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Pleistocene aeolianites at Cape Spencer, South Australia; record of a vanished inner neritic cool-water carbonate factory

NOEL P JAMES* and YVONNE BONE† **Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada (E-mail: jamesn@queensu.ca)*

†*School of Earth and Environmental Sciences, Geology, University of Adelaide, Adelaide, South Australia 5005, Australia*

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ABSTRACT

Aeolianites are integral components of many modern and ancient carbonate depositional systems.

Southern Australia contains some of the most impressive and extensive late Cenozoic aeolianites in the modern world. Pleistocene aeolianites on Yorke Peninsula are sculpted into imposing seacliffs up to 60 m high and comprise two distinct imposing complexes of the Late Pleistocene Bridgewater Formation.

The lower aeolianite complex, which forms the bulk of the cliffs, is a series of stacked palaeodunes and intervening palaeosols. The diagenetic low Mg-calcite sediment particles are mostly bivalves, echinoids,

bryozoans and small benthic foraminifera. This association is similar to sediments forming offshore

today on the adjacent shelf in a warm-temperate ocean. By contrast, the upper aeolianite complex is a

series of mineralogically metastable biofragmental carbonates in a succession of stacked lenticular

palaeodunes with impressive interbedded calcretes and palaeosols. Bivalves, geniculate coralline algae

and benthic foraminifera, together with sparse peloids and ooids, dominate sediment grains. Fragments of

large benthic foraminifera including *Marginopora vertebralis*, a photosymbiont-bearing protist, are

particularly conspicuous. Palaeocean temperatures are interpreted as having been sub-tropical,

somewhat warmer than offshore carbonate factories in the region today. The older aeolianite complex is

tentatively correlated with Marine Isotope Stage 11, whereas the upper complex is equivalent to Marine

Isotope Stage 5e. Marine Isotope Stage 5e deposits exposed elsewhere in southern Australia (Glanville

Formation) are distinctive with a subtropical biota, including *M. vertebralis*. Thus, in this example,

palaeodune sediment faithfully records the nature of the adjacent inner neritic carbonate factory. By

inference, aeolianites are potential repositories of information about the nature of long-vanished marine

systems that have been removed due to erosion, tectonic obliteration or are inaccessible in the subsurface.

Such information includes not only the nature of marine environments themselves but also

palaeoceanography.

Keywords Aeolianite, calcarenite, cool-water carbonate, Pleistocene, Southern Australia.

INTRODUCTION

Aeolianites ('eolianites', Sayles, 1931), wind-blown dunes composed of calcareous particles, are integral elements of many modern carbonate depositional systems and aeolianite limestones are important elements of the rock record (Abegg *et al.*, 2001; Brooke, 2001; Frébourg *et al.*, 2008); they are most conspicuous today as parts of high-energy marginal marine beach complexes in tropical and temperate latitudes, and are especially well-developed beneath atmospheric high-pressure cells in the horse latitudes. The best documented of these deposits are in Bermuda, the Bahamas, Mexico, the Persian Gulf and southern Australia (Brooke, 2001). The focus of previous studies has been to describe the spectacular bedforms (Abegg *et al.*, 2001), to understand the depositional dynamics, to relate the complexes to Pleistocene palaeoclimate and sea-level change (Frébourg *et al.*, 2008), and to use the deposits as examples of progressive meteoric diagenesis (Land, 1970; Reeckmann & Gill, 1981; Vollbrecht & Meischner, 1996).

Aeolianites can have several associated lithofacies. An *aeolianite complex* is, for the purpose of this paper, defined as a suite of genetically related aeolianites, ancient soils (palaeosols), beach sediments, and local shallow marine calcareous sands and calcarenites. Southern Australia has one of the most extensive Quaternary aeolianite depositional systems in the modern world, one that stretches intermittently as a series of seacliffs over many thousands of kilometres. The deposits extend from Victoria across South Australia and into Western Australia (Brooke, 2001); thus, they provide important analogues for the interpretation of similar deposits throughout the rock record.

This contribution examines one of the most spectacular of the Pleistocene shoreline escarpments at Cape Spencer along the southern coast of Yorke Peninsula (Figs 1 and 2). The purpose of this study is: (i) to ascertain whether different parts of the succession record changing offshore marine carbonate factories and thus varying temporal palaeoceanography; and (ii) to determine how many sea-level cycles are represented in this 80 m thick series of stacked palaeodunes. This type of analysis is now possible not only because of recent detailed analysis of modern inner neritic environments but also of open ocean seagrass meadows (James *et al.*, 2009) and macroalgal forests (James *et al.*, 2013).

Resolution of such questions involves detailed analysis of the sediments and their stratigraphy. Results will help with the interpretation of many similar successions across southern Australia and elsewhere and answer the question as to whether aeolianites can be used as archives of vanished marine carbonates throughout geological time. If there is a compositional linkage between the marine and adjacent aeolian carbonate deposits, then the aeolianites could prove a fruitful source of information about shallow marine environments whose deposits have been removed, eroded, deformed, or obscured by subsequent geological events.

SETTING

Overview

Southern Australia has a protracted geological history with Archean and Palaeoproterozoic basement rocks exposed across the region (Drexel *et al.*, 1993). These protoliths are overlain by Palaeozoic cover rocks as a series of early Palaeozoic fold and thrust belts with a north–south grain that are locally covered by Permian glaciogene strata (Drexel & Preiss, 1995). The present east–west physiography of the region is a product of Mesozoic rifting and drifting between Australia and Antarctica (Willcox & Stagg, 1990) with

parts of the resultant passive margin covered by Palaeogene and early Neogene limestones. Middle Miocene uplift brought these carbonates to the surface and many are now exposed, together with extensive Quaternary aeolianites, along ocean facing shorelines. The poorly lithified carbonates are easily eroded into seacliffs by cyclonic storm waves and rolling swells that are driven onshore by persistent westerlies. These escarpments provide excellent if largely inaccessible sections of Pleistocene limestones, many of which are aeolianites. The southern shore of the Yorke Peninsula is no exception.

QUATERNARY STRATIGRAPHY

The Quaternary record in this area comprises an offshore ragged blanket of cool-water marine carbonates and an onshore suite of aeolianites, local marine limestones and saline lake deposits (Belperio, 1995; James & Bone, 2011). Exposed Quaternary carbonates are grouped into several formations (Fig. 3).

The Bridgewater Formation encompasses all aeolianites (Boutakoff, 1963). The details of these rocks have been described across South Australia (Belperio, 1995; Wilson, 1991) and this stratigraphy is followed with simplification herein. The aeolianites are both stacked dune complexes, or in other areas, prograding suites of linear dune ridges. The nature and age of these aeolianites is best understood in the southeast of South Australia where they form a series of 13 shore-parallel palaeodune ridges separated by lagoonal corridors that become progressively older with distance from the modern coast (Cook *et al.*, 1977; Huntley *et al.*, 1993; Murray-Wallace *et al.*, 1999, 2001, 2010; Sprigg, 1979). These prograding deposits span *ca* 800 kyr of dune formation with each ridge corresponding to an interglacial sea-level highstand; they have developed in this way because of gradual regional tectonic uplift throughout the Pleistocene (Murray-Wallace, 2002; Sandiford, 2003). The most seaward of the ridges is generally referred to as the ‘upper Bridgewater member’ and formed during the last major interglacial *ca* 80 to 120 ka [Marine Isotope Stage (MIS) 5]. Coeval shallow marine and beach deposits of this unit are referred to

as the Glanville Formation and accumulated in waters somewhat warmer than those offshore today (Ludbrook, 1976). Holocene coastal and shelf carbonates are contained within the St. Kilda Formation (Belperio, 1995).

The ocean-facing coast of southern Yorke Peninsula is dominated by Bridgewater Formation aeolianites and intervening palaeosols (Fig. 4). These locally form either a formidable rampart of continuous cliffs or are isolated headlands of aeolianite separated laterally by wide arcuate beaches. The cliffs comprise dune complexes whose fronts have been eroded to beautifully expose internal stratal geometries (Fig. 2). On Yorke Peninsula these dunes decrease in height landward typically descending to just above sea-level within a few kilometres behind the coast. Depressions leeward of the dunes are locally occupied by small St. Kilda Formation (Holocene) saline lakes and lake complexes that host stromatolites, dolomites, and evaporites (Warren, 1982). This depiction is, however, overly simple because of the vagaries of coastal orientation, offshore sediment factories, and underlying topography that result in a complex intercalation of sedimentary facies resulting in individual exposures varying dramatically from outcrop to outcrop.

The aeolianite cliffs at Cape Spencer itself are composed of two aeolianite complexes. The lower aeolianite complex is correlated with the Bridgewater Formation whereas the upper aeolianite complex (Figs 2B and 5) will be demonstrated to be equivalent to the upper Bridgeport member and Glanville Formation. Regional mapping confirms that this stratigraphy can be carried throughout the area. Whereas most of the seacliff is resistant stacked aeolianites, the upper unit is somewhat recessively-weathering. These upper beds descend from the top of Cape Spencer down the lee side of the palaeodunes into a complex series of bedded calcarenites and calcretes in the depressions behind (Fig. 5).

METHODOLOGY

The Pleistocene section was documented using standard stratigraphic techniques of measuring, sample collecting, and lithological description. Samples were collected from all accessible units. Abseiling was employed in the middle part of the section that was otherwise inaccessible (Fig. 6B). Thin sections prepared from samples were described using standard petrographic techniques with the volumetric proportions of components assessed using comparator charts (Flügel, 2004). Mineralogy and magnesium content of calcites and dolomites were determined by X-Ray Diffraction at Queen's University on a Philips X'PERT PRO with an X'celerator detector (PANalytical BV, Almelo, The Netherlands) using standard protocols (Tucker, 1988). Several marine molluscs were analyzed by amino acid racemization (AAR) at the University of Wollongong following the technique of Murray-Wallace *et al.*, (2010). The results are reported in Table 1.

CAPE SPENCER REGION

Lower aeolianite complex (Bridgewater Formation)

Introduction

Approximately 56 m of aeolianite calcarenites with up to 10 intervening palaeosols (Fig. 6) rest unconformably on rounded erosional whalebacks of crystalline rock and form vertical to near vertical cliffs. Beds are typically lenticular (Fig. 6C and F) with a few continuous layers. Units are generally 2 to 4 m thick although some are up to *ca* 5 m. Intervening red-brown palaeosols are usually 1 to 2 m thick with some reaching *ca* 3 m (Fig. 4). Palaeowind directions as measured from cross-laminations are mainly west/south-west (Bateman, 1987). The dune sands are all now diagenetic low Mg-calcite (dLMC) and have undergone extensive meteoric diagenesis.

Calcarenites

The calcarenites are either structureless or strongly cross-bedded with single bed sets extending through the entire thickness of m-scale units (Fig. 6). Cross-beds are typically at a high angle $>15^\circ$. Many are weathered by a series of vertical to subvertical hollow tubes interpreted as being modern small karst dissolution conduits whereas others are characterized by rhizomorphs. Beds grade upward into palaeosols that typically have sharply truncated tops.

Petrography

The rocks are grainstones with particles that range in size from fine to coarse sand; they are predominantly biofragmental with a consistent 10 to 20% terrigenous fraction, most of which is angular to subrounded quartz. A thin calcite cement rind comprising $<5\%$ of the rock volume surrounds most grains. Although there are local meniscus cements, most are isopachous crusts 0.1 to 0.05 mm thick with local pyramidal crystal terminations, suggesting precipitation from phreatic waters. Most pore space is primary intergranular with only a few local vugs.

Composition

Biogenic grains (Table 2; Figs 7 and 8) are locally whole skeletons but most are broken and abraded to form rounded (Fig. 7) pieces. Molluscs (20 to 30%) and their moulds (10 to 20%) are the most volumetrically abundant particles. Moulds are empty except for micrite and red-brown oxide-filled microborings (micrite envelopes) along the margins. Epibenthic foraminifera comprise a consistent 20 to 25% of the sediment. Most are the large mixotroph *Amphistegina* sp. with a suite of numerous small miliolids and many *Elphidium* sp., together with conspicuous biserial infaunal tests. Echinoid plates and spines make up 10 to 20% of the sediment and are consistently surrounded by a thin rim of epitaxial

calcite cement. Bryozoan fragments are generally articulated branches, with some units having only a few such particles whereas others contain as much as 20% by volume. Coralline algae are mostly geniculate rods but never constitute more than 10% of the sediment. Barnacle pieces never comprise more than 5% of the grains but are present in most units. Relict particles (cf. James & Bone, 2011), generally fragmented bioclasts filled with red brown micrite, comprise *ca* 10% of the sediment. Finally, there are a few scattered older Cenozoic benthic foraminifera in the sediment (Milnes & Ludbrook, 1986).

Dolomite crystals are a minor but consistent part of the deposits (Fig. 7F). Rhombs are fine to medium sand size and range from clear to Fe-stained. Crystals vary from euhedral to subrounded to rounded grains. Most particles are Ca-rich (43.5 to 46.0 mole% MgCO_3 ; $n = 16$) but some have a second near-stoichiometric phase (48.0 to 49.5 mole% MgCO_3). This later phase may be a distinct 0.03 mm thin rind that is present in some rhombs as a final stage. Such rhombs are a common component of Cenozoic limestones across southern Australia (James *et al.*, 1993; Kyser *et al.*, 2002) and are clearly detrital as they are, for example, in the Plio-Pleistocene Roe Calcarenite (James & Bone, 2007; James *et al.*, 2006) and modern sediments on the continental shelf (Bone *et al.*, 1992).

Palaeosols

Palaeosols (Fig. 9) are generally soft and argillaceous. Many have conspicuous rhizomorphs and glaebules at or near the top. Colour range from uniform red-brown to mottled buff and red-brown with a sub-vertical fabric. The clay is illite (XRD; $n = 6$) and the red colouration is from Fe-oxides. Most contain angular black pebbles that are locally more numerous towards the top of any one palaeosol. The palaeosols are predominantly carbonate but they contain 35 to 41% insolubles ($n = 3$; average = 38).

Upper contact

The upper *ca* 2.5 m at modern ground level is a series of hard, laminated calcretes with numerous black pebbles and calcarenite clasts underlain by *ca* 1 m of chalky carbonate.

Upper aeolianite complex (upper Bridgewater Member)

This unit (Figs 4 and 5) has two distinct facies, an *Upland Facies* developed on top of the lower aeolianite complex and a *Lowland Facies* located in topographic depressions behind the dunes. These two facies form end members of a continuous series of deposits (Fig. 5).

Upland facies

Introduction

This unit is *ca* 16 m thick and is generally less lithified than deposits of the lower aeolianite complex. Beds are highly lenticular, with internal bedding parallel to sand body margins, even more so than in the lower unit, and disappear laterally over distances of 50 to 70 m (Figs 10 and 11A). Beds are up to 2 to 5 m thick and the whole section comprises from five to seven beds.

Calcarenites

These limestones are structureless to strongly trough cross-bedded with a few beds showing low-angle (<10°) planar laminations; rhizoliths are common. Each calcarenite grades from poorly cemented at the base to hard at the top. Some beds have poorly defined m thick red brown layers (Fig. 11B). The upper third of many beds is mottled red and buff with rhizoliths, local glaebules and black pebbles that increase

in numbers upward (Fig. 12). Units are typically characterized by penetrative pedogenic calcrete capped by a hard calcrete that is locally fragmented. Cross-bed measurements indicate a predominantly south-east palaeowind direction (Bateman, 1987).

Petrography

Unlike the lower aeolianite complex, individual beds are not easily separated into calcarenite and palaeosol because many calcarenites are slightly altered and not laterally continuous. The deposits overall can be completely unlithified or lightly cemented by spotty meniscus low-Mg calcite. The rock texture ranges from grainstone to packstone with up to 30% mud. All grains are well rounded and range in size from fine to very coarse sand. There is an infinitesimal quartz content, generally <5% and even this amount decreases upward in the section. Minerals present include high-Mg calcite, aragonite, and low-Mg calcite.

Sediment composition (Table 2)

The most volumetrically abundant grains (20% and 30%, respectively) are molluscs and coralline algae (Fig. 13). The mollusc fragments are mostly bivalve pieces with only rare gastropods. The coralline algae are all geniculate comprising broken *Corallina* sp. and lesser *Jania* sp. rods. Benthic foraminifera are almost as abundant, comprising 15 to 20% of the grains. The large, generally whole tests of *Amphistegina* sp. and fragments of *Marginopora vertebralis* are abundant together with numerous whole *Elphidium* spp. and various miliolids. Echinoderms and bryozoan pieces each comprise less than 10% of the sediment. The bryozoans are mainly branching types as bioclasts with cement, suggesting that many originate from Cenozoic limestones. Barnacles occur throughout as highly fragmented grains but never form more than 5% of the deposit. Clasts include relict bioclasts and fragments of Cenozoic limestone.

Peloids and ooids (Fig. 13E and F) are unique to the upper aeolianite complex. Micrite peloids are round to ovoid grains that form 10 to 20% of the grains. Superficial ooids, consisting of a peloid core and a thin cortex of tangential aragonite are scattered throughout but never form more than 5% of the deposit.

Lowland facies

Introduction

These complex interbedded calcarenites and calcretes become progressively more numerous with decreasing elevation, forming most of the topographically lower limestones in bays between stacked aeolianite headlands of the lower aeolianite complex. Lowland Facies limestones are exposed at a variety of beaches, especially Pondalowie Bay, Cable Bay, Chinaman Hat Bay and Willyama Bay (Figs 1 and 10).

The Lowland Facies limestones are strikingly heterogeneous and composed of a variety of interbedded lithologies, none of which are more than a metre or two thick (Figs 11 and 12). Strata are generally subhorizontal and locally pinch out against or grade laterally into large dunes of the upland facies with their uppermost beds overlapping these (Fig. 2). The maximum thickness of this facies is only *ca* 8 m, much thinner than the upland facies. All lithologies contain black clasts (cf. Miller *et al.*, 2013; Figs 11E, 11F and 12A). Lowland Facies carbonates are either cross-bedded aeolianite, brown carbonate sand with rhizoliths, conglomerates or repeated calcrete horizons. Mineralogically the carbonates are mostly dLMC with only local occurrences of lithologies with <10% HMC < LMC and aragonite.

Aeolianites

Aeolianites form lenticular bodies (Fig. 11A) tens of metres across and a few metres thick. The units can be cross-laminated with angles up to 30° or intensively disturbed by rhizoliths (Fig. 11C and D). Many have been affected by calcretization to varying degrees (Figs 11E, 11F, 12A and 12B) becoming porous and chalky locally.

Shallow marine calcarenites

A few thin lenticular units of marine calcarenites (Glanville Formation) are interbedded with aeolianite facies at Cable Bay and Pondalowie Bay (Fig. 12C and D). The fossils within these are wholly molluscs, both bivalves and gastropods.

The relatively thin 50 to 80 cm unit at Cable Bay overlies a well-cemented calcarenite and is capped by a calcrete with black clasts. The sediment is a bivalve floatstone with profuse *Katalysia peroni* in all orientations. Single shells and clusters of tiny *Batillaria australis*, larger *Diloma adelaidae* and a few scattered small *Bembecium nanum* comprise the gastropod biota. Rare *Turbo* sp. are also present along with small rhodoliths up to 2 cm in diameter. The large numbers of the infaunal cockle *Katalysia* sp. indicate a beach environment whereas the numerous whelks and periwinkles probably came from shallow adjacent offshore grass beds or macroalgal reefs (Edgar, 2000; James *et al.*, 2009, 2013; Ludbrook, 1984). Samples of *Katalysia* sp. have been dated by acid racemization to be 120 ka (Bateman, 1987). This MIS 5e geochemical age was confirmed by AAR analysis of a *Katelsia scalarina* shell that yielded similar results to those reported by Murray-Wallace *et al.* (2010, tables 5 and 6, fig. 8) in south-east South Australia (Table 1).

The 40 cm thick fossil-rich layer at Pondalowie Bay overlies a 20 cm thick hard brown calcarenite with no microfossils. This layer darkens upward to form a palaeokarst surface with solution-widened joints, solution pits, and vugs. The overlying fossiliferous molluscan rudstone is cream to brown, and soft at the base but hardens upward. Numbers of black pebbles also increase near the surface. The unit is overlain by a thin calcrete that locally extends down into the sediment as a series of irregular anastomosing crusts. The sequence ends with a 10 cm thick, clay-rich, calcarenite capped by another calcrete horizon.

Biota of the fossiliferous unit is distinctively more diverse than that at Cable Bay but still molluscan-dominant. Bivalves include *Chama ruderalis*, *Dosinia victoriae*, *Tellina albinella* and *T. deltoidalis*, *Sanguinolaria (Psammotellina) biradiata*, and *Brachiodontes erosus*. These are all shallow water (<20 m) infaunal sand dwellers or inhabit rocky substrates. The gastropods are a variety of predatory and herbivorous forms. Specifically they are *Sydaphera undulate*, *Haustrum flindersi*, *Conus anemone*, *Diloma adelaidae* (similar to *Clanculus* sp.), *Turbo torquatus*, *Phasianella* sp., *Columbellidae* sp. (whelk), *Mitrella* sp., *Nerita atramentosa* and *Amalda monilifera*. This assemblage lives today in sheltered areas of rocky coasts, under rocks, on offshore reefs and in intertidal to shallow seagrass or macroalgal environments, but always <10 m water depth (Edgar, 2000; James *et al.*, 2009, 2013; Ludbrook, 1984). Analysis of a *Sanguinolaria (Psammotellina) biradiata* shell and a *Turbo* sp. operculum yielded similar AAR results to those obtained from MIS 5e strata in other areas from southern Australia (Belperio, 1995). Thus, although the Cable Bay and Pondalowie Bay limestones are not necessarily from precisely the same stratigraphic horizon, the similarity of their ages indicates that comparable facies were present in the Cape Spencer region during MIS 5e.

Brown pedogenic sand

Brown to red-brown calcareous sands with profuse small rhizoliths (presumably terrestrial grass roots and related features) form metre-scale lenticular to laterally extensive beds (Fig. 11). These beds are interpreted as recording deposition in marginal marine environments with terrestrial grasses reflecting hiatuses within the sequence. Individual layers grade upwards from poorly cemented calcarenite with increasing depth of colour and more numerous black pebbles and rhizoconcretions towards the top capped by hard, laminated centimetre thick calcrete.

Conglomerates

Conglomerates are a series of hard, angular to slightly rounded calcarenite clasts with a relatively soft calcarenite matrix and numerous black fragments. Clasts include pebbles of aeolianite and of laminar calcrete from underlying beds but also limestones with no obvious local source.

Calcretes

Most of this facies consists of calcretes of various compositions (Figs 11 and 12) ranging from chalky, to hard crusts, pisolitic, cellular and rhizolites. Laminar micritic calcrete is penetrative and encrusts units of differing compositions. Layers are 0.5 to 3 cm thick; their general appearance is similar to that of calcretes worldwide (James, 1972; Wright & Tucker, 1991). Most calcretes are capped by a hard crust and contain numerous black pebbles that increase in abundance upward.

The most complex calcrete units are irregular and conspicuously lenticular on a metre-scale. Within these units, individual horizons consist of cellular and laminar calcrete containing angular clasts. Cellular calcrete comprises 10 to 50 cm size domains of relatively soft calcarenite surrounded by hard crusts several millimetres in thickness. From a distance the domains resemble large clasts; they are, however, autochthonous surrounded by calcarenites similar to those within the domain itself. Domain margins are gradational. Glaebules or pisoids are especially well developed between domains. In some areas the whole profile has a gradational basal contact with the calcarenite below but elsewhere is separated by one or two laminar calcrete horizons. The matrix between clasts and cellular domains is variably buff to red brown.

INTERPRETATION

Introduction

Interpretation of the age, stratigraphic correlation and origin of aeolianites is particularly challenging (Abegg *et al.*, 2001). There are typically no macrofossils by which to determine palaeoenvironments and not enough material to date the rocks geochemically. The grains are uniformly small and abraded fragments. With increasing time and subaerial exposure, metastable carbonate grains are subject to relatively rapid meteoric diagenesis and alteration to diagenetic low-magnesium calcite (Land, 1970). The original chemistry is quickly lost (James & Choquette, 1990), and interpretation must rely on petrography and knowledge of the biofragments. The deposits are, therefore, best understood by focusing on the origin of the dune sediment and how composition has varied through time.

Aeolianite sediment

Aeolianites are ultimately sourced from beaches (Short, 1988; Short & Hesp, 1982) and beach sediments are therefore the feedstock for all of these deposits. Beach sediment is, however, both allochthonous and autochthonous. Allochthonous materials come from: (i) longshore drift (carbonate and quartz grains); (ii) the offshore subtidal marine carbonate factory; and (iii) aeolian transport from the hinterland.

Autochthonous material includes the indigenous beach biota (mainly bivalves and gastropods). Of these sources, the offshore is the most important because of relatively high production rates. Selective sorting by waves and winds on the beach also modifies the sediments. Nevertheless if beach and onshore components can be subtracted from the sediment it may be possible to determine the nature of the offshore marine carbonate factory from dune samples.

Offshore marine environment

The adjacent offshore marine environment in this region is well documented (James & Bone, 2011). The main carbonate factories include: (i) rocky intertidal platforms; (ii) extensive seagrass meadows; (iii) subtidal rocky reefs with macroalgae; and (iv) open rippled calcareous sand plains. On a global scale the sediment-producing biota is strongly partitioned by sea water temperature between warm temperate (15 to 20°C) and subtropical (>20°C).

Beach environment

The beach environment is a biologically hostile carbonate factory with comparatively little carbonate production because of periodic sand movement caused by winds, waves and active terrestrial predators (for example, birds and crabs). Thus, organisms do not live ON the sand but must burrow INTO it. The

infaunal biota includes crabs, worms, molluscs and irregular echinoids. Infaunal irregular echinoids are not common on modern beaches in the area and bivalves dominate the autochthonous biota.

Provenance of lower aeolianite complex grains

Carbonate particles in the lower aeolianite complex are strikingly similar to those forming in the neritic zone offshore today (James & Bone, 2011). The grains are dominated by molluscs and epibenthic foraminifera with accessory echinoids. Bryozoans, although ubiquitous, are not numerous. Low numbers of corallines and barnacles together with relict Quaternary and older Cenozoic biofragments occur throughout.

Provenance of upper aeolianite complex grains

Upper aeolianite complex grains are wholly of marine origin, mostly molluscs, benthic foraminifera, coralline algae and bryozoans, together with peloids and minor ooids. Molluscs (bivalves and gastropods) live in both fully marine and beach settings. Benthic foraminifera include miliolids and *Elphidium* spp. that are characteristic of shallow cool to subtropical marine environments and are common offshore today in a variety of settings. Miliolids (10 to 30°) range from inner shelf to saline lagoon environments (Murray, 1991). The large benthic protist *Amphistegina* sp. is temperature-tolerant and is found mostly in warm-temperate regions above 14°C and to depths of 130 m (Betzler *et al.*, 1997; Murray, 1991). By contrast, *Marginopora vertebralis* is confined to sea water temperatures above *ca* 20°C (Langer & Hottinger, 2000; Murray, 1991) and although it lives on soft sediment, calcareous algae, seagrasses and rocky marine substrates, it is particularly common on seagrass (Hallock, 1984). This algal-symbiont bearing foraminifer is common in the Glanville Formation but not in other southern Australian Pleistocene carbonates (Belperio, 1995; Cann & Clarke, 1993; Ludbrook, 1976). It is

estimated that during the last interglacial the temperatures of inner shelf waters in southern Australia were *ca* 23 to 25°C roughly 7 to 9°C warmer than today, (Williams, 2001). Bryozoans are numerous in modern inner neritic warm temperate environments as are geniculate coralline algae, especially on marine seagrasses (*Amphibolis* and *Posidonia*) meadows (James & Bone, 2011). The relatively high proportion of mollusc fragments in the rock is undoubtedly due not only to the subtidal biotas but also to infaunal species on the beach itself. Finally, burrowing infaunal echinoids are most abundant in offshore open sand because of the difficulty of burrowing through seagrass rhizome systems.

Small superficial aragonite ooids (Fig. 13F) make up only a small fraction of the upper aeolianite complex, but their presence is significant. These grains are not calcrete glaebules; they have a distinctive cortex composed of tangentially oriented aragonite crystallites and are unlikely to be of lacustrine origin because of their association with marine biofragments. Marine ooids form today in shallow tropical subtidal environments in waters <6 m deep with temperatures >20°C (Peryt, 1983; Simone, 1981; Tucker & Wright, 1990). Water temperatures of this order are also suggested by preservation of the peloids that must have been lithified early (cf. Bathurst, 1975).

Palaeoceanography

Both upper and lower Cape Spencer aeolianites have the same basic characteristics with similar proportions of molluscs, but differ in detail. Grains in the lower aeolianite complex reflect a typical warm-temperate assemblage composed mostly of small benthic foraminifera, echinoids, molluscs and bryozoans. By contrast, the upper aeolianite complex has higher proportions of coralline algae and large *Marginopora vertebralis*, but distinctly fewer bryozoans and echinoids. The source areas were, therefore, different. The sediments of the lower aeolianite complex were largely derived from a marine environment like that offshore today, mostly warm-temperate with rocky reefs and open sand plains

(James & Bone, 2011). By contrast, the upper aeolianite complex sands came from warmer waters with abundant seagrass meadows. These components together with a few ooids, suggest that sea water temperatures were sub-tropical. Coral reefs were not present during either time.

DISCUSSION

The vanished marine record

Since the aeolianite components are derived from the adjacent marine realm they should reflect the character of inner neritic environment at the time when they formed. Although most particles are biogenic, if the Holocene of the South Australian margin is any guide (James & Bone, 2011), there should also be some stranded grains, relict grains, Cenozoic limestone fragments, dolomite and siliciclastic particles. Compositional analysis confirms that the two members of the Bridgewater Formation at Cape Spencer were derived from different marine settings. This finding has two major implications, one local and the other universal.

Local implication

The modern shelf off southern Australia is the largest cool-water carbonate depositional system in the modern world (James & Bone, 2011). The shelf itself is, however, mostly covered by metre thick layers of Holocene sediments mixed with stranded and relict grains on top of a karsted Miocene surface and locally older carbonate rocks (Hill *et al.*, 2009; James & Bone, 2011). There is little record of the intervening Pleistocene except in local onshore outcrops, beneath Holocene gulf sediments, and along the upper slope (Feary *et al.*, 2004). The present study confirms that the unique warm-temperate environment during MIS 5e is faithfully recorded in upper aeolianite complex palaeodunes at Cape Spencer. The deposits are quite different from the sediments in underlying older aeolianites, with the implication that

the older dunes had a different source area, i.e. the offshore marine environment was different. Thus, the palaeodunes contain a record of a style of sedimentation that is not operating today. A further implication is that the aeolianites across southern Australia should also reflect the now-erased offshore Quaternary marine depositional systems.

Universal implication

This discovery has implications for the older rock record. The aeolianites contain a record of marine depositional systems that have since been erased, tectonically obliterated, or are inaccessible in the subsurface.

This study confirms that this record should be preserved, although perhaps slightly modified, in coastal aeolianites across the region. Or, vice versa, the aeolianites contain important information about the nature of the adjacent inner neritic environments when they were formed. This latter aspect has great palaeoceanographic importance.

Pleistocene aeolianites and sea-level change

The relationship between aeolianite formation and sea-level is far from straightforward (see discussion in Brooke, 2001). Most (but not all) Quaternary aeolianite complexes worldwide are, following examples from Bermuda and elsewhere (Abegg *et al.*, 2001; Brooke, 2001; Frébourg *et al.*, 2008), interpreted as having formed in the following way. Aeolianites accumulated during interglacial sea-level highstands when the carbonate factory was close to shore. Palaeosols formed during glacial sea-level lowstand periods when the marine carbonate factory was below the platform edge or far from the accumulation

area. It is also clear, however, that some aeolianites could have formed during lowstands, especially where the shelf was narrow, whereas others could have resulted from reworking of recently exposed shelf sediments during the initial stages of subsequent sea-level fall. There is no single origin and each area is different but if the deposits are thick and extensive there must have been a temporally continuous nearby source of carbonate sediment. Early reworking depends largely on local climate; if it was humid or semi-arid the exposed sediment could have been fixed by vegetation or in the latter case covered by a calcrete carapace; if arid with strong onshore winds then some recently exposed marine sediment could have been blown onto the palaeoshoreline dunes (Brooke, 2001).

The thick section of lower aeolianites at Cape Spencer has well-developed terra rossa-like palaeosols, indicating a relatively humid climate (Schaetzl & Anderson, 2005). Together with rhizoliths this attribute suggests a vegetated palaeolandscape. Palaeosols in the upper aeolianite complex are similar but have more calcretes implying a semi-arid glacial climate (Esteban & Klappa, 1983).

Single or multiple sea-level highstands

The Cape Spencer section comprises two thick, stacked aeolianite complexes. Each complex is, however, composed of numerous aeolianites and palaeosols. The question is whether, as outlined above, each palaeosol represents a glacial period and each aeolianite an interglacial time, or whether each complex is the result of deposition during one highstand? Each complex is herein thought to represent only one interglacial highstand or MIS event for the following reasons:

1 Individual palaeodunes are lenticular and enclosing palaeosols bifurcate laterally; only rarely are they laterally continuous (Fig. 6). If palaeosols represented individual sea-level lowstands then most of them should be laterally traceable.

2 Sediments in each major aeolianite complex are compositionally different but internally indistinguishable from top to bottom. Even the prograding aeolianite ridges of the south-east Australian plain are different in composition from one to another (Belperio, 1995).

3 Palaeowind directions are similar throughout each of the two complexes; whereas there should be some variation if they were the result of different sea-level highstands and attendant distinctive climatic regimens.

4 Mineralogy is similar within each complex (a similar diagenetic grade) but different in each complex, implying different lengths of time in the meteoric diagenetic environment for each unit; a long period for the lower aeolianite complex, a comparatively short period for the upper aeolianite complex. If the units within the complexes were progressively younger upward and deposited during separate interglacials then the diagenetic grade should decrease from older to younger strata within a complex, but it does not.

As a result of the above, it is interpreted herein that the lower aeolianites along southern Yorke Peninsula do not represent a series of aeolianites with each one recording a sea-level highstand separated by a lowstand palaeosol. Instead the succession is thought to reflect deposition throughout one major interglacial highstand. This interpretation is supported in part by comparing the two complexes. The upper complex is *ca* 17 m thick and consists of seven discrete units separated by calcrete palaeosols. The last interglacial (MIS 5), with which it is correlated, consists of three highstands represented by units 5a, 5c and 5e with ages of 80 ka, 100 ka and 120 ka, respectively (Murray-Wallace *et al.*, 2001). This forms three discrete linear aeolianite ridges on the Coorong-Gambier coastal plain, some of which (for example, the Woakwine complex) are compound (Murray-Wallace *et al.*, 1999). Thus, the seven units of the upland facies of the upper complex at Cape Spencer do not represent a single sea-level highstand but

represent the result of a complex series of dune-building events that stretched across this time period. Using this analogue, the underlying lower aeolianite complex is interpreted as having been deposited either: (i) over a prolonged interglacial period; or (ii) as a stacked series of dunes many of which (and their intervening palaeosols) accumulated over several interglacial periods. The similarity in sediment composition strongly suggests the former.

Age of the lower aeolianite complex

The upper aeolianite complex was clearly deposited during the last interglacial (isotope stage 5e). This interpretation is supported by the presence of *Marginopora* sp. in the aeolian sediment; this protist is only found in the Glanville Formation and not in any older Pleistocene units (Cann & Clarke, 1993). In addition, many of the sediments consist of metastable carbonate minerals (HMC and aragonite) as do most Glanville Formation deposits (Belperio, 1995).

The age of the lower aeolianite complex that forms most of the cliff faces is, however, difficult to pinpoint; most evidence from correlative units (Belperio, 1995) suggests Middle Pleistocene. This is the age of most units on the Coorong-Gambier coastal plain (Cook *et al.*, 1977; Murray-Wallace *et al.*, 2001). Magnetostratigraphic measurements of this unit at Cape Spencer yield a Middle Pleistocene age (Bateman, 1987) wherein all units are normal magnetic, less than 690 kyr old. Thermoluminescence analyses of stratigraphically equivalent aeolianites on Eyre Peninsula to the west indicate an age between 180 ka and 630 ka (Wilson, 1991).

Possible resolution

The age of the lower aeolianite complex can be temporally framed via magnetostratigraphy and thermoluminescence but not assigned to a specific MIS (Murray-Wallace & Woodroffe, 2014). Geochemistry is not applicable because the sediments have been diagenetically altered (Bradley, 1999). Even though the sediments are changed to dLMC, the absence of extensive dissolution or karst suggests that the lower complex has not been in the meteoric diagenetic environment for a prolonged period and so on balance is likely to be Middle Pleistocene (Belperio, 1995). Most Early Pleistocene deposits are well-lithified limestones with extensive karst features (Brooke, 2001; Hearty, 1988; Hearty & O'Leary, 2008; Land, 1970; Murray-Wallace & Woodroffe, 2014; Vacher *et al.*, 1995).

Data for this time period comes from a variety of sources (see Murray-Wallace & Woodroffe, 2014) including the uplifted Coorong-Gambier Coastal Plain. The aeolianites in this elevated region in south-east South Australia are called 'ranges' and many have numerous beach ridges signalling slight fluctuations in sea-level during each 10 to 30 ky highstand (Sprigg, 1952, 1979).

Marine isotope stage 7 (*ca* 245 to 233 ka; *ca* 12 kyr duration) was one of the coolest interglacials in the last 400 kyr and sea-levels were lower, roughly 10 to 20 m below present levels. There is evidence globally of three peaks separated by substantially lower sea-level interludes. This is correlated with the Dairy and Reedy Creek ranges. The Dairy range has 14 beach ridges and the Reedy Creek has 10 to 20 beach ridges.

The MIS 9 highstand (*ca* 335 to 316 ka; *ca* 19 kyr duration) is not well-preserved in south-east Australia but sea-level seems to have been within a few metres of that today. It is equivalent to the West Avenue Range with three to four beach ridges representing stillstands or hesitations.

The MIS 11 highstand (420 to 360 ka; *ca* 60 ky duration) was the warmest of recent interglacials with attendant highstands that range from +10 to +20 m compared to today. This MIS is equivalent to East Avenue, Ardune and Baker ranges with as many as eight beach ridges each.

The lower aeolianite complex should be MIS 7 if stratigraphy were continuous. Marine isotope stage 7 is a good candidate because of numerous beach ridges in the southeast that could correlate with the 13 or so exposed palaeosols. On the other hand, it is not a good fit because sea-level was substantially below that at present. During MIS 9, although sea-level was close to modern, the deposits are not widely exposed worldwide and it has only a few beach ridges in the southeast. Perhaps the best possibility is MIS 11 with a high sea-level, long period highstand, several dunes in the Coorong region, and as many as 16 beach ridges. If this (MIS 11) is the case then the complex is not unique and has parallels in the numerous palaeodune–palaeosol packages in MIS 5a aeolianite complexes on Rottnest Island, western Australia (Hearty, 2003).

Internal aeolianite structure

The problem of the relationships between dune accretion and intervening palaeosols was recognized early in the Bermuda Pleistocene succession (Bretz, 1960). Two different palaeosols are recognized there: (i) true Terra-Rossa soils or palaeosols; and (ii) accretionary soils or protosols (Bretz, 1960; Vacher, 1971). True palaeosols record prolonged weathering, and are clay-rich, with attendant meteoric diagenesis

occurring during sea-level lowstands. Thus, the rocks below the palaeosol are more altered than those above. By contrast, protosols are much more calcareous and are generally in the shape of lenses or small blankets. Bounding limestones are of the same diagenetic grade. Protosols are interpreted as representing back-beach soils or grassy soils either in a topographic low between contemporaneous dunes or on the undulating windward flank of an inactive dune covered by a younger dune (Vacher, 1971). In short, protosols and aeolianites are roughly contemporaneous. Most of the lower aeolianite complex soils are likewise interpreted as protosols and are not lowstand palaeosols. Thus, most of the Bridgewater Formation as represented by the lower complex at Cape Spencer, is a series of intercalated palaeodunes and perhaps local palaeosols generated during short-lived sea-level falls during interglacials.

CONCLUSIONS

1 Pleistocene aeolianite seacliffs along the southern Yorke Peninsula comprise two discrete units; the basal Bridgewater Formation and the overlying 'upper Bridgewater member' herein referred to as the lower aeolianite complex and upper aeolianite complex, respectively. Each complex consists of a series of stacked palaeodunes and thinner intervening protosols.

2 The lower aeolianite complex forms the bulk of the cliffs as a 56 m thick succession of isolated or coalesce dune complexes. Sediment particles are mostly from bivalves, echinoids, bryozoans and small benthic foraminifera. This association is similar to that of sediments forming offshore today in a warm-temperate ocean. The whole succession is thought to have formed during one major sea-level highstand, namely Marine Isotope Stage (MIS) 11. Thus, the soils are interpreted as protosols that developed at the same time as the dunes and not the result of individual sea-level lowstands.

3 The thinner 16 m thick upper aeolianite complex comprises a succession-capping *upland facies* and a *lowland facies* that extends down the lee side of the lower aeolianite complex. Dating confirms that this member is *ca* 120 ka (MIS 5e) and so equivalent to the regional marine Glanville Formation. Lenticular units, metastable mineralogies, and impressive interbedded calcretes and palaeosols characterize these upper calcarenites. Bivalves, geniculate coralline algae and benthic foraminifera, together with sparse peloids and ooids, dominate sediment grains. Fragments of large benthic foraminifera with photosymbionts include *Amphistegina* sp. and *Marginopora vertebralis*. Palaeocean temperatures are interpreted as having been sub-tropical.

4 The aeolianite grains were primarily derived from adjacent inner neritic waters. Thus, they contain information about the neritic realm at the time when they formed. Such information includes not only the nature of the marine environments themselves but also palaeoceanography. These are invaluable repositories of information about marine systems that have disappeared because of the vagaries of time, erosion or tectonics.

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Table 1 Extent of amino acid racemization for fossil molluscs from the upper aeolianite complex, Cape Spencer, South Australia

Location	Sample (Queen's)	Sample (UWGA)	Material	D/L GLU	D/L VAL	D/L LEU	D/L ASP
Cable Bay	CB-1	10614	<i>Kataysia</i> <i>scalarina</i>	0.420±0.002	0.334±0.006	0.569±0.028	0.622±0.002
Pondalowie Bay	PB-4	10615	<i>Turbo</i> sp. operculum	0.416±0.001	0.535±0.006	0.593±0.001	0.629±0.001
Pondalowie Bay	PB-3	10616	<i>Sanguinolaria</i> <i>biradiata</i>	0.519±0.003	0.402±0.004	0.571±0.035	0.769±0.001

Amino acids: GLU = glutamic acid; VAL = valine; LEU = leucine; ASP = aspartic acid.

Table 2 Composition of Cape Spencer Bridgewater lithologies

Component	Bridgewater %	Upper Member Upland Facies %	Upper Member Lowland Facies %
Grain size	Fine – Coarse	Fine – Very Coarse	Fine – Very Coarse
Siliciclastic	10–20	<5	<5
Biogenic Fraction			
Mineralogy	LMC	LMC – HMC – Arag	LMC – trace Arag
Particles			
Echinoids	10–20	Trace–10	10–20
Bryozoans	0–20	Trace–10	5–10
Benthic Foraminifera	20	15–20	20
Planktic Foraminifera	Trace	Trace	Trace
Corallines (geniculate)	<10	20–25	10–15
Molluscs	20–30	20–30	20–30
Moulds	10–25	0	0
Barnacles	<5	<5	0
Peloids	0	10–20	10–20
Ooids	0	<i>ca</i> 5	0
Relict	10	0	0
Clasts	<5	5	5
Unidentified	15	10	10–20
Number of samples	25	16	3

HOLOCENE	ST KILDA FM.	
LAST INTERGLACIAL	GLANVILLE FORMATION <i>shallow marine limestones</i>	UPPER BRIDGEWATER MEMBER <i>aeolianites and palaeosols</i> <i>upper aeolianite complex</i>
EARLIER PLEISTOCENE	BRIDGEWATER FORMATION <i>aeolianites and palaeosols</i> <i>lower aeolianite complex</i>	

BRIDGEWATER FORMATION

CAPE SPENCER

CALCAREOUS SAND & CALCARENITE

PALEOSOL

CROSSBEDDING

← SAMPLE LOCATION

18 UNIT NUMBER

PLEISTOCENE AEOLIANITE SOUTHERN YORKE PENINSULA

BRIDGEWATER FORMATION AEOLIANITE COMPOSITION

UPPER AEOLIANITE COMPLEX

LOWER AEOLIANITE COMPLEX

WILLYAMA BAY