermudian dunes formed sinuous transverse ridges.

2.2.4. Models of beach-dune systems.

The morphodynamics of sandy coastlines react to the balance between sediment input, loss and storage which constitute the sediment budget for a beach system (Terwindt et al, 1984). Input and loss are outcomes of onshore/offshore and longshore sediment transfer by wind, waves or currents. The beach type (e.g. strandplain or barrier) and profile (e.g. reflective or dissipative) are controlled by autogenic factors such as wave exposure, tidal range, seabed profile, particle size and sediment budget as well as by the allogenic movement of RSL (relative sea level) (Reading and Collinson, 1996; Woodroffe, 2002). The sediment budget is the principal determinant of whether beaches are transgressive (retrogradational) or regressive (progradational). It also affects the development, morphology and stability of coastal eolian dunes (Carter and Wilson, 1993; Hellemaa, 1998; Psuty, 2004) which during storms present a physical barrier against coastal flooding and mitigate coastal erosion through the release of stored sand to the beach.

Many modern beaches owe their existence to former Holocene progradation which has, in turn, been attributed to mobilization of relict Pleistocene shelf/platform sands (Terwindt et al., 1994; Short et al., 1986). However, to the detriment of many coastal communities, the majority of the world's beach-dune systems are now experiencing erosion and retreat concomitant with exhaustion of these sediments (Dixon and Pilkey, 1991; Bird, 2007). This sediment-budget deficit coupled with continued rising RSLs accounts for late-Holocene/modern formation of unstable advancing dunes in Australia (Short et al., 1986) and transgressive barrier-beach systems on the east coast of the Unites States (Hesp, 2005).

Compilations of coastal dune construction models developed in many parts of the world, including the eastern and western coasts of the U.S.A. (notably Oregon), by Pye and Tsoar (1990), Brooke (2001) and Lees (2006) all prominently feature those which have been conceived in Bermuda. The four models presented by Pye and Tsoar (1990) included the Bretz (1960) highstand model and the Sayles (1931) regressive/lowstand model from Bermuda. Brooke (2001), who discussed the Bermuda models in the context of the impact of sea-level change on global eolianite accumulation, placed more credence in the later Bretz (1960) and Vacher et al. (1995) models than Sayles's (1931) model. Lees (2006), on the other hand, included Sayles' (1931) contribution as one of five viable coastal dune-building models that have been developed globally.

2.2.5. Timing of Quaternary coastal dune-building around the world

Glacio-eustatic changes in sea-level during the Pleistocene and Holocene epochs have been of exceptionally high magnitude and frequency (Siddall et al., 2007) and have a significant if not dominant impact on coastal morphodynamics. There is a consensus that RSL change is a primary control on the timing of coastal dunefield construction (Brooke 2001). Versions of this relationship from around the world are briefly reviewed in this section.

Figure 2.2. Advancing dune field fronted by a precipitation ridge. Oregon coat U.S.A. (photographed by Charlie Bristow)

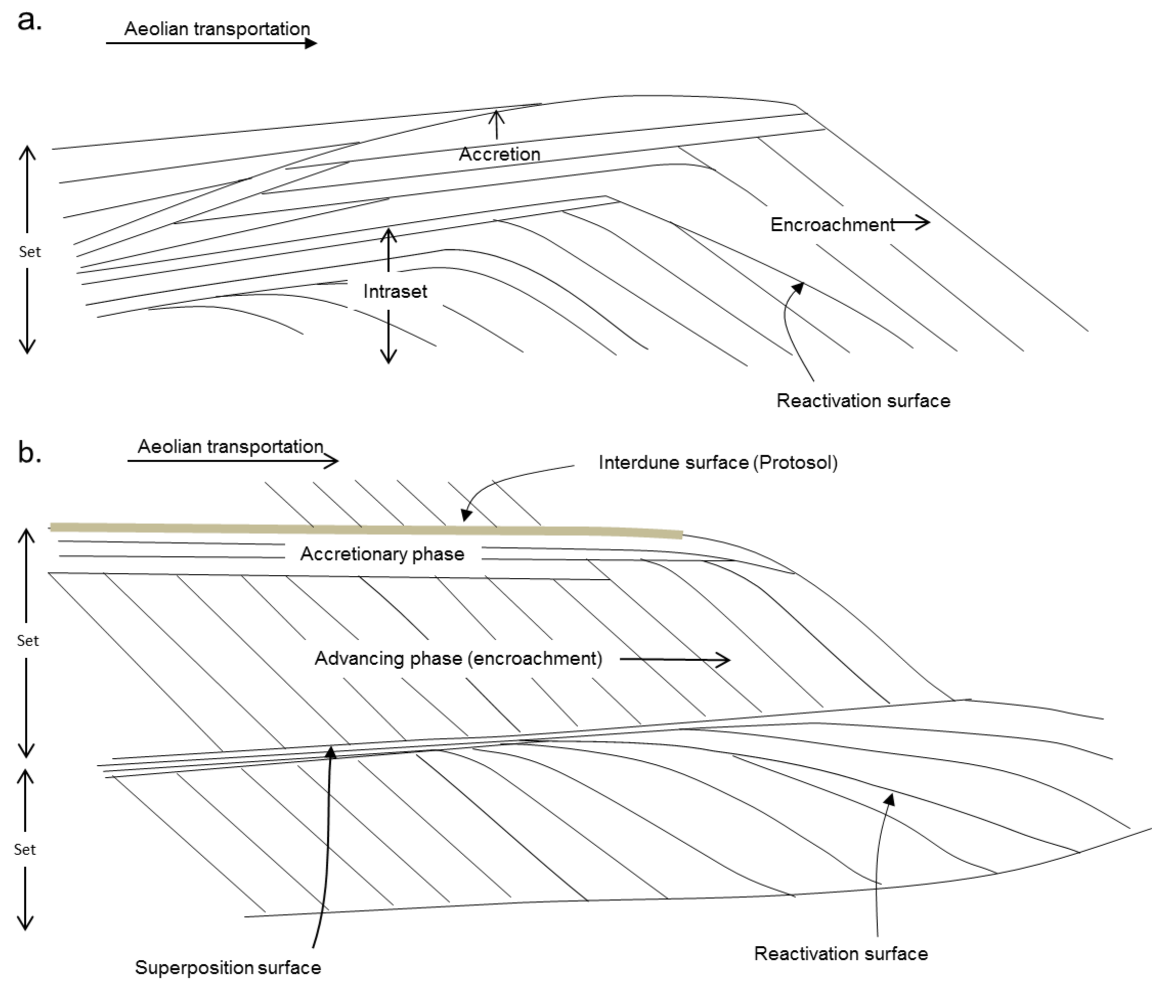


Figure 2.3. A retentive coastal dune structure compared to that of an advancing dune. **a.** A mound shaped dune as seen in San Salvador (Bahamas) showing preservation of a largely stabilised bedform (adapted from Caputo, 1995). **b.** Mobile advancing dunes as seen in Bermuda (Gunpowder Tavern, St George's) showing truncation of foresets at low angle bounding surfaces. Heights of dunes are ~10m.

Dune building during a rising RSL (relative sea-level). Based partly on his observations on the Oregon coast Cooper (1958) noted that "an advancing sea is ordinarily a powerful stimulant to dune activity". Likewise Short et al. (1986) argued that when a rising RSL floods onto a shelf, a "high energy window" is created which generates a landward flux of sediments and associated dune-building, through shoreface erosion. Pye and Tsoar (1990) concluded, on the other hand, that it is the destruction of foredunes by a marine transgression on exposed coastlines that releases large volumes of sand for wind transportation and the formation of advancing dunes (Figure 2.4). The last scenario was termed the "Cooper-Thom" model of transgressive coastal dune development by Lees (2006).

In eastern Australia (Pye and Bowman, 1984) and in southern Australia (Short et al., 1986) advancing dunes with ages of 10 to 6 ka attest to dune activity during the Holocene transgression which acted as a "forcing function" according to Pye and Bowman (1984). Similar ages and an association with rising RSL were also attributed by Hesp (2005) and Bird (2007) to dunes of eastern USA and Cornwall (UK), respectively. In the Bahamas Carew and Mylroie (1995) depicted the "bulldozing" of sediments into high dune ridges as Holocene seas flooded the platform at a rate which temporarily outpaced reef growth, thus creating high energy "open" conditions. Equally in Denmark it was the exposure of nearshore sediments to increased wave energy concomitant with a rapid rise in RSL at the end of the Little Ice Age that was considered responsible for the activation of coastal dunefields (Aagaard et al., 2007).

Dune building at a peaking RSL. Following a comprehensive review of published carbonate coastal dune research from around the world Mauz et al. (2013) concluded that at approximately half of the 20 localities dunes were deposited as a "highstand systems tract" i.e. at a peaking RSL. In South Australia preserved Pleistocene highstand dune ridges of the Robe ranges have been documented by Huntley et al. (1993) and Murray-Wallace (2002). In New Zealand (Hesp and Thom, 1990) and in California (Orme, 1990), barrier-dune systems developed as the late Holocene rise in RSL slowed. At the same time in the Netherlands, and locally in Australia, late Holocene seaward progradation of such barriers was noted by Woodroffe (2002). Even though on the eastern and Gulf coast of the USA late Holocene barrier-dune systems have largely gone into retreat and have suffered foredune degradation (Hesp, 2005) due to exhaustion of the sediment supply, where barrier systems experience only a slight sediment budget deficit, foredunes such as those of Perdido Key, Florida have been able to retain their mass or even grow contemporaneously with shoreline retreat (Psuty, 1993 and 2004).

On tropical platforms, such as the Bahamas, reduced energy "closed" conditions prevailed in the late Holocene due to reef-growth "catch-up" (Kindler, 1995) causing dune building to falter. Bird (2007) noted that reefs which have caught up with sea-level not only filter wave energy but

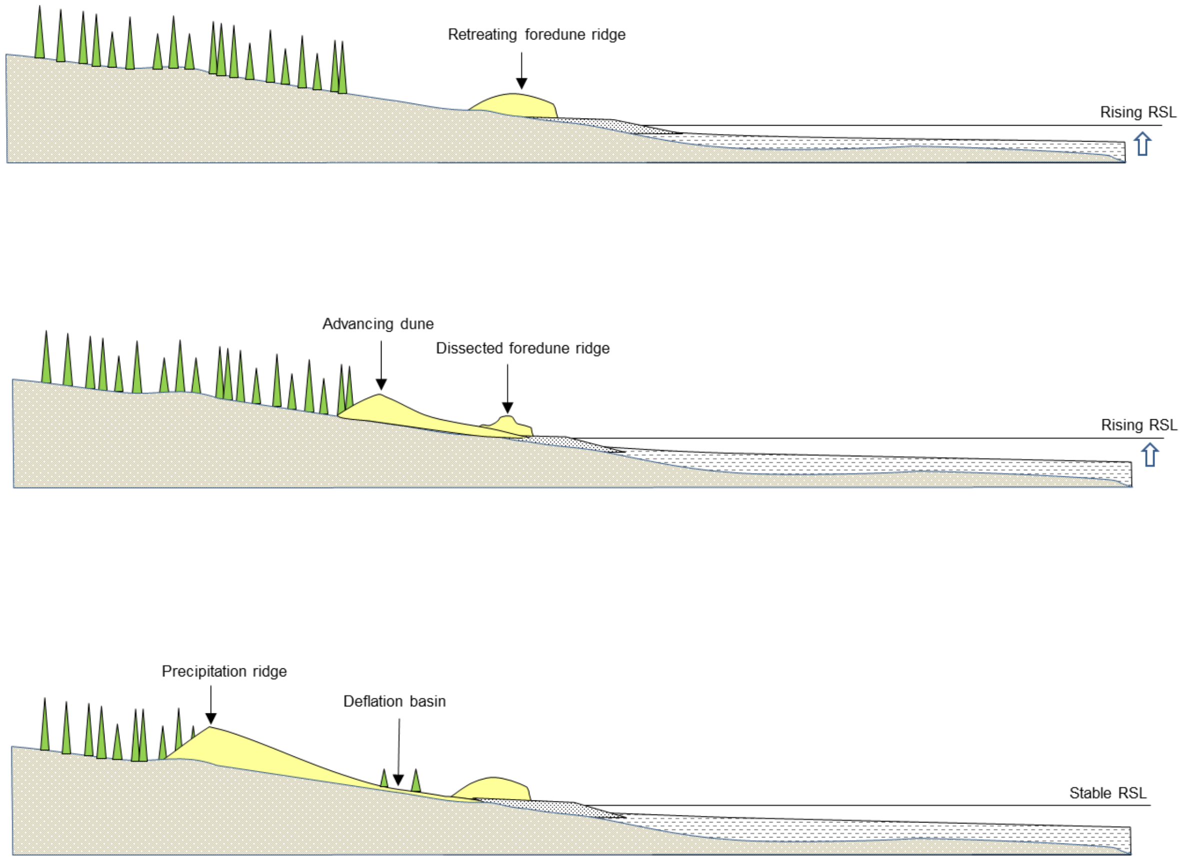


Figure 2.4. Dune-building during a rising relative sea-level. Littoral processes during a rising relative sea-level caused by release of sand from a wave-destabilised foredune ridge. Gaps in the ridge are opened into widening blowout troughs through which sand is fed to landward advancing dunes. These coalesce into a dune-field with a transverse leeward slip face which aggrades into a precipitation ridge as it encroaches into forested terrain. A reduction in sediment supply as the foredune ridge becomes re-established, due to a change in climate or slowing rate of relative sea-level rise, starves the still advancing dune-field of new sediment. This causes stoss slope erosion and the creation of a deflation basin which ultimately becomes forested. (based on Cooper, 1958).

can present a physical barrier to landward transport of nearshore sands. On the other hand in higher latitudes, in the absence of such biogenic reefs, deepened shelf-waters can enhance nearshore wave energy. This occurred during the Holocene on the shores of Lake Huron where, as the relative lake water-level peaked, glacial sediments were driven shoreward onto beaches and thence into a transverse dune ridge which advanced ahead of a transgressive beach (Davidson-Arnott and Pyskir, 1988).

Dune building during a falling RSL. At many localities around the world prograding shorelines with multiple stabilized foredune ridges are associated with falling RSLs such as Washington State, USA (Cooper, 1958), southern Brazil (Hesp et al., 2005) and southeastern Australia (Bristow and Pucillo, 2006). However, as discovered in the case of the late-Holocene deposits in north-west Ireland (Carter and Wilson, 1993), lowering of the wave base during a falling RSL can create a shoreward flux of shelf sediments sufficient to overwhelm the retentive capacity of vegetation and thus generate unstable advancing dunes (Figure 2.5).

In eastern Australia episodes of dune activity were associated with the regressive phase of Holocene RSL fluctuations (Lees, 2006). Similarly Orford et al. (2000) attributed a “once-off” phase of dune building on the Northumberland coast in the UK to sub-aerial exposure of inter-tidal sediment at the onset of the “Little Ice Age”. The chronostratigraphy of coastal dunes in Western Australia (Fairbridge, 1995; and Price et al., 2001) and South Africa (Bateman et al., 2004) demonstrate maximum depositional activity in post interglacial periods as RSLs started to fall. Optically stimulated luminescence dating of dunes on the eastern Mediterranean coast undertaken by Mauz et al. (2013) indicates that episodes of dune ridge development were associated with successive late Quaternary falling sea level stages.

Island dune activity has been correlated with falling RSL at Lord Howe (Woodroffe, 2002) and Molokai (Fletcher et al., 1999) in the Pacific, and at San Salvador in the Bahamas (Carew and Mylroie, 1995). The timing of such activity in tropical regions has been linked to high sediment production as newly emergent coral reefs succumbed to exposure and were rapidly broken down by biological and mechanical erosion. Emergence of these sediments on widening beaches, as RSL fell, created conditions conducive to eolian transportation.

Dune building during a low RSL. “Low sea-level”, for the purpose of this discussion, are considered those at which shelf or platform sediments become emergent. Certainly the Quaternary eolian deposits identified at 140 m below present sea-level in south-eastern Australia (Bird, 2007) are an indication of dune activity at a time of shelf exposure. The carbonate dunes of Western Australia have also been related to low RSLs by Fairbridge (1995) and on the basis of ~40 ka ages from thermo-luminescence dating have been correlated with the Last Glacial period (Kendrick et al., 1991). Similar ages have been attributed to expansive

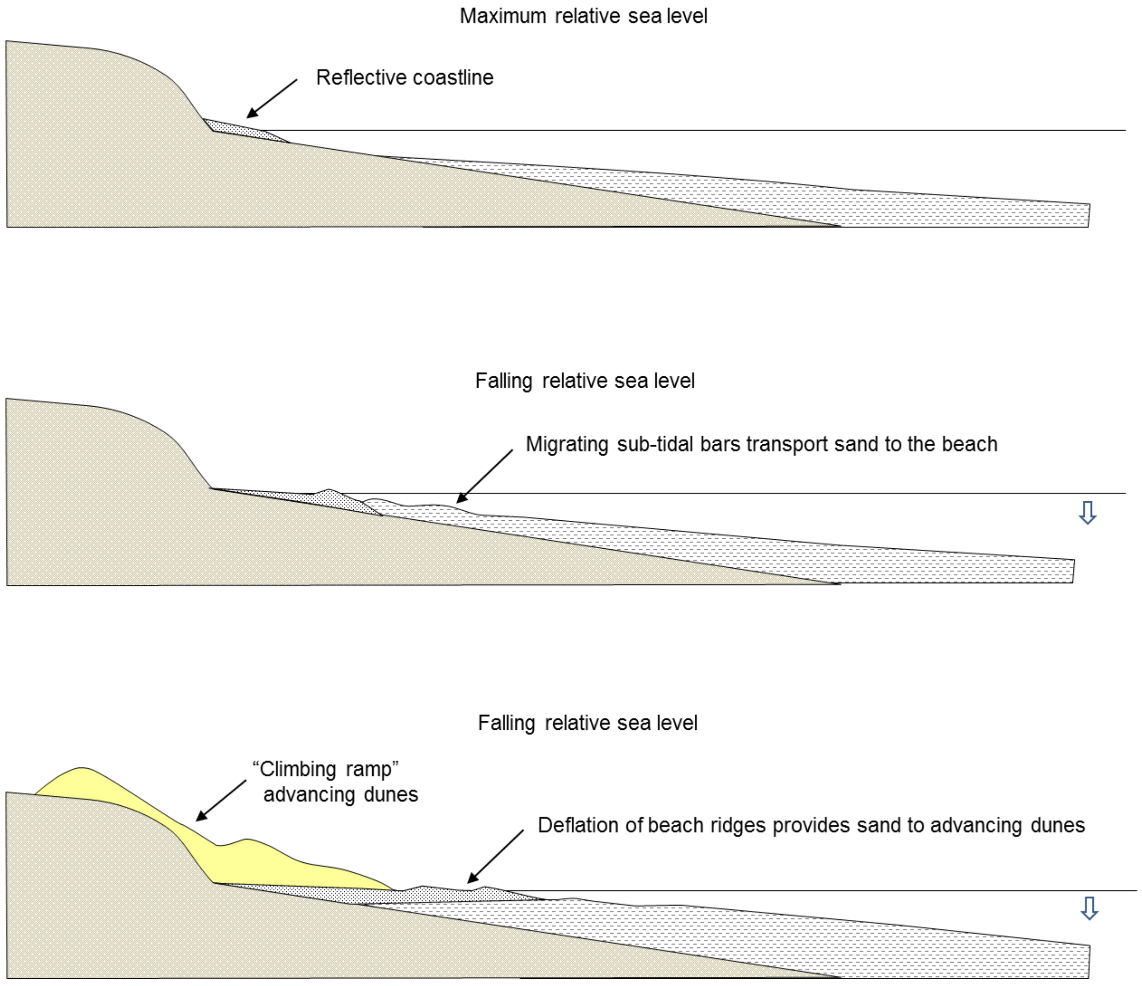


Figure 2.5. Dune-building during a falling relative sea-level. Littoral processes following a sea-level maximum which resulted in dune-building on the north-west coast of Ireland (Carter and Wilson, 1993). A falling relative sea-level lowered the wave-base onto platform sediments which were driven shoreward onto expanding beaches. Deflation of emergent beach ridges supplied wind-blown sand to advancing dunes at a rate which overwhelmed the retentive capacity of vegetation.

dune-fields which were deposited in Sardinia when sea levels were tens of metres below the present level and copious volumes of marine sediment were sub-aerially exposed (Andreucci et al., 2010). Likewise the accumulation of eolianites on Hawaii (Muhs et al., 1993) and the Californian Channel Islands (Muhs, 1992) were attributed to eolian reworking of exposed shelf deposits at times of low sea-level between 80 and 14 ka. Other examples from the Mediterranean (cited by Brooke 2001) occur in late Quaternary successions in which eolian deposits, dating from glacial periods, overlie emergent marine deposits separated by a well-developed palaeosol.

Dune building during an oscillating RSL. Dune activity reported to be associated with secondary sea-level (sub-MIS stage) oscillations tend to be coincident with the temporary reversal of a rising or falling trend or a "saw tooth" sea-level curve. Lees (2006), for example, working in eastern Australia postulated that it is the reversal or interruption of a trend that is the "marine trigger" required to cause "shoreline disturbance", noting that at Cooloola "dune formation events seem to correlate with interruptions of a trend of marine recession and of sea-level rise respectively" and that this correlation with interruptions seems to be a "repeating pattern". Bateman et al. (2004) concluded that dune activity on the South African Cape coast coincided with "post-interglacial periods when sea levels were fluctuating". Hesp (2005) speculated that it is the nature of oscillations and the rate of the rise or fall of sea level that may be important factors in dune initiation and behavior. Working on the Oregon coastline (USA), Cooper (1958) surmised that major dune advances were caused by interruptions of a rising RSL or minor reversals. He concluded that pulses of advancing-dune activity were recorded by successive precipitation ridges, each responding to a "trigger action" in the form of periods of renewed eustatic sea-level rise. Bird (2007) attributed the "shorewards sweeping" of sediment, required for Holocene dune building in Cornwall (UK), to minor oscillations of sea level.

2.2.6. Timing of dune-building on Bermuda in relation to changing RSL.

Sayles (1931) attributed the initiation of dune building on Bermuda to harsh climatic conditions and falling RSL at the onset of a glacial period. He correlated maximum dune activity with a sea level that had been lowered 10 to 20 metres or more from its current position, thus exposing the seabed on the Bermuda platform. This is inferred from his depiction of "great flats covered by marine shells exposed to the air" which were caused "to pile up as dunes". Although Sayles (1931) implied that dune activity persisted after sea-level dropped below the platform edge at glacial lowstands, he recognized that such activity was dependent on prior platform flooding and concomitant generation of bioclastic carbonate sediment.

Bretz (1960), in rejecting Sayles' (1931) model, interpreted facies assemblages in Bermuda's north shore exposures, such as Blackwatch Pass, as representing the transgression of beach-like marine deposits onto a dune as RSL peaked. This putative intimate spatial relationship between beach and dune corresponded with his conviction that Bermuda's dunes - acting effectively as foredunes - were fixed by incipient cementation at their point of origin on the beach-backshore. Elsewhere Bretz (1960) found evidence of a second phase of more expansive dune building which he attributed to a re-advance of sea-level after its first peak. The presence of a protosol, which intervenes between the marine deposits and these later larger dunes, was explained by Bretz (1960) as coincident with the marine regression which preceded a "minor re-advance of the ….receding strandline". In other words the protosol and later dunes were correlative with a high order sea-level oscillation superimposed on a higher order marine regression, the protosol being a record of sea-level retreat and the dunes of sea-level re-advance. Thus, as did Cooper (1958) with respect to Oregon dunes, Bretz (1960) stressed the importance of a rising RSL to "agitate" Bermuda's coastal deposits and "keep the sand loose" for eolian transportation. The dune-building model which he espoused was, therefore, essentially transgressive (i.e. associated with a marine transgression).

Vacher (1972) reasoned that maximum dune building on Bermuda's high energy south shore coincided with the progressive development of a biologically-generated, autogenic, sediment budget surplus in the late stages of an interglacial highstand. This, according to Vacher (1972), is evidenced by lateral and vertical gradation of emerged Pleistocene beaches into eolianites. On Bermuda's north shore, which is separated from the open ocean by 12 km of shallow waters (≤20 m depth) of the North Lagoon, Vacher (1972) proposed quite a different scenario. He contended that dune activity was associated with a rapid rise in RSL which outpaced reef growth, similar to circumstances described in the Bahamas by Carew and Mylroie (1995). The increase in water depth compromised the wave-filtering capacity of the reefs, which formerly had dampened sediment mobility. Large waves traversing the drowned reefs were able to shift sediment landward along the lagoon floor creating wide beaches and large frontal dunes on Bermuda's north shore. Thus Vacher (1972), while advocating an autogenic sediment-supply model for the south shore, favoured a transgressive model equivalent to that developed by Bretz (1960) for the north shore.

The Rocky Bay Fm succession in Blackwatch Pass was interpreted by Bretz (1960) and Land et al. (1967) as eolian dunes eroded at the prominent bounding surface (PBS) by a rising sea level which deposited beach strata against the PBS. Hearty et al. (1998) argued that the PBS and overlying strata were produced by storm-wave run-up at a late MIS 5e sea level surge. Bretz (1960), Land et al (1967) and Hearty et al. (1998) all contended that at least two sea level oscillations were responsible for development of the Rocky Bay Fm stratigraphy during MIS 5e. The putative marine deposits at Blackwatch Pass were attributed by Bretz to an early low-order highstand and by Land et al. (1967) and Hearty et al. (1998) to a late low-order highstand. Vacher et al. (1995) were the first to argue that all strata on the north shore extending upwards of 1 to 2 m ASL are aeolian. This interpretation was supported by Kindler and Strasser (2000) who attributed pinstripe lamination within these deposits to inverse sorting by eolian translatent climbing ripples which typically form on dune stoss-slopes. However, Hearty et al. (2002)

defended Hearty et al.’s (1998) assertion that the sedimentological characteristics were consistent with marine deposition.

Regardless of variations in the interpretation of the exact timing and nature of the events on Bermuda’s north shore during deposition of the Rocky Bay Fm, it has been a unanimously held position, from Bretz (1960) onwards, that the transition between marine and aeolian deposits, at low or high elevation, attests to transgressive dune-building.

3. BELMONT FORMATION FACIES AND SEA-LEVEL INDICATORS

3.1. THE STATUS OF PALAEO-SEA-LEVEL RESEARCH AT BERMUDA

There is general agreement among those who have studied Bermuda's emergent Pleistocene coastal marine deposits within the last 20 years on the approximate timing and amplitude of the major interglacial highstands at Bermuda, other than at the penultimate interglacial period, or MIS7 (marine isotope stage 7). The consensus has been that palaeo-RSLs (relative sea-levels) exceeded present mean sea-level at Bermuda during MIS 11, MIS 5e and MIS 5a. Similarly in the case of MIS 7, RSL at Bermuda was considered by many researchers to have exceeded the present level. Extensive emergent beach deposits of the Belmont Fm were interpreted as a record of a MIS 7 highstand (Land et al., 1967; Vacher, 1972; Harmon et al., 1983; Hearty and Kindler, 1995; Vacher and Rowe, 1997). This position was however challenged by Hearty (2002) and Hearty et al. (2007), who asserted instead that the Belmont deposits were the outcome of a MIS5e highstand and that MIS 7 RSLs did not leave an imprint because they peaked below present mean sea-level. These contentions have not only compromised subsequent attempts to resolve eustatic vs non-eustatic components of the RSL signal at Bermuda, which has been accorded global significance (Potter and Lambeck, 2004; Bowen, 2010; Dutton and Lambeck, 2012; Raymo and Mitrovica, 2012) but also raised questions about a key component of Bermuda's stratigraphy.

Combining facies analyses with accurate elevation measurements and U-series dating is a new approach to establishing palaeo-RSL positions at Bermuda that has been developed for this study. For the reasons given above, the focus here is on the mid-late Pleistocene Belmont Fm, which happens to display the widest and most complete range of sedimentary "structural facies" (after Clifton et al., 1971), representative of environments from shallow waters of the shoreface to the terrestrial backshore. New U-series ages for coral fragments as well as new sedimentary and fossil evidence are applied here to establish the timing and minimum height of the marine transgression(s) associated with the Belmont Fm. This chapter focusses on the sedimentary evidence, while Chapter 4 presents the evidence from U-series age data.

3.2. LITHOFACIES

3.2.1 Sedimentary structures

The near-absence of growth position fossil corals in Bermuda is compensated for by the wealth of clastic depositional features, whose elevation at the time of their development was constrained to some degree by contemporaneous mean sea level. Ten principal lithofacies have been identified, primarily on the basis of structural characteristics of the deposits following the approach taken by Clifton et al. (1971) in their classification of nearshore sediments into "structural facies" on the southern Oregon (USA) coast. The necessary field work was undertaken over the last 4 years, principally within the Belmont Fm of the south shore between

Grape Bay and Watch Hill Park. These lithofacies, their associations and two-dimensional stacking patterns as well as the elevation of key surfaces have been catalogued at 50 study sites (Appendix F) . Based on examination of modern equivalents in Bermuda and on published descriptions of analogous coastal deposits elsewhere in the world, these lithofacies have been attributed respectively to: the upper shoreface, the beach-foreshore and the beach-backshore as shown in Table 3.1 and Figure 3.1.

Sea-level indicator facies (SIFs) are defined here as those facies which have particularly well constrained vertical relationships to coeval mean sea level. Belmont Fm SIFs are: 1) high-angle medium-scale planar, seaward-directed avalanche cross-strata (Hapm); 2) low-angle large-scale, seaward-dipping planar cross-strata (Lapl); and 3) medium-scale tabular sets of trough cross-strata (Trm).Through consideration of flow regimes and comparison with analogous facies that have been described in the literature, as well as through recognition of their spatial association with other facies, these have been interpreted as follows: Hapm represents the beach step or plunge step (Bauer and Allen, 1995; Dabrio et al., 2011) of the upper shoreface, equivalent to the “inner rough facies” of Clifton et al. (1971); Lapl represents the swash zone of the foreshore, equivalent to “inner planar facies” of Clifton et al. (1971); Trm (and associated Flp) represents shallow-water washover or tidal-lagoon deposits of a back-barrier environment. The respective elevation constraints on coeval sea level associated with the three key facies are summarized in Table 3.2.

SIF equivalents can be observed on modern beaches of Bermuda where the sloping beach-face (of the swash zone) and the beach step (of the upper shoreface) are habitually well developed. The beach step, or plunge step, is created by seaward directed backwash, along the seabed, at the base of the swash zone. Its existence as a “topographic step” was recognized by Clifton et al. (1971). Its development, maintenance and migration under various states of the tide was described by Bauer and Allen (1995), who noted the importance of a backwash vortex in sustaining the ~20° avalanche face as detailed by Matsunaga and Honji (1983) and Larson and Sunamwa (1993). Reverse flow in the vortex is manifested as climbing ripple sets superimposed on the foresets, as commonly observed within Hapm of the Belmont Fm (Figures 3.1 and 3.3).

The distinctive characteristics of Hapm facies, and its inferred development as a beach step at a laterally and vertically constrained position on the shore, qualifies it as the foremost sea-level indicator facies (SIF) in Bermuda. Its existence other than at Grape Bay (Figure 3.2), where Meischner et al. (1995) described it as a “ramp”, has never previously been documented in Bermuda, despite making an appearance at multiple localities and elevations from 0 m to ~+4 m ASL. The value of the beach step as a sea level marker has been established by studies in Spain where small allogenic fluctuations in palaeo-sea-level are manifested by vertical and lateral shifts of the Hapm facies in Miocene and Pleistocene coastal sandstone bodies (Roep et al.,1998; Dabrio et al., 2011; Dabrio and Polo,2013). Dabrio et al. (2011) rejected the possibility

Facies	Sedimentary structures and texture	Dip of x-strata	Facies thickness	Typical Associations	Fossil features	Environment
Hapl	High-angle parallel, planar, large scale x-strata. Medium grained, well sorted.	Various directions 30° to 34°	2 – 10m	Subjacent to Lal	*Juniperus bermudiana* and *Sabal bermudana* trunk moulds and leaf impressions.	1.Advancing dune slip-face (landward dipping). 2.Foredune talus slope (seaward dipping).
Rof	Structureless zone. Fine to medium grained, well sorted.		0.2 - 1m	Subjacent to Hapl	Rhizocretions and *Poecilozonites* land snails	Protosol
Flp	Flat, laminated strata. Very fine to medium grain, well sorted.	Horizontal	0.1 - 1.5m	Superposed on Trm	Shelly beds including *Lucina* and *Brachidontes*	Shallow lagoon or slack.
Trm	Trough, medium scale x-strata. Medium to very coarse grained, moderately sorted.	Various directions including alongshore	0.2 - 0.5m	Superposed on Lapl		1.Washover (landward dipping) 2. Return flow (seaward dipping) 2.Tidal lagoon (alongshore dipping)
Lal	Low-angle, sub-parallel, large scale x-strata. Medium grained, well sorted.	Various directions. 0° - 25°	1.5 - 4m	Superposed on Lapl or Hapl		1. Upper beach/foredune 2. Dune stoss slope (when superposed on Hapl)
Bof	Intensively bioturbated zone with *Psilonichnus* traces. Medium grained, well sorted.		0.5 - 1.0m	Superposed on Lapl	*Gecarcinus lateralis* crab burrows. 4 – 6cm diameter	Berm or upper beach.
Lapl	Low-angle planar, large scale x-strata. "Inner planar facies" (Clifton et al., 1971). Medium to coarse grained, well sorted.	Seaward. 0° to 12°	1.5 - 3.0m	Transitions down-dip into Hapm		1. Reflective beach-face (seaward dipping) 2. Berm (sub-horizontal)
Hapm	High-angle parallel, planar, medium scale x-strata. "Inner rough facies" (Clifton et al., 1971). Medium to very coarse grained, moderately sorted.	Seaward. 20° - 24°	0.2 - 1.0m	Occurs in vertical succession between Laws and Lapl		Beach step created in back-wash vortex at base of swash zone.
Laws	Low-angle symmetrical small scale x-strata. "Outer planar facies" (Clifton et al., 1971). Medium to coarse grained, moderately sorted.	Various directions symmetrical	0.1 – 1.0m	Subjacent to Hapm		Wave rippled upper shoreface
Sof	Wavy, chaotic or sub-planar medium scale x-strata commonly obscured by bioturbation. Upward fining cobbles to coarse grained sand, poorly sorted.	Various directions but frequently landward dipping.	1 to 2 m	Subjacent to Rof. Superposed on erosional unconformity	Numerous broken marine shells, notably *Cittarium pica* in the Rocky Bay Formation	Transgressive shoreface deposit/lag on a high energy rocky shore.

Table 3.1. Ten "structural facies" of Bermuda. These facies are distinguishable by cross-strata scale and geometry, and by the spatial relationship with other facies. The codes are abbreviations of the structural and lithological characteristics of the facies. The Hapl facies for example comprises high-angle (Ha) planar (p) large scale (l) cross-strata interpreted as eolian slip-face deposits. Some of the component characteristic-codes are: Ha – high-angle cross-strata (≥ 20°); La - low-angle cross-strata (< 20°); Fl – flat strata; Tr - trough shaped cross-strata; p - planar strata; o – obscured structure; w - near symmetrical ripple cross-strata; s - small scale cross-strata set (< 5cm); m - medium scale cross-strata set (5 cm – 1m) ; l - large scale-cross strata set (> 1m).

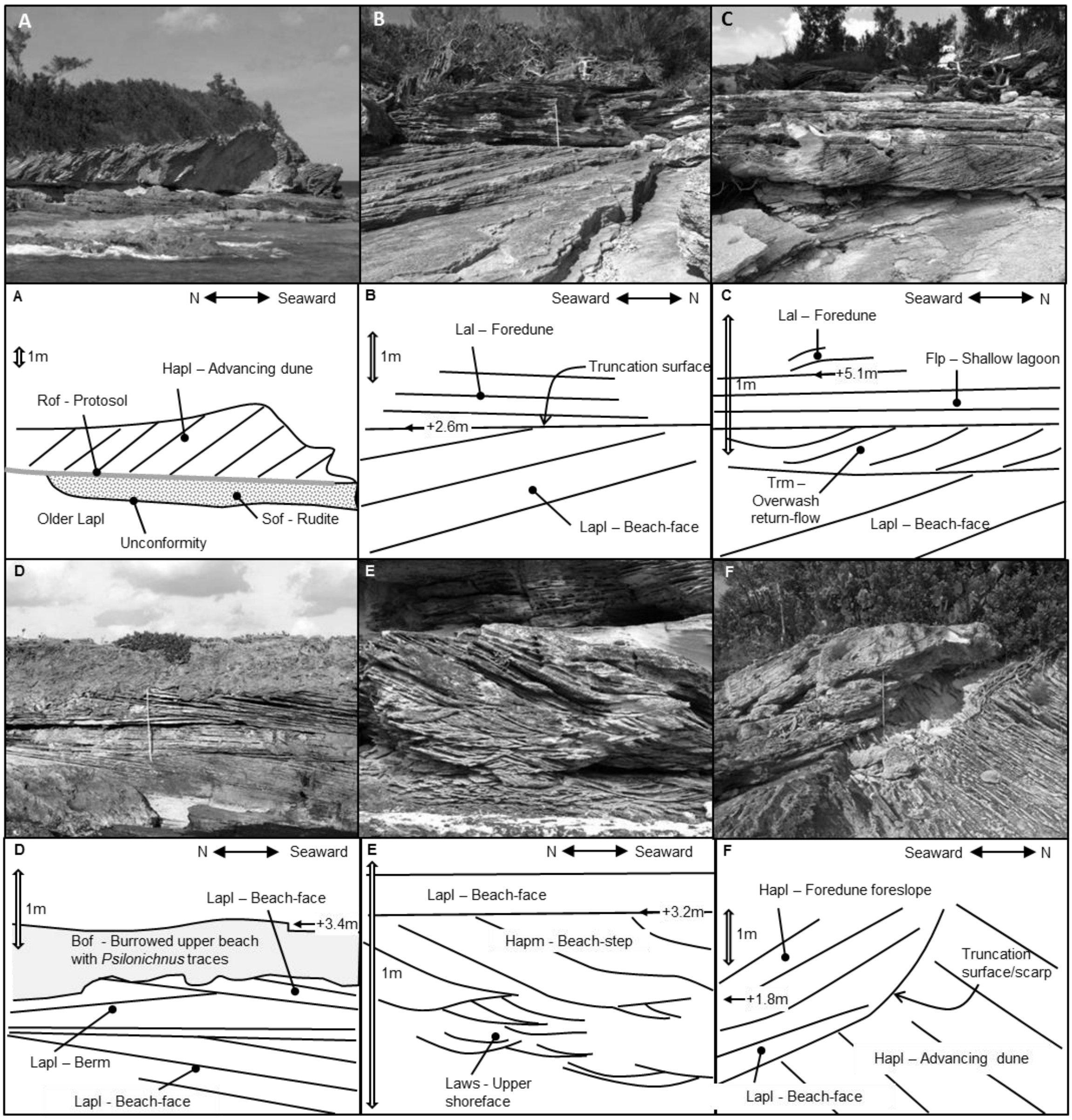


Figure 3.1. Examples of Bermuda's Pleistocene coastal facies and their associations. A. The Rocky Bay Fm at Rocky Bay, featuring Sof, Rof and Hapl facies - Interpretation: burrowed shoreface sediments superposed by a protosol and advancing-dune deposits. B. The Belmont Fm at Devonshire Bay featuring Lapl and Lal facies with an intervening bounding surface - Interpretation: truncated reflective beach-face deposits superposed by a foredune. C. The Belmont Fm at Hungry Bay east, featuring Lapl, Trm and Flp facies with intervening bounding surfaces - Interpretation: truncated reflective beach-face deposits superposed by trough cross-stratified overwash deposits and laminated shelly lagoonal deposits. D. The Belmont Fm at Doe Bay, featuring Lapl and Bof facies - Interpretation: beach-face and berm strata superposed by upper beach deposits which were intensively burrowed by land crabs (*Gecarcinus lateralis)*. E. The Belmont Fm at Spittal Pond west, featuring Laws and Hapm facies - Interpretation: shoreface symmetrical wave-ripple strata over which upper shoreface beach-step deposits prograded. F. The Belmont Fm at Devonshire Bay featuring Hapl (landward dipping), Lapl and Hapl (seaward dipping) facies - Interpretation: advancing-dune strata (from an earlier depositional cycle) truncated and scarped by a transgressive marine erosion surface which is superposed by a beach and the avalanching foreslope of a foredune. (Measurements in metres, e.g. +3.2m, indicate the elevation above present sea level).

that any beach steps in their study area had developed in association with storm surges, which is an important conclusion with respect to reliable interpretation of the mean sea-level position. It is agreed here that ambient swash zone conditions under which well-developed beach steps are known to be generated (Bauer and Allen, 1995) would not be replicated, at a higher elevation, at the height of a storm. Large storm surges and associated waves invariably erode and flatten Bermuda's modern beaches (Figure 3.2) and, therefore, the foreshore accretion that would be required to preserve beach step strata above current mean sea level is absent.

The low-angle planar Lapl facies, interpreted as the beach-face, is a reliable SIF, albeit with a margin of error that is larger than that of the Hapm facies. This is because of the variability of its maximum elevation (at the berm crest) from +1.0 m up to +2.5 m ASL (above sea-level), associated with cycles of storm erosion and beach re-building, exhibited by "winter" and "summer" profiles. Also detracting from the precision of Lapl, as an SIF, is frequent evidence of its truncation and, thus, incomplete preservation, in Bermuda's Belmont Fm. Identification of the Lapl facies and Hapm facies are mutually corroborated where the former transitions down-dip, and in a seaward direction, into the latter (Figure 3.3).

As will be detailed in Chapter 7, the Belmont Fm facies architecture attests to an episode, or episodes, in which beach progradation transitioned into aggradation in response to a rising RSL. Trm and the flat bedded shelly laminae of Flp, are manifestations of increased vulnerability of the backshore to inundation, as the marine transgression outpaced sediment supply and, possibly, reef growth. Larger waves and the related development of dissipative beaches may have exacerbated this vulnerability to intermittent backshore flooding, The Trm and Flp facies are typically found in direct vertical succession superposed on the Lapl facies (beach-face deposits). The tabular trough cross-beds of Trm record alongshore or seaward directed currents, sometimes bi-directional, characteristic of water flow at the top-end of the lower flow regime (Harms and Fahnestock, 1965), as would be expected when the backshore is flooded by high tides and/or by storm washover (there are no rivers in Bermuda). The absence of equivalent flooding on Bermuda's modern reflective beaches probably attests to a relatively stable late Holocene sea level and associated equilibrium conditions with respect to sediment supply, reef growth and beach accretion.

3.2.2. Composition and texture

The biological composition of Bermuda's Pleistocene calcarenites has been referred to briefly in relatively few studies (Vacher, 1972; Vollbrecht and Meischner, 1996). A record kept of sediment texture and the presence of key skeletal fragments that are recognizable by hand lens (such as the distinctive pink foram *Homotrema*) during geological mapping of the islands (Vacher et al. 1989) did not prove to be a useful stratigraphical tool. The only lithological characteristics that have had stratigraphical application in Bermuda are those which developed through post-depositional, predominantly meteoric, diagenesis as documented by Land et al. (1967) as discussed in Section 2.1.1.

Recognition of north shore lagoonal-derived eolianite and south shore reef-derived eolianite by Vacher (1972) was credited to the work of Upchurch (1970) who attempted to correlate biota represented in skeletal debris with physiographic provinces. Upchurch (1970) determined that there was poor correlation other than well within the bounds of the North Lagoon and on the outer-flanks of the reef terrace where the sediment is composed almost wholly of lagoonal and reef debris, respectively. The principal constituents of Upchurch's lagoonal suite are fragments of green algae *Halimeda* and small infaunal bivalves such as *Crasinella*, while those of the reef suite are *homotrema*, corals, coralline algae, gastropods and Serpulids. Within the reef tract which circumscribes the North Lagoon, Upchurch (1970) found that the inter-reef areas include an even mixture of lagoon and reef sediments. Within the reef tract of the platform margins which skirts the south shore the reef-derived sediments are, however, dominant. The large reservoir of lagoonal sediments in the North lagoon explains the age-independent contrast in composition between the north shore and south shore eolianites, noted by Vacher (1972). Compositional differences between dunes of the Rocky Bay Formation facies assemblage (north shore), as defined in this study, and near-contemporaneous Rocky Bay Formation dunes on the south shore corroborate Vachers' (1970) findings. No meaningful compositional variation within eolianites of the two shores is detectable by non-statistical observation. In reference to cross-contamination of the physiographic provinces with sediment of different biotopes, Upchurch (1970) noted that "one should expect equal complexity in the fossil record, including discrepancies between biota and sedimentary structure." The "discrepancies" he refers to are unexpectedly low correlations between sediment composition and depositional environments.

The Belmont and ravinement-infill facies assemblages, of this study, being situated adjacent to the south shore reef tract are composed predominantly of reef-suite sediments. The platform on the south shore is too narrow and too exposed to accommodate a true-lagoonal environment. Differences between facies, within the south shore assemblages, are primarily textural and are a function of conditions within the depositional environment rather than of the source material or the position of RSL. This can be inferred, in part, from Upchurch's (1970) observation of "extreme similarities in the texture of sediment from the major (source) environments". Fine grained laminated deposits of the Flp facies are associated with low energy back barrier conditions; whereas poorly sorted medium grained to gravel deposits of the Hapm or Sof facies are the outcome of high energy conditions found, respectively, at the beach

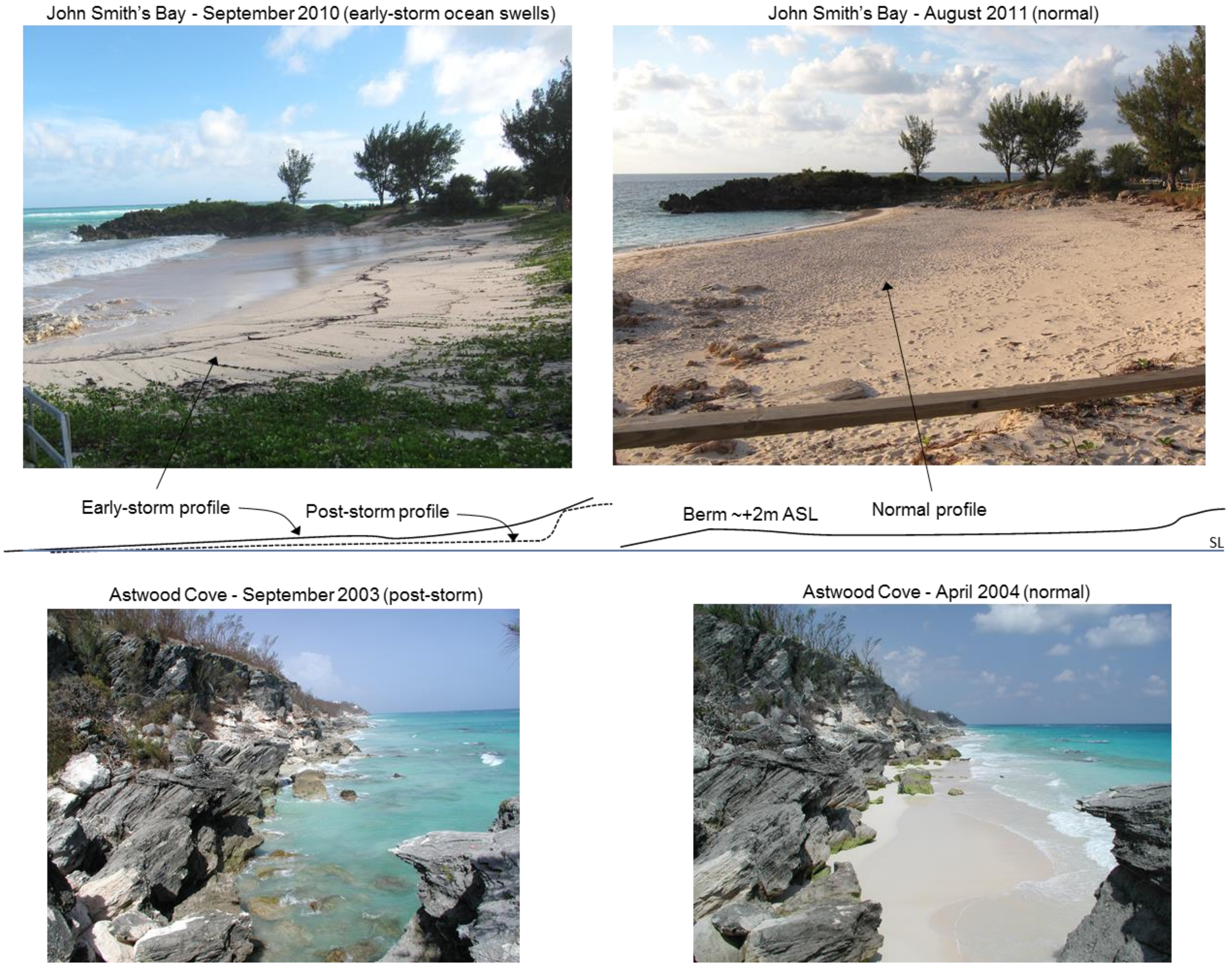


Figure 3.2. Beach erosion by storm waves. Upper left photo shows flattening of John Smith's Bay beach by early-storm ocean swells in September 2010. The normal beach (upper right photo and profile below) features a seaward sloping beach face, a raised berm and wide dry upper beach. The profile on the left illustrates further flattening of the beach which took place during the storm, with associated creation of a scarp in the foredune foreslope. This is a typical response of Bermuda beaches to storm waves. Lower left photo shows complete erosion of the beach at Astwood Cove during a storm in September 2003. The beach had returned to its normal condition within 1 year (right photo).

Key sea-level indicator facies (SIFs)					
Facies	Symbol	Description	Associations	Interpretation	Mean sea-level Relative to top surface of facies
Trm		Tabular, trough cross-strata, small to medium scale.	**Trm** overlies prograded beach sequences.	Beach backshore - washover/tidal flats	- 2 to - 0.5 m
Lapl		Low angle seaward dipping, planar cross-strata, large scale.	**Lapl** either exhibits a truncated upper surface or is overlain by burrowed upper beach deposits. **Lapl** transitions seaward and down-dip into **Hapm.**	Foreshore - beach face	- 1.0 to - 2.5 m
Hapm		High angle seaward dipping planar cross-strata, medium scale.		Upper shoreface - beach step.	0 to + 1.0 m

Table 3.2. . Key sea-level indicator facies (SIF) of Bermuda's Belmont Formation. Hapm and Lapl are the products of wave action at the seaward front of a beach; whereas Trm developed in shallow flowing water which inundated the backshore during storms or at high tides. Their respective relationships to coeval mean sea level are inferred from modern equivalents in Bermuda and from analogous facies whose depositional environments have been reconstructed (by others) elsewhere in the world.

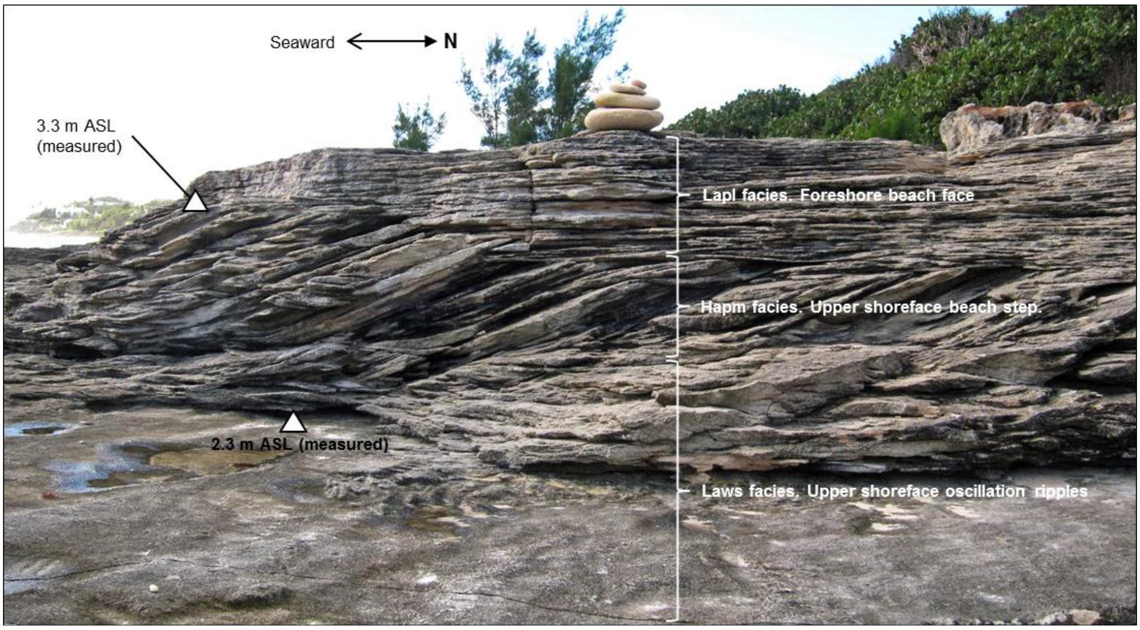


Figure 3.3. The Hapm facies in the Belmont Formation at Grape Bay. (Site 6, Appendices F and G). The sequence is interpreted as representing the progradation of a beach face (Lapl) and beach step (Hapm) over wave rippled upper shoreface deposits (Laws; in the foreground). Contemporaneous mean sea level stood at +3 to +4 m ASL (above present mean sea-level). Not far to the west of this locality a +4 to +5 m ASL palaeo-sea-level is recorded by a similar sequence (Figure 3.4).

step or in pocket beaches on rocky shores. South shore emergent beach deposits (Lapl facies) are of medium to coarse grain-size and less well sorted than the medium grained eolianites (Hapl and Lal facies). The fine material which might be expected to occur in the eolianites was either blown beyond the dunes where it accumulated in protosols (Rof facies), or, as asserted by Upchurch (1970), was preferentially dissolved by percolating rain water.

3.3. BELMONT RELATIVE SEA-LEVEL ELEVATIONS

Some of the higher facies sequences of the Belmont Fm, as exemplified at North's Point, Hungry Bay East, Hungry Bay West and Grape Bay (Figure 3.4), represent a transition from progradational to aggradational deposition in response to a marine transgression. Progradation is inferred from lateral accretion of seaward dipping cross-stratification and upward shallowing facies successions (Figure 3.5). Aggradation and RSL rise is inferred from inter-tidal SIFs (sea level indicator facies) that increase in elevation and transition laterally, in a seaward direction, into sub-tidal SIFs. The facies architecture which developed at that time is similar to that described by Dabrio and Polo (2013) under analogous circumstances within the late Miocene carbonates of southeast Spain. The facies associations at Bermuda, collectively, evidence palaeo-RSLs which ranged from close to present sea level up to several metres above it (Figure 3.4). The highest Hapm facies found so far, at Grape Bay, attests to a Belmont mean sea level at ~+4.5 m ASL (Figure 3.5).

Evidence of a higher, ≥+6m, palaeo-RSL associated with the Belmont Fm is found at Watch Hill Park where Lapl (beach face deposits), shelly layers and incipient foredunes are elevated up to 2 m above their highest counterparts at other localities along the south shore (such as those of Figure 3.4). More conclusively, an erosional notch populated by in-situ sessile and lithophagic marine fossils at Watch Hill Park (Figure 3.6) is now attributed to submergence by a Belmont sea, which must have surpassed +6.0 m ASL. Earlier interpretations that the feature was a product of a subsequent Rocky Bay highstand were shown to be erroneous when a new exposure was revealed by storm erosion. The second notch is demonstrably onlapped by un-colonised Belmont Lapl facies. From this, it is inferred that a post-Belmont highstand was not responsible for the marine imprint in question. The fact that it is an aeolian calcarenite of the Town Hill Fm - the immediate predecessor of the Belmont Fm - which is notched and colonised, provides an upper age constraint for the highstand.

Corroboration of an exceptionally high Belmont marine transgression is provided, again at Watch Hill Park, in the form of coeval marine phreatic cementation (associated with prolonged submergence) within Belmont calcarenites at ≥+7.0 m ASL, as reported by Vollbrecht and Meischner (1996). It is thus asserted here that RSL peaked at ≥+4.5 m and probably at ≥+6 m ASL during deposition of the Belmont Fm at MIS7. Some of the contentious low-elevation Belmont sea-level imprints reported by Land et al. (1967) and Hearty and Kindler (1995) were, no doubt, caused by transitory sea-level positions on a rising or falling trend. The case for two or more Belmont Fm highstands is discussed further in Chapter 7.

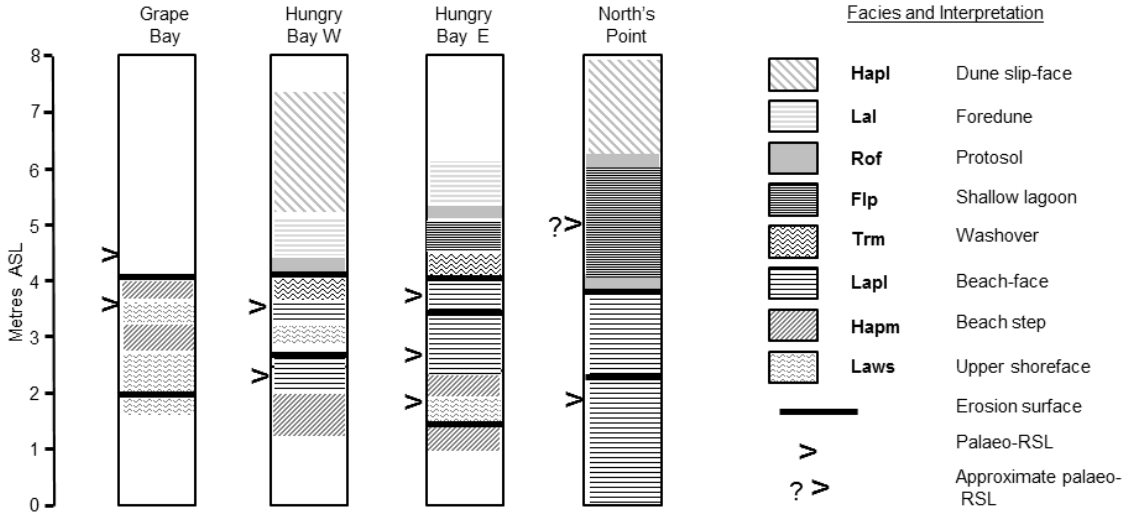


Figure 3.4. Four examples of Belmont Formation facies sequences from Bermuda's south shore. The key sea-level indicator facies (SIFs) are considered to be: Hapm, Lapl, Trm, attributed, respectively, to the upper shoreface, foreshore and backshore environments. Arrows (>) represent transitory positions (± 0.5m) of a generally rising RSLs (and later falling RSLs) within each sequence interpreted from SIFs. Question marks plus arrows (?>) represent transitory positions of sea-level as recorded by non-SIF. The highest palaeo-RSL inferred from these sequences is ≥+4.5 m ASL.

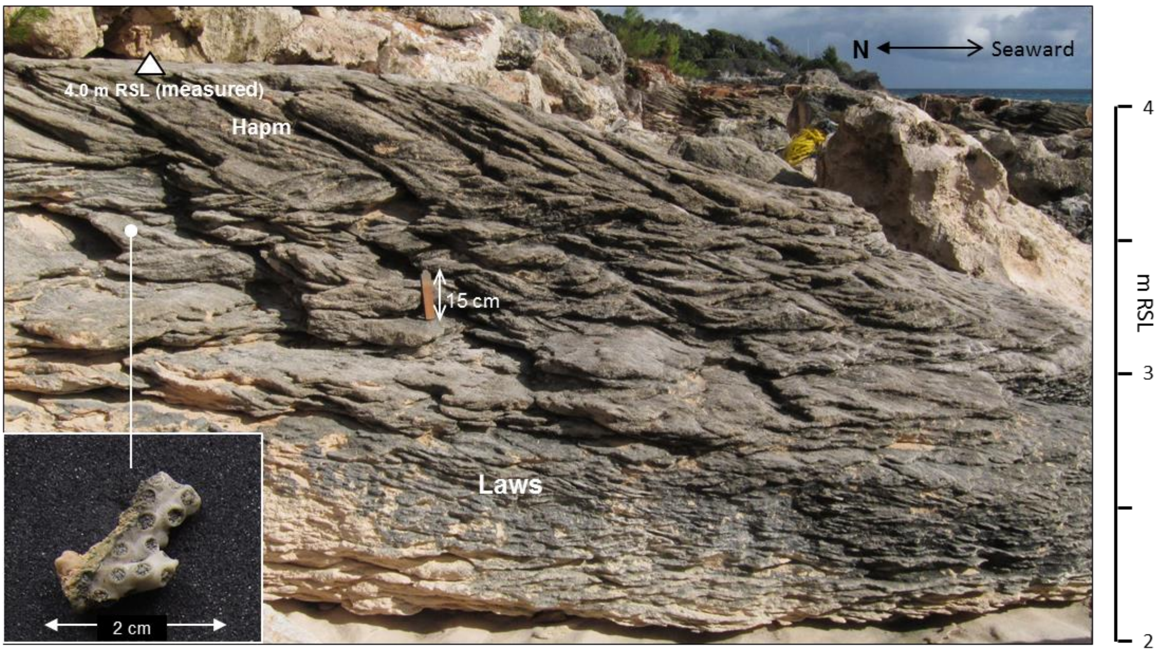


Figure 3.5. Facies sequence at Grape Bay. (Site 3, Appendices F and G). The shallowing-upward sequence at this locality is equivalent to the top of the Grape Bay succession shown in Figure 3.3. It represents progradation of the beach step (Hapm) over oscillation ripple cross laminae (Laws) of the upper shoreface (interpretation confirmed by Cristino Dabrio (pers comm., 2012)). Intervening between the two are medium scale cross beds (wave ripples) of the inner rough facies (Clifton et al, 1971). A palaeo-RSL of +4.0 to +5.0 m ASL is inferred. The *Oculina* fragment "C" (bottom left) which yielded an age of 197 ka ±3 ka was found, nearby, at the base of the Hapm facies.

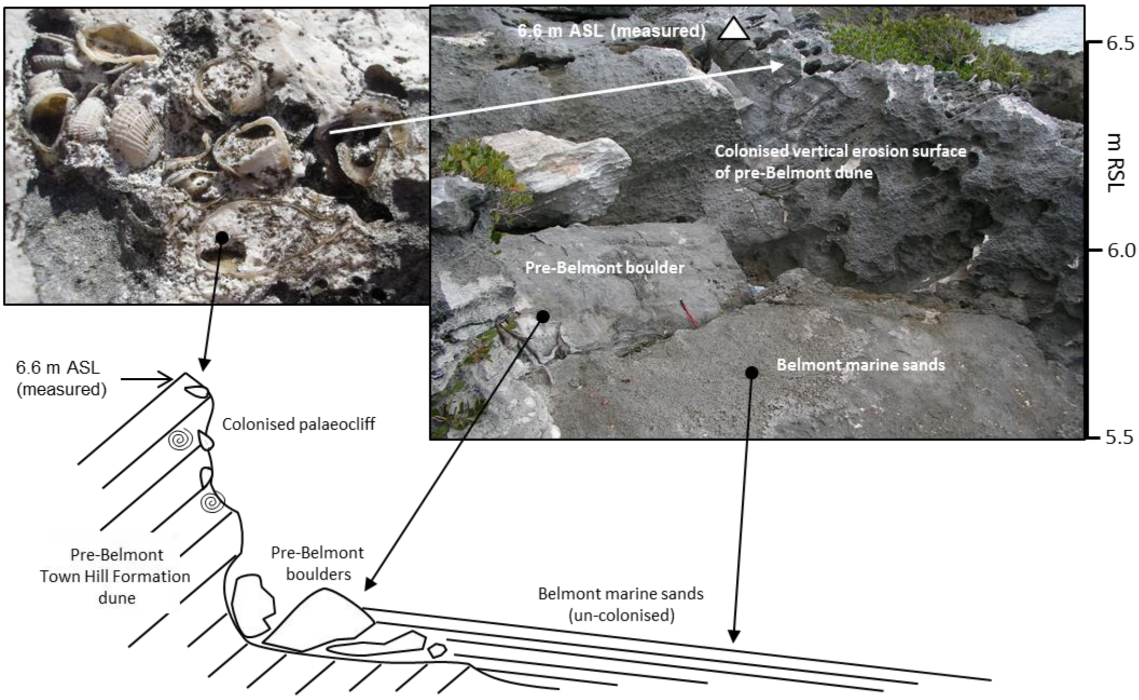


Figure 3.6. Emergent accretionary lip and palaeo-cliff, at Watch Hill Park. (Site 50, Appendix G) Partial-submergence of this site in the past is evidenced by life-position lithophagic bivalves (Brachidontes domingensis) and encrusting vermetid worms which would have inhabited a high energy inter-tidal rocky shoreface. Boulders and marine sands which rest against the cliff are mapped as Belmont Fm marine deposits. Consistent with other evidence in the vicinity, such as high elevation marine phreatic cementation, these features are indicative of a Belmont highstand at of ≥ +6.0 m ASL.

4. AGE OF THE BELMONT FORMATION OF BERMUDA

4.1. ESTABLISHING AGES

4.1.1. Provenance of dated coral fragments.

Although the modern Bermuda Platform features a proliferation of biogenic reefs, including those of the vermetid cup variety in the nearshore (Thomas and Stevens, 1991), only an occasional emergent, growth-position fossil coral has been reported in the literature (Harmon et., 1983). Their existence has subsequently been difficult to verify and, at this time, none are known from the extensive Belmont Fm outcrops of the south shore. As a consequence, it is not possible to use *insitu* corals as sea-level indicators. However, broken pieces of corals have been found within the upper shoreface and beach deposits of the Belmont Fm at Grape Bay and Spittal Pond (Appendix A). These coral fragments are from the genus *Oculina* which have been selected for ^{230}Th/U dating in previous studies (Ludwig et al., 1996; Muhs et al., 2002). They are ‘clean’, not incorporated into lithoclasts or covered by encrusting fauna and relatively unworn (Figure 3.5). In addition, the coral pieces are much larger than the sand particles of the calcarenite facies from which they were collected. Taken together these characteristics suggest limited reworking, and a short transport-time from source to sink. This conclusion is consistent with the interpretation that the Belmont Fm deposits, from which the *Oculina* fragments were collected, represent progradational deposition associated with a high positive sediment budget.

Successive limestone formations, in Bermuda, record episodes of carbonate productivity on the platform, at highstands, interrupted by lengthy glacial periods during which only solutional/pedogenic processes prevailed. While conglomerates on erosional flooding-surfaces, termed transgressive lags, are prone to contamination by old material as a result of reworking, beach or shoreface calcarenites which accumulated on the shore of a productive carbonate platform are expected to yield clustered ages, which are effectively contemporaneous with deposition. These circumstances are borne out by U-series age data from coral fragments, as well as amino acid racemization (AAR) relative age-data from marine mollusk shells. Dating of: 22 coral fragments from the Southampton Fm (Harmon et al.,1983; Ludwig et al., 1996; Muhs et al., 2002) ; 7 fragments from the Rocky Bay Fm (Harmon et al., 1983; Muhs et al., 2002); 5 fragments from the Belmont Fm (Muhs et al., 2002; and this study); and 4 fragments from a modern beach (Ludwig et al. 1996), in each case yielded a cluster of ages that are exclusively correlative with a single marine isotope sub-stage (Figure 4.1) . These findings were corroborated by 43 AAR ages from marine shells which clustered into three distinct “aminozones” corresponding to the Belmont, Rocky Bay and Southampton formations from which they were collected (Hearty et al., 1992). This prompted Hearty et al. (1992) to conclude that “there is a striking agreement between the succession of aminozones and the relative ages implied by the mapped lithostratigraphy of the host deposits”.

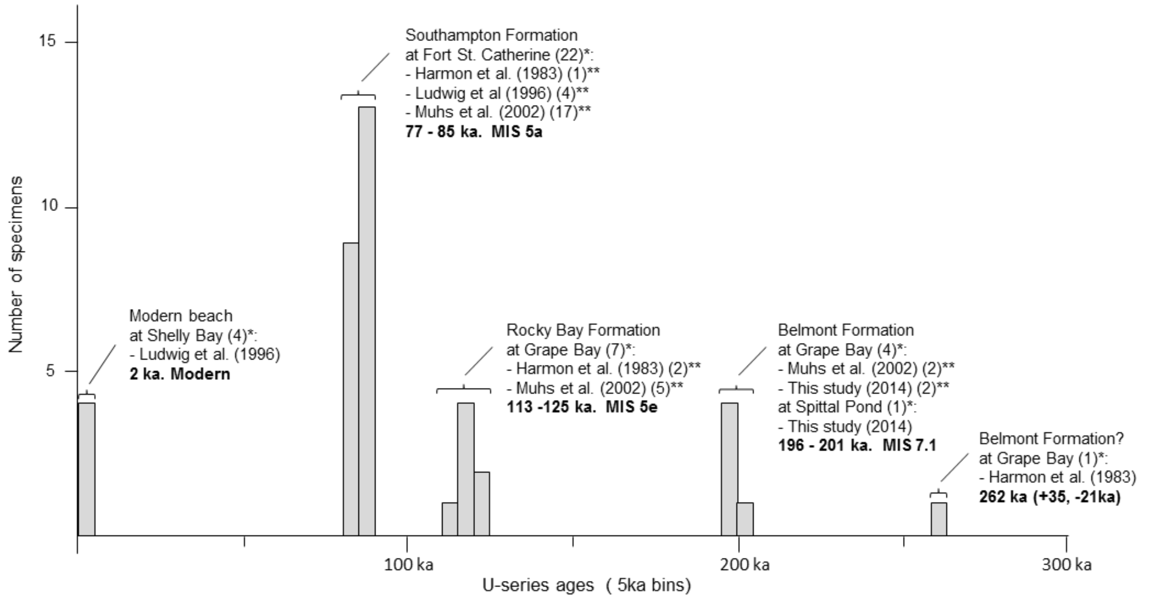


Figure 4.1. U-series ages of 36 coral fragments from Bermuda. These were collected from progradational and aggradational foreshore and shoreface calcarenite deposits on Bermuda. Stated margins of error in the age measurements are < ±3 ka in all but three cases where they range up to ± 6 ka and in one case - the 262 ka age of Harmon et al., 1983 - where it exceeds ±20 ka. Harmon et al. (1983) expressed uncertainty over any of their ages greater than 220 ka. The 262 ka age is included here for the sake of completeness. **Explanation:** * - Number of dated coral fragments from named location. ** - Number of coral fragment ages from cited article.

Even where marine facies of successive formations are in direct contact, as at Grape Bay (Figure 4.4), U-series ages yielded by the respective formations are grouped into two distinct clusters separated by ~ 70 ka (Figure 4.1). Such consistency in the correspondence of U-series age distribution with the established stratigraphy, supports the concept (applicable to Bermuda) of a relatively short time-gap between the growth of an organism and the deposition of its skeletal remains in a beach; and refutes any meaningful impact of reworking on Bermudian chronostratigraphy.

4.1.2. U-series dating (by Karine Wainer, Oxford University).

Three coral fragments of *Oculina* collected from the Belmont Fm at Grape Bay (2) and Spittal Pond (1) were prepared for U-Th dating. Because of the potential for diagenetic effects which can result in a biased age, attempts should be made to limit working on affected portions of samples and to favour inner portions that are more protected against diagenesis. To this end, the entire external surfaces of the Bermuda samples were removed and only the core of the samples were analysed. Exterior surfaces, including septae, were thus carefully abraded using a diamond coated, rounded hand-drill bit. Pieces of ~300 mg were then isolated using a circular diamond saw, ultra-sounded in deionised water and dried down. They were then treated with a mixed ^{229}Th-^{236}U spike and dissolved in nitric acid, before refluxing in reverse aqua regia to remove all traces of organic matter and ensure sample-spike equilibration. Chemical separation of U and Th from the sample matrix followed procedures adapted from Edwards et al. (1986). Measurements of U and Th were performed by Nu-Instrument Multicollector-inductively coupled plasma mass spectrometer (MC-ICP-MS) at the University of Oxford.

The following recently updated half-lives were used to compute the results in Appendix A: 245,620 +/-260a for ^{234}U and 75,584 +/-110a for ^{230}Th (Cheng et al., 2013). The modern sea water value of the ^{234}U/^{238}U activity ratio is 1.147 ‰ (Delanghe et al., 2002). The level of diagenesis was assessed through the U^{234}/U^{238} initial activity ratio. For all three samples, the ^{234}U/^{238}U initial activity ratio is close to that of sea water on the basis of known variability of past seawater ^{234}U/^{238}U ratios during the glacial-interglacial cycle (Stirling et al., 1998 and Esat et al., 2006). Nevertheless, in an attempt to arrive at an age cleared of diagenetic bias, as completely as possible, the protocol of Thompson et al. (2003) was applied to the Bermuda U-series data using an Excel macro.

4.2. RESULTS OF U-SERIES DATING

As part of this study, three coral fragments were collected from the Belmont Fm for dating. One from Spittal Pond yielded an age of 196 ka ± 3 ka . Two from Grape Bay, 4.5 km to the east, which were found approximately 30 metres apart, both yielded ages of 198 ka ± 3 ka (Appendix A). The small offset in the ^{234}U/^{238}U activity ratio suggests that the samples have suffered sufficiently limited diagenesis to state with confidence that the corals grew within the time span of MIS 7. For the sake of completeness, a correction for diagenesis (Thompson et al., 2003) was made, and the resultant ages fall within the error bars of those initially calculated with the exception of coral fragment B which came in ~9 ka younger than the original value. If accepted, this would attribute growth of “B” - the youngest coral fragment in the group - to a period of climatic transition between 190 and 185 ka or to a very late MIS 7 episode of warming tentatively identified by Henderson et al. (2006).

All three coral fragments were found near the base of the hapm facies at +2.5 to +3.5 m ASL. Since the Belmont Fm, by definition, includes no unconformities or other evidence of significant hiatuses equivalent to a full glacial stage, its MIS 7 assignment (based on coral dating) at one locality, where for example a +3.0 m to + 4.0m sea level is inferred, can be extended to Belmont marine imprints, elsewhere, including those indicative of a ≥+6.0 m ASL palaeo-RSL.

Two *Oculina* fragments previously collected from the Belmont Fm at Grape Bay by Muhs et al. (2002) yielded ages of 199 ±2 and 201 ±2 ka. One collected by Harmon et al. (1983), also from Grape Bay, had a reported age of 262 +35 -27 ka, which if correct could represent an early or mid- MIS 7 highstand. To date, no fragments from corals whose growth could have occurred at an interglacial period other than MIS 7 have ever been found within demonstrable Belmont Fm deposits. Taking into consideration the consistency of the 5 precise ages, ranging from ~201 to ~196 ka (or possibly ~185ka), and the taphonomy of the coral fragments (see Section 3.1), it is concluded here that the U-Th ages are attributable to first cycle sediments that were not subjected to the cross-formational contamination invoked by Hearty (2002).

There is agreement that the deposits traditionally assigned to the Belmont Fm, record a palaeo-RSL of at least +1 m to +2.5 m ASL on Bermuda (Land et al., 1967; Harmon et al., 1983; Hearty and Kindler 1995; Vacher and Rowe, 1997; Hearty, 2002; and Hearty et al., 2007). What has become contentious is the elevation at which the associated palaeo-RSL peaked, and the age of these Belmont deposits. Irrespective of elevation, which is discussed in the previous chapter, it is re-asserted here that the youngest deposits of the Belmont Fm of Bermuda’s south shore are correlative with late MIS 7.

4.3. DISCUSSION

Hearty’s (2002) revision of Bermuda’s palaeo-RSL curve (Figure 4.1) as well as the stratigraphy required compression of the time gap between the Belmont Fm and Rocky Bay Fm into the time span of MIS 5e.However the undisputed MIS 5e age of the Rocky Bay Fm, coupled with the preponderance of ~200 ka ages attributed to the Belmont sediments (Harmon et al., 1983; Muhs et al., 2002; and this study), refute this shortened time scale (Figure 4.3).

The Shore Hills geosol and the correlative unconformity have, based on their characteristics, long been considered the outcome of a period of sub-aerial solutional and pedogenic processes equivalent to a full glacial stage (Sayles, 1931; Bretz, 1960; Land et al., 1967, Vacher, 1972, Herwitz and Muhs, 1995). It is suggested, here, that Hearty’s (2002) re-characterisation of the

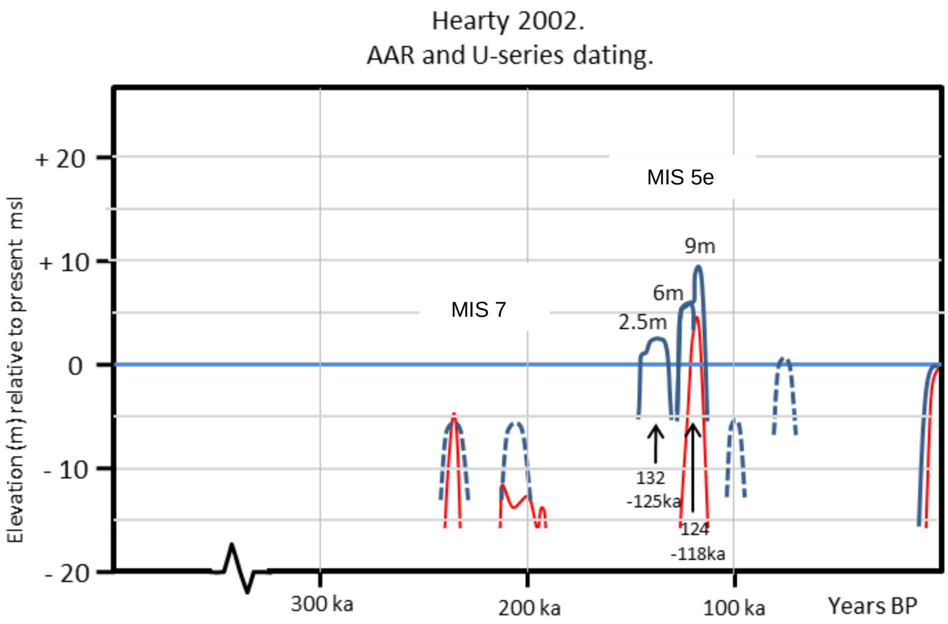


Figure 4.2. Palaeo-RSL curve for Bermuda as proposed by Hearty (2002). This interpretation (blue) was favoured by Hearty because it conforms reasonably well to global glacio-eustatic palaeo-RSL curves such as that produced by Bintanja et al. (2005) (red).

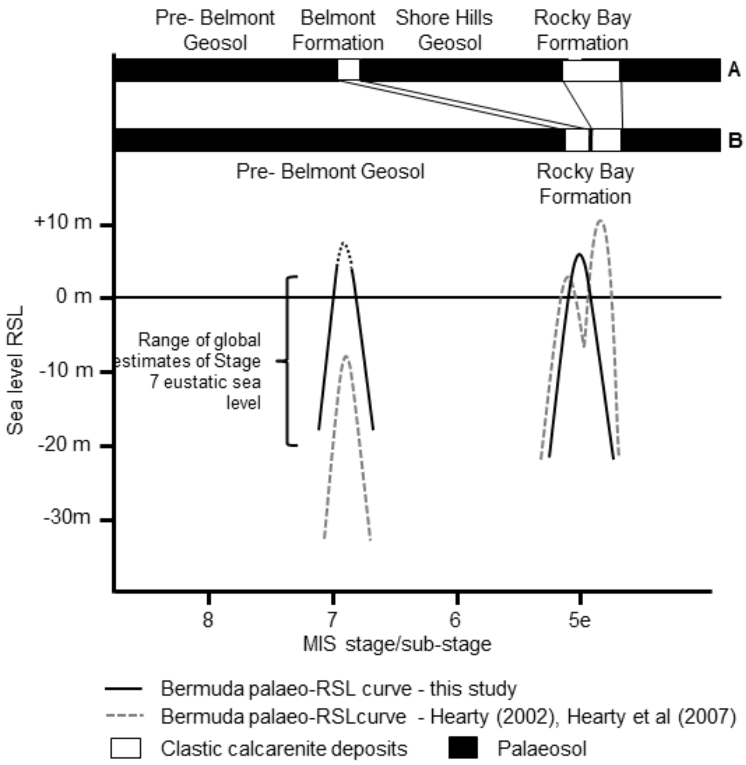


Figure 4.3. Mid to late Pleistocene stratigraphy of Bermuda in relation to palaeo-RSL. **A** is the version challenged by Hearty (2002), which is re-instated here. It includes the Belmont Formation deposited at a MIS 7 highstand. **B** is the version proposed by Hearty (2002) and Hearty et al. (2007) which re-allocates the "Belmont" deposits to the, MIS 5, Rocky Bay Formation and correspondingly downgrades the Shore Hills Geosol to an intra-formational colluvium.

Shore Hills geosol as an intra-formational, as opposed to inter-formational, "soil-like" colluvial deposit can be attributed to his focus on low elevation coastal exposures, as referenced in his article. At such localities, it is evident that the mature Shore Hills geosol was stripped away (Figure 4.4), destabilised or reworked by subsequent marine transgressions into a reddened non-pedogenic sediment layer. At these coastal exposures in-situ remnants of the Shore Hills geosol, if there are any, comprise only red-stained solution pipes (Figure 4.5). What was identified as the Shore Hills geosol by Hearty is in fact a surficial soily rubble, which has no stratigraphic significance being the product of reworking by waves at MIS 5e and MIS 5a as well as during the present highstand.

Upon a review of AAR data, Hearty (2002) concluded that the differences in d-alloisoleucene/L-isoleucine (or A/I) ratios between material collected from the Belmont Fm and that collected from the Rocky Bay Fm (Hearty et al., 1992) supported his hypothesis of a relatively small age difference between the two deposits. To explain contradictory interpretations (Hearty, 2002 versus Harmon, 1983 and Hearty et al., 1992) he cited an earlier failure to account for markedly accelerated epimerization rates associated with climatic warmth at MIS 5e. However, the scale of such temperature-related effects on A/I ratios, at Bermuda, is not known with any degree of certainty. Thus, although a short time gap can be rationalised, the AAR data can best be described as inconclusive.

It is demonstrated here that at least one Belmont Fm sea-level highstand rose several metres above present sea-level. It significantly exceeded global eustatic sea-level elevation during MIS7, as estimated from a variety of sources (Porter, 1989; Petit et al. 1999; Bitanja et al., 2005; Dutton et al., 2009; Rohling, 2009) (Figure 2.1). Plausible explanations for this anomaly must include vertical displacement of the Bermuda seamount caused by glacio-hydro isostacy and/or tectonic instability.

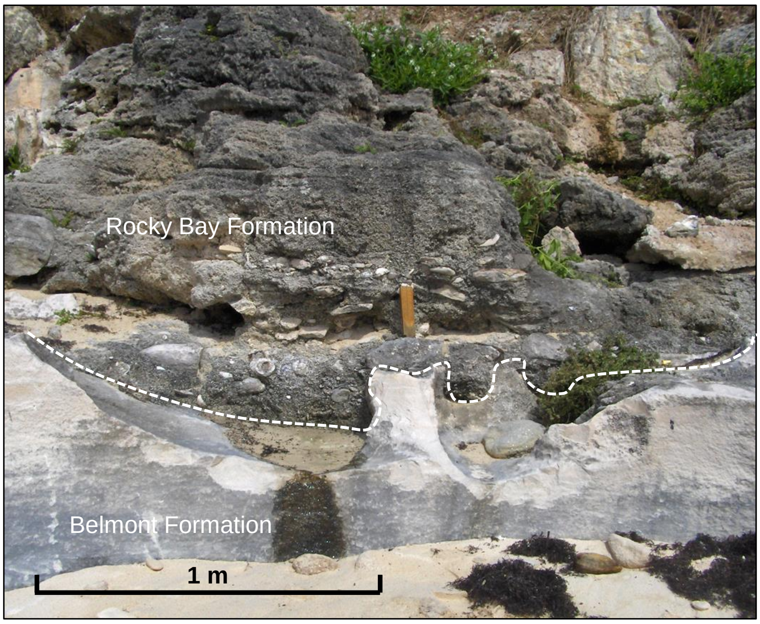


Figure 4.4. An unconformity correlative with the Shore Hills geosol. (Near Site 2, Appendix G). At this Grape Bay coastal exposure Rocky Bay Formation rudaceous deposits (above the broken white line) overlie heavily cemented Belmont shoreface deposits. The intervening Shore Hills geosol was stripped away by a MIS 5e transgression. The irregular Belmont Formation surface is partly attributable to erosion and partly to pedogenic/solutional processes. The evident contrast in diagenetic histories between the two formations is a manifestation of the large time gap which is corroborated by U-series coral dating at this

Figure 4.5. Solution pipes penetrating a Belmont Formation surface at Grape Bay. (Near Site 7, Appendix G). These structures are interpreted as pedogenic features associated with the “solutional unconformity” (Land et al. 1967) at the Belmont Formation/Rocky Bay Formation contact. They are remnants of the Shore Hills geosol which has been largely stripped away. Many of the “pipes” have an integral soil lining and, when seen in section, are frequently “bowl” or “cone” shaped which corroborates pedogenic origins, as opposed to them being tree trunk casts, which typically are infilled with sand not soil.

5. THE TECTONIC STABILITY OF BERMUDA

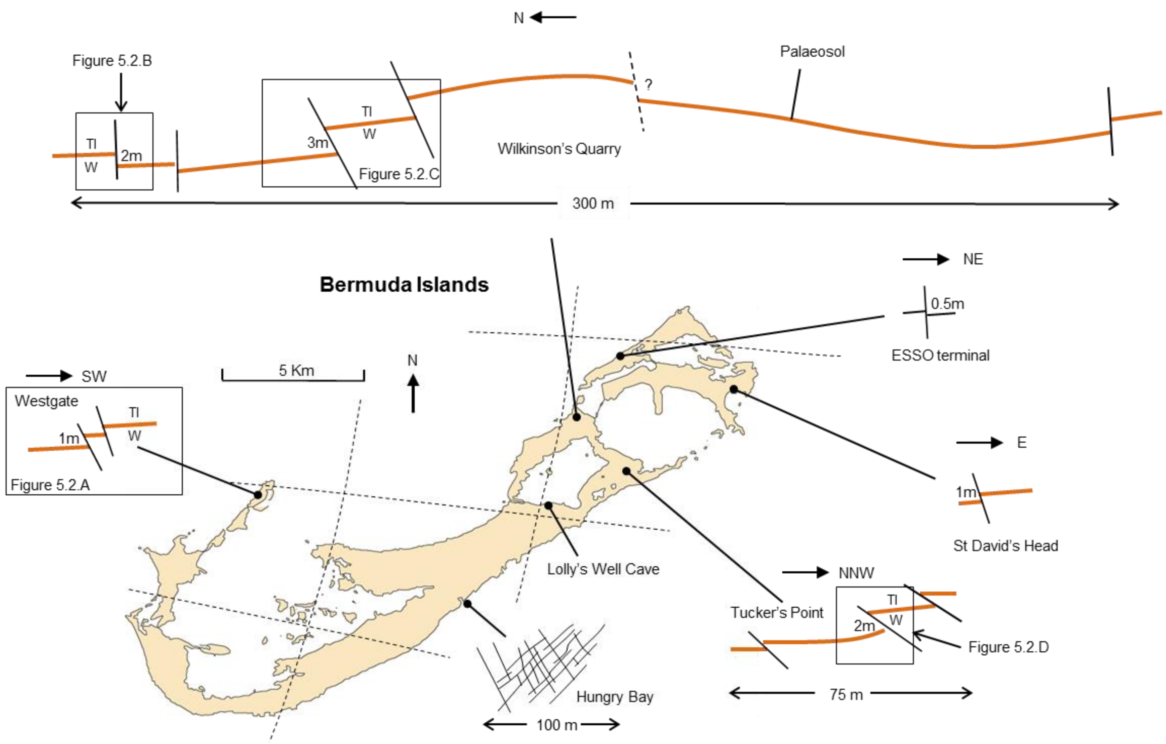
5.1. INTRODUCTION

Bermuda's preeminent global status as a tide-gauge for Pleistocene eustatic sea levels has been proclaimed over many decades (Land, 1967 to Hearty, 2002). Nevertheless, the attendant assumption of tectonic stability at Bermuda (Section 2.1.4) has been increasingly questioned (Peckenham et al.,1981; Rowe, 1998; and Bowen, 2010). Features of Bermuda's geology which justify this doubt include: 1). normal and reverse faulting (Figures 5.1 and 5.2); 2). rectilinear fracturing (Hartsock et al., 1995) that conforms to an orientation consistent with stress trajectories in the North American plate (Scheidegger 1976) (Figure 5.1); 3). a history of idiosyncratic tectonic/isostatic behaviour of the Bermuda volcanic seamount, such that the expected subsidence due to a combination of gravitational loading and cooling (Clague and Moore, 2006) has been offset by uplift as is evidenced by ~30 million year old pillow lavas encountered in drill holes at shallow depths of ~-30m BSL, where sub-aerial eruptives or sedimentary carbonates would be expected; and 4). Anomalously high seismic activity within the Bermuda Rise (Zoback et al., 1986; Vogt and Jung, 2007).

That Bermuda is prone to earth tremors is well known to the inhabitants and that they can sometimes be powerful is attested to by a church record dated 1664 which describes "a great and fearful Earthquake which did shake Churches and Houses, Yea and the hearts of man too" (Bermuda Government archives). A record of earthquakes collated by Bermudian geologist, Martin Brewer (pers. comm.) catalogues a total of 56 earthquakes affecting Bermuda over the last 350 years. His analysis of the data reveals, for example, that those earthquakes which are defined as "moderate" on the Mercalli intensity scale (~> 4.3 Richter magnitude) have recurred at an average frequency of once every 11 years since 1842. The earthquake of 1664, mentioned in the church records, is considered by Brewer to have qualified as "destructive" with an estimated Richter magnitude of ~ 6.3.

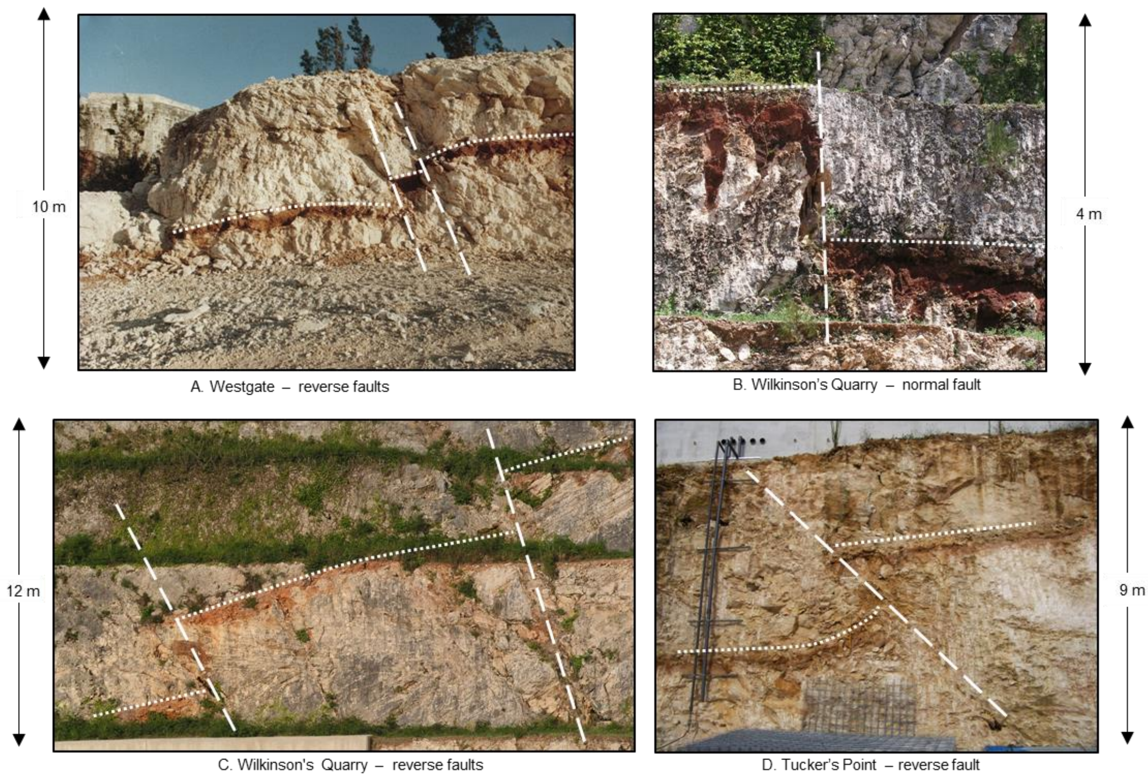
5.2. FAULTING

The first reverse faults documented in Bermuda (Rowe, 1998) were a pair, with a combined displacement of 1.5m, found at the entrance to Westgate Prison (Figure 5.2.A). At Wilkinson's Quarry, there is a system of reverse and normal faults, expressed as 1 to 3m offsets of a palaeosol, extending over a 300m north-south aligned quarry face. While, at Tuckers Point a series of low angle reverse faults exposed in a north-northwest trending rock face, displace a palaeosol by a total of >3m (Figures 5.1 and 5.2). All of these faults are within the Quaternary Walsingham and Lower Town Hill Fms (Bermuda's oldest two formations) but smaller faults and conspicuous fissuring occur throughout the stratigraphical column. Good accounts of fissure alignment in Bermuda and the potential association with stress trajectories in the North Atlantic plate (Figure 5.1) are provided by Scheidegger (1976) and Hartsock et al. (1995).



W - Walsingham Formation   Tl - Lower Town Hill Formation   Tu - Upper Town Hill formation

Figure 5.1. Location of Bermuda faults. Displacement geometries are shown, along with the alignment of the rock faces in which the faults are exposed. Fault strikes are not known with sufficient accuracy to plot on the map. Also shown are the stress trajectories (broken lines) inferred from joint/fracture orientations in Bermuda as plotted by Scheidegger (1976) who related the pattern to geotectonic stress in the North American oceanic plate. The joint system exposed in the seabed off Hungry Bay (shown in plan-view traced from aerial photos) has an orientation which is consistent with those documented on land by Scheidegger (1976) and Hartsock et al. (1995)



A. Westgate – reverse faults   B. Wilkinson's Quarry – normal fault

C. Wilkinson's Quarry – reverse faults   D. Tucker's Point – reverse fault

Figure 5.2. Examples of normal and reverse faults in Bermuda's two oldest limestone formations - the Walsingham and Lower Town Hill Formations. See Figure 5.1 for locations.

There is no inventory of faults for Bermuda and none are identified on the geological map (Vacher et al, 1989). Geologists who have worked in Bermuda, in the past, may each have been aware of a fault or two but these were discounted, perhaps wishfully, as anomalous products of localised cave collapse. The number of faults that have been definitively identified - invariably on the basis of palaeosol displacement - has continued to grow over the last few decades. However, it is likely that less than half of existing exposed faults have been recorded, even now, because of reluctance to do so in the absence of a prominent displaced horizon such as a palaeosol.

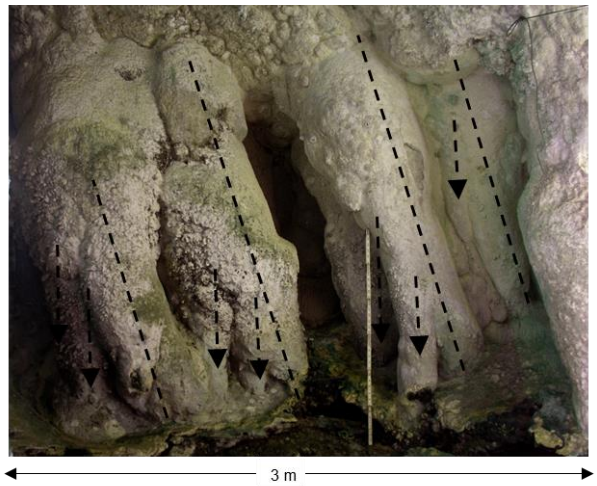
Caves, to which faulting has been linked, occur at a high density within the Walsingham Fm. The vast majority of these caves are the product of collapse by the incremental failure of breakdown domes – a process otherwise known as upward "stoping" (Figures 5.3.a and b). The question arises as to whether phreatic solutional void-creation combined with gravitational loading were solely responsible for these internal roof failures or did tectonic instability in the form of earthquakes play a role (Figures 5.3.c and d.)?

Combinations of normal and reverse faults have been associated elsewhere in the world with subsidence of magmatic chambers (Walter and Troll, 2001) and, on rare occasions, with the collapse of coalesced cave systems (McDonnell et al, 2007; Loucks, 2007). These occurred on a large scale, affecting significant thicknesses of overburden which settled, or sagged, into laterally extensive chambers multiple hundreds of metres wide. Given that the depth to volcanic rock in the areas of Bermuda where faulting is most common is only 30 metres below sea level, little space is afforded, within the limestone "cap", to develop a cave system of adequate dimensions to explain settlement-faulting. Deep SCUBA dive expeditions both within flooded caves and along the platform margin, at sea, which have been undertaken with the specific objective of penetrating a system of interconnected chambers, or collapsed remnants thereof, at the base of the limestone have failed to do so. Furthermore, numerous boreholes with which the author is personally familiar, invariably exhibit a sharp contact between limestone and volcanic rock, with no sign of the vadose conduits into which overburden might have collapsed as envisaged by Mylroie (1984) and by Mylroie and Carew (1995). The concept of subterranean vadose stream-flow along the upper surface of the volcanic pedestal is predicated on an assumption that ground water completely drained away at low sea levels. It is more probable that phreatic (saturated) conditions persisted at the limestone/volcanic rock contact throughout the Pleistocene other than peripherally, where springs emerged at the coast.

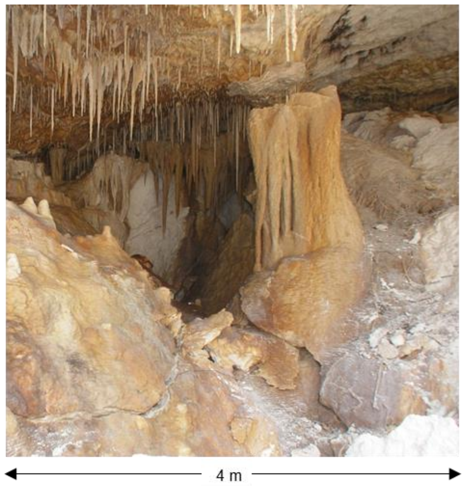
The existence of a capacious vadose cave system into which overburden settled/collapsed, thereby providing a mechanism for faulting, appears doubtful. An alternative model for cave development on Bermuda has been provided by research on the island of Mallorca; where rather than attributing collapse and physical removal of material to the existence of vadose channels, Gines and Gines (2007) propose that phreatic processes, spanning multiple interglacial

a. Cave at Government Quarry. Note intact arched roof and large breakdown blocks. The cave is the void that has been created between these two

b. Cave at Lolly's Well exposed by excavation. Note interior breakdown blocks (not related to excavation) and the thin cave roof, which has progressively collapsed from below.



c. Cave at St David's Head with speleothem columns tilted at ~15 ° relative to vertical. Bifurcation (arrows) appears to represent post-tilting re-growth. (White rule was set exactly to vertical).



d. Cave at Lolly's Well. A long period of speleothem growth was interrupted by an event which caused fracturing and displacement of the large column.

Figure 5.3. *Features of Bermuda's cave which attest to structural instability.*

highstands, made space for progressive collapse by removal in solution of both bedrock and breakdown material. Tidal pumping, known to be pervasive throughout Bermuda's cave system, was identified in Mallorca as the mechanism by which large quantities of dissolved limestone could be transported out of the caves. Gines and Gines (2007) argue that falling sea-levels at the end of each interglacial would have been conducive to roof collapse as the buoyant support previously provided by ground water was withdrawn to a lower level. Such a model of intermittent internal roof collapse is consistent with the observed scale and characteristics of Bermuda's caves and their intact vaulted roofs (Figures 5.3.a and b).

In short, there is no persuasive model, applicable to Bermuda, by which gravitational cave collapse could translate into faulting, even if large deep voids were to be discovered here. This conclusion is supported by the absence of faulting associated with Mallorcan caves, despite the existence of "mega-chambers", which span to 5000 to 10000 m^2 (Gines, 2000).

5.3. DISCUSSION

Tectonic instability has repercussions for the application of glacio-hydro isostatic models which have been developed in part on the basis of RSL data from Bermuda, such as Raymo and Mitrovica (2012) and Dutton and Lambeck (2012). However given the scale of the anomalies attributed to GIA of at least 10m at MIS 11 (Bowen, 2010) and MIS 5a (Muhs et al., 2002) vertical displacement of more than 2m would probably be required over the last half million years to threaten the viability of these models. Given the preferential concentration of faulting in the oldest formations of the early Pleistocene the evidence of significant recent instability is quite low. Nevertheless, the Bermuda palaeo-RSL curve continues to be problematic. While all of the Pleistocene palaeo-RSL imprints on Bermuda (now to include MIS7) are metres higher than those at stable far-field localities, that at MIS5e (~+6m ASL) is at the same elevation as those at more southern localities. This is to say that at MIS5e the combination of GIA and glacio-eustatic signals at Bermuda produced the same sea-level, relative to present sea-level, as that attributable to a dominant glacio-eustatic signal at far-field sites. According to Potter and Lambeck (2004) the critical factor here is the taking of measurements "relative to present sea-level". The isostatic adjustment of the mantle and lithosphere lags behind ice sheet volume changes to different degrees depending on the rapidity of those changes and on lingering interference from prior cycles. In short, Potter and Lambeck's (2004) argue that because the history of ice-sheet volume-changes leading up to MIS5e was different to, for example, that at MIS5a their respective measured elevations, relative to the present sea-level datum (which is still subject to GIA), cannot be compared directly. If correct, this preserves the credibility of the GIA model at intermediate-field localities such as Bermuda and Florida and tectonic instability need not necessarily be invoked.

Regardless of the evidence from relative sea-level change, faults and earthquakes are phenomena of Bermuda which are readily attributable to tectonic stress within the oceanic plate around the seamount. Sea floor spreading at the Mid Atlantic Ridge generates compressive forces and associated flexuring of the oceanic crust that would account for such stress.

Significantly, this in turn could have the potential to cause non-isostatic vertical movement of Bermuda. On the other hand, in other parts of the world, earthquakes and faulting have been associated with glacial-isostacy (Morner, 1991). It is possible therefore that glacio hydro-isostacy at Bermuda has activated weaknesses within a tectonically-flexured crust and triggered the propagation of minor faults through the seamount. This may be difficult to prove, but would mean that rather than structural instability being an anathema to models of glacio hydro-isostacy, it could be a manifestation of the phenomenon.

6. A NEW MODEL FOR THE CONSTRUCTION OF BERMUDA BY LANDWARD-ADVANCING MOBILE DUNES

6.1. INTRODUCTION

6.1.1. The eolianite-dominated geology of Bermuda

Bermuda's eolianites accumulated in hummocky ridges which generally parallel the closest shoreline. At its widest point, in the central parishes, the main island of Bermuda comprises three such ridges which are approximately E-W aligned and separated by linear depressions locally occupied by marshland. Ridge crests, typically, reach elevations of 40 to 50 m above sea level, but can be higher where ridges have coalesced. Bermuda's highest hill - Town Hill - at 76m above sea level is an example of such a composite structure.

The Geological Map of Bermuda (Vacher et al., 1989) identifies six eolianite-dominated limestone formations separated by geosols (Figure 6.1, Appendix I). Generally, it upholds Sayles' (1931) division of the Bermuda islands into a core of older limestones fronted on the seaward sides by ridges of topographically more prominent, younger limestones. Bermuda's eolianites are uniquely well exposed in natural coastal cliff faces, in road cuts, in quarries and in excavated rock faces behind the many houses that are "notched" into the hillsides. The quantity and extent of exposures and the high definition of sedimentary structures is attributable, respectively to a hilly topography and differential cementation of the eolianites which emphasises fine laminae. Large sets of dune cross-strata alternating with palaeosols are revealed in interior exposures; while the minority of coastal cliffs which are not formed entirely of eolianites, display sequences of emergent sub-tidal, inter-tidal and supra-tidal deposits associated with Pleistocene sea-level highstands. The extent and quality of the eolianite exposures has allowed reconstruction of dune bedforms, from which the depositional history as well as the mobility of the dunes can be inferred.

6.1.2. Modern dunes of Bermuda

Modern dunes on Bermuda take the form of vegetated foredunes, and are restricted to the backshore of a few embayed beaches along the south shore, such as Horseshoe Bay, Warwick Long Bay (Figure 6.2) and Elbow Beach.

Notwithstanding their current state of relative stability, Bermuda's coastal dunes have exhibited pulses of activity in the 19th century. At Elbow Beach, dunes which climbed to a height of 55 metres and advanced at rates of 3 to 6 metres per year, as documented by Nelson in 1837, were still active when visited, as an object of scientific curiosity, by British scientists of the Challenger expedition in 1873 (Figure 6.3). Later still, Heilprin (1889) observed active dunes at Elbow Beach and Tuckers Town which he described as "great tongues of sand" and "sand glaciers…stealthily encroaching on hilltops of the interior and burying everything" including houses at both locations.

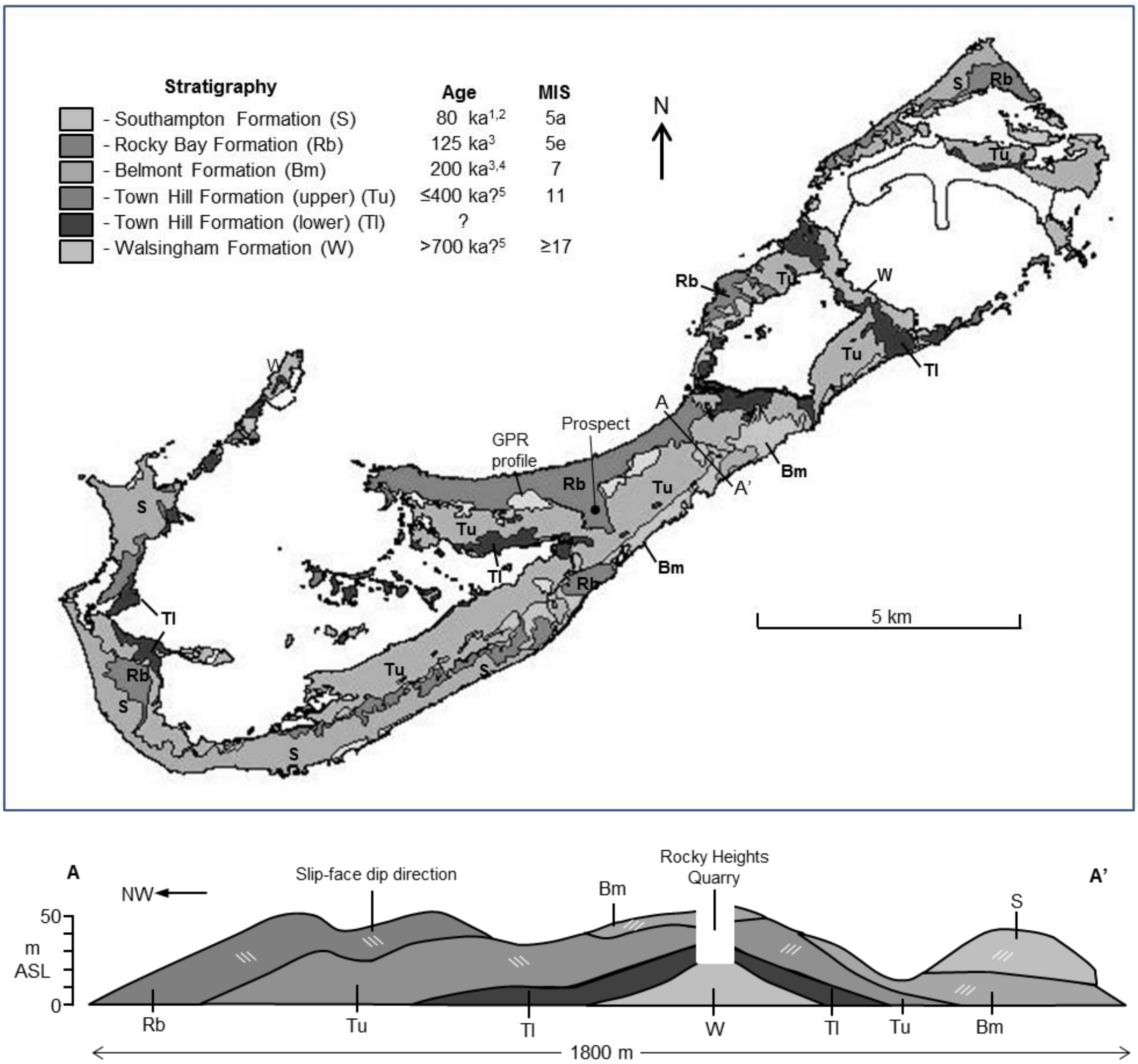


Figure 6.1. The geological map of Bermuda and cross-section (after Vacher et al, 1989). Six allostratigraphic formations are dominated by eolianites. A central core of older formations fringed on the seaward side by younger formations is consistent with a beach-source of sand for dune-building. Landward encroachment of the dunes is evidenced by inland projections, such as in the Rocky Bay Formation at Prospect. Vertical stacking of the formations (Section A – A') is not consistent with growth of Bermuda by lateral accretion of successive beach-tied ridges as depicted by Bretz (1960) and subsequent researchers. Average ages of the three youngest formations were determined by U-series dating of coral fragments collected from marine members of respective formations ([1] Ludwig et al., 1996; [2] Muhs et al., 2002; [3] Harmon et al., 1983; [4] Rowe et al., 2014). Stated ages ([5] Hearty and Kindler, 1995) of older formations, whose relationship with datable marine members is uncertain, are based on limited data from a variety sources and can be considered estimates.

Some of this, historical, dune activity in Bermuda was tentatively attributed to "clearing of brush" during construction of coastal fortifications. However, this explanation does not fully account for the coincidence of dune advances at separate locations which persisted for several decades. Possibly, destruction of foredunes by a major hurricane and associated widening of beaches would have permitted wind-blown sand to accumulate in new un-stabilised dunes at a rate that temporarily outpaced colonisation by vegetation. Today, there is little remaining evidence of this historical dune encroachment; and even as early as 1931, Sayles observed an almost total absence of dune activity on modern Bermuda.

6.1.3. Investigating dune morpho-dynamics on Bermuda

Bermuda's eolianites have consistently been portrayed in the literature as accretionary bedforms which following deposition by storm winds (Vacher, 1972; Hearty and Olson, 2011) were promptly immobilised by rapid cementation (Bretz, 1960; Vacher, 1960; Mackenzie, 1964; Hearty, 2002). Testing of these hypotheses is aided by the excellent exposure of the internal structure of the eolianites along with the availability of over 3700 slip-face dip azimuth measurements and 20 years of hourly-wind data compiled in spreadsheets for this study. A drift potential analysis is employed to establish the theoretical orientation of dunes had they developed solely under the control of prevailing winds (above the threshold velocity). This orientation - the resultant drift direction - is used as a reference point against which observed orientations can be compared.

6.2. RESULTS

6.2.1. Winds and climate at Bermuda

Bermuda's climate is subtropical and frost-free. Average daytime temperatures range from approximately 19°C in February to 29°C in August. Rainfall is relatively evenly distributed throughout the year with an annual average of 1458 mm. Annual potential evapotranspiration is approximately equal to rainfall, with water budget surpluses in the winter compensating for summer deficits. Rain tends to be delivered by frontal systems in the winter and by tropical disturbances and local thunderstorms in the summer. Extended wet periods are usually caused by slow-moving weather fronts tracking eastward from North America.

As part of this study, an analysis was conducted of 20 years of hourly wind data collected between 1975 and 1995 at the US Naval Air Station in Bermuda (Appendix C). This returned average and modal wind directions of approximately southwest and south-southwest, respectively. These prevailing winds are associated with a high pressure system which builds to the east of the islands in the summer months - the "Bermuda-Azores High". Winds with higher strengths exhibit a bias towards a west-northwesterly direction (Figure 6.4). They are often associated with low pressure systems, and related fronts, which track eastward across the North Atlantic in the winter - at a time when the high pressure system, which otherwise tends to block these lows, has migrated to the south. A drift potential analysis (Fryberger, 1979) applied to the

Figure 6.2. A fully stabilised foredune ridge on a reflective beach at Warwick Long Bay, 2012. During hurricanes the foredunes are scarped and the beach is flattened into a dissipative profile by large waves. This last occurred in Hurricane Fabian in 2003. (oil barrel for scale)

Figure 6.3. Historic dune encroachment at Elbow Beach (where now there is none). On the left is a photograph taken by members by the Challenger expedition to Bermuda in 1873 and on the right is a true-to-life 1830's painting from the Johnson Savage MD Collection, National Museum of Bermuda.

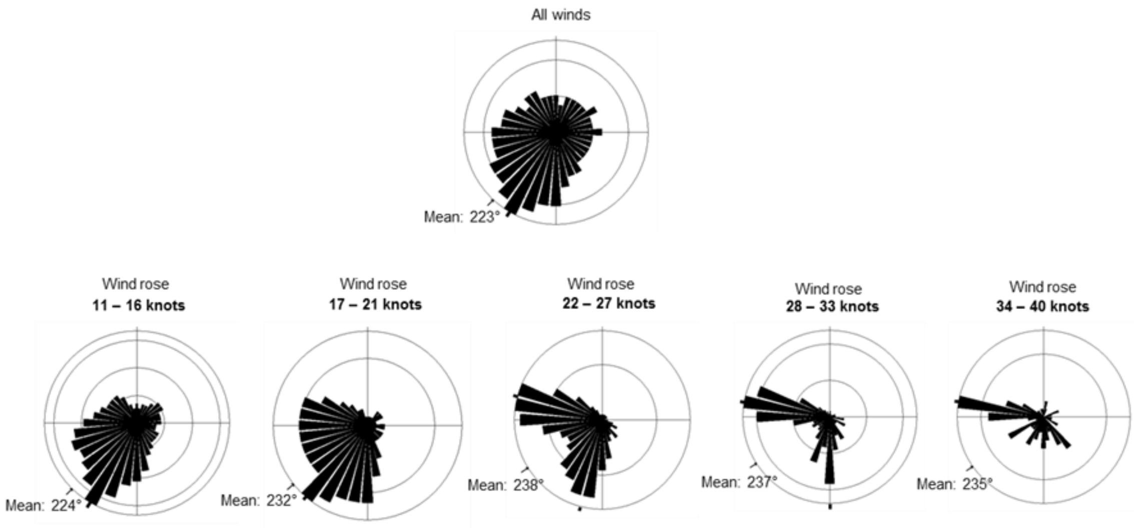


Figure 6.4. Wind roses for Bermuda based on an analysis of hourly wind data collected at the US Naval Air Station over 20 years between 1975 and 1995. Note increasing bimodal directional bias with higher wind strength bins up to that of 28 to 33 knots. Data for winds below the threshold velocity of 12 knots (Fryberger, 1979) are omitted.

wind data, as described in Section 1.4.5, produced a resultant drift direction of 054° which is consistent with the average direction of the wind in the strength ranges which had the highest vector units (Appendix C).

6.2.2. Dune vegetation

In 2012, 28 species of vegetation comprising vines, herbs, shrubs, grasses and a few trees were identified on a 150m transect which traversed the upper beach, the foredune ridge and the back-dune swale near Warwick Long Bay on Bermuda's south shore (Appendix D). This compares with 23 species identified at the same location in the 1960s (Watson et al., 1965) and 17 dune species catalogued by Harshberger in 1908 for Bermuda as a whole.

Although the biodiversity of Bermuda's dune plant-life has significantly increased, over the last century, because of introduced species, many of the prominent shrubs and plants of today which trap airborne sand, such as the beach croton (*Croton punctatus*) and beach lobelia (*Scaevola plumieri*) also occupied the dunes at the time of Harshberger's 1908 survey. As for vines and grasses: seaside morning glory (*Ipomoea pes-caprae*) and seashore rush grass (*Sporobolus virginicus*) continue to contribute to ground cover much as they always did, while the burr grass (*Cenchrus tribuloides*), a newcomer to the dunes, appears to have partially filled a niche previously occupied by the disease-inflicted St Augustine's grass (*Stenotaphrum secundatum*)

6.2.3. Eolianite Stratification and bounding surfaces

Preserved slipface-less bedforms with low-angle seaward and landward dipping strata, characteristic of retentive dune structures, such as Stage 1 foredunes (Hesp, 1988), are relatively rare in Bermuda. Where such bedforms exist, they are invariably superposed on prograded beach foreshore deposits at coastal exposures, and are entombed by later dune strata which include slip-face foresets (Figure 6.5). Since they developed proximally on the beach, the scarcity of demonstrable foredunes is almost certainly attributable to coastal erosion. It is the, more distal, slip face foresets of the dunes which advanced landward beyond the foredunes that tend to be preserved at the present coast.

Slip-face foresets are a prominent feature of the eolianite exposures in Bermuda. They comprise high-angle planar cross-stratification which dips generally landward at between 32° and 34° - close to the angle of repose of dry sand. Sets of these strata, typically 5 to 15m in thickness, (Figure 6.6) are interpreted as the deposits of mobile advancing sand dunes. Their preservation indicates that individual aeolian dunes in Bermuda must have reached at least these dimensions in height and were most likely higher, given the evidence of their truncation.

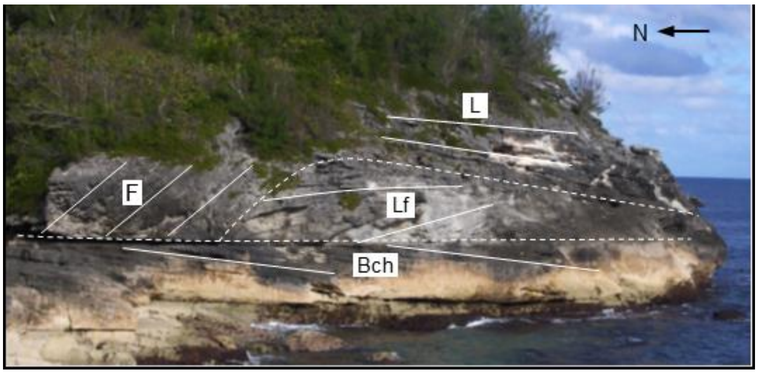


Figure 6.5. A 5 metre high foredune (Lf) overlying a prograded beach (Bch) is overtopped by low angle aeolian stoss slope strata (L) which feed into landward dipping slip face foresets (F) in the Belmont Formation at Spittal Pond west. (Site 38, Appendix G). For enlarged view see Figure 7.6.

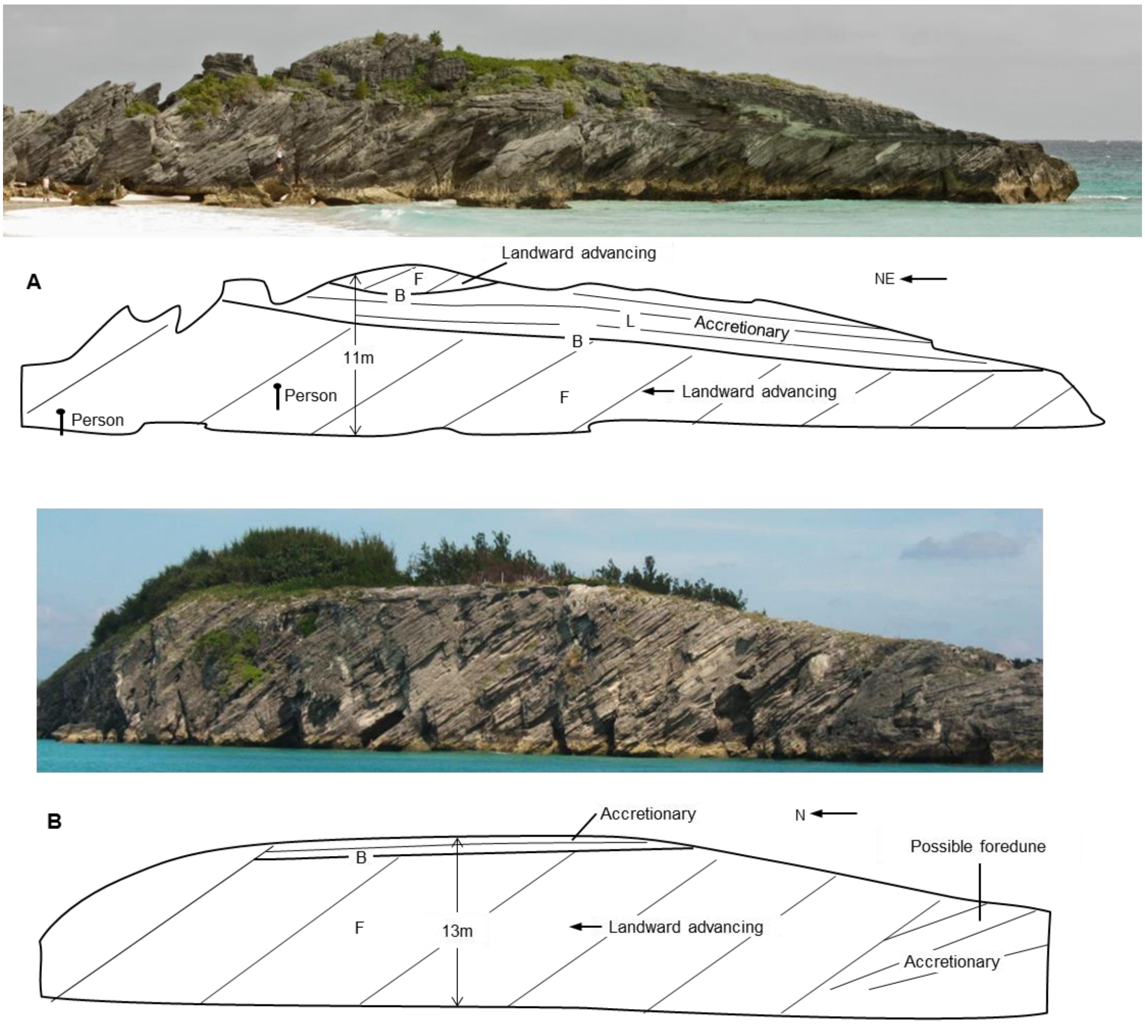


Figure 6.6. Large sets of slip face foresets preserved in the Rocky Bay Formation at two localities on Bermuda's south shore. In both cases the foresets are truncated by a sub-horizontal bounding surface superposed by low-angle strata. At locality A - Horseshoe Bay - two phases of lateral encroachment recorded by slip-face foresets are separated by period of vertical accretion. At locality B - Nonsuch Island - the overstepping of a slipface-less dune by a large advancing dune may represent a reduction in stability as sediment supply exceeded the retentive capacity of vegetation perhaps in response to a sea-level regression (see Chapter 7). Note that in both cases that substantive dune building coincided with sea level that was lower-than-present, as evidenced by partially submerged slip-face foresets.

Low-angle sub-horizontal laminated deposits are typically superposed on planar bounding surfaces which truncate slip-face foresets (Figures 2.3 and 6.6). Their thicknesses are usually on the order of a few metres but can exceed this, thereby matching or exceeding the volume of the usually dominant slip-face strata (Figure 6.7). Goldsmith (1973) attributed low-angle sub-parallel strata in coastal dunes to accumulation of wind-blown sand on vegetated surfaces. Hunter (1977) and Pye and Tsoar (1990) pointed to aeolian climbing ripple migration as the process responsible for accumulation of low-angle planar strata, termed "sub-critically climbing translatent stratification" within coastal dunes. White and Curran (1993) concurred with respect to Bahamian Holocene eolianites, that accretion was predominantly the outcome of climbing wind ripple migration. It is probable that low-angle sub-parallel lamination on the stoss slope of Bermudian dunes developed under similar circumstances, involving climbing ripple deposition and retention of sand in vegetation to varying degrees.

6.2.4. Slip-face foreset orientation

The extent and quality of exposures in Bermuda has allowed measurement of 3751 foreset dip directions across the islands. Figure 6.8 summarises these data, with each arrow accurately indicating the mean dip azimuth for one of the 168 sample areas (Appendix E). The three dominant slip-face dip directions - northward, eastward and southward - are correlative with spatial distribution relative to the shoreline. Slip-faces close to the north shore tend to dip south, those close to the west shore tend to dip east and those close to the south shore tend to dip north. The scarcity of westward dipping slip-face foresets can simply be attributed to the extremely low frequency of winds, in any strength category, from the east.

The orientation of dune bedding is consistent with the observation of "pervasive landward dipping cross-bedding near the angle of repose" by Vacher (1972). These data similarly uphold Sayles' (1931) conclusion that "The direction in which the dunes migrate is not primarily a function of the prevailing winds, but is in part controlled by the source of supply. Obviously sand must migrate away from its source". In terms of the impact of winds, it is the resultant drift direction (Fryberger, 1979) that best predicts the net direction of sand transportation for a given wind regime. Knowing this direction, which is 054° (Figure 6.8), does little to elucidate the question of observed dune orientations on Bermuda.

Equivalency between present-day climatic conditions and those of previous Pleistocene interglacials has been inferred from deuterium profiles within Antarctic ice cores (Jouzel et al., 2007). Comparable global temperatures are, also, inferred by eustatic sea level which peaked within 10m or so of present sea level at successive interglacial highstands (Siddall et al., 2006). Since dune building on Bermuda is correlated with interglacials, it can be argued that the wind regime in which eolianites accumulated was broadly similar to that of today, as represented by a northeasterly resultant drift direction.

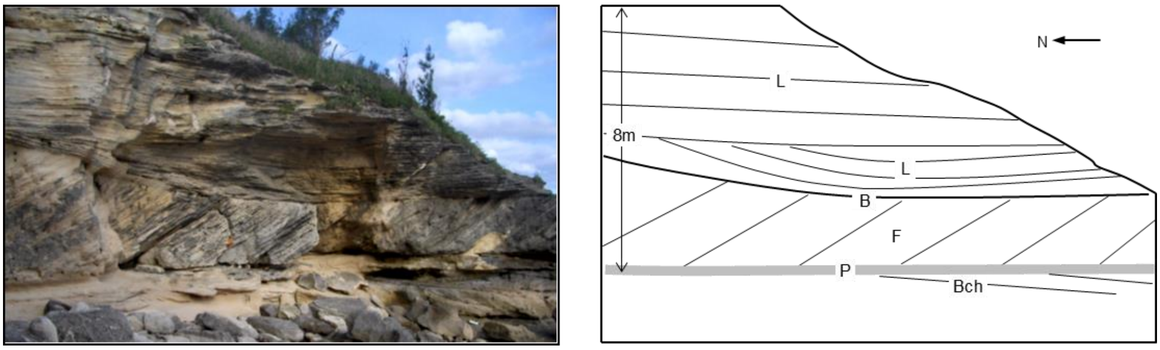


Figure 6.7. Low-angle aeolian strata in the Belmont Formation at Spittal Pond West. (Site 35, Appendix G). The low-angle stoss slope strata (L) are, in this case, superposed on lesser thicknesses of slip-face foresets (F) with an intervening bounding surface (B). Below the dune foresets is a protosol (P), then beach (Bch) and shoreface deposits. The low angle stratification (L) is interpreted as the product of wind ripple migration and retention of sand in vegetation.

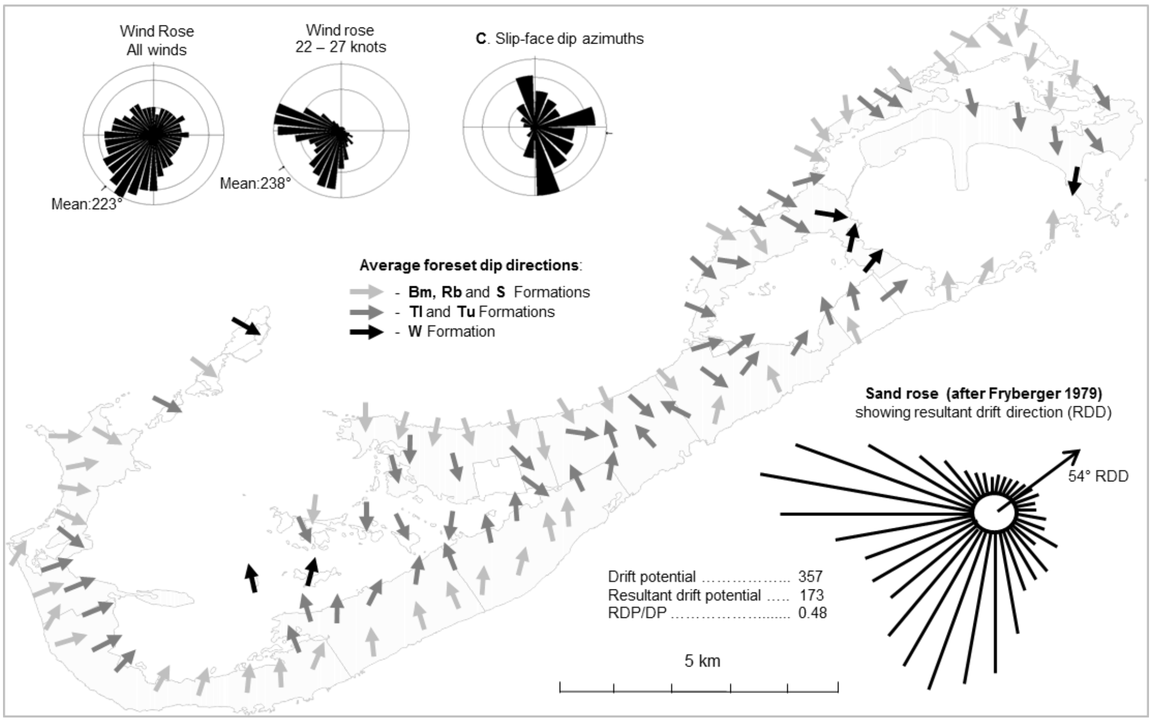


Figure 6.8. Slip-face dip azimuths on Bermuda in relation to wind direction data. Foresets dip predominantly landward, or towards interior basins, whereas winds with the highest drift potential in Bermuda, in the range of 22 to 27 knots, tend to blow from the south and west as reflected in the northeast resultant drift direction (RDD). Abbreviations of formation names are shown in Figure 6.1. See Appendix E for more detail.

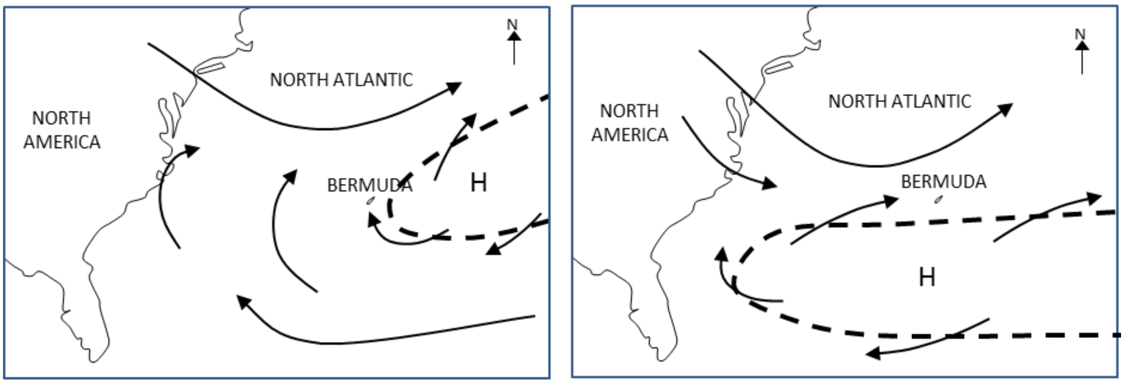


Figure 6.9. Change in atmospheric circulation pattern around Bermuda in response to a shift in the dominating high pressure system from its current summer position (left) to a more southerly summer position (right) which is postulated in the event of cooler global temperatures. (adapted from Watson et al. 1965)

General circulation models for the North Atlantic suggest that winds at Bermuda during the Pleistocene, as today, were dictated by the position of a high pressure system sitting to Bermuda's east and south. This is responsible for an airflow, which originates in Africa and then arcs across the Caribbean before arriving at Bermuda in the form of southerly winds (Herwitz et al., 1996). During glacial periods, the high pressure system would have drifted south, subjecting Bermuda to a higher frequency of westerly winds than at present (Figure 6.9). Conversely, had the Pleistocene interglacial climates been somewhat warmer than present, as implied by the oxygen isotope levels recorded in Bermuda speleothems (Harmon et al., 1978), Bermuda would have been subjected to the influence of a more northerly-situated high pressure system, and southerly winds would have persisted for more months of the year than they do now. The evidence is tenuous, however, and potential climate variations add little to our understanding of dune orientations which appear to be source-controlled. Indeed a putative tendency towards more persistent southerly winds during interglacials is contradictory to the high frequency of southward dipping slip-face foresets, presumably associated with northerly winds.

6.2.5. Ground Penetrating Radar (GPR) Survey

A 300m long profile was collected along the road cutting of the Black Watch Pass which was excavated, during the 1930s, through a prominent topographic dune ridge in order to connect the north shore with the City of Hamilton. The road cutting is up to 30m deep and exposes a section through cross-stratified limestones that are part of the Rocky Bay Fm. This exposed road cut is interpreted to include sets of trough cross-stratification overlying landward (southward) dipping slip-face strata deposited by advancing dunes that appear to overly foredune ridges with protosol development. One aim of the GPR survey was to image beneath the road-level in the hope of identifying beach deposits in an equivalent, subjacent, position relative to aeolian strata as observed on the south shore.

The GPR profile shown in Figure 6.10 has imaged to a depth of approximately 12m. At its northern end, closest to the shoreline, the radargramme shows discontinuous inclined reflections that dip towards the north at around 11°. These low-angle inclined reflections are interpreted as sets of cross-stratification that accumulated as foreslope, or stoss-slope, accretion on the seaward side of the dune ridge. The inclined reflections can be correlated with thin-bedded, inclined strata exposed in the road cutting. After 50m, continuous, high amplitude, convex reflection appears at a depth of around 8m and rises towards the surface beneath 80m and then dips down to a depth of 10m beneath 100m. Beneath the high amplitude reflection there are inclined reflections that dip inland towards the south. The inclined reflections are interpreted as cross-strata deposited by an advancing dune migrating inland.

The convex, high-amplitude reflection that appears to preserve the dune morphology is interpreted as a palaeosol capping a foredune, although this cannot be confirmed due to a lack of exposure. Between 100m and 190m the radargramme shows discontinuous concave reflections that are interpreted as sets of trough cross-stratification produced by dunes that were migrating perpendicular to the profile, most likely driven by the prevailing southwesterly winds. Between

190 and 207m there is a horizontal reflection at a depth of 4m which coincides with the section of the road cutting that runs through a tunnel. The horizontal reflection is interpreted to be an airwave reflection from the roof of the road tunnel. Between 245 and 300m the upper part of the radargramme is dominated by a wedge of low-angle inclined reflections that thickens towards the south. These reflections, which dip landward at approximately 15°, are similar in character to the seaward dipping low-angle inclined reflections at the northern end of the profile but with an opposing dip. They could be interpreted as backslope dune deposits on the landward side of a foredune ridge. However, at the time of deposition, the area to the south of the ridge which is now marshland might have been a lagoon with its own shoreline, in which case the low-angle inclined reflections could represent foreslope accretion from the lagoon shore, mirroring the low-angle reflections at the northern end of the radargramme. Beneath the low-angle inclined and concave reflections there is a continuous reflection that can be traced along most of the radargramme which is interpreted as the water table. The reflection slopes gently towards the sea. At 300m it is at a depth of 8.5m and at 100m it is at a depth of 12m. The unexpectedly high gradient of the water table could be apparent rather than real; being attributable to a subtle inclination of the road which was not corrected for.

Interpretation of the GPR profile at Black Watch Pass suggests that the section beneath the road level and above the water-table is composed of eolianites. No evidence either for beach deposits beneath the dunes or for beach deposits which transition laterally into dunes was found at this location. Instead, the eolianites exposed above road level in the Black Watch Pass overlie an older eolianite capped by a protosol, revealed by GPR. This demonstrates that there are two stages of substantive dune building represented in this Rocky Bay Fm ridge. Foredunes (preserved largely below road level) developed in the first stage, and following a hiatus, advancing dunes (preserved largely above road level) advanced over the foredunes from the north. If correctly interpreted, this reflects an evolution from static to migrating bedforms similar to that observed in some south shore exposures (Figures 6.5 and 6.6.B).

6.3. DISCUSSION

6.3.1. Emplacement of dunes

A pattern of seaward accretion of aeolian dune ridges is generally upheld by the geological map of Bermuda (Vacher et al, 1989). However, closer examination of the arrangement of formations, particularly in cross-section, tells a somewhat different story. In many instances, it is apparent that sinuous dune ridges and their lobate projections have encroached onto older elevated terrain and overstepped or by-passed their predecessors (Figure 6.1). The same conclusion was drawn by Carew and Mylroie (1995) with respect to the Bahamas - that individual topographic ridges are not the outcome of single depositional events. There, as in Bermuda, the topography is a manifestation of vertical stacking and overlapping of eolianite formations. Exceptions do exist, such as the substantial ridgeline on the north shore of Bermuda's central parishes (the site of the GPR profile), which is largely constituted of a single geological formation - the Rocky Bay Fm;

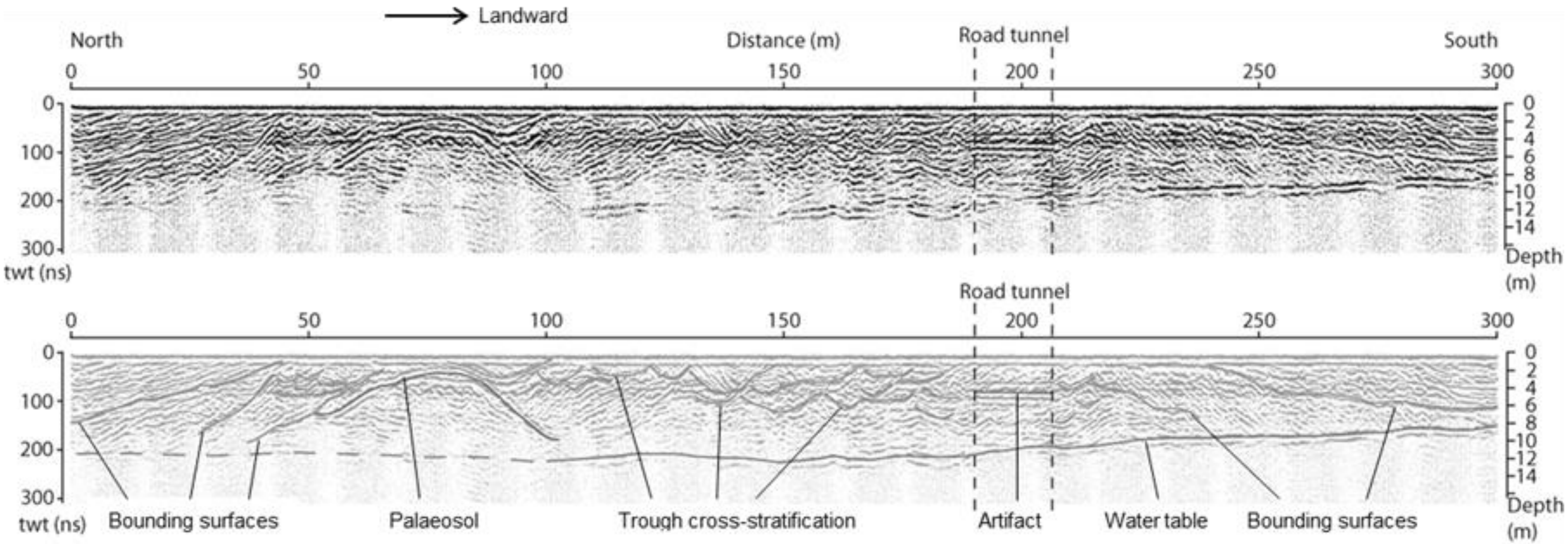


Figure 6.10. Ground Penetrating Radar (GPR) profile below road level at Blackwatch Pass. The road is near-level so no topographic correction was applied. See text for interpretation.

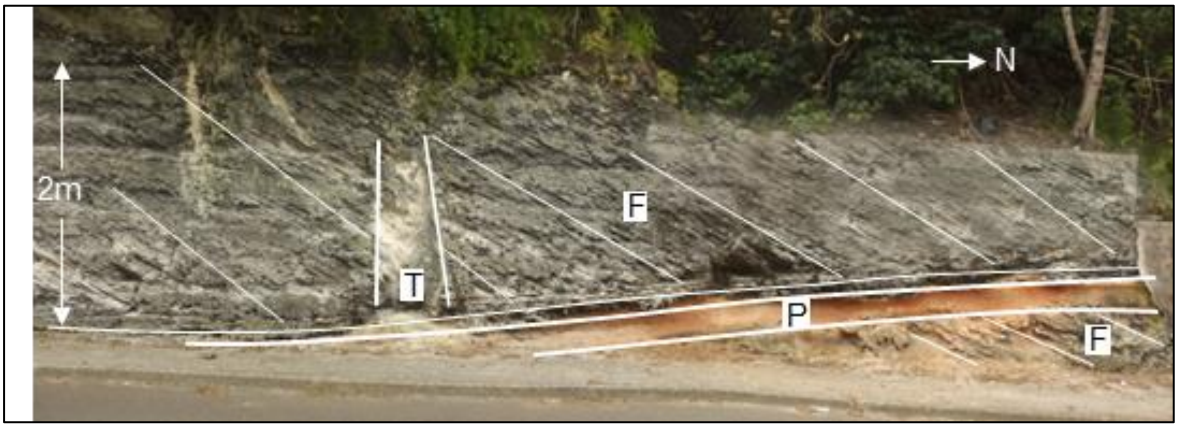
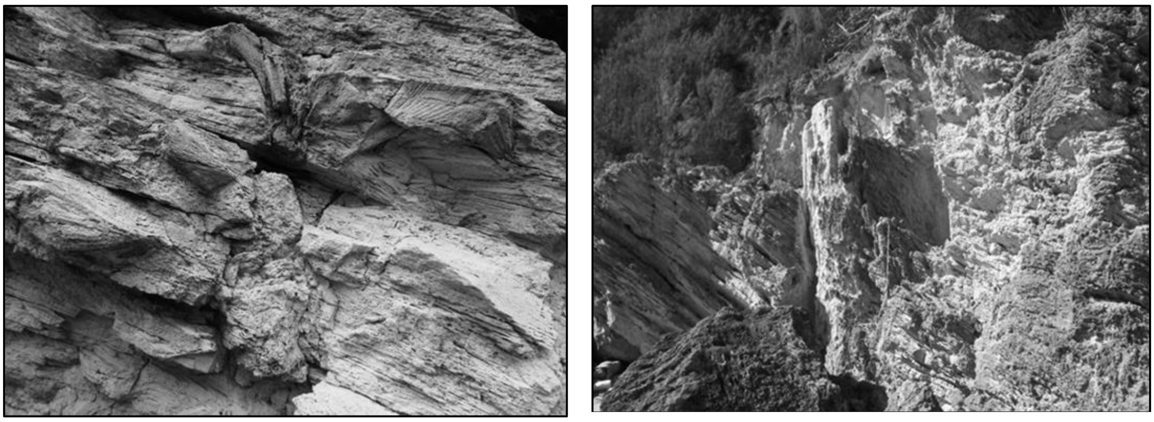


Figure 6.11. Slip-face foresets of an advancing dune in the Rocky Bay Formation. The foresets (F) at Khyber Pass in Warwick Parish encroached onto an interior terrain 30m above present sea level and 750 m from the present south shore. Burial of a wooded landscape is recorded by preservation of a palaeosol (P) and tree mould (T). Foresets of the Belmont Formation, which in this part of Bermuda is largely overstepped by the Rocky Bay Formation, are preserved below the palaeosol.



a **b**

Figure 6.12. Fossil tree moulds and palm frond impressions. **a.** Mould of 4 metre high palmetto tree trunk (*Sabal bermudana*) and impressions of the ribbed branching fronds preserved within eolianite of the Rocky Bay Formation at Hungry Bay west. **b.** Mould of an approximately 1 metre diameter tree trunk (thought to be *J. Bermudiana*) preserved within eolianite of the Belmont Formation at Saucos Hill.

albeit that internal protosols evidence two of more phases of dune building. It is possible that this ridge developed at a lower sea level than most other eolianites. This would have shifted the source-beach further to seaward allowing space on a prograded shoreline for the accumulation of dunes which for the most part remain topographically distinct from their landward predecessors. The arguably retentive morphology of this ridge is gainsaid by large sets of slip-face strata, in the road cut at Blackwatch Pass, and by an advancing tongue which projects centrally, at Prospect, onto elevated terrain comprising older formations (Figure 6.1).

Unlike fixed coastal frontal dunes, or foredunes, which rest on contemporaneous littoral sediments (Land, 1964 and Hesp, 2005), most of Bermuda's substantive Pleistocene dunes are superposed directly on a palaeosol (Figure 6.11); the exception being where they occasionally lie against an erosional unconformity which is stratigraphically correlative with the palaeosol. Such encroachment onto a soil or rocky terrain is, according to Woodroffe (2002), the definition of "transgressive dune" behaviour, which here would be termed "advancing dune" behaviour.

6.3.2. Tree fossil preservation

Well preserved impressions of palm fronds (Figure 6.12.a) are quite common in Bermuda's eolianites. They have been cited (Hearty and Olson, 2011) as evidence of rapid dune deposition (see later) and prompt cementation. The grounds for such conclusions have not, however, been fully explained. Dead palmetto leaves tend to be very resistant to decomposition and probably even more so when entombed in fine aeolian sand. Certainly carbonate dunes eventually undergo cementation, but no empirical evidence has been presented that establishes at what rate of cementation, relative to the rate of decomposition, preservation of a frond impression is ensured.

Tree trunks are often preserved within dunes as moulds comprising cylinders of structureless sand (Figure 6.12.b). This suggests that following burial or partial burial, inside-out decomposition created a cast into which un-cemented dune sand later flowed. Furthermore, the occasional clean truncation of fossil tree molds at bounding surfaces evidences a significant delay prior to dune re-activation - a delay long enough for complete decomposition of the tree but not long enough for dune cementation to take place, assuming that only un-cemented dunes can be re-activated. Ongoing investigations by Indiana University (http://www.iun.edu/news/2014/baldy-research-argyilan.htm) into tubular collapse features in active dunes at Mount Baldy National Park in the U.S.A. appear to corroborate this progression of events that leads to tree-cast infilling. The delay between tree burial by advancing dunes and creation of a void is approximately 70 years according to Erin Argyialan of Indiana University (pers. comm.).

6.3.3. Dune morphology

The slip-face dip azimuths of Bermudian dunes are directed predominantly onshore, with an average standard deviation for individual dunes of no more than 20 degrees according to Mackenzie (1964). Mackenzie viewed this as evidence that a large proportion of Bermudian dunes advanced inland along sinuous transverse fronts – a conclusion which is corroborated by the analysis of foreset orientations, completed as part of this study (Figure 6.14 and Appendix E). Given his endorsement of Bretz's position on incipient dune cementation, Mackenzie (1964) must have been unaware that transverse morphology and an internal structure dominated by slip-face foresets are diagnostic of mobile advancing dunes. Foreset strikes are aligned sub-parallel to ridge crest-lines and to shorelines. Convex-outward foreset arcs associated with sand tongues and lobate projections from the leeward front of transverse ridges (Figure 6.14) match those described by Cooper (1958) in Oregon (Figure 2.2) where dunes remain mobile until stabilised by vegetation. Sinuous ridges with projections should not be mistaken for "coalesced retentive mounds", which is how Bermuda's dunes have been traditionally characterised (Bretz, 1960; Mackenzie,1964; Vacher, 1972).

From geological mapping (Vacher et al., 1989) and from the analysis of facies assemblages (Chapter 7) it is inferred that dunes which extend 0.5km or more inland today were sourced from contemporaneous beaches to seaward and, likely, below the present shoreline. Vertical stacking of multiple eolianite formations (Figure 6.1) belies the prevailing hypothesis that the Bermuda islands were constructed through lateral accretion of immobile beach-tied dune ridges; each being deposited on the seaward flank of its predecessor.

6.3.4. Internal structure and orientation of slip-face strata

The interpretation of the internal architecture of a typical Bermudian dune as representative of a purely aggradational structure is contradicted by the conspicuous internal planar erosion surface or "characteristic bounding surface in the form of truncated foresets" (Vacher, 1972). While the internal structure of Caputo's (1995) San Salvadoran coastal dunes attests to retention, aggradation and aborted attempts at migration (Figure 2.3.a), the structure of a typical Bermudian dune attests to episodes of unrestrained landward encroachment in which new and recycled sand was transported to the slip face across an unstable planar dune top, faster than it could accumulate vertically. The large, often tabular, sets of exclusively slip-face foresets truncated by a superposed sub-horizontal bounding surface (Figures 2.3.b and 6.6.b) replicates architecture, identified by Rubin and Hunter (1982), that is diagnostic of sub-critically climbing transverse dunes. It is contended, here, that concomitant with fluctuations in sediment supply, periods of super-critical climbing, manifested as vertical accretion, alternated with periods of sub-critical climbing, manifested as stoss-slope erosion.

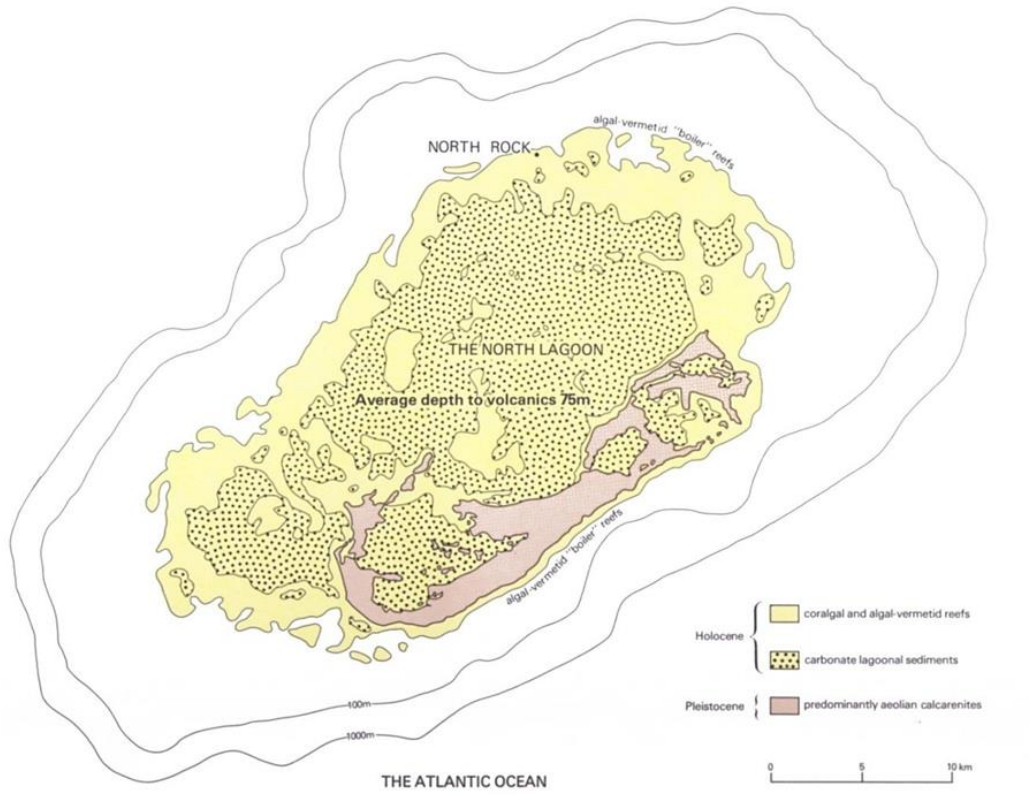


Figure 6.13. The Bermuda platform and the North Lagoon. (Vacher et al., 1989)

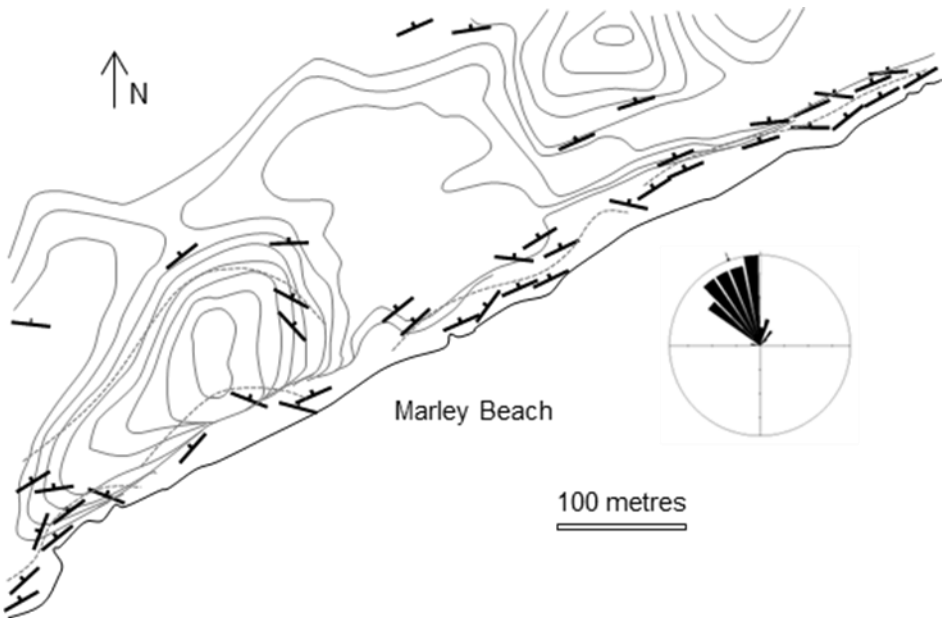


Figure 6.14. Orientation of slip-face foresets on Bermuda's South Shore. Unimodality exhibited in the rose diagram of dip azimuths, is diagnostic of a sinuous transverse dune ridge. Localised convex-outward curvature can be attributed to lobate projections from the ridge which appears to be preserved in the local topography at this locality in the Southampton Formation at Marley Beach.

The influence of geospatial factors on slip-face orientation is perhaps best illustrated by the domination of southward dipping slip-face foresets on Bermuda's long northern coastline. This is despite a wind regime which should, if similar to that of today, result in net sand transportation towards the northeast, as inferred by the resultant drift direction (Figure 6.8). This phenomenon is probably attributable to the position of the Bermuda islands on the southeastern edge of a large reef-rimmed lagoon (Figure 6.13) which acts as a massive sink for well-comminuted marine sands. Such an abundance of sediment available for transport, sitting to the north of the islands would, at critical stages of the glacio-eustatic cycle, have facilitated landward-directed dune building along Bermuda's northern shores, even if as today there were relatively few occasions when the winds blew favourably from the quadrant between north-west and north-east.

The question arises as to why the pattern of landward sediment transportation away from source beaches, was not appreciably modified by prevailing winds towards the resultant drift direction, i.e. towards the northeast. One answer could be that dune advance was more responsive to onshore winds, simply because they carried more sand. Another answer could be topographical wind modification caused by: 1). the sheltering effect of an interior hilly terrain which creates turbulence and degrades the sand-carrying capacity of wind other than that directed onshore. In other words, the effect of fetch. 2). A change in the angle-of-approach of winds which cross the shore from a seaward direction, more towards shore-normal, caused by drag-induced refraction at the boundary between sea and land.

6.3.5. Fixation by vegetation

While there may be differences as to the exact sequence of events which lead to dune building episodes on Bermuda, it is widely accepted that platform flooding at an interglacial highstand was required to generate carbonate sediment and transport it to the beaches which fed the dunes. Eolianite deposition has, thus, long been correlated with interglacial periods (Bretz, 1960; Land et al. 1967; Vacher, 1972). Even so, Herwitz (1992) took a position that dune activity was facilitated by severe climatic conditions at Bermuda prior to and during glacial maxima of the Pleistocene. He questioned the ability of aeolian dunes to form at nearly 80 metres above present sea level, unless there had been a reduction in vegetation cover caused by a cooling climate. Sayles (1931) had come to a similar conclusion. Unfortunately, attempts to establish a chronology of dune activity which is correlative with Pleistocene climatic fluctuations, as has been undertaken by optically stimulated luminescence dating for many global dune-fields (Kendrick et al., 1991; Andreucci et al., 2009; Roskin et al., 2011; Mauz et al., 2013), has not been possible in Bermuda due to negligible quartz content in the calcarenites.

Climatic conditions at Bermuda today are thought to be generally comparable to those of prior interglacial periods. The coastal dune activity models developed by Tsoar (2013) indicate that Bermuda's present climate regime would result in stable dunes, as presently observed, or a mixture of stable and active dunes. A much higher drift potential and/or much lower precipitation than are experienced today would be required to degrade vegetation and cause a transition to fully active dunes according to the Tsoar (2013) models. The need to invoke such extreme conditions is however questionable. The potential effect of sediment supply - not taken directly into account by the Tsoar models - must be considered first. Tsoar and Illenberger (1998) concluded that when winds with a high drift potential are coupled with a high sediment supply, flourishing vegetation can be overwhelmed even in a humid climate. In the case of the Holocene dunes of Northern Ireland, Carter and Wilson (1993) determined that when the sand supply exceeded 0.6 to 0.8 metres per year of vertical accretion the retentive capacity of thriving dune vegetation was exceeded and advancing dune activity ensued.

There is no reason to suppose that the various roles that trees, shrubs, vines and grasses play in the stabilization of Bermuda's dunes, today, were not adequately filled during the Pleistocene, albeit by fewer species. Evidence that sub-tropical conditions coincided with advancing dune activity on Bermuda is provided by frond impressions and trunk moulds of the endemic frost-averse palmettos (*Sabal bermudana)* within large thicknesses of slip-face strata (Figure 6.12.a). Furthermore, the survival of the endemic palmetto until today, through at least two full glacial periods, suggests that climate fluctuations were not extreme. Eolianites with internal protosols (immature soils), rich in fossil land snails (*Poecilozonites* genus), provide evidence that plants and shrubs were flourishing and capable of rapid dispersal across the dunes when sediment supply temporarily diminished. While vegetation with a low botanical diversity typical of an isolated mid-ocean island would on occasion have been exploited by disease, pests and fire, thereby contributing to dune instability, it is contended here that the principal control on dune activity was sediment supply. This will be discussed further in Chapter 7.

6.3.6. Fixation by cement

The case made for incipient cementation of Bermuda's dunes by Bretz (1960) and by most that followed (Land et al., 1967; Mackenzie, 1964; Vacher, 1972; Hearty et al., 2002) is contradicted by: the presence of laterally extensive sub-horizontal bounding surfaces; the dominance of slip-face strata over other types; and the emplacement of dunes on elevated, wooded interior terrain. These are the characteristics of mobile advancing dunes which have accreted laterally away from source beaches, as opposed to being "closely tied" to them as claimed by Bretz (1960). The low angle bounding surfaces which truncate slip-face foresets attest to episodes when the rate of sand deposition on the lee side approximately equaled the rate of erosion on the stoss slope. These processes, which represent recycling of sand from within the bedform, would be precluded by incipient cementation as defined by Bretz (1960).

The small foredunes on Bermuda's modern beaches (Figure 6.2) may develop a degree of cohesiveness through compaction and dampness, but the sand can otherwise be described as loose and friable. Their stabilisation, as with foredunes elsewhere in the world, is owed to binding and trapping by vegetation not to cementation. Through 19th century accounts of active "sand glaciers", it has been demonstrated that when the retentive capacity of vegetation is overwhelmed by sand supply, modern dunes of Bermuda are capable of extended periods of mobility. This corroborates evidence from the Pleistocene eolianites that carbonate cementation was not "incipient".

6.3.7. Rates of accumulation

Rapid deposition of Bermuda's dunes by storm winds was espoused by Vacher (1972) and more recently by Hearty and Olson (2011). The evidence they cite includes "enormous" uninterrupted sets of conformable foresets with no interbedded soil horizons, and the preservation of moulds of mostly upright palmetto tree trunks with associated impressions of un-decayed fronds, which supposedly witness burial in a single depositional event. Hearty and Olson (2011) invoked extreme high energy conditions in which they envisage "wet air-filled sediment cascading over the crest and into the lee of coastal dunes creating uninterrupted foresets … that rapidly buried terrigenous landscapes."

Storm conditions, with an associated sea-level surge and large waves, typically reduce the width of a beach and this, in turn, diminishes the capacity of wind to transport sand landward. Aeolian accumulation may thus be curtailed during the most severe storms (Davidson-Arnott and Law, 1990). Hesp and Thom (1990), commenting on coastal dune activity in Australia and New Zealand, observed that the most intense storms and associated foredune degradation do not necessarily, on their own, stimulate dune building.

The preservation of uninterrupted foreset bedding, said to represent a massive flux of sediment under extreme conditions (Hearty and Olson, 2011), is likely to provide evidence of just the opposite. Slip-face stratification in Bermuda's eolianites, as shown in Figure 6.15, is consistent with dry grain-flow alternating with grain-fall deposition, and commonly incorporates fine, millimeter scale lamination characteristic of reworking by ripple migration acting under prevailing, stable conditions. Mackenzie (1964) was of the same opinion: that the slip-face accretion in Bermuda was overwhelmingly the product of any typical onshore wind that was sufficiently strong to transport sand. This is corroborated by observations of historically active dunes, described as "sand glaciers", which advanced "stealthily" (Heilprin, 1889) over periods spanning many decades at three locations along Bermuda's south shore during the 19^{th} century.

The need to invoke extreme weather conditions to account for the entombment of complete trees within Bermuda's Pleistocene dunes is dubious. Slow burial under ambient conditions, does not necessarily cause death, as is evidenced on the coastal plains of Egypt, where tall palm trees, being “slowly covered” by an advancing precipitation ridge, survive up to the point of complete burial (El-Fayoumya et al., 1993). The same applies, under very different conditions, on the coast of Oregon where large slip-faces, advancing at rates of only 1 metre per year, almost completely bury tall conifers which occasionally emerge alive decades later, on the stoss slope, as the dune moves forward (Cooper, 1958). Even if rapid accumulation must be invoked, it does not have to be the product of extreme storms. Coastal dunes, in other parts of the world, with similar characteristics to those of Bermuda are known to advance under normal conditions at rates of 10 to 20 metres per year (Hesp and Thom, 1990; Bird, 2007).

The concept of dune building by extreme storms was perhaps born out of the conviction of Bretz (1960), Land et al. (1967) and by Vacher (1972) that Bermuda dunes were rapidly cemented in position and that accumulation could only proceed by conformable draping of layers. Such a process, which omits sediment recycling, does require the delivery of enormous quantities of “new” sand to achieve appreciable aggradation and lateral accretion.

As an alternative to storm deposition, it is contended here that the Bermuda’s Pleistocene dunes having been activated by a landward flux of sediment, encroached beyond the beach backshore in response to typical, moderate to strong, onshore winds. They were unstable advancing structures in which accretion, at the slip face, was attributable in part to sand recycling from the stoss-side of the dune. Had dunes been built by gale force winds as has been asserted, then wind data suggests (Figures 6.4 and 6.8) that the slip-face dip azimuths would have a more easterly bias than they do.

6.3.8. Development of advancing coastal dunes

Coastal dunes which have encroached, by slip-face accretion, sufficiently far inland relative to the beach to be defined as advancing (“transgressive”) dunes, can continue to advance as transverse ridges (of which precipitation ridges are a sub-set) as long as a positive sediment budget persists and/or there is a good thickness of loose sand in the sub-stratum. As observed on the Oregon coast (Cooper 1958) and many other parts of the world (Hesp, 2013), advancing dune-fields fronted by precipitation ridges can be supplied directly off the beach via sand sheets, or from exposed flanks of degraded foredunes, or through blowout troughs in a dissected foredune ridge (Figure 2.4). Critical evidence as to the genesis of Bermuda’s dunes is usually lacking, due to the loss of their seaward extremities to coastal erosion (Figure 6.6.a). In the few instances where the more proximal portions are preserved, the internal structure records the entombment of small foredunes by large advancing dunes (Figures 6.5 and 6.6b). This suggests the source of sand for substantive dune building was not from the foredunes but from the beach beyond. There appears to have been an evolution in dune building processes from that in which retention was dominant to that in which transportation was dominant. This is,

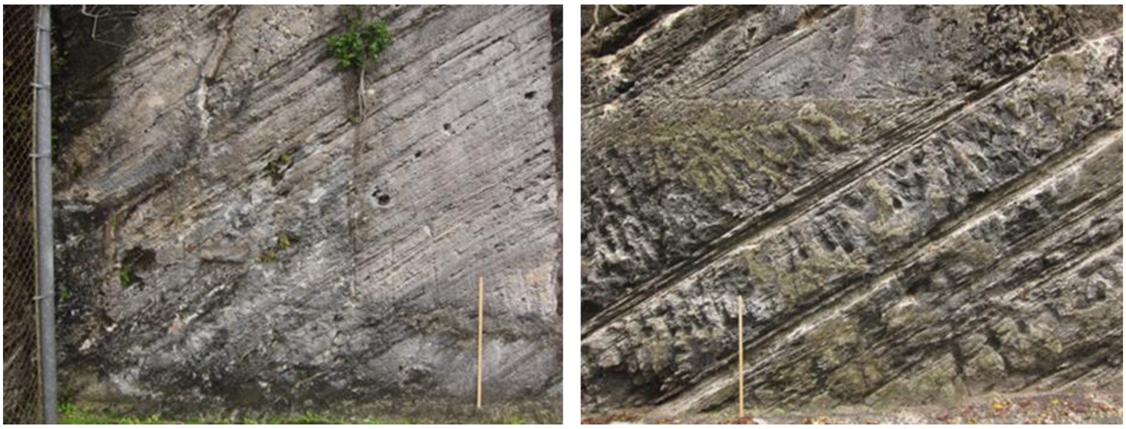


Figure 6.15. Slip-face strata at Khyber Pass, St George's. The southward dipping strata in these two exposures belong to the same Southampton Formation dune situated at an elevation of approximately 45m above sea level and 370m from the north shore. Thin strata of even-thickness (left photo) invoke deposition by consistent, moderate winds above the threshold velocity. Strata of more variable thickness (right photo) including one or more massive beds and wind ripple laminae are suggestive of less consistent deposition over a period which included storm winds. The repeating sequences of stratification-types correspond to weather cycles which likely spanned weeks or months. They refute accumulation in a single extreme storm event. (1m rule for scale).

likely, attributable to a growing flux of sediment supplied off a widening beach, at a falling relative sea level as argued in Chapter 7.

Bermuda's eolianites manifest a sufficient number of attributes which are diagnostic of landward mobility to confidently classify them as advancing dunes (Table 6.1). Episodes of mobility were ultimately curtailed as the balance between sediment supply and stabilisation reversed, in favour of the latter. If a boost in sediment supply was responsible for the initiation of advancing dunes, then the inevitable trend towards stabilization (Hesp, 2013) was likely the outcome of sediment supply decline due to decoupling from their source – the beach. The near-absence of classic parabolic forms coupled with evidence of episodic stoss slope accretion suggests, however, that as vegetation became established, sediment supply continued at a moderate rate right up to the point of complete stabilisation. This explanation is consistent with observed accumulations of low-angle, stoss slope, backsets beds superposed on truncated foresets and the frequent transition of the backsets, upwards, into a palaeosol.

Attribute	Bermuda eolianites
Position relative to the beach	Eolianite formations are not limited in extent to a single shore-parallel ridge. They became separated, by significant horizontal and vertical distances, from the known position of contemporaneous beach deposits. In the process of achieving this separation dunes over-topped pre-existing topography, and in some cases completely overstepped older dune formations as demonstrated by geological mapping.
Stratification	There is an abundance of sets of slip-face foresets which are truncated by sub-horizontal planar bounding surfaces. These features uphold advancing behaviour and confute growth by simple accretion. Typical dune architecture can be summarised as remnant bedforms that underwent sub-critical climbing.
Orientation	Slip-face foresets consistently dip landward with a low standard deviation evoking deposition as mobile sinuous transverse ridges
Nature of substratum	Typically there is a sharp contact between slip face foresets and a subjacent palaeosol. This, along with the evidence of buried trees, testifies to lateral encroachment of dunes onto a terrain which supported mature vegetation or a forest.
Fossil tree imprints	Tree moulds in-filled with sand and truncated by bounding surfaces demonstrate that dune sands remained friable, and potentially mobile, over the time taken for large trees to fully decay.
Historical activity	Accounts of 19th century dune encroachment, described as “sand glaciers” at three locations on Bermuda’s coast demonstrate the capability of Bermudian dunes to progressively advance under ambient modern interglacial conditions over periods spanning several decades.

Table 6.1. Attributes of Bermuda eolianites which qualify them as uncemented mobile advancing dunes at the time of their emplacement.

7. PLEISTOCENE GLACIO-HYDRO ISOSTATIC SEA LEVEL CONTROLS ON THE EVOLUTION OF BEACH-EOLIANITE SUCCESSIONS OF BERMUDA

7.1. INTRODUCTION

Diverse models from around the world have been developed that correlate states of changing relative sea level (RSL) with stages of the beach-dune evolutionary cycle (see Section 2.2.5). The focus of new Bermuda-based research, presented here, is on the stages of the cycle, spanning Pleistocene sea-level highstands, which culminated in expansive dune-building. Conclusions of the preceding chapters with respect to interpretations of palaeo-RSLs and dune morphodynamics are built on here. The objective is a better understanding of the potential responses of beaches and dunes to changing RSL. This is critical to an assessment of the vulnerability of many coastal communities which depend on coastal dunes to provide a buffer against marine flooding and a reservoir of sediment for natural beach recharge during storm events (Doody, 2012; Everard et al., 2010).

7.1.1. Development of models for beach-dune evolution – contributions from Bermuda

There is a scarcity of beach deposits preserved in the geological record, worldwide (Bird, 2007). The excellent shore-normal exposures of emergent Pleistocene littoral deposits of Bermuda, which include marine-eolian facies assemblages, therefore provide a rare opportunity to study the cycle of depositional and erosional events associated with the evolution of beach-dune systems. The Bermuda assemblages that are exposed at multiple localities, notably within the Belmont Fm, record an initial marine transgression, beach progradation, barrier formation and dune building. The progression of these events can be correlated with RSL changes which are recorded by shifting elevations of key facies (Table 3.2) within these assemblages.

The dominance of eolianites and their intercalation with mature palaeosols has stimulated eminent researchers to develop competing models which account for episodic dune-building on Bermuda. Compilations of coastal-dune-building models from around the world (Pye and Tsoar, 1990; Brooke, 2001; Lees, 2006) frequently reference this body of work from Bermuda. These compilations are, however, essentially review papers and, as such, depend on the veracity of the published research undertaken in Bermuda. There is no re-examination of the field evidence. At times it appears that later models from Bermuda have been afforded greater credibility simply because they are more recent and claim to correct earlier versions; even though limited new data or facies analyses are presented in support of the later models. Given the stature of Bermuda in the field of eolianite geology and coastal geomorphology it is considered that an on-site review of the contradictory coastal-dune-building models is overdue. This is especially so in light of unresolved controversies over facies interpretation that have arisen in recent decades and relatively new information that has been gathered from geological mapping and high resolution facies analyses in Bermuda.

7.1.2. Modern depositional conditions at Bermuda

Bermuda's present-day coastline is characterised by low cliffs, rocky headlands and embayed beaches which tend to be concentrated on the high energy south shore. Where beaches do occur, as at many other localities around the world today they are subject to a neutral or slightly negative sediment budget. These conditions contrast markedly with those manifested in Bermuda's Pleistocene geology which features prograded beaches and large sets of eolianite slip-face strata.

As a whole Bermuda's coastline is erosional, but only marginally so due to the wave-filtering effect of biological reefs, which extend from the shoreline out to the platform edge. As described in section 6.1.2, there are historical accounts of limited dune instability and advancement at three beaches (Nelson, 1837; Heilprin, 1889). However, the only preserved evidence of Holocene or modern dune activity is in the form of small vegetated foredune ridges on a few of the larger south shore beaches, such as Horseshoe Bay and Warwick Long Bay (Figure 6.2). Shallow patches of shoreface sediments feed into modern beaches, but more significant volumes of sand remain unavailable for transportation, being trapped in deep sandy moats between modern and relic reef tracts (Meischner and Meischner, 1977). Some of Bermuda's beaches are stable while others such as Horseshoe Bay are in slow retreat, as evidenced by aerial photographs spanning several decades.

7.1.3. Established chronostratigraphy

No reliable method of dating pure carbonate dunes has yet been developed. Furthermore, there are no known emergent Pleistocene reefs with life-position corals extant in Bermuda. Only a small number of stratigraphically meaningful emergent marine deposits have yielded sufficient numbers of coral fragments to derive a statistically robust U-series age for the host unit. These are marine members of Bermuda's geological formations (Vacher et al., 1989). They are demonstrably water-lain units comprising one, or a combination, of the Laws, Hapm, Lapl, Trm, Flp and Sof facies. They are the Belmont Fm marine member, the Rocky Bay Fm marine member (also known as the "Devonshire" marine unit) and the Southampton Fm marine member. They are identified on the geological map respectively by the notations Qbm, Qdm and Qsm. (Appendix I). Average ages attributed to these units, respectively, are ~200 ka (Section 4.2), ~120 ka (Harmon et al., 1983) and ~80 ka (Muhs et al., 2002). By plotting these ages, along with interpreted palaeo-RSL elevations, against a consensus version of the Pleistocene eustatic sea-level curve (Figure 7.1), the chronostratigraphy of emergent marine deposits on Bermuda can be established in relation to global glacio-eustatic events.

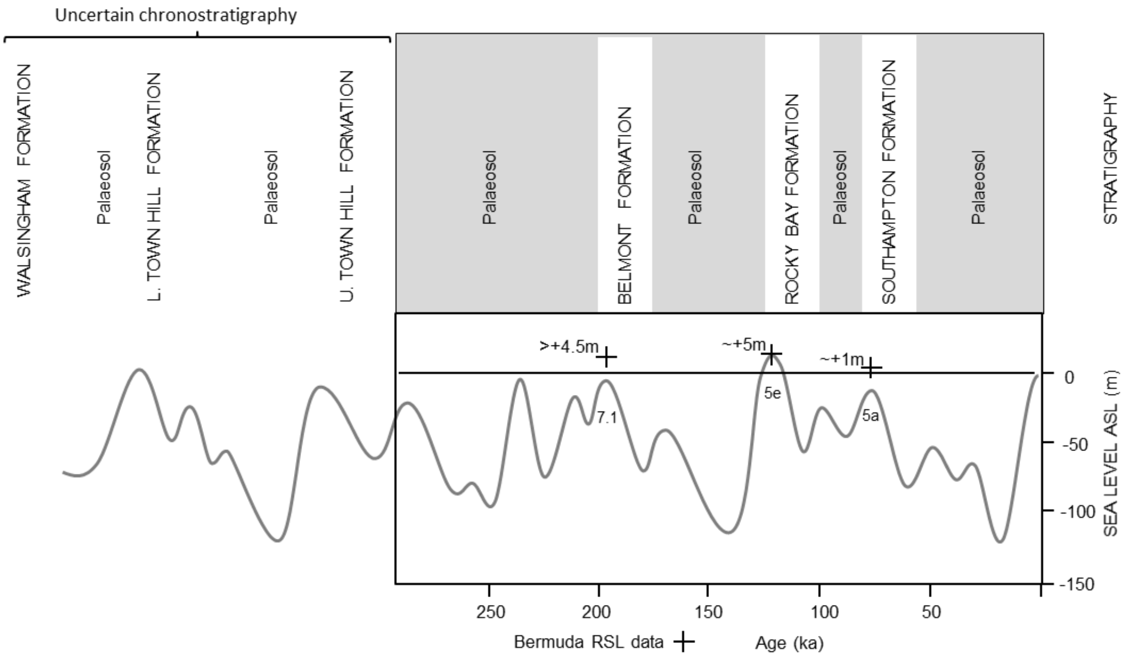


Figure 7.1. The stratigraphy of Bermuda in relation to global palaeo-RSL history (adapted from Siddall et al., 2007). Published relative palaeo-RSL elevations for Bermuda at MIS 7.1, 5e and 5a are indicated by crosses. In the top part of the figure, white bands represent calcarenite deposition predominantly in the form of advancing dunes and gray bands represent the formation of platform-wide palaeosols during hiatuses. Formation ages have been determined by U-series dating of coral fragments collected from marine members (Harmon et al., 1983; Muhs et al., 2002; Rowe et al., 2014).

Putative lateral field transitions between emergent marine deposits and eolianites which attest to synchronicity between peak RSLs and expansive dune-building were noted but not well documented by Bretz (1960) on the north shore and by Land et al. (1967) on the south shore. Notwithstanding the equivocal nature of these field relationships, what is not in dispute is that in many coastal exposures, Belmont Fm, Rocky Bay Fm and Southampton Fm eolianites overlie emergent marine deposits, which have been correlated by dating with MIS 7.1 (Marine Isotope Stage 7.1), MIS 5e and MIS 5a highstands, respectively. These eolianites are invariably separated from the underlying marine deposits by an intra-formational protosol representing a hiatus. It can therefore be concluded that dune-building occurred late in the same sedimentary cycle that was responsible for emergent marine deposition. This dates the dunes to highstand terminations.

7.1.4. Facies analyses

The MIS 7 Belmont Fm includes the widest range of emergent littoral facies in Bermuda. It is almost continuously exposed along 6 km of the south coast of the central parishes. As concluded earlier (Section 3.3) the corresponding sea level at Bermuda rose to a minimum of +4.5m ASL on at least one occasion. As a consequence of their current state of emergence the critical contacts between shoreface deposits, foreshore deposits and eolianites are exceptionally well exposed in low cliffs and wave-cut platforms. A lengthy process of logging and surveying two-dimesional facies associations in these coastal exposures at 50 study sites under-pins this study (Appendix F). The accurate elevation measurements makes possible reconstruction of beach-dune evolution in-step with Belmont palaeo-RSL fluctuations recorded by “sea-level indicator facies” (SIFs) (Table 3.2)

7.1.5. Missing coral reef facies

Modern algal-vermetid reefs and coral reefs on the Bermuda platform have, respectively, grown vertically up to mid-tide level and to within approximately 3m of mid-tide level (Meischner and Meischner, 1977). At some point in the future, when RSLs are lower than today, emergent remnants of these reefs will be preserved as witnesses to the Holocene highstand; especially those which are attached to rocky shores as a “littoral fringe” (Meischner and Meischner, 1977). Yet, unlike many relatively stable Pleistocene coastlines such as in Florida (Muhs, et al., 2011), the Bahamas (Carew and Mylroie, 1995), south Australia (Murray-Wallace, 2002), west Australia (Hearty et al., 2007) and the Seychelles (Israelson and Wohlfarth, 1999), there are no known emergent coral reefs and only one small exposure, known, of an in-situ algal-vermetid accretionary lip on Bermuda (at Watch Hill Park). The few in-situ corals which have been reported in the literature are inadequately documented and their existence cannot be verified. This is despite tens of kilometres of coastal exposure and robust evidence (Harmon et al. 1983; Hearty and Kindler, 1995; Meischner et al., 1995; Rowe et al.,

2014) of RSLs which exceeded that of the present day by 4m or more on at least three occasions.

The most credible explanation for the paradox of Bermuda's missing reef facies is that RSL rise at Pleistocene highstands out-paced reef growth and was then rapidly reversed. These circumstances are consistent with the observed tendencies of reef growth, in response to a rising sea level, to "keep-up", "catch-up or "give-up" as expounded by Neumann and Macintyre (1985). The difference between Bermuda, where reef growth apparently did not keep-up, and other localities where reef growth did keep-up at Pleistocene highstands, may be attributable to a unique glacio-hydro isostatic signal at Bermuda, which was potentially modified by a tectonic component (Chapter 5), coupled with retarded coral recruitment associated with the island's northern latitude.

Even though recently-drowned reefs have been documented on Bermuda's outer platform (Meischner and Meischner, 1977), predominantly late Holocene reef-growth at Bermuda has kept-up or caught-up with RSL rise. This may reflect a late-Holocene RSL rise which underwent significant deceleration as it flooded the Bermuda platform, and produced a prolonged highstand (perhaps anomalously so) which stopped short of its MIS 7 and MIS 5e, Mid-Late Pleistocene, counterparts (Figure 7.1).

7.2. RESULTS

7.2.1. Coastal facies assemblages of Bermuda

The majority of Bermuda's advancing-dune eolianites are not in direct contact vertically or laterally with facies which are interpreted as contemporaneous beach deposits. They terminate abruptly at the shoreline where they form cliffs of partially submerged landward dipping slip-face foresets. Or as astutely noted by Heilprin (1889): "Manifestly, the cliffs are merely the inner halves of dunes the outer slopes of which have been carried away by the sea. The height of the cliffs indicates dunes of great extent, but it will probably never be told at what point in what is now sea they originated….". In absolute terms there is no "complete" coastal facies assemblage which records both depositional events that laid the foundation for dune building as well as events contemporaneous with dune accretion which were responsible for sediment delivery. Even in the relatively complete assemblages the beach deposits which directly supplied the advancing dunes are absent.

The two types of coastal facies assemblages detailed below which include marine deposits and eolianites in succession are termed here the "Belmont Formation facies assemblage" and the "ravinement infill facies assemblage". The latter, which occurs in more than one formation, comprises only three facies in total. The Belmont Formation facies assemblage of the south shore, by contrast, includes multiple facies within the emergent marine deposits, and is divided into two successions associated, respectively, with a rising and a falling RSL. Also described below is a Rocky Bay Formation assemblage from the north shore which previously had been considered to represent both marine and eolian facies (Bretz, 1960; Land et al., 1967; Vacher, 1972). However, this conclusion is challenged here because of the high elevation to which the putative marine facies extends; the eolian characteristics of the strata; and the absence of any features which are exclusive to marine deposits.

7.2.2. The Belmont Formation (south shore) facies assemblage

Succession 1 (S1) **- Progradational-aggradational littoral deposition during a rising RSL.** Where the distal/basal portion of the Belmont Formation facies assemblage is exposed, such as at Hungry Bay West and Devonshire Bay (Figures 7.2 and 7.3, Appendix H), evidence of an initial erosive marine transgression takes the form of either a planar bounding surface, which dips seaward parallel to conformably superposed Lapl (low-angle planar large-scale cross strata); or a scarp which truncates weakly cemented strata of older advancing-dune deposits (Figure 3.1.F). Subsequent Laws (low-angle symmetrical small-scale ripple cross-strata), Hapm (high-angle planar medium-scale cross-strata) and Lapl (low-angle planar large-scale strata) of S1 (Succession 1) are interpreted as recording significant shoreface and foreshore (beach) progradation which precede a more aggradational trend. The seaward increase in elevation and/or thickening of facies at a number of localities, including Hungry Bay West, Devonshire Bay and Hungry Bay East (Figures 7.2, 7.3 and 7.4), attest to deposition that was concurrent with a RSL which continued to rise.

Near the top of S1 there is invariably a horizon which indicates backshore saturation and intermittent flooding at elevations which tend to cluster around +3.2 ±0.2m (e.g. at Devonshire Bay) and +4.4 ±0.4m ASL (e.g. at Hungry Bay and Spittal Pond). This horizon typically features prominent horizontal bounding surfaces; trough cross-strata (Trm facies) (Figure 7.4 and 3.1.C) attributed to subaqueous dune migration caused by overwash and return flow (landward and seaward dipping Trm cross-strata); and flat strata with intercalated fine laminae and lags of marine bivalve shells (Flp facies). In combination these are interpreted to record overwash events into shallow lagoons and episodic wind deflation. The typical maximum elevation of this horizon, at ~4.4m ASL, is consistent with evidence from elsewhere within the Belmont Fm, such as at Grape Bay, of a late MIS 7 RSL rise to ≥ 4.5m ASL (Section 3.3). In most cases foreshore beach-face deposits are truncated at a horizontal bounding surface at the base of this flooding horizon such that the berm and upper beach have been removed. This perfectly flat surface likely developed through backshore deflation to the water table as opposed to marine erosion, which in a reflective-beach environment typical of Bermuda tends to create seaward-dipping erosion surfaces or scarps. Where locally (e.g. between Doe Bay and Hungry Bay) the berm and upper beach have not been removed, they are preserved as Lapl facies and crab-burrowed Bof facies as seen at Doe Bay (Figure 3.1.D). The top-most

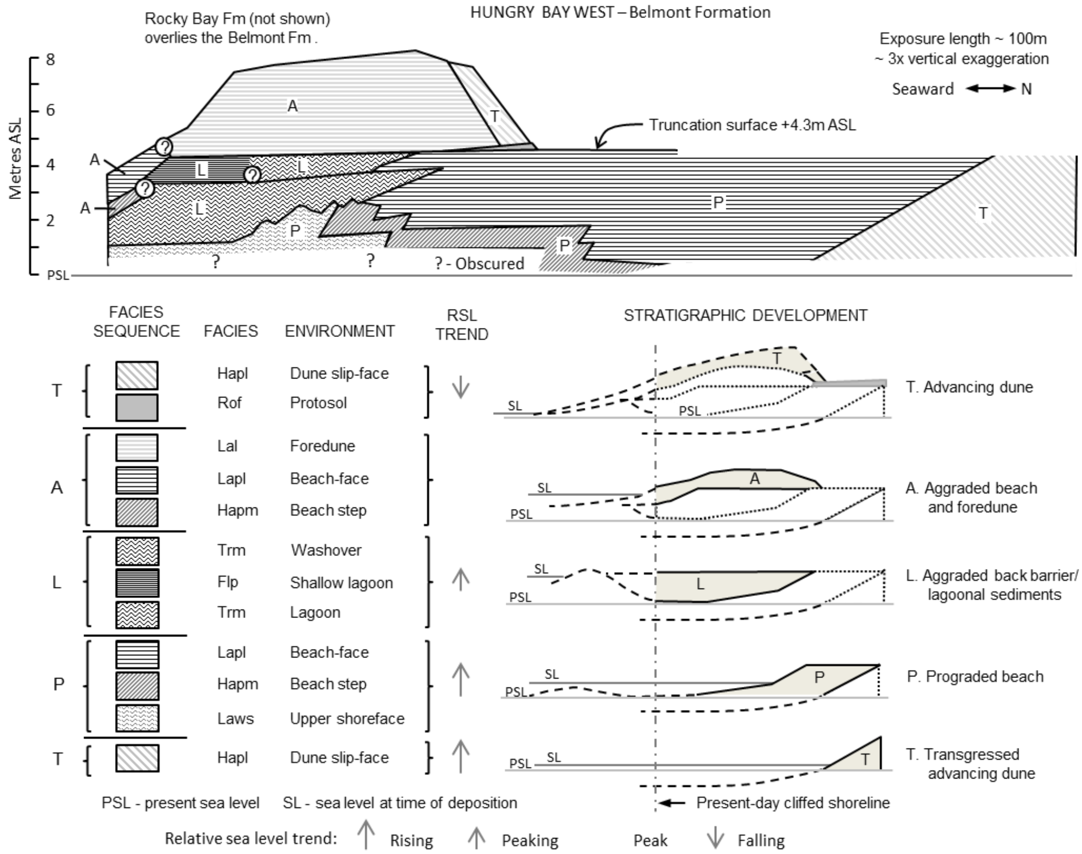


Figure 7.2. Belmont Formation facies assemblage at Hungry Bay West. (Sites 8 and 9, Appendices F and G). A weakly cemented dune from an earlier depositional cycle (T) is transgressed by a re-advancing sea. Prograded foreshore and shoreface deposits (P) are fronted on the seaward side by an aggradational sequence of coarse trough cross-bedded calcarenites (dipping alongshore), as well as landward-directed washover deposits and flat laminated lagoonal deposits (L). The inferred development of a barrier/spit to seaward of the former foreshore is corroborated by the appearance of a second, proximal beach and associated foredune (A) as RSL peaked. Emergence of the infilled back-barrier lagoon, on a falling RSL, preceded accumulation of a protosol. Exposure of the nearshore deposits, as RSL regressed, provided a source of sand for an advancing dune (T) which overtopped the foredune. A RSL which peaked at ~ +4.2m ASL is implied by this assemblage. Succession 1 (developed during a rising RSL) = P+L+A. Succession 2 (developed during a falling RSL) = T. **See Appendix H for a photo-mosaic and illustration of this section with no vertical exaggeration.**

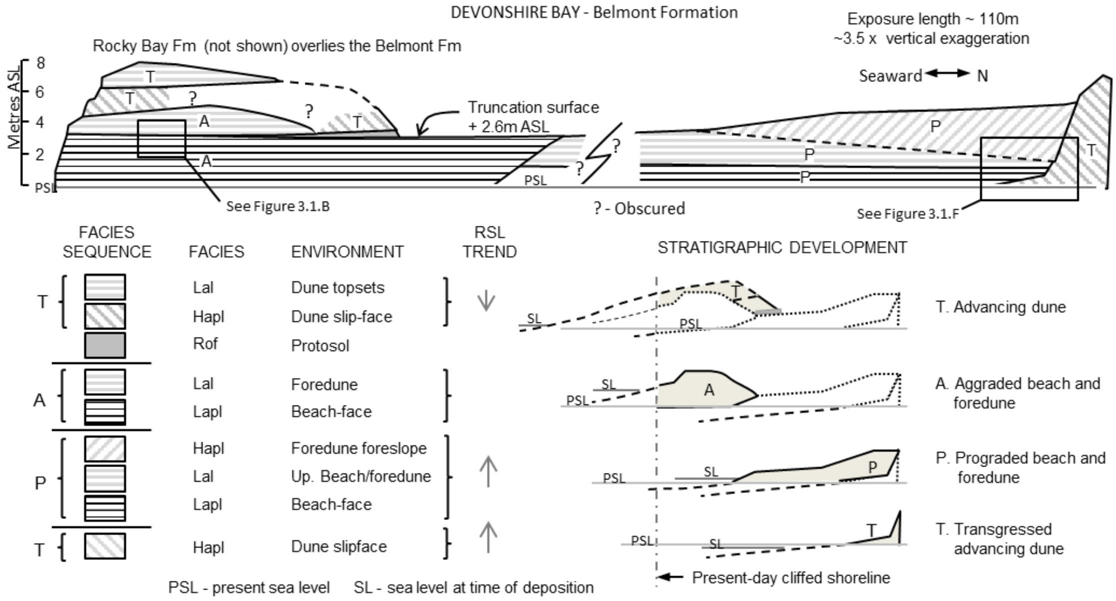


Figure 7.3. Belmont Formation facies assemblage at Devonshire Bay. (Sites 20, 21, 22 and 23, Appendices F and G). A weakly cemented dune of an earlier depositional cycle (T) is transgressed by a rising RSL. Prograded upper-beach and foredune deposits (P) are onlapped by foreshore deposits (early A). Littoral aggradation, as RSL peaks, is represented by a small low-profile foredune superposed on thickened foreshore deposits (A). Development of a protosol marks emergence of the backshore which had previously been prone to flooding and deflation evidenced by a flat bounding surface and shelly lag. Exposure of nearshore deposits as RSL fell provided a source of sand for an advancing dune (T) which overstepped the foredune. Note the absence of sub-tidal shoreface deposits above present sea level at this locality, unlike at Hungry Bay West or East (Figures 7.2 and 7.4). Also, the truncation/deflation surface, and superposed protosol are at a low elevation relative to those at other localities. A RSL which peaked at ~ +3m ASL (above present mean sea-level) is implied by this assemblage. Succession 1 (developed during a rising RSL) = P+A. Succession 2 (developed during a falling RSL) = T. **See Appendix H for a photo-mosaic and illustration of this section with no vertical exaggeration.**

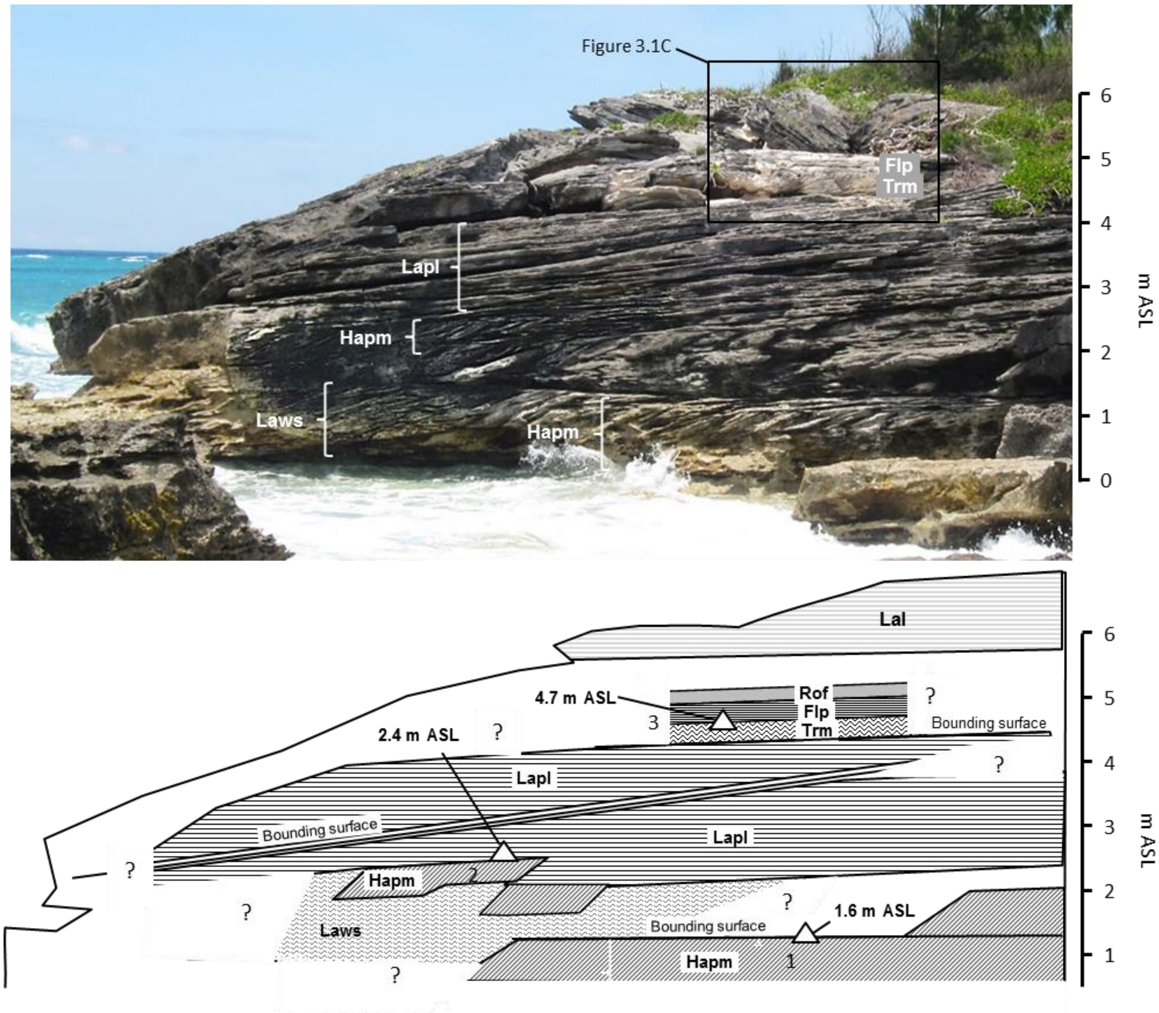


Figure 7.4. Belmont Formation facies architecture at Hungry Bay east. (Site 11, Appendices F and G). Development of Succession 1 (S1) is recorded here by the transition of beach progradation (1) to beach aggradation (2) as manifested by the shifting position of the beach step (Hapm). Intermittent flooding across the foreshore (Lapl) associated with rising RSL is represented by high elevation trough cross-bedded (Trm) and flat bedded shelly (Flp) deposits (3). These are interpreted as backshore overwash/lagoonal deposits. Palaeo-RSL rising from ~+2 m to >+4 m is inferred at this locality. Measured elevations ASL (above present mean sea level) are indicated by triangles.

deposit of S1, the Lal facies, is interpreted as the accumulation of a stable foredune ridge during a period of shoreline equilibrium at peak RSL. This facies is typically superposed directly on the truncated Lapl facies, of the beach face, at the proximal (seaward) end of the section (Figure 7.3, 7.5 and 7.6). This relationship is responsible for past interpretations of contemporaneity between Bermuda's eolianites and high emergent beach deposits. For example Vacher et al. (1995) report "proximal coastal marine deposits (which) grade upwards without a break into gently inclined eolian cross bedding representing a beach ridge that nucleated the growth of the main part of the complex." Such interpretations make no mention of the protosol that distally separates the marine deposits from the aeolian deposits; and they do not differentiate between deposits dominated by the Lal facies from those dominated by the Hapl facies, interpreted here respectively as foredunes and advancing dunes. While there is agreement with previous researchers that the beach and volumetrically insignificant foredune deposits (Lal facies) are penecontemperaneous, it is evident that the formation of the expansive advancing dunes (Hapl facies), of which the Bermuda islands are constructed, was a distinct event which followed a hiatus. The small foredune ridge whose development preceded advancing dune construction would have temporarily acted as a barrier to landward sediment-transport from the beach. This would have resulted in the preservation of a back-barrier basin which if deflated to the water table may have developed into an ephemeral lagoon or dune slack. These circumstances are known from the coasts of Oregon in the USA (Wiedemann, 1998), Finland (Hellemaa, 1998), and Israel (Tsoar, 2000). In Bermuda's past they may have been responsible for, or have perpetuated, features such as flat bounding surfaces and laminated water-lain deposits of the back-barrier flooding horizon, which upon emergence were superposed by the protocol of S2.

Succession 2 (S2) **- Terrestrial deposition including advancing dune development during a falling RSL.** The commencement of S2 (Succession 2) accumulation is marked by the formation of a structureless calcarenite horizon, termed the Rof facies, featuring land snails of the *Poecilozonites* genus and rhizocretions. It is interpreted to represent protosol development concomitant with plant-colonization of the emergent backshore. A hiatus is indicated by calcrete horizons within the protosol and the growth of very large trees which were entombed by subsequent dunes and preserved as columnar moulds of structureless sand. The imprints of these trees, identified as Bermuda cedars (*J. bermudiana*) by the ≥ 1 metre girth of the trunk moulds, are best seen in the coastal exposures at Saucos Hill (Figure 6.12.b). Overlying the protosol are the high-angle, planar, large-scale landward-dipping cross-bedding of the Hapl facies (Figures 7.5 and 7.6) interpreted as slip face foresets of advancing dunes. It will be argued that these dunes, which over-topped the foredune ridge of S1, were sourced from a widening regressive beach. They encroached landward beyond the backshore onto an elevated interior terrain as witnessed by burial of mature palaeosols (Figure 6.11) and trees.

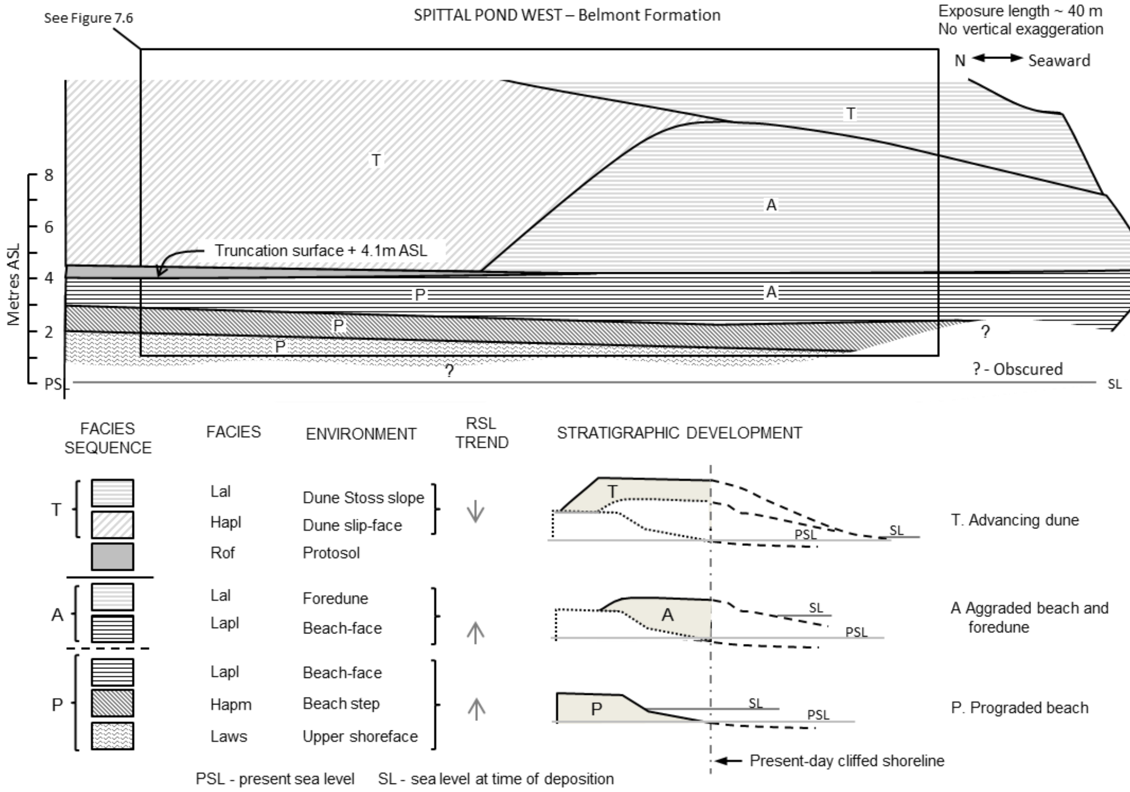


Figure 7.5. Belmont Formation facies assemblage at Spittal Pond west - illustration. (Site 38, Appendices F and G). Prograded beach foreshore and shoreface sediments (P) were truncated by the effects of backshore flooding and deflation. Aggradation of a foredune on thickened foreshore deposits (A) represents stabilization of the shoreline as a rising RSL peaked. This was followed by accumulation of a protosol on an exposure surface and then, as RSL continued to fall, the encroachment of an advancing dune (T). A RSL which peaked at ~ + 4m ASL is implied by this assemblage. Succession 1 (developed during a rising RSL) = P+A. Succession 2 (developed during a falling RSL) = T.

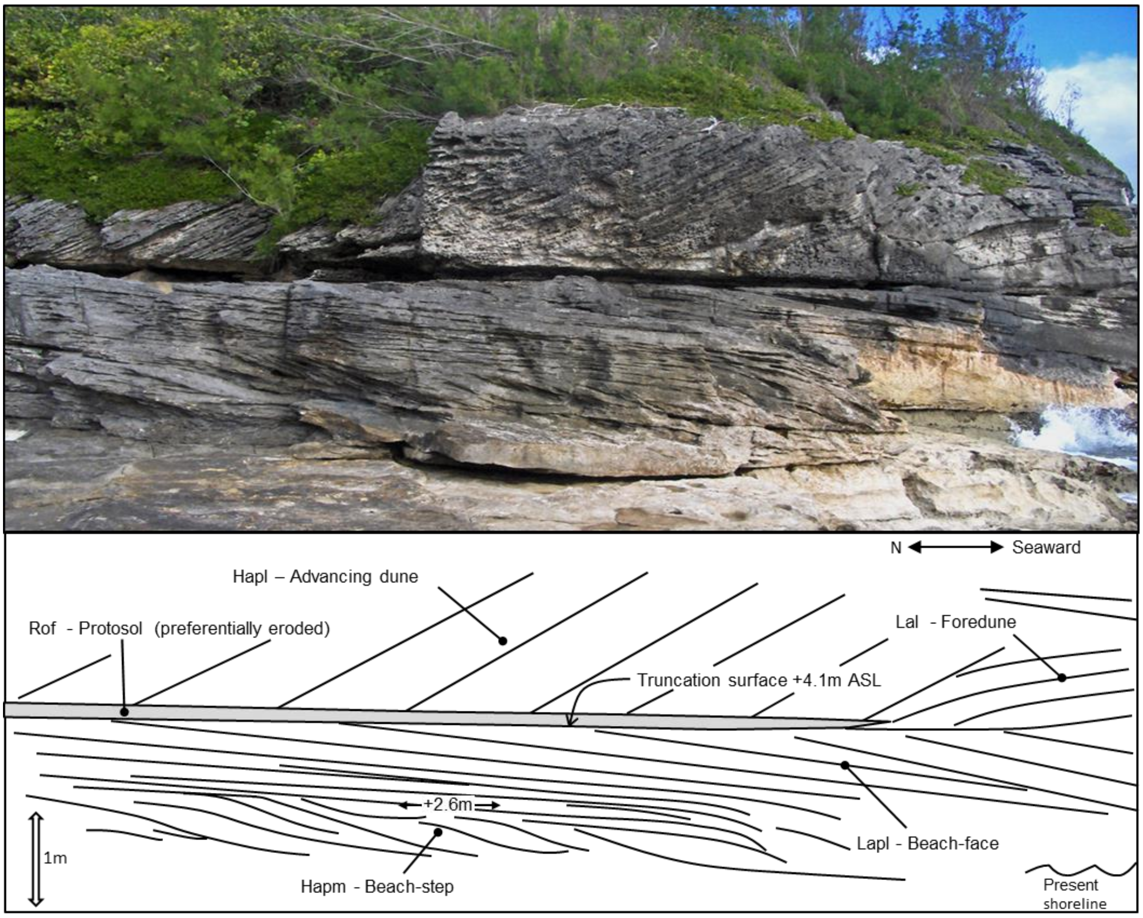


Figure 7.6. Belmont Formation facies assemblage at Spittal Pond west – photo. (Site 38, Appendices F and G). Shoreface (Hapm facies) and beach (Lapl facies) progradation is shown proximally transitioning into beach/foredune (Lal facies) aggradation. The planar truncation surface at ~+4m ASL is a common feature in the Belmont Formation. At some localities it is accompanied by accretion associated with flooding (Figure 3.1.C) at others, as here, it is simply a shelly bounding surface (Figure 3.1.B) which may implicate deflation down to the level of a raised water table, associated with a peak RSL. Accretion of the protosol (Rof facies) represents emergence of the previously flooded/saturated backshore. Subsequent advancing-dune encroachment (Hapl facies) is interpreted as the outcome of sediment exposure on expanding beaches as RSL fell probably below its present level.

7.2.3. The ravinement infill facies assemblage

The ravinement infill facies assemblage features prominently in all of the seminal articles on Bermuda's geology from Sayles (1931) to Bretz (1960) and Land et al. (1967). Vacher (1972) termed it an "erosional" assemblage in contrast to other assemblages which he termed "depositional". It differs from the Belmont Fm facies assemblage, described above, in that there is limited progradation and the marine unit is made up of a single facies.

The ravinement infill facies assemblage is typically superposed on a transgressive ravinement surface and comprises an upward-fining, rudaceous to arenaceous marine deposit (Sof facies) overlain by a protosol (Rof facies) followed by a relatively small advancing dune (Hapl facies). The assemblage tends to occur in isolated coastal exposures of limited lateral extent. Well known examples can be seen at Hungry Bay (Rocky Bay Fm), Rocky Bay (Rocky Bay Fm) (Figure 3.1.A), Whalebone Bay (Rocky Bay Fm) and Fort St. Catherine (Southampton Fm). The marine facies (Sof) is interpreted as the product of a high energy shoreface or inter-tidal environment. Stratification can be wavy and chaotic, and locally is obscured by bioturbation. The ravinement infill facies assemblage has been characterised as "shallowing upward" (Hearty, 2002). However, an interruption of deposition and/or erosion is inferred from the absence of well-defined foreshore deposits which would be expected to record emergence between the sub-tidal Sof facies and the terrestrial Rof (protosol) facies.

The conglomeratic basal deposit of the ravinement infill facies assemblage is interpreted as the shoreface accumulation of wave eroded material related to a marine transgression on a rocky shoreline – in other words a transgressive lag. Conditions would have been similar to the coastal environment of present-day Bermuda, which is dominated by low cliffs. Development of a protosol directly on this coarse marine facies is indicative of emergence and a hiatus. The construction of small advancing dunes ensued. This assemblage is effectively an abbreviated, sediment-starved version of the Belmont Formation facies assemblage of the south shore.

7.2.4. The Rocky Bay Formation (north shore) facies assemblage.

The facies assemblage that occurs within the Rocky Bay Fm on the north shore (central parishes) includes putative marine-dune transitions, the geometry of which formed the basis for the dune-building models of Bretz (1960) and Vacher (1972). The controversy surrounding the depositional environment of these strata is revisited in this section.

Blackwatch Pass is a deeply excavated road-cut on Bermuda's north shore which provides the most extensive vertical and lateral exposure of the internal structure of a Bermudian eolianites. The near-horizontal roadway of the "Pass" was excavated perpendicularly through a 40m high E-W aligned dune-ridge of the Rocky Bay Fm which is interpreted as a last interglacial (MIS 5) deposit (Land et al, 1967; Vacher, 1972; Harmon et al., 1983; Hearty and Kindler, 1995).

Approximately 50m beyond the northern end of the pass is the sea, and the same distance beyond the southern end is a sea-level marsh. The succession of cross-stratified calcarenites exposed in the rock faces of the Pass are representative of those at other localities along this north shore ridge.

A combination of field observations and a GPR survey completed as part of this study shows that low-angle undulating cross-strata dominate the succession below a northward dipping protosol in Blackwatch Pass as illustrated in Figure 7.7. Superposed on the protosol, above the road level, is a 10 to 15m thick set of southward dipping slip-face foresets (Hapm facies) truncated at the top by a gently undulating northward dipping bounding surface. This surface is in turn superposed by low-angle eolian strata with some large scale trough cross-stratification. Towards the northern end of the pass there is a prominent northward dipping bounding surface (PBS) above which is a wedge of seaward dipping low-angle sub-parallel strata (Lal facies) (Figures 7.8 and 7.9).

As illustrated in Figure 7.7, the dominant exposed facies along several kilometers of coast on the north side of North Shore Road in Bermuda’s central parishes is the Lal facies. The undisputed eolian slip-face strata of Hapl facies is confined to the south (landward) side of North Shore Road, where it is exposed subjacent to Lal facies deposits. It is re-asserted here (after Vacher et al., 1995; and Kindler and Strasser, 2000) that the Lal facies shown Figure 7.9 is an eolian stoss-slope deposit and that no demonstrable water-lain marine strata exist on the north shore of Bermuda’s central parishes. The prominent bounding surface (PBS) can be explained as a deflation surface perhaps related to a storm event. No sedimentary structures diagnostic of wave action in the shoreface or foreshore environment as documented by Andrews et al. (1969), Clifton et al. (1971) and Short (1984) are evident in exposures above or below North Shore Road. Rather, the characteristics of the Lal facies of the north shore are entirely consistent with aeolian stoss-slope deposits seen elsewhere in Bermuda. These sub-parallel gently seaward-dipping cross-strata evoke dune-foreslope accretion coincident with vegetation growth as described by Goldsmith (1973), Hesp (1988) and Bristow et al. (2000). Moreover the elevation of > +15m ASL to which the facies extends, corroborates eolian deposition because, by consensus, the maximum MIS 5 palaeo-RSL at Bermuda was approximately +5m ASL (Figure 7.1). Other features of note which support sub-aerial origins are: 1). horizons with mouldic porosity, up to pencil-size in diameter, interpreted as rhizomorphs (root casts); 2). Seaward-sloping rill marks close to present sea level (~+1m ASL) which evidence small scale erosion by sub-aerial ground water exfiltration; and 3). An absence, along a 5 km continuous exposure, of any observed (by the author) or reported clast or shell so heavy that it could only have been transported by water. The consequence of this interpretation is that prevailing transgressive dune-building models of Bretz (1960) and Vacher (1972) are unsupported. The conspicuous absence of a marine imprint on or within the north shore deposits of the central parishes indicates that development of the large dune ridge did

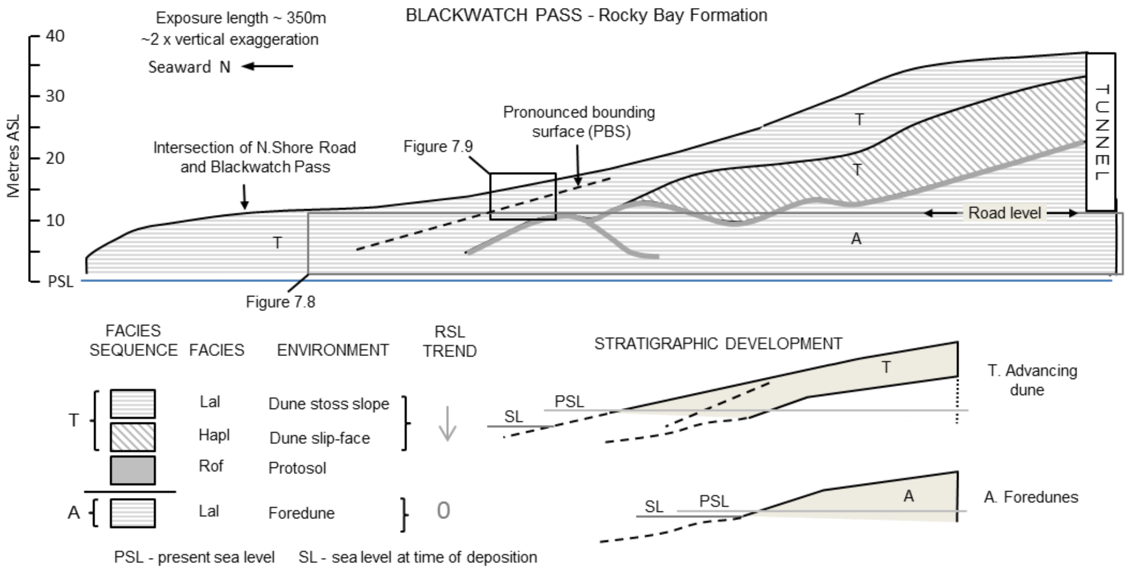


Figure 7.7. Internal structure of a Rocky Bay Fm dune ridge at Blackwatch Pass, compiled from field observations of the road cut exposure and a ground penetrating radar survey. Foredunes (A) with low angle (Lal facies) hummocky strata at the base of the section are overlain by a protosol (Rof facies). This is superposed by an advancing dune (T), comprising slip-face foresets (Hapl facies) and seaward-dipping sub-parallel low-angle strata (Lal facies) of the stoss-slope. Stratigraphic development of the succession is shown which represents one scenario in which advancing dunes could have formed in response to a falling RSL.

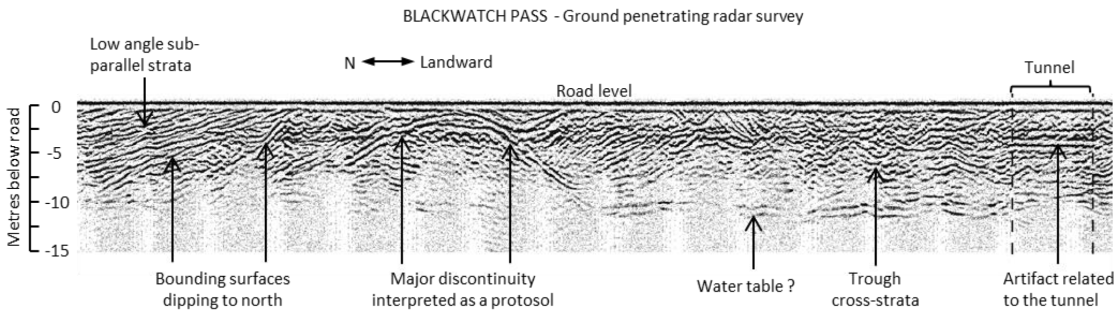


Figure 7.8. Ground penetrating radar survey at Blackwatch Pass. A series of mound-shaped foredunes with low angle trough cross-strata are onlapped, on the seaward (north) side, by low-angle seaward–dipping, sub-parallel strata, which are interpreted as dune stoss-slope deposits. Seaward-dipping planar bounding surfaces at the northern end of the profile are thought to record episodic deflation. Trough cross-strata are interpreted as the deposits of dunes migrating towards the east, into the plane of section, driven by the prevailing southwesterly winds.

Figure 7.9. Road-cut exposure at the northern end of the Blackwatch Pass on the north shore (north and the sea are to the left). This controversial succession of Lal facies, was once believed to record the transgression of a beach onto a foredune (Bretz, 1960). Here, these deposits are interpreted as stoss–slope strata which accreted within vegetation on the windward slope of an advancing dune. The seaward-dipping prominent bounding surface (PBS) can be attributed to deflation which may have occurred during a storm. Note the projecting pinstripe laminae, above the PBS, comprising well cemented fine sand. This type of stratification which is prevalent in Bermuda's eolianites is diagnostic of inverse sorting produced by eolian climbing ripple migration. Also, compare the non-planar sub-parallel aeolian strata (Lal facies) at this locality with the planar parallel water-lain strata (Lapl facies) typical of a beach face shown in Figures 3.1.b and 7.6.

not precede or coincide with a marine transgression which peaked significantly above present sea level, such as that at MIS 5e.

7.3. DISCUSION

7.3.1. Revised model for a highstand depositional cycle interpreted from the Belmont Formation facies assemblage.

It is inferred from the erosion surface at the base of the Belmont facies assemblage at Hungry Bay West (Figure 7.2, Appendix H) and Devonshire Bay (Figure 7.3, Appendix H) that the commencement of S1 (Succession 1) sediment accumulation was preceded by a marine transgression onto weakly-cemented advancing dunes of an earlier depositional cycle. As RSL continued to rise a prograding sediment prism comprising shoreface and foreshore facies became more aggradational as witnessed by increasing thicknesses and elevations of beach deposits in a seaward direction. A decline in sediment supply relative to the rate of creation of accumulation space is reflected by erosion which removed the berm and upper beach deposits at a horizontal bounding surface to be replaced locally by current deposits of the Trm facies and lagoonal deposits of the Flp facies (Figure 3.1.C). Development of a small foredune ridge directly on the proximal, seaward, end of the truncated beach perpetuated erosion by depriving the backshore of marine and eolian sediment in what became a deflated back-barrier basin or slack (Figure 7.10). This implied near-contemporaneity between the beach and foredune can be questioned because of the intervening truncation surface. However, at the proximal end of the succession, the truncation surface is sharp and typical of soft-sediment erosion with no evidence of encrustation, incipient pedogenesis or plant growth. Furthermore, there is a consensus among researchers (Bretz, 1960; Land et al., 1967; Vacher et al., 1995) that the vertical sequence of beach (Hapl facies) and low-angle aeolian strata (Lal facies) represents net aggradation within one depositional cycle. The truncation surface, which had not previously been documented, is here interpreted as disruption of this aggradation by transgressive flooding of the beach.

The small proximal foredunes preserved in the Belmont successions record the termination of a highstand. As RSL peaked, an exposure surface in the form of a protosol started to develop distally behind the foredune ridge on the formerly flooded/saturated and deflated backshore. This marked the beginning of the S2 succession. The foredune of S1 may have remained partially active during this period, continuing to exchange sand with the beach, but early stabilization is evidenced at some localities where the protosol overlies or transitions into the foredune’s lee slope. Large Bermuda cedar trees (*J. bermudiana*) which were rooted in the protosol and entombed by later dunes attest to a marine regression and concurrent seaward expansion of the freshwater aquifer given the intolerance of these cedars to a beach environment and shallow saline ground water. The lowering of RSL is corroborated locally by a seaward dip of the protosol and by its direct superposition on intertidal beach and, locally, sub-tidal shoreface deposits. Because the supra-tidal protosol constrains RSL to a lower position than that at which the immediately subjacent marine deposits accumulated, a lowering of RSL is demonstrated. The subsequent deposits of S2, of the Hapl facies, are indicative of an advancing dune which expanded from a seaward direction overtopping the foredune and encroaching onto the protosol. The shoreward flux of sediment represented by the advancing dune is attributed, here, to the exposure of shallow marine reef-suite (Section 3.2.2) sediments on beaches whose width began to exceed the critical fetch during a fall in RSL (Figure 7.10). The “critical fetch” is a distance that wind must travel across a dry beach to entrain sufficient sand to stimulate coastal dune activity (Moura et al., 2007). For the advancing dunes to be sustained, the sediment supply had to overwhelm the retentive capacity of growing vegetation as quantified by Carter and Wilson (1993) with respect to late-Holocene advancing dunes of north-west Ireland. While the predominantly marine deposits of S1 are now preserved above present sea level, the beach deposits which nourished the advancing dunes of S2 are missing. Their absence can in large part be attributed to coastal erosion but the completeness of their absence in outcrop and in shallow geophysical profiles is consistent with their submergence below present sea level.

The relatively short hiatus represented by the regressive protosol of S2 suggests that subsequent advancing dunes formed as part of the same post-highstand regressive trend. This is consistent with the expected effects of lowering of RSL, such as degradation of sub-aerially exposed reef-tops and the accumulation of comminuted sediment on emerging beaches (Figure 7.10). Sediment composition might, accordingly, be considered a useful tool in the identification of sources of eolianite sediment, which would help establish the position of RSL at the time of maximum dune-building activity. This approach has been possible in an analogous situation in the Bahamas where the deposition of oolitic eolianites was correlated with shallow platform water-depths, whereas the deposition of younger bioclastic eolianites was correlated with subsequent deeper waters (Kindler, 1995). In Bermuda’s waters, as discussed in Section 3.2.2., there are two co-existing important sediment suites namely: the lagoonal suite which is only recognizable as a distinct assemblage within the North Lagoon (Upchurch, 1970); and the reef suite which is commonly mixed with the lagoonal suite but is dominant in high energy areas such as the south shore. Upchurch (1970) found no bathymetrical or physiographical zonation of skeletal-debris composition or texture that could readily be used to track the shifting position of past aeolian sediment sources as sea level changed. The now-submerged areas within which Pleistocene beaches could have formed on the north shore are dominated by lagoonal-suite sediments whereas on the south shore these areas are dominated by reef-suite sediments. Predictably, the eolianites on these shores have pre-diagenetic compositions that correlate respectively with these sources (Vacher, 1972). Statistical analyses of eolianite particles of the type undertaken on modern sediments by Upchurch (1970) would be required to detect more subtle potential variations in texture and source beaches.

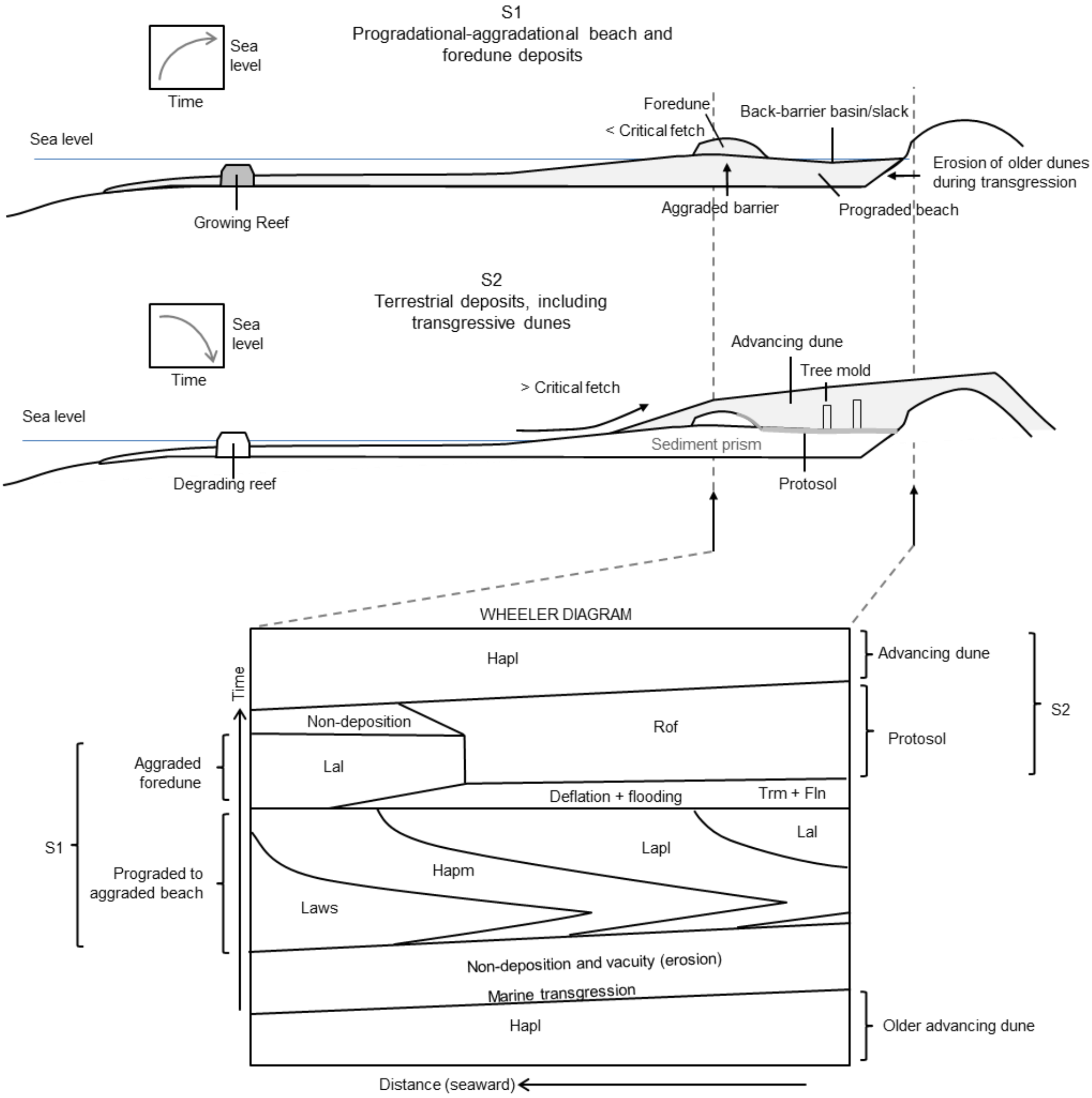


Figure 7.10. Successions 1 and 2 record two stages of littoral sediment accumulation. Predominantly marine deposits of Succession1 (S1) accumulated in a nearshore sediment-prism in response to a rising RSL. At the top of S1, barrier deposits including a small foredune ridge were associated with peak RSL. An exposure surface, in the form of a protosol, developed at the base S2 in response to coastal emergence. S2 deposition culminated in the formation of advancing dunes sourced from shallow-water sediments newly exposed on an expanding beach.

It could be argued that a brief reversal of the falling RSL trend stimulated advancing dune activity, which would be classified as transgressive as opposed to regressive. Such transgressive-phase dunes have been documented by Carew and Mylroie (1995) in the Bahamas and by Moura et al. (2007) in Southern Portugal. Nevertheless the observation, in Bermuda, that neither the preserved Pleistocene transgressive facies successions (S1) nor the deposits of the Holocene and modern transgressive coastlines include advancing dunes, suggests otherwise.

An alternative hypothesis with respect to the timing of advancing dune construction in Bermuda invokes a degraded vegetation-cover associated with severe climatic conditions at the onset of glaciations (Herwitz, 1992). However, as argued in Section 6.3.5, the preservation of leaf impressions of frost-averse palmetto (*Sabal bermudana*) within the slip-face strata is inconsistent with deterioration of the climate to the extent that according to the models of Tsoar (2013) is required to release fully active dunes.

In summary, a Belmont Formation facies assemblage of the south shore is, here, separated into a predominantly marine succession (S1) and a non-marine succession (S2), whose accumulation was forced respectively by a rising RSL and a falling RSL, which spanned a sea-level highstand. The significance attributed here to this partition and the intervening hiatus distinguishes the proposed model from previous ones, which depict linear progression from marine accumulation into eolian deposition: 1) at a peaking RSL, in the case of the Bretz's (1960) and Vacher's (1972) North Shore transgressive models; and 2) late in a highstand in the case of Vacher's (1972) South Shore autogenic sediment-supply model.

7.3.2. The contribution of high order sea-level cyclicity

Shoreface and foreshore sediment accretion, of S1, concurrent with a rising RSL contradicts the prevailing characterization of Bermuda's Belmont Fm marine facies sequences as "downlapping" in a seaward direction (Meischner et al., 1995). Transgressive accretion, demonstrated here, requires a high positive sediment budget which is conspicuously absent at Bermuda's present-day coastline. It is argued, here, that the principal potential source from which the Pleistocene littoral sediment accumulations were fed, was reworked material that was generated and accumulated earlier in the same highstand (Figure 7.11). This interpretation is corroborated by extant assemblages which begin with a marine transgression onto weakly cemented dunes (Figures 3.1.F, 7.2 and 7.3), presumably of an earlier depositional cycle at the same interglacial. The concept of high order, sub-stage, allocyclicity at Bermuda is nothing new. Based on a variety of stratigraphic to petrographic observations Bretz (1960), Land et al. (1967), Vacher (1972), Meischner et al. (1995) and Hearty and Kindler (1995) all espoused the occurrence of more than one depositional cycle during interglacial highstands at Bermuda.

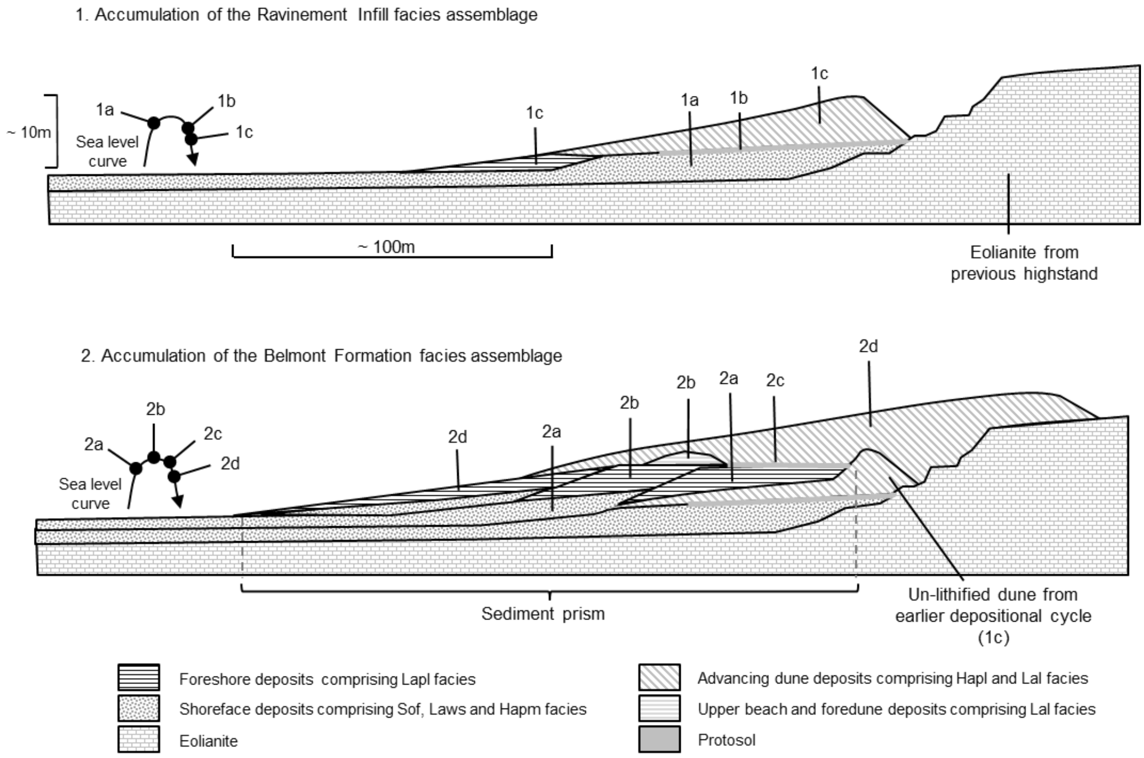


Figure 7.11. The progression of facies development in the ravinement infill facies assemblage (1) and Belmont Formation facies assemblages (2), respectively. The distal (landward) portions of each of these assemblages are preserved at several localities along Bermuda's south shore. Parts of the two assemblages may be preserved together at Hungry Bay west and Devonshire Bay although there is insufficient exposure to demonstrate this. The ravinement infill facies assemblage is thought to have developed concomitant with early flooding of the Bermuda platform at the beginning of an interglacial period. Preserved assemblages comprise coarse transgressive marine deposits, a protosol and small advancing dune, but no prograding beach. The Belmont Formation facies assemblage incorporates progradational and aggradational shoreface and foreshore deposits (Succession 1) which accumulated during a rising RSL. Terrestrial deposits (Succession 2) including expansive advancing dunes are interpreted as the product of a falling RSL.

Accurate measurement (± 0.2m) of the elevation of sea-level indicator facies within outcrops of the Belmont Fm at separate localities distributed laterally along Bermuda's south shore, yield contradictory palaeo-RSL evidence suggestive of multiple RSL peaks at ~+3.2m, ~+4.5m and >+6 m ASL respectively (Section 3.3). For example, the assemblage at Devonshire Bay (Figure 7.3, Appendix H), which includes no emergent sub-tidal (shoreface) deposits and features a protosol at less than +3m ASL, appears to represent a lower elevation, asynchronous version of the facies assemblages at Hungry Bay West (Figure 7.2, Appendix H) and Spittal Pond (Figure 7.5) where sub-tidal facies are fully emerged at elevations which exceed +3m ASL. The development of a supra-tidal protosol, complete with land snails and large trees, directly on inter-tidal or sub-tidal deposits represents a point of emergence within each of the assemblages, but at differing elevations, ranging from +1m ASL at Saucos Hill to +5m ASL at Spittal Pond. Had all the assemblages accumulated as part of the same transgressive or autogenic succession then the evidence of intermediate emergence events at three, or more, elevations is problematic. Arguably, an oscillating RSL superimposed on a transgressive trend would provide a partial fit to observations. However, the upward succession from protosol to an advancing dune, within each assemblage, suggests that separate emergence events were sustained for significant lengths of time. There is no evidence of a reversion from terrestrial to marine conditions within any of the assemblages that would be expected from an overall transgressive trend. On the other hand, a regressive trend, with assemblages deposited at higher RSLs being earlier than those deposited at lower sea levels, cannot be ruled out. It is, however, a speculative scenario in the absence of precise ages or clear stratigraphic relationships between the exposures of key assemblages which are distributed laterally on ≥6 km of coastline.

Although post-depositional tectonic movements could be responsible for the elevational discrepancies between Belmont Formation facies assemblages, there are no tilted or deformed strata at the relevant localities to support this, despite almost continuous exposure. Here it is argued that the conflicting vertical positions of respective facies assemblages constitute evidence of allocyclicity, as would be expected in association with high frequency RSL oscillations. Dabrio et al. (2011) similarly reconstructed "millennial/submillennial sea-level fluctuations" from almost identical Pleistocene littoral facies assemblages in Spain.

The argument that allocyclic control was responsible for the evolution and preservation of Pleistocene beach-dune systems in Bermuda is equivalent to that made by Reading and Collinson (1996) with respect to ancient stacked peritidal cyclothems, which follow similar cycles of progradation, inundation and emergence as identified in Bermuda. According to Reading and Collinson (1996) the intercalated sub-aerial exposure surfaces within many of these stacked sequences refute models which simply comprise autocyclic accumulation of sediment within accommodation space created by progressive subsidence (i.e. a RSL transgression). They reason, instead, that the vertical succession of facies within carbonate shelf cyclothems such as those of the Carboniferous deposits of Utah attest to a "hierarchy of stratigraphic forcing" (Goldhammer et al., 1991) by RSL fluctuations. The difference in Bermuda is that there is no backdrop of ongoing tectonic subsidence, so the assemblages are not stacked, but occupy approximately the same horizon between 0 and +10 m (ASL) distributed laterally along the south shore.

In addition to facies architecture, there is other evidence which corroborates high-frequency RSL fluctuations during MIS 7 at Bermuda. For example, the occurrence, within sub-tidal Belmont deposits, of at least one prominent horizontal bounding surface that is colonized by encrusting organisms as identified by Meischner et al. (1996). This attests to sediment submergence, emergence, cementation and re-submergence i.e. more than one sub-stage RSL oscillation (Meischner et al., 1995). Additionally, Vollbrecht and Meischner (1996) identified multiple layers of circumgranular cement around intraclasts, which had been truncated as a result of "sedimentation, lithification, grain remobilization and renewed sedimentation". Significantly, early cement layers comprised low-magnesium calcite of meteoric (sub-aerial) origin, and subsequent layers comprised high-magnesium calcite of marine-phreatic origin. Vollbrecht and Meischner (1996) concluded that sub-aerial cementation processes had been interrupted at an early stage by marine reworking, which is entirely consistent with marine erosion of weakly cemented dunes witnessed at the base of some Belmont Formation facies assemblages (Figures 7.2 and 7.3).

Coral fragments collected for this study from prograded beach deposits of the Belmont Fm were dated to ~ 200 ka (Section 4.2) which places them at the last of three MIS 7 eustatic sea-level cycles (Figure 7.1). Furthermore, the large MIS 5 Rocky Bay Fm dune ridge on Bermuda's north shore, on which there is no marine imprint, must have post-dated a globally recognized MIS 5e highstand at ~120 ka, whose imprint on Bermuda's south shore is well documented (Harmon, 1983). These chronologies lend support to the contention that significant littoral sediment-accumulation occurs in the later stages of a given interglacial period. Prior sea-level fluctuations would have mobilized re-worked littoral sediments by the "sweeping" action of the wave-base depicted by Bird (2007), and would have accelerated sediment production through the alternate sub-aerial degradation and regeneration of reefs as RSL, respectively, fell and rose.

If Belmont Formation facies assemblage developed in response to sediment abundance towards the end an interglacial period, it follows that the sediment-limited ravinement infill facies assemblage was probably the outcome of platform flooding early in an interglacial period. These extremes of the facies assemblage development are represented hypothetically in succession in Figure 7.11.

7.3.3. A review of the depositional models

It has been shown that prevailing transgressive (rising RSL) dune-building models, such as those developed by Bretz (1960) and Vacher 1972) for Bermuda's north shore, were based on misidentification of low-angle stoss-slope dune strata as marine strata. In the absence of a demonstrable marine-dune transition, the north shore deposits do not provide cogent evidence in support of any particular dune-building model. What we do know now is that the MIS 5 north shore dune ridge post-dated the highest MIS 5 highstand and therefore its formation coincided with a falling RSL trend, with potential superimposed oscillations.

On Bermuda's south shore, Bretz (1960) also espoused contemporaneity between emergent Pleistocene beaches and eolianites. Similarly, Mackenzie (1964), Land et al. (1967), as well as Vacher and Hearty (1989) respectively portrayed "intimate associations", "transition zones" and "gradations" between marine and eolian deposits preserved above present sea-level. However, notwithstanding the established near-contemporaneity between small foredunes and high emergent beaches (e.g. Spittal Pond , Figures 7.5 and 7.6), there is no exposed depositional transition between demonstrable beach deposits and advancing-dune eolianites which constitute the bulk of Bermuda's land mass. Where Hapl facies (dune slip-face) and Lapl facies (beach) do occur in succession, they are separated by a protosol representing a hiatus and a significant allogenic environmental transition. Bretz's (1960) claim of an intimate spatial relationship between beach and dune corresponded with his conviction that Bermuda's dunes - acting effectively as foredunes - were fixed by incipient cementation at their point of origin on the beach-backshore. It is demonstrated here that this concept of beach-tied static dunes is contradicted by their landward advancement (Section 6.3.1) and by the geometry of their cross-stratification (Section 6.3.4).

Vacher at al. (1995) were very specific in stating that dune-building, of his south shore sediment-supply model of Vacher (1972), was not forced by RSL change but, rather, was the outcome of autogenic sediment-supply processes and time. However, in the absence of a forcing agent, it is unclear as to what in the Vacher model would trigger the transition from foredune aggradation to advancing-dune construction. Where there is a positive sediment budget and a stable sea level foredunes typically develop in series of shore-parallel regressive ridges, each ridge having formed seaward of its predecessor, as observed in eastern Australia (Short et al.,1986), Israel (Tsoar, 2000) and Ireland (Carter, 1990). Furthermore, the Vacher model does not account for the observed features and facies architecture which attest to transgressive marine deposition. Vacher (1972) and Vacher et al. (1995) in espousing gradual autogenic facies transitions failed to incorporate a critical division, at a hiatus, of the Belmont Fm depositional cycle into a phase of submergence represented by

S1, followed by a phase of emergence, represented by S2 (Figure 7.10) which implicate RSL forcing.

Sayles' (1931) falling sea-level/lowstand model has been out-of-favor since it was considered to have been "completely reversed" (Land et al., 1967) by Bretz (1960). It is not dissimilar to that proposed here in terms of the trigger for dune building. However, Sayles invoked a significant 10 to 20m drop in sea-level and concomitant exposure of expansive platform sediments. This makes it difficult to explain the scarcity of submerged eolianites in platform cores (Vollbrecht, 1990) when compared with the copious eolianites which are stacked "onshore" within the narrow confines of the present islands. This distribution of eolianites, as argued by Bretz (1960), confutes a crucial aspect of Sayles' model as it implies that source-beaches were formed close to the present shoreline at successive interglacial highstands.

By incorporating a mechanism for the accumulation of a littoral sediment prism at a peaking RSL the model, advanced here, meets the criteria of a sediment source which is well-stocked, contiguous with the shore and which would be summarily exposed at the onset of a RSL regression (Figure 7.10). Furthermore, now that it can be demonstrated that Sayles' (1931) assumption of dune mobility was correct, we can contemplate the onshore deposition of advancing-dune deposits sourced from beaches forming on the sediment prism somewhat beyond and below the present-day strandline. This had been ruled out by Bretz (1960), Vacher (1972) and Hearty et al. (2002) who, un-swayed by the dominance of landward-dipping slip-face strata, asserted that incipient cementation of dunes by rain water rendered them incapable of lateral encroachment.

Although it is suggested here that expansive dune-building is correlative with a falling RSL trend, the entire process of sediment generation and emplacement, represented by S1 and S2, spans a peaking RSL. Arguably, dune-building is dependent on prior high order sea-level cycles to
"prime" nearshore accommodation space with sediment. It may be more appropriate, therefore, to attribute dune activity on Bermuda to an oscillating RSL as opposed to the particular trend or position of RSL at which the sediment became available for eolian transportation and was delivered to the dunes.

7.3.4. Present-day conditions at Bermuda

Modern Bermuda under the influence of a long period of relatively stable but rising RSL represents something of a dilemma for those who have advocated a model which involves dune building at, or close, to peak RSLs. Present highstand conditions on both the north and south shore contrast strikingly with copious littoral deposition represented by several emergent Pleistocene coastal facies assemblages. After a prolonged late Holocene highstand, there is still no evidence at Bermuda of beaches onlapping penecontemperaneous dunes, as would be expected from Bretz's (1960) transgressive model or from the example of Bahamian Holocene transgressive dunes (Carew and Mylroie, 1995). Conditions on Bermuda's coastline today are equivalent to those of the Pleistocene ravinement infill facies assemblage (Figure 7.10) which did not produce emergent prograded beaches. The biologically-generated positive sediment budget required for future eolianite deposition, invoked by Vacher and Rowe (1997), has not materialized. Furthermore, satellite images of Bermuda captured during hurricanes "Gert", "Fabian" and "Gonzalo" in 1999, 2003 and 2014, respectively, show massive plumes of sediment streaming many kilometers away from the Bermuda platform, being permanently lost to deep oceanic waters (Figure 7.12). Such events must counteract, to an unknown degree, biological production of new carbonate material and challenges the concept of inevitable, progressive accumulation of platform sediment which culminates in unforced, autogenic, littoral progradation and formation of advancing dunes.

It is conceivable that a prolonged stable post-Holocene sea level will ultimately produce prograding foreshore and shoreface deposits which entomb contemporaneous reefs and then spawn advancing dunes as observed in Pleistocene successions of the Bahamas (Carew and Mylroie, 1995). Arguably the cooler, less productive, ocean waters at Bermuda can be compensated for by the availability of time at prolonged interglacial highstands - time in which the carbonate factory can fill accommodation space. This could be the post-Holocene future for Bermuda, and the apparent absence of Pleistocene counterparts may be attributable to erosion or submergence of critical outcrops.

7.3.5. Potential application of the two-stage Bermuda model elsewhere in the world

The coastal dune-building model developed, here, for Bermuda is based on the interpretation of events represented by the architecture of coastal facies assemblages. The existence of some excellent shore-normal coastal exposures in Bermuda - at Hungry Bay, Devonshire Bay and Spittal Pond for example - has facilitated this approach. The ability to develop a model from facies analyses, in Bermuda, is offset somewhat by the absence of a reliable dating technique that can be applied to the almost pure carbonate eolianites. The two depositional stages of the Bermuda model comprise a stage (S1) of progradation of beach/barrier and shoreface sand deposits just prior to the peak of a marine transgression; and a stage (S2) of advancing-dune deposition as a result of aeolian re-working of these sands when exposed on widening regressive beaches. These conditions of net littoral accretion appear to contradict the status of many present-day coastlines, including that of Bermuda, which uphold the relationship between a marine transgression and coastal erosion described in the Bruun model (1954) and Davidson Arnott (2005) model of shoreline response to changing RSL. However, Short et al. (1986) and Bird (2007) note that, S1-type, progradation of foreshore and shoreface deposits will occur under certain circumstances when RSL is rising. Examples are seen in the prograded coastal barriers which evolved in the mid-Holocene in eastern North America, the Netherlands and southeast Australia (Dillenburg et al. 2006). Recognition of the phenomenon,

Figure 7.12. Loss of platform sediment caused by Hurricane Gonzalo. From Royal Gazette 22nd October 2014. "The Aqua and Terra satellites caught before and after pictures of the Island from space, showing streams of sandy waters extending to the east and south of the Island." Note that Hurricane Gonzalo made landfall on 17th October whereas the "after" satellite photo is dated 19th October when there were clear skies. Similar plumes which transport sediment permanently off the Bermuda platform have been observed in previous hurricanes.

by sequence stratigraphers, is formalised by the “Highstand System Tract” which incorporates a phase of coastal sediment progradation near peak sea level, when sediment supply outpaces the creation of accommodation space (Coe, 2003).

True “transgressive” dunes have been associated with RSL rise in several parts of the world (Cooper 1958; Thom, 1978; Short et al. 1986, Brooke 2001; Kindler, 1995; Carew and Mylroie 1995; and Moura et al., 2007), and are the product of high energy “open” conditions on sandy shorelines. Analogous Quaternary transgressive dunes were believed to have existed in Bermuda (Bretz, 1960 and Vacher, 1972). Stratigraphic evidence presented here, however, demonstrates that Bermuda’s dunes post-dated peak RSL. They represent the second stage (S2) of littoral deposition in which advancing dunes formed in association with a RSL regression. This stage features beaches of a width that exceeds the critical fetch (Moura et al., 2007) and a supply of wind-blown sand sufficient to overwhelm the retentive capacity of vegetation. Coastal dune activity elsewhere in the world, which has been similarly triggered by a regressive RSL have been catalogued by Brooke (2001) and Mauz et al. (2013). Pleistocene versions have been documented on several islands, such as the Bahamas (Carew and Mylroie, 1995), Hawaii (Fletcher et al.,1999) and Lord Howe Island (Woodroffe, 2002).

Testing the transferability of the Bermuda coastal-dune-building model, including the Stage 1 transgressive and Stage 2 regressive phases is constrained by the different forms of evidence available i.e. stratigraphical versus chronological. The well preserved emergent facies successions which are the foundation of the Bermuda model owe their existence to a RSL curve at Bermuda which is elevated above those at most other localities where eolianites have formed. Equivalent evidence at the other sites, if it exists, is now largely submerged or has been erased by erosion. Because of the effect of GIA (glacio-hydro-isostatic adjustment), accurate high resolution ages, as an alternative to stratigraphic interpretation, are not a panacea for the development coastal dune building models. The chronology of ice-volume changes determined by proxies such as marine oxygen isotopes does not necessarily correlate with the palaeo-RSL curve. During the Holocene for example despite a global eustatic sea-level rise, GIA-controlled RSL regressions have occurred and continue to occur at many localities. Subtle GIA influences during the Pleistocene are much more speculative than those of the Holocene, meaning that even the most accurate age does not always translate into an understanding of a dune-system’s relationship to metre-scale RSL change.

There are localities where a dune-building chronology, which is consistent with the two-stage Bermuda model, has been established as a result of some combination of reliable dating, a robust palaeo-RSL curve and stratigraphical evidence. Examples are Norfolk, UK - Holocene (Orford et al., 2000), the Bahamas - Late Pleistocene (Carew and Mylroie,1995), Sardinia - Late Pleistocene (Andreucci et al., 2009), South Africa - late Pleistocene (Bateman et al., 2004), Southern Portugal – Holocene (Moura et al., 2007) and Brazil - Holocene to present

(Hesp et al., 2005). In some of these cases dune-building was not exclusive to the falling limb of the sea-level curve, so that more than one model must be adopted to explain all of the dunes. For example "transgressive" and "regressive" dunes are identified by the Carew and Mylroie (1995) in the Bahamas and by Moura et al. (2007) in Southern Portugal.

On the Norfolk and Northumberland coasts of the UK, prograding littoral sequences formed on transgressive shorelines through high sediment supply (Orford et al., 2000). This process has similarities with S1 in Bermuda. Infrared stimulated luminescence and ^{14}C dating show that maximum dune development at 0.2 to 0.6 ka coincided with the Little Ice Age and a related fall in RSL which, in turn, is analogous to S2 in Bermuda. In the Grotto Bay Fm of San Salvadore island (Bahamas), emergent coral reefs which yield U-series ages of 132 – 119 ka are entombed by foreshore and shoreface calcarenites. These marine deposits are superposed by a protosol and dune sands, completing a facies succession equivalent to that seen in Pleistocene Bermuda (without the coral reefs). The Bahamian succession is attributed by Carew and Mylroie (1995) to rapid progradation of littoral sediments of a "still-stand phase" followed by a "regressive phase" of dune building associated falling RSL. They do not interpret the protosol, but it must represent a hiatus that coincides with a change in the depositional environment between the interglacial still-stand and the RSL regression. It is arguably equivalent to the protosol that developed between stages S1 and S2 in the Belmont Fm of Bermuda.

On the coast of South Africa, OSL dating attributes dune construction events to 160 -189 ka (post-MIS7), 104-128 ka (post-MIS5e) and 67-80 ka (post-MIS5a). Bateman et al. (2004) who undertook the dating, note the similar chronostratigraphy of these coastal dunes to those of Bermuda. At South Africa and Bermuda, dune ridges formed successively in the same position close to the present coastline and are now being eroded by the sea, having been deposited, post-highstand, when sea-level was marginally lower than present. Similarly in Sardinia, OSL dating by Andreucci et al. (2009) indicates that substantial dune-fields formed post-MIS5a at ~75ka. They conclude that, consistent with the Bermuda model, a sand reservoir accumulated at successive highstands (MIS 5e, c, a) when the sea level was the same or higher than at present; and that dune-building was primarily associated with drops in RSL, which provide sediment as well as space on the backshore.

In the Algarve of southern Portugal "transgressive dunes" started to accumulate in the bay during the rapid RSL rise of the mid-Holocene at between 8.8 to 6.6 ka (Moura et al., 2007). At ~5.5 ka the dunes became inactive when RSL was approximately at the present level and available dry sediment was unable to be windblown because the beach width was narrower than the critical fetch. This was equivalent to the termination of S1 in Bermuda where the stable shoreline comprised a reflective barrier-beach and small foredunes. A new phase of dune generation occurred in the Algarve after ~3.2 ka due to a seaward movement of shoreline when beach width was greater than the critical fetch.

The Holocene RSL history of the Brazilian coast is out-of-synchronisation with many other localities, being significantly influenced by GIA. RSL rose to a few metres above present level at 5.1 ka followed by an overall fall of RSL (Dillenburg et al., 2006) to the present-day level. The Holocene barrier which started to prograde at ~7 ka is topped by advancing ("transgressive") dunefields (Hesp et al., 2005). Late Holocene to modern aeolian facies thus overlie foreshore and shoreface facies. This represents beach progradation succeeded by dune deposition associated, respectively, with rising and falling RSL stages equivalent to S1 and S2 in Bermuda.

8. CONCLUSIONS

From new U-series coral age-data combined with re-interpreted sedimentological and fossil evidence, it is concluded that that MIS 7 RSL (relative sea levels) at Bermuda exceeded the present level by at least 4.5m, and probably reached or surpassed +6.0m ASL (above present mean sea level). The MIS 7 maximum RSL at Bermuda is, thus, shown to be above the top of the range of eustatic palaeo-sea-levels, associated with that period, inferred from studies in most other parts of the world. Anomalously elevated highstands at Bermuda, not only at MIS7, are consistent with a lagging hydro-glacio isostatic response at intermediate-field sites as predicted by glacio-isostatic adjustment (GIA) models (Dutton and Lambeck 2012; and Raymo and Mitrovica, 2012). The application of such models should, however, be undertaken with caution because of potential tectonic instability attested to by significant seismic activity around Bermuda and the existence of reverse and normal faulting in the islands' Quaternary limestones.

The findings, here, with respect to MIS 7 sea levels at Bermuda are based on ages of coral fragments collected from marine deposits traditionally ascribed to the Belmont Fm. This has important implications for the stratigraphy of Bermuda. The robust MIS7 ages mean that assignment of these deposits to the MIS5e Rocky Bay Fm, in some of the more recent articles (Hearty, 2002; Hearty et al., 2007) on Bermuda's Quaternary geology, is refuted. These prominent emergent beach deposits and superposed dunes are thus re-established as members of the Belmont Fm - a fundamental component of Bermuda's stratigraphy.

Quaternary sea-level oscillations have had a significant if not dominant impact on coastal morphodynamics, globally. There is a consensus that these cycles and the concomitant alternate flooding and emergence of island platforms, as well as continental shelves, were the primary control on the timing of coastal dunefield construction. Cross stratified eolianites which dominate Bermuda's geology and constructed the topography of ≥ 50m high ridges are the product of sediment generation and mobilisation associated with these cycles. An analysis of several thousand slip-face dip azimuths indicate that the dunes advanced, not in conformity with the "resultant drift direction" of today, but in landward direction - away from source beaches on the north, west and south shores of the islands. They formed sinuous transverse ridges with lobate projections, burying mature soils and trees whose existence is now witnessed by tree-trunk moulds and palm frond impressions preserved within the eolianites. Planar sub-horizontal truncation of slip-face foresets, a common feature of Bermudian eolianites, attests to highly mobile, sub-critical climbing behaviour. Relative to the short period of time when sediment-supply conditions were conducive to the accumulation of dunes, meteoric diagenetic cementation proceeded too slowly to play a part in curbing their mobility. The prevailing model in which dunes were summarily stabilised by "incipient cementation" following rapid accumulation in extreme storm winds is rejected here. An alternative model is proposed in which the dunes remained mobile, or were susceptible to reactivation, over periods spanning many decades. Only much later, following permanent stabilisation by vegetation, were they lithified predominantly by the effects of infiltrating rain-water.

Emergent Pleistocene marine-eolian coastal successions in Bermuda are classified as either ravinement infill facies assemblages or Belmont Formation facies assemblages. The former represent deposition associated with an initial transgression onto a rocky shore and includes a basal transgressive lag with minimal beach progradation or eolianite accumulation. The Belmont Formation facies assemblages are by contrast laterally extensive and relatively voluminous. They comprise ten structural facies which are divided, by an exposure surface, into a predominantly marine succession (S1) and a terrestrial (S2) succession, which were deposited, respectively, during a glacio-hydro isostatically controlled rising and falling RSL, spanning a highstand. S1 commenced with the accumulation of shoreface and foreshore deposits in a progradational facies sequence which was followed by upper-beach erosion and backshore flooding. At peak RSL the shoreline stabilised in the form of an aggraded barrier system, capped by small foredunes. Emergence is represented by a protosol, at the base of S2, marking the transition from an ephemerally-flooded backshore basin, or slack, to a vegetated and then wooded terrain. Continuation of the RSL regression was attended by the development of advancing dunes which overtopped the barrier foredunes and encroached landward across the wooded backshore onto a topography of older eolianites. The mobilization of these advancing dunes depended on a shoreward flux of sediment sufficient to overwhelm the retentive capacity of vegetation. This need was met by progressive sub-aerial exposure of a well-stocked nearshore sediment prism which had accumulated during S1.

It is proposed here that the high positive sediment budgets of the Belmont Formation assemblages were likely generated by successive high order, sub-stage, RSL oscillations, which facilitated generation and reworking of nearshore sediments. The occurrence of high order, high-frequency eustatic sea-level cycles is corroborated globally by a variety of Pleistocene sea-level proxies. Evidence of RSL cyclicity within the time span of the Belmont Fm, at Bermuda, includes: the existence of multiple facies assemblages of which at least three include sea-level indicator facies (SIFs) at contradictory elevations; a history of inter-granular cement development which evidences re-working; and an encrusted exposure surface observed within sub-tidal shoreface deposits.

It is significant that the two-phase depositional model, developed here for Bermuda, appears to be applicable to other, ancient as well as presently active, littoral systems around the world where the same chronologies of marine and aeolian deposition relative to changing RSL have been demonstrated through precise dating of sediments supported by stratigraphical evidence. Examples, cited in this study, are Norfolk, UK - Holocene, the Bahamas - Late Pleistocene, Sardinia - Late Pleistocene, South Africa - late Pleistocene, Southern Portugal – Holocene, and Brazil - Holocene to present. The evolution of coastal dunes at these localities share the following important developmental stages with the Bermuda model: 1. an episode dominated by marine processes which redistribute nearshore sand into prograding prism of foreshore and shoreface sediments coincident with the late stages of an RSL transgression; 2. an episode of minimal sediment deposition or of coastal retreat at peak RSL; and 3. The formation of landward advancing dunes as a result of aeolian entrainment of sand sourced from widening beaches which develop concomitant with a falling RSL.

On most present-day shorelines, globally, RSL is rising slowly following a rapid Holocene transgression. Evidence from Bermuda's Pleistocene coastal deposits indicates that a rising RSL was temporarily accompanied by beach progradation. However, as sediment supply diminished there was increased vulnerability of the beach-backshore to flooding, which translated into erosion and retrogradation prior to stabilization as RSL peaked. At this point the barrier-beaches which formed did not achieve the critical fetch (width) required to construct substantial dunes which could act as a buffer to storm erosion. These are the conditions that prevail on many present-day sandy coasts, suggesting that the Bermuda's Pleistocene model of beach-dune evolution can be applied not only in the interpretation of equivalent ancient deposits but also as an analogy for modern coastal deposits which are being subjected to the effects of transitions in RSL and in sediment supply near the height of an interglacial period.

References

Aagaard,T., Orford,J.D, and Murray,A.S., 2007, Environmental controls on coastal dune formation; Skallingen Spit, Denmark: Geomorphology v. 83, Issues 1-2, p. 29-47.

Agassiz, A., 1895, A visit to the Bermudas in March, 1894: Bulletin Museum Comparative Zoology, Harvard, v. 26, p. 209-279.

Andreucci,S.A., Clemmensen, L.B., and Pascucci,V. 2010, Transgressive dune formation along a cliffed coast at 75 ka in Sardinia, Western Mediterranean: a record of sea-level fall and increased windiness: Terra Nova, v. 22, p. 424–433.

Andreucci, S., Pascucci, V., Murray, A.S, Clemmensen, L.B., 2009. Late Pleistocene coastal evolution of San Giovanni di Sinis, west Sardinia. Sedimentary Geology, 216: 104-116

Andrews, P.B, Van Der Lingen, G.J., 1969, Environmentally significant sedimentological characteristics of beach sands: New Zealand Journal of Geology and Geophysics, May Issue, P. 119-137.

Bagnold.R.A., 1954, The Physics of Wind Blown Sand and Desert Dunes: New York, Dover Publications Inc. p. 165

Bateman, M. D., Holmes, P.J., Carr, A.S., Horton, B.J., and Jaiswal, M.K., 2004, Aeolianite and barrier dune construction spanning the last two glacial–interglacial cycles from the southern Cape coast, South Africa: Quaternary Science Reviews v. 23, p. 1681-1698.

Bauer, B.O., Allen, J.R. 1995., Beach steps: an evolutionary perspective. Marine Geology, 123: 143-166

Bauer, B.O., and Sherman,D.J. 1999, Coastal Dunes: Problems and Prospects, *in* Goudie, ,A.S., Livingstone.I. and Stokes, S., eds., Aeolian Environments, Sediments and Landforms: Chichester, UK, John Wiley & Sons, p. 71-104.Bird, E.C.F., 1990, Classification of European dune coasts, Bakker, T, W., Jungerius, P. D. and Jungerius, J. Klijn, J.,eds.: Catena Supplement, v. 18, p. 15–24.

Bigarella, J.J., Becker, J.B., Duarte, G.M., 1969. Coastal dune structure from Parana (Brazil).: Marine Geology, 7: 5 – 55.

Bintanja, R., van de Wal, R. S., & Oerlemans, J., 2005. Modelled atmospheric temperatures and global sea levels over the past million years: Nature, 437(7055), p. 125-128.

Bird, E.C.F, 2007, Coastal Geomorphology. An Introduction. Chichester, UK, John Wiley & Sons. p 411.

Bowen, D.Q., 2010. Sea level ~400 000 years ago (MIS 11): analogue for present and future sea-level? Climate of the Past, 6: 19-29, 2010.

Bretz, J.H., 1960, Bermuda a partially drowned. late mature, Pleistocene karst: Bulletin of the Geological Society of America v. 71, p. 1729 – 1754.

Bristow, C.S., and Pucillo, K., 2006, Quantifying rates of coastal progradation from sediment volume using GPR and OSL: the Holocene fill of Guichen Bay, south-east South Australia. Sedimentology v. 53, p. 769-788.

Brooke, B., 2001, The distribution of carbonate eolianite. Earth-Science Reviews v.55,p.135–164.

Caputo, M.V., 1995. Sedimentary architecture of Pleistocene eolian calcarenites, San Salvadore Island, Bahamas. Geological Society of America. Special paper 300, 63 – 76

Carew, J.L., and Mylroie, J.E., 1995, Depositional model and stratigraphy for the Quaternary geology of the Bahamas: Geological Society of America Special Paper 300, p. 5-32.

Carter, R.W.G. 1990. The geomorphology of coastal dunes in Ireland. In Bakker, Th.W. & P. D. Jungerius, J. Klijn (eds.): Catena (Suppl.) 18: 31–39.

Carter, R.W.G., Wilson, P. 1993. Aeolian processes in northwest Ireland. Geological Society of London. Special Publication 72, 173-190.

Chappell, J. Shackleton, N.J., 1986. Oxygen isotopes and sea level. Nature, 324: 137 – 140

Cheng, H., Edwards, R.L., Shen, C., Polyak, V.J., Asmeromd, Y., Woodhead, J., Hellstrom, J., Wang, Y., Kong, X., Spötl, C., Wang, X., Alexander. C Jr., 2013. Improvements in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U–Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. Earth and Planetary Science Letters(371-372): 82-91.

Clague, D.A., Moore, J.G., 2006. Vertical motions of oceanic volcanoes: EOS Transactions American Geophysical Union, 87, (52), Fall Meeting Supplement, Abstract V31E-01.

Clifton, H.E., Hunter, and R.E., Phillips, R.L., 1971, Depositional structures and processes in the non-barred high-energy nearshore: Journal of Sedimentary Petrology. V. 41, no. 30, p. 651-670.

Coe, A.L., 2003. *The sedimentary record of sea-level change*. Cambridge University Press.

Cooper, W.S. 1958. Coastal sand dunes of Oregon and Washington. Geol.Soc. Am Bull 72. 169p
Bretz J.H. 1960. Bermuda a partially drowned. late mature, Pleistocene karst. Bulletin of the Geological Society of America 71, 1729 – 1754.

Creveling, J. R., Mitrovica, J. X., Hay, C. C., Austermann, J., & Kopp, R. E., 2015. Revisiting tectonic corrections applied to Pleistocene sea-level highstands. *Quaternary Science Reviews*, *111*, 72-80.

Dabrio, J.D., Polo, M.D., 2013. Cyclic coastal sedimentation in Sorbas (Messinian, SE Spain). Sociedad Geologica Espana, Geoceta, 54: 31 – 34.

Dabrio, C.J., Zazo,C., Cabero, A., Goy, J.L., Bardají, T., Hillaire-Marcel, C., González-Delgado, J.A., Lario, J., Silva, P.G., Borja, F.,García-Blázquez, A.M., 2011. Millennial/submillennial-scale sea-level fluctuations in western Mediterranean. Quaternary Science Reviews, 30: 335 – 346.

Davidson-Arnott, R.G.D., Law, M.N., 1990. Seasonal patterns and controls on sediment suply to coastal foredunes, Long Point, Lake Erie. Coastal Dunes: Form and Processes. Ed Nordstrom.K.F,N.P.Psuty and R.W. Carter. 177- 200

Davidson-Arnott, R.G.D., Pyskir, N.M., 1988. Morphology and formation of an Holocene coastal dune field, Bruce Peninsula, Ontario. Geographie physique et Quaternaire. 42.2, 163-170

Delanghe, D., Bard, H., Hamelin, B., 2002. New TIMS constraints on the uranium-238 and uranium-234 in seawaters from the main ocean basins and the Mediterranean Sea. Marine Chemistry 80 (1): 79–93

Dillenburg, S.R., Tomazelli, L.J., Hesp, P.A., Barboza, E.G., Clerot, L.C.P. and Silva, D.D., 2006. Stratigraphy and evolution of a prograded transgressive dunefield barrier in southern Brazil. *Journal of Coastal research*, pp.132-135.

Dixon, K. L., and Pilkey Jr, O. H., 1991, Summary of beach replenishment on the US Gulf of Mexico shoreline: Journal of Coastal Research, v. 7, No.1, p. 249-256.

Doody, J. P., 2012, Sand dune conservation, management and restoration: Springer Science & Business Media. v. 4

Dorale, J.A., Onac, B.P., Fornos, J.J., Gines, J., Gines, A., Tuccimei, P., Peate, D.W., 2010. Sea-level highstand 81,000 years ago in Mallorca. Science 327: 860 -863.

Dutton, A., Bard, E., Antonioli,F., Esat, T.M., Lambeck, K., Mecculloch, M.T., 2009. Phasing and amplitude of sea level and climate change during the penultimate interglacial. Nature Geoscience, 2: 355 – 359.

Dutton, A., Lambeck, K., 2012. Ice Volume and Sea Level During the Last Interglacial. Science, 337: 216 -219

Edwards, R. L., Chen, J.H., Wasserburg, G.J., 1986. 238 U- 234U_ 230 Th- 232 Th systematics and the precise measurement of time over the past 500,000 years. Earth and Planetary Science Letters, 81: 175-192.

El-Fayoumya, F., Gheith,M., Abd-Alla, M.A., Toubar,.M.G, 1993. Geomorphological Features and Primary Sedimentary Structures of the deltaic coastal plain, Burullus Lake Area, Egypt. Marine Science 4, 115 -131

Esat, T. M., Yokoyama Y., 2006. Variability in the uranium isotopic composition of the oceans over glacial-interglacial timescales. Geochimica et Cosmochimica Acta, 70(16): 4140-4150.

Everard, M., Jones, J., and Watts, B., 2010, Have we neglected the societal importance of sand dunes? An ecosystems services perspective. Aquatic Conservation, v. 20, p. 476-487.

Fairbridge, R.W., 1995, Eolianites and eustasy: early concepts on Darwin's voyage of HMS Beagle: Carbonates and Evaporites, v. 10, No. 1, p. 92 - 101.

Fairbridge, R.W., and Johnson, D.L., 1978, Eolianite, in Fairbridge, R.W., and Bourgeois, J., eds., The Encyclopedia of Sedimentology: Stroudburg, Pennsylvania, Dowden, Hutchinson and Ross, p. 279 -282.

Fletcher, C.H., Murray-Wallace, C.V., Glenn, C.R., Sherman,C.E., and Popp, B., 1999, Late Quaternary eolianite geochemistry,petrology and aminostratigraphy at Kaiehu Point (Mo'omomi).Moloka'i, Hawaii, *in* Fletcher, C.H., Ed.,, Molokai Fieldtrip Guidebook, IGCP Project 437. University of Hawaii, Honolulu, p. 15-41.

Fryberger, S.G., 1979. Dune forms and wind regime. In: A study of global sand seas. E.D. McKee (ed.), 137 – 69. Professional Paper 1052, USGS, Denver, Colorado.

Gardner, R.A.M., 1983, Aeolianite, in Goudie, A.S., and Pye, K., eds., Chemical sediments and Geomorphology: London, Academic Press, p. 265 – 300.

Gardner, D.E., 1955, Beach-sand heavy-mineral deposits of eastern Australia: *Bureau of Mineral Resources Bulletin, v.* 28,, 103 p.

Gines, A., 2000. Patterns of collapse chambers in the endokarst of Mallorca (Balearic Islands, Spain). Acta Carsologica, 29/2 (9): 139-148.

Gines, A., Gines, J., 2007. Eogenetic karst, glacioeustatic cave pools and anchialine environments on Mallorca Island: a discussion of coastal speleogenesis. International Journal of Speleology 36(2): 57 – 67.

Goldhammer, R. K., Oswald, E. J., and Dunn, P. A., 1991, Hierarchy of stratigraphic forcing: Example from Middle Pennsylvanian shelf carbonates of the Paradox Basin: Kansas Geological Survey Bulletin, v. 233, p. 361-413.

Goldsmith, V., 1973. Internal geometry of vegetated coastal dunes. Journal of Sedimentary Petrology 43, 1128-1142.

Goldsmith, V., 1989. Coastal dunes as geomorphological systems. *Proceedings of the Royal Society of Edinburgh. Section B, Vol. 86*, 3-15.

Harmon, R.S., Mitterer, R.M., Kriausakul, N., Land, L.S., Schwarcz, H.P., Garrett, P., Larson, G.J., Vacher, H.L., Rowe, M.P., 1983. U-series and amino-acid racemization geochronology of Bermuda: implications for eustatic sea-level fluctuation over the past 250,000 years. Palaeogeography, Palaeoclimatology, Palaeoecology, 44 : 41—70.

Harmon, R.S., Schwarcz, H.P., Ford, D.C. 1978. Late Pleistocene Sea Level History of Bermuda. Quaternary Research, 9: 205 – 218.

Harmon, R.S., Thompson, P., Schwarcz, H.P., Ford, D.C., 1978. Late Pleistocene Paleoclimates of North America as Inferred from Stable Isotope Studies of Speleothems. Quaternary Research 9, 54 – 70.

Harms, J. C., Fahnestock, R. K., 1965. Stratification, bed forms, and flow phenomena (with an example from the Rio Grande). In Middleton, G. V. (ed.) Primary sedimentary structures and their hydrodynamic interpretation. Special Pubilication. Soc. Econ. Paleont. Miner 12, 84-115.

Harshberger, J.W., 1908. The comparative leaf structure of the sand dune plants of Bermuda. Proceedings of the American Philosophical Society. XLVII, 98-110.

Hartsock, J.K, Woodrow, D.L., McKinney, D.B. 1995. Fracture systems in northeastern Bermuda Geological Society of America Special Papers, 300: 325-334

Havholm, K.G., Ames,D.V., Whittecar,G.R., Wenell,B.A., Riggs,S.R., Jol,H.M., Berger,G.W. Holmes,M.A., 2004. Stratigraphy of back barrier coastal dunes, Northern Carolina and South Virginia. Journal of Coastal Research 20.4, 980-999.

Hearty, P.J., 2002. Revision of the late Pleistocene stratigraphy of Bermuda. Sedimentary Geology 153, 1 -21.

Hearty, P.J., Hollin, J.T., Neumann, A.C., O'Leary, M.J. and McCulloch, M., 2007., Global sea-level fluctuations during the Last Interglaciation (MIS 5e): *Quaternary. Science. Reviews, v.* 26 (17), p. 2090–2112.

Hearty, P.J., Kindler, P., 1995. Sea level High Stand Chronology from Stable Carbonate Platforms (Bermuda and The Bahamas). Journal of Coastal Research 11 (3): 675-689.

Hearty, P.J., Kindler, P., Cheng, H., and Edwards, R.L.,1999, A +20 m middle Pleistocene sea-level highstand (Bermuda and the Bahamas) due to partial collapse of Antarctic ice: *Geology, v.* 27, p. 375-378.

Hearty, P.J., Neumann, A.C., and Kaufman, D.S.,1998, Chevron ridges and runup deposits in the Bahamas from storms late in oxygen isotope substage 5e: Quaternary Research*, v.* 50, p. 309-322.

Hearty, P.J., Olson, S.L., 2008. Mega-highstand or mega-tsunami? Discussion of McMurtry et al. (2007). Sedimentary Geology 203 (3-4), 307 – 312.

Hearty, P.J., Olson.S.L., 2011. Preservation of trace biota by intense storms in mid-last interglacial (MIS 5c) dunes on Bermuda, with a model for development of hydrological conduits. Palaios. 26, 394 – 405.

Hearty, P.J. Tormey, B.R., Neumann.C.A., 2002. Discussion of "Palaeoclimatic significance of co-occurring wind- and water-induced sedimentary structures in the last-interglacial coastal deposits from Bermuda and the Bahamas" (Kindler and Strasser, 2000, Sedimentary Geology, 131: 1 -7). Sedimentary Geology, 147: 429 – 435.

Hearty P.J., Vacher, H.L. and Mitterer, R.M., 1992. Aminostratigraphy and ages of Pleistocene limestones of Bermuda. Geo. Soc. Am.Bull., 14: 471-480

Heilprin, A., 1889. The Bermuda Islands: a contribution to the physical history and zoology of the Somers archipelago. Privately published. Academy of Natural Sciences. 231p.

Hellemaa,P., 1998. The development of coastal dunes and their vegetation in Finland: Helsinki, Fennia, v. 176, p 111 – 121.

Henderson, G.M., Robinson, L.F., Cox, K., Thomas, A.L., 2006. Recognition of non-Milankovitch sea-level highstands at 185 and 343 thousand years ago from U–Th dating of Bahamas sediment. Quaternary Science Reviews 25: 3346–3358

Herwitz, S.R., 1992. Quaternary vegetation change and dune formation on Bermuda: A discussion. Global Ecology and Biogeography Letters. 2(3), 65-70.

Herwitz, R.H., Muhs, D.R., 1995. Bermuda solution pipe soils: A geochemical evaluation of eolian parent material. Geological Society of America, Special Paper, 300: 311 – 323.

Herwitz, S.R., Muhs,D.R., Prospero,J.M., Mahan,S.,Vaugh,B., 1996. Origin of Bermuda's clay-rich Quaternary palaeosols and their paleoclimatic significance. J.Geophysical Research. 101. D18. 389-400.

Hesp, P.A., 1988. Morphology, dynamics and internal stratification of some established foredunes in southeast Australia. Sedimentary Geology, 55 (1988) 17-41

Hesp, P.A., 2005, Coastal fluxes in the Anthropocene, Crossland, C.J., Kremer, H.H., Marshall, H.J., Crossland, M.D., Le Tissier, A., Eds., The International Geosphere-Biosphere(IGP) Series: Berlin, Germany, Springer. 231 p.

Hesp, P. A., 2013. Conceptual models of the evolution of transgressive dune field systems. Geomorphology, 199, 138-149.

Hesp, P.A., Dillenburg,S.R., Barboza,E.G., Tomazelli,L.J., and Ayup-Zouain,R.N., 2005, Beach ridges, foredunes or transgressive dunefields. Definitions and an examination of the Torres to Tramandai barrier system, Southern Brazil: Annals of the Brazilian Academy of Sciences, V. 77, no. 3, p. 493-508.

Hesp.P.A., and Thom, B.G.,1990. Geomorphology and evolution of active transgressive dunefields, *in* Nordstrom.K.F, Psuty, N.P., and Carter, R.W. eds., : Coastal Dunes: Form and Process: Chichester, UK, John Wiley & Sons, p. 254-288.

Hesp, P.A. and Walker, I.J, 2013. Aeolian environments: coastal dunes, *in* Shroder, J., Lancaster, N., Sherman, D.J., Baas, A.C.W., eds., Treatise on Geomorphology, v. 11: Aeolian Geomorphology., San Diego, CA,, Academic Press,, p. 109-133.

Holcome,R. 2011. GEOrient, ver 9.5.0. Software for graphical analyses of structural orientations. http://www.holcombe.net.au/software/rodh_software_georient.htm

Hunter, R.E., 1977. Basic types of stratification in small eolian dunes. Sedimentology 24, 361-387.

Huntley, D.J., Hutton, J.T., and Prescott, J.R., 1993, The stranded beach-dune sequences of south-east South Australia: a test of Thermoluminescence dating, 0-800 ka: Quaternary Science Reviews v. 12, p.1-20.

Inmal, D.L., Ewing,G.C., Corliss,J.B., 1966. Coastal Sand Dunes of Guerrero, Baja Californis, Mexico. Geological Society of America Bulletin 77 (8), 787-802

Israelson, C., and Wohlfarth, B., 1999, Timing of the Last-Interglacial high sea level on the Seychelles Islands, Indian Ocean: Quaternary Science Reviews, v. 51, p. 306–316.

Jaffey, A. H., Flynn, K. F., Glendenin, L.F., Bentley, W.C., Essling, A. M ., 1971. Precision measurements of half-lives and specific activities of 235U and 238U, Phys Rev. C.4: 1889-1906

Jouzel, J., et al. (2007), Orbital and millennial antarctic climate variability over the past 800,000 years, Science, 317, 793–796.

Kendrick, G.W., Wyrwoll, K.H., and Szabo, B.J., 1991, Pliocene–Pleistocene coastal events and history along the western margin of Australia: Quaternary Science Reviews, v. 10, p. 419–439.

Kindler, P. 1995. New data on the Holocene stratigraphy of Lee Stocking Island (Bahamas) and its relation to sea-level history:Geological Society of America. Special Paper 300, p. 105 - 116.

Kindler, P., and Strasser, A., 2000, Palaeoclimatic significance of co-occurring wind- and water-induced sedimentary structures in the last-interglacial coastal deposits from Bermuda and the Bahamas: Sedimentary Geology, v. 131, p. 1 – 7.

Land, L.S. 1964. Eolian Cross-Bedding in the beach dune environment, Sapelo Island, Georgia. Journal of Sedimentary Petrology. 34 (2), 389-394

Land, L.S. , Mackenzie.F.T., and Gould.J.S. 1967, Pleistocene History of Bermuda: Geologicial Society of America Bulletin 78, v. 993–1006.

Larson, M. and Sunamura, T., 1993. Laboratory experiment on flow characteristics at a beach step, Journal of Sedimentary Petrology, 63(3): 495-500.

Lees. B., 2006, Timing and formation of Coastal Dunes in Northern and Eastern Australia: Journal of Coastal Research, v. 22, no. 1, p. 78-89.

Loucks, R.G., 2007. A review of coalesced, collapsed-paleocave systems and associated supstratal deformation. Time in Karst. Postojna: 121 – 131.

Ludwig, K.R., Muhs, D.R., Simmons, K.R., Halley, R.B. Schinn, E.A., 1996. Sea level records at ~80ka from tectonically stable platforms: Florida and Bermuda. Geology, 24: 211 – 214.

Mackenzie.F.T., 1964, Bermuda Pleistocene Eolianites and Paleowinds: Sedimentology, v. 3, p. 52-64.

Mackenzie.F.T. 1964. Geometry of Bermuda calcareous Dune Cross-Bedding. Science 114, 1449 – 1450.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore Jr., T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages development of a high-resolution 0 to 300 000-year chrostratigraphy. Quaternary Research 27, 129.

Matsunaga, N. and Honji, H., 1983. The steady and unsteady backwash vortices. Journal of Fluid Mechanics, 135: 189 - 197.

Mauz, B., Hijma, M.P., Amorosi, A., Porat, D., Galili, E., and Bloemendal, E.J., 2013, Aeolian beach ridges and their significance for climate and sea level: Concept and insight from the Levant coast (East Mediterranean): Earth-Science Reviews, v. 121, p. 31-54.

McDonnell, A., Loucks, R.G., Dooley, T. 2007. Quantifying the prigin and geometry of circular sag structures in northern Fort Worth Basin, Texas: Paleocave collapse, pull-apart fault systems or hydrothermal alteration?. American Association of Petroleum Geologists Bulletin, 91 (9): 1295 – 1318.

McMurtry, G.M., Tappin, D.R., Sedwick, P.N., Wilkinson, I., Fietzke, J.,Sellwood, B., 2007. Elevated marine deposits in Bermuda record a late Quaternary megatsunami: Sedimentary Geology, v. 200 (3-4), p.155–165.

Meischner, D., and Meischner, U., 1977. Bermuda South Shore Reef Morphology. A preliminary Report. Proceedings of the third International Coral Reef Symposium. Univeristy of Miami. , 243 – 25.

Meischner, D., Vollbrecht, R, and Wehmeyer, D., 1995, Pleistocene sea-level yoyo recorded in stacked beaches, Bermuda South Shore: Geological Society of America. Special Paper 300, p. 295- 309.

Milnes, A.R., Ludbrook, N.H., Lindsay, J.M., Cooper, B.J., 1983.The succession of Cainozoic marine sediments on Kangaroo Island, South Australia. Transactions of the Royal Society of South Australia 107 (1/2), 1–35.

Milsom, J., 1996, Field Geophysics, 2nd edition, Wiley, Chichester.

Morner, N., 1991. Intense earthquakes and seismotectonics as a function of glacioisostacy. Tectonophysics, 188: 407 – 410.

Moura, D., Veiga-Pires, C., Albardeiro, L., Boski, T., Rodrigues, A. L.,and Tareco, H., 2007, Holocene sea level fluctuations and coastal evolution in the central Algarve (southern Portugal): Marine Geology, v. 237, no. 3, p. 127-142.

Muhs, D.R., 1992, The last Interglacial–Glacial transition in North America: evidence from uranium-series dating of coastal deposits, *n* Clark, P.U., Lea, P.D., eds., The Last Interglacial–Glacial Transition in North America: The Geological Society of America, Special Paper 270, v. 31–51.

Muhs, D.R., Pandolfi, J.M., Simmons, K.R., and Schumann, R.R., 2012, Sea-level history of past interglacial periods from uranium-series dating of corals, Curaçao, Leeward Antilles islands: Quaternary Research, 78: 157-169.

Muhs, D.R., Simmons, K.R., Schumann, R.R., and Halley, R.B., 2011, Sea-level history of the past two interglacial periods: New evidence from U-series dating of reef corals from south Florida: Quaternary Science Reviews, v. 30, p. 570-590

Muhs, D.R., Simmons, K.R., and Steinke, B., 2002, Timing and warmth of the last interglacial period: New U-series evidence from Hawaii and Bermuda and a new fossil compilation for North America. Quaternary Science Reviews, v. 21, p. 1355-1383

Muhs, D.R., Whelan, J.F., Kennedy, G.L., and Rockwell, T.K., 1993, Late Quaternary sea-level history of the pacific coast of North America: a detailed record of the Last Glacial/Interglacial cycle, *in* Kelmelis, J.A., Snow, M., eds. US Geological Survey Global Change Research Forum. US Geological Survey, p. 101–102.

Murray-Wallace, C. V., 2002, Pleistocene coastal stratigraphy, sea-level highstands and neotectonism of the southern Australian passive continental margin - a review: Journal of Quaternary Science, v. 17, no. 5, p.469-489

Murray-Wallace, C.V., Banerjee, D., Bourman, R.P., Olley, J.M., and Brook, B.P., 2002, Optically stimulated luminescence dating of Holocene relict foredunes, Guichen Bay, Australia: Quaternary Science Reviews v. 21, p. 1077-1086.

Mylroie, J.E. 1984. Speleogentic contrast between the Bermuda and Bahama Islands. Proceedings of the second symposium on the geology of the Bahamas. Ed. Teeter, J.W.. 113 – 127.

Mylroie, J.E., Carew, J.L., 1995. Karst developments on Carbonate islands. In: Budd, D.A., Saller, A.H., Harris. P.M. (Eds.) – Unconformities and porosity in carbonate strata. American Association of Petroleum Geologists: 55 – 76.

Nelson,.R.J., 1837, On the Geology of the Bermudas: Transactions of the Geological Society of London, v. 5, p. 103-123.

Neumann, A.C. and Macintyre, I., 1985, Reef response to sea level rise: keep–up, catch–up or give–up, *in Delesalle, B. et al. eds.* Proceedings, 5th International Coral Reef Congress (Tahiti): International Society for Reef Studies, Antenne Museum-Ephe, Moorea, French Polynesia, v. 3, p. 105-110.

Olson, S. L., & Hearty, P. J., 2009. A sustained+ 21m sea-level highstand during MIS 11 (400ka): direct fossil and sedimentary evidence from Bermuda. Quaternary Science Reviews, 28(3), 271-285.

Orford J.D., Wilson, P., Wintle, A.G., Knight, J., and Braley, S., 2000, Holocene coastal dune initiation in Northumberland and Norfolk, eastern UK: climate and sea-level changes as possible forcing agents for dune initiation: Geological Society of London Special Publication 166, p. 197-217.

Orme, A.R., 1990, The instability of Holocene coastal dunes: The case of Morro Dunes, California, *in* Nordstrom, K.F, Psuty, .N.P., and Carter, R.W., eds., Coastal Dunes: Form and Process: Chichester, U.K., John Wiley and Sons, p. 315–336.

Pearson, A.K., 2008. Coastal Bermuda. 10 Walks and 73 Plants…you'll see along the way. BioQuill Publishing, Princeton,USA. 103p.

Peckenham, J.M., Hall, J.M., Schenk, P.E., 1981. A proposal for Further Investigation of the Sedimentary and Volcanic Basement of the Bermuda Islands by Deep Drilling. Dalhousie University, Canada: 29p.

Petit, J.R., J. Jouzel, D. Raynaud, N.I. Barkov, J.-M. Barnola, I. Basile, M. Benders, J. Chappellaz, M. Davis, G. Delayque, M. Delmotte, V.M. Kotlyakov, M. Legrand, V.Y. Lipenkov, C. Lorius, L. Pépin, C. Ritz, E. Saltzman, and M. Stievenard. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399: 429-436

Playford, P.E., 1997. Geology anf Hydrogeology of Rottnest Island, Western Australia. In Vacher.H.L.,Quinn,T. (Editors), Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology, 54, p. 783 – 810.

Porter, S. C. 1989. Some geological implications of average Quaternary glacial conditions. Quaternary Research, 32, p. 245–61.

Potter, E. K., & Lambeck, K., 2004. Reconciliation of sea-level observations in the Western North Atlantic during the last glacial cycle. Earth and Planetary Science Letters, 217(1), 171-181.

Price, D.M., Brooke, B.P., and Woodroffe, C.D., 2001, Thermoluminescence dating of aeolianiites from Lord Howe Island and south-west Western Australia: Quaternary Science Reviews. Quaternary Geochronology, v. 20, p. 841–846.

Psuty, P.N., 1990. Foredune mobility and stability, Fire Island, New York. In Nordstrom.K.F, Psuty.N.P., Carter,R.W., Coastal Dunes: Form and Processes, 159 – 176. Chichester: John Wiley and Sons.

Psuty, N.P., 1993, Foredune morphology and sediment budget, Perdido Key, Florida, USA. in Pye,K. (Editor). The dynamics and environmental context of aeolian sedimentary systems. Geological Society Special Publication 72, 145 – 157.

Psuty, N.P., 2004, The coastal foredune: a morphological basis for regional coastal dune development, *in* Luisa, M.M., and Psuty, N.P., eds., Coastal Dunes, Ecology and Conservation: Berlin, Germany, Springer, p. 11-27.

Pye, K. and Bowman, G.M., 1984, The Holocene marine transgression as a forcing function in episodic dune activity on the eastern Australian coast, *in* Thom, B.G., Ed., Coastal Geomorphology in Australia: Sydney, Australia, Academic Press, Sydney, p. 179-129.

Pye, K. and Tsoar, H., 1990, Aeolian Sand and Sand Dunes: London, U.K., Unwin Hyman 396 p.

Raymo, M.E., Mitrovica, J.X., 2012. Collapse of polar ice sheets during the stage 11 interglacial. Nature, 483: 453–456.

Reading, H.G., and Collinson, J.D., 1996, Clastic Coasts. *in* Reading H.G., Ed., Sedimentrary Enviornments: Processes, facies and stratigraphy: Blackwell publishing. 688p

Reynolds, J.M., 1997, An Introduction to Applied and Environmental Geophysics, John Wiley & Sons, Chichester, pp.796.

Reynolds, P.R., and Aumento, F.A., 1974, Deep Drill 1972: Potassium-Argon dating of the Bermuda drill core: Canadian Journal of Earth Sciences, v. 11, p. 1269 – 1273.

Richards, D.A., Smart, P.L., Edwards, R.L., 1994. Maximum sea levels for the last glacial period from U-series ages of submerged speleothems. Nature 367, 357–360.

Roep, T.B., Dabrio, C.J., Fortuin, A.R., Polo, M.D., 1998. Late highstand patterns of shifting and stepping coastal barriers and washover-fans (Late-Messinian, Sorbas Basin, SE Spain). Sedimentary Geology, 116: 27 - 56.

Rohling, E.J., Grant, K., Bolshaw, M., Roberts, A.P., Siddall, M., Hemleben, Ch, Kucera, M., 2009. Antarctic temperature and global sea level closely coupled over the past five glacial cycles. Nature Geoscience, 2: 500 - 504.

Roskin, J., Tsoar, H., Porat, H.N., Blumberg, D.G., 2011. Palaeoclimate interpretations of Late Pleistocene vegetated linear dune mobilization episodes: evidence from the northwestern Negev dunefield, Israel. Quaternary Science Reviews 30, 3364 – 3380

Rowe, M.P., 1998. An explanation of the geology of Bermuda. Bermuda Government Publication. 30 pp.

Rowe, M.P., Wainer, K.A., Bristow, C.S., and Thomas, A.L., 2014, Anomalous MIS 7 sea-level recorded on Bermuda: Quaternary Science Reviews v. 90, p. 47 - 55.

Rubin, D.M., Hunter,R.E., 1982. Bedform climbing in theory and nature. Sedimentology 29, 121 – 138.

Rust, I.C., and Illenberger, W.K., 1996, Coastal dunes: sensitive or not?: Landscape and Urban Planning, v. 34, p. 165–169.

Sayles. R.W. 1931. Bermuda during the Ice Age. Proceedings of the American Academy of Arts and Sciences. V. LXVI. No 11, 382-467

Scheidegger, A.E., 1976. Joints on Bermuda. Rivista Italiana Di Geofisica e Scienze Affini, 3: 121 – 125.

Schellmann, G., Radtke, U., 2004. A revised morpho and chronostratigraphy of the late and middle Pleistocene coral reef terraces on Southern Barbados (West Indies). Earth-Science Reviews 64, 157–187.

Shackleton, N.J. and Opdyke, N.D., 1973, Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a 10^5 year and 10^6 year scale: Quaternary Research, v. 3, p. 39-55.

Shackleton, N.J., and Pisias, N.G., 1985, Atmospheric carbon dioxide, orbital forcing, and climate, in Sunquist, E.T., and Broecker, W.S. eds., The carbon cycle and atmospheric CO2: Natural Variations Archean to Present: Washington, D.C., American Geophysical Union, p. 303-317.

Short, A. D., 1984, Beach and nearshore facies: southeast Australia: Developments in Sedimentology, v. *39*, p. 261-282.

Short, A.D., Fotheringham. D.G., Buckley, R.C., 1986. Coastal morphodynamincs and Holocene evolution of the Kangaroo Island Coast, South Australia. Coastal Studies Unit Technical Report 86/1. Department of Geography, University of Sydney. p. 178

Short, A.D., Hesp, P.A., 1982. Wave, Beach and dune interactions in Southeastern Australia. Marine Geology 48, 259 – 284

Siddall , M., Chappell J., Potter E. K., 2006: Eustatic Sea Level During Past Interglacials, in: `The climate of past interglacials,' F. Sirocko, T. Litt, M. Claussen, M. F. Sanchez-Goni (eds.), Elsevier, Amsterdam

Siddall, M., Chappell, J., and Potter, E.K., 2007, Eustatic sea level during past interglacials: *Developments in Quaternary Sciences, v.* 7, p. 75-92.

Stirling, C. H., Esat T.M., Lambeck K., McCulloch M.T., 1998. Timing and duration of the Last Interglacial: evidence for a restricted interval of widespread coral reef growth. Earth and Planetary Science Letters 160: 745-762.

Terwindt, J.H.J., Hulsbergen, C.H., and Kohsiek, L.H.M., 1984, Structures in deposits from beach recovery, after erosion by swell waves around the southwestern coast of Aruba: Marine Geology, 60, p. 283-311.

Thomas, M.L.H., and Stevens, J.A., 1991. Communities of constructional lips and cup reef rims in Bermuda. Coral Reefs 9: 225-230

Thompson W. G., Spiegelmann M. W., Goldstein S. L., and Speed R. C., 2003. An open-system model for U-series age determinations of fossil corals. Earth and Planetary Science Letters 210 (1-2): 365-381.

Thomson, C.W., 1873, Geological peculiarities of the Bermudas: Nature v. 13, p. 266–267.

Tsoar, H., 2000, Geomorphology and paleogeography of sand dunes that have formed the kurkar ridges in the coastal plain of Israel: Israel Journal of Earth Sciences, v. 49, p. 189–196.

Tsoar, H. 2013. Critical environments: Sand dunes and climate change." In Treatise on Geomorphology. Shroder, J.F. (Ed) 11, 414-427. Academic Press, San Diego.

Tsoar, H., Illenberger, W. 1998. Reevaluation of sand dunes' mobility indices. Journal of Arid Land Studies 7S, 265–268.

Vacher, H.L., 1972. Coastal Dunes of Younger Bermuda, *in* Coates, D., ed., Coastal Geomorphology: Binghamton, NY, State University of New York, p. 355–39.

Vacher, H.L., 1997. Introduction: Varieties of carbonate islands and historical perspective. In Vacher, H.L., Quinn, T. (Editors), Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology, 54: 949, 35-90

Vacher, H.L., Hearty, P.J. 1989. History of Stage 5 sea level in Bermuda: review with new evidence of a brief rise to present sea level during Sub-Stage 5a. Quaternary Science Review, 8: 159 – 168.

Vacher, H.L., Hearty, P.J., and Rowe, M.P., 1995, Stratigraphy of Bermuda: Nomenclature, concepts, and status of multiple systems of classification: Geological Society of America. Special Paper 300: 271–294.

Vacher, H.L., Quinn, T. (Editors), 1997. Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology, 54: 949, 35-90

Vacher, H.L., Rowe, M.P. 1997. Geology and Hydrogeology of Bermuda. In Vacher.H.L., Quinn,T. (Editors), Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology, 54: 949, 35-90

Vacher, H.L., Rowe, M.P., Garrett, P., 1989. The Geological Map of Bermuda. Public Works Department publication, The Government of Bermuda.

van Hengstum, P. J., Scott, D. B., Javaux, E. J., 2009. Foraminifera in elevated Bermudian caves provide further evidence for+ 21m eustatic sea level during Marine Isotope Stage 11. *Quaternary Science Reviews*, *28*(19), 1850-1860

Verrill, A.E., 1907. The Bermuda Islands. Part IV. Geology and palaeontology, and Part V, An account of the coral reefs. Connecticut Academy of arts and Sciences, Transactions, 12: 45 - 348.

Vesica, P.L, Tuccimei, P., Turi, B., Fornos, J.J., Gines, A., Gines, J. 2000. Late PLeistocene Paleoclimates and sea-level change in the Mediterranean as inferred from stable isotpe and U-series studies of overgrowths on speleothems, Mallorca, Spain. Quaternary Science Reviews, 19: 865 – 879.

Vogt, P.R., and Jung, W.-Y., 2007, Origin of the Bermuda volcanoes and the Bermuda Rise: History, observations, models, and puzzles. In: Foulger, G.R., and Jurdy, D.M., eds., Plates, plumes, and planetary processes: Geological Society of America Special Paper 430, p. 553-591.

Vollbrecht, R., 1990, Marine and meteoric diagenesis of submarine Pleistocene carbonates from the Bermuda Carbonate Platform: Carbonates and Evaporites, 5: 13–96.

Vollbrecht, R., and Meischner,D. 1996, Diagenesis in coastal carbonates related to Pleistocene sea-level, Bermuda Platform: Journal of Sedimentary Research, v. 66, no. 1: 243-258.

Walter, T.R., Troll, V.R., 2001. Formation of caldera periphery faults: An experimental study. Bulletin of Volcanology, 63: 191 – 203.

Watson, J.W., Oliver, J., Foggo,C.H. 1965. Climate and Vegetation. In: A Geography of Bermuda. Government of Bermuda publication. 69-82.

Wedepohl, K.H., 1995. The composition of the continental crust. Geochimica Et Cosmochimica Acta 59 (7): 1217-1232.

White, B., Curran, H.A., 1988. Mesoscale physical sedimentary structures and trace fossils in Holocene carbonate eolianites from San Salvador Island, Bahamas. Sedimentary Geology 55, 163 – 184.

White, B., Curran, H.A., 1993. Sedimentology and Ichnology of Holocene dune and backshore deposits, Lee Stocking Island, Bahamas. Proceedings of the Sixth Symposium on the Geology of the Bahamas. Ed B. White. 181 – 191

Wiedemann, A.M. 1998. Coastal foredune development, Oregon, USA: Journal of Coastal Research (Special Issue) 26: 45–51.

Woodroffe, C.D. 2002. Coasts, Form Processes and Evolution. Cambridge University Press. p. 623

Yaalon, D.H., Laronne,J. 1971. Internal structures in eolianites and paeowinds, Mediterrenean coast, Israel. Journal of Sedimentary Petrology. 41(4), 1059-1064

Zoback, M.L., S.P. Nishenko, R.M. Richardson, H.S. Hasegawa, M.D. Zoback, 1986. Mid-plate stress, deformation, and seismicity, in Vogt, P.R., and B.E. Tucholke, eds., The Geology of North America, v. M, The Western North Atlantic Region, Geol. Soc. Amer., Boulder, 297-312.

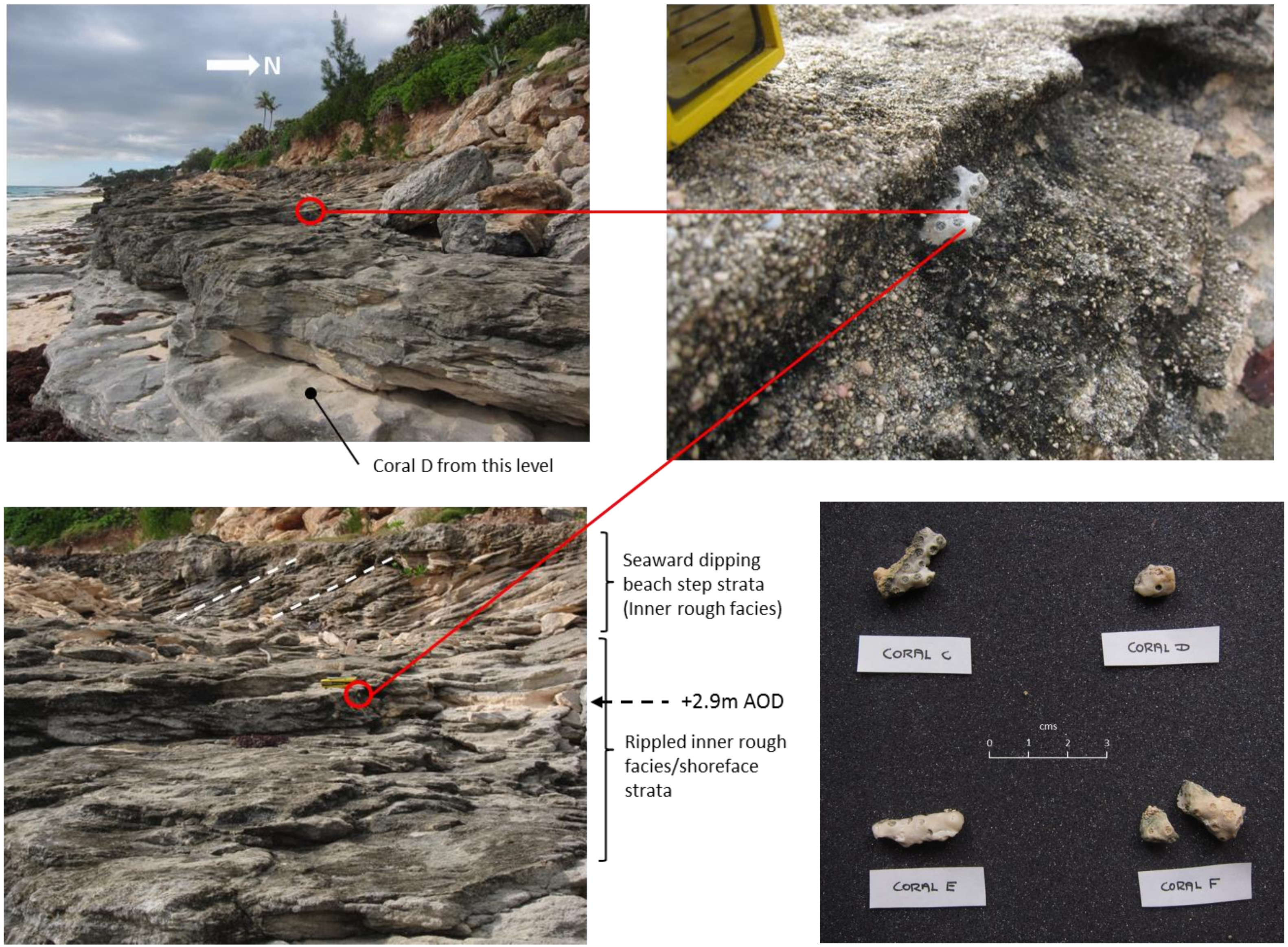
APPENDIX A – coral collection and ages

Coral fragments were collected from facies such as the beach step (Hapm) in which coarse material accumulates. The ages of those fragments whose isotopic chemistry is consistent with closed-system behaviour were determined by U-series dating. The following photographs in this appendix provide an example of how the sample localities and sample positions were recorded.

The first table catalogues all sample localities including a description of the deposit and elevation measurements or estimates.

The last table, prepared by Karine Wainer of Oxford University lists the three corals from which viable ages could be obtained. She notes that ages are provided versus the 1950 reference. 95% confidence interval are quoted. Decay constants used are $9.1706 * 10^{-6}$ yr^{-1} for ^{230}Th, $2.822 * 10^{-6}$ yr^{-1} for ^{234}U (Cheng et al., 2013) and $1.55125 * 10^{-10}$ yr^{-1} for ^{238}U (Jaffey et al., 1971). Ages are corrected for detrital ^{230}Th using ($^{238}U/^{232}Th$) activity ratio = 0.8 ± 0.4 (derived from Wedepohl, 1995).

Coral C – Grape Bay January 2013



Type	ID	Month/ year collected	Location	Grid ref BNG (2000) bermuda maps.bm	Locality Description	Geological Formation	Geological setting/ Facies	Elevation Estimated m AOD	Elevation measured m AOD
Coral (Montastraea cavernosa)	A	12/12	Stoke's Point	555747 141484	Coastal quarry face, facing north. Private land.	Town Hill (?)	Coarse shelly conglomerate at horizontal erosional disconformity. Walsingham - Town Hill contact.	3.5	
Coral (Oculina)	B	12/12	Spittal Pond West (at the Checkerboard fracture system)	552183 134326	Low rock face, facing south. 20m from shoreline. Public park.	Belmont	Base of sub-tidal beach (plunge) step facies. Belmont formation.	2.5	
Coral (Oculina)	C	1/13	Grape Bay East	548559 131523	Top of horizontal (not planar) rock surface. Private beach.	Belmont	Rippled surface extending out from below beach step strata. Inner rough facies.		2.9
Coral (Oculina)	D	1/13	Grape Bay East	548599 131523	Top of sub-planar gently rippled platform. Private beach.	Belmont	Top of compacted/cemented planar surface. Outer planar facies		1.9
Coral (Oculina)	E	1/13	Grape Bay East	548641 131590	Seaward dipping rock surface. Private beach.	Belmont	Sloping face of beach step bedding		3.3
Coral (Oculina)	F	1/13	Grape Bay East	548641 131590	Ripple x-bedded rock face. Private beach.	Belmont	Within rippled beach step bedding. Inner rough facies.		2.3

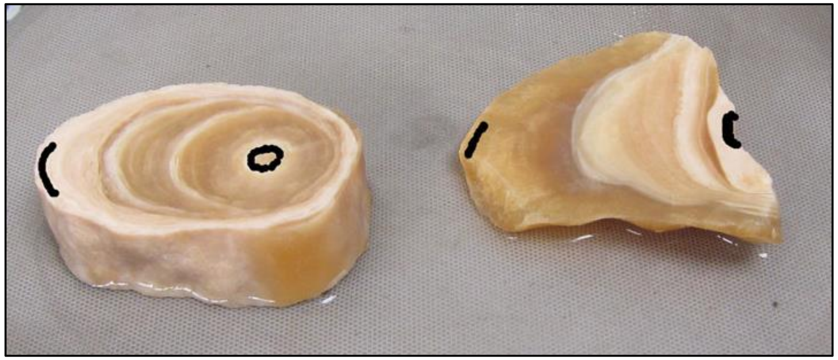
Site	sample ID	species	^{238}U	$^{230}Th/^{238}U$	±	$^{234}U/^{238}U$	±	$^{232}Th/^{238}U$	±	Uncorrected age	err+	err-	Corrected age	err+	err-	$^{234}U/^{238}U_{initial}$	±
			ppm	activity ratio		activity ratio		activity ratio								activity ratio	
Spittal pond	Coral B	Oculina	2.089	0.93221	0.00413	1.09458	0.00445	0.00000	0.00002	196.385	2.93	2.691	193.385	2.930	2.692	1.165	0.007
Grape Bay	Coral E	Oculina	2.189	0.92759	0.00402	1.08720	0.00456	0.00005	0.00001	198.038	2.921	2.755	198.035	2.922	2.756	1.152	0.007
Grape Bay	Coral C	Oculina	2.234	0.92683	0.00337	1.08572	0.00424	0.00027	0.00001	198.490	2.556	2.397	198.470	2.556	2.391	1.150	0.007

APPENDIX B – speleothem sampling and ages

Five speleothems were collected from Wilkinson's Quarry cave for U-series dating of growth layers. Continuous growth or interruptions of growth potentially provide evidence of non-submergence and submergence respectively.

The first photograph on the left shows the 5 speleothem samples (A.B,C, D and E) that were removed from the cave along with 1m rule. The second photograph shows removal of C by a hammer and chisel after making cuts with a cordless sabre-saw (I am shown standing on a ladder waste deep in water in a cave pool). The third photograph is of polished slices made through speleothems B (to the left) and A (to the right). The black marks indicate the exact positions where sub-samples were taken for dating. These positions are close to the innermost and outermost growth layers in order to establish the time span covered by the growth of the speleothem. This span, in turn, informs us of the likelihood that a submergence event was recorded somewhere within the growth layers, based on knowledge of the global Pleistocene eustatic sea-level curve.

The table, prepared in early 2012 by Oxford University, presents preliminary ages for some of the sub-samples which range from 5 ka to 109 ka. So far no demonstrable palaeo-sea-level events of significance appear to have been recorded, but work is still in progress.



Original label	Karine's label	**Raw age (kyrs)**	plus 2sigma	minus 2 sigma	238U conc. (ppb)	delta 234	4/8 activity ratio	0/8 activity ratio	0/2 activity ratio	**Age corr for initial Th (kyrs)**	plus 2sigma	minus 2 sigma	**Age corr for initial Th and relative to 1950 (kyrs)**	
E1A	K1_1	**10.186**	0.097	0.098	192.91	48.20273	1.048203	0.09342	96.24346	**10.106**	0.105	0.095	**10.044**	
C4B	K1_2	**14.203**	0.144	0.130	148.50	49.56484	1.049565	0.128127	108.4528	**14.105**	0.147	0.150	**14.043**	
A1B	K1_3	18.584	0.187	0.182	218.49	72.4241	1.072424	0.168117	402.5312	18.550	0.168	0.183	18.488	
B2B	K1_4	**72.355**	1.221	1.250	152.72	44.97162	1.044972	0.508395	307.4108	**72.218**	1.168	1.325	**72.156**	
B2A	K1_5	**109.352**	1.304	1.351	338.86	10.58276	1.010583	0.640277	1288.617	**109.309**	1.368	1.433	**109.247**	
A3A	K1_6	20.065	0.207	0.187	224.97	72.72491	1.072725	0.180405	424.8663	20.031	0.228	0.185	19.969	Feb-12

Original label	Karine's label	**Raw age (yrs)**	plus 2sigma	minus 2 sigma	238U conc. (ppb)	delta 234	4/8 activity ratio	0/8 activity ratio	0/2 activity ratio	**Age corr for initial Th (yrs)**	plus 2sigma	minus 2 sigma	**Age corr for initial Th and relative to 1950 (yrs)**	
D1A	K2_1	**29030.68**	283.389	301.068	139.6	91.8			327	**28972**	280.225	307.805	**28910**	
D1B	K2_2	**8102.483**	161.398	145.013	178.4	76.5			69	**8015**	166.63	153.707	**7953**	
C3A	K2_3	**18209.63**	119.627	99.392	313.4	57.8			467	**18182**	120.906	101.885	**18120**	
C4A	K2_4	**5105.412**	76.74	81.567	231.4	69.6			134	**5078**	77.843	83.639	**5016**	
A1A	K2_5	**21020.53**	152.044	117.065	321.6	84.9			1024	**21007**	148.455	118.416	**20945**	
E1B	K2_6	**8248.010**	89.369	106.905	178.5	41.8			40	**8089**	122.621	129.604	**8027**	
														Apr-12

APPENDIX C – Wind and drift potential data

Summary of wind data

The first table of the appendix is a summary of twenty years of hourly wind data collected by the U.S. Navy at the Bermuda Airport between 1975 and 1995. The data are compiled into 10 degree wind-direction categories (36 rows) and 12 wind-strength categories ranging up to >55 knots (12 columns).

Drift potential analysis

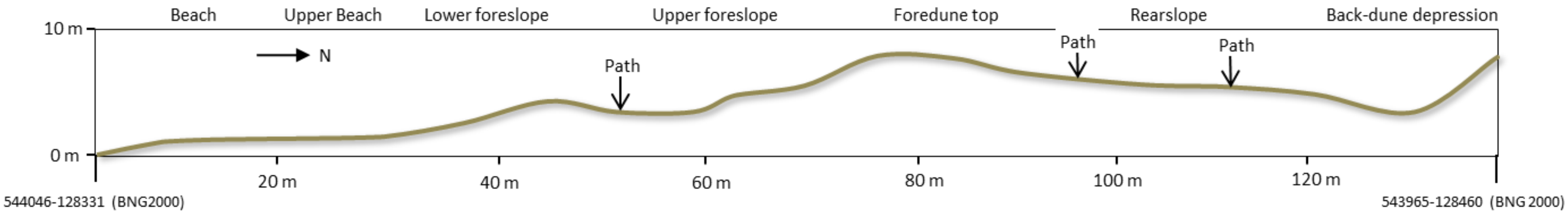
In the second table, wind categories below the threshold velocity, taken as 12 knots (after Fryberger, 1979), are eliminated from the data-set as are those above 40 knots which at Bermuda comprised, over the study period, less than 2% of recorded hourly winds. The percentage of occurrences of winds from given directions within each of the remaining five wind categories are multiplied by Fryberger's (1979) weighting factors. The product, quoted in "vector units", is a measure of the potential amount of sand drift in a given direction.

	0 - 1	%	1 - 3	%	4 - 6	%	7 - 10	%	11 - 16	%	17 - 21	%	22 - 27	%	28 - 33	%	34 - 40	%	41 - 47	%	48 - 55	%	>55	%		TOTAL	%
Direction	Knots		Knots		Knots		Knots		Knots		Knots		Knots		Knots		Knots		Knots		Knots		Knots			**HOURS**	
0	4537																							2.6		4537	2.6
10	46	0.03	445	0.3	819	0.5	774	0.4	482	0.3	49	0.0	11	0.0	4	0.0	3	0.0		0.0		0.0		0.0		2633	1.5
20	49	0.03	504	0.3	984	0.6	872	0.5	665	0.4	88	0.1	9	0.0	1	0.0	2	0.0	2	0.0		0.0		0.0		3176	1.8
30	57	0.03	563	0.3	1100	0.6	953	0.5	724	0.4	122	0.1	12	0.0		0.0		0.0		0.0		0.0		0.0		3531	2.0
40	42	0.02	394	0.2	964	0.5	863	0.5	884	0.5	144	0.1	11	0.0	2	0.0		0.0		0.0		0.0		0.0		3304	1.9
50	35	0.02	359	0.2	945	0.5	1039	0.6	1005	0.6	176	0.1	9	0.0		0.0		0.0		0.0		0.0		0.0		3568	2.0
60	41	0.02	442	0.3	1204	0.7	1087	0.6	1090	0.6	178	0.1	12	0.0	1	0.0		0.0		0.0		0.0		0.0		4055	2.3
70	34	0.02	451	0.3	1193	0.7	1050	0.6	854	0.5	103	0.1	15	0.0	4	0.0	3	0.0	0	0.0	1	0.0		0.0		3708	2.1
80	35	0.02	525	0.3	1260	0.7	1044	0.6	845	0.5	92	0.1	8	0.0	3	0.0	1	0.0	0	0.0	1	0.0		0.0		3814	2.2
90	25	0.01	579	0.3	1403	0.8	1158	0.7	831	0.5	164	0.1	10	0.0	1	0.0	0	0.0	1	0.0		0.0		0.0		4172	2.4
100	21	0.01	329	0.2	975	0.6	991	0.6	720	0.4	138	0.1	19	0.0	8	0.0	2	0.0	1	0.0	2	0.0		0.0		3206	1.8
110	19	0.01	259	0.1	940	0.5	1099	0.6	778	0.4	97	0.1	33	0.0	8	0.0	1	0.0	2	0.0	1	0.0		0.0		3237	1.8
120	25	0.01	336	0.2	1106	0.6	1293	0.7	943	0.5	166	0.1	56	0.0	10	0.0	4	0.0	1	0.0	2	0.0		0.0		3942	2.2
130	15	0.01	345	0.2	1149	0.7	1107	0.6	938	0.5	142	0.1	33	0.0	5	0.0	0	0.0	0	0.0	1	0.0		0.0		3735	2.1
140	22	0.01	338	0.2	1031	0.6	1169	0.7	941	0.5	194	0.1	74	0.0	6	0.0	9	0.0	2	0.0	1	0.0	1	0.0		3788	2.2
150	18	0.01	424	0.2	1220	0.7	1264	0.7	1064	0.6	216	0.1	57	0.0	15	0.0	7	0.0	1	0.0		0.0		0.0		4286	2.4
160	20	0.01	396	0.2	1160	0.7	1215	0.7	1203	0.7	328	0.2	73	0.0	12	0.0	4	0.0	1	0.0		0.0		0.0		4412	2.5
170	25	0.01	338	0.2	1191	0.7	1559	0.9	1779	1.0	540	0.3	130	0.1	21	0.0	6	0.0	2	0.0		0.0		0.0		5591	3.2
180	29	0.02	444	0.3	1269	0.7	1784	1.0	2170	1.2	755	0.4	162	0.1	42	0.0	5	0.0	1	0.0	1	0.0		0.0		6662	3.8
190	19	0.01	329	0.2	1290	0.7	1903	1.1	2268	1.3	776	0.4	252	0.1	20	0.0	4	0.0	0	0.0	1	0.0		0.0		6862	3.9
200	28	0.02	340	0.2	1317	0.8	2127	1.2	2790	1.6	825	0.5	249	0.1	29	0.0	5	0.0	1	0.0		0.0		0.0		7711	4.4
210	34	0.02	382	0.2	1472	0.8	2377	1.4	3247	1.9	887	0.5	215	0.1	15	0.0	7	0.0		0.0		0.0		0.0		8636	4.9
220	31	0.02	352	0.2	1389	0.8	2100	1.2	2780	1.6	963	0.5	192	0.1	11	0.0	4	0.0		0.0		0.0		0.0		7822	4.5
230	25	0.01	413	0.2	1453	0.8	1909	1.1	2418	1.4	697	0.4	135	0.1	9	0.0	4	0.0		0.0		0.0		0.0		7063	4.0
240	24	0.01	421	0.2	1388	0.8	1806	1.0	2350	1.3	712	0.4	124	0.1	13	0.0	9	0.0	1	0.0		0.0		0.0		6848	3.9
250	21	0.01	325	0.2	1028	0.6	1653	0.9	2467	1.4	719	0.4	146	0.1	11	0.0	1	0.0	1	0.0	0	0.0	1	0.0		6373	3.6
260	27	0.02	286	0.2	943	0.5	1707	1.0	2231	1.3	692	0.4	187	0.1	22	0.0	4	0.0		0.0		0.0		0.0		6099	3.5
270	49	0.03	314	0.2	1113	0.6	1545	0.9	1871	1.1	706	0.4	256	0.1	45	0.0	13	0.0		0.0		0.0		0.0		5912	3.4
280	30	0.02	308	0.2	995	0.6	1342	0.8	1544	0.9	676	0.4	283	0.2	54	0.0	20	0.0		0.0		0.0		0.0		5252	3.0
290	40	0.02	347	0.2	993	0.6	1118	0.6	1437	0.8	709	0.4	275	0.2	47	0.0	8	0.0	1	0.0	1	0.0	1	0.0		4977	2.8
300	44	0.03	472	0.3	1044	0.6	1156	0.7	1300	0.7	559	0.3	177	0.1	21	0.0	5	0.0		0.0		0.0		0.0		4778	2.7
310	37	0.02	356	0.2	838	0.5	988	0.6	1192	0.7	384	0.2	97	0.1	9	0.0	2	0.0		0.0		0.0		0.0		3903	2.2
320	50	0.03	393	0.2	888	0.5	1052	0.6	1247	0.7	297	0.2	61	0.0	6	0.0	1	0.0		0.0		0.0		0.0		3995	2.3
330	47	0.03	540	0.3	1099	0.6	1065	0.6	1017	0.6	171	0.1	35	0.0	1	0.0		0.0		0.0		0.0		0.0		3975	2.3
340	62	0.04	475	0.3	1073	0.6	916	0.5	778	0.4	150	0.1	15	0.0	3	0.0	1	0.0		0.0		0.0		0.0		3473	2.0
350	56	0.03	416	0.2	987	0.6	937	0.5	606	0.3	81	0.0	18	0.0	2	0.0	2	0.0		0.0		0.0		0.0		3105	1.8
360	52	0.03	468	0.3	1051	0.6	940	0.5	621	0.4	45	0.0	7	0.0	1	0.0	2	0.0		0.0		0.0		0.0		3187	1.8
	5771		14408		40274		46962		50080		13741		3458		462		139		18		12		3			175328	100.0

	Knots		Vector	Knots		Vector	Knots		Vector	Knots		Vector	Knots		Vector		**Total**
	11 - 16	Weighting	units	17 - 21	Weighting	units	22 - 27	Weighting	units	28 - 33	Weighting	units	34 - 40	Weighting	units		**Vector**
Direction	%			%			%			%			%				**Units**
10	0.27	2.70	0.74	0.03	7.6	0.21	0.01	75	0.47	0.00	172	0.39	0.002	342	1		**2**
20	0.38	2.70	1.02	0.05	7.6	0.38	0.01	75	0.38	0.00	172	0.10	0.001	342	0		**2**
30	0.41	2.70	1.11	0.07	7.6	0.53	0.01	75	0.51	0.00	172	0.00	0.000	342	0		**2**
40	0.50	2.70	1.36	0.08	7.6	0.62	0.01	75	0.47	0.00	172	0.20	0.000	342	0		**3**
50	0.57	2.70	1.55	0.10	7.6	0.76	0.01	75	0.38	0.00	172	0.00	0.000	342	0		**3**
60	0.62	2.70	1.68	0.10	7.6	0.77	0.01	75	0.51	0.00	172	0.10	0.000	342	0		**3**
70	0.49	2.70	1.32	0.06	7.6	0.45	0.01	75	0.64	0.00	172	0.39	0.002	342	1		**3**
80	0.48	2.70	1.30	0.05	7.6	0.40	0.00	75	0.34	0.00	172	0.29	0.001	342	0		**3**
90	0.47	2.70	1.28	0.09	7.6	0.71	0.01	75	0.43	0.00	172	0.10	0.000	342	0		**3**
100	0.41	2.70	1.11	0.08	7.6	0.60	0.01	75	0.81	0.00	172	0.78	0.001	342	0		**4**
110	0.44	2.70	1.20	0.06	7.6	0.42	0.02	75	1.41	0.00	172	0.78	0.001	342	0		**4**
120	0.54	2.70	1.45	0.09	7.6	0.72	0.03	75	2.40	0.01	172	0.98	0.002	342	1		**6**
130	0.53	2.70	1.44	0.08	7.6	0.62	0.02	75	1.41	0.00	172	0.49	0.000	342	0		**4**
140	0.54	2.70	1.45	0.11	7.6	0.84	0.04	75	3.17	0.00	172	0.59	0.005	342	2		**8**
150	0.61	2.70	1.64	0.12	7.6	0.94	0.03	75	2.44	0.01	172	1.47	0.004	342	1		**8**
160	0.69	2.70	1.85	0.19	7.6	1.42	0.04	75	3.12	0.01	172	1.18	0.002	342	1		**8**
170	1.01	2.70	2.74	0.31	7.6	2.34	0.07	75	5.56	0.01	172	2.06	0.003	342	1		**14**
180	1.24	2.70	3.34	0.43	7.6	3.27	0.09	75	6.93	0.02	172	4.12	0.003	342	1		**19**
190	1.29	2.70	3.49	0.44	7.6	3.36	0.14	75	10.78	0.01	172	1.96	0.002	342	1		**20**
200	1.59	2.70	4.30	0.47	7.6	3.58	0.14	75	10.65	0.02	172	2.84	0.003	342	1		**22**
210	1.85	2.70	5.00	0.51	7.6	3.84	0.12	75	9.20	0.01	172	1.47	0.004	342	1		**21**
220	1.59	2.70	4.28	0.55	7.6	4.17	0.11	75	8.21	0.01	172	1.08	0.002	342	1		**19**
230	1.38	2.70	3.72	0.40	7.6	3.02	0.08	75	5.77	0.01	172	0.88	0.002	342	1		**14**
240	1.34	2.70	3.62	0.41	7.6	3.09	0.07	75	5.30	0.01	172	1.28	0.005	342	2		**15**
250	1.41	2.70	3.80	0.41	7.6	3.12	0.08	75	6.25	0.01	172	1.08	0.001	342	0		**14**
260	1.27	2.70	3.44	0.39	7.6	3.00	0.11	75	8.00	0.01	172	2.16	0.002	342	1		**17**
270	1.07	2.70	2.88	0.40	7.6	3.06	0.15	75	10.95	0.03	172	4.41	0.007	342	3		**24**
280	0.88	2.70	2.38	0.39	7.6	2.93	0.16	75	12.11	0.03	172	5.30	0.011	342	4		**27**
290	0.82	2.70	2.21	0.40	7.6	3.07	0.16	75	11.76	0.03	172	4.61	0.005	342	2		**23**
300	0.74	2.70	2.00	0.32	7.6	2.42	0.10	75	7.57	0.01	172	2.06	0.003	342	1		**15**
310	0.68	2.70	1.84	0.22	7.6	1.66	0.06	75	4.15	0.01	172	0.88	0.001	342	0		**9**
320	0.71	2.70	1.92	0.17	7.6	1.29	0.03	75	2.61	0.00	172	0.59	0.001	342	0		**7**
330	0.58	2.70	1.57	0.10	7.6	0.74	0.02	75	1.50	0.00	172	0.10	0.000	342	0		**4**
340	0.44	2.70	1.20	0.09	7.6	0.65	0.01	75	0.64	0.00	172	0.29	0.001	342	0		**3**
350	0.35	2.70	0.93	0.05	7.6	0.35	0.01	75	0.77	0.00	172	0.20	0.001	342	0		**3**
360	0.35	2.70	0.96	0.03	7.6	0.20	0.00	75	0.30	0.00	172	0.10	0.001	342	0		**2**
	28.56		**77.12**	7.84		**59.56**	1.97		**147.92**	0.26		**45.32**	0.079		**27.11**		**357**
																TOTAL	**173**

APPENDIX D – botanical transect across a beach backshore

The following graphic depicts the profile of a December 2102 south-north botanical transect on Bermuda's south shore at Stonehole Bay near Warwick Long Bay. The table shows the presence or absence of listed species at intervals along the transect. The photographs illustrate the dune topography and identify vegetation cover at four points along the transect.

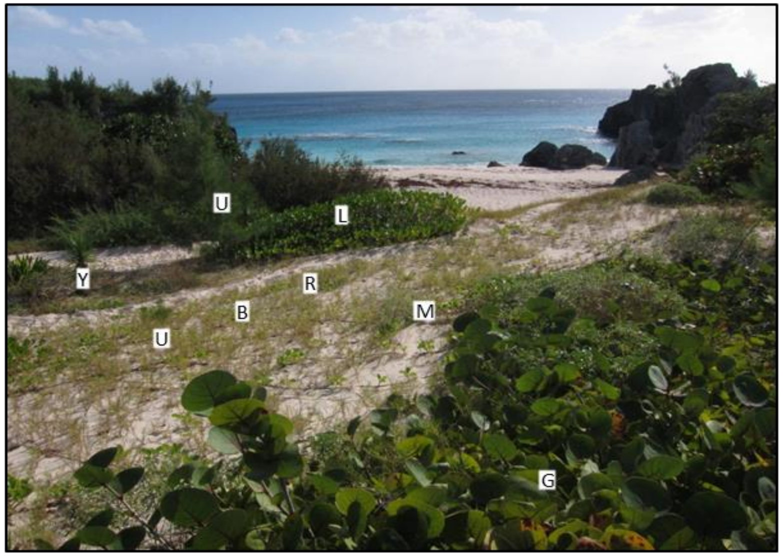


Sporobolus virginicus	Seashore rush grass	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Ipomoea pes-caprae	Seaside Morning Glory **(H)**	●	●	●	●	●	●	●	●	●	●	●	●				●	
Cenchrus tribuloides	Burr Grass		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Foeniculum vulgare	Fennel				●	●	●	●	●	●	●	●	●	●	●	●	●	
Yucca aloifolia	Spanish Bayonet		●		●	●			●	●	●	●	●			●	●	●
Sisyrinchium bermudiana	Bermudiana **(H)(E)**			●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Coccoloba uvifera	Bay Grape			●	●			●	●	●	●	●	●	●	●	●	●	
Casuarina equisetifolia	Casuarina			●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Solidago sempervirens	Seaside Goldenrod **(H)**		●					●	●	●		●	●	●	●	●	●	
Eustachys petraea	West Indian Grass				●	●	●	●	●	●	●	●	●	●	●	●	●	
Croton punctatus	Beach Croton **(H)**						●	●	●	●	●							
Oenothera drummondii	Beach Evening Primrose							●	●	●	●	●	●		●			
Wadelia trilobata	Seaside Daisy														●	●	●	●
Scaevola plumieri	Beach Lobelia/Inkberry **(H)**					●	●	●										
Suriana maritima	Tassel plant		●	●	●		●											
Lantana involucrata	lantana/.Common Sage **(H)**														●	●	●	
Tamarix gallica	French Tamarisk		●	●														
Schinus terebinthifolia	Mexican Pepper Tree																	●
Euphorbia heterophylla	Josephs coat				●									●	●			
Stenotaphrum secundatum	St. Augustine Grass **(H)**														●	●	●	
Scaevola taccada	Pacific Lobelia				●													
Bidens pilosa	Beggars Tick														●			
Canavali lineata	Bay Bean **(H)**					●												
Pittosporum tobira	Japanese Pittosporum																	●
Opuntia Stricta	Prickly Pear **(H)**																●	
Borrichia arborescens	Sea Ox-eye **(H)**												●					
Cakile lanceolata	Sea Rocket **(H)**				●													
Hymenocallis littoralis	Spider Lily					●												

(H) - Identified on Bermuda's dunes by Harshberger in 1908 **(E)** - Endemic

Lower dune foreslope (facing north)

Upper dune foreslope (facing south)



Dune top (facing south)

Back-dune depression (facing north)

B - Burr Grass; **C** - Beach croton; **F** - French Tamarisk; **G** - Bay Grape; **I** - Bermudiana; **K** - Beggars Tick; **L** - Beach Lobelia; **M** - Seaside Morning Glory; **N** - Fennel; **O** - Seaside Goldenrod; **P** - Beach Evening Primrose; **R** - Seashore Rush Grass; **S** - Sage; **T** - Iodine bush ; **U** - Casuarina; **W** - Seaside Daisy; **X** - Mexican Pepper; **Y** - Yucca

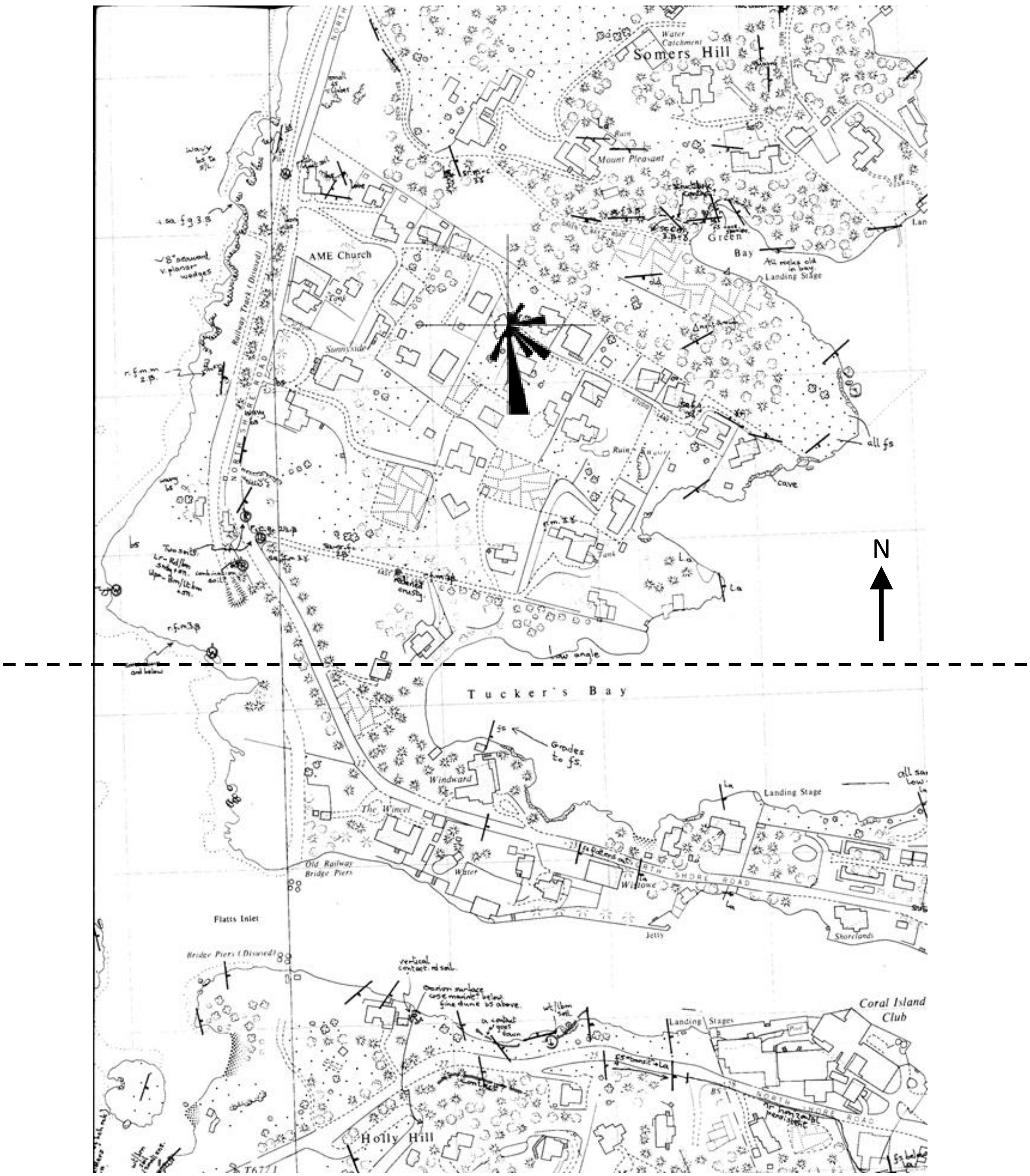
APPENDIX E – eolianite slip-face azimuth data

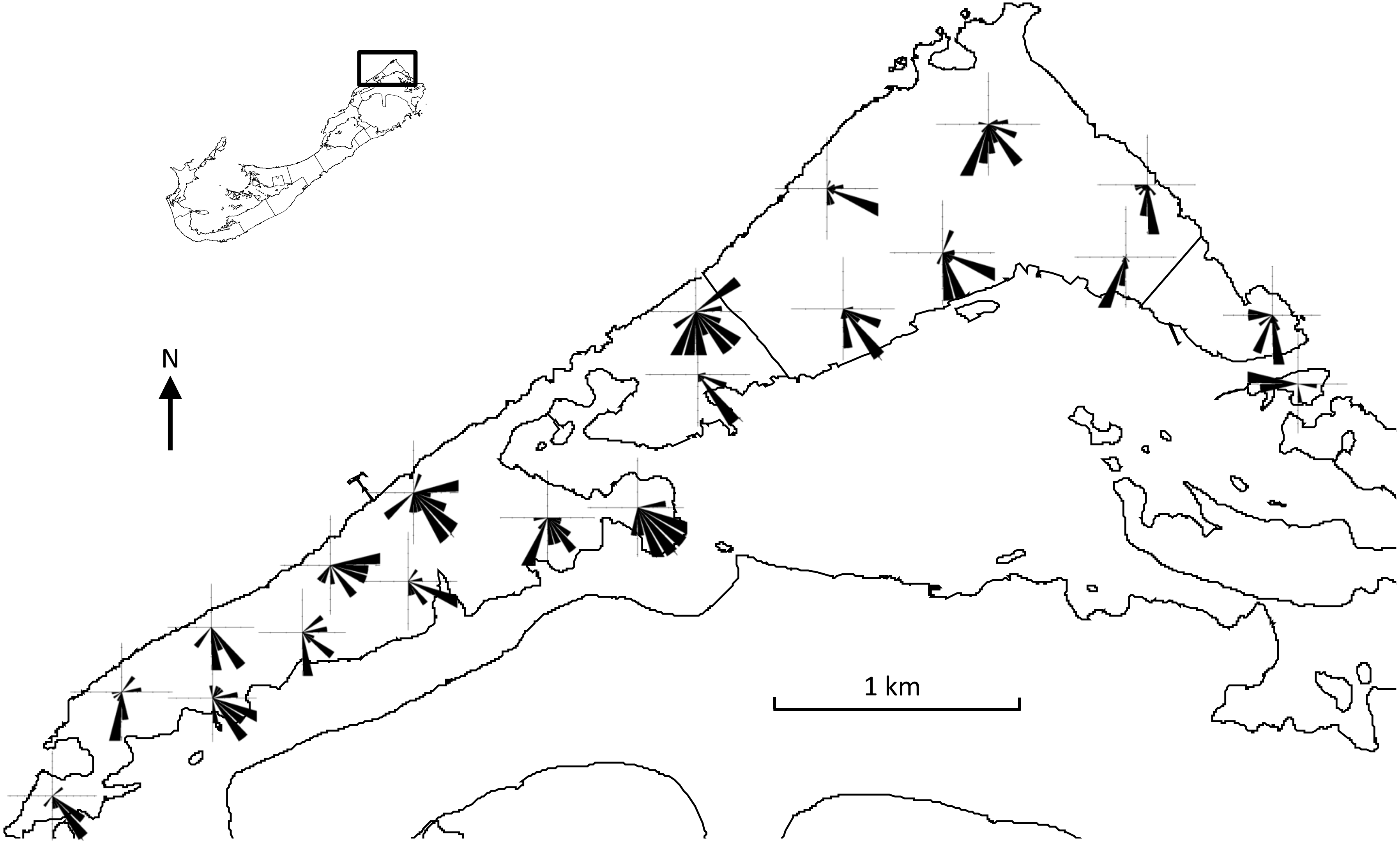
The orientation of slip-face foresets, that typically dip at 30 to 34 degrees, were recorded during geological mapping which spanned the mid-1980s and culminated in the production of the Geological Map of Bermuda (Vacher, Rowe and Garrett, 1989). Attempts to accurately measure slip-face orientation in the field with a compass were soon abandoned. This was because exposures predominantly comprise relatively smooth vertical rock faces. Given that dips of slip-faces are more or less constant, the apparent dip (between 0° and 32°) was used to estimate bedding strike relative to rock faces. Approximate strike alignments relative to that of the rock faces were sketched onto the field maps. Numerical data were generated for entry into a spreadsheet by using a protractor to measure strike alignment (converted to dip azimuth) relative to grid north for each strike and dip notation on the field maps (which took a long time!).

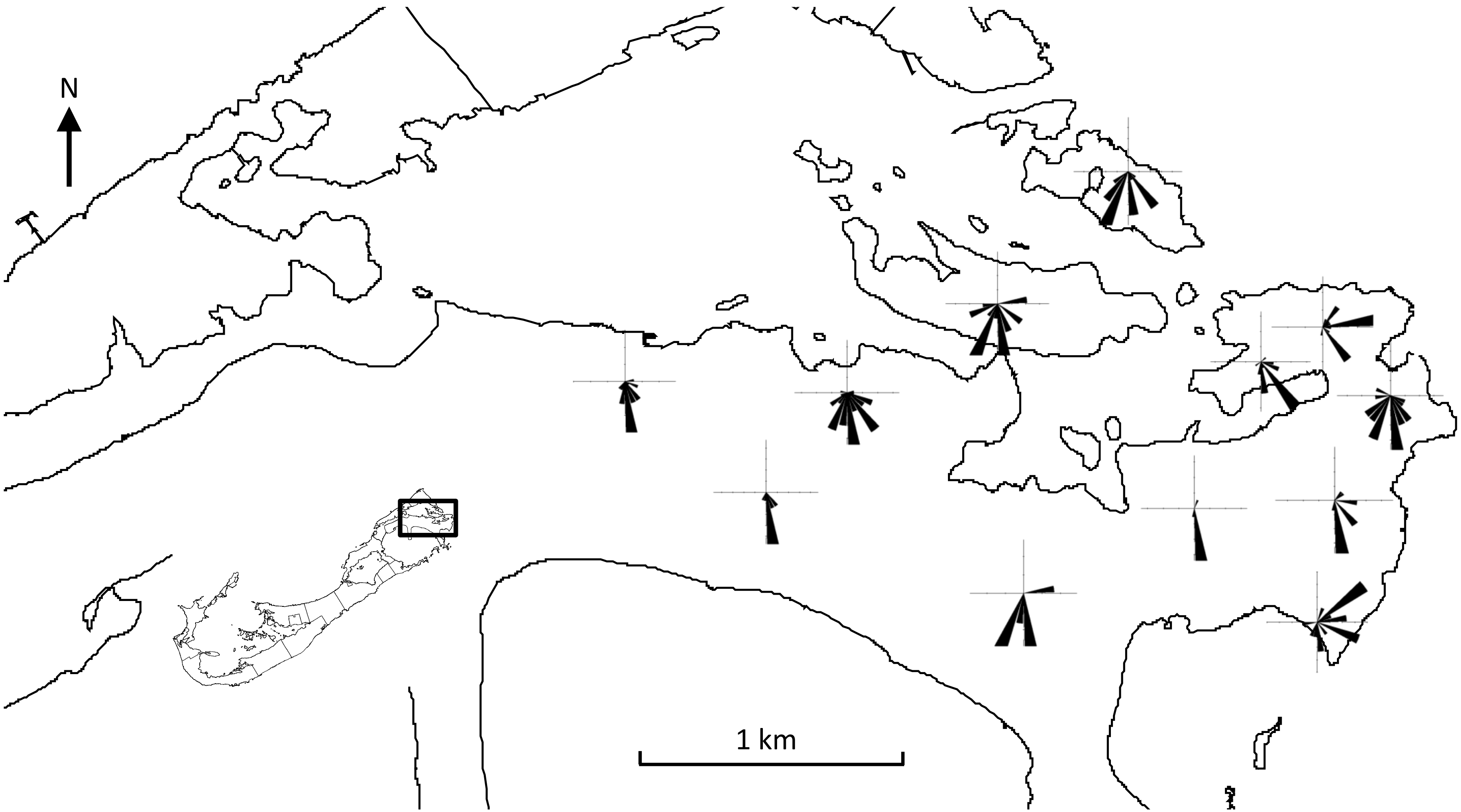
The specific objective of recording approximate slip-face orientations during geological mapping was to locate the boundary between geological units on the basis of changes in dune orientation. This was advantageous in the many areas where there was a paucity of exposures featuring geosols, which had been designated as allostratigraphic formation boundaries.

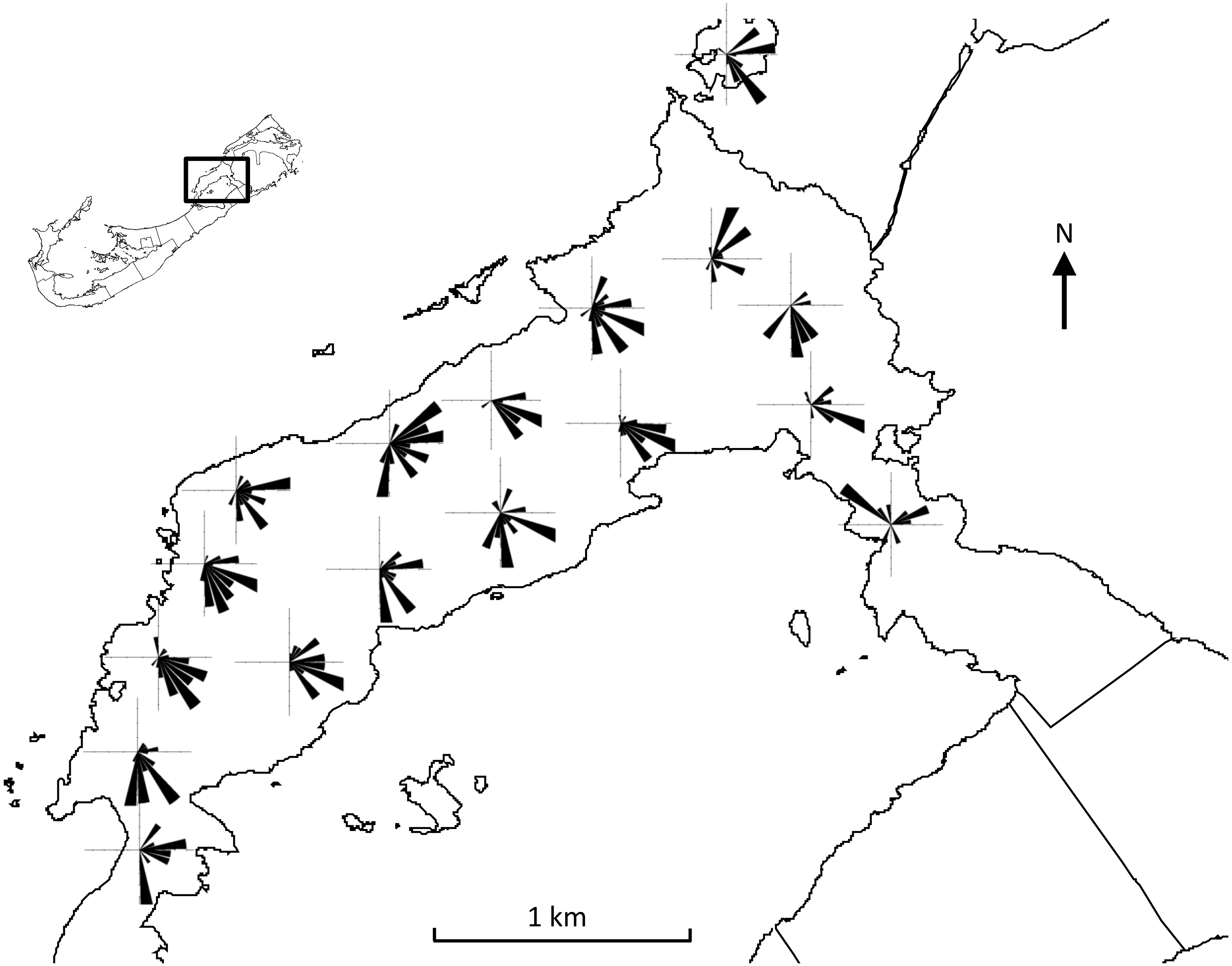
3751 slip-face dip azimuths extracted from the 1:2500 scale field maps (see example below) were compiled in an Excel spreadsheet. The data were broken down (separate columns) into geographic areas whose size – typically ranging from 35,000 to 65,000 square metres - depended partly on the spatial density of data. For each area, a geometric analysis was completed and a rose diagram produced using GEOorient version 9.5.0 (Holcome, 2011). 168 rose diagrams, produced in this way, are presented on the maps that follow. A summary is presented in the body of this thesis in Figure 6.8.

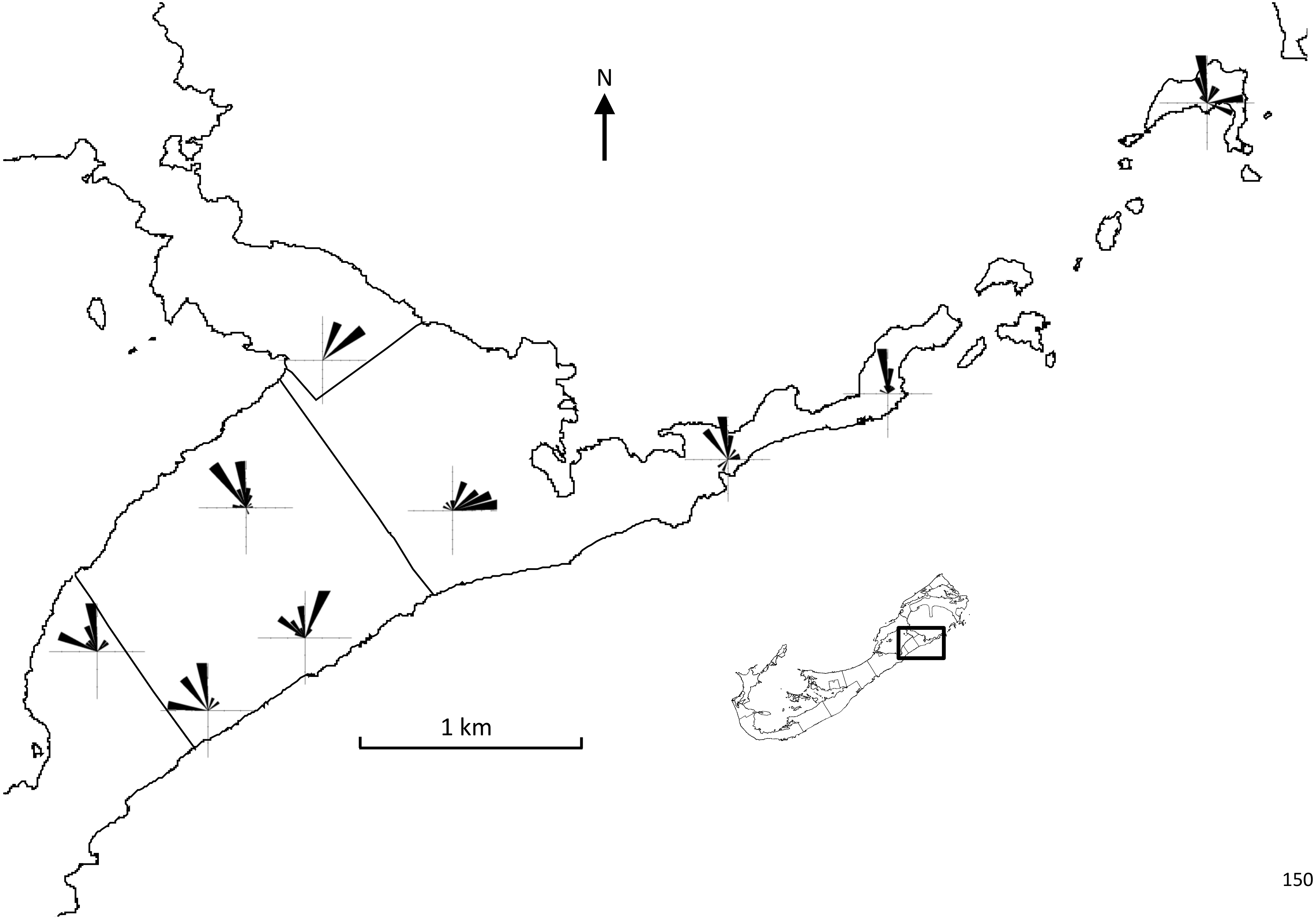
Example of a 1:2500 field map showing slip-face strike and dip notations. The dotted line across the middle, marks division between areas into which orientation data was divided. This map covers approximately 800 metres x 1000 metres or 80,000 square metres. The Rose diagram for the northern area is shown.

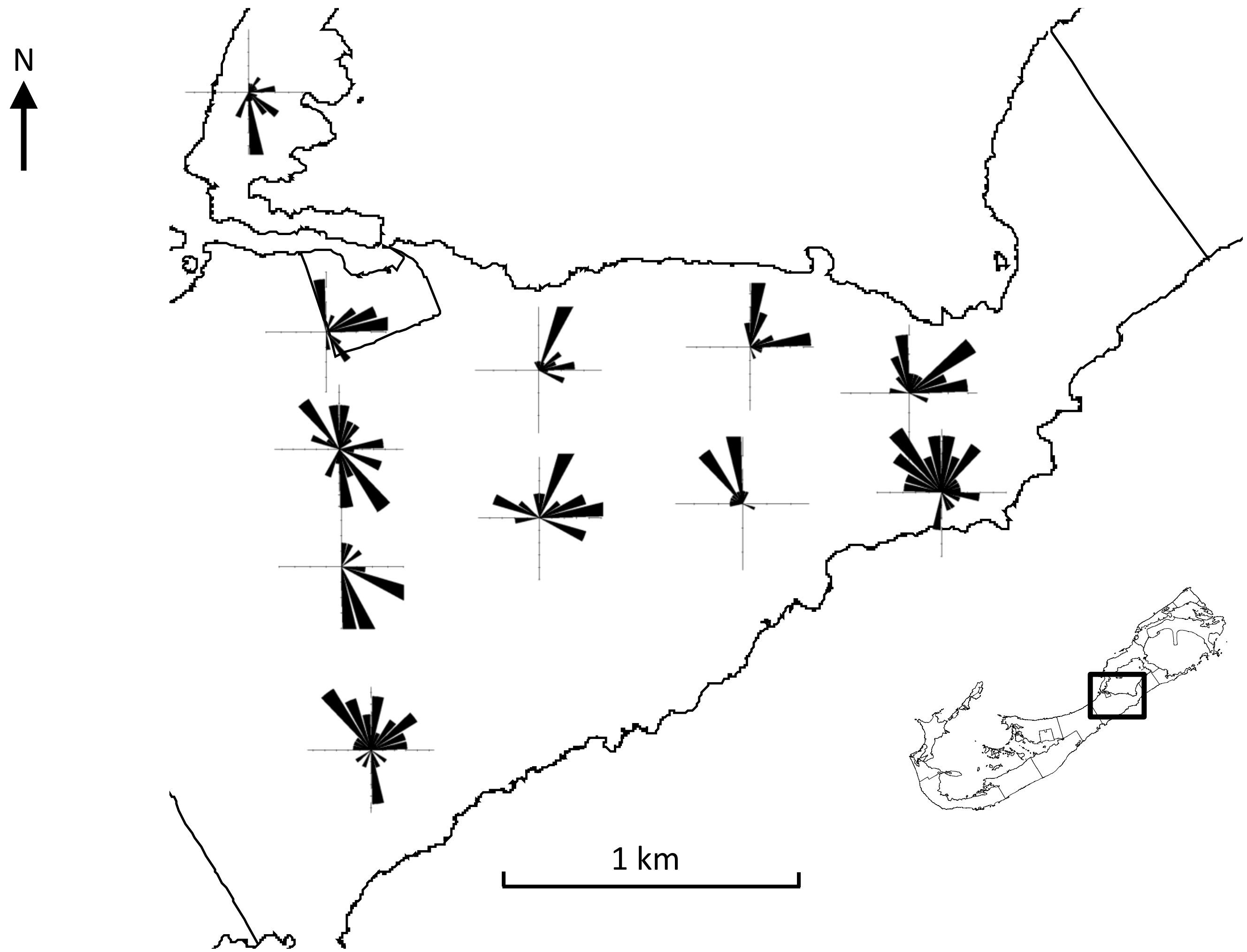


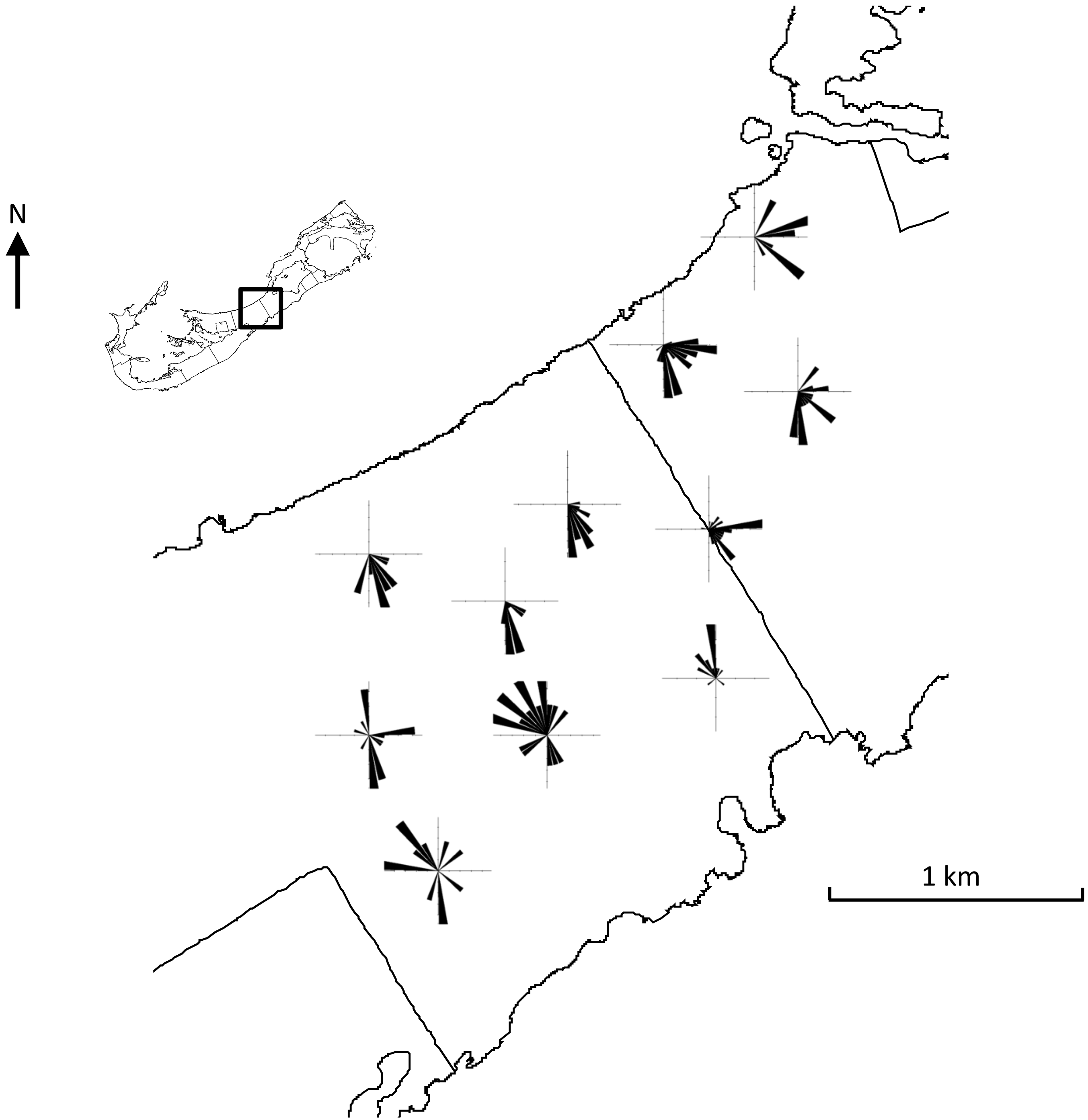

N
1 km


N
1 km

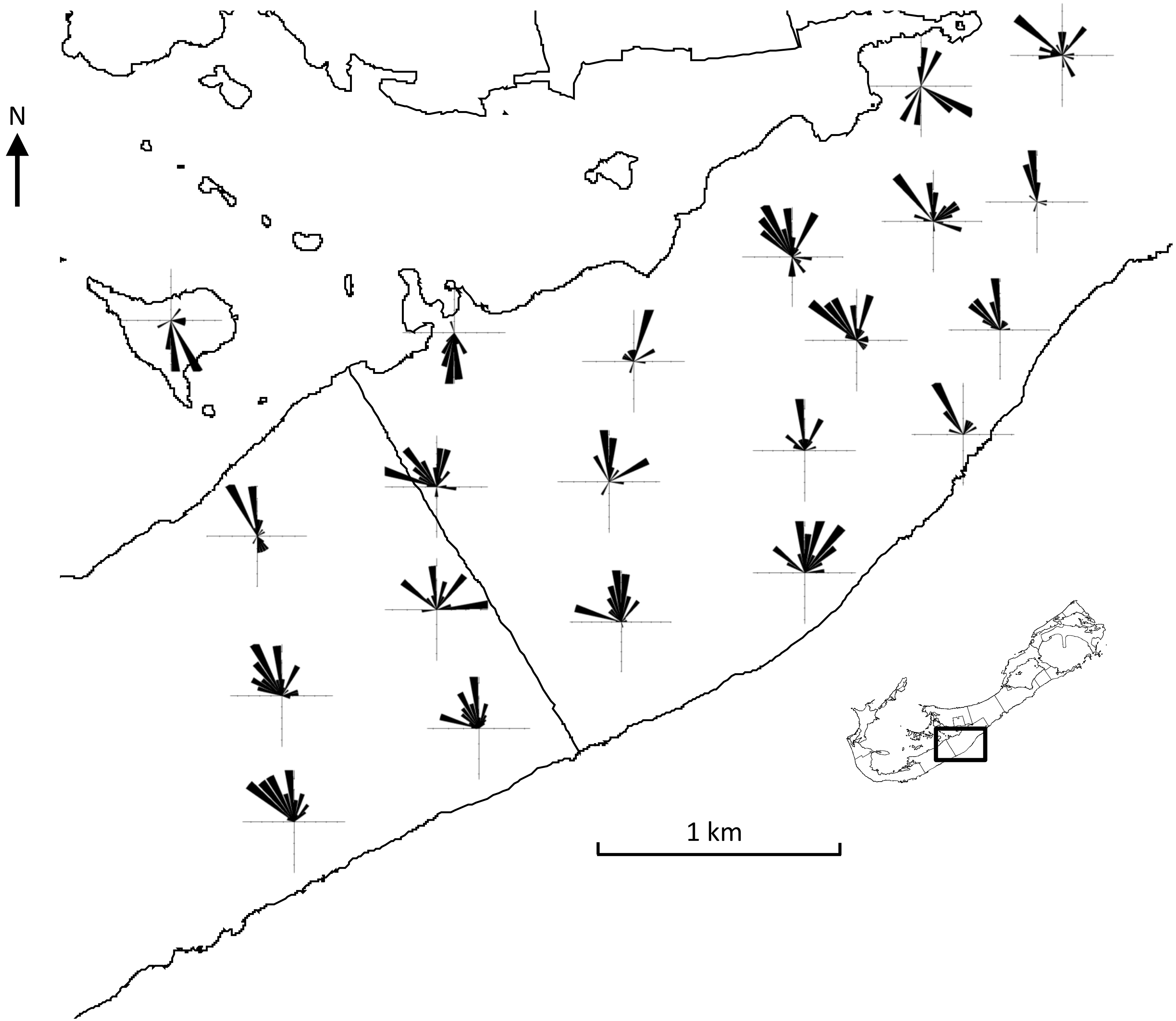

N
1 km

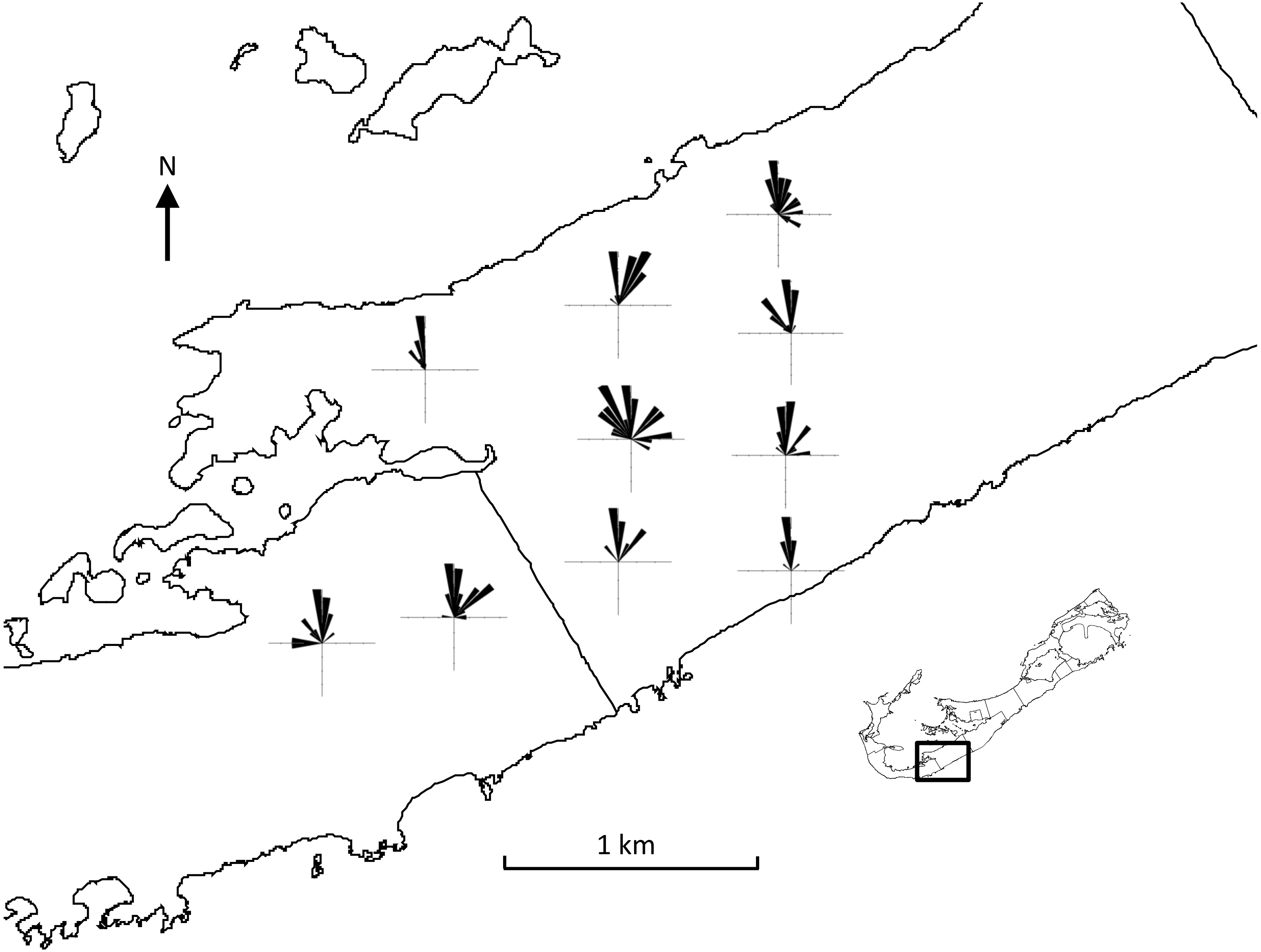

N
1 km

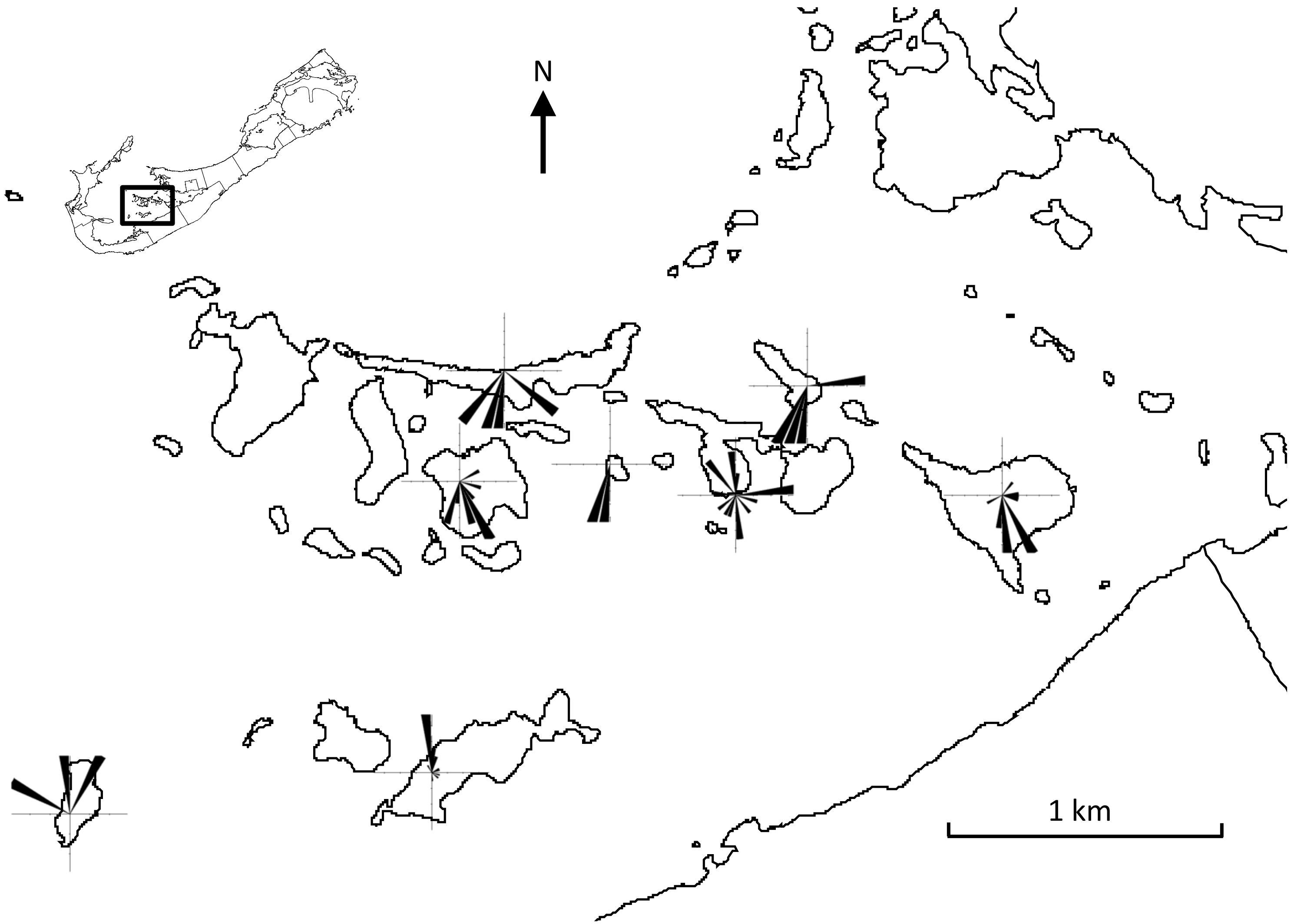

N
1 km


N
1 km


N
1 km

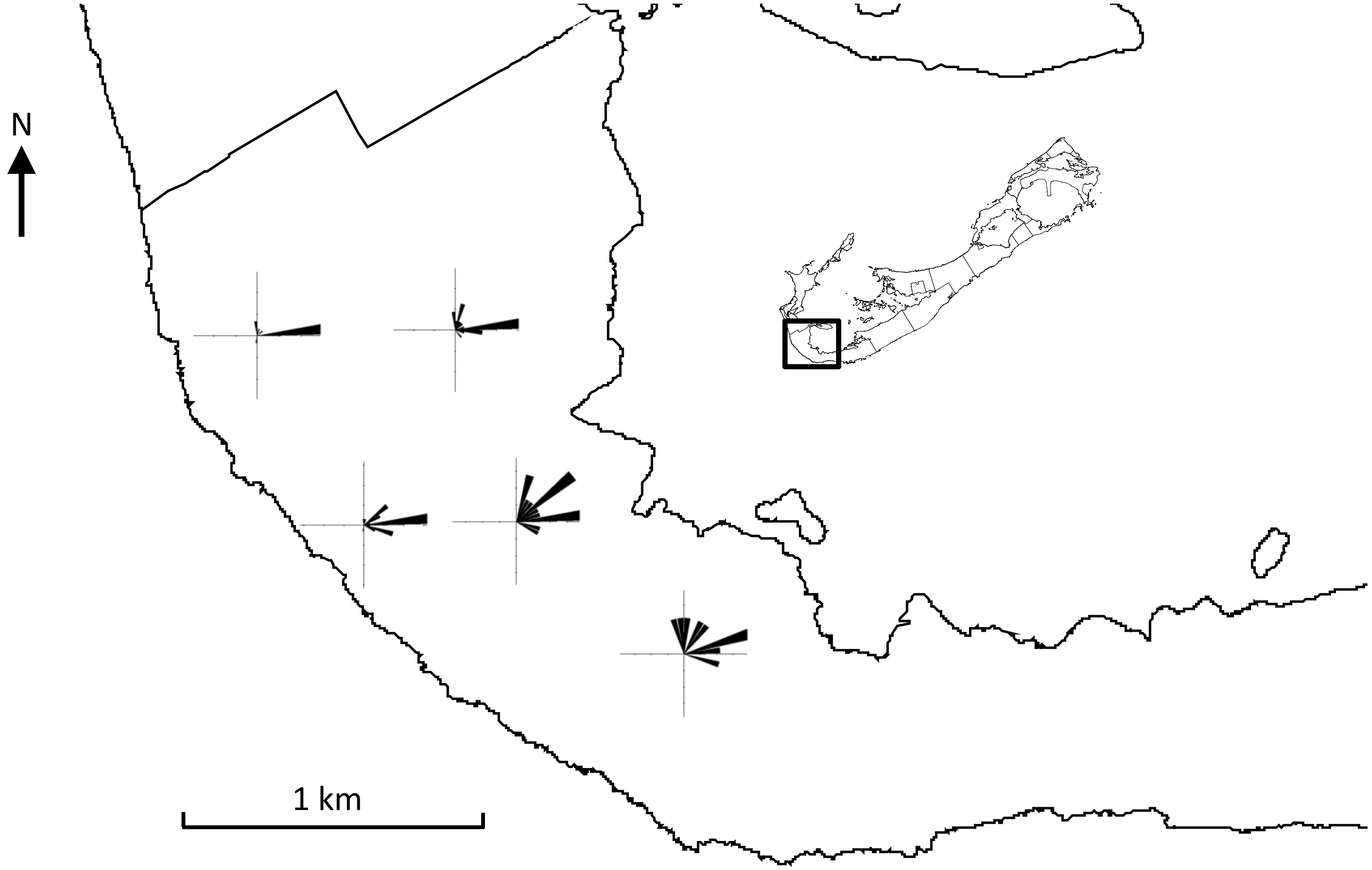

N
1 km


N
1 km

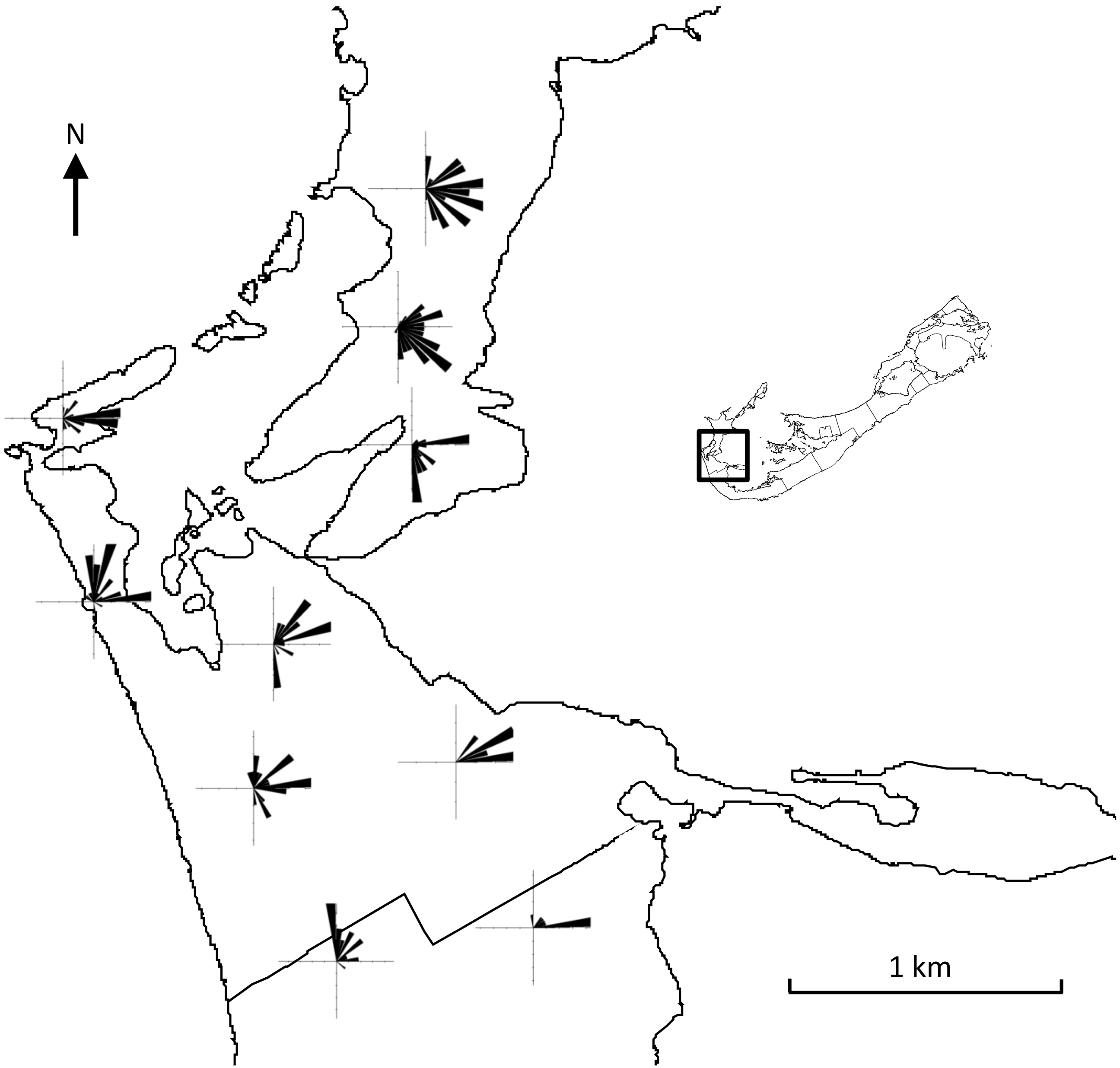


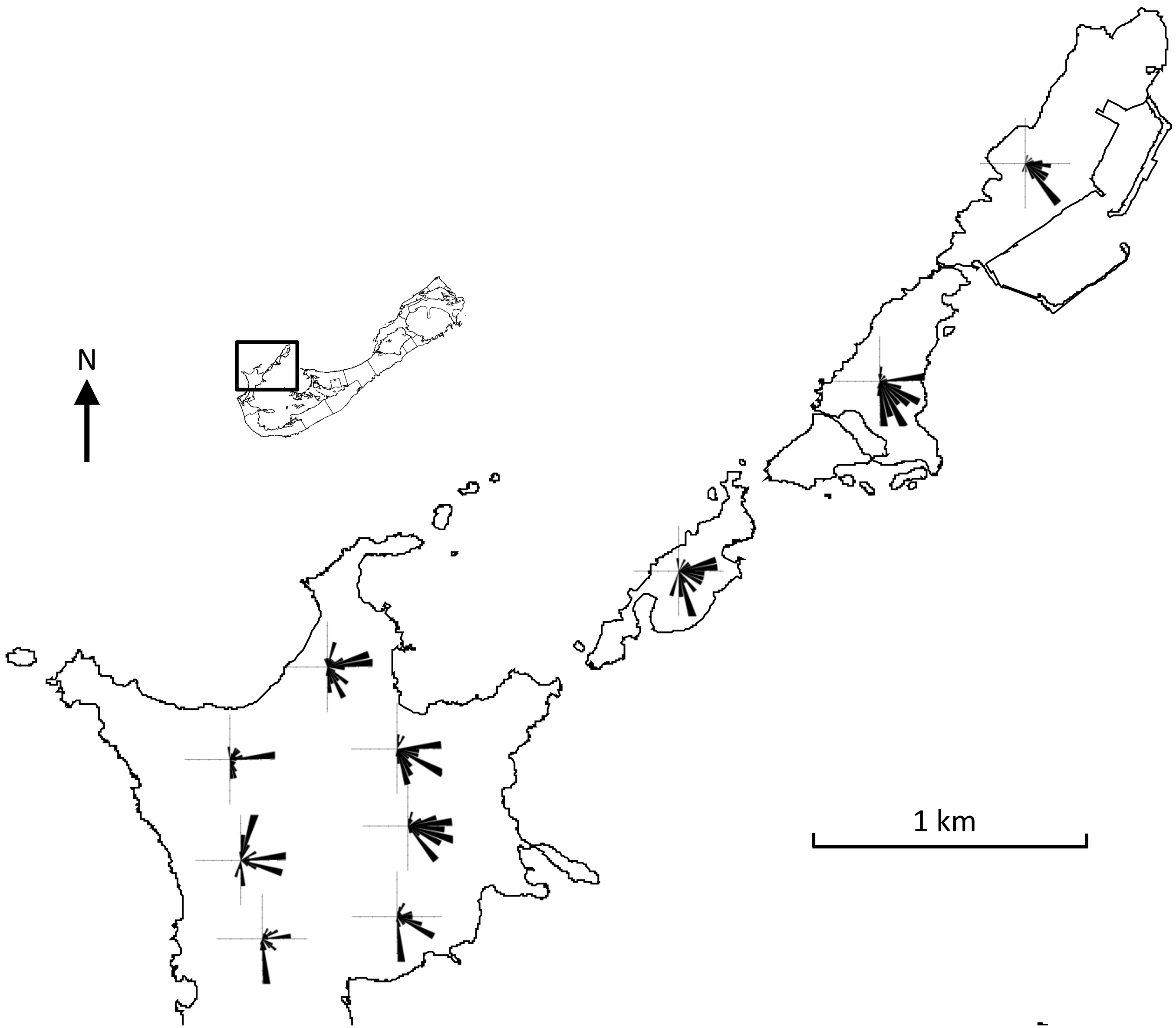
N
1 km


N
1 km



N
1 km


N
1 km


N
1 km

APPENDIX F – field-work documentation

Critical to this research was field work undertaken between 2011 and 2013. This became progressively more focused on the Belmont Fm coastal exposures of the south shore between Grape Bay in the west and Watch Hill Park in the east (Appendix G). General observations of sedimentary features and strike and dip of strata were noted on field maps (~1:2500) during early visits. Later on, given the importance of understanding the history of depositional events relative to changing RSLs, it was necessary to catalogue vertical sections at multiple localities along the south shore and document the two-dimensional architecture of facies assemblages. Elevations of key facies and surfaces were measured relative to the sea surface, noting the time of day in order that these elevations could later be converted to ASL values (above mean sea level at Bermuda). More details on the process of establishing elevations are provided in Section 1.4.2.

Field sketches

The following illustrations of vertical sections through Belmont Fm (south shore) facies assemblages are reproductions of field sketches. The small numbers shown against the black arrow-heads are the measured elevations (metres above mean sea-level) of the top surfaces of facies or of distinct surfaces and features. The sketches are organised by locality names and by site numbers, which increase from west to east along the south shore starting at the Grape Bay locality and ending at Watch Hill Park locality. Where, on occasion, a locality number is missing from the illustrations (e.g. Doe Bay, Site 15) this means that a measurement was taken and the facies was described but not sketched. All sites including those not sketched are listed in elevation data table (see below) and their locations are shown on a satellite photo-mosaic of the shoreline presented as Appendix G.

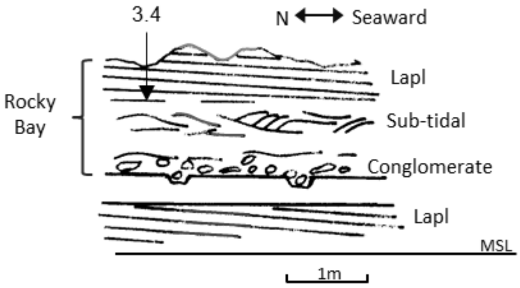
Elevation-data table

The table that follows the field sketches is a summary of the elevation calculations. Measurements were taken relative to the "current" sea surface using surveying equipment as described in Section 1.4.2. Recorded in the table are: the time and date of measurement; the elevation, ACSL, of the facies/feature relative to that of the (current) sea surface; the elevation, CSL, of the (current) sea surface relative to mean sea level as recorded by a NOAA tide gauge; the corrected elevation, ASL, of the facies/feature relative to mean sea level; and the longitude and latitude of the site. Note that where site numbers are repeated within the table, the elevation of more than one facies/feature was measured at that site (refer to field sketches). Those measurements with a "Mid-tide" notation were taken mid-way (temporally) between high tide and low tide and no corrections were made. The elevation data is not very precise (estimated <±0.3m) in these cases because mid-tide on a given day, only approximates to mean sea level. Accordingly, these measurements are preceded by a ~ symbol on the field sketches. Critical elevations quoted in the thesis were measured using the more accurate (<±0.2m) method which includes the NOAA correction.

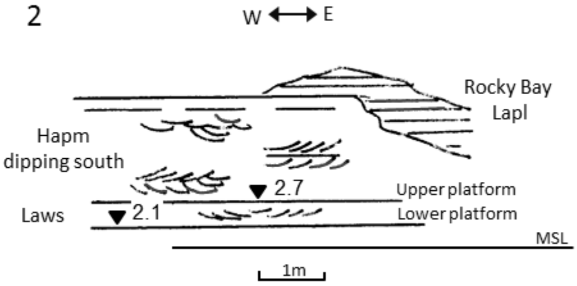
APPENDIX F - FIELD SKETCHES

Grape Bay

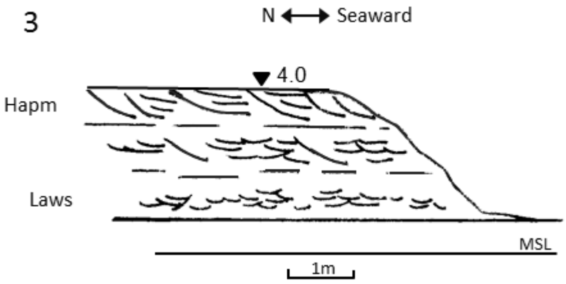
1



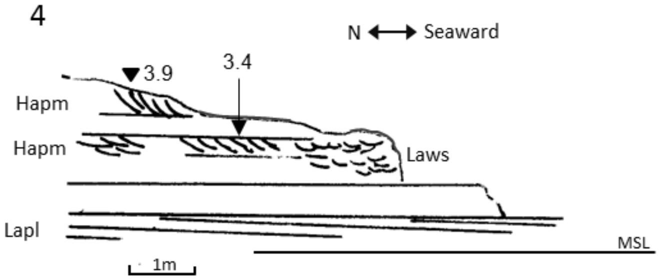
2



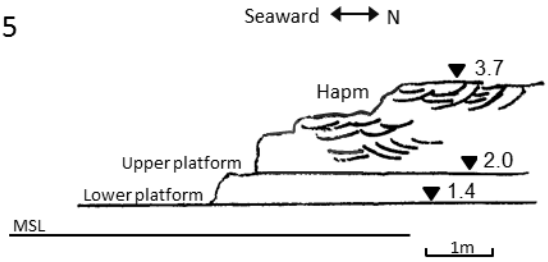
3



4

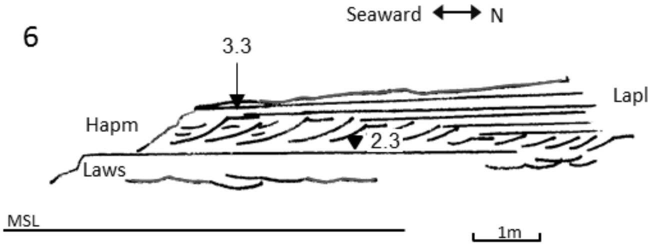


5



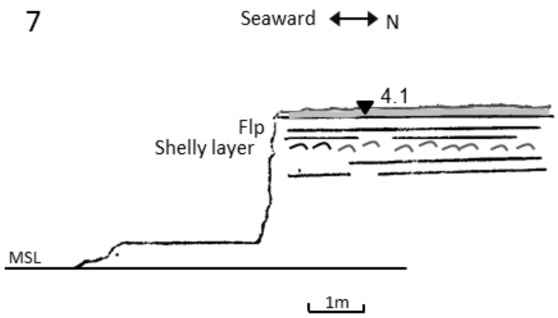
Grape Bay (cont.)

6

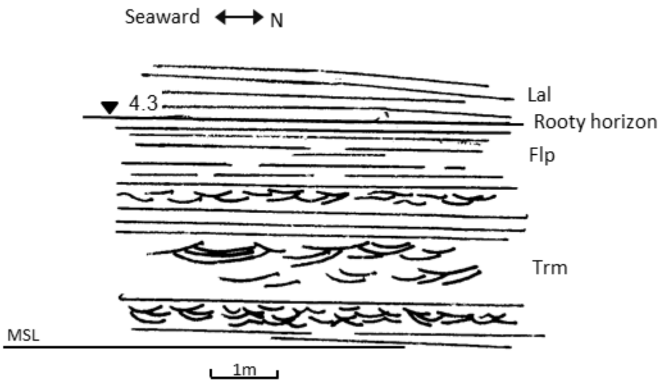


Hungry Bay West

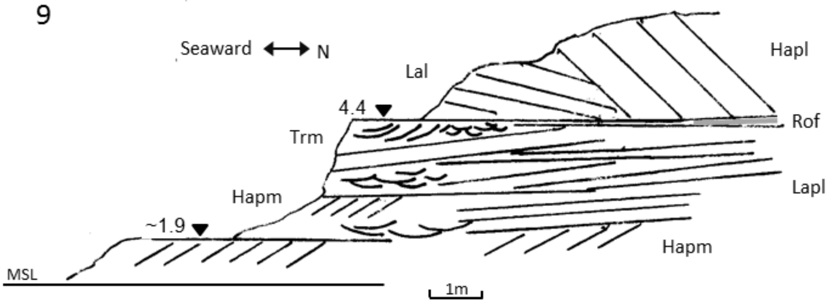
7



8

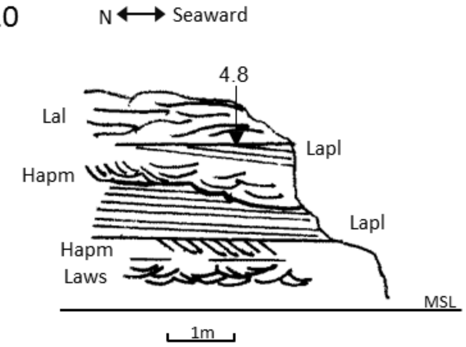


9

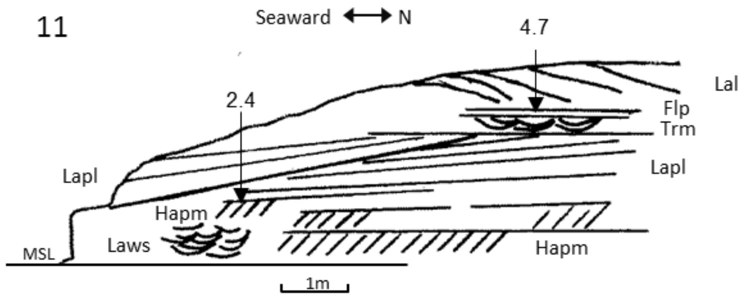


Hungry Bay East

10

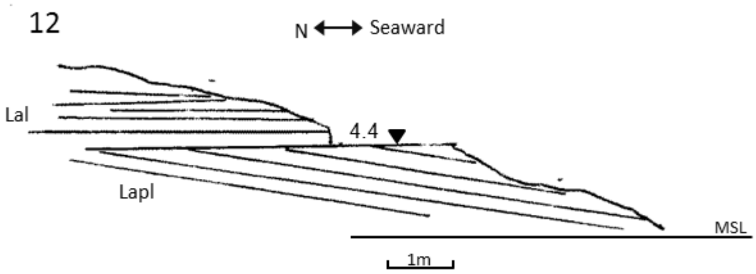


11

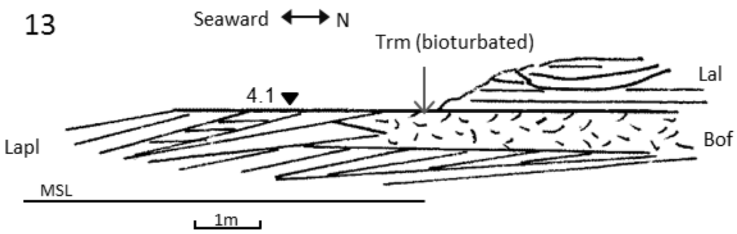


Doe Bay

12

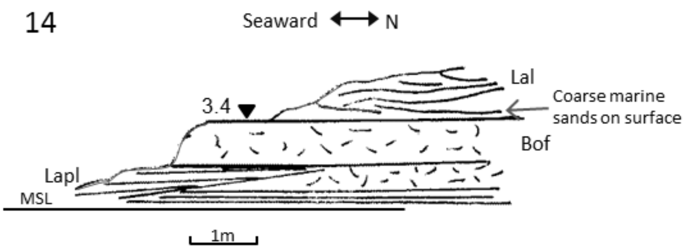


13

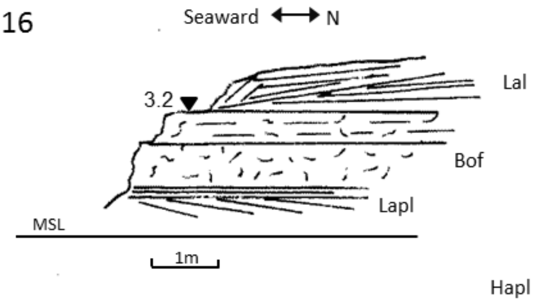


Doe Bay (cont.)

14

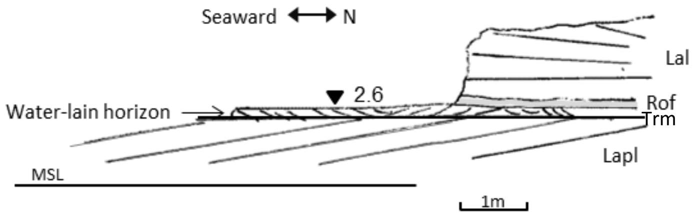


16



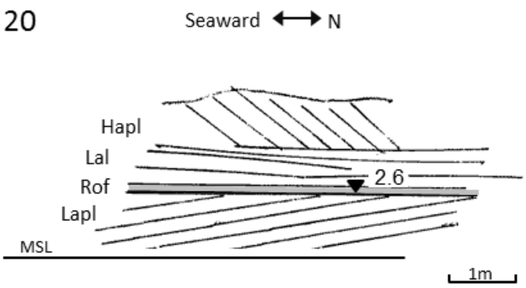
Rocky Bay

19



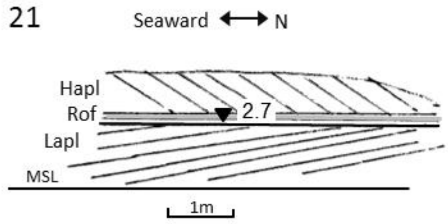
Devonshire Bay

20

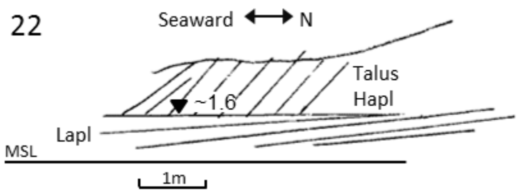


Devonshire Bay (cont.)

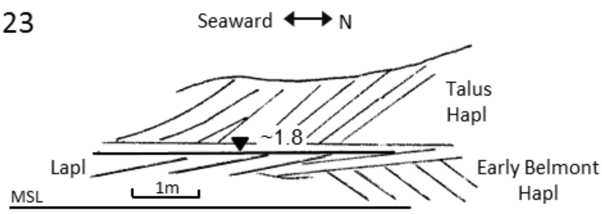
21



22

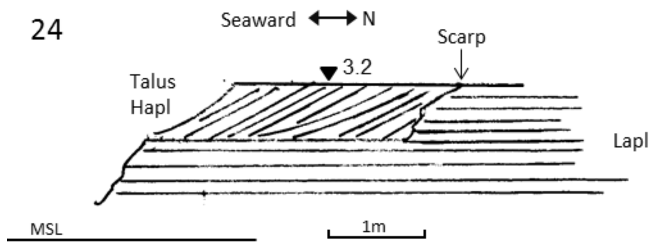


23

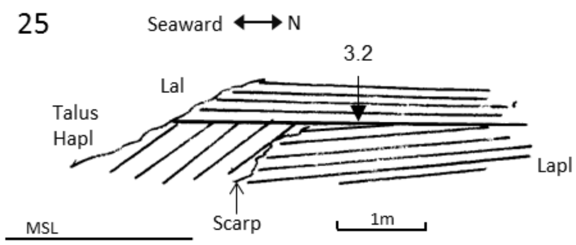


Cloverdale

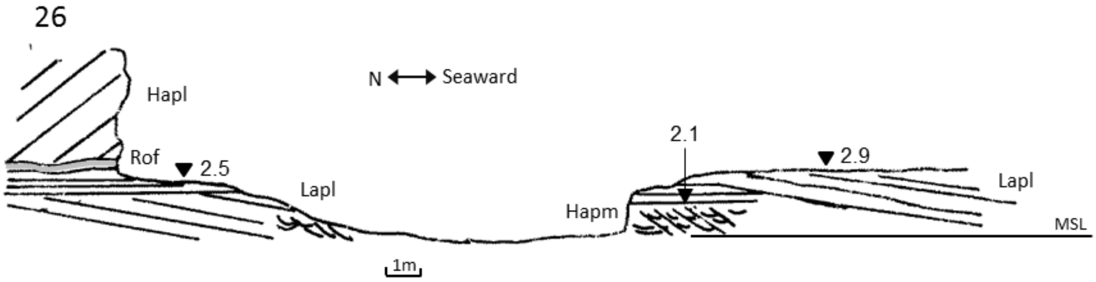
24

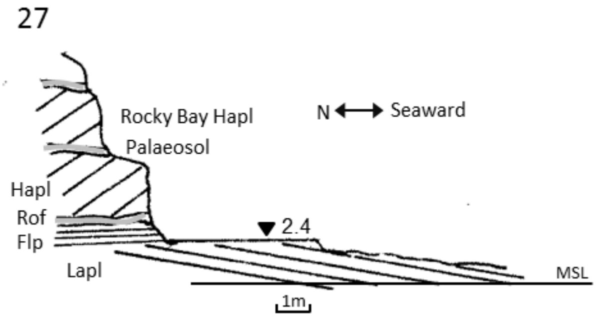


25

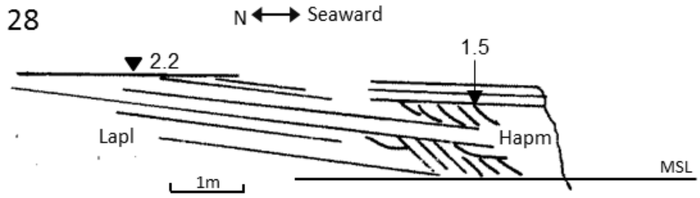


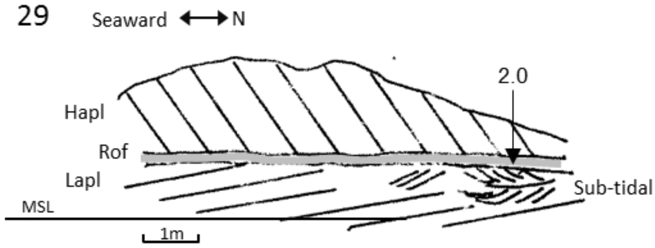
Saucos Hill West





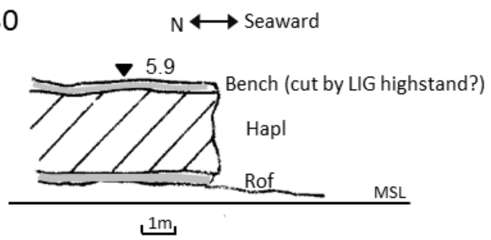
Saucos Hill



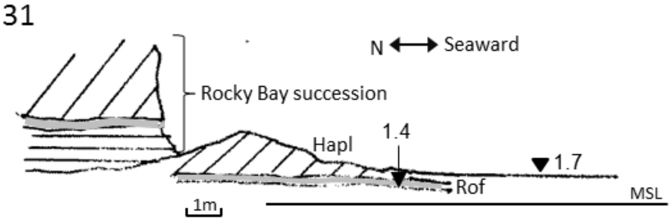


Saucos Hill (cont.)

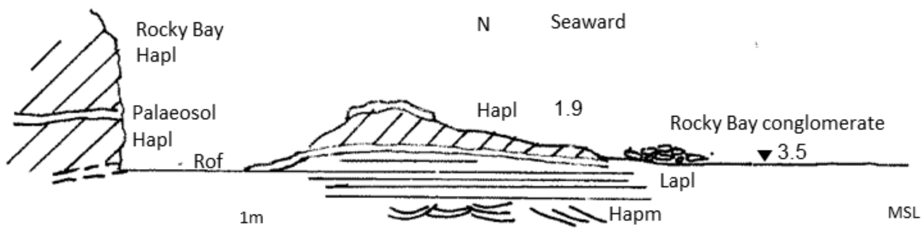
30



31

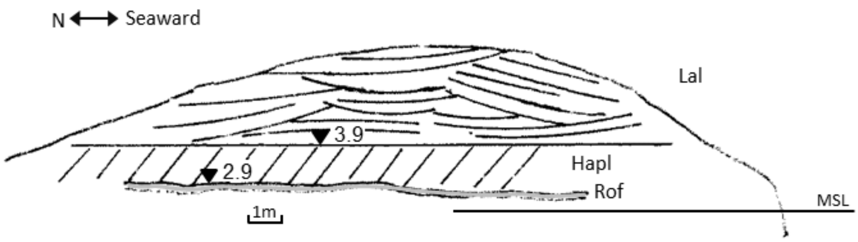


32



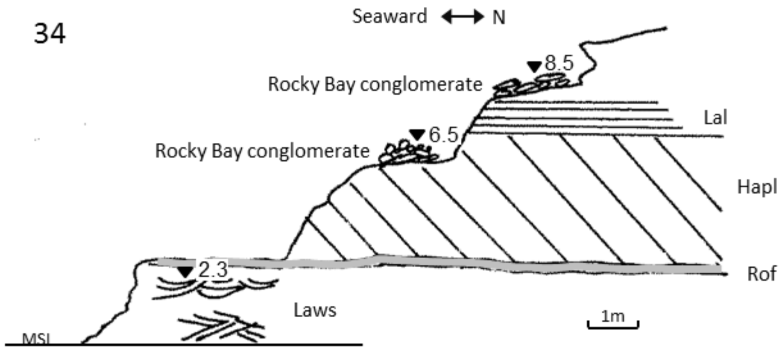
Saucos Hill East

33

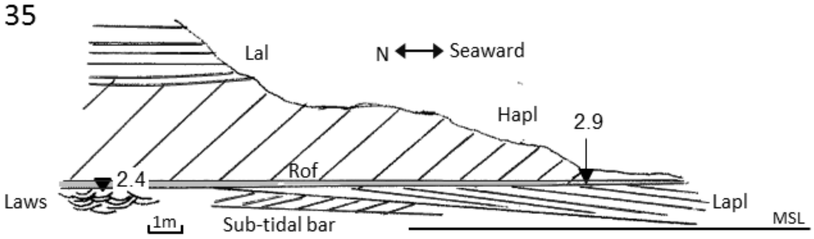


Spittal Pond West

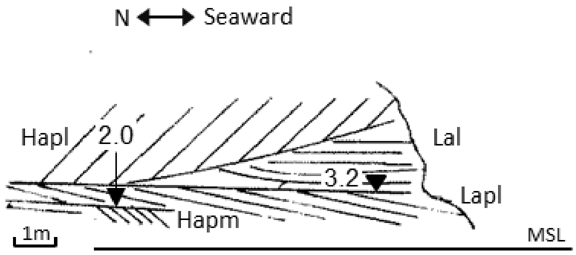
34



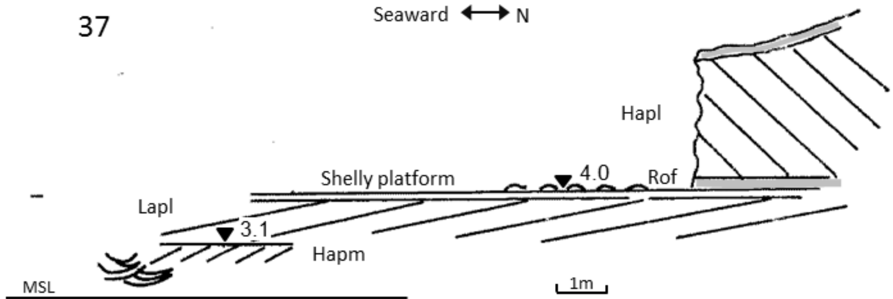
35



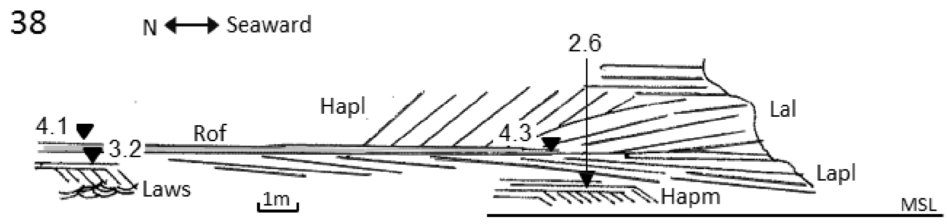
36



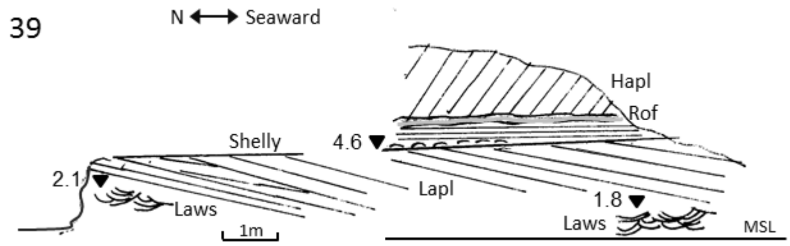
37

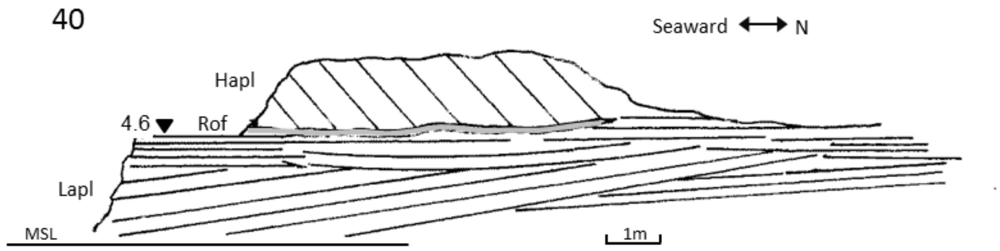


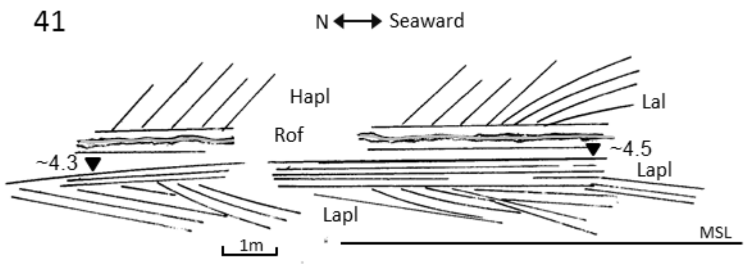
Spittal Pond West (cont.)



Spittal Pond

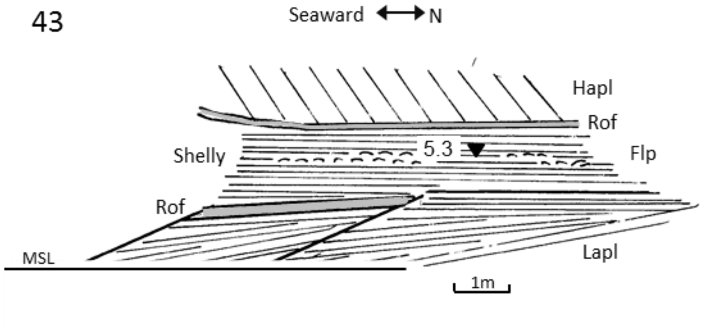






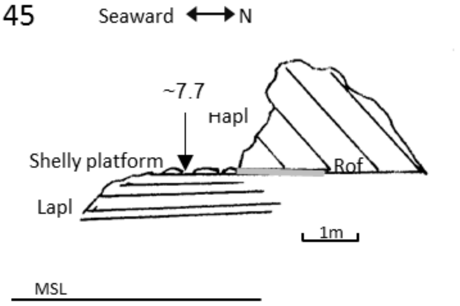
North Point

43

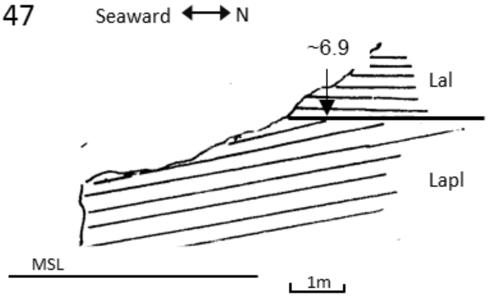


Watch Hill Park

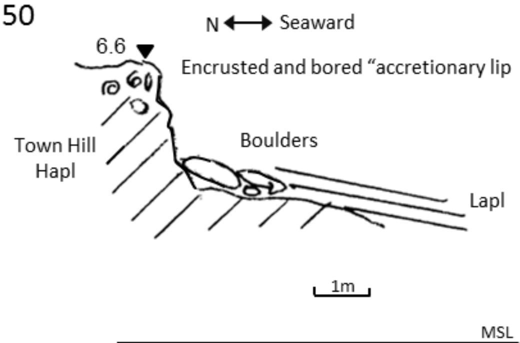
45



47



50



APPENDIX F (cont.) - ELEVATION DATA TABLE

Elevation data table

Locatality	Site #	Facies/Feature	Date	Time	ACSL(m)	CSL(m)	ASL(m)	Longitude N	Latitude W
Grape Bay	1	Lapl	22/11/12	10:15	3.5	-0.1	3.4	32 16 57.8	64 46 01.1
"	2	Hapm	22/11/12	11:00	4.6	-0.1	4.5	32 17 00.9	64 45 58.3
"	2	Upr platform	22/11/12	11:00	2.8	-0.1	2.7	32 17 00.9	64 45 58.3
"	2	Lwr platform	22/1//12	11:00	2.2	-0.1	2.1	32 17 00.9	64 45 58.3
"	3	Hapm	23/11/12	12:00	4	0.0	4.0	32 17 02.0	64 45 57.4
"	4	Upr Hapm	9/1/13	10:55	4.4	-0.5	3.9	32 17 02.9	64 45 55.9
"	4	Lwr Hapm	9/1/13	10:55	3.9	-0.5	3.4	32 17 02.9	64 45 55.9
"	5	Hapm	9/1/13	10:55	4.4	-0.5	3.9	32 17 03.8	64 45 54.5
"	5	Upr platform	9/1/13	10:55	2.5	-0.5	2.0	32 17 03.8	64 45 54.5
"	5	Lwr platform	9/1/13	10:55	1.9	-0.5	1.4	32 17 03.8	64 45 54.5
"	6	Hapm	22/11/12	12:30	3.2	0.1	3.3	32 17 05.2	64 45 52.2
"	6	Upr platform	22/11/12	12:30	2.2	0.1	2.3	32 17 05.2	64 45 52.2
Hungry Bay West	7	Flp	14/8/12	11:10	4.2	-0.1	4.1	32.17 14.1	64 45 37.3
"	8	Flp	14/8/12	10:35	4.3	0.0	4.3	32 17 15.3	64 45 36.8
"	9	Trm	14/8/12	10:05	4.3	0.1	4.4	32 17 17.1	64 45 37.2
Hungry Bay East	10	Lapl	21/6/12	13:45	4.7	0.1	4.8	32 17 18.1	64 45 34.3
"	11	Trm	21/6/12	13:00	4.5	0.2	4.7	32 17 20.5	64 45 31.8
"	11	Hapm	21/6/12	12:00	2.2	0.2	2.4	32 17 20.5	64 45 31.8
Doe Bay	12	Lapl	21/6/12	14:20	4.4	0.0	4.4	32 17 22.4	64 45 30.1
"	13	Trm	21/6/12	12:30	3.8	0.3	4.1	32 17 23.4	64 45 29.0
"	14	Bof	21/6/12	11:55	4	0.4	4.4	32 17 25.3	64 45 26.1
"	15	Shelly platform	21/6/12	11:00	2.7	0.5	3.2	32 17 26.9	64 45 24.4
"	16	Bof	21/6/12	10:30	2.7	0.5	3.2	32 17 28.5	64 45 22.6
"	17	Bof	Mid-tide		3.4	-	3.4	32 17 35.9	64 45 12.8
"	18	Laws	Mid-tide		2.9	-	2.9	32 17 40.7	64 45 07.5
Rocky Bay	19	Lapl	20/6/12	16:40	2.5	0.1	2.6	32 17 53.7	64 44 44.5
Rocky Bay	20	Lapl	25/8/12	8:00	2.7	-0.1	2.6	32 17 54.7	64 44 39.3
"	21	Lapl	25/8/12	9:50	2.9	-0.2	2.7	32 17 57.0	64 44 40.1
"	22	Lapl	Mid-tide		1.6	-	1.6	32 18 00.8	64 44 42.6
"	23	Lapl	Mid-tide		1.8	-	1.8	32 18 01.6	64 44 42.8
Cloverdale	24	Hapl (Talus)	11/2/12	10:10	2.7	0.5	3.2	32 18 05.3	64 44 35.4
"	25	Hapl (Talus)	11/2/12	10:25	2.7	0.5	3.2	32 18 06.1	64 44 35.5
Saucos Hill West	26	Lapl	24/10/12	11:25	2.9	0.0	2.9	32 18 10.2	64 44 16.4
"	26	Hapm	24/10/12	11:05	2.1	0.0	2.1	32 18 10.2	64 44 16.4
"	26	Rof	10/8/12	10:00	2.5	0.0	2.5	32 18 10.2	64 44 16.4
"	26	Lapl	10/8/12	10:00	2.3	0.0	2.3	32 18 10.2	64 44 16.4
"	27	Lapl	10/8/12	10:45	2.3	0.1	2.4	32 18 15.2	64 44 14.2
Saucos Hill	28	Lapl	20/5/13	15:20	1.9	0.3	2.2	32 18 21.1	64 44 03.8
"	28	Hapm	20/5/13	15:20	1.2	0.3	1.5	32 18 21.1	64 44 03.8
"	29	Rof	20/5/13	15:55	1.6	0.4	2	32 18 24.0	64 44 00.9
"	29	Laws	20/5/13	15:55	1.4	0.4	1.8	32 18 24.0	64 44 00.9
"	30	Bench Hapl	10/8/12	11:10	5.7	0.2	5.9	32 18 24.8	64 44 00.3
"	31	Bench Hapl	10/8/12	11:30	1.5	0.2	1.7	32 18 24.0	64 44 00.9
"	31	Rof	10/8/12	11:30	1.2	0.2	1.4	32 18 24.0	64 44 00.9
"	32	Lapl	10/8/12	12:45	3.1	0.4	3.5	32 18 28.4	64 43 51.2
"	32	Hapm	10/8/12	12:45	1.5	0.4	1.9	32 18 28.4	64 43 51.2
Saucos Hill East	33	Hapl	10/8/12	13:20	3.4	0.5	3.9	32 18 31.0	64 43 44.3
"	33	Rof	10/8/12	13:20	2.4	0.5	2.9	32 18 31.0	64 43 44.3
Spittal Pond West	34	Top	26/3/12	18:00	2.6	-0.3	2.3	32 18 32.0	64 43 40.6
"	35	Lapl	26/3/12	18:00	3.2	-0.3	2.9	32 18 32.6	64 43 40.0
"	35	Laws	26/3/12	18:00	2.7	-0.3	2.4	32 18 32.6	64 43 40.0
"	36	Lapl	18/12/12	12:15	2.8	0.4	3.2	32 18 32.4	64 43 39.2
"	36	Hapm	18/12/12	12:15	1.6	0.4	2	32 18 32.4	64 43 39.2
"	37	Lapl	30/11/12	15:35	4.4	-0.4	4.0	32 18 33.8	64 43 37.5
"	37	Hapm	30/11/12	15:35	3.5	-0.4	3.1	32 18 33.8	64 43 37.5
"	38	Lapl	18/12/12	13:10	4.1	0.2	4.3	32 18 34.4	64 43 35.9
"	38	Hapm	30/11/12	15:15	3	-0.4	2.6	32 18 34.4	64 43 35.9
"	38	Platform	30/11/12	15:15	4.5	-0.4	4.1	32 18 34.4	64 43 35.9
"	38	Hapm	30/11/12	15:15	3.6	-0.4	3.2	32 18 34.4	64 43 35.9

Elevation data table (cont.)

Spittal Pond	39	Laws	30/11/12	14:50	2.2	-0.4	1.8	32 18 43.4	64 43 24.4
"	39	Lapl	11/10/12	10:05	4.1	0.5	4.6	32 18 43.4	64 43 24.4
"	39	Laws	11/10/12	10:30	1.7	0.5	2.2	32 18 43.4	64 43 24.4
"	40	Platform	Mid-tide		4.6	-	4.6	32 18 44.6	64 43 21.1
"	41	Lapl	Mid-tide		4.5	-	4.5	32 18 44.4	64 43 19.8
"	41	Platform	Mid-tide		4.3	-	4.3	32 18 44.4	64 43 19.8
North Point	42	Lapl	Mid-tide		4.4	-	4.4	32 18 46.3	64 43 16.9
"	43	Shelly horizon Flp	8/10/12	11:30	4.7	0.6	5.3	32 18 47.4	64 43 16.5
"	44	Shelly horizon	Mid-tide		4.8	-	4.8	32 18 50.0	64 43 16.7
"	45	Lapl	Mid-tide		7.7	-	7.7	32 18 51.3	64 43 12.9
Watch Hill Park	46	Phreatic cave	Mid-tide		8.2	-	8.2	32 18 15.4	64 43 11.5
"	47	Lapl	Mid-tide		6.9	-	6.9	32 18 52.0	64 43 09.8
"	48	Shelly platform	Mid-tide		7.2	-	7.2	32 18 52.5	64 43 08.1
"	49	Conglomerate	Mid-tide		9.1	-	9.1	32 18 53.0	64 43 06.1
"	50	Marine encrustatio	29/22/12		6.4	+0.2	6.6	32 18 52.8	64 43 05.6

APPENDIX G - Locality and site map (loose folded insert)

A satellite photo-mosaic of the south shore along the central parishes of Bermuda identifies locality names and site numbers where facies associations, stacking patterns and elevations were recorded (Appendix F).

APPENDIX H - Vertical sections at Hungry Bay West and Devonshire Bay (loose folded insert)

Key facies assemblages in shore-normal exposures at Hungry Bay West and Devonshire Bay. These are presented with no vertical exaggeration as photo-mosaics and as line drawings showing facies boundaries from which vertically exaggerated versions, Figures 7.2 and 7.3, in the thesis were produced.

APPENDIX I - Geological Map of Bermuda (loose folded insert)

Geological Map of Bermuda at 1:25000 (Vacher et al., 1989)