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Origin of the Late Neogene Roe Plains and their calcarenite veneer: implications for sedimentology and tectonics in the Great Australian Bight

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The Roe Calcarenite, a 2–3 m-thick, soft, quartzose molluscan sand of grainstone to rudstone texture, is a critical unit for deciphering the geodynamic and sea-level history of the southern Australian continental margin. Biostratigraphic and Sr-isotope analysis of molluscs and brachiopods confirms that the unit is Late Pliocene. Amino acid racemisation analyses indicate a minimum age of Early Pleistocene. The general depositional environment was a shallow illuminated shoreface to the inner shelf with the seafloor probably covered by seagrass, much like the modern seafloor offshore the Roe Plains today, but perhaps somewhat warmer. The calcarenite lies on an interpreted marine erosion surface cut into Upper Oligocene to Middle Miocene Eucla Group cool-water carbonates. Such planation, which affected all of the inner shelf, took place throughout the Early Pliocene due to the combination of uplift via basin inversion and eustatic highstand. The process, which led to ~85 km of cliff retreat in ~3 million years, is interpreted to be a variant on the shaved shelf process operating on the shelf today. The Roe Calcarenite is envisaged as the last of many calcarenites deposited during small-scale highstands that were eroded during subsequent transgressions. It is preserved because the Roe Plains were uplifted immediately after deposition, part of a widespread Plio-Pleistocene boundary tectonic event. It has been continuously exposed since uplift and subject to arid-zone pedogenic diagenesis. This succession is a relatively quiescent example of uplift, erosion and deposition related to basin inversion. It was much less intense than coeval events further east in the St Vincent, Otway and Gippsland Basins. Together, these Late Neogene tectonic-sedimentary packages illustrate the spectrum of stratigraphic successions that might be expected from basin inversion along an otherwise passive continental margin.

KEY WORDS: basin inversion, Great Australian Bight, Pleistocene, Pliocene, Roe Calcarenite, shaved shelf.

INTRODUCTION

The southern continental margin of Australia has been the site of cool-water carbonate deposition throughout the Cenozoic (McGowran *et al.* 1997). The inboard, shallow-water facies, however, have been variably subtropical in character at different times during this period (Lowry 1970; James & Bone 1989; Boreen & James 1993; Alley & Lindsay 1995; Lukasik *et al.* 2000).

Perhaps the most laterally extensive Late Neogene marine unit now exposed is the Roe Calcarenite, which occurs on land near the centre of the Great Australian Bight (Figure 1). Although described as part of the larger Eucla Basin (Lowry 1970), the Roe Calcarenite remains undocumented in detail. At present, it is thought to be Pliocene and/or Pleistocene in age (Ludbrook 1978) and so is critical to understanding the role of Late Neogene eustasy, tectonics and palaeoceanography along the northern part of the Southern Ocean.

The purpose of this paper is to: (i) document the main physical attributes of the Roe Calcarenite; (ii) determine the age of the sediments; and (iii) evaluate the significance of the formation in the wider context of Late Cenozoic history and development of the southern Australian passive continental margin. Detailed sedimentology will be part of a separate contribution.

SETTING

The Roe Calcarenite underlies the Roe Plains (Figure 1a), an arcuate platform near the geographic centre of the Great Australian Bight, just barely above sea level, and backed by the Hampton Range (Lowry 1970). It is situated between modern seacliffs (Figure 2a) that extend 200 km to the west (Baxter Cliffs) and 220 km to the east (Nullarbor Cliffs). The Roe Plains are ~35 km across at their widest point and extend east–west ~300 km, from Twilight Cove to Wilson Bluff (Figure 1b).

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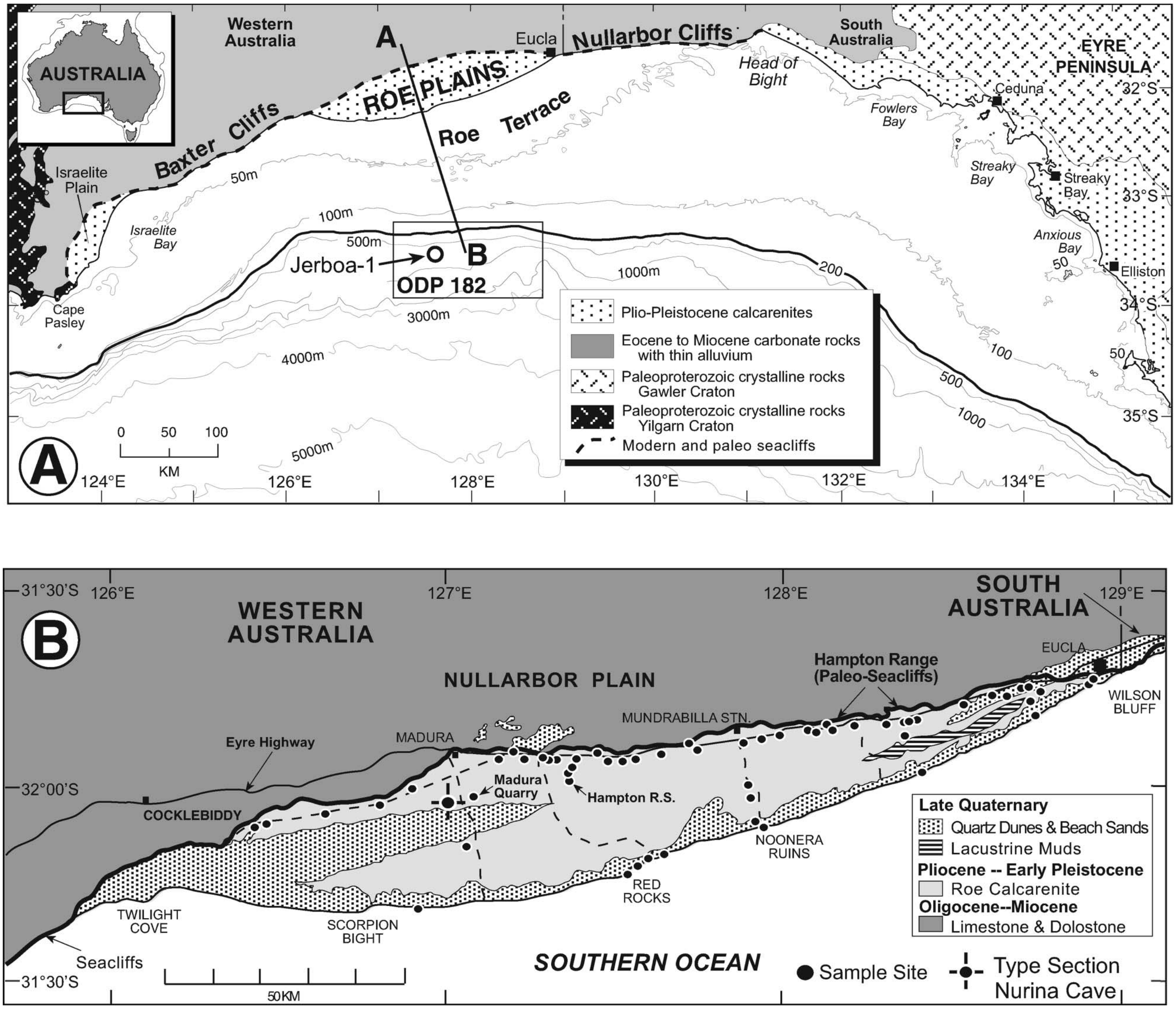

Figure 1 (a) Location, geography, bathymetry, and surface geology of the Great Australian Bight region; Roe Plains are located between Baxter Cliffs and Nullarbor Cliffs. The location of section A–B (Figure 3) is shown. The box indicates the region of the ODP Leg 182 drillsites. (b) Surface geology of the Roe Plains and location of sites investigated. Hampton R.S., Hampton Repeater Station.

The surface rises gently from sea level to a maximum height of ~30 m at Madura.

Today, the flat, arid, dusty clay plain is sporadically vegetated by grass, low halophytic shrubbery, tea-tree and mallee scrub (Figure 2b). The western end is covered with moribund, sparsely vegetated Pleistocene quartz aeolian sand dunes up to 100 m high that have migrated eastward some 100 km across the plain. This quartz sand, derived from the Albany coast in the very southwest of Western Australia (Lowry 1970), also fringes much of the Roe Plains coast as a series of partially mobile to grass-fixed dunes. There are no water courses on the plains. Parts of the eastern end of the Plains are veneered with Quaternary lacustrine clays and shelly quartzose sands.

The Hampton Range (Tate 1879) is an 80–90 m-high scarp along the inner margin of the Roe Plains and forms the front of the Nullarbor Plain. The escarpment (Figure 2b) is a palaeoseacliff (Tate 1879; Ludbrook 1958b; Lowry 1970) although some workers (Frost 1958) have invoked a tectonic, fault, origin. The degraded and commonly tree-covered cliff rises from the plain across a talus pile of clay, limestone and calcrete debris to the scalloped edge of the escarpment.

REGIONAL GEOLOGY

Overview

The southern perimeter of Australia that includes the Great Australian Bight is a divergent, passive continental margin. Cenozoic sedimentation in the Great Australian Bight produced an extensive but relatively thin (up to 800 m) Eucla Basin succession deposited in a predominantly platform-sag to platform-edge tectonic regime (Stagg *et al.* 1999). The Great Australian Bight portion of Australia's southern continental margin has been relatively stable throughout the Cenozoic, with geohistory analysis of the offshore Jerboa 1 well

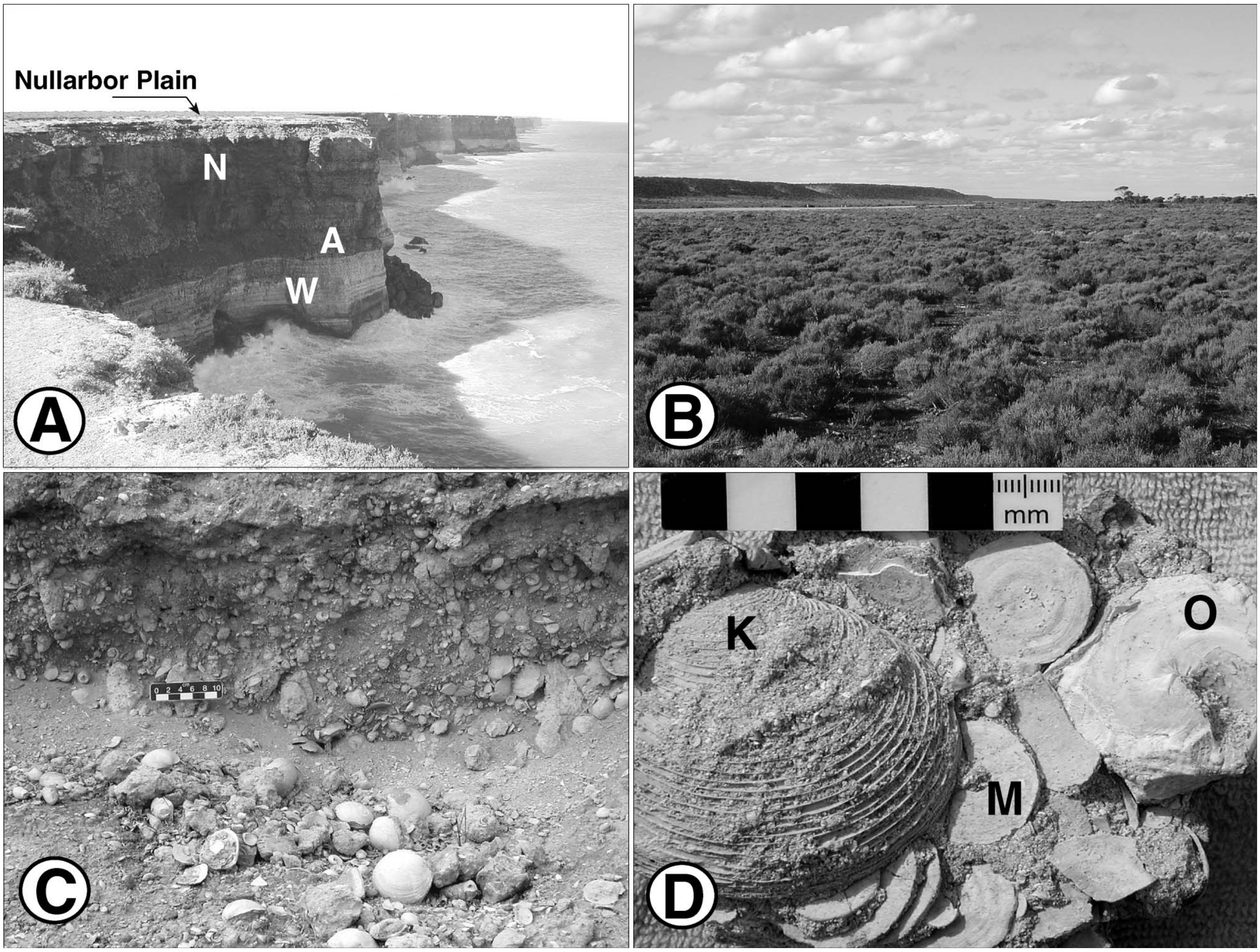

Figure 2 (a) Nullarbor Cliffs, about 70 m high looking east from the cliff top about 50 km east of Eucla (Figure 1), W, Wilson Bluff Limestone; A, Abrakurrie Limestone; N, Nullarbor Limestone. (b) Standing on Roe Plains looking northeast toward Hampton Range palaeoseacliffs, which are about 80 m in height. (c) Outcrop of Roe Calcarenite with innumerable bivalves (*Dosinia* sp. in foreground) in a small quarry near the Hampton Repeater Station (Figure 1b), scale in 2 cm increments. (d) Close view of Roe Calcarenite illustrating the bivalve *Katelysia* sp. (K), numerous tests of the large benthic foraminifer *Marginopora vertebralis* (M), and an oyster fragment (O).

(Figure 1a) indicating minimal Tertiary subsidence (Hegarty *et al.* 1988). Middle Miocene tectonics resulted in uplift and exposure of the Nullarbor Plain, and restriction of most Neogene sedimentation to the modern outer shelf and upper slope (Figure 3).

The Eucla Basin itself extends up to 350 km inland from the present coastline, and seaward some 200 km to the modern shelf edge and upper slope (Feary & James 1998). Most onshore carbonates (Figure 4) have been subaerially exposed since the Middle Miocene, and the modern surface, particularly away from the coast, is an extensive, flat karst plateau with little vegetation (the Nullarbor Plain).

Onshore Eucla Basin

EOCENE

The oldest Cenozoic unit (Figure 4) is the thin, Middle to Late Eocene, estuarine–fluvial to marine Hampton Sandstone (Lowry 1970; Benbow 1990; Clarke *et al.* 2003). This is overlain by the ~300 m-thick Wilson Bluff Limestone, a white, muddy, burrowed unit of Middle and Late Eocene age rich in bryozoans and planktonic foraminifers (Lowry 1970).

OLIGOCENE–MIOCENE

The Oligocene to Early Miocene Abrakurrie Limestone is a coarse-grained bryozoan calcarenite (James & Bone 1991; Li *et al.* 1996), is distinctly cyclic, contains numerous hardgrounds (James & Bone 1992), and is locally dolomitised. The late Early Miocene to early Middle Miocene Nullarbor Limestone is a hard, fossiliferous, muddy limestone (Lindsay & Harris 1975; Benbow & Lindsay 1988). It has a distinctly warmer water aspect than the underlying Abrakurrie Limestone, as reflected by ubiquitous coralline algae, numerous large benthic foraminifers, more abundant molluscs and local concentrations of zooxanthellate corals (Lowry 1970).

PLIO-PLEISTOCENE

Eucla Group carbonates on the Roe Plains are veneered by the Roe Calcarenite (Figure 2c, d), a thin (1–3 m)

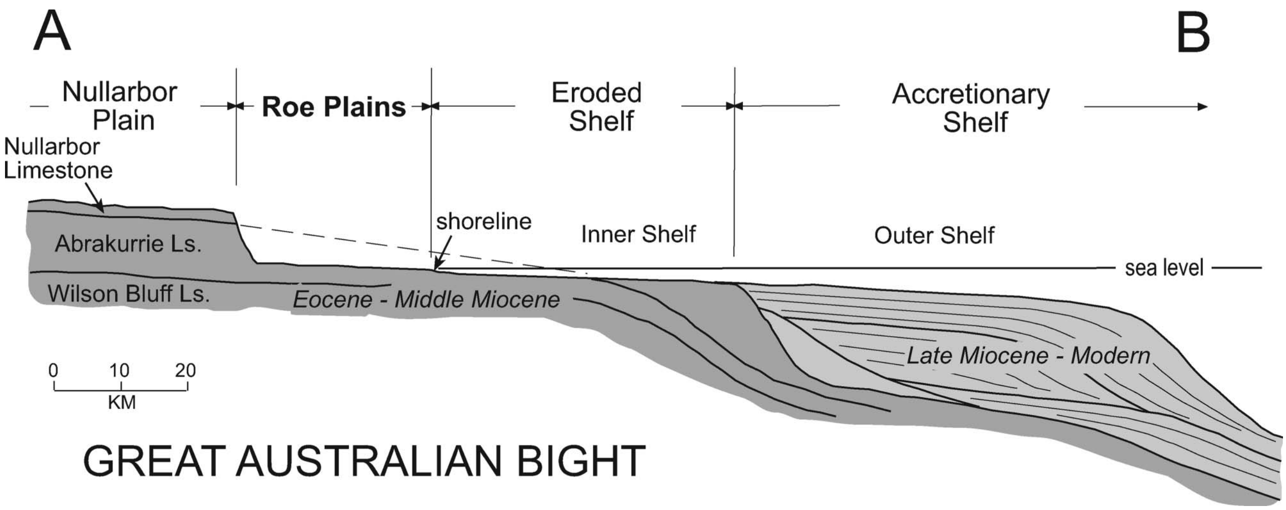

Figure 3 Schematic cross-section of strata on the outer part of the Nullarbor Plain and beneath the adjacent continental shelf based on Lowry (1970), Feary and James (1998), and Feary *et al.* (2000). Location on Figure 1a. The dotted line is the position of contact before erosion. Vertical exaggeration: ×40.

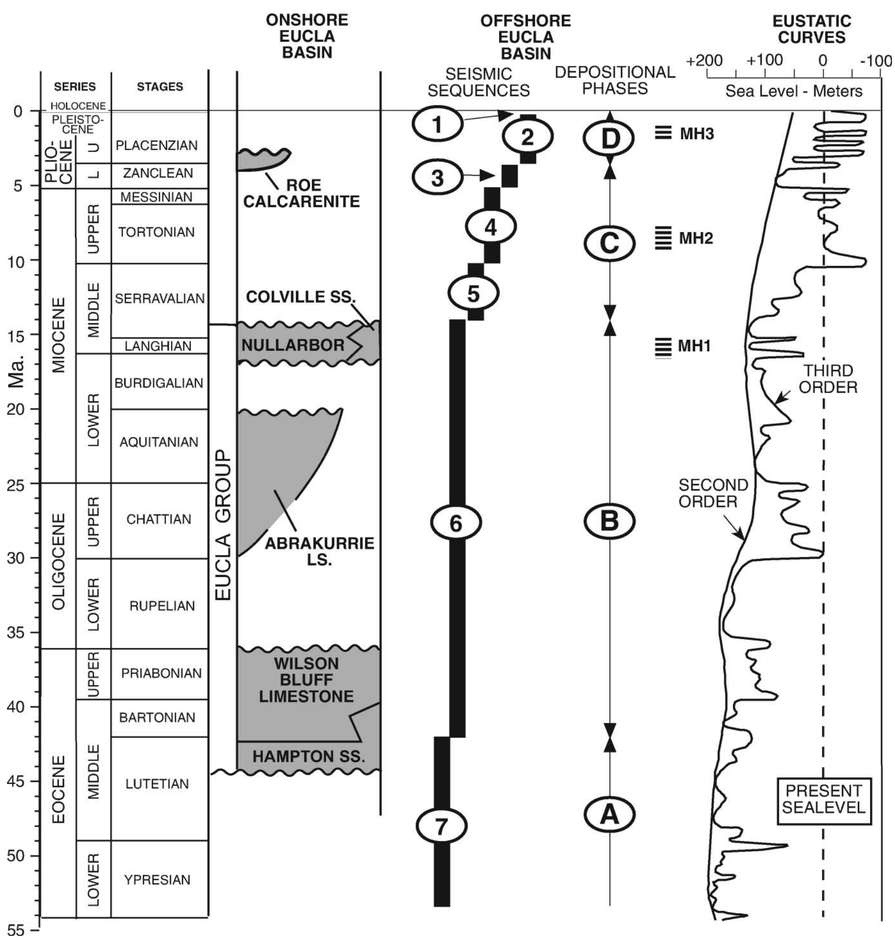

Figure 4 Simplified stratigraphic section of Cenozoic sedimentary rocks in the Eucla Basin. Onshore Eucla Basin stratigraphy after Lowry (1970), James and Bone (1991) and Li *et al.* (1996). Offshore seismic sequences and depositional phase after Feary and James (1998) and Feary *et al.* (2000). MH, Mega Hiatus events after Li *et al.* (2004). Eustatic curves after Haq *et al.* (1987).

fossiliferous limestone particularly rich in a diverse assemblage of shallow-water gastropods, bivalves and large foraminifers (Ludbrook 1969; Lowry 1970; Craig 1999).

Offshore Eucla Basin

There are no drillholes on the shelf, but seismic imaging allows the succession to be divided into seven sequences

that are interpreted to reflect four major depositional phases (Feary & James 1998) (Figure 4). Images further reveal that the shelf comprises two sectors: (i) an inner part, composed of seismic sequences 6 and 7 (depositional phases A and B, Eocene – Middle Miocene), that has been differentially uplifted and is now subject to erosion; and (ii) an outer part, formed of seismic sequences 1–5 (depositional phases C and D) that is accretionary and post-Middle Miocene in age (Figure 3). Basic sequence stratigraphy of the upper slope has been confirmed by ODP drilling during Leg 182 (Feary *et al.* 2000, 2004).

The Roe Plains are thus part of a much larger system (Figure 3) within which they comprise the inner erosional shelf sector. This sector terminates abruptly against seacliffs that are up to 90 m high and many hundreds of kilometres in extent except along the front of the Roe Plains where the shoreline is a series of extensive calcarenite dunes interspersed with local low bedrock outcrops.

Modern shelf

The Great Australian Bight today is a site of cool-water carbonate sedimentation throughout (Wass *et al.* 1970) ranging from locally warm temperate inboard to cool-temperate outboard (James *et al.* 1994, 1997, 2001). The inner shelf is an area of abundant macrophytes and seagrasses, active carbonate sediment production and variable accumulation. Much of the seafloor is a shaved shelf with only a metre-thick sediment veneer over Cenozoic bedrock. The outer shelf and upper slope is a variably productive carbonate factory characterised by prolific calcareous epibenthic growth (especially bryozoans) on hard substrate 'islands' which shed particles into surrounding sands and muds. Patterns of Holocene sedimentation are linked to modern oceanography in this high-energy setting, which is characterised by overall downwelling (Rochford 1986; James *et al.* 2001). Numerous rhodoliths occur on the northwest inner shelf, where summer waters are the warmest in the Great Australian Bight, locally rising to 23°C. The outer shelf and upper slope are areas of prolific bryozoan growth, likely linked to upwelling, except in the central Great Australian Bight, a region of year-round downwelling (James *et al.* 2001) where the regime is one of offshelf fine sediment transport and carbonate mud deposition.

ROE CALCARENITE

Disposition

The Roe Calcarenite is an unlithified to friable lime sand, rich in conspicuous large macrofossils (Figure 2c), that overlies a planar surface eroded into the Abrakurrie and locally Wilson Bluff Limestones (Figure 5). Originally mentioned by Tate (1879) and Ludbrook (1958a, b), the unit was more thoroughly and formally described by Lowry (1970). The type section, 1.5 m thick, is located at the entrance to Nurina Cave (Figure 1). Construction activity in recent years has greatly increased the number of exposures available for inspection. Most are small, environmentally groomed borrow pits about 1 m deep, along sides of the Eyre Highway between Eucla and Madura. Other localities are present around small dolines and sinkholes along dirt tracks to the shoreline and to the west-southwest of Madura (Figure 1b). The best sites are adjacent to new microwave towers and at a large road metal quarry south of Madura. Lowry (1970) also

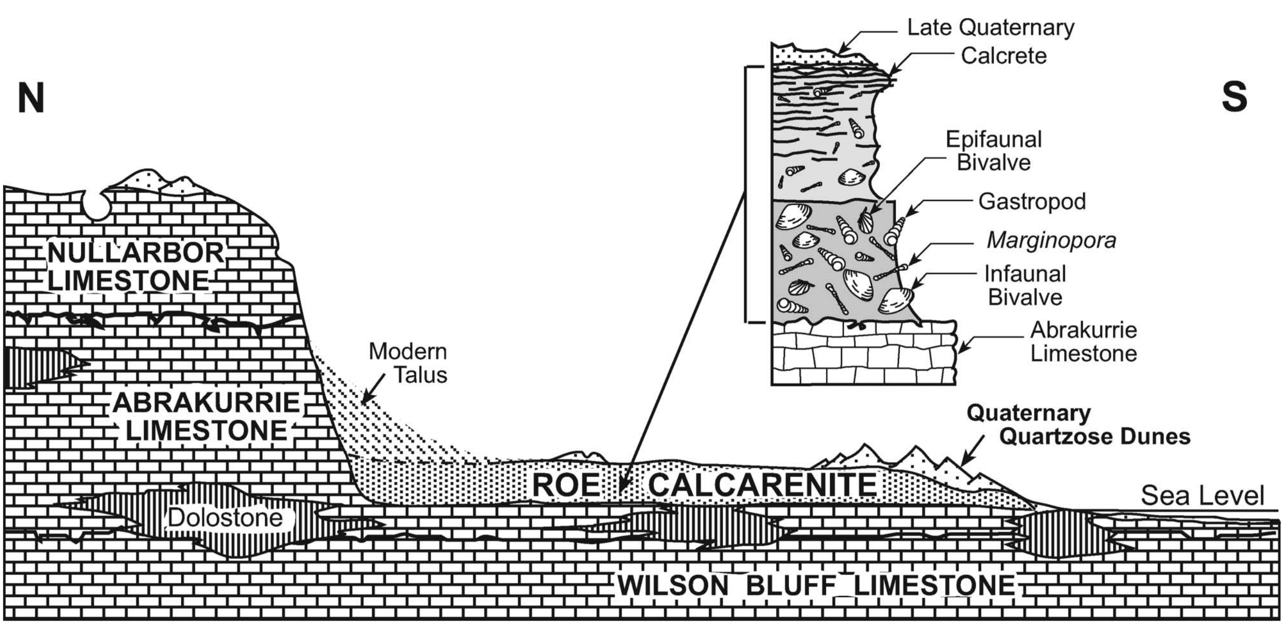

Figure 5 Diagrammatic cross-section of the Roe Plains from Madura southward to the coast. The inset is a summary section of the 2-m-thick Roe Calcarenite.

included elevated beach deposits in the Roe Calcarenite of probable last interglacial (5e) age, but these isolated, compositionally different deposits are not included here.

The climate in the area has been arid to semiarid since deposition, resulting in extensive calcretisation. Such alteration affects the upper several tens of centimetres and commonly extends to depths of a metre or more, variably obscuring the depositional fabric. The arid climate has also resulted in the precipitation of gypsum in the sediment, especially adjacent to the Hampton Range.

Underlying surface

The underlying surface is mostly cut into Abrakurrie Limestone that is variably lithified but generally hard. This substrate is only locally visible and is completely buried along the foot of the Hampton Range. Where best exposed at Madura Quarry, over an area of about 0.2 km^2, it is remarkably flat and planar. The surface is conspicuously textured by root casts related to post-depositional, pre-Roe Calcarenite terrestrial vegetation. The surface is eroded into dolomite at Red Rocks (Figure 1b).

Stratigraphy and composition

The sediment is best described as a poorly cemented molluscan calcarenite. The mollusc rudstones to floatstones are rich in bivalves and gastropods, and the conspicuous large foraminifer *Marginopora vertebralis* (Figure 2d), in a matrix of numerous coralline algae, molluscan fragments and smaller benthic foraminifers, principally miliolids, and minor quartz. The rich molluscan fauna includes some 265 species (Ludbrook 1978). The fossils are well preserved apart from minor epizoan borings or encrustation, and juvenile and bivalved specimens are common. The fauna contains a conspicuous Indo-Pacific tropical element including cypraeids, volutids, mitrids, coniids and spondylids, the larvae for which were advected into the area by the warm proto-Leeuwin Current. These tropical taxa occur intermixed with endemic southern temperate species. Though the majority of forms present belong to living species (65–70%: Ludbrook 1978 p. 29), extinct taxa, mostly of warm-water affinities, include *Miltha, Anodonta, Timoclea* and *Hartungia*. Gastropods are still aragonite, and other constituents remain high-Mg calcite, indicating little post-depositional diagenesis, which is not unexpected in this relatively arid region.

At most localities, the unit is essentially a single facies. Rarely, there is a distinct stratigraphy (Figure 5 inset), and at such localities, Abrakurrie Limestone is directly overlain by bioturbated mollusc rudstone with a pink cast. This can be capped by a ~10–20 cm-thick, finely laminated, fine- to very fine-grained mollusc–foraminifer grainstone, or a burrowed *Thalassinoides* omission surface. This middle unit varies laterally over 50–100 m. The upper metre or so, typically altered by calcretisation, is similar in composition to the lower unit, but less fossiliferous. Inboard, adjacent to parts of the Eyre Highway, the upper unit grades into a fine grainstone with fewer macrofossils.

AGE

Biostratigraphy

On the basis of the molluscan assemblage, Ludbrook (1978) inferred an Early Pleistocene age for the Roe Calcarenite, whereas Lowry (1970) proposed an Early or Middle Pleistocene age. Ludbrook (1983) took the view that the presence of the planktonic gastropod *Hartungia chavani* supported an Early Pleistocene age. Based on the restriction of this species in the New Zealand fossil record to the late Waitotaran and early Nukumaruan (*ca* 3.0–2.0 Ma) and its absence from the Pleistocene fossil record there, the abundance of *Hartungia chavani* in the Roe Calcarenite suggests a slightly older, Late Pliocene age (Beu & Maxwell 1990 p. 292; Kendrick *et al.* 1991). The presence of the bivalve *Cucullaea* likewise suggests a Pliocene age (Darragh 1985). McGowran *et al.* (1997), on the basis of microfossil and sequence stratigraphic correlation, also favoured a Pliocene age. Thus, integrated biostratigraphic attributes strongly argue for a Late Pliocene age. The abundance of tropical taxa in the Roe Calcarenite is consistent with its deposition both during the warmer Pliocene period in general and at an interglacial highstand of sea level in particular.

Sr-isotopes

METHODS

The $^{87}Sr/^{86}Sr$ composition of mollusc and brachiopod shells (Table 1) was measured using the techniques described by Kyser *et al.* (1998). The mineralogy of each sample was first determined by standard XRD techniques and observed under cathodoluminescence to substantiate the lack of diagenetic alteration. The Sr-isotope curve for seawater used in this study is from Farrell *et al.* (1995).

RESULTS

The majority of results ($n=7$) from Madura Quarry (No. 54) and Hampton Repeater Station (No. 25/18) (Figure 1b) fall in a narrow range 0.709066–0.709085. A second set from Hampton Repeater Station (No. 22/18) ranges from 0.709050 to 0.709055 ($n=2$). A third set from Hampton and Madura Quarry, the only analyses on the large gastropod *Campanile* ($n=2$: aragonite), ranges from 0.709125 to 0.709130, conspicuously higher than all the others. This third set of analyses may reflect some meteoric neomorphism, although both samples tested as pure aragonite by XRD, and cathodoluminescence examination showed no alteration.

Using a Pleistocene–Pliocene boundary value of 1.8 Ma (Berggren *et al.* 1995) and the lookup table of McArthur *et al.* (2001), most analyses (Figure 6) fall in the Late Pliocene window (*ca* 3.4–2.0 Ma). However, the placement of the Plio-Pleistocene boundary, in precise chronostratigraphic terms, is a topic of current reconsideration (Remane 1997; Shackleton 1997; Pillans & Naish

Table 1 $^{87}Sr/^{86}Sr$ values of molluscs and brachiopods.

Sample	Location	Material	$^{87}Sr/^{86}Sr^a$	Age (Ma)	Uncertainty (Ma)
NR 22/18-Br	Hampton Repeater Station	Brachiopod	0.709053	4.14	3.81 – 4.40
NR 22/18-P	Hampton Repeater Station	Pecten	0.709049	4.45	4.15 – 4.68
NR 25-C	Hampton Repeater Station	*Campanile*	0.709130	1.15	1.11 – 1.19
NR 25/18B-Bi	Hampton Repeater Station	Bivalve	0.709066	3.13	2.57 – 3.44
NR 25/18B-Br	Hampton Repeater Station	Brachiopod	0.709085	2.02	1.89 – 2.14
NR 25/18B-O	Hampton Repeater Station	Oyster	0.709080	2.18	2.07 – 2.29
NR 25/18B-P	Hampton Repeater Station	Pecten	0.709068	2.62	2.47 – 3.29
NR 54-Br	Madura Quarry	Brachiopod	0.709081	2.15	2.04 – 2.26
NR 54-C	Madura Quarry	*Campanile*	0.709128	1.17	1.13 – 1.22
NR 54-D	Madura Quarry	*Anodontia*	0.709076	2.30	2.20 – 2.44
NR 54-P	Madura Quarry	Pecten	0.709083	2.09	1.96 – 2.20

[a]Normalised to SMR 987 = 0.710235 (Hodell *et al.* 1991). Numerical age and uncertainty factor from McArthur *et al.* (2001).

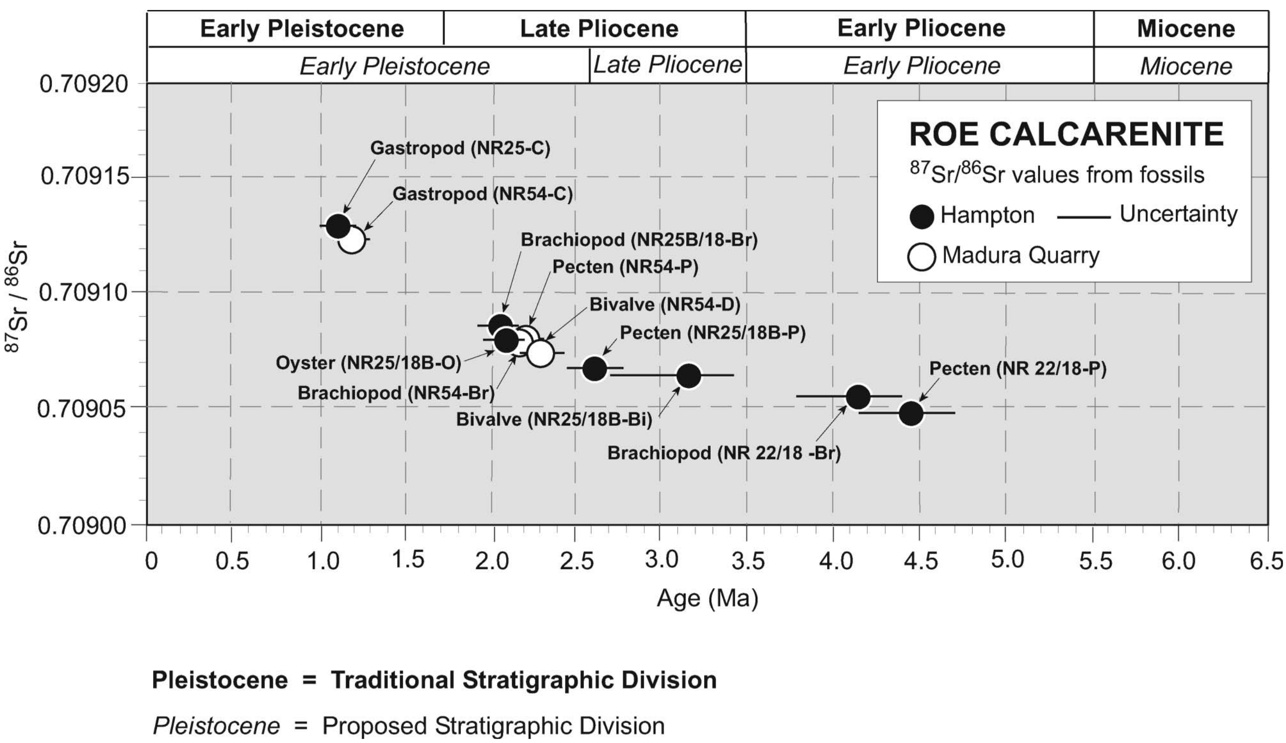

Figure 6 $^{87}Sr/^{86}Sr$ isotope values for fossils from the Roe Calcarenite (Table 1) and numerical ages determined using tables from McArthur *et al.* (2001). Error bars are at the 95% confidence limit. The traditional and proposed placements of the Plio-Pleistocene boundary are indicated at the top of the plot.

2004). The traditional approach would place the boundary, as adopted by the 27th International Geological Congress in Moscow in 1984, at 1.8 Ma. In contrast, the newly proposed boundary would be lowered to 2.6 Ma, coincident with the Gauss – Matuyama magnetic reversal (Partridge 1997; Suc *et al.* 1997; Pillans & Naish 2004). Sr-isotope dating of the Roe Calcarenite places it precisely within the 2.6 – 1.8 Ma interval of discussion.

Amino acid racemisation

METHODS

The fossil cockle *Katelysia rhytiphora* from a borrow pit at the Hampton Repeater Station (Figure 1b) was analysed for the degree of amino acid racemisation in the total acid hydrolysate and free amino acid fractions. Shells are from 2 m below ground surface. The mean annual air temperature at Madura is 18°C.

Calcareous sediment adhering to shell surfaces and diagenetically modified aragonite were removed with a dental drill, followed by successive washes in distilled water using an ultrasonic bath. The remaining outer surfaces of the shells (~10 – 15% by mass) were removed by a dilute acid etch (2 mol HCl). Shell samples were then digested in 8 mol HCl. Half of the solution was hydrolysed for 22 h at 110°C in 8 mol HCl. The unhydrolysed portion was analysed for free amino acids. Following cation-exchange isolation of amino acid residues (total acid hydrolysate and free amino acid

fractions), sample eluents were freeze-dried and derivatised following a standard procedure. Chromatography of the N-pentafluropropionyl D, L-amino acid 2-propyl esters was performed following the technique of Murray-Wallace (1993). Enantiomeric ratios were determined for the slow racemising amino acids leucine (LEU) and valine (VAL).

RESULTS

A high degree of amino acid racemisation is evident in the samples. The degree of leucine and valine racemisation (total acid hydrolysate) far exceeds that measured in *K. rhytiphora* of Last Interglacial age (marine oxygen isotope substage 5e; 125 ka) from the Minim Cove Member of the Tamala Limestone, Perth Basin. The current mean annual temperature at this site is equivalent to the Roe Plains, and by analogy, both deposits may have experienced similar long-term diagenetic temperatures (Murray-Wallace & Kimber 1989) (Table 2). The Roe Calcarenite is, therefore, significantly older than the Last Interglacial maximum, based on the degree of racemisation. The degree of racemisation is similar to that for the *K. rhytiphora* from the Plio/Pleistocene Jandakot Member of the Yoganup Formation, Perth Basin, suggestive of a similar age (Murray-Wallace & Kimber 1989) (Table 2). The Jandakot sediments were assigned a Plio-Pleistocene age by Mallett (1982) based on the presence of phylogenetically primitive forms of *Globorotalia truncatulinoides*.

With the exception of one shell specimen (UWGA-1051, Table 2), the degree of racemisation in the free amino acid fraction in *K. rhytiphora* is consistently higher than that in the total acid hydrolysate, a trend previously noted for *K. scalarina* from the same formation (Murray-Wallace 1987). The degree of free amino acid racemisation is close to equilibrium (i.e. approaching a D/L ratio of 1) confirming the great age of these shells (Table 2).

The degree of racemisation for the total acid hydrolysate in *Katelysia* spp. from the Roe Calcarenite statistically is significantly lower than that measured in the free amino acid fraction, implying that the racemisation reaction for the total acid hydrolysate has not yet reached equilibrium and therefore does not represent an infinite age (i.e. once equilibrium is established, only minimum ages can be determined).

The paucity of amino acid data for the Middle and Early Pleistocene from southern Australia makes it difficult to empirically calibrate racemisation rates for numerical age assessments for Early Pleistocene or Pliocene fossils. Accordingly, any numerical age assessment using this method should be viewed with caution. Similarity in the extent of amino acid racemisation in Roe Calcarenite *K. rhytiphora* and similar fossils from the Jandakot Member of the Yoganup Formation probably indicates an equivalent age. Thus, amino acid data are consistent with a Late Pliocene age for the Roe Calcarenite.

DISCUSSION

Southern Australia is, in general terms, a post-Jurassic passive continental margin that has undergone Late Cenozoic basin inversion due to a change in stress field brought about by collision and subduction in the north along the Australia–Pacific plate boundary

Table 2 Extent of leucine and valine racemization in specimens of the fossil cockle *Katelysia rhytiphora* and *Katelysia scalarina* from the Roe Calcarenite, Roe Plains, Western Australia.

Sample	Amino acid D/L ratio			
	Leucine		Valine	
	Total	Free	Total	Free
Katelysia rhytiphora				
UWGA-1051	0.697 ± 0.014	0.539 ± 0.012	0.768 ± 0.033	0.752 ± 0.011
UWGA-1052	0.608 ± 0.007	0.901 ± 0.009	0.779 ± 0.009	0.985 ± 0.002
UWGA-1053	0.807 ± 0.007	0.908 ± 0.025	0.875 ± 0.001	0.977 ± 0.002
UWGA-1066	0.647 ± 0.009	0.814 ± 0.041	0.912 ± 0.007	0.955 ± 0.026
UWGA-1067	0.791 ± 0.031	0.829 ± 0.017	0.911 ± 0.016	0.975 ± 0.004
***Katelysia scalarina* (Murray-Wallace 1987)**				
(1)	0.961 ± 0.005	0.809 ± 0.005	0.761 ± 0.005	0.711 ± 0.043
(2)	0.788 ± 0.005	1.000 ± 0.010	0.807 ± 0.002	–
(3)	0.774 ± 0.004	0.906 ± 0.003	0.806 ± 0.002	0.919 ± 0.005
(4)	0.789 ± 0.012	0.834 ± 0.008	0.842 ± 0.003	0.898 ± 0.025
(5)	0.619 ± 0.015	0.646 ± 0.001	0.810 ± 0.006	0.845 ± 0.056
(6)	0.698 ± 0.055	0.704 ± 0.015	0.967	0.816 ± 0.001
***Katelysia rhytiphora* Last Interglacial (125 ka), Minim Cove Member, Tamala Limestone, Perth Basin (Murray-Wallace & Kimber 1989)**				
	0.48 ± 0.03	0.79 ± 0.03	0.33 ± 0.02	0.51 ± 0.01
***Katelysia rhytiphora* Plio/Pleistocene Jandakot Member, Yoganup Formation, Perth Basin (Murray-Wallace & Kimber 1989)**				
	0.64 ± 0.11	0.85 ± 0.12	0.82 ± 0.05	0.83 ± 0.05

Total, total acid hydrolysate; Free, free amino acids.

(Coblentz *et al*. 1995; Perincek & Cockshell 1995; Veevers 2000; Dickinson *et al*. 2002). Formation of the Roe Plains and Roe Calcarenite is somehow a consequence of this Neogene tectonics and superimposed global eustasy (Figure 7). The problem is twofold: (i) genesis of the underlying unconformity; and (ii) origin of the Roe Calcarenite itself. The palaeoseacliffs (Hampton Range) and sub-Roe Calcarenite unconformity cannot be older than early Middle Miocene (Langhian Stage) because the face is cut into the Nullarbor Limestone (Lowry 1970; this study) (Figure 5). They also cannot be younger than Late Pliocene because the erosional surface is overlain by the Roe Calcarenite. Thus, the problem is constrained to events in the Great Australian Bight during the Late Miocene and Pliocene.

Unconformity

LATE MIOCENE

The mid-Miocene Nullarbor Limestone forms the upper surface of the Nullarbor Plain (Figure 7). The base of the Nullarbor Limestone is today tilted gently southward (~0.03°) and when projected oceanward intersects the outer part of the eroded inner shelf (Figure 3). Seismic images and shallow coring confirm that the inner part of the modern seafloor is bevelled, cut into progressively older Eucla Group carbonates landward (James *et al*. 1994; Feary & James 1998). The Roe Plains are contiguous with, and part of, this larger erosional inner Great Australian Bight shelf sector.

A Late Miocene tectonic event is present throughout southern Australia (McGowran *et al*. 1997) and generally interpreted to record early stages of basin inversion (Dickinson *et al*. 2002; Sandiford 2003). It also coincides with the change from Eocene–Oligocene cool-water carbonates (with brown coals in Victoria) to Plio-Pleistocene sandstones and siliciclastic-rich calcarenites. The age of the unconformity in the St. Vincent, Otway and Gippsland Basins is framed by folded and faulted Middle Miocene carbonates below and variably flat-lying Pliocene sediments above. ODP Leg 182 slope cores in the Great Australian Bight record slumps and stratigraphic gaps of varying duration during the Late

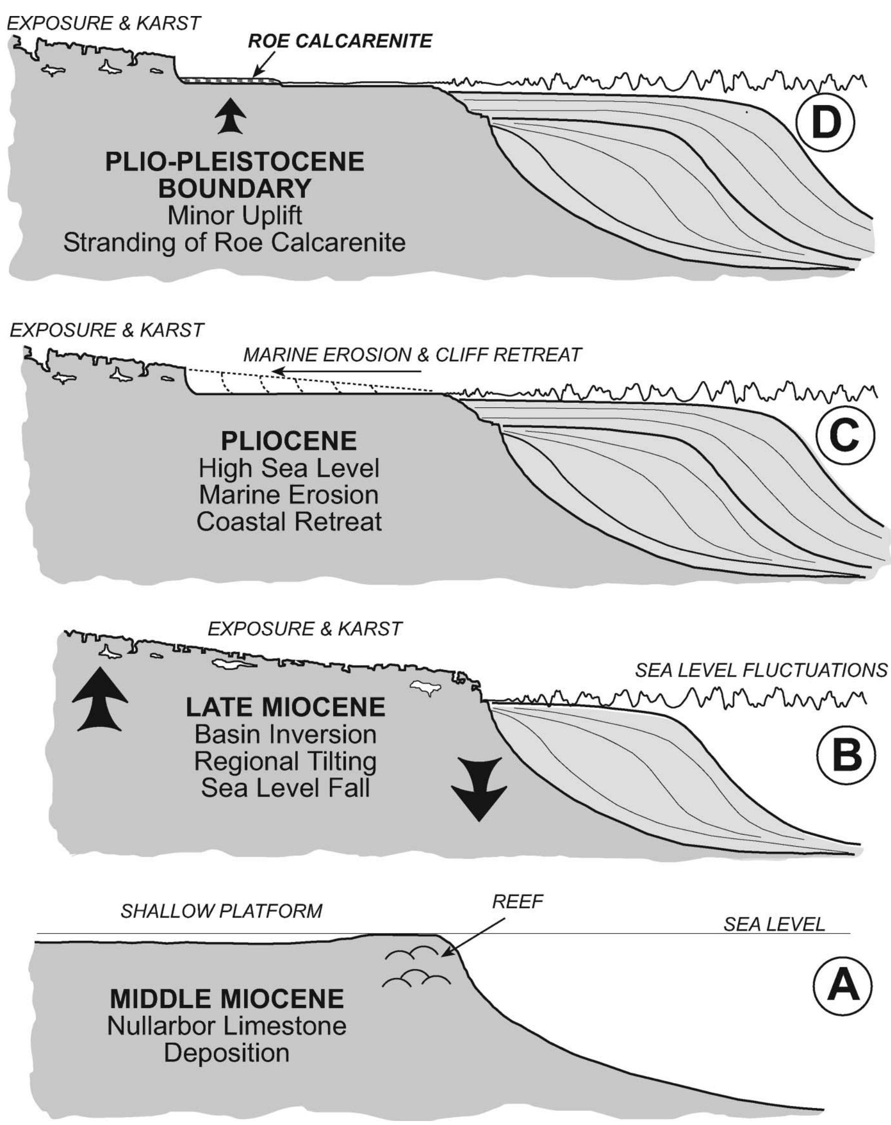

Figure 7 Development of the shelf and adjacent onland portion of the Eucla Basin during the Late Miocene to Early Pleistocene. Section roughly along the section A–B on Figure 1a.

Miocene (Feary *et al.* 2000). The interval is designated as Megahiatus 2 (9 – 8 Ma) (Figure 4) and interpreted to reflect mass wasting and erosion due to a series of strong, rapid uplift and subsidence events (Li *et al.* 2004). Uplift and seaward tilting of Eucla Group strata is interpreted to be the record of this event in the Great Australian Bight.

Late Miocene is a time of globally low sea-levels (Haq *et al.* 1987; Miller *et al.* 1998) (Figure 4). The newly tilted Eucla Group was likely subject to subaerial exposure and karstification at this time, with deposition confined to the outer accretionary shelf sector (Feary & James 1998). This was the start of the prolonged period of karsting that characterises the Nullarbor Plain today. At this time, the shoreline lay at or near the shelf edge, roughly 50 km seaward of the modern Roe Plains shoreline (Figure 7).

PLIOCENE

Overall, the Pliocene is an interval of high sea-level and warm conditions both globally (Zachos *et al.* 2001) and throughout the Southern Ocean (Hodell & Warnke 1991).

The unconformity surface below the Roe Calcarenite is smooth and flat, and is interpreted to be the result of marine erosion. It lacks any surface karst features, and there is no calcrete. Where exposed at Madura Quarry, it bevels pre-existing karst, confirming that prolonged subaerial exposure, here interpreted as Late Miocene, preceded planation. The regional Pliocene transgression is the most likely time for shoreline and marine erosion to have begun, a conclusion also reached by Dickinson *et al.* (2002) for the succession in Victoria. Marine and coastal erosion continued until Late Pliocene and is ongoing today along most of the submerged Great Australian Bight. Assuming that the Roe Plains were part of the inner shelf during this time, the total horizontal distance of planation that they represent is $\sim$85 km, and the time involved is $\sim$3 million years (5.5 – 2.5 Ma). This results in a calculated cliff-retreat of 28.3 m/10^3 y. Because the height of the cliffs being eroded would have increased over time, earlier rates would probably have been faster, and later rates slower, than this average.

However, it is unclear how this erosion proceeded: as one event or incrementally. For it to have resulted from one inundation, the rate of seacliff erosion ($\sim$ 85 km in 40 000 years—the length of an entire typical low-order cycle) would have been $\sim$2.1 km/10^3 y. This is between 15 and 200 times more rapid than any known rate of marine limestone erosion (Sunamura 1992; Murray-Wallace *et al.* 1998). Alternatively, the marine erosion could have been incremental and intermittent, occurring during periodic interglacial highstands. This is similar to processes occurring offshore today where the modern shaved shelf acts as a carbonate factory in which sediment is produced in shallow waters (within the zone of wave abrasion) but does not stay there; instead, much of the material is transported landward or seaward (James *et al.* 1994). Regionally, the Holocene veneer over Tertiary bedrock confirms that most or all previous Pleistocene deposits have been erased by marine/shoreline ravinement associated with transgression and regression.

The warm nature of Pliocene climate (Tiedemann *et al.* 1994) is consistent with generally high sea-levels. Nevertheless, Milankovitch cyclicity exists throughout the Pliocene stratigraphic record and indicates the presence also of regular eustatic cyclicity of 30 – 40 m magnitude. In addition, several more severe coolings, and large sea-level withdrawals, may have occurred in the Late Pliocene (Carter & Gammon 2004). The inner shelf of the Great Australian Bight must have been repeatedly flooded and exposed during this climate sea-level cycling. Overall, a low-lying hinterland and a cessation or even reversal of tectonic subsidence precluded sediment accumulation. Any sediment deposited during the brief highstands would have been rapidly removed in the subsequent phase of exposure, erosion and re-transgression.

PRESERVATION OF THE ROE CALCARENITE

A consequence of this interpretation is that the Roe Calcarenite is one of many previous thin calcarenites, but it is preserved while others have been removed by erosion. For preservation to be the result of eustasy alone, the highstand that produced the Roe Calcarenite must have been greater than any subsequent sea-level stand, or the sediments would have been likewise removed. Inspection of the eustatic curve for the last 4 Ma, derived from various proxies (Carter & Gammon 2004; Lisiecki & Raymo 2005), indicates that there is no highstand after *ca* 2 Ma whose peak is greater than those around 2.5 Ma, although many are very close. Thus, preservation likely had a eustatic component.

The presence of Roe Calcarenite sediments some 30 m above sea-level near the Hampton Range, much higher than any Plio-Pleistocene highstand, indicates that there must have been some uplift after deposition. ODP Leg 182 cores from the Great Australian Bight indicate a major Plio-Pleistocene boundary tectonic event, designated as Megahiatus 3, at *ca* 2.5 – 1.5 Ma (Li *et al.* 2004). This event, of lesser intensity than the Late Miocene one, is also seen in the St. Vincent, Otway and Gippsland Basins (Dickinson *et al.* 2002; Wallace *et al.* 2005). Therefore, the most likely explanation for the Roe Calcarenite is that it was deposited during the Late Pliocene highstand that most closely preceded the uplift associated with the regional Megahiatus 3 tectonic event. Thereby, the Roe Calcarenite represents a frozen snapshot of the character of the Great Australian Bight inner shelf sediment prism during the Late Pliocene.

Palaeoenvironment of the Roe Calcarenite

These sediments thus, in a microcosm, reflect the composition of a Pliocene inner shelf shoreface that was very similar to its modern counterpart (James *et al.* 1994, 2001; Feary & James 1998) and probably also to its Late Neogene predecessors. Ecologically, the prolific Roe Calcarenite molluscan fauna is dominated by taxa whose modern representatives live on a sandy, littoral seabed (e.g. *Glycymeris radians, Katelysia scalarina*).

That many of the bivalves present are preserved with conjoined valves, and that most fossils are well preserved, suggests that the shells accumulated nearby to their living habitat. As well as intertidal and littoral species, however, the Roe fauna also contains strong admixtures of species from three adjacent environments. These comprise species whose modern distribution is largely confined to: (i) inlets, enclosed bays and estuaries (*Cominella eburnea, Salinator fragilis, Anapella cycladea, Spisula trigonella*, *Campanile*); (ii) intertidal and shallow subtidal rock platforms and kelp beds (trochids, neritids); and (iii) offshore habitats, either pelagic (*Hartungia chavani*) or soft-bottom epibenthic [*Cymbiola (Aulicina) irvanae, Nanula galbina, Ericusa fulgetrum orca*]. It is apparent, therefore, that the Roe Calcarenite was deposited along a coastline and shallow sublittoral region in which tidal currents operated to move materials from bays and estuaries to nearby sites of littoral drift, and where open-sea swells intermittently moved pelagic and epibenthic shells onshore and added them to the accumulating shore-connected sediment prism.

The prolific large benthic foraminifers (Figure 2) confirm, as do the corallines, an illuminated seafloor in warm waters generally >20°C. Similar environments are present today on the inner part of the Great Australian Bight, although *Marginopora vertebralis* and similar photosymbiont-bearing foraminifers are smaller (James *et al.* 2001). Even warmer environments, with both large benthic foraminifers and azooxanthellate corals, are present along the Albany–Esperance coast of west Australia (Cann & Clarke 1993). These modern subtropical environments (Betzler *et al.* 1997; James *et al.* 1997) appear to be the result of the Leeuwin Current advecting warm tropical waters south along the west coast and east along the southern continental margin. Conditions appear to have been even warmer during Pleistocene highstand 5e, with *M. vertebralis* and subtropical molluscs present in shallow-water marine sediments as far east as St. Vincent Gulf (Murray-Wallace & Belperio 1991; Cann & Clarke 1993; Belperio 1995; Murray-Wallace *et al.* 2000). Thus, the Roe Calcarenite is an expected lithology developed in a warm, inner shelf environment in an otherwise cool ocean.

IMPLICATIONS

The origin of this thin, local unit in an otherwise vast depositional system has important implications for both palaeoceanography in the southern Australian region and the identification of basin inversion related to interplate stress in the geological record.

Palaeoceanography

Pliocene units across southern Australia are transgressive and usually interpreted as consistent with a warm climate and regionally high sea-level (McGowran 1977; Alley & Lindsay 1995). The biota of the Roe Calcarenite, including its contained tropical elements, is similar to the modern inner shelf flora and fauna of the western Great Australian Bight. This biota is consistent with the intermittent advection of warm water into the region during sea-level highstands, via the palaeo-Leeuwin Current, but tells us nothing about conditions during the intervening (presumably cooler) lowstands.

Lithostratigraphy

Basin inversion has dramatically changed the nature of deposition along the Great Australian Bight shelf from Eocene–mid-Miocene Eucla Group passive margin accumulation to a partitioned shelf system in the Neogene. Uplift on the inner shelf has resulted in essentially no accommodation space, and the record is therefore one of marine planation and little or no sediment accumulation. If interpreted correctly, this is one expression of carbonate sedimentation under high-energy conditions. Eucla Group sediments, because of ongoing subsidence and increasing accommodation, are manifest as a series of hardground-capped cycles, the hardgrounds being produced as the sea-level fell, and the seafloor entered the zone of wave abrasion (James & Bone 1994). A similar process occurred during the Eocene in the St. Vincent Basin (James & Bone 2000) and the Oligo-Miocene in the Otway Basin. In contrast, because of the lack of accommodation space, the sediment cycle produced during later Neogene highstands in the Great Australian Bight was eroded during each subsequent transgression. The stratigraphy is palimpsest: if the erosional surface is the papyrus, then the writing on the papyrus has been erased, only to be written on again and once more erased, time after time. The end result is a bare planar erosion surface with little or no sediment. The presence of phosphates along the surface in Victoria (Dickinson *et al.* 2002) further highlights the non-depositional attributes of this event.

Sedimentary record of basin inversion

The record of basin inversion in the Eucla Basin–Great Australian Bight region is one of relative quiescence. The major periods of uplift, while abruptly truncating deposition, are mostly followed by marine erosion and planation. Such tectonics may also have impinged upon the continental slope, causing mass wasting (Li *et al.* 2004). This contrasts with sedimentary basins further east, where basin inversion was accompanied by major uplift, doming and reverse faulting (Dickinson *et al.* 2002; Wallace *et al.* 2005). Thus, the Eucla region illustrates one end member of the spectrum of possible sedimentary responses to gentle tectonic uplift, where the uplift is marked mainly by a hiatus followed by an extremely thin sedimentary sequence.

SUMMARY AND CONCLUSIONS

Biostratigraphic and Sr-isotope dating methods confirm that the thin, mollusc-rich Roe Calcarenite is Late Pliocene (*sensu* traditional) in age. The extent of amino acid racemisation points to a Late Pliocene age based on a correlation with the Jandakot Member of the Yoganup Formation in the Perth Basin. Sediments rest on a planar unconformity interpreted to be the product of

Early to Late Pliocene marine erosion that removed most of the Nullarbor Limestone in the vicinity of the Roe Plains. The biota indicates deposition in a warm, inner shelf environment much like that of Pleistocene marine isotope stage 5e. The unit and underlying unconformity are the result of Late Miocene basin inversion along the southern continental margin, and global eustasy. The Roe Calcarenite itself, the product of deposition – erosion under high-energy marine conditions, similar to the modern offshore shaved shelf, is preserved probably because it was deposited during a highstand and stranded by a widespread Plio-Pleistocene boundary uplift event. The overall geodynamic response was much less in this sector than further east, highlighting the tectonic variability and different stratigraphic successions to be expected as a response to inter-plate stress.

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