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Stratigraphy and timing of eolianite deposition on Rottnest Island, Western Australia

Paul J. Hearty

School of Earth Sciences, James Cook University, Townsville, Queensland, 4811 Australia

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Abstract

Over 100 whole-rock amino acid racemization (AAR) ratios from outcrops around Rottnest Island (32.0° S Latitude near Perth) indicate distinct pulses of eolian deposition during the late Quaternary. Whole-rock D-alloisoleucine/L-isoleucine (A/I) ratios from bioclastic carbonate deposits fall into three distinct modal classes or "aminozones." The oldest, Aminozone E, averages 0.33 ± 0.04 ($n = 21$). Red palaeosol and thick calcrete generally cap the Aminozone E deposits. A younger Aminozone C averages 0.22 ± 0.03 ($n = 63$); comprising two submodes at 0.26 ± 0.01 ($n = 14$) and 0.21 ± 0.02 ($n = 49$). Multiple dune sets of this interval are interrupted by relatively weak, brown to tan "protosols." A dense, dark brown rendzina palaeosol caps the Aminozone C succession. Ratios from Holocene dune and marine deposits ("Aminozone A") center on 0.11 ± 0.02 ($n = 15$), comprising submodes of 0.13 ± 0.01 (9) and 0.09 ± 0.01 (6). Calibration of *A/I* averages from Aminozones E and A are provided by U/Th and ^{14}C radiometric ages of 125,000 yr (marine oxygen isotope stage (MIS) 5e and 2000–6000 ^{14}C yr B.P. (MIS 1), respectively. The whole-rock A/I results support periodic deposition initiated during MIS 5e, continuing through MIS 5c, and then peaking at the end of MIS 5a, about 70,000–80,000 yr ago. Oceanographic evidence indicates the area was subjected to much colder conditions during MIS 2–4 (10,000 to 70,000 yr ago), greatly slowing the epimerization rate. Eolianite deposition resumed in the mid Holocene (~6000 yr ago) up to the present. The A/I epimerization pathway constructed from Rottnest Island shows remarkable similarity to that of Bermuda in the North Atlantic (32° N Latitude). These findings suggest that, like Bermuda, the eolian activity on Rottnest occurred primarily during or shortly after interglacial highstands when the shoreline was near the present datum, rather than during glacial lowstands when the coastline was positioned 10–20 km to the west.

Keywords: Western Australia; Late Quaternary; Whole-rock amino acid racemization; Carbonate eolianite; Sea-level changes

Introduction

Because of the inferred stability of its shoreline and shelf, Western Australia holds an important position in the global context of Quaternary geology, sea-level, and climate studies. Rottnest Island is among the best-studied of the Western Australian sites (for reference, see Playford, 1988; 1997; Brooke, 2001), and is of international scientific interest for highly productive cool-water carbonates (Collins, 1988; James et al., 1999). Yet beyond the obvious applications of radiometric dating to late Pleistocene and Holocene corals and shells, little is known about the depositional processes and timing of carbonate dunes that cover a majority of the island. Conversely, abundant data from studies on the mainland around Perth (Hewgill et al., 1983; Murray-Wallace and Kimber, 1989; Kendrick et al., 1991; Bastian, 1996). Bastian (1996) established that several shore-parallel dune ridges were tied to interglacial sea-level cycles.

Lying just 18 km west of Fremantle in Western Australia, Rottnest Island (Fig. 1) has been a focal point of studies over the past several decades. Early references were made to the geology of the region by Somerville (1921), while Teichert (1950) made the first detailed and systematic scientific study of the geology of Rottnest. The history of study on Rottnest is well summarized by Playford (1988; 1997).

The Rottnest dunes were first broadly grouped into the "Coastal Limestone" (Teichert, 1950; Fairbridge and Teichert, 1953), and later the "Tamala Eolianite and Limestone" (Logan et al., 1970; Playford et al., 1976) (Table 1).

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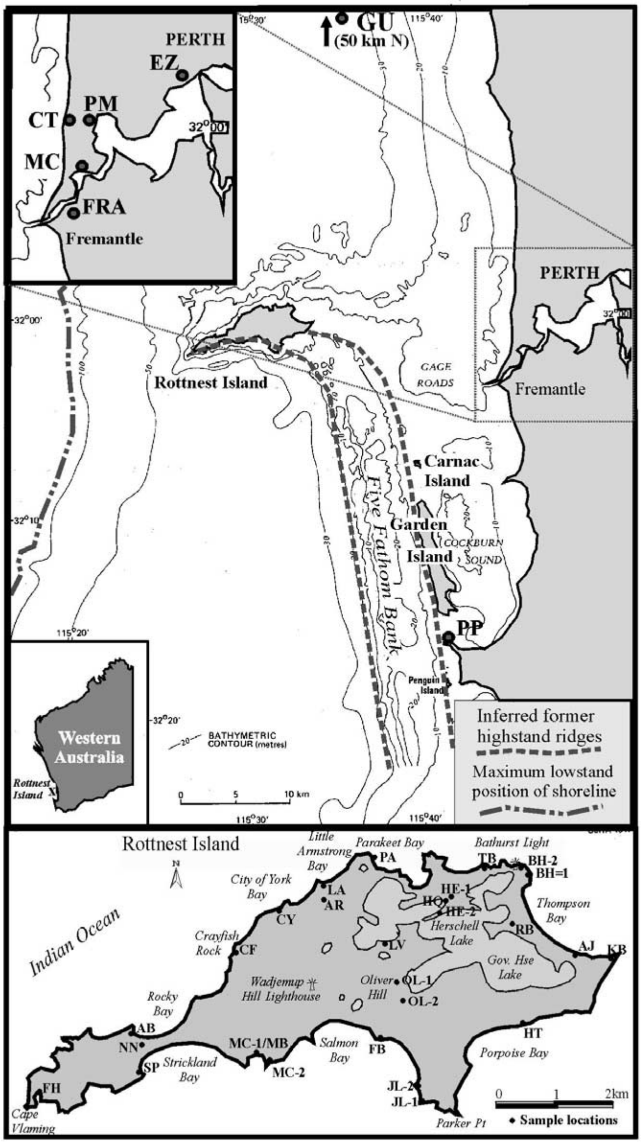

Fig. 1. Location map showing the Perth and Rottnest Island localities. The upper map was modified from an original Geological Survey of Western Australia map. Dashed lines indicate the inferred position of former highstand and lowstand shorelines. Study sites are identified in the lower figure by capital letters. These letters, with the addition of a prefixes "R", "P", and "W" correspond with sample data in Table 2.

The latter has its type locality over 600 km to the north at the Zuytdorp Cliffs on the western margin of Shark Bay.

Shell beds from Herschell Quarry (Fig. 1) produced ages between 6000 and 2000 ^{14}C yr B.P. (Playford, 1988) while an emergent coral reef at Fairbridge Bluff was correlated with MIS 5e (Veeh, 1966; Szabo, 1979). Evidence of reef growth between 127,000 and 125,400 yr ago was confirmed by thermal ionization mass spectrometric (TIMS) U/Th ages (Stirling et al., 1995). Hesp et al. (1999) established provisional amino acid ages of >50,000 yr on *Austrosuccinea* sp snails from soil levels in Rottnest dunes, while thermoluminescence (TL) studies have suggested that many of the carbonate deposits of Rottnest and Perth were deposited during times of glacially lowered sea levels (Price et al., 2001).

The theory and utility of amino acid racemization (AAR) geochronology is well explained in Rutter and Blackwell (1995). The whole-rock AAR method was first introduced systematically in Bermuda (Hearty et al., 1992), and has since been successfully applied to Quaternary shorelines of the Bahamas (Hearty and Kaufman, 2000), Hawaii (Hearty et al., 2000), and the Coorong Peninsula of South Australia (Murray-Wallace et al., 2001). Organic residues in bioclastic or skeletal carbonate sand samples show similar kinetic behavior and yield consistent amino acid ratios when compared to molluscan sample results (Hearty et al., 1992). Through detailed stratigraphic studies and whole-rock AAR, eolianite units can be correlated and grouped in modal classes (or "aminozones"). With independent calibration, combined with kinetic models (e.g., Bermuda; Hearty et al., 1992), the age of the aminozones can be estimated with reasonable accuracy. This accuracy has been repeatedly tested against stratigraphic superposition and independent radiometric chronologies (Hearty and Kaufman, 2000; Hearty et al., 2000).

The purpose of this study is to: (1) stratigraphically characterize and correlate carbonate-rich deposits on the island; 2) provide estimates of their ages through aminostratigraphy, calibration, kinetic models, and comparison with sites on the mainland, and; (3) discuss the mechanisms and timing of eolianite formation relative to Quaternary sea-level changes.

Approach and methods

The Quaternary stratigraphy of Rottnest consists of a succession of bioclastic dune and shoreline facies separated at eroded and/or weathered contacts. Weathered karst surfaces are often mantled with soils and calcrete. At many localities, stacked eolianites and weak soils occur in vertical succession (Fig. 2). The major difficulty in resolving the succession of deposits in the field is that most deposits have undergone little recognizable diagenetic alteration. Most of the eolianites consist of weakly to moderately cemented, fine to coarse carbonate sand. Microscopic examination reveals the primary bioclastic components to be mollusks, calcareous algae, foraminifera, and echinoderms (Kinna, 2002). The biogenic composition of the dunes appears to vary little through the stratigraphic section and across the island. Preservation of the primary grain textures and color can be attributed to the young age of the deposits, and the cool and relatively dry climate.

An insoluble fraction of nearly pure quartz sand is generally less than 5 to 10%, but in a few cases it exceeds 50% (Table 2). Soils generally contain higher percentages of insoluble grains. Bastian (1996) was convinced that quartz-rich soils around Perth were the result of dissolution of carbonate eolianite; thus are "residual soils." However,

Table 1
Correlation table of stratigraphic names used previously and in this study of Rottnest Island

<table>
<tr><th>Period epoch</th><th>Teichert (1950)</th><th colspan="2">Playford (1988, 1997)</th><th>Murray-Wallace and Kimber (1989)</th><th>This study</th><th>Correlated MIS</th></tr>
<tr><td>Holocene</td><td rowspan="8">Coastal Limestone</td><td>Herschell Limestone</td><td>Baghdad Mb
Vincent Mb</td><td>Herschell Limestone of TLS</td><td>Unit VI Beach, salt lake, and dune deposits</td><td>1</td></tr>
<tr><td>Last glacial cycle</td><td colspan="2">?</td><td>?</td><td>Black rendzina paleosol</td><td>4-2</td></tr>
<tr><td rowspan="3">Late Pleistocence</td><td colspan="2" rowspan="3">Rottnest Limestone</td><td rowspan="3">Minim Cove Mb-of TLS</td><td>Unit V Dunes and weak paleosols</td><td>5c-5a</td></tr>
<tr><td>Terra rossa paleosol</td><td>≤5d</td></tr>
<tr><td>Unit IV Reef, beach, and minor dunes</td><td>5e</td></tr>
<tr><td rowspan="2">Middle Pleistocene</td><td colspan="2" rowspan="3">Tamala Limestone (TLS)</td><td>Peppermint Grove Mb of TLS</td><td>Unit III Subtidal, beach, and dunes</td><td>9-7</td></tr>
<tr><td>?</td><td>Unit II Large coastal ridge</td><td>11-9</td></tr>
<tr><td>Early Pleistocene?</td><td>?</td><td>Unit I Large coastal ridge</td><td>>11</td></tr>
</table>

given that most eolianites are over 90% carbonate (Table 2), this would require that enormous masses of dune material be dissolved since the last interglaciation to concentrate the quartz in the soils. However, as primary dune morphology is the dominant geomorphic feature on Rottnest, and there is no evidence of significant loss of volume by dissolution, the "residual soil" theory, in this case, is implausible.

At each site, stratigraphic sections were logged and photographed. Samples were collected from over 30 outcrop sections (Fig. 1) across the island (Table 2). Sites representative of the island's stratigraphic history are illustrated in Fig. 3.

Over 100 whole-rock amino acid samples were analyzed. Two or more ratios were determined from each stratigraphic level (Table 2). AAR ratios from vertical successions of eolianites (e.g., Fig. 2) were determined where practical, and in all cases, stratigraphic order of the whole-rock D-alloisoleucine/L-isoleucine (or A/I) ratios was demonstrated.

The A/I ratio is a measure of the extent of epimerization of isoleucine. In living organisms, the A/I ratio is initially near zero ($\sim$0.015) and increases with age to a ratio of $\sim$1.30. As whole-rock method analyzes aggregates of skeletal grains that form over time (i.e., having an "inherited age"), entirely "modern" ratios are not expected. For example, samples 2000 ^{14}C yr B.P. from Herschell Quarry have a mean ratio around 0.09. This sample would include a mix of sand grains of mid to late Holocene age. Modern beach deposits are likewise expected to contain grains representing a mix of ages of 2000–3000 yr. Mixing of intraclasts from older interglacial deposits may occur in some cases, but is not a significant factor as the concentration of amino acids decreases exponentially with age. Thus, even moderate proportions of older grains in younger samples have negligible influence on the ultimate whole-rock A/I ratio (Hearty and Kaufman, 2000).

Rottnest Island experiences a Mediterranean climate (present mean annual temperatures (MAT) of 18°C) with extremely dry summers and cool, wet winters, with annual evaporation exceeding rainfall by over 700 mm (http://www.bom.gov.au/cgi-bin/climate). Because of the island's small size, it is safe to assume that all sites of similar age have experienced equivalent climate histories.

Sample preparation and analysis

Whole-rock sample preparation procedures are outlined in Hearty and Kaufman (2000). Samples were gently disaggregated and sieved to obtain the 250- to 850-μm sand fraction. Previous studies have shown that this size range is typical of beach and dune facies, and tends to exclude fine

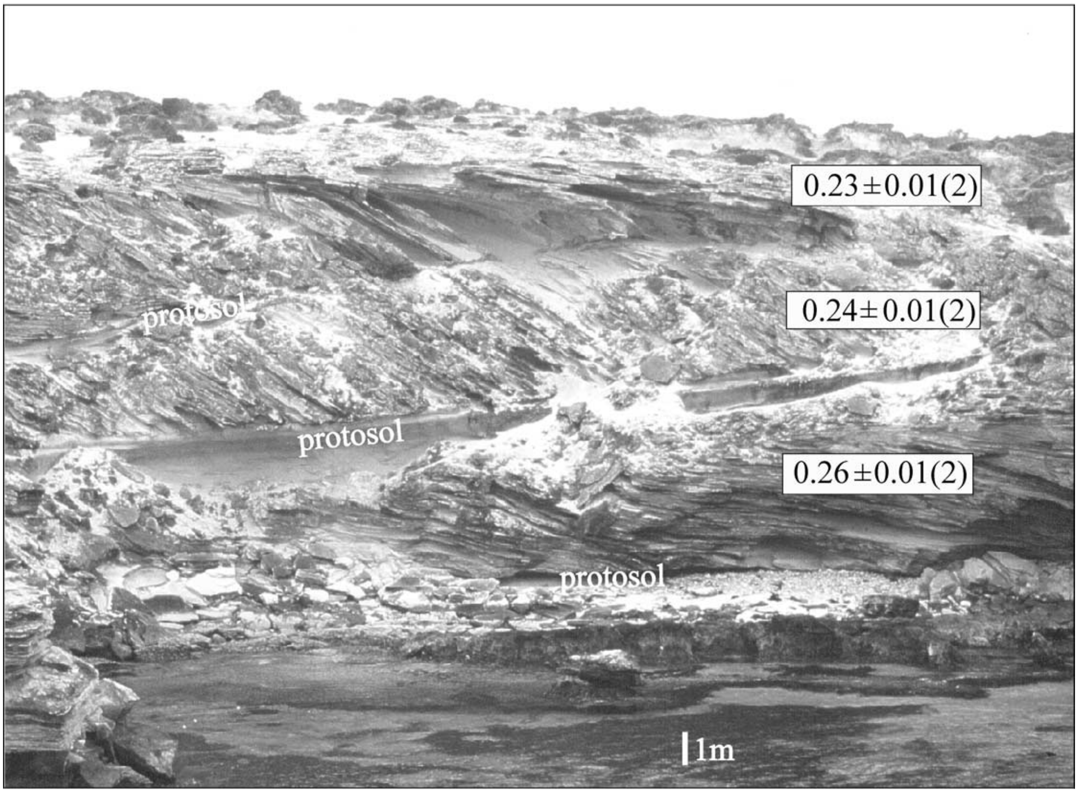

Fig. 2. A photograph of the stratigraphic sequence at Fish Hook Bay near Cape Vlaming in western Rottnest Island. The sequence is composed of three alternating sets of eolian foresets beds capped by weak soils ("protosols" of Vacher and Hearty, 1989) representing alternating intervals of dune building and dune stabilization by vegetative growth. Numbers in the figures indicate whole-rock A/I ratios (Table 2). The succession of ratios reflects rapid and consecutive dune-building events, separated by short intervals of stability. The short pulses of dune deposition are probably the result of wind transport of sand from adjacent shorelines during major storm events.

intergranular cements as well as large grains or shells that could disproportionately influence the A/I ratio.

Sample analyses were performed at the Amino Acid Laboratory of Northern Arizona University (D. Kaufman, Director) and followed standard procedures prescribed in Miller and Brigham-Grette (1989). Approximately 100 mg of each sample was first leached in dilute hydrochloric acid (HCl) to remove 30% of the sample weight and reduce the possibility of contamination by cements or organic residues on grain surfaces. Samples weighing approximately 30 mg were dissolved in 7 M HCl containing 6.25 μM norleucine (a synthetic amino acid used as an internal standard). Samples were flushed with N_2, sealed in sterile vials, hydrolyzed at 110°C for 22 h, and then evaporated under N_2 in a heat block or vacuum. After rehydration, samples were injected onto an ion-exchange high-performance liquid chromatograph (HPLC) that employs postcolumn derivitization in OPA and fluorescence detection.

Each sample solution was analyzed two to three times to determine the mean and analytical error which was typically $<$3% (Table 2). To monitor analytical drift and facilitate comparison with other laboratories, the Interlaboratory Comparative Standards of Wehmiller (1984) were routinely measured (footnote, Table 2).

Quaternary morphostratigraphy of Rottnest Island and the Perth area

Rottnest Island was formed during the late Quaternary by nearshore marine and eolian sedimentation. Today, long, sandy "catenary" beaches are suspended between headlands. Marine deposits and dune sets often outcrop in stacked or lapping successions, and are separated by paleosols. On the basis of these and other field criteria, the succession of the deposits can often be directly assessed.

Bastian (1996) and Kendrick et al. (1991) determined morphological and paleontological characteristics of Plio-Pleistocene deposits in the Perth area. These deposits are correlated with MIS 5e or older highstands (Hewgill et al., 1983; Murray-Wallace and Kimber, 1989), and for this study are ranked by increasing apparent age as Unit IV (Minim Cove and Cottesloe Beach, late Pleistocene; MIS 5e), Unit III (Peppermint Grove and Fremantle Fort, middle Pleistocene; MIS 7–9?), Unit II (inland Guilderton, middle Pleistocene, MIS 11?), and Unit I (Mt. Eliza, older Pleistocene).

On Rottnest, three major units (IV, V, and VI) are identified, each with several minor elements. Unit IV consists of generally coarse-grained and shelly subtidal calcarenite,

Table 2
Whole-rock amino acid data from Rottnest Island organized in lithostratigraphic order by site[a]

Site name	Field number	$CaCO_3$ (% ± 3%)	GPS Latitude South	GPS Longitude East	Whole-rock A/I ratio	Standard deviation (No. samples)	Aminozone zone
L. Armstrong Bay W	RLA2a	57	31° 59′ 30.5′′	115° 30′ 19.0′′	0.097	0.007 (2)	A
Fairbridge Bluff	RFB1x	90	32° 00′ 57.5′′	115° 30′ 43.6′′	0.126	0.001 (2)	A
Rottnest Bore	RRB1a	99	31° 59′ 56.4′′	115° 32′ 18.5′′	0.133	0.007 (2)	A
Army Jetty	RAJ	98	32° 00′ 14.4′′	115° 30′ 14.0′′	0.12	0 (2)	A
Herschell Quarry	RHQ1cd	90	31° 59′ 45.3′′	115° 31′ 30.1′′	0.089	.005 (4)	A
	RHQ1a (2)	98			0.131	.005 (4)	A
L. Herschell dune	RHE2	97	31° 59′ 45.3′′	115° 31′ 30.2′′	0.187	0 (2)	C2
Herschell Hill	RHE1a	98	31° 59′ 43.8′′	115° 31′ 32.7′′	0.210	0.007 (2)	C2
Henrietta Rocks	RHT1a	98			0.221	0.006 (2)	C2
Lake Vincent	RLV1a	99	32° 00′ 03.1′′	115° 30′ 45.5′′	0.210	0.017 (2)	C2
Narrow Neck	RNN1a	48	32° 00′ 55.2′′	115° 28′ 29.5′′	0.171	0 (2)	C2
Abraham's Bay	RAB1a	97	200 m N of RNN		0.195	0.000 (2)	C2
Oliver Hill base	ROL1a	97	32° 00′ 25.5′′	115° 30′ 57.0′′	0.229	0.002 (2)	C2
Oliver Hill RR	ROL2a	99	32° 00′ 39.4′′	115° 30′ 57.0′′	0.211	0 (2)	C2
Parakeet Bay	RPA1a	71	31° 59′ 56.4′′	115° 30′ 43.5′′	0.201	0.016 (2)	C2
The Basin	RTB1a (2)	90	31° 59′ 26.8′′	115° 31′ 59.8′′	0.207	0.008 (2)	C2
Armstrong Hill	RAR1a	95	31° 59′ 40.7′′	115° 30′ 14.0′′	0.206	0.004 (2)	C2
South Point	RSP1e	98	32° 01′ 16.2′′	115° 28′ 07.5′′	0.196	0.008 (2)	C2
	RSP1c	98			0.218	0.002 (2)	C2
Kingston Barracks	RKB1a	99	32° 00′ 15.5′′	115° 33′ 20.8′′	0.171	0.004 (2)	C2
Crayfish Rock	RCF1c	92			0.234	0.005 (2)	C2
	RCF1a	99			0.230	0.022 (2)	C2
L. Armstrong Bay E	RLA1e	95	31° 59′ 32.6′′	115° 30′ 18.4′′	0.235	0.004 (2)	C2
	RLA1c	95			0.276	0.008 (2)	C1
Fish Hook Bay	RFH1g	99	32° 01′ 28.4′′	115° 26′ 57.7′′	0.227	0.002 (2)	C2
	RFH1e	98			0.243	0.008 (2)	C1
	RFH1c	94			0.263	0.007 (2)	C1
City of York Bay	RCY1c	99	31° 59′ 48.8′′	115° 29′ 38.8′′	0.203	0.006 (2)	C2
	RCY1a	81			0.254	0.016 (2)	C1
Bathurst Lighthouse	RBH2c	94	100 m W of RHB1		0.252	0.012 (2)	C1
Bathurst Point	RBH1a	93	31° 59′ 30.1′′	115° 32′ 26.7′′	0.312	0.019 (2)	E
Fairbridge Bluff	RFB4x	96	0.5 km E of RFB1		0.232	0.007 (2)	C2
	RFB5a	98	Q at road near RFB1		0.222	0.012 (2)	C2
Post corals	RFB1c	82	32° 00′ 57.5′′	115° 30′ 43.6′′	0.245	0.021 (2)	C1
Below corals	RFB1a	98			0.344	0.08 (4)	E
Jeannie's Lookout 1	RJL1c	97	32° 01′ 37.8′′	115° 31′ 20.8′′	0.261	0.004 (2)	C1
Jeannie's Lookout 2	RJL2a	97	0.5 km north of RJL1		0.371	0.008 (2)	E
Mary Cove East	RMB2g	97	200 m E of RMB1		0.165	0.004 (4)	C2
	RMB2e	95			0.200	0.011 (2)	C2
Mary Cove West	RMB1e	90	32° 01′ 08.9′′	115° 29′ 27.2′′	0.280	0.003 (2)	C1
	RMB1c	99			0.339	0.056 (4)	E
	RMB1a	96			0.34	0.018 (2)	E
			Perth area, Swan River Estuary				
Mimim Cove	PMC2d	71, 54, 97	32° 01′ 26.5′′	115° 45′ 54.8′′	0.300	0.036 (7)	E
		59	32° 01′ 28.6′′	115° 46′ 02.3′′			
Point Peron	PPP1	nd	32° 19.6′	115° 24.8′	0.329	0.009	E
Guilderton	PGU5a	70	31° 21′ 10.4′′	115° 29′ 51.3′′	0.324	0.029	E
01.10.2001	PGU5c	91			0.272	0.007	E
Cottesloe Beach/Rx	WCT1b	52			0.322	0.041	E
Peppermint Grove	WPM1b	76, 69, 68	31° 59′ 30′′	115° 46′ 10′′	0.395	0.042 (4)	F/G
Fremantle fort	PRA1				0.478	0 (2)	G/H
Guilderton	PGU1a	83	31° 19′ 47.9′′	115° 30′ 37.2′′	0.523	0.024	G/H
Mt. Eliza	PEZ1a	19, 35	31° 57.788	115° 50.535	ND	ND	?

Mean aminozone values: Aminozone E overall mean, 0.331 ± 0.044 (21); Rottnest E = 0.334 ± 0.047 (11); Mimim E = 0.300 ± 0.034 (7); Aminozone C overall mean, 0.218 ± 0.031 (63); submean C1 = 0.261 ± 0.013 (14); submean C2 = 0.206 ± 0.022 (49); Aminozone A overall mean = 0.114 ± 0.020 (15); submean A1 = 0.129 ± 0.008 (9); submean A2 = 0.092 ± 0010 (6); Wehmiller (1984) Standards 3/01 to 3/02: ILC-A = 0.146 ± 0.006 (18); ILC-B = 0.473 ± 0.013 (18); ILC-C = 1.016 ± 0.020 (17).

[a] The prefix capital letter ("R", "W", or "P") is dropped from the field numbers in Figure 1.

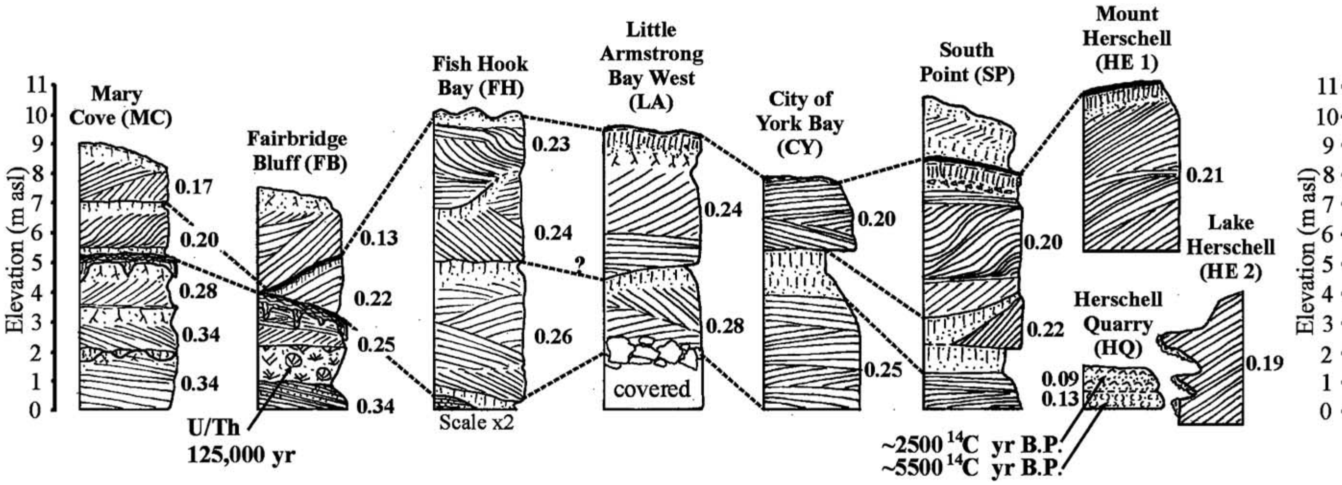

Fig. 3. Key schematic stratigraphic sections from Rottnest Island. Numbers in the figures are mean whole-rock A/I ratios (see Table 2), which demonstrate stratigraphic superposition in all cases. Locations are identified in Figure 1 by capital letters. Cartographic symbols are explained in Figure 6.

coral and algal reef, intertidal beach and shoal, minor eolianite, and palaeosol deposits. Unit IV is largely buried yet forms most of the major headlands on Rottnest, for example, at Fairbridge Bluff, the east end of Salmon Bay, and Bathurst Point. The Unit IV sequence is capped by a reddish calcrete and terra rossa palaeosol complex with deep root casts filled with red-stained, quartz-rich sands. The quartz grains are often well rounded and pitted, and are presumably of continental dune origin (Semeniuk and Glassford, 1988; Glassford and Semeniuk, 1990). The red soil and thick calcrete cap on Unit IV forms the stratigraphic boundary between Units IV and V.

Volumetrically, the majority of Rottnest Island consists of two to five bioclastic carbonate eolianite dune sets composed of predominantly foreset bedforms. These are interrupted by disconformities or weak soils ("protosols" of Vacher and Hearty, 1989). This succession is designated Unit V. The intercalated brown to tan protosols are composed of fine calcareous sand to silt enriched in humus. The protosols converge and bifurcate regularly, and bracket large eolianite accumulations. Small terrestrial gastropods such as *Austrosuccinea* spp. (Hesp et al., 1999) are also present, but the ubiquitous Western Australian genus *Bothriembryon* has not been observed in any pre-Holocene deposits on Rottnest. This is probably due to periodic inundation of the island during the last interglaciation. The dunes of Unit V vary from very fine bioclastic sands to coarse and shelly deposits. Grain-size changes may reflect variations in distance from source to sink (beach to dune), with an added component of storm intensity.

Capping Unit V is a well-developed "rendzina" soil (Fig. 4). The C-horizon is generally tan to brown silty sand, with abundant brecciated limestone clasts to depths of 0.5 to 2 m. The A/B horizon is composed of a dense silt, with rich dark brown to nearly black organic coloration. Where preserved and unbroken (e.g., Fig. 4, inset), a thin 0.5- to 2-cm-thick calcrete layer caps Unit V.

The youngest Unit VI complex consists of unconsolidated to lightly cemented, subtidal to intertidal shelly beds and lacustrine marls, interfingering with eolianites in coastal and interior locations in the east. Where stabilized, the Holocene dunes are capped with a weak, sandy gray to light brown soil containing abundant *Bothriembryon* and introduced land snail taxa. At South Point, a comparison of the superimposed paleosols of Units V and VI (Fig. 4) indicates a much greater development of the lower paleosol.

Active dune blowouts along the south and west coasts of the island are perhaps the result of human degradation. Historical accounts indicate that over 65% of Rottnest was covered by native forest only 100 years ago (see Pen and Green, 1983), which was further reduced to only 5% in recent times by fire and overgrazing. Burning of the protective forest cover and penetration of the thin soils and calcrete by hoofed animals would subject the weakly cemented carbonate dunes to deflation.

Aminostratigraphy of Rottnest Island and the Perth area

The results of over 100 whole-rock analyses from Rottnest and Perth area localities are reported in Table 2. A/I data are presented in the format 0.21 $\pm$ 0.02 (49), where 0.21 is the mean, $\pm$ 0.02 is 1σ, and (49) is the number of whole-rock samples analyzed. The frequency diagram in Fig. 5 shows the distribution of ratios and the modal classes representing aminozones. The results confirm that all sampled exposures on Rottnest are MIS 5e or younger. Stratigraphic order is maintained *in all cases* where multiple stacked units were sampled (Table 2). No AAR determinations were excluded. Similar or equivalent whole-rock A/I ratios are repeated from site to site (Fig. 3) and correspond with dunes of distinct stratigraphic position. Given this degree of reproducibility between units and sites (Table 2),

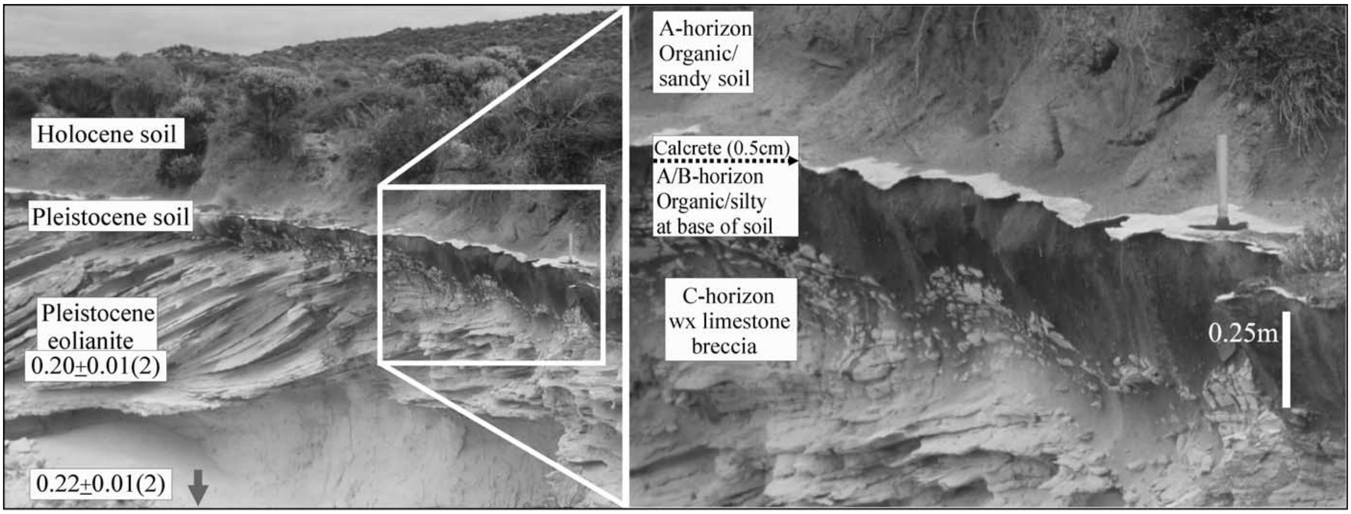

Fig. 4. Photos of the South Point (SP) section at the southwestern end of Strickland Bay. A complex sequence of dunes and protosols is exposed in the lower half of the section. The dunes are capped by well-developed rendzina soil, exhibiting intensive brecciation in the C-Horizon, succeeded by a dense black silt, and a 0.5- to 2-cm-thick calcrete. Overlying the lower paleosol is a soil of Holocene age, representing development over the past few thousand years. After the formation of the Pleistocene dunes (with Aminozone C ratios around 0.20), the degree of development of the lower paleosol suggests that several tens of thousands of years of formation were required for its formation. In this study, the basal eolianites are correlated with interglacial highstands late in MIS 5, while the two periods of soil formation are equated with MIS 2–4, and MIS 1. Numbers in the figures are mean whole-rock A/I ratios (see Table 2).

it is reasonable to conclude that reworking, contamination, or other problems have not significantly affected the whole-rock chronostratigraphy. A measure of the volumetric importance of depositional events is implied from the frequency and distribution of whole-rock data.

Units I–III—Sites older than the last interglaciation

Whole-rock A/I data from several sites in and around Perth yield ratios significantly older than those from known MIS 5e sites (Fairbridge Bluff and Minim Cove), placing these sites within the middle Pleistocene. Bulk sediment was analyzed from Peppermint Grove, the fort at Fremantle, and the site at Guilderton north of Perth, which yield mean ratios of 0.40 ± 0.04, 0.48 ± 0.00, 0.52 ± 0.02, respectively (Table 2). These sites are part of large coastal ridges showing greater diagenesis progressively inland, reflecting a succession of older interglacial highstands (Murray-Wallace and Kimber, 1989; Bastian, 1996).

Unit IV—Aminozone E, the peak last interglaciation

Whole-rock A/I ratios of Aminozone E are broadly distributed between 0.41 and 0.29, averaging 0.33 ± 0.04 (n = 21). In situ coral ages from Fairbridge Bluff (Stirling et al.,

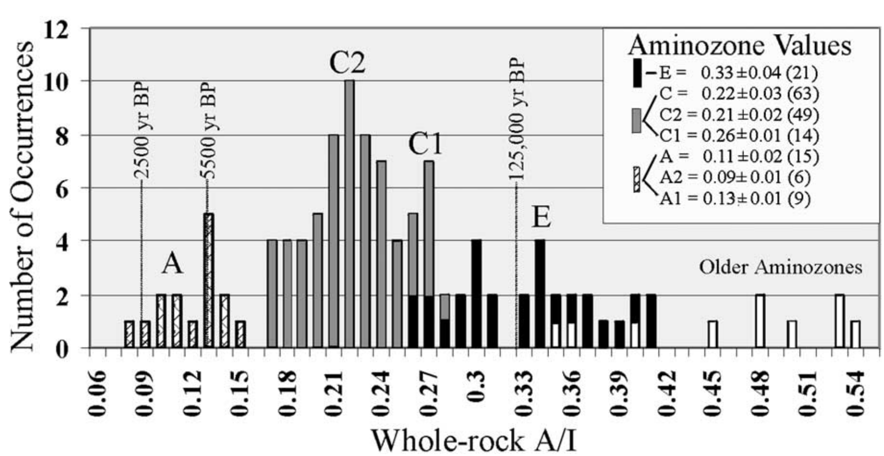

Fig. 5. A histogram of whole-rock A/I ratios determined in this study. Major modal classes are centered at 0.33 (black), 0.23 (gray), and 0.12 (cross hatched) representing Aminozones E, C, and A, while submodes are noted in Aminozone C. The distribution of A/I ratios indicate an increasing rate of eolian sedimentation on Rottnest Island between Aminozones E and C (MIS 5e to 5c/5a). Ratios representing older aminozones (white) extend from 0.36 to 0.54 on the right of the graph.

1995) provide a calibration of 0.33 ± 0.04 with a 125,000 yr age.

Minim Cove yields a mean of 0.30 ± 0.04 (n = 7), slightly below that of MIS 5e deposits at Fairbridge Bluff. Hewgill et al. (1983) affirmed a correlation between the two sites. Beach and dune deposits at Guilderton (50 km north of Perth) yield similar MIS 5e values of 0.30 ± 0.04 (4). Point Peron (Fairbridge, 1950), which lies at the southern extension of the morphological trajectory from Rottnest to Carnac and Garden Islands (Fig. 1), produced an Aminozone E average of 0.33 ± 0.01 (2). It is not certain whether a small apparent difference in values between mainland sites and Rottnest and Point Peron reflects localized warmer thermal histories under the influence of the Leeuwin Current (Playford, 1997; James et al., 1999), normal variation in ratios, or perhaps a somewhat younger MIS 5e age of the mainland sites.

Unit V—Aminozone C

With only minor overlap of Aminozone E (Fig. 5), Unit V eolianites yield ratios between 0.28 and 0.17, comprising Aminozone C. Submodes C2 and C1 equate with means of 0.21 ± 0.02 (49) and 0.26 ± 0.01 (14), respectively (Fig. 5). The C2 submode composes nearly 50% of samples and sites on Rottnest Island, pointing to its importance in the island-building process.

Unit VI—Aminozone A

The whole-rock mean of Aminozone A is 0.11 ± 0.02 (15), with A2 and A1 submodes of 0.09 ± 0.01(6) and 0.13 ± 0.01(9), respectively. These submodes correspond with deposits at Herschell Quarry yielding ages between 2000 and 6000 ^{14}C yr B.P. (Playford, 1988). Similar ratios were determined from mid to late Holocene dunes at Fairbridge Bluff (0.13), Rottnest Bore (0.13), and Army Jetty (0.12). The youngest Rottnest whole-rock ratios (~0.09) are appropriate to a mix of bioclastic grains formed somewhat before 2000 ^{14}C yr B.P. and do not indicate the significant effects of mixing of grains from older deposits.

Ages of units and kinetics of the whole-rock epimerization reaction

A composite stratigraphic section in Fig. 6 illustrates the stages of buildup of Rottnest through the late Quaternary. U-series ages confirm that the major shoaling of Rottnest began during, or *just after* 125,000 yr ago. Headlands of Unit IV (and Aminozone E) are capped by a terra rossa palaeosol (Fig. 6), providing nucleation points for subsequent deposition. A major dune buildup of Rottnest continued, reaching a peak at the end of Aminozone C (Fig. 5). After an extended hiatus, sediment formation resumed during Aminozone A (MIS 1), between 2000 and 6000 ^{14}C yr B.P. (Playford, 1988).

Given independent calibration of Aminozone E and A at 125,000 and 2000–6000 yr B.P., a most conservative (linear) interpolation would place the age of Aminozone C ratios at >50,000 yr. A model of apparent parabolic kinetics (APK of Mitterer and Kriausakul, 1989), keyed to an MIS 5e calibration, provides a nominal age estimate of Aminozone C between approximately 50,000 and 80,000 yr. However, the APK model is based on a linear temperature history, and thus cannot account for the apparent dramatic lowering of SSTs in the region during glacial conditions of MIS 4-2. Based on transfer functions on foraminifera, Wells and Wells (1994) interpreted summer SST anomalies in Western Australia during MIS 2–4 of 6° to 10°C colder than MIS 1 and 5. This cooling apparently corresponds with the shutdown of the Leeuwin Current during glacial times. Given these considerably cooler conditions on the shelf over most of the last 70,000 yr, APK would significantly underestimate the age Rottnest's Aminozone C.

When A/I is plotted against apparent age (Fig. 7), a distinctly nonlinear pattern emerges. Four kinetic phases are identified: (*Phase I*) a very rapid A/I evolution over the last 6000 yr, reflecting the combined effects of Holocene warmth and rapid initial epimerization (Hearty and Dai Pra, 1992); (*Phase II*) an apparent interval of relatively slow epimerization between 10,000 and 70,000 yr ago; (*Phase III*) an interval of increasingly rapid epimerization between 70,000 and 130,000 yr ago, reflecting the warmth of MIS 5; and (*Phase IV*) a final interval of slowly decreasing rate from 0.40 onward. The dramatic shifts in ocean conditions interpreted by Wells and Wells (1994) would explain the greatly slowed rate during Phase II, as well as the relatively rapid rates during Phase I and III.

Aminozone values from Bermuda reveal a nearly identical epimerization history compared to Rottnest Island (Fig. 7). Mean whole-rock ratios are statistically identical between the two sites. These localities also share the same latitude (32°) north and south of the Equator, and have similarly endured the "switching" on and off of their respective warm currents. Bermuda's Aminozone C, with a mean A/I ratio of around 0.23, corresponds with a considerable number of TIMS U/Th ages averaging ~83,000 yr (Ludwig et al., 1996; Muhs et al., 2002). Aminozone E, with a mean of 0.33 ± 0.04 (25), is calibrated to ages of ~125,000 yr (Harmon et al., 1983; Muhs et al., 2002). Direct comparison of the Rottnest A/I results with a Bermuda kinetic model (Hearty et al., 1992; Hearty, 2002) supports the correlation of Unit V and Aminozone C with MIS 5c/5a at ~100,000 to 70,000 yr ago.

The timing of eolianite deposition on Rottnest Island relative to late Quaternary sea-level changes

Interpretation of the results of this survey of eolianites of Rottnest finds that three major and several minor intervals of carbonate sedimentation occurred during MIS 5 high-

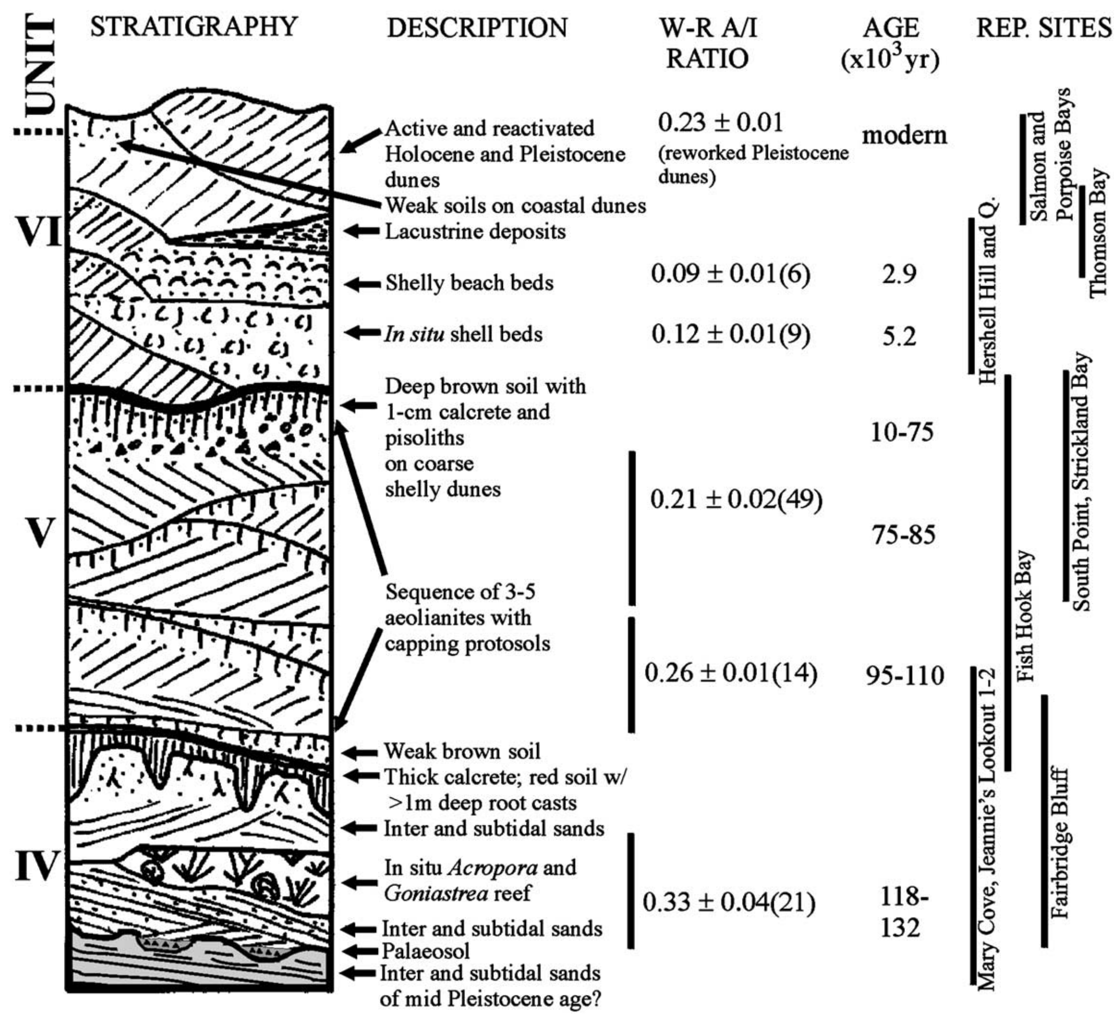

Fig. 6. A composite stratigraphic section of Rottnest Island showing the three major stratigraphic intervals of deposition: Unit IV, during MIS 5e with subtidal, intertidal, and supratidal facies represented; Unit V, a succession of two to five eolianites separated by protosols deposited during the period including MIS 5c to MIS 5a. Unit VI, subtidal and intertidal marine deposits, dunes, and eolianite of MIS 1. Localities on Rottnest Island that are representative of this stratigraphic scheme (REP.SITES) are indicated on the right of the figure.

stands (Units IV and V), and the latter half of MIS 1 (Unit VI). Support for the timing and sequence of these events is provided by stratigraphy, radiometric dates, and whole-rock A/I ratios during the growth of the MIS 5e reef. Extensions of the morphostratigraphy of Rottnest are expressed regionally as submerged ridges and emergent islands on the shallow shelf. The older Unit IV headlands on Rottnest extend in a low ridge east and southward to Carnac Island, Garden Island, and Point Peron. At some point, after an early episode of reef building while sea level was positioned at circa 3 m at Fairbridge Bluff (Stirling et al., 1995), the coastal/eolian depocenter shifted far landward to Minim Cove during a maximum transgressive (?) MIS 5e highstand of over +7 m (Fairbridge, 1953). This was followed by a subsequent and final regressive (?) seaward shift to Cottesloe Beach to ≤1 m, probably toward the end of MIS 5e.

The majority of Rottnest was built up during Aminozone C (Unit V) when presumably sea level was near the present datum. Indeed, a broad coastal ridge extends from the western tip of Rottnest several tens of kilometers south along "Five Fathom Bank" (Fig. 1). The presence of these ridges and their continuity with Rottnest strongly supports their formation during highstand events. In Bermuda, sea levels during MIS 5a and 5c were estimated at circa +0.5 and −10 m, respectively (Vacher and Hearty, 1989; Hearty, 2002).

After an extended period of soil formation, Holocene sea level transgressed to <+1 m upon a topography created during Units IV and V, flooding interior basins and interdune swales. Numerous embayments were formed in the eastern half of the island. Late in the Holocene, shelf sediments were remobilized into dunes at Thompson Bay, severing Rottnest's eastern embayments from open marine waters, creating the present-day salt lakes. The closure of the embayment probably occurred on a falling sea level, necessarily some time after the deposition of the youngest marine shells (2200 ^{14}C yr B.P.; Playford, 1988) in Herschell Quarry.

Thus, this study endorses the model of Bretz (1960) and

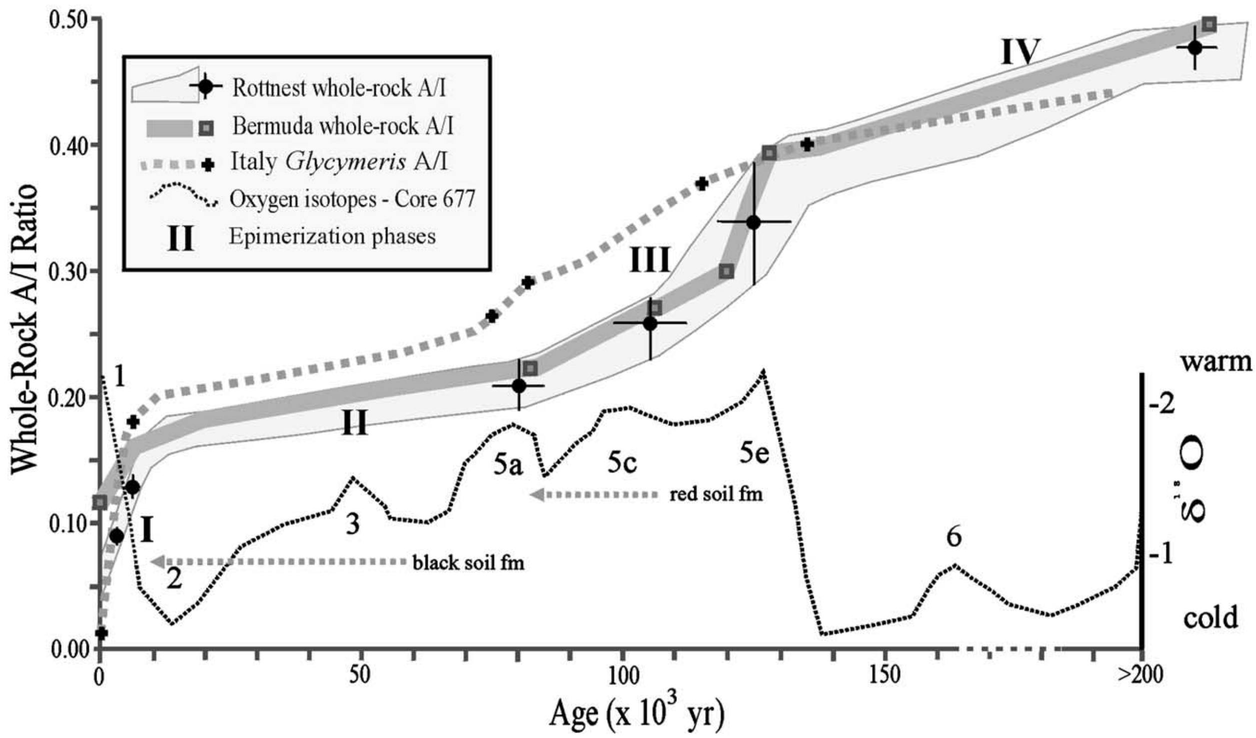

Fig. 7. A comparison of whole-rock A/I kinetic pathways from Rottnest Island and Bermuda. The *Glycymeris* (marine shell) A/I pathway from South Italy (Hearty and Dai Pra, 1992) shows similar kinetic trends. Four kinetic intervals can be distinguished from the Rottnest whole-rock A/I data: (*Phase I*) an initial interval of rapid epimerization rate; (*Phase II*) an interval of greatly reduced rates; (*Phase III*) an interval rapid epimerization in response to the climatic warmth during the last interglaciation; and (*Phase IV*) an extended interval of progressively slowing rates beyond A/I of 0.40. Insufficient data from the Perth area does not allow precise definition of the trends beyond 0.50 in Phase IV. See text for further explanation of changing epimerization rates.

Land et al. (1967) who postulated that Bermuda eolianites were not migratory across an exposed shelf, but the landward facies of interglacial sandy shorelines. Numerous observations in tropical and subtropical settings by Brooke (2001) provide further critical support for a Bretz (1960) model of carbonate eolianite deposition during and shortly after interglacial highstands.

Whole-rock A/I ratios reflect stratigraphic order, internal, and incremental consistency in all test cases, and show no concordance ($r^2 = 0.23$) when plotted against TL ages (Price et al., 2001) from many of the same deposits. Thus, the results of this study do not support the findings of Price et al. (2001) or significant eolian deposition during glacial lowstands (MIS 4-2) (Playford 1988, 1997).

There are other fundamental reasons that the glacial timing of Rottnest eoliantes is unlikely:

(1) The ocean waters were too cool and deep for voluminous carbonate sand production to occur. Using parallel conditions today in Australian waters, a 6 to 10°C depression of the SSTs on the Rottnest shelf (Wells and Wells, 1994; McGowran et al., 1997) would greatly reduce or nearly exclude the production of organic carbonate on the narrow shelf and slope. Parallel SST conditions might exist today in western Tasmania, where carbonates comprise only a fraction of coastal sediments (personal observation).

(2) Rapid induration would prevent long distance migration of carbonate dunes. If carbonate dunes were to form along the coastline or on the shelf during glacial lowstands, it is probable that they would not migrate far (10–20 km to Rottnest from −120 m contour), as rapid surface vegetation and induration by meteoric diagenesis would occur soon after subaerial exposure. James et al.'s (1999) identified "ridge complexes" offshore of Guilderton lying parallel to, and immediately landward of, the lowstand notches, but offered no evidence of trans-shelf migration (e.g., "stranded" dunes on mid-shelf areas). For comparison, some Holocene dune cordons in Western Australia are several kilometers wide, but this broad expanse of sand is generally the result of seaward progradation (Murray-Wallace et al., 2002), rather than landward migration.

Thus the combined effects of significantly cooler ocean temperatures and the great distance dunes would be required to migrate are inadequate to account for an *increase* in sedimentation rate during Aminozone C, and the nearly complete coverage of Rottnest Island from east to west with Unit V dunes. A caveat is offered where significant carbonate dune deflation might occur under conditions of sustained ecological disturbance by fire and/or grazing animals (e.g., Hearty et al., 2000).

Conclusions

From this study, morphostratigraphic relations and relative degrees of paleosol development are the basis for a model of sea-level modulation of carbonate eolian sedimentation primarily during highstand events. Reliable ^{14}C and U-series ages establish the connection between eolianite deposition and two of three highstand events over the past 125,000 yr. Whole-rock AAR ratios, when calibrated with the independent ages, provide a means to interpolate and estimate the age of Aminozone C between 70,000 and 100,000 yr ago (MIS 5a/5c). The broad data gap between Aminozones C and A corresponds with an extensive period of soil formation under much cooler oceanographic conditions *when no dunes were formed on Rottnest*, i.e., the last glacial period (MIS 4-2).

In summary, three intervals of carbonate deposition are recognized in the geomorphology and surficial geology of Rottnest Island. Older deposits are found on the mainland several kilometers inland north and south of Perth. The major depositional intervals on Rottnest Island are separated by distinctive red and black soils, while minor breaks are accentuated by weak brown to tan soils. The extensive and thick blanket of fine to coarse carbonate sand and regional geomorphology strongly suggests the immediate proximity of the source sediments along the shoreline during sea-level highstands near the present datum (i.e., MIS 5c and 5a). Existing U/Th and ^{14}C ages, combined with whole-rock A/I data, confirm that nearly all of Rottnest Island formed by eolianite deposition during the last interglacial period (MIS 5), with minor additions during the last 6000–8000 yr (MIS 1) of the Holocene. The kinetic model generated from this study is remarkably similar to that of Bermuda, providing additional support for the interglacial timing of the deposition of Rottnest Island eolianite.

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