PERGAMON

Quaternary Science Reviews 22 (2003) 859–880

QSR

Quaternary calcarenite stratigraphy on Lord Howe Island, southwestern Pacific Ocean and the record of coastal carbonate deposition

Brendan P. Brooke[a,*,1], Colin D. Woodroffe[a], Colin V. Murray-Wallace[a], Hendrik Heijnis[b], Brian G. Jones[a]

[a] *School of Geosciences, University of Wollongong, NSW 2522, Australia*
[b] *Environment Division, Australian Nuclear Science and Technology Organisation, Menai, NSW 2234, Australia*

Abstract

Lord Howe Island is a small, mid-ocean volcanic and carbonate island in the southwestern Pacific Ocean. Skeletal carbonate eolianite and beach calcarenite on the island are divisible into two formations based on lithostratigraphy. The Searles Point Formation comprises eolianite units bounded by clay-rich paleosols. Pore-filling sparite and microsparite are the dominant cements in these eolianite units, and recrystallised grains are common. Outcrops exhibit karst features such as dolines, caves and subaerially exposed relict speleothems. The Neds Beach Formation overlies the Searles Point Formation and consists of dune and beach units bounded by weakly developed fossil soil horizons. These younger deposits are characterised by grain-contact and meniscus cements, with patchy pore-filling micrite and mirosparite. The calcarenite comprises several disparate successions that contain a record of up to 7 discrete phases of deposition. A chronology is constructed based on U/Th ages of speleothems and corals, TL ages of dune and paleosols, AMS ^{14}C and amino acid racemization (AAR) dating of land snails and AAR whole-rock dating of eolianite. These data indicate dune units and paleosols of the Searles Point Formation were emplaced during oxygen isotope stage (OIS) 7 and earlier in the Middle Pleistocene. Beach units of the Neds Beach Formation were deposited during OIS 5e while dune units were deposited during two major phases, the first coeval with or shortly after the beach units, the second later during OIS 5 (e.g. OIS 5a) when the older dune and beach units were buried.

Large-scale exposures and morphostratigraphical features indicate much of the carbonate was emplaced as transverse and climbing dunes, with the sediment source located seaward of and several metres below the present shoreline. The lateral extent and thickness of the eolianite deposits contrast markedly with the relatively small modern dunes. These features indicate that a slight fall (2–10 m) in sea level may be required to mobilise relatively large volumes of sediment onto the island. The stratigraphy of the calcarenite, combined with the shallow depth of the platform surrounding the island (30–50 m present water depth) and the geochronological data, suggest that cycles of carbonate deposition on the island are linked to interglacial and interstadial periods of high or falling sea level.

1. Introduction

Lord Howe Island is a small, remote island in the Southwest Pacific Ocean (31°30′ S, 159°04′ E; Fig. 1a). The island is of especial scientific interest because of its wide range of endemic biota, high-latitude fringing coral reef, exposures of volcanic rocks related to hot spot volcanism, and for fossils of the extinct Pleistocene horned turtle *Meiolania platyceps*. Lord Howe Island is also in a key location from a biogeographical and climatic point of view, as it is one of the few land masses between Australia and New Zealand. In view of its unique, well-preserved environment, the island was included on the World Heritage List in 1982.

Lord Howe Island sits on a volcanic pedestal that rises from the western margin of the Lord Howe Rise (Fig. 1b), a submarine plateau of continental crust attached to the Australian plate (McDougall et al., 1994). The island is composed of Late Miocene basalt that erupted as the Australian plate migrated northwards over a hotspot situated at approximately 35°S

*Corresponding author.
E-mail address: Brendan.Brooke@ga.gov.au (B.P. Brooke).
[1] Petroleum and Marine Division, Geoscience Australia, GPO Box 378, Canberra, ACT 2601, Australia

0277-3791/03/$ - see front matter
doi:10.1016/S0277-3791(02)00253-6

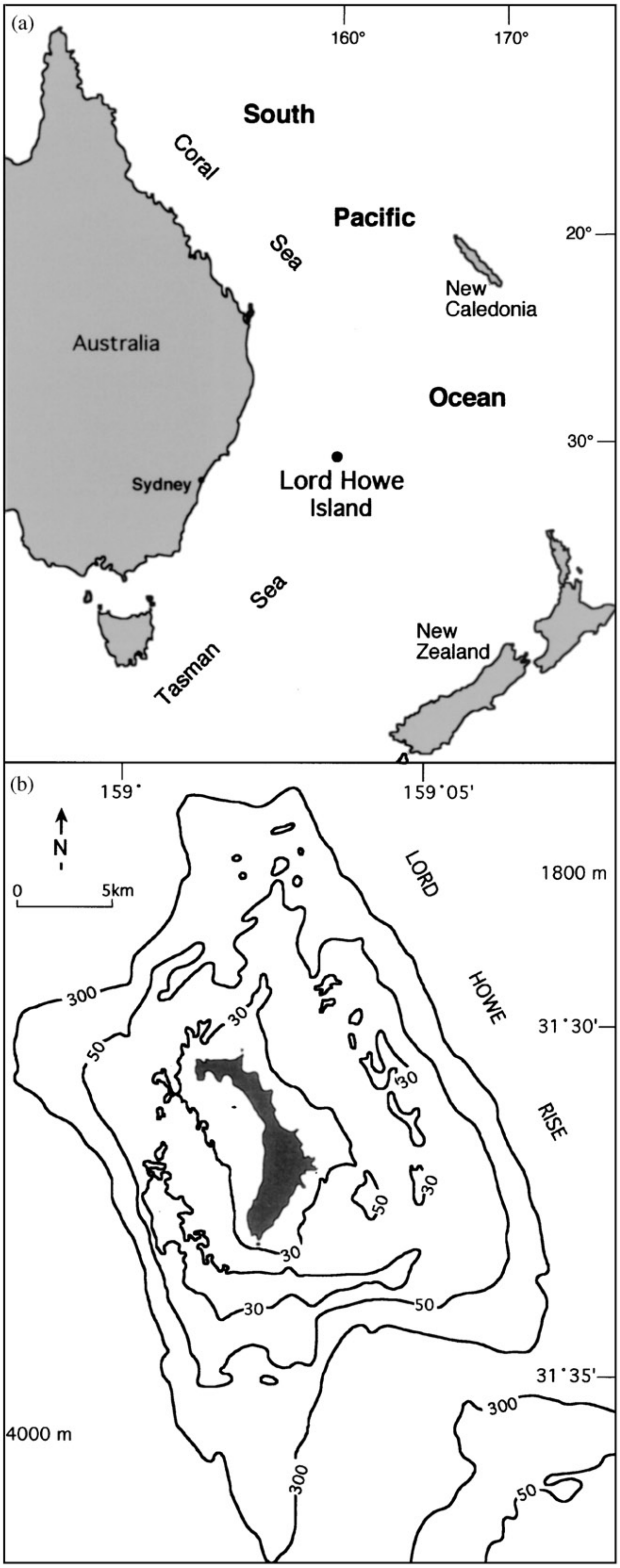

Fig. 1. The location of Lord Howe Island in the southwest Pacific Ocean. (a) The island lies approximately 700 km NE of Sydney, Australia. (b) The island is surrounded by a shallow submarine platform on the top of a volcanic pedestal that sits on the Lord Howe Rise.

(McDougall et al., 1981). On the lower sections of the subaerial remnant of the Miocene volcano, Quaternary eolianite and marine calcarenite, and unconsolidated carbonate beach deposits, form low ridges and coastal plains.

Calcarenite on Lord Howe Island is predominantly eolian in origin, comprising thick (3–25 m) cross-beds of skeletal carbonate grainstones that are extensively exposed in the coastal cliffs, especially along the northeastern coast at Neds Beach and Middle Beach (Fig. 2). Subordinate beach units are also extensively exposed at Neds Beach. The calcarenite has previously been mapped as a single lithostratigraphic formation, the Neds Beach Calcarenite (Standard, 1963; McDougall et al., 1981; NSW Department of Mineral Resources, 1987), based primarily on an eroding section at Neds Beach (Etheridge, 1889; Standard, 1963). The eolianite was considered to represent the products of eolian reworking of shelf sediments exposed during the last or earlier glacial sea-level lowstands (Squires, 1963; Standard, 1963; Sutherland and Ritchie, 1977; McDougall et al., 1981). The interpretation that all the ancient dunes had been emplaced during periods of low sea level was supported by the exposures of eolianite that extend several metres below present sea level, finite ^{14}C ages for land snails (*Placostylus bivaricosus*) from a protosol in the eolianite succession at Middle Beach (Squires, 1963) and ^{14}C ages for eolianite samples from the west coast (Kaplin, 1981).

In this paper, the results of our mapping and facies architectural analysis of the calcarenite succession are described. A new stratigraphic classification is presented that accommodates a far longer history of dune accumulation than previously reported. New lithostratigraphic formations are described that preserve a record of several cycles of dune deposition on the island, and the timing of dune formation is identified with a range of geochronological data. Our findings suggest the history of eolianite deposition on Lord Howe Island is linked to periods of relatively high sea level during the Middle and Late Pleistocene.

2. Methods

Mapping included the measurement of 48 sections exposed in coastal cliffs supplemented by sections measured in quarries and gullies and by augering. Building a stratigraphic classification for the eolianite involved lithostratigraphical, allostratigraphical and geochronological methods described below (Sections 2.1 and 2.3). Cross-bedding dip azimuth measurements were made at all suitable eolianite exposures. The distributions of the mean vector trends (Mardia, 1972; Batschelet, 1981) of foreset cross-bedding in the major dune and beach units were plotted to infer past wind

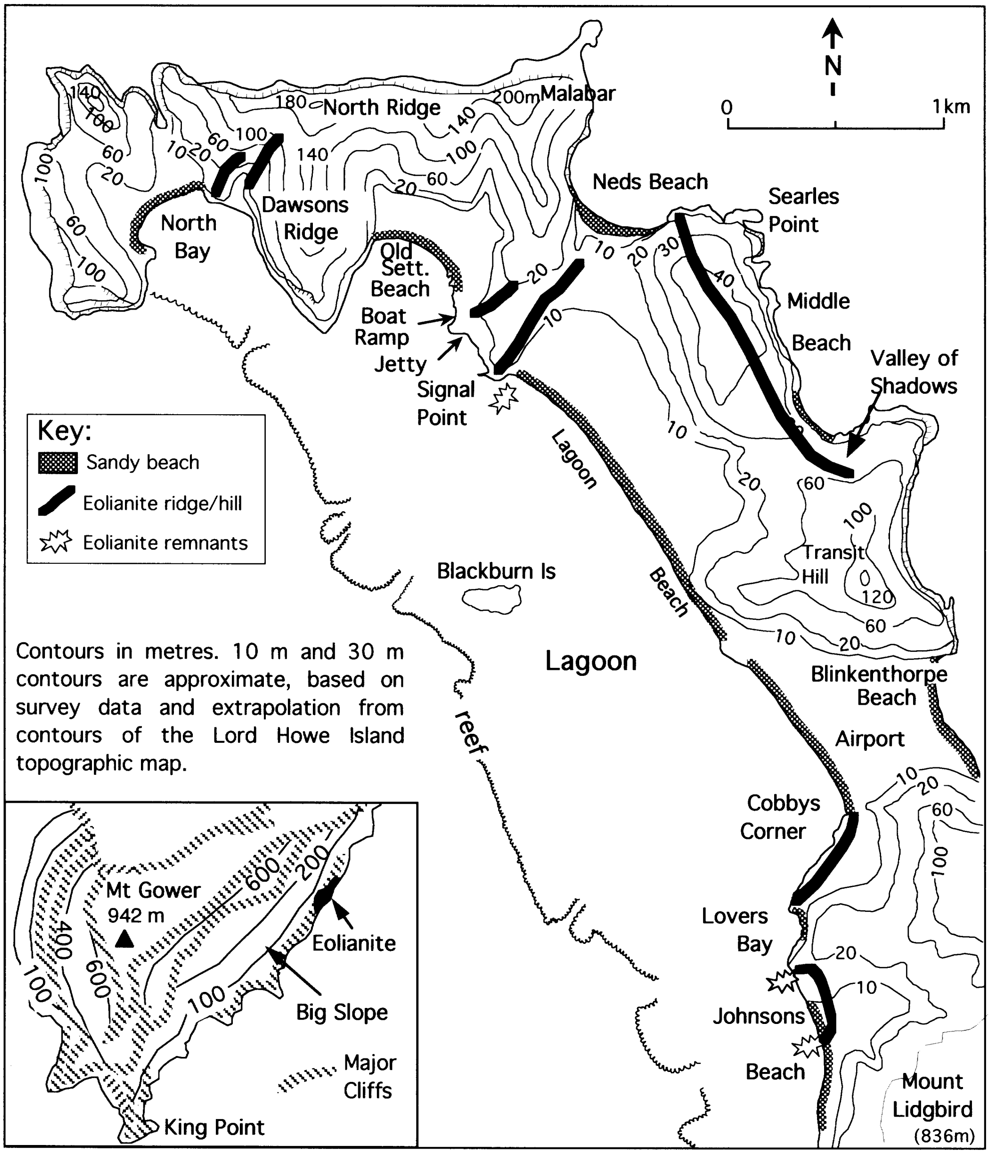

Fig. 2. The northern half of Lord Howe Island, showing the location of the main eolianite ridges and hills. The inset shows the position of eolianite at the southern end of the island, on the flank of Mt Gower (after Australian Environmental Publications, 1992).

regimes and shoreline currents. The lithological composition of selected units in several major exposures of calcarenite was assessed by point-counting thin sections of sample material (1–4 samples per unit, 400 points counted).

2.1. Lithostratigraphical classification

The nature of eolianite, comprising discontinuous units of relatively homogenous sediment that generally lack distinctive biostratigraphical markers, presents difficulties in adopting traditional lithostratigraphical procedures for examining depositional successions within these deposits.

Calcarenite on Lord Howe Island has previously been classified as one lithostratigraphical unit because of the predominance of the skeletal carbonate component (NSW Department of Mineral Resources, 1987). This classification, however, lacks the degree of resolution needed to differentiate between calcarenite units that have significantly different assemblages of allochemical constituents or degrees of diagenetic alteration that may represent discrete phases of carbonate accumulation. In order to elucidate the Quaternary stratigraphy of the island, a lithostratigraphical approach that differentiates units on the basis of more subtle characteristics, observable in the field, and integrated into a chronostratigraphical classification, was needed. Eolianite and subordinate beach units in the calcarenite exhibit different degrees of meteoric alteration. Lithostratigraphic units were discriminated, therefore, on the basis of their physical characteristics as revealed in cliffs, gullies, road cuts and quarries in the eolianite, supplemented by the examination of thin sections. Lithostratigraphic formations and members were mapped by tracing out wherever possible, the bounding paleosols, protosols and major erosional unconformities. This field-based approach follows that adopted by Vacher et al. (1995) on Bermuda, where they classified eolianite units based on relative diagenetic maturity because that method was found to be the only means of differentiating the deposit into lithostratigraphical units. However, a limitation of this approach is that once the more diagenetically mature eolianite units become heavily cemented, they may no longer be distinguished lithologically in the field (Vacher et al., 1995). These older calcarenite units, however, can be mapped using allostratigraphical methods.

2.2. Allostratigraphy and morphostratigraphical features

Allostratigraphical classification is especially useful in studies of Quaternary stratigraphy where successions of compositionally similar sediment are in fact the products of different processes or demonstrably different age (North American Commission on Stratigraphic Nomenclature, 1983; Walker, 1992). On Lord Howe Island, distinct differences in the types of bounding discontinuities are evident for calcarenite units, ranging from clay-rich *terra rossa* paleosols, to weakly developed sandy fossil soil horizons termed protosols. Paleosols represent prolonged subaerial exposure potentially in the order of tens of thousands of years, while protosols are bounding surfaces that may have been vegetated but do not exhibit features typical of a mature soil profile (Vacher et al., 1995). Protosols may exhibit a range of forms and allostratigraphic units can be bound by protosols with discernible pedogenic alteration that reflects a more stratigraphically significant or regional hiatus. Although relatively major discontinuities may be discerned within eolianite exposures, lateral and complex stratigraphical relationships typify these successions (e.g. Garrett and Gould, 1984; Carew and Mylroie, 1991; Hearty and Kindler, 1993; Vacher et al., 1995).

The depositional forms of ancient coastal carbonate dunes are often preserved due to relatively rapid cementation and the formation of a protective calcrete or clay-rich soil cap (e.g. Yaalon, 1967; McKee and Ward, 1983; Brooke, 2001; Murray-Wallace et al., 2001). Such morphostratigraphical features on Lord Howe Island were identified in the field, from aerial photographs and from topographic maps (discussed in Section 3.1). Stratigraphical architectural features that also provide insights into the mode of sediment emplacement were identified in large-scale coastal exposures produced by marine and stream erosion of the calcarenite.

2.3. Geochronology

More than 100 samples of calcarenite were collected from the main representative exposures to derive a geochronological framework. The uranium-series (U/Th, α-spectrometry) method was applied to corals from exposures and drill core, and short cores of remnant calcitic cave flowstones. AMS ^{14}C and amino acid racemization (AAR) dating methods were used on well-preserved aragonitic shells of the terrestrial snail *Placostylus bivaricosus* recovered from paleosols and protosols, and whole-rock samples of the dune and beach units were also dated by AAR (Brooke et al., 2003). Thermoluminescence (TL) dating was undertaken on the trace of quartz found after dissolution of bulk samples of eolianite and paleosol (Price et al., 2001).

3. Results and discussion

Morphostratigraphic features of the calcarenite, type sites for the lithostratigraphic formations and members, and other significant exposures are described below. An island-wide allostratigraphic classification is also proposed that incorporates the geochronological data and the results of the field mapping. The TL analytical results and ages are discussed in Price et al. (2001), and details of the AMS ^{14}C and AAR dating program are examined in Brooke et al. (2003). U/Th ages for remnant speleothems are presented in Table 1, and a summary of the previously reported geochronological data is provided in Table 2.

3.1. Morphostratigraphical features

Mapping indicates that approximately 80% of the calcarenite on Lord Howe Island is eolianite, which forms low ridges and hills (mostly <45 m, Fig. 2). These deposits are cliffed along their seaward margins, both on the open east coast and lagoonal shoreline, which indicates they are remnants of larger deposits and, therefore, a legacy of erosion by the post-glacial marine transgression and slope processes.

3.1.1. East coast

A prominent eolianite ridge extends from Neds Beach to Valley of The Shadows (Fig. 2). This shore-parallel ridge has a steep western flank and formerly had a gently sloping eastern flank, as indicated by shore-normal exposures at Middle Beach, (e.g. site 1, Figs 3, 7a). These features are typical of the leeward and windward slopes of a dune. The ridge, therefore, appears to represent a source-bordering dune, with the former shoreline located seaward of the present coast. The internal structure of the ridge is also displayed in exposures at Neds Beach and the quarries on Middle

Table 1
U and Th isotope data and $^{230}Th/^{234}U$ ages of remnant flowstones at the Lagoon Boat Ramp, Neds Beach, Searles Point and North Bay

ANSTO lab.number	Location and sample depth from top of flowstone	Uranium (ppm)	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	$^{234}U/^{238}U$	$^{230}Th/^{234}U$ age (ka)
Lagoon Boat Ramp						
	Site 4 (shown in Fig. 3)					
5596L1	13 mm	0.100	48.593 ±23.166	0.847 ±0.058	1.134 ±0.064	190^{+30}_{-20}
5595L2	20 mm	0.113	33.173 ±9.937	0.849 ±0.061	1.136 ±0.087	190^{+30}_{-25}
5595L1	28 mm (base)	0.101	50.776 ±26.884	0.946 ±0.077	1.076 ±0.073	285^{+120}_{-65}
Neds Beach/Searles Point						
	Site 6					
6085L1	Core 1, 40 mm	0.416	52.470 ±9.165	0.941 ±0.044	1.034 ±0.054	290^{+60}_{-40}
	Site 8					
5594L1	W end of point 40 mm	0.806	251.191 ±112.654	0.934 ±0.045	1.105 ±0.049	260^{+45}_{-30}
	Site 9 (flowstone 1)					
6106L1	23 mm	0.187	31.293 ±6.480	0.973 ±0.054	1.099 ±0.061	320^{+90}_{-60}
5592L1	95 mm	0.269	79.734 ±27.068	0.895 ±0.043	1.067 ±0.047	230^{+35}_{-25}
5593L1	100 mm	0.229	99.084 ±38.540	0.998 ±0.053	1.051 ±0.057	> 350
6107L1	110 mm	0.166	87.280 ±37.242	0.969 ±0.063	1.080 ±0.079	320^{+110}_{-60}
	Site 9 (flowstone 2)					
7474L1	23 mm	0.345	126.633 ±82.624	0.851 ±0.050	1.011 ±0.051	205^{+30}_{-25}
7473L1	90 mm	0.380	168.542 ±111.321	0.915 ±0.051	1.109 ±0.055	240^{+45}_{-30}
North Bay						
	Site 4					
5597L1	90 mm	0.212	70.729 ±28.028	0.733 ±0.042	1.074 ±0.064	145±15
5597L2	90 mm	0.221	36.367 ±9.859	0.471 ±0.034	1.102 ±0.093	70±5
5598L1	50 mm	0.242	37.910 ±10.649	0.501 ±0.029	1.070 ±0.061	75±5
5599L1	340 mm (8 mm slice)	0.325	80.654 ±31.024	0.517 ±0.028	1.120 ±0.066	80±5
5599L2	340 mm	0.285	35.601 ±8.169	0.586 ±0.032	1.150 ±0.060	95^{+5}_{-10}
6108L1	175 mm	0.314	71.186 ±26.778	0.507 ±0.030	1.052 ±0.061	75±5

Laboratory methods follow standard procedures used at the Environmental Radiochemistry Laboratories at the Australian Nuclear Science and Technology Organisation (ANSTO), which are very similar to those described in Lally, 1992; and Ivanovich and Murray, 1992. The calculated ages appear reliable because the $^{230}Th/^{232}Th$ ratios are > 20, and U concentrations and $^{234}U/^{238}U$ ratios of multiple samples from single flowstones do not exhibit a positive correlation, consistent with a closed system.

Beach and Anderson Roads (Section 3.2). Farther south at Blinkenthorpe Beach and Big Slope, eolianite was emplaced as climbing dunes on steep basalt and talluvial slopes, the dunes fed from a source offshore from the present coast (Figs 2, 9b, c).

3.1.2. West coast

Eolianite on the northwestern flank of Dawsons Ridge, at North Bay, sits up to 75 m above mean sea level (MSL; Fig. 2). Erosional scarps reveal these dunes infilled a former valley and then climbed northwards up the steep basalt slope. Dolines, caves and caverns in this eolianite indicate the deposit has undergone significant solutional weathering and subsequent erosion.

At Signal Point there is also a low (4–12 m) eolianite ridge, remnants of which extend 150 m seaward of the present coast (Fig. 2). These remnants show that the

Table 2
A summary of ^{14}C, U/Th, TL and AAR dating results for samples from the various lithostratigraphic units. The most likely oxygen isotope stages (OIS) during which the various deposits were emplaced are also indicated.

Location (Fig. 5 reference)	Facies	Allo-stratigraphy	Sample material	Mean D/L ratios[a]		Age (ka)	δ^{18}O stage
				Leucine	aIle/Ile (n)		
Modern Deposits							
Signal Point (Fig. 5c)	Soil	modern	*Placostylus*	0.03±0.01	0.02±0.01 (2)		
Old Settlement Beach	Soil	pre settlement	*Placostylus*	0.03±0.00	0.03±0.01 (3)	0.34±0.07 ^{14}C	
Johnsons Beach (5d)	Soil	modern	*Placostylus*	0.04	0.03 (1)	modern(>1950)^{14}C	1
Lagoon Beach	Beach	modern	skeletal grains	0.07±0.03	0.08±0.01 (2)		
Neds Beach Formation							
Neds Beach (5a, *3b*)	Beach	N1	whole rock	0.48±0.01	0.59±0.02 (3)		5e
			coral			120^{+10}_{-5} U/Th	
			quartz			116±18 TL	
						138±21 TL	
Neds Beach (5a, *3c*)	Dune	N1	whole rock	0.35	0.40 (1)	86±33 TL	5c–5a
Neds Beach (5a, 3, *p2*)	Protosol	N1	*Placostylus*	0.44±0.03	0.36±0.04 (3)	>42 ^{14}C	5c–5a
Middle Beach (5b, *2d*)	Dune	N1	whole rock	0.38	0.47 (1)		5e–5c
Middle Beach (5b, *2e*)	Dune	N1	whole rock	0.33	0.42 (1)		5e–5c
Middle Beach (5b, *2d* & *5b*)	Dune	N1	whole rock	0.42±0.05	0.49±0.03 (2)	94±52 TL	5e–5c
Middle Beach (5b, *17a*)	Dune	N1	whole rock	0.39	0.45 (1)	98±16 TL	5e–5c
Middle Beach (5b, site 17)	Protosol	N1	*Placostylus*	0.45±0.03	0.38±0.02 (5)	35±0.08 ^{14}C	5c–5a
Big Slope	Dune	N1	whole rock	0.41±0.02	0.50±0.02 (2)	323±35 TL	5e–5c
North Bay	Beach?	N1	whole rock	0.47±0.02	0.56±0.06 (2)		5e
Boat ramp (5c, *5c*)	Beach	N1	whole rock	0.51±0.01	0.58±0.01 (2)		5e
Jetty, Core 11	Reef	N1	coral			120^{+9}_{-8} U/Th	5e
Core 12	Dune?	N1	whole rock	0.40±0.02	0.53±0.04 (3)		5e–5c
Lovers Bay (5d, *5a*)	Beach	N1	whole rock	0.50±0.02	0.57±0.01 (2)		5e
Signal Pt (5c, *p2*)	Protosol	N1	*Placostylus*	0.45±0.06	0.35±0.01 (2)	40.8±1.7 ^{14}C	5c–5a
Signal Pt (5c, *1b*)	Dune	N1	whole rock	0.37	0.48 (1)	151±18 TL	5e–5c
Signal Pt (5c, *1c*)	Dune	N2	whole rock	0.34±0.01	0.44±0.01 (2)		5c–5a
Johnsons Beach (5d, *2a*)	Dune	N1	whole rock	0.36	0.45 (1)		5c–5a
Johnsons Beach (5d, *p2*)	Protosol	N1	*Placostylus*	0.43±0.04	0.35±0.03 (7)	>42 ^{14}C	5c–5a
						39.7±2.4 ^{14}C	
Johnsons Beach (5d, *p1*)	Protosol	N1	*Placostylus*	0.44±0.01	0.38±0.01 (4)		5e–5c
Quarry Middle Beach Rd (5d)	Protosol	N1	*Placostylu*	0.40±0.01	0.33±0.01 (2)		5c–5a
	Dune	N1	whole rock	0.36	0.44 (1)		5c–5a
Ocean View Lodge	Dune	N1	whole rock	0.53	0.57 (1)		5e–5c
Middle Beach Member							
Middle Beach (5b, *2h*)	Dune	N2	whole rock	0.29	0.37 (1)		5c–5a
Middle Beach (5b, *17b*)	Dune	N2	whole rock	0.30±0.02	0.36±0.03 (3)		5c–5a
Quarry Middle Beach Rd (5d)	Dune	N2	whole rock	0.33	0.40 (1)	91±21 TL	5c–5a
Cobbys Corner Member							
Cobbys Corner (5d, *1b*)	Dune	N1	whole rock	0.45±0.02	0.52±0.01 (2)		5e–5c
Searles Point Formation							
Neds Beach (5a, site 5, *p3*)	Paleosol	S6	*Placostylus*	0.64±0.06	0.73±0.06 (4)		7
Neds Beach (5a, *3a*)	Dune	S6	quartz			222±28 TL	7
Neds Beach (5a, site 5, *p2*)	Paleosol	S4	quartz			274±56 TL	7–9
Middle Beach (5b, *1a*)	Dune	S1	whole rock	0.49[b]	0.67[b]		>7
Middle Beach (5b, site 5 *p1*)	Paleosol	S4	*Placostylus*	0.76±0.02	0.93±0.01 (2)		7–9
			quartz			201±19 TL	
North Bay, site 2	Dune	S7 - S4?	whole rock	0.58	0.81 (1)		⩾7
North Bay, site 4	Dune	S7 - S4?	whole rock	0.62±0.00	0.85±0.00 (3)	92±11 TL	⩾7

N1, N2: Alloformations within Neds Beach Fm. S1 - S7: Alloformations within Searles Point Fm.
[a] aIle/Ile: D-alloIsoleucine/L-Isoleucine, n = number of individual samples analysed.
[b] Minimum value, AAR data indicate some loss of amino acids from the sample (Brooke et al., 2003).

deposit has been significantly eroded and the former dunes were deposited when sea level was at least 2 m lower than present. There are similar remnant outcrops in the southern end of the Lagoon, adjacent to Johnsons Beach. The orientation of bedding revealed in the eolianite shore platform at Johnsons Beach indicates this deposit originally formed a transverse or oblique dune ridge (Fig. 2).

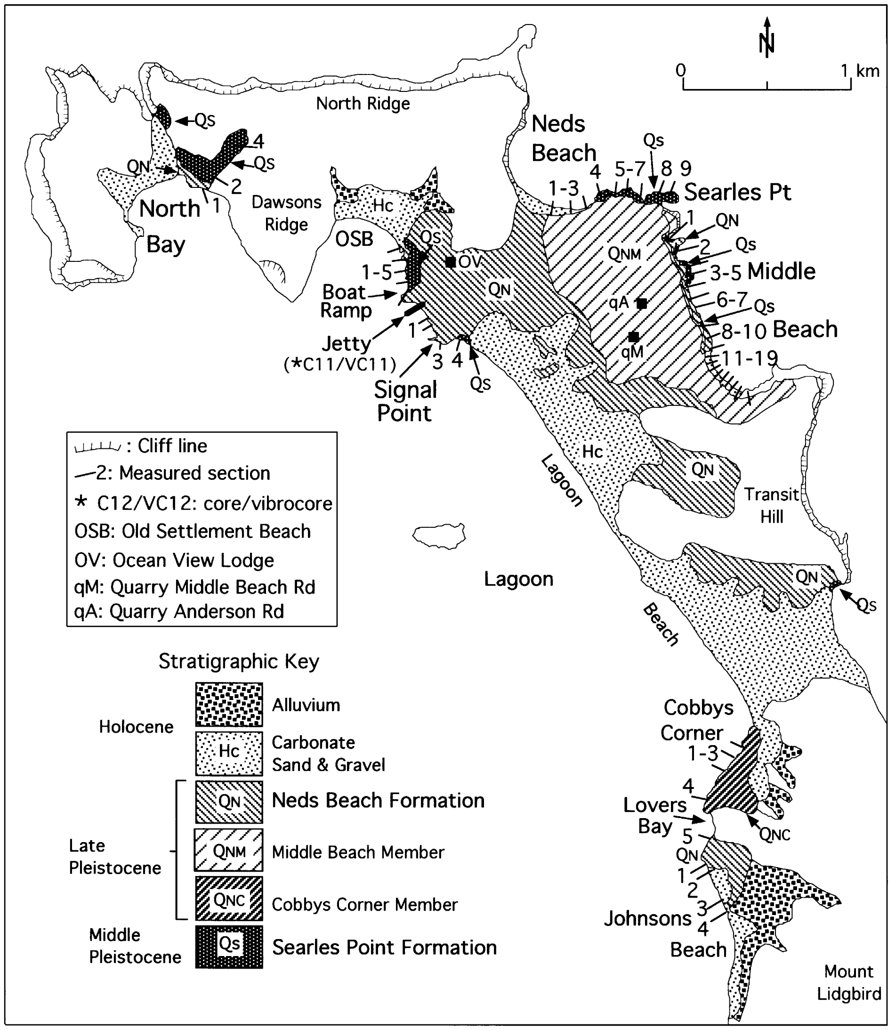

Fig. 3. A lithostratigraphic map of calcarenite on Lord Howe Island. The locations of the measured sections (Fig. 5) are indicated. Areas without a pattern are basalt.

3.2. Lithostratigraphy

All the calcarenite units comprise skeletal carbonate of subtropical and temperate fauna, with varying proportions of red algal, molluscan, foraminiferal, bryozoan and volcanic grains and only traces of coral (Table 3). In general, samples from the modern beaches were found to exhibit a similar suite of skeletal fragments. Outcrops between Neds Beach and Middle Beach are the most extensive eolianite exposures on the island, both in terms of the thickness of sections and their lateral extent.

In this work, two formations are recognised in the calcarenite, the Searles Point Formation and the overlying Neds Beach Formation (Fig. 3, Table 4). The Searles Point Formation comprises eolianite units bounded by clay-rich paleosols and protosols. These deposits are predominantly cemented by pore-filling sparite and microsparite, and recrystallised grains and grain dissolution features are common. Outcrops also exhibit karst features such dolines, caves and subaerially exposed relict speleothems that record former cave environments in the eolianite. Dune units of the Neds Beach Formation are generally much thicker than the older deposits and include rhizoliths and solution tubes but lack mature pedogenic features (paleosols, clay-pot structures) and subaerially exposed relict speleothems that are common in the older succession. They are also characterized by grain-contact and mensicus cements and relatively high primary porosity (Tables 3, 4).

3.2.1. Searles Point Formation

Major exposures of the Searles Point Formation occur in the low-lying central section of the island between Neds Beach and Searles Point, at Old Settlement Beach, and on the flank of a basalt ridge at North Bay. These grainstones typically range in color from yellow (10YR 7/6, Munsell color; Munsell, 1990) to very pale brown (10YR 7/4). They are classified as the Searles Point Formation because of the good exposure of

Table 3
The granular composition of calcarenite samples from the various lithostratigraphic units, measured in thin sections

Location (*n*)	Skeletal	Foram	Composition %				
			Peloidal	Volcanic	Cement	Matrix	Pore Space
Searles Point Formation							
North Bay (2)	45	1	12	7	23	6	7
Boat ramp (2)	42	1	13	3	38	3	1
Neds Beach (3)	43	1	13	3	29	2	10
Middle Beach (2)	41	1	16	2	31	5	5
Neds Beach Formation							
Neds Beach (3)	38	3	21	2	6	1	30
Middle Beach (4)	41	3	17	3	14	1	22
North Bay (1)	49	1	17	1	22	3	8
Signal Point (2)	42	3	13	4	9	1	28
Lovers Bay (1)	37	1	18	7	8	<1	30
Johnsons Beach (2)	33	2	19	3	7	<1	36
Middle Beach Member							
Middle/Neds Beach (3)	32	13	13	<1	7	<1	35
Cobbys Corner Member							
Cobbys Corner (2)	31	2	11	21	11	1	23

n: Number of samples for point-counting, 400 points per slide counted.
Skeletal: coral, mollusc, bryozoan, recrystallised/unknown; Peloidal: micritic and faecal; Foram.: Foraminiefera, including fusulinid, rotalid and miliolid forms.

mappable outcrop on Searles Point (Fig. 3). The base of the formation overlies basalt or basaltic paleosols, while the top is highly karstified, capped by paleosols or overlain by little-altered deposits of the younger formation. Exposures between Neds Beach and Searles Point, and at the northern end of Middle Beach (Fig. 3), verify the superposition of the Neds Beach Formation over the Searles Point Formation.

Neds Beach. The Last Interglacial beach unit exposed in the base of the calcarenite cliff at Neds Beach (Woodroffe et al., 1995) has been regarded as representing the basal calcarenite unit on Lord Howe Island (Squires, 1963; Standard, 1963; described in 3.2.2). Shoreline exposures east of these beach beds, however, reveal that the basal calcarenite units at Neds Beach are eolianites of the Searles Point Formation, with reference sections at sites 3 and 5 (Fig. 3). In the base of the cliff at site 3, the beach beds onlap light yellowish brown to pale brown, well indurated dune strata of the Searles Point Formation (Figs 4b, 5a). At the eastern end of Neds Beach (site 4) the older eolianite unit is 3.5 m thick, capped by a paleosol and contains relict solution pipes (Fig. 4c). This dune was probably deposited in oxygen isotope stage (OIS) 7 based on TL ages of 222 ± 28 ka (W2166) for the dune unit and 274 ± 56 ka (W2071) for the underlying paleosols, and relatively high D/L ratios of *Placostylus* shells from the paleosols capping the dune unit (e.g. D/L leucine: 0.64 ± 0.06, Table 2). These geochronological data indicate the mature pedogenic features presumably developed during a prolonged period of subaerial exposure prior to the Last Interglacial and deposition of the Neds Beach Formation.

Dune units of the Searles Point Formation, bounded by paleosols or well-developed protosols, can be traced along the shoreline from Neds Beach to Searles Point (sites 4–9, Fig. 4d, 5a), forming a vertical and lateral eolianite succession. Stacked dune units and paleosols are particularly well displayed in the undercut cliff at site 5.

Light brown and white laminated calcitic flowstone on the eolianite bench at site 6 has a U/Th age of 290^{+60}_{-40} ka (Table 1). Flowstones at site 7 and between sites 7 and 8 (Figs 3, 5a) suggest there has been preferential marine erosion of a cavernous section of eolianite. A U/Th age for one these flowstones, 260^{+45}_{-30} ka (Table 1), likewise indicates a Middle Pleistocene age for the underlying eolianite.

Searles Point (sites 8 and 9) is an eolianite promontory of well-indurated and etched yellow grainstone and paleosols (Fig. 4e, 5a). The eolianite has numerous solutional depressions, likely developed in former cave environments, three of which contain white to pale brown laminated flowstones, up to 150 mm thick. U/Th ages for two of these flowstones range from 205^{+30}_{-25} ka to >350 ka (Table 1), again indicating the original dune carbonate was deposited in the Middle Pleistocene.

Middle Beach. A succession of eolianite units and paleosols of the Searles Point Formation is exposed in the lower 3–5 m of the bluff at the northern end of Middle Beach (sites 1–5; Figs 5b, 6b). Reference sections

Table 4
A summary of the stratigraphical, lithological and geochronological characteristics of the lithostratigraphic units comprising calcarenite on Lord Howe Island

Lithostratigraphical unit		Distinctive lithological features	Stratigraphical setting	Max. thickness	Type section	Age (OIS stage)
	Middle Beach Member	White (10YR 8/1), miliolid-rich, meniscus & grain-contact micrite.	Top dune unit at Neds Beach, Middle Beach & Quarries.	23 m at Middle Beach	S end of Middle Beach, site 17.	5a?
Neds Beach Calcarenite Formation		Very pale brown (dune units, 10YR 7/4) to brownish yellow (beach units, 10YR 6/6); meniscus, grain-contact & patchy pore-filling cements; fossiliferous beach units; protosols.	Dune & beach units overlie the Searles Point Formation at Neds Beach, Middle Beach & Lagoon Boat Ramp, but overlies basalt at Lovers Bay.	35 m at Middle Beach	Neds Beach, sites 2-3; Middle Beach, sites 2-5; additional reference sections, Middle B., sites 14-17.	5e – 5c
	Cobbys Corner Member	Brownish yellow (10YR 6/3) to yellowish brown (10YR 5/3), volcanic-rich; clay-rich grain-contact & patchy pore-filling cement.	Dune units between Cobbys Corner & Lovers Bay.	11 m at Cobbys Corner	Cobbys Corner, site 2.	5e – 5c
Searles Point Calcarenite Formation		Yellow (10YR 7/6) to pale-brown (10YR 6/3), well-lithified exposures; pore-filling sparite, recrystallised & dissolved grains; karstified, subaerially exposed relict speleothems; clay-rich palaeosols.	Basal calcarenite at Neds Beach, Middle Beach, Lagoon Boat Ramp & North Bay where it overlies basalt. Onlapped by beach units of NBF at Neds Beach, Old Settlement Beach & Boat Ramp.	~8 m at Neds Beach/Searles Pt, ~20 m at North Bay	Searles Point; additional reference sections, site 5 Neds Beach, site 1 & 2 Middle Beach.	7, >7

for the formation are located at sites 1 and 2. The eolianite onlaps basalt at site 1, and comprises yellow grainstone, with veins of calcite and small speleothems in and around fractures in the well-indurated beds (aIle/Ile: 0.67, Table 2).

Three dune units of the formation, bounded by paleosols, are exposed at the northern and southern sides of the cove at site 2 (Figs 3, 5b). They form part of a lateral eolianite succession between sites 2 and 5 in which successively younger dune units crop out towards the south. The paleosol and clay-pot structures in the eolianite bench at site 2 indicate a former long period of pedogenesis. The TL age of the paleosol at site 4, 201 ± 19 ka (W2118), suggests deposition of the underlying dune beds occurred during or prior to OIS 7. *Placostylus* shells collected from the paleosol at site 5 have mean D/L ratios (e.g. leucine: 0.76 ± 0.02) consistent with a Middle Pleistocene age (Brooke et al., 2003; Table 2). These geochronological data suggest the dune units lower in the succession at site 2 were likely deposited prior to OIS 7. Apart from a small outcrop of the Searles Point Formation at site 8, no exposures of the formation were observed in the southern sites (9–19, Fig. 3).

North Bay. On the western flank of Dawsons Ridge, the Searles Point Formation comprises thick (3–10 m) foreset beds of light yellowish brown to yellow, well-indurated grainstone (Fig. 3). Samples from outcrops are characterised by pore-filling sparite and microsparite, and grain recrystallisation and dissolution features are common. In contrast, samples from caves have their pores infilled with micrite, and recrystallised grains are rare. Samples from the caves, therefore, were used for AAR dating (Brooke et al., 2003). The D/L ratios of these whole-rock samples suggest a Middle Pleistocene age for the dune units (e.g. leucine: 0.62 ± 0.00; Table 2).

U/Th ages for a flowstone from site 4 range between 145±15 ka −70±5 ka (Table 1), indicating the dunes were probably deposited prior to the Last Interglacial. A TL age of 92±11 ka (W2117) for an eolianite sample from site 4, however, suggests the dunes were deposited in OIS 5. Diagenetic features of the eolianite, such as pores filled with silt and micrite and weathered volcanic grains, may have influenced this TL age assessment (Brooke, 1999; Brooke et al., 2003).

Old Settlement Beach and Lagoon Beach. Between Old Settlement Beach and the Lagoon Boat Ramp (Fig. 3) dune beds of the Searles Point Formation extend below lowest astronomical tide (LAT). Between sites 4 and 5, a thick paleosol contains fossil snails (*Gudeoconcha sophiae*) and speleothems which appear to represent a remnant cave deposit. The U/Th age of a laminated flowstone from this deposit, 190^{+30}_{-25} ka (Table 1), implies the underlying dune units were emplaced prior to or during OIS 7. An exposure of calcarenite and paleosol of the Searles Point Formation at the northern end of Lagoon Beach (site 4, Fig. 3) has also undergone considerable meteoric alteration, with recrystallised *Placostylus* shells, veins of calcite and flowstone remnants.

Overview of the Searles Point Formation. Mature pedogenic, diagenetic and karst features of the older eolianite succession are typical of Middle Pleistocene eolianites and reflect relatively long periods of surficial exposure and burial (Vacher et al., 1995; Carew and Mylroie, 1997). It has also been shown that the diagenetic alteration of eolianite, such as the development of pore-filling cements and grain dissolution, can vary spatially and be significantly enhanced in the littoral environment (Gardner and McLaren, 1994; McLaren, 1995). The geochronological data, however, indicate that the distinctive lithological characteristics of the Searles Point Formation are also a product of the Middle Pleistocene age of these deposits.

3.2.2. Neds Beach Formation

The younger formation overlies the much older dune units or paleosols of the Searles Point Formation, slope debris or basalt and represents the island's most extensive calcarenite deposit (Fig. 3). Beach and dune units in the formation are characterised by grain-contact cements, with patches of pore-filling micrite and microsparite, and relatively high porosity (~27%, Table 3). The dune units are predominantly lighter colored than the Searles Point Formation, typically very pale brown (10YR 8/4) to white (10YR 8/1). Beach units, however, are darker ranging from brownish yellow (10YR 6/6) to pale brown (10YR 6/3). The formation includes the yellowish brown (10YR 6/4), volcanic-rich Cobbys Corner Member and the white (10YR 8/1), miliolid-rich Middle Beach Member (Tables 3, 4). The most extensive and stratigraphically significant exposures are found at Neds and Middle Beaches on the east coast, and North Bay, Signal Point, Cobbys Corner and Johnsons Beach on the west coast. The formation is named after the reference section at the eastern end of Neds Beach (sites 2, 3).

Neds Beach. The calcarenite cliff at Neds Beach has long been regarded as one of the most significant exposures on the island (Etheridge, 1889; Fig. 4a, b). It was nominated as a type site for the calcarenite on the basis of which the one formation was called Neds Beach Calcarenite (Standard, 1963; McDougall et al., 1981; NSW Department of Mineral Resources, 1987). In the lower 4 m of the cliff, low-angle seaward-dipping planar cross-laminae, traceable laterally for tens of metres, have been interpreted as a beach deposit based on bedding structures and the presence of isolated coral

(a)

(b)

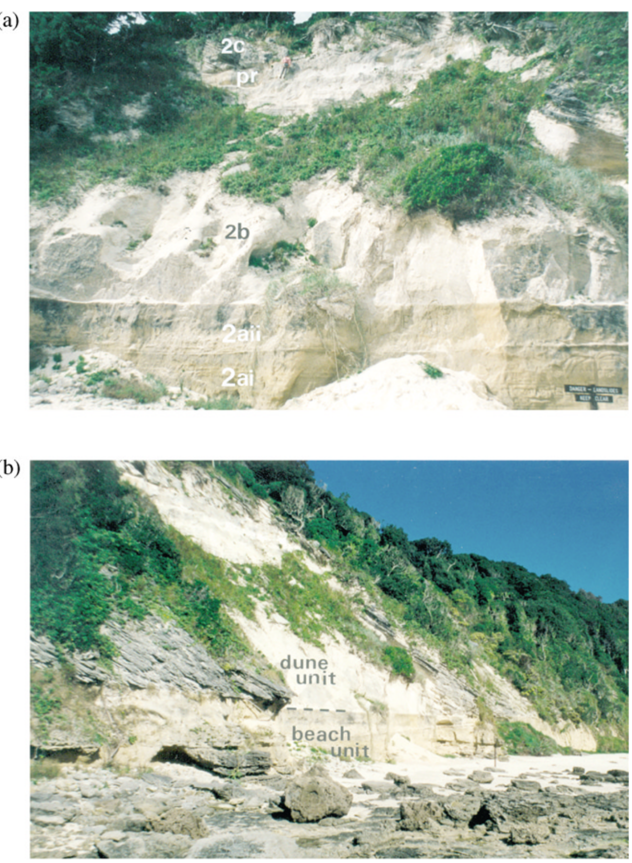

Fig. 4. Photographs of exposures between Neds Beach and Searles Point. (a) The 30 m thick calcarenite cliff at site 2. The darker beach unit, beds *2ai*, *2aii*, are overlain by two dune units, *2b* and *2c*. A protosol, *pr*, separates the dune units. The geologist on the cliff, next to *pr*, provides a scale. (b) The original 'type site' for calcarenite on Lord Howe Island at Neds Beach, looking W along the 30 m thick exposure from site 3. (c) Site 4, showing the older dune unit, *4a*, and paleosol, *p*. Between sites 3 and 4 the Last Interglacial beach beds onlap *4a*. Solution pipes, *s*, in *4a* extend down from the paleosol. (d) Site 5: a series of eolianite beds (a, b, c: beds 5a, 5b and 5c in Fig. 5a) and paleosols (p1, p2) of the Searles Point Formation are exposed in the lower 8 m of the cliff. (e) A depression in Searles Point contains a remnant flowstone (*f*), The geological hammer (arrow) is 28 cm long.

(c)

(d)

(e)

Fig. 4 (*continued*).

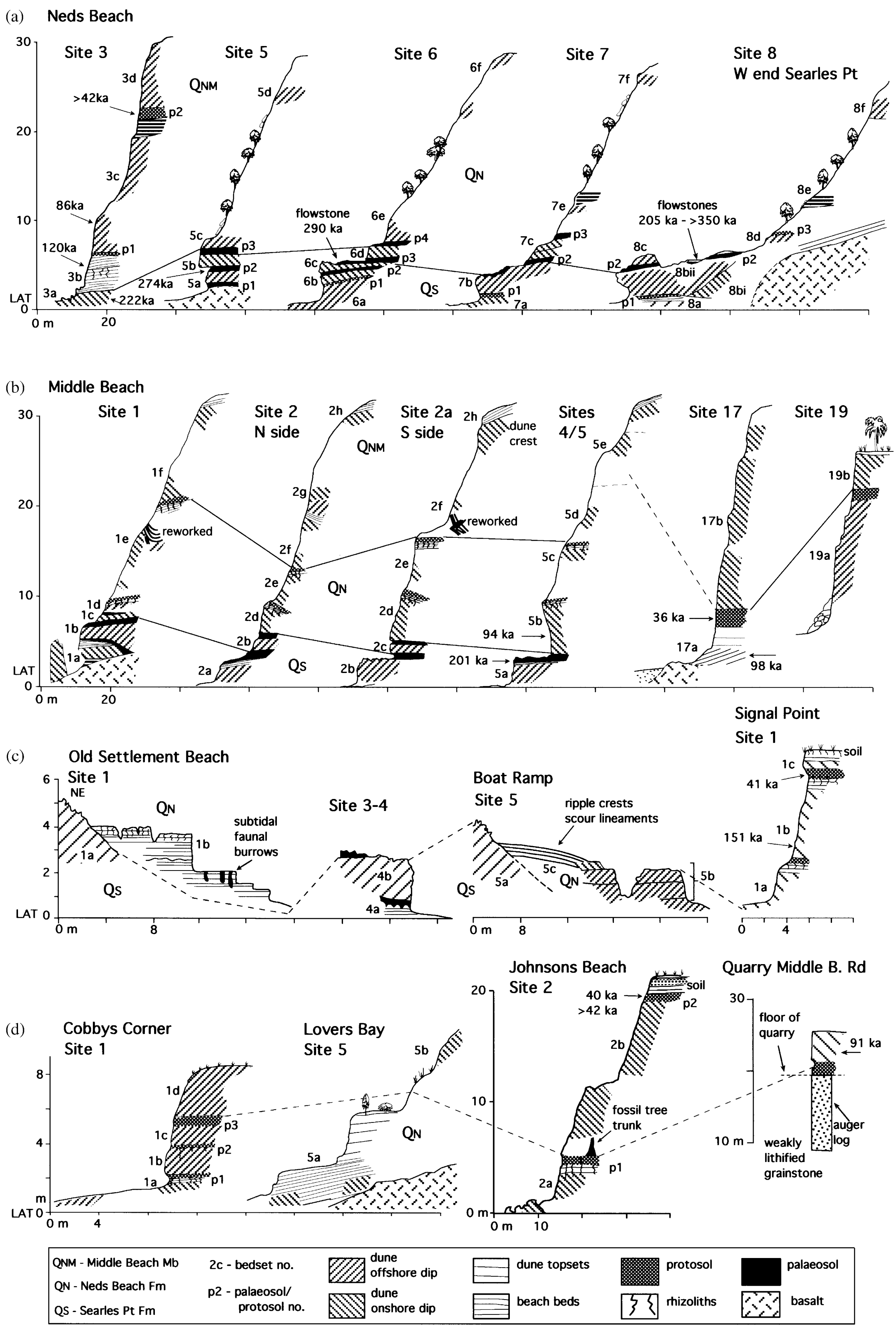

Fig. 5. Key sections measured in the calcarenite. TL, ^{14}C and U/Th ages of several units are indicated. The locations of the sections are shown in Fig. 3.

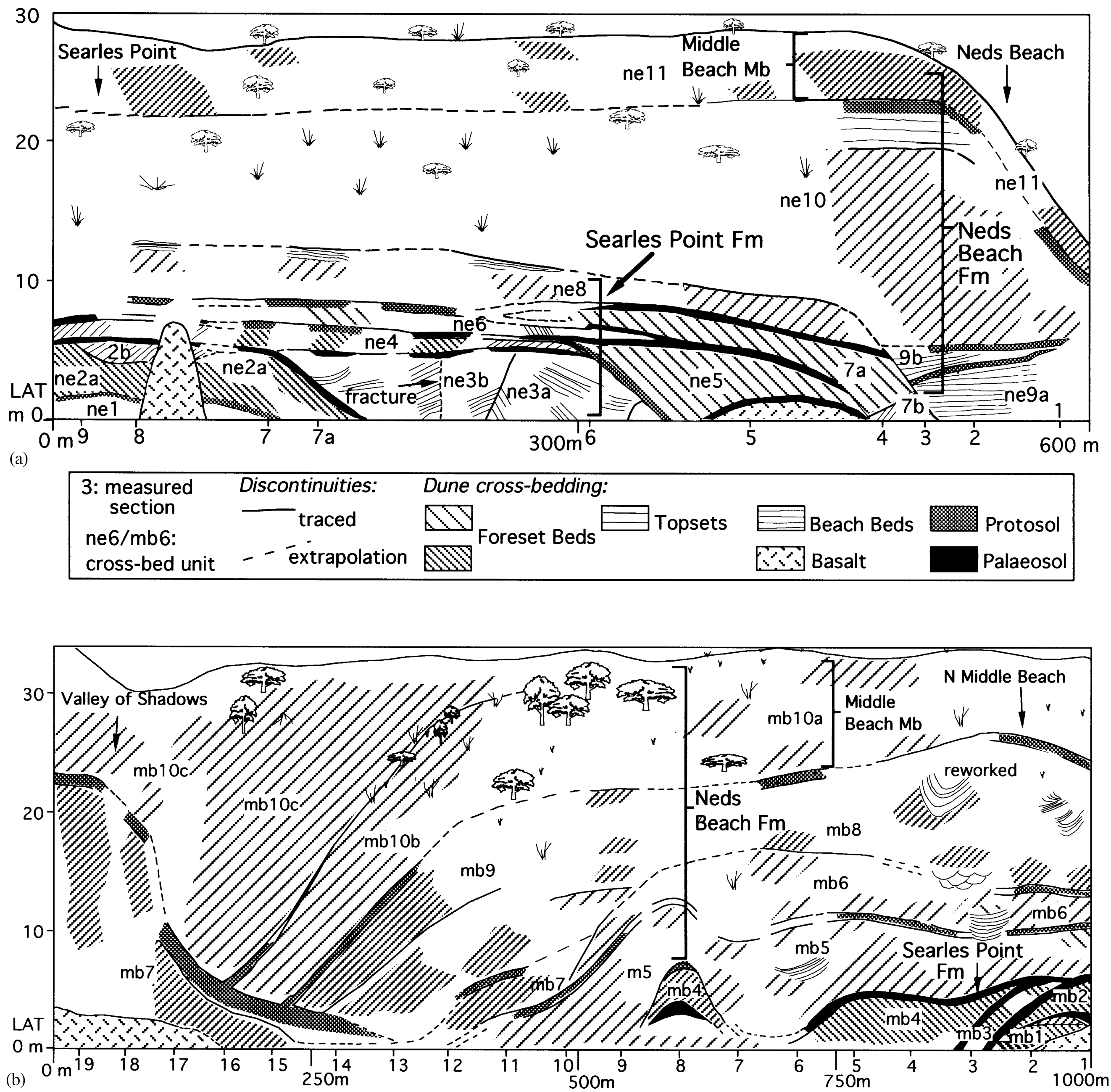

Fig. 6. Schematic long sections for the east coast, showing approximate areas of exposure and lithostratigraphic units in the coastal cliffs and bluffs. (a) Neds Beach to Searles Point: cross-bed units *ne1 – 8* are part of the Searles Point Formation, and units *ne9 – ne11* represent the Neds Beach Formation. (b) Middle Beach and the Valley of Shadows: dune units *mb1 – 4* are part of the Searles Point Formation, while the Neds Beach Formation comprises units *mb5–mb10*.

and pumice and transported molluscs (Standard, 1963; Mattes, 1974; Woodroffe et al., 1995).

The beach deposit includes two bedsets separated by an erosional unconformity (Figs 4a, 5a). A weakly developed protosol in the upper bedset marks the short hiatus before the overlying thick dune beds were deposited (Fig. 4b). The beach unit has been interpreted as representing the earlier of two major episodes of carbonate accumulation on the island (Squires, 1963; Mattes, 1974), the second episode being represented by the overlying dune units. More recent geochronological data for the beach unit have indicated that it was emplaced during the Last Interglacial (Woodroffe et al., 1995), most probably during the highstand of OIS 5e (e.g. coral U/Th age of 120^{+10}_{-5} ka, Table 2; Brooke et al., 2003). These ages contrast with earlier ^{14}C ages for the unit, which range between approximately 20–39 ka (Squires, 1963; Mattes, 1974; Kaplin, 1981) and must be the products of contamination of the much older material by carbon with a modern activity.

Exposures between sites 2 and 3 provide a reference section for the Neds Beach Formation. Here, conformably overlying the beach unit is a thick (15 m) coset of dune foreset and topset beds (Fig. 5a), capped by a well-developed protosol. The protosol is in turn conformably overlain by the top dune unit, which contains a relatively large proportion (~13%) of miliolid foraminiferal grains. This unit forms part of the Middle Beach Member of the Neds Beach Formation (Tables 3, 4). An overview of the stratigraphy of the Neds Beach area is provided in Fig. 6a, which displays the thick beds of the Neds Beach Formation overlying the Searles Point Formation.

A range of geochronological data indicate the ages of the dune units are beyond the range of ^{14}C dating. These include a TL age of 86 ± 33 (W1728) for the dune unit that overlies the beach deposit, and a non-finite ^{14}C age (>42,000 BP, OZC-312) for a *Placostylus* shell from the protosol that caps the dune unit (Table 2). Amino acid D/L ratios of eolianite and *Placostylus* samples also suggest ages for these deposits that lie within OIS 5 (Table 2, Brooke et al., 2003). However, as indicated by the uncertainties of the TL age, the geochronological data do not unequivocally identify an OIS 5 age for dune units of the Neds Beach Formation.

Middle Beach. At Middle Beach the contact between the two formations is clearly exposed between sites 1 and 5, with foresets of the Neds Beach Formation sitting on clay-rich paleosols of the Searles Point Formation (Figs 3, 5b). Unlike Neds Beach, no beach facies were identified at Middle Beach. Two reference sections for the Neds Beach Formation are located at the northern (sites 1 & 2) and southern (sites 14–17) ends of the Middle Beach coast.

The formation comprises up to 4 dune units at sites 1 and 2 (Fig. 5b). Protosol horizons occur in the top of these units, with rhizoliths and solution pipes extending down into foreset bedding. The top dune unit is part of the Middle Beach Member, consistent with the dune succession at Neds Beach. In the headland and cliffs at site 2 there is a stacked succession of four dune units, with landward-dipping foresets up to 11 m thick that contain a fossilised *Ficus* tree trunk (Fig. 7a–c). Whole-rock D/L ratios for three of these dune units are in stratigraphic order (e.g. leucine: 0.38, *2d*; 0.33, *2c*; 0.29, *2 h*) and similar to D/L ratios for dune units of the Neds Beach Formation at Neds Beach and at the southern end of Middle Beach (Table 2, Fig 5b). The lower dune unit can be traced to site 5. Samples from here and site 4 have slightly higher D/L ratios (e.g. leucine: 0.42) and a TL age of 94 ± 52 ka (W1894; Table 2).

At the southern reference section, sites 14–17, the basal dune unit overlies basalt and is capped by a well-developed protosol that marks the discontinuity between the Neds Beach Formation and the overlying Middle Beach Member (Fig. 5b). This large-scale exposure shows that the white, weakly lithified dune beds of the Middle Beach Member are up to 25 m thick and have infilled a swale formed by the Neds Beach Formation. A former swale is also reflected in clay lenses in the protosol. A TL age for the dune unit capped by the protosol, 98 ± 16 ka (W1765), suggests deposition occurred during OIS 5. *Placostylus* shells from the protosol have D/L ratios (e.g. aIle/Ile: 0.38 ± 0.02) comparable to *Placostylus* from a similar protosol at Neds Beach (0.36 ± 0.04, Table 2). One of the *Placostylus* from Middle Beach has a ^{14}C age of $35{,}800 \pm 750$ y BP (OZC-311) that may reflect minute contamination by carbon with a modern activity (Brooke et al., 2003; see Section 3.2.3). An overview of the eolianite succession at Middle Beach in Fig. 6b shows thick beds of the Neds Beach Formation overlying the Searles Point Formation in the north, while in the south the Middle Beach Member thickens to form the majority of the deposit.

Architectural features. Foreset bedding in the Neds Beach Formation at Middle Beach often exhibits deformation structures, such as massive and brecciated slumps and high-angle asymmetric folds, features that reflect a humid depositional environment (Fig. 7e; McKee and Ward, 1983). Dune crest 'roll-over' structures are common and indicate the top dune strata are preserved. Extensive (200 m) exposures of truncated foresets in the intertidal platform between sites 6 and 10 (Fig. 3) have a consistent onshore dip and shore-parallel strike that indicates the platform has been cut from eolianite deposited as a transverse dune when sea level was lower than present.

Exposures at Neds Beach and Middle Beach display how the carbonate deposits have been anchored around the volcanic high ground at Hells Gates (Fig. 8a). The geochronological and stratigraphical features of the deposits suggest that the dunes were emplaced in two phases, the first in a source-bordering setting shortly after and possibly coeval with deposition of the OIS 5e beach deposits. During at least part of this first phase, the eolianite exposures indicate sea level was several metres lower than present. The second phase of deposition occurred following a period of regional pedogenesis, recorded by a well-developed protosol at both locations, likely at the end of OIS 5.

Big Slope. Previously unmapped eolianite on the southeastern footslope of Mount Gower (Fig. 2) comprises two dune units, the lower up to 8 m thick (Fig. 9c). D/L ratios of whole-rock samples (e.g. aIle/Ile: 0.50 ± 0.02) and lack of recrystallized grains are typical of the Neds Beach Formation (Table 2). A TL age for this unit suggests a Middle Pleistocene age, however (Table 2). Pore-filling cement in this deposit may have influenced the TL age assessment (Brooke, 1999; Brooke et al., 2003).

North Bay. Low-angle beds at the eastern side of North Bay sit up to 3 m above MSL and may represent

Fig. 7. Photographs of exposures at Middle Beach (a–e) and the Lagoon Boat Ramp (f). (a) The headland on the southern side of site 1, which comprises a 15 m thick dune coset of foreset and topset beds, *1e*. The base of *1e* rises to the west as indicated by the dashed line. (b) The lower 15 m of exposure on the northern side of site 2 (S side of the headland shown in 7a). Dune units of the Searles Point Formation, *2a* and *2b*, are capped by paleosols (p1, p2) and thicken to the left (south). The thick foresets above *p2*, *2d*, *2e* and *2f*, are part of the Neds Beach Formation. (c) A segment of tree trunk (possibly *Ficus*, which is extant on the island) preserved in dune unit *2f*, at site 2. (d) Dune crest bedding in the top 2 m of the bluff at site 4. A dune 'roll over' is evident, with low-angle topsets, *a*, translating into foresets, *b*. (e) Deformation structures in the foreset bedding at site 10, Middle Beach. Slumping (sl) and brecciated folds (b) are evident in the strata. The geological hammer is 28 cm long. (f) An exposure of foreshore bedding at the Lagoon Boat Ramp. Numerous worm burrows are visible in the bedding above the tape measure. The tape measure is 10 cm long.

foreshore deposits, however, they lack distinctive fossil evidence (Site 1, Figs 3, 9d). Whole-rock D/L ratios for this unit are consistent with whole-rock samples from the OIS 5e beach unit at Neds Beach (e.g. aIle/Ile: 0.56 ± 0.06, Table 2).

3.2.3. *West coast and quarry sites*

Beach calcarenite is exposed at Old Settlement Beach, Lagoon Boat Ramp and Lovers Bay (Fig. 3). These beds are generally low-angle, parallel laminated and extend laterally for tens of metres (Fig. 5c, d). They include

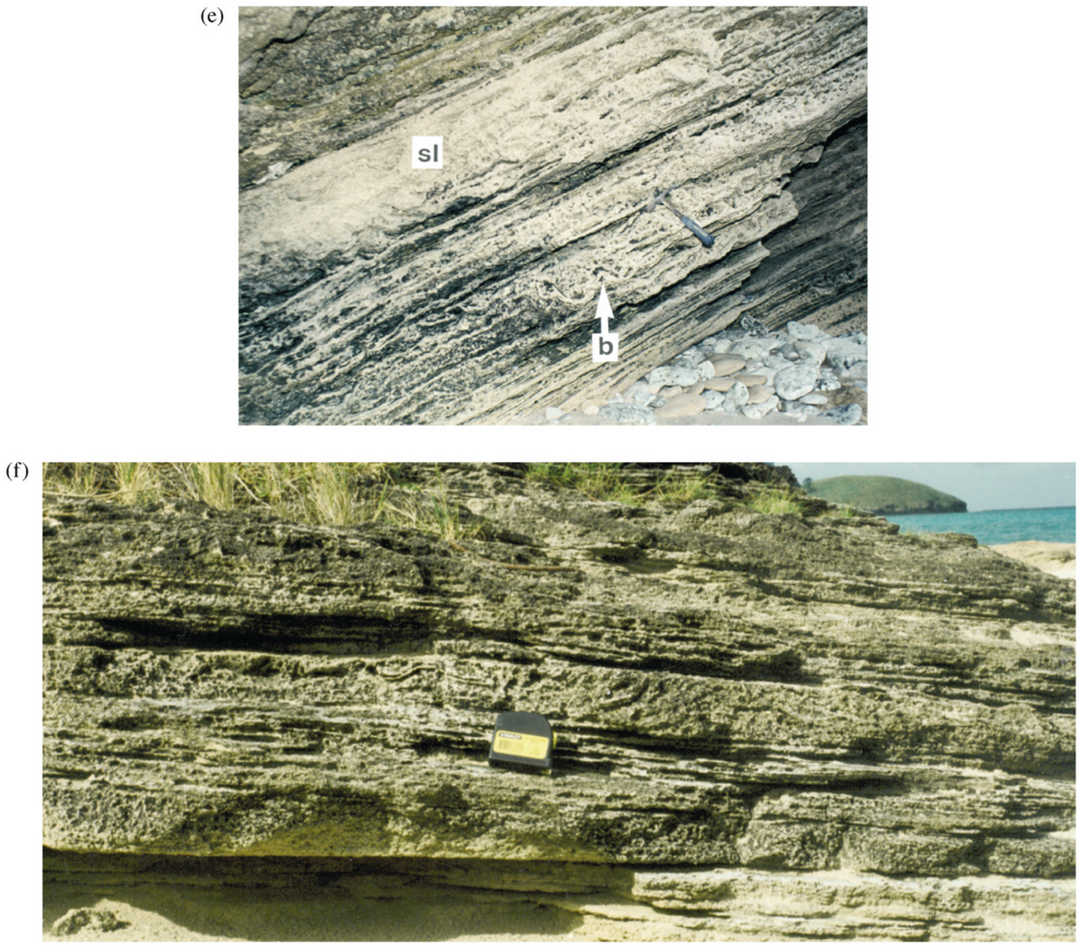

Fig. 7 (*continued*).

faunal burrows and worm tubes, rhythmic ripple crests and current scour lineaments, typical of an intertidal to shallow subtidal depositional environment (Frey and Pemberton, 1984). At the boat ramp, the low-angle foreshore beds grade seawards into steeply dipping foresets, 0.5–0.7 m thick, a succession typical of a foreshore to shoreface depositional environment (Figs 5c, 7f; Tucker and Wright, 1990). The mean whole-rock D/L ratios of beds at the Boat Ramp and Lovers Bay (e.g. aIle/Ile: 0.58 ± 0.01) are statistically indistinguishable from D/L ratios for the beach unit of OIS 5e age at Neds Beach (e.g. aIle/Ile: 0.59 ± 0.02; Table 2), suggesting the deposits are of similar age.

Vibrocores and drill cores recovered from the end of the Lagoon Jetty, 80 m south of the Boat Ramp, include 3 m of mostly weakly lithified calcarenite below unconsolidated lagoonal sediment (Kennedy and Woodroffe, 2000), with two mollusc- and coral-rich beach or back-reef units below the calcarenite (Fig. 9e). An in situ coral in the upper reefal unit has a U/Th age of 120^{+9}_{-8} ka (core 11, Table 2). Corals in the lower unit, however, are recrystallised and possibly record an earlier interglacial period of high sea level. Calcarenite samples from core 12 (reefal margin of the lagoon) have D/L ratios typical of eolianite units in the lower Neds Beach Formation (e.g., aIle/Ile: 0.53 ± 0.04, Table 2; Brooke et al., 2003).

Up to four dune units are discernible in the eolianite cliffs at Signal Point, Cobbys Corner, Johnsons Beach and in disused quarries on Middle Beach and Anderson Roads (Fig. 5c, d). Eolianite at Cobbys Corner is classified as the Cobbys Corner Member of the Neds Beach Formation because of its distinctively light yellowish-brown to brownish-yellow color, which is a product of the relatively high proportion of dark, mostly volcanic grains and pale brown micrite (Tables 3, 4). Whole-rock D/L ratios for these units (e.g. aIle/Ile: $0.35 - 0.52 \pm 0.01$) are similar to those for eolianite units of the Neds Beach Formation on the east coast (Table 2). TL ages for dune units at Signal Point, 151 ± 18 ka, and the quarry on Middle Beach Road, 91 ± 21 ka, suggest a wide range in the timing of dune deposition.

Placostylus from well-developed protosols at the quarry on Middle Beach Road, Signal Point and Johnsons Beach have D/L ratios (e.g. aIle/Ile: 0.35 ± 0.03; non finite ^{14}C age: OZC-219, Table 2) that

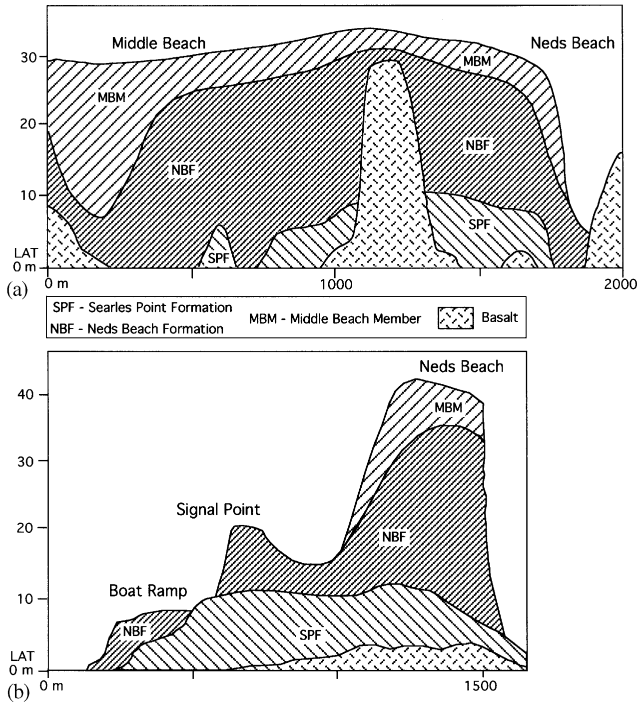

Fig. 8. Schematic sections of the calcarenite showing the arrangement of the lithostratigraphic units: (a) a long section between Neds Beach and Valley of The Shadows with volcanic highground at Hells Gate; (b) a composite cross-section between Neds Beach on the east coast and Lagoon Boat Ramp on the west coast.

are statistically indistinguishable from the D/L ratios of *Placostylus* from protosols at Neds and Middle Beach (aIle/Ile: 0.36 ± 0.04 and 0.38 ± 0.02, respectively). These data indicate a similar age for the *Placostylus* that is likely well beyond the limit of the ^{14}C method (e.g. 91 ± 21 ka, the TL age for the dune unit that overlies *Placostylus* at the quarry on Middle Beach Rd). *Placostylus* from sand sheets (<1 m thick) in the top of the sections at Signal Point and Johnsons Beach have very low *D/L* ratios (e.g. aIle/Ile: 0.03) and a modern ^{14}C age (post 1950, OZC-220) that suggest recent deposition of the sand, possibly following the clearance of native vegetation (Fig. 5c, d).

An overview of the stratigraphic relationships of the lithostratigraphic units across the island, between Neds Beach and Signal Point/Lagoon Boat Ramp is displayed in Fig. 8b. This figure also displays the much greater thickness of calcarenite on the east coast, and the likely extension of the Searles Point Formation across this section of the island.

An apparently in situ fossil of the Pleistocene horned turtle *Meiolania platyceps* was found at Ocean View Lodge, the eolianite hill above the Boat Ramp, during excavation work (K Wilson, lodge owner, pers. comm.; Fig. 3). This is one of several important specimens of the turtle that have been found on the island (Gaffney, 1983). The eolianite here is light yellowish brown, weakly lithified grainstone of the Neds Beach Formation. Whole-rock *D/L* ratios for the deposit (e.g. aIle/Ile: 0.57) are typical of samples from the lower part of the formation (Table 2).

Architectural Features. Large dune foresets in the quarries show that the Middle Beach Member forms the upper part of the main eolianite ridge (Fig. 8b). At Old Settlement Beach and the Boat Ramp, beach laminae onlap dune strata of the Searles Point Formation, marking the unconformity between the two calcarenite formations. Exposures on the lagoonal coast also indicate that eolianite here was derived from a source west of and below the current shoreline (Figs. 5c, d, 8).

3.3. Island-wide allostratigraphy

The Searles Point Formation at Neds Beach includes up to eight allostratigraphical units (dune units ne1–ne8 in Fig. 6a) that record cycles of dune accumulation and pedogenesis, of variable duration, during the Middle Pleistocene. At Middle Beach the formation comprises four allostratigraphic units (mb1–mb4, Fig. 6b). Exposures of the Neds Beach Formation at Neds Beach include a well-developed protosol that marks a significant hiatus between two phases of sedimentation (ne9/10 and ne11, Fig. 6a). Similarly, at Middle Beach the same two phases of carbonate accumulation are recorded in the Neds Beach Formation (mb5–9 and mb10, Fig. 6b).

An allostratigraphical framework is proposed that includes all the calcarenite successions on Lord Howe Island and incorporates the geochronological data (Fig. 9). The Searles Point Formation includes up to seven allostratigraphic formations at Neds Beach, *S1–S7* (Fig. 9a). At Middle Beach, four alloformations are evident. If the basal eolianite units at both sites, which overlie basalt, are coeval then the succession at Middle Beach comprises alloformations *S1–S4*. Fewer alloformations, however, could be discerned at other sites of the Searles Point Formation. For example, only two are exposed at Old Settlement Beach (Fig. 9e). Paleosols, caves and cave deposits that characterise *S1–S7* clearly reflect their diagenetic maturity. U/Th and TL ages and whole-rock aIle/Ile ratios indicate they were deposited prior to the Last Interglacial, in OIS 7 and earlier in the Middle Pleistocene.

There are two alloformations within the Neds Beach Formation, *N1* and *N2*, the discontinuity marked by a prominent protosol that is exposed at most sites (Fig. 9). *N1* includes beach and dune deposits, the beach facies being emplaced during OIS 5e. The overlying eolianite was deposited during or shortly after OIS 5e, based on the TL, AAR and ^{14}C ages of the dune units and the weak pedogenic alteration of the beach deposit (Table 2). Subtidal exposures show that several dune units were emplaced during periods when sea level was several metres lower than present.

Alloformation *N2* includes the Middle Beach Member and other dune units of the Neds Beach Formation that sit above the prominent protosol, as displayed at Neds and Middle Beach, Signal Point, the quarry on Middle Beach Rd, Cobbys Corner and Johnsons Beach (Fig. 9). These little-altered dune units were deposited after substage 5e and prior to approximately 42 ka, based on AAR, TL and ^{14}C data (Table 2). This last phase of eolianite deposition may have occurred during substage 5a, when sea level was relatively high ($\sim$20 m below present MSL, Chappell et al., 1996).

3.4. Paleoenvironments

Subaerially exposed Last Interglacial coral reef is not evident on Lord Howe Island, however, reef of that age was encountered in drill core from the Lagoon (Fig. 9e; Kennedy and Woodroffe, 2000) and there are large clasts of coral in the beach unit at Neds Beach. These deposits indicate that at least some patch reef was in place on the island during the Last Interglacial high-stand. Marine environments are also recorded in beach deposits on both the east and west coasts. The well-sorted carbonate sand of the ancient beaches, with rare coral clasts, is typical of an open coastal setting, in contrast to the gravelly deposits of the modern Lagoon Beach (Fig. 2). At all sites of exposure, the beach deposits form the basal unit of the Neds Beach Formation and have not experienced significant pedogenic alteration. The overlying thick dune units, therefore, were emplacement shortly after deposition of the beach sediment, likely all within OIS 5.

Mean vectors of foreset dip orientations for dune units in the two formations at Neds and Middle Beach indicate a wide range of effective winds (Fig. 10a, b). Similar results were obtained for these two major eolianite successions, with distinctly different mean vectors for the two formations. At Neds Beach, dune units in the Searles Point Formation were apparently predominantly emplaced by winds from the S–NW, and from the W at Middle Beach. Dune units in the Neds Beach Formation, in contrast, were deposited under winds from the E - NE and NW at Neds Beach and from the NW - NE at Middle Beach.

Mean vectors for dune units at all sites display a similar pattern (Fig. 10c, d): dune bedding in the Searles Point Formation records apparent effective winds from the S and W. Those deposits form the core on which most of the dunes of the Neds Beach Formation were anchored. Mean vectors for the Neds Beach Formation indicate deposition by winds from all quadrants, but mostly under winds from NW to NE and SE, with little deposition under winds from the SW to W (Fig. 10d). Apparent differences in the wind regimes recorded in the two formations probably relate to changes in the volume of carbonate reaching different sections of coast rather than changes in wind regime because the island has probably always experienced a highly windy environment (Pickard, 1983). As Lord Howe Island sits at the latitudinal limit to reef growth (Kennedy and Woodroffe, 2000), it may be that there were no substantial fringing reefs during interglacials of the Middle Pleistocene. Therefore, the location and rate of carbonate supply to the island may have varied over time.

Mean vectors for the Last Interglacial foreshore beds at Neds Beach, Old Settlement Beach and the Boat Ramp indicate onshore directed deposition similar in orientation to the nearby modern beach systems, with sea level up to 4 m above the present (Fig. 5a, c). The west coast deposits indicate that a marine passage may have extended between Old Settlement Beach and Neds Beach during the Last Interglacial, which infilled with beach sediment and was subsequently covered by eolianite (Fig. 2).

Rapid emplacement of the ancient dunes is recorded by thick foreset beds, up to 25 m thick at Middle Beach, and the entombment of trees and a *Meiolania*. The primary depositional forms of dunes are visible at many exposures, with topset and dune crest 'roll-over' bedding showing that the upper-most, readily eroded sections of the dunes are often preserved. In the Neds Beach Formation, deformation structures in foreset bedding suggest a humid environment prevailed during deposition. Caves and remnant cave deposits and well-formed pedogenic features preserved in the older eolianite also record a relatively humid environment following deposition. Large snails and rhizoliths within paleosols and protosols also point to significant soil moisture, while the lack of significant calcrete beds indicates there were no major seasonal deficits of soil moisture (Milnes and Hutton, 1983).

The Neds Beach Formation is far larger than remnants of the earlier phases of deposition recorded in the Searles Point Formation. Differences in the scale of the deposits are at least partially related to the older dune units having experienced longer periods of denudation and erosion and, possibly, marine erosion during previous sea-level highstands.

Both the scale and depositional setting of the large ancient dunes contrast markedly with modern dunes on the island. The largest modern deposit is a 6 m high foredune at Blinkenthorpe Beach, while foredunes on the Lagoon coast are generally around 1 m high. Indeed, the present interglacial appears to have been largely an erosional regime as indicated by eolianite remnants in the Lagoon and extensive (up to 90 m wide) shore platforms cut into the eolianite on the east coast. The lack of a modern analogue for the eolianite, and the extension of several eolianite units below present sea level, suggest major phases of dune deposition are linked

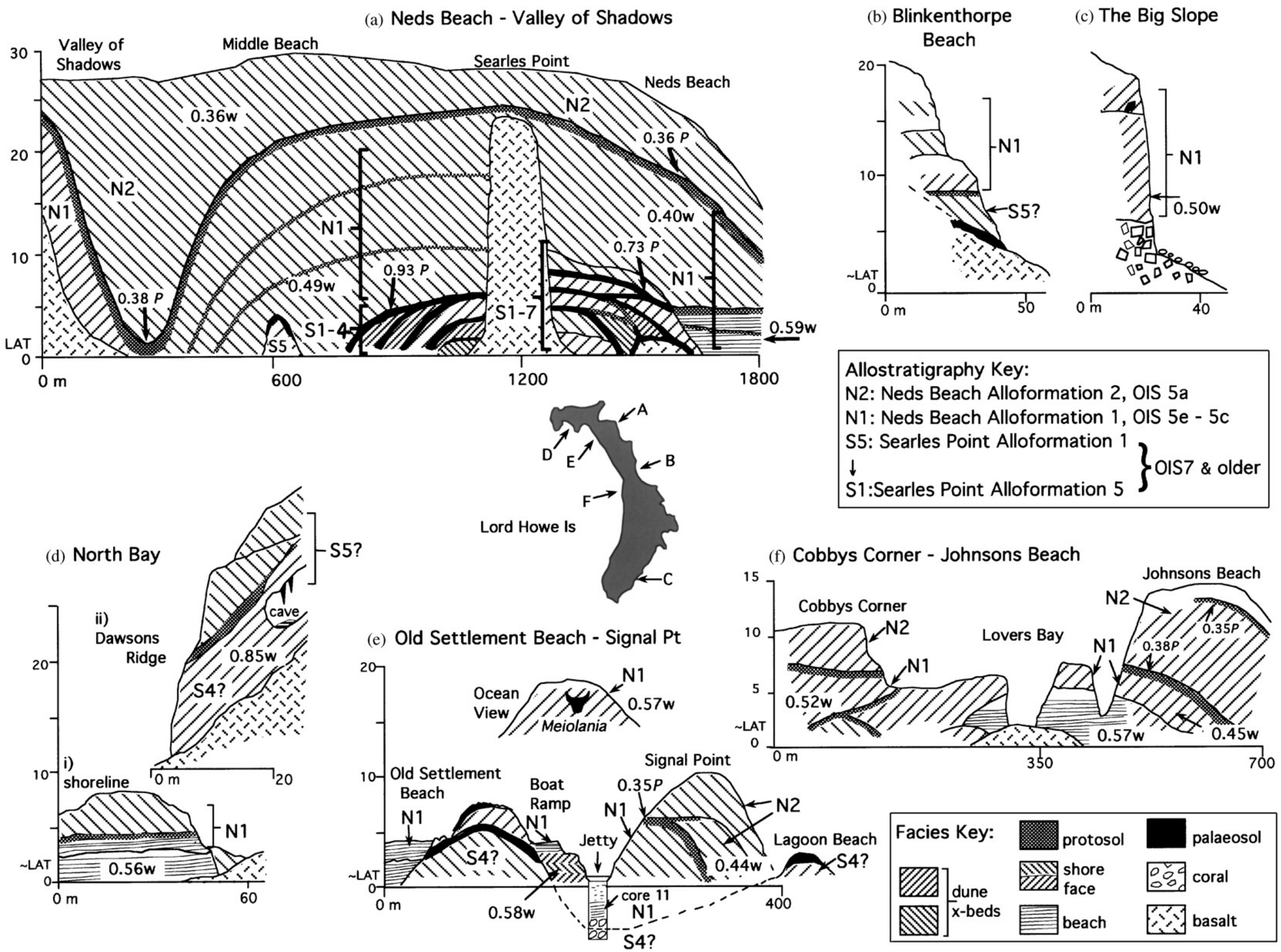

Fig. 9. An island-wide allostratigraphy of calcarenite on Lord Howe Island. Successions of dune and beach units at the disparate sites are classified into allostratigraphic formations. Dune units in the Searles Point Formation comprise seven alloformations, *S1 - S7*. Beach and dune units in the Neds Beach Formation form two alloformations, *N1* and *N2*. Also indicated are aIle/Ile ratios for *Placostylus* (*P*) and whole-rock samples (w).

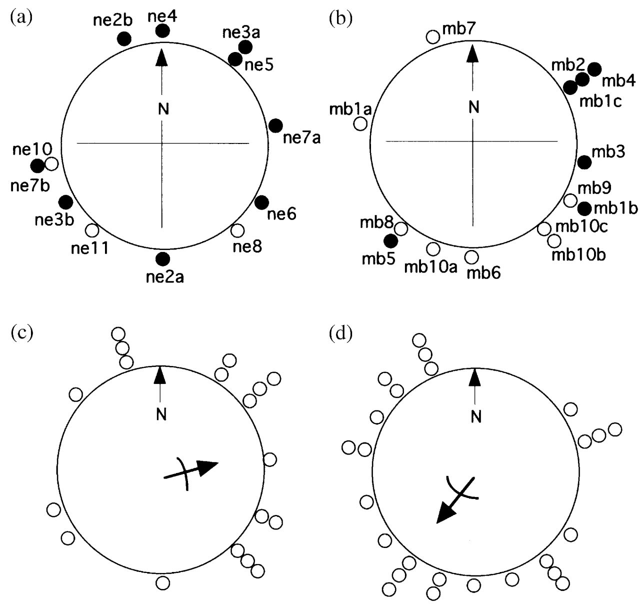

Fig. 10. The hemispherical distributions of the mean vectors of dip azimuths measured in foreset beds. (a) Mean vectors for dune units between Neds Beach and Searles Point (dark circles: Searles Point Formation, open circles: Neds Beach Formation). (b) Mean vectors for dune units at Middle Beach. 10c and 10d display the mean vectors for all sites (arrows & 1σ uncertainty), for dune units in the Searles Point Formation (c), and the Neds Beach Formation (d).

to sea levels slightly lower than present. For coastal, source-bordering dunes to be emplaced on the island, sea level needs to be less than approximately 30 m below present sea level for the steep sided platform surrounding the island to be significantly flooded and form a carbonate province (Fig. 1b). Dune units in the Neds Beach Formation, therefore, may be linked to regressions during or following OIS 5e, and the latter periods of relatively high sea level during substages 5c and 5a (Chappell et al., 1996; Eisenhauer et al., 1996), when the platform would have been at least partially flooded. During these periods a slightly larger island would have been surrounded by a very shallow water (10–20 m deep) carbonate platform. Following Substage 5a, sea level dropped below the outer rim of the platform that surrounds the island (−30 to −50 m MSL), cutting the potential supply of carbonate to the coast. Allostratigraphical units in the Searles Point Formation, therefore, likely also represent past phases of dune accretion during periods of relatively high sea level. This record of carbonate deposition is broadly comparable with eolianite islands in the Bahamian Archipelago (Carew and Mylroie, 1997; Kindler and Hearty, 1997) and Bermuda (Vacher et al., 1995; Vacher and Rowe, 1997). Quaternary sea-level fluctuations, therefore, have been a major control on the timing of formation and stratigraphical character of calcarenite on these oceanic islands.

4. Conclusions

(1) Two lithostratigraphic formations are recognised in the calcarenite. The Searles Point Formation comprises diagenetically mature dune units bounded by paleosols and well-formed protosols. This succession records up to seven phases of deposition that are separated by a regionally significant hiatus. U/Th, TL and AAR dating indicates the dunes were deposited during OIS 7 and earlier in the Middle Pleistocene. The younger Neds Beach Formation consists of little-altered beach and dune units emplaced in two major phases, the hiatus marked by a well-formed protosol. The first phase comprised beach and dune units and occurred during OIS 5e, while dunes were also deposited slightly later when sea level was lower. The second phase, when only dunes were deposited, probably occurred in substage 5a.

(2) Beach units of the Neds Beach Formation record open coastal environments on the east and west coasts. Many dune units in the formation were deposited as thick, source-bordering or oblique transverse to lobate and climbing coastal dunes, under onshore winds on both coasts.

(3) Several dune units in both formations extend at least several metres below present sea level, however, the submarine platform surrounding the island limits coastal deposition to periods when sea level is <30 m below present sea level. Therefore, many of the dune units were probably emplaced during interglacial regressions or transgressions, and interstadial highstands, which is consistent with the geochronological data. This depositional record is similar to several other mid-ocean calcarenite islands, reflecting the major control of sea level on the timing and style of carbonate sedimentation on these islands.

Acknowledgements

This work was supported by an Australian Postgraduate Research Award and Australian Institute of Nuclear Science and Engineering Postgraduate Award to Brooke, the Australian Research Council, Australian Nuclear Science and Technology Organisation (ANSTO) and the *Quaternary Environments Research Centre* at the University of Wollongong. Fieldwork was undertaken with the permission and assistance of the Lord Howe Island Board and with the help of David Kennedy, Stephen Barry, Eugene Wallensky, Damien Kelleher, Mark Dickson and Frank Mostyn. U/Th dating was undertaken with the assistance of Robert Chisari (ANSTO). The two anonymous reviewers are thanked for their comments that have considerably improved the paper. This paper is a contribution to IGCP Project 437 'Coastal Environmental Change During Sea-Level Highstands: A Global Synthesis with

Implications for Management of Future Coastal Change'.

References

Australian Environmental Publications, 1992. Lord Howe Island World Heritage Area, 1:15,000 topographic map. Australian Environmental Publications, Sydney, Australia.

Batschelet, E., 1981. Circular Statistics in Biology. Academic Press, New York.

Brooke, B.P., 1999. Quaternary stratigraphy and evolution of eolianite on Lord Howe Island. Ph.D. Thesis (Unpublished), School of Geosciences, University of Wollongong, Australia.

Brooke, B.P., 2001. Distribution of carbonate eolianite. Earth Science Reviews 55, 135–164.

Brooke, B.P., Murray-Wallace, C.V., Woodroffe, C.D., Heijnis, H., 2003. Quaternary aminostratigraphy of eolianite on Lord Howe Island, southwest Pacific Ocean. Quaternary Science Reviews 22, 213–232.

Carew, J.L., Mylroie, J.E., 1991. Some pitfalls in paleosol interpretation in carbonate sequences. Carbonates and Evaporites 6, 69–74.

Carew, J.L., Mylroie, J.E., 1997. Geology of the Bahamas. In: Vacher, H.L., Quinn, T. (Eds.), Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology, Vol. 54. Elsevier Science, Amsterdam, pp. 91–139.

Chappell, J., Omura, A., Esat, T., McCulloch, M., Pandolfi, J., Ota, Y., Pillans, B., 1996. Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. Earth and Planetary Science Letters 141, 227–236.

Eisenhauer, A., Zhu, Z.R., Collins, L.B., Wyrwoll, K.H., Eichstätter, R., 1996. The last interglacial sea level change: new evidence from the Abrolhos Islands, West Australia. Geologie Rundschrift 85, 606–614.

Etheridge, R., 1889. The physical and geological structure of Lord Howe Island. Memoirs no. 2, The Australian Museum, Sydney, pp. 99–126.

Frey, R.W., Pemberton, S.G., 1984. Trace fossil facies models. In: Walker, R.G. (Ed.), Facies Models, Reprint Series 1. Geoscience Canada, St Johns, Newfoundland, pp. 189–207.

Gardner, R.A.M., McLaren, S.J., 1994. Variability in early vadose carbonate diagenesis: a review. Earth Science Reviews 36, 27–45.

Gaffney, E.S., 1983. The cranial morphology of the extinct horned turtle, *Meiolania platyceps*, from the Pleistocene of Lord Howe Island, Australia. Bulletin of the American Museum of Natural History 175, 361–480.

Garrett, P., Gould, S.J., 1984. Geology of New Providence Island, Bahamas. Geological Society of America Bulletin 95, 209–220.

Hearty, P.J., Kindler, P., 1993. New perspectives on Bahaman geology: San Salvador Island, Bahamas. Journal of Coastal Research 9, 577–594.

Ivanovich, M., Murray, A., 1992. Spectroscopic methods. In: Ivanovich, M., Harmon, R.S. (Eds.), Uranium-series Disequilibrium: Applications to Earth, Marine and Environmental Sciences. Clarendon Press, Oxford, pp. 125–173.

Kaplin, P.A., 1981. Relief, age and types of oceanic islands. New Zealand Geographer 37, 3–12.

Kennedy, D.K., Woodroffe, C.D., 2000. Holocene lagoonal sedimentation at the latitudinal limits of reef growth, Lord Howe Island, Tasman Sea. Marine Geology 169, 287–304.

Kindler, P., Hearty, P.J., 1997. Geology of the Bahamas: Architecture of Bahamian Islands. In: Vacher, H.L., Quinn, T. (Eds.), Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology, Vol. 54. Elsevier, Amsterdam, pp. 141–160.

Lally, A.E., 1992. Chemical procedures. In: Ivanovich, M., Harmon, R.S. (Eds.), Uranium-series Disequilibrium: Applications to Earth, Marine and Environmental Sciences. Clarendon Press, Oxford, pp. 95–126.

Mardia, K.V., 1972. Statistics of Directional Data. Academic Press, New York.

Mattes, B., 1974. Aspects of the Sedimentary Geology of Lord Howe Island (B.Sc. Hons Thesis). University of Sydney, Department of Geology and Geophysics, Sydney.

McDougall, I., Embleton, B.J., Stone, D.B., 1981. Origin and evolution of Lord Howe Island, southwest Pacific Ocean. Journal of the Geological Society of Australia 28, 155–176.

McDougall, I., Maboko, M.A.H., Symonds, P.A., McCulloch, M.T., Williams, I.S., Kudrass, H.R., 1994. Dampier Ridge, Tasman Sea, as a stranded continental fragment. Australian Journal of Earth Sciences 41, 395–406.

McLaren, S.J., 1995. The role of sea spray in vadose diagenesis in Late Quaternary coastal deposits. Journal of Coastal Research 11, 1075–1088.

McKee, E.D., Ward, W.C., 1983. Eolian environment. In: Scholle, P.A., Bedout D.G., Moore, C.H. (Eds.), Carbonate Depositional Environments. AAPG Memoir, 33, American Association of Petroleum Geologists, Tulsa, Oklahoma, pp. 132–169.

Milnes, A.R., Hutton, J.T., 1983. Calcretes in Australia. In: Soils: an Australian Viewpoint. Academic Press, London, pp. 119–162.

Munsell, 1990. Munsell Soil Color Charts. Macbeth Division of Kollmorgen Instruments Corporation. Baltimore, Maryland.

Murray-Wallace, C.V., Brooke, B.P., Cann, J.H., Belperio, A.P., Bourman, R.P., 2001. Whole rock aminostratigraphy of the Coorong Coastal Plain, South Australia: towards a 1 million year record of sea-level highstands. Journal of the Geological Society of London 158, 111–124.

North American Commission On Stratigraphic Nomenclature, 1983. North American stratigraphic code. The American Association of Petroleum Geologists Bulletin 67, 841–875.

NSW Department of Mineral Resources, 1987. Lord Howe Island Geology, 1:15,000 Geological Map of Lord Howe Island. New South Wales Department of Mineral Resources, Sydney, and Lord Howe Island Board, Lord Howe Island.

Pickard, J., 1983. Vegetation of Lord Howe Island. Cunninghamia 1, 133–266.

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

Squires, D.F., 1963. Carbon-14 dating of the fossil dune sequence, Lord Howe Island. The Australian Journal of Science, (March) 412–413.

Standard, J.C., 1963. Geology of Lord Howe Island. Journal of the Proceedings of the Royal Society of New South Wales 96, 107–121.

Sutherland, L., Ritchie, A., 1977. Defunct volcanoes and extinct horned turtles. In: Lord Howe Island. The Australian Museum, Sydney, pp. 7–12.

Tucker, M.E., Wright, V.P., 1990. Carbonate Sedimentology. Blackwell Scientific Publications, Oxford, p. 482.

Vacher, H.L., Hearty, P.J., Rowe, M.P., 1995. Stratigraphy of Bermuda: nomenclature, concepts, and status of multiple systems of classification. In: Curran, H.A., White, B. (Eds.), Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda, Geological Society of America Special Paper 300. Geological Society of America, Boulder, Colorado, pp. 271–294.

Vacher, H.L., Rowe, M.P., 1997. Geology and hydrogeology of Bermuda. In: Vacher, H.L., Quinn, T.M. (Eds.), Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology, Vol. 54. Elsevier, Amsterdam, pp. 35–90.

Walker, R.G., 1992. Facies, facies models and modern stratigraphic concepts. In: Walker, R.G., James, N.P. (Eds.), Facies Models Response to Sea Level Change. Geological Association of Canada, Ontario, Canada, pp. 1–14.

Woodroffe, C.D., Murray-Wallace, C.V., Bryant, E.A., Brooke, B.P., Price, D.M., Heijnis, H., 1995. Late Quaternary sea-level highstands from the Tasman Sea: evidence from Lord Howe Island. Marine Geology 125, 61–72.

Yaalon, D.H., 1967. Factors affecting the lithification of eolianite and interpretation of its environmental significance in the coastal plain of Israel. Journal of Sedimentary Petrology 37, 1189–1199.