University of Wollongong

Research Online

Faculty of Science, Medicine and Health -
Papers: Part B

Faculty of Science, Medicine and Health

1-1-2020

Identification of reworked foraminifera in temperate carbonate sediments - A pilot study from the Coorong Coastal Plain, southern Australia

Thomas Oliver

Toru Tamura

Colin V. Murray-Wallace

University of Wollongong, cwallace@uow.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/smhpapers1>

Publication Details Citation

Oliver, T., Tamura, T., & Murray-Wallace, C. V. (2020). Identification of reworked foraminifera in temperate carbonate sediments - A pilot study from the Coorong Coastal Plain, southern Australia. Faculty of Science, Medicine and Health - Papers: Part B. Retrieved from <https://ro.uow.edu.au/smhpapers1/1106>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Identification of reworked foraminifera in temperate carbonate sediments - A pilot study from the Coorong Coastal Plain, southern Australia

Abstract

The extent of aspartic acid and valine racemization (total hydrolysable amino acids) in single tests of the benthic foraminifer *Lamellodiscorbis dimidiatus* is examined as a potential method for identifying reworked fossils within temperate, bioclastic carbonate sediments. The foraminifer *Lamellodiscorbis dimidiatus* is a physically robust species capable of withstanding reworking from weathered calcarenites, and has the potential to experience multiple sedimentary cycles of deposition and erosion with subsequent inclusion in younger sedimentary units. The extent of racemization measured in single tests of *Lamellodiscorbis* sp., reveals that the skeletal carbonate sand sampled from the modern foreshore at Long Beach, Guichen Bay, southern Australia, contains foraminifera ranging in age, from modern individuals, to specimens of late Holocene and Late Pleistocene age. The age of individual foraminifer, however, cannot easily be distinguished based on their taphonomic appearances. The AAR data for *Lamellodiscorbis* sp., imply that a significant proportion of the skeletal carbonate constituents within the calcarenites of the Coorong Coastal Plain represent reworked bioclasts. The reworked sedimentary constituents within younger sediments, has resulted from the erosion of older calcarenites during glacial cycles.

Publication Details

Oliver, T., Tamura, T. & Murray-Wallace, C. (2020). Identification of reworked foraminifera in temperate carbonate sediments - A pilot study from the Coorong Coastal Plain, southern Australia. *Marine Geology*, 421

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/337875791>

Identification of reworked foraminifera in temperate carbonate sediments – A pilot study from the Coorong Coastal Plain, southern Australia

Article in *Marine Geology* · December 2019

DOI: 10.1016/j.margeo.2019.106096

CITATIONS

0

READS

56

3 authors:

Thomas Sidney Newton Oliver

UNSW Canberra, ADFA

26 PUBLICATIONS 156 CITATIONS

[SEE PROFILE](#)

Toru Tamura

National Institute of Advanced Industrial Science and Technology

80 PUBLICATIONS 1,064 CITATIONS

[SEE PROFILE](#)

Colin V. Murray-Wallace

University of Wollongong

147 PUBLICATIONS 3,745 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:

QuakeRecNankai [View project](#)

PhD Research [View project](#)

Letter

Identification of reworked foraminifera in temperate carbonate sediments – A pilot study from the Coorong Coastal Plain, southern Australia

Thomas S.N. Oliver^{a,*}, Toru Tamura^{b,c}, Colin V. Murray-Wallace^d

^a School of Science, University of New South Wales Canberra, Northcott Drive, Campbell, ACT 2612, Australia

^b Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Central 7, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8567, Japan

^c Graduate School of Frontier Sciences, The University of Tokyo, 5 Chome-1-5 Kashiwanoha, Kashiwa, Chiba 277-8561, Japan

^d School of Earth, Atmospheric and Life Sciences, University of Wollongong, Northfields Ave, Wollongong, NSW 2522, Australia

ARTICLE INFO

Editor: Edward Anthony

Keywords

Amino acid racemization
Sandy barrier
Coastal dunes
Sediment reworking
Foraminifera
Lamellodiscorbis dimidiatus

ABSTRACT

The extent of aspartic acid and valine racemization (total hydrolysable amino acids) in single tests of the benthic foraminifer *Lamellodiscorbis dimidiatus* is examined as a potential method for identifying reworked fossils within temperate, bioclastic carbonate sediments. The foraminifer *Lamellodiscorbis dimidiatus* is a physically robust species capable of withstanding reworking from weathered calcarenites, and has the potential to experience multiple sedimentary cycles of deposition and erosion with subsequent inclusion in younger sedimentary units. The extent of racemization measured in single tests of *Lamellodiscorbis* sp., reveals that the skeletal carbonate sand sampled from the modern foreshore at Long Beach, Guichen Bay, southern Australia, contains foraminifera ranging in age, from modern individuals, to specimens of late Holocene and Late Pleistocene age. The age of individual foraminifer, however, cannot easily be distinguished based on their taphonomic appearances. The AAR data for *Lamellodiscorbis* sp., imply that a significant proportion of the skeletal carbonate constituents within the calcarenites of the Coorong Coastal Plain represent reworked bioclasts. The reworked sedimentary constituents within younger sediments, has resulted from the erosion of older calcarenites during glacial cycles.

1. Introduction

Skeletal carbonate sediments are an important sand source for many coastal areas around the world (Brooke, 2001; Davies, 1973; James and Bone, 2011). In such locations the growth and breakdown of molluscs, coralline algae, bryozoans, echinoids, foraminifers and other marine invertebrates commonly result in the production of sand-sized particles of skeletal carbonate. The skeletal carbonate sands generated within these continental shelf and platform environments are commonly transported onshore forming coastal dunes and barriers. Historically, the production rates of skeletal carbonate sand, by mechanical abrasion of marine invertebrates, as well as the onshore transport within these sedimentary environments has been difficult to quantify.

Temperate, cool-water carbonate sedimentary environments dominate much of the southern and western coastal margins of Australia (Hearty and O'Leary, 2008; Short, 2000, 2019; James and Bone, 2011). In areas of higher wave energy, the source of skeletal carbonate grains is generally from continental shelf biota and fringing reefs, where present, while in lower-energy settings, seagrass meadows are important for carbonate production (Belperio et al., 1984; Short, 2010). The sediment grains form sandy beach ridges and coastal

dune complexes in a variety of morphostratigraphical forms along these temperate coastal margins (Bourman et al., 2016; Short, 2019). A knowledge of the proportion of relict carbonate grains within Holocene and modern sediments provides insights on sediment production rates and how these environments may respond to future sea-level rise and shoreline recession. In this pilot study, preliminary results are presented showing that the extent of amino acid racemization (AAR) may be used to identify relict carbonate grains within Holocene and modern sediments from temperate coastlines, based on the extent of AAR in single tests of the benthic foraminifer *Lamellodiscorbis dimidiatus* (Hansen and Revets, 1992). This analytical approach, based on the application of reverse phase, high performance liquid chromatography, represents a significant advance in AAR analyses, as gas chromatography, required up to 500 foraminiferal tests for a single analysis.

2. Regional setting

The Coorong Coastal Plain (CCP) is located in the southeast of the State of South Australia (Fig. 1). A series of emergent coastal barriers, locally termed dune ranges, occurs across the coastal plain, which formed during interglacial and warm interstadial sea-level highstands (Sprigg, 1952, 1979; Hossfeld, 1950; Murray-Wallace, 2018

* Corresponding author.

E-mail address: t.oliver@adfa.edu.au (T.S.N. Oliver)

Fig. 1. Map of the southern portion of the Coorong Coastal Plain showing the relict coastal dune barriers, in particular, the Woakwine Range (MIS 5e) and Robe Range (MIS 5a 5c). Guichen and Rivoli Bays have formed at breaks in the Robe Range. The inset shows the extent of carbonate-dominated regions around Australia which are a significant proportion of Australia's temperate coastline.

). Near the town of Naracoorte, some 100 km inland from the modern coastline, the relict barrier (West Naracoorte Range) is approximately 800 ka old (Huntley et al., 1994). A series of up to 20 coastal barriers occur seaward from this dune range and are preserved, in part, as a result of the interplay of glacio-eustatic sea-level changes and epeirogenic uplift (Hossfeld, 1950; Sprigg, 1952; Murray-Wallace, 2018). In a line of section from Robe to Naracoorte, uplift of the coastal plain has occurred at an average rate of 0.07 mm/yr over the past 1 million years (Murray-Wallace et al., 2001) such that the West and East Naracoorte Ranges are approximately 75–100 m above present sea level.

Robe Range is the most recent of these Pleistocene barrier landforms. The Late Pleistocene barrier complex formed during the warm interstadials of the last interglacial *sensu lato* when sea level was some 9–20 m below present level (MIS 5c, 105 ka and MIS 5a, 82 ka; Huntley et al., 1994; Murray-Wallace et al., 2001; Murray-Wallace, 2018; Fig. 2). The emergent barrier structure is covered by a succession of Holocene coastal dunes, which rest unconformably on the calcreted upper surface of the Robe Range aeolianites. The partially vegetated and unconsolidated Holocene dunes formed since the culmination of the post Last Glacial marine transgression, which in this far-field region, began some 7000 years ago (Lewis et al., 2013; Dougherty

Fig. 2. View of Robe Range looking southeast from Cape Dombey, Robe, southern Australia.

et al., 2019). Robe Range extends for 155 km along the modern coastline between the towns of Robe and Port MacDonnell in the south-east (Fig. 1). The dune range occurs above present sea level in this region due to regional uplift, whereas progressively to the north of Robe, fewer outcrops of the dune range are evident due to subsidence. North of Kingston SE (Fig. 1) localised erosional remnants of Robe Range crop out within the Coorong Lagoon, between the modern/Holocene Younghusband Peninsula and the Last Interglacial (MIS 5e) Woakwine Range (Cann and Murray-Wallace, 2012). Between Robe and Port MacDonnell, the dune range calcarenites are exposed in prominent sea cliffs up to 20 m high, and elsewhere are covered by extensive fields of active, modern coastal parabolic dunes.

Eroded remnants of Robe Range occur as near-shore islands up to 1–2 km offshore attesting to substantial erosion of this barrier (0.14–0.29 m/year landward erosion) and as a significant source of relict skeletal carbonate sand to nourish Holocene beach ridge plains within the region (Oliver et al., 2020). The islands are surrounded by narrow shore platforms. Since the formation of Robe Range, sea level remained below present until the onset of the Holocene highstand. Accordingly, the formation of the shore platforms surrounding the small island remnants of Robe Range can only have formed since 7000 years ago. The substantial erosion of Robe Range most likely occurred during the Holocene (past 11.7 ka). The Late Pleistocene component of this dune range is capped by pervasive pedogenic carbonate (calcrete) which would have protected this coastal barrier landform during the sea level lowstands of the last glacial cycle. For much of its history (c. 82–11.7 ka) Robe Range would have been subaerially exposed, enhancing calcrete development.

In this cool-water, carbonate setting, the relict barrier sediments of the Pleistocene Bridgewater Formation (Boutakoff, 1963; Sprigg, 1979) are dominated by bioclastic, skeletal carbonate grains. Characteristically, the sediments comprise mixed quartz-skeletal carbonate grains of medium to coarse sand sized particles with a minor, terrestrially derived heavy mineral component (rutile, tourmaline and zircon; Colwell, 1979; James and Bone, 2011). The carbonate component is derived from the physical comminution of marine invertebrates and is commonly between 21 and 98% (Murray-Wallace, 2018).

At the end of the post Glacial Marine Transgression around 7000 years ago (Lewis et al., 2013; Dougherty et al., 2019), the seaward side of Robe Range experienced rapid marine erosion. Guichen and Rivoli Bays represent major erosional breaks within Robe Range (Fig. 1), which partially filled with Holocene beach ridge plain suc-

cessions following the attainment of present sea level (Oliver et al., 2020). The depositional history of the Holocene embayment fills at Guichen and Rivoli Bays, represented by a series of elongate, shore-parallel relict foredune ridges, has been described elsewhere and dated using Optically Stimulated Luminescence (OSL; Murray-Wallace et al., 2002; Oliver et al., 2020). The OSL chronologies for these embayment fill successions, suggests a period of initially rapid deposition before 5000 years ago followed by a slower rate of deposition within these embayments up to the present day. These Holocene sediments are primarily composed of a mixture of relict, bioclastic carbonate grains supplemented by modern biogenic carbonate grains with a minor quartz component.

The Bonney Shelf adjacent to Guichen and Rivoli Bays is a narrow (30–80 km in cross section), low gradient, unrimmed shelf with slopes of 2–7°. The surficial sediments of the inner Bonney Shelf have been described in terms of wave energy and sediment assemblages (James et al., 1992; Boreen et al., 1993). The strandline and inner shelf with a water depth <70 m is a palimpsest sedimentary facies and wave abrasion causes destructive diagenesis and erosion (James et al., 1992; Boreen et al., 1993). The proportion of relict carbonate in this zone is approximately 50% and dominated by bryozoans, especially *Adeona* sp. with a variety of growth forms (James et al., 1992; James and Bone, 2011).

3. Methods

To evaluate the magnitude of reworking of carbonate grains, and avoid a genus-effect on racemization, which could lead to misinterpretations of fossil age, AAR analyses were restricted to the benthic foraminifer *Lamellodiscorbis dimidiatus*. The species was selected for its mechanically robust nature and its general utility in AAR geochronology (Lachlan, 2011). AAR analyses were undertaken on single foraminifer. Foraminifera tests were separated from the skeletal carbonate sands, cleaned in an ultrasonic bath and pre-treated with 3% H₂O₂ (2 h) to remove organic contaminants and were then examined under a microscope to select the physically best preserved tests to ensure reliable AAR analyses. AAR analyses are for the total hydrolysable amino acids with results reported for glutamic acid (Glu), aspartic acid (Asp) and valine (Val). The AAR samples were then hydrolysed for 22 h at 110 °C in 7 M HCl spiked with the internal standard L-homo-arginine (0.01 M). After hydrolysis, the residual amino acids were derivatized using o-phthalaldehyde (OPA) together with the chiral thiol, N-isobu-

tyrtyl-L-cysteine (IBLC) to yield fluorescent diastereomeric derivatives of the chiral primary amino acids.

Amino acid D/L values were determined on peak area calculations and analytical precision for replicate measurements of a single foraminifer test was typically $\leq 3\%$. AAR analyses were undertaken using an Agilent 1100 reverse phase, high-performance liquid chromatograph with a Hypersil C-18 column and auto-injector, following the analytical methods established by Kaufman and Manley (1998).

4. Sample sites

To assess the degree of recycling of the skeletal carbonate sediment particles from the Late Pleistocene Bridgewater Formation (Robe Range) to Holocene and modern coastal sediments, AAR samples were collected from three locations. The oldest sediment analysed is from Robe Range (Robe III in the terminology of Schwabel, 1984; Figs. 1, 2). The sample (AAB5) is from an auger hole 30 cm into the cliff face and located 3 m below the original land surface within the MIS 5c, 105 ka component of Robe Range, from the western headland at Glass Beach at Robe (S37°09'50.2"; E139°45'02.6"; Fig. 1). The sediment is a free-flowing skeletal carbonate sand obtained from beneath a case hardened calcarenite surface.

The two youngest sediment samples are from Guichen Bay, immediately to the north of the town of Robe (Fig. 1). The sample of Holocene sediment (AAB3) is from a borrow pit, 850 m landward from Long Beach, which fronts the Holocene beach ridge plain at Guichen Bay (S37°08'01.3"; E139°48'14.2"; Fig. 1). The sample was collected from 3 m below the crest of a relict foredune and comprises medium to coarse-grained skeletal carbonate sand. The underlying and associated littoral facies at this locality has a marine reservoir-corrected and calibrated radiocarbon age of 2290 ± 180 yr cal BP (SUA-1368) based on the analysis of shell fragments of the bivalve mollusc *Amesodesma* sp. (Thom et al., 1981). The Holocene sediment sample is also bracketed by Optically Stimulated Luminescence ages of 1800 ± 80 yr and 2900 ± 130 yr for the aeolian facies of two relict foredunes, situated 185 m seaward and 296 m landward respectively of the augered sediment (Murray-Wallace et al., 2002). Sample AAB2 is from the modern foreshore of Long Beach at Guichen Bay and was collected 2 cm below the sediment-atmosphere interface at the mid-point of the modern beach profile (S37°07'57.7"; E139°47'45.8"; Fig. 1).

5. Results and discussion

Visual inspection of the individual specimens of *Lamellodiscorbis dimidiatus* using a binocular microscope revealed various levels of dissolution and staining. Samples of younger sediment contained a higher number of translucent foraminifera tests consistent with a younger age. Foraminifera from the older sedimentary units generally contained a higher percentage of iron (hematite) stained specimens or individuals showing dissolution and weathering (James and Bone, 2011).

A plot of the extent of aspartic acid (Asp) against valine (Val) racemization for the three samples; modern foreshore sand, Holocene dune sand and Late Pleistocene Robe Range III aeolianite (MIS 5c; 105 ka) illustrate the complexity of depositional and erosional processes in this temperate sedimentary carbonate environment (Fig. 3; Table 1). The modern foreshore sand sample contains almost a full spectrum of D/L values, representing modern, Holocene and older foraminifera, the latter derived from a Late Pleistocene source. The truly modern individuals have the lowest D/L values with Asp and Val D/L values < 0.16 and 0.03 respectively. These D/L values typify modern individuals and indicate that these foraminifera were rapidly incorporated within the modern foreshore sediments, with minimal time in *post-mortem* transportation. The spread of higher D/L values for *Lamellodiscorbis dimidiatus* from the modern foreshore sample indicates that a significant component of relict foraminifera are present in this sediment sample (Fig. 3). The significantly higher D/L values for

Fig. 3. Extent of aspartic acid (ASP) against valine (VAL) racemization (total hydrolysable amino acids) within individual specimens of the benthic foraminifer *Lamellodiscorbis dimidiatus* from three sediment samples from different coastal landforms. The samples are from (a) modern foreshore sands (2 cm below modern beach face), (b) a Holocene relict foredune, and (c) part of the Late Pleistocene composite coastal barrier, Robe Range (Marine Isotope Sub-Stage 5c – 105 ka). The colours denote the sample localities and illustrate the original provenance of the foraminifera based on their measured D/L values indicating their relative age. The modern foreshore sample (a) contains a mixed population of modern foraminifera with low extents of racemization (oval 1), indicating recently deceased individuals produced contemporaneously with the current shoreline position, as well as reworked specimens of Holocene age (the three higher D/L values within oval 1). A reworked Late Pleistocene component is also present in the modern foreshore sand characterised by significantly higher D/L values. The Holocene relict foredune sample (b) contains a population of *L. dimidiatus* (oval 2) which would have lived close to the time of foredune formation, as well as reworked individuals from the erosion of Robe Range, the latter indicated by higher D/L values extending to oval 3. D/L values between ovals 2 and 3 are possibly of MIS 5a age, from the youngest Late Pleistocene component of Robe Range. *In situ* specimens of *L. dimidiatus* from Robe Range (c) reveal a greater range in amino acid D/L values (see text for explanation). The reworked individuals within the modern and Holocene sediments suggest Robe Range is an important secondary sediment source augmenting shoreline progradation over the mid- to late- Holocene at Guichen Bay.

some *Lamellodiscorbis* within the modern beach sediment reveal that they are derived from the erosion of Robe Range. Eleven foraminifera from the modern beach sample have D/L values that fall within the field representing *in situ* specimens of *Lamellodiscorbis dimidiatus* from Robe Range III (MIS 5c, 105 ka; Fig. 3). Some of the *Lamellodiscorbis* sp. specimens have D/L values between the Holocene and Late Pleistocene fields of D/L values. It is possible that the higher D/L values in this intermediate group relate to individuals derived from Robe II, a Late Pleistocene component of Robe Range that is below present sea level. Robe II formed during the Late Pleistocene warm interstadial MIS 5a some 82 ka ago (Schwabel, 1984). Accordingly, the barrier feature will have formed at a time of lower interstadial sea level, some 15 m below present sea level, explaining the seaward position of this barrier structure compared with Robe III, which crops out above present sea level, in part due to neotectonic uplift.

The Holocene dune sample displays two populations of D/L values (red circles in Fig. 3). A discrete population of D/L values represents a Holocene age for the foraminifera, showing extents of racemization consistent with the independently derived radiocarbon and OSL ages (Murray-Wallace et al., 2002; Lachlan, 2011; Blakemore et al., 2015). The amino acid D/L values for this population of *Lamellodiscorbis dimidiatus* range from 0.299–0.355 for Asp and 0.08–0.167 for Val and is in accord with a radiocarbon age of 2290 ± 180 yr cal BP on associated littoral facies and the bracketing OSL ages of 1800 ± 80 yr and 2900 ± 130 yr (Murray-Wallace et al., 2002; Table 1). This range of D/L values is also consistent with that noted for other Holocene fossils in southern Australia (Murray-Wallace et al., 2010; Nicholas et al., 2019). Accordingly, the age of these foraminifera

Table 1

Extent of amino acid racemization (total hydrolysable amino acids) in single specimens of the benthic foraminifer *Lamellodiscorbis dimidiatus* from modern, Holocene and Late Pleistocene skeletal carbonate sediments, Robe, southern Australia.

Sample code	Laboratory code	Amino acid D/L value		
		Aspartic acid	Aspartic acid	Valine
Modern foreshore				
AAB2-1	UWGA-6600	0.585	0.341	0.428
AAB2-2	UWGA-6601	0.555	0.328	0.515
AAB2-4	UWGA-6602	0.590	0.366	0.504
AAB2-5	UWGA-6603	0.578	0.338	0.503
AAB2-6	UWGA-6604	0.584	0.380	0.472
AAB2-7	UWGA-6605	0.427	0.195	0.212
AAB2-9	UWGA-6607	0.574	0.335	0.427
AAB2-11	UWGA-6637	0.522	0.282	0.417
AAB2-12	UWGA-6638	0.168	0.078	0.042
AAB2-13	UWGA-6639	0.590	0.345	0.449
AAB2-14	UWGA-6640	0.277	0.117	0.099
AAB2-15	UWGA-6641	0.137	0.059	0.040
AAB2-16	UWGA-6642	0.395	0.119	0.181
AAB2-17	UWGA-6643	0.489	0.150	0.294
AAB2-18	UWGA-6644	0.111	0.040	0.025
AAB2-19	UWGA-6645	0.573	0.298	0.426
AAB2-21	UWGA-6646	0.464	0.211	0.274
AAB2-22	UWGA-6647	0.553	0.324	0.370
AAB2-23	UWGA-6648	0.537	0.271	0.337
AAB2-25	UWGA-6650	0.532	0.304	0.404
AAB2-26	UWGA-6651	0.235	0.095	0.072
AAB2-27	UWGA-6652	0.595	0.346	0.403
AAB2-28	UWGA-6653	0.260	0.117	0.095
AAB2-29	UWGA-6654	0.561	0.324	0.401
Holocene beach ridge (relict foredune)				
AAB3-2	UWGA-6608	0.329	0.130	0.138
AAB3-3	UWGA-6609	0.347	0.142	0.167
AAB3-4	UWGA-6610	0.327	0.125	0.156
AAB3-5	UWGA-6611	0.560	0.356	0.500
AAB3-6	UWGA-6612	0.590	0.337	0.482
AAB3-7	UWGA-6613	0.346	0.144	0.131
AAB3-8	UWGA-6614	0.627	0.466	0.574
AAB3-9	UWGA-6615	0.564	0.327	0.463
AAB3-11	UWGA-6655	0.549	0.313	0.370
AAB3-12	UWGA-6656	0.306	0.118	0.091
AAB3-13	UWGA-6657	0.549	0.315	0.397
AAB3-14	UWGA-6658	0.769	0.702	0.715
AAB3-15	UWGA-6659	0.573	0.330	0.399
AAB3-16	UWGA-6660	0.521	0.218	0.322
AAB3-17	UWGA-6661	0.342	0.115	0.096
AAB3-18	UWGA-6662	0.587	0.381	0.466
AAB3-22	UWGA-6665	0.588	0.390	0.450
AAB3-23	UWGA-6666	0.300	0.113	0.097
AAB3-24	UWGA-6667	0.314	0.128	0.115
AAB3-25	UWGA-6668	0.355	0.142	0.129
AAB3-26	UWGA-6669	0.343	0.144	0.119
AAB3-27	UWGA-6670	0.449	0.205	0.249
AAB3-28	UWGA-6671	0.481	0.209	0.234
AAB3-29	UWGA-6672	0.299	0.109	0.080
Robe Range III				
AAB5-1	UWGA-6617	0.646	0.439	0.551
AAB5-1	UWGA-6618	0.601	0.352	0.443
AAB5-3	UWGA-6619	0.589	0.354	0.441
AAB5-4	UWGA-6620	0.557	0.294	0.342
AAB5-5	UWGA-6621	0.589	0.353	0.437
AAB5-7	UWGA-6623	0.579	0.354	0.432
AAB5-8	UWGA-6624	0.569	0.288	0.314

Table 1 (Continued)

Sample code	Laboratory code	Amino acid D/L value		
		Aspartic acid	Aspartic acid	Valine
AAB5-9	UWGA-6625	0.627	0.423	0.521
AAB5-10	UWGA-6626	0.597	0.347	0.443
AAB5-11	UWGA-6673	0.634	0.445	0.531
AAB5-12	UWGA-6674	0.625	0.380	0.465
AAB5-13	UWGA-6675	0.606	0.353	0.445
AAB5-15	UWGA-6677	0.598	0.391	0.451
AAB5-17	UWGA-6679	0.603	0.373	0.426
AAB5-18	UWGA-6680	0.578	0.346	0.409
AAB5-21	UWGA-6681	0.609	0.332	0.380
AAB5-22	UWGA-6682	0.550	0.283	0.328
AAB5-24	UWGA-6683	0.574	0.349	0.415
AAB5-26	UWGA-6685	0.586	0.358	0.452
AAB5-27	UWGA-6686	0.558	0.288	0.336
AAB5-28	UWGA-6687	0.579	0.331	0.398

is essentially contemporary with foredune formation during the late Holocene, and most likely pre-date foredune formation by only a few years. A second population of D/L values from the Holocene relict foredune sample represents the inherited population of remanié foraminifera characterised by significantly higher amino acid D/L values. The spread of higher D/L values reveals that a significant proportion of the Holocene sediment also contains older relict carbonate grains and foraminifera derived from the erosion of Robe Range. Fifty four per cent of the *Lamellodiscorbis* sp., from the Holocene sand are remanié fossils, of which 10 individuals are most likely derived from Robe Range III, and 3 individuals from a younger Late Pleistocene source, possibly Robe II (MIS 5a, 82 ka).

The sample from Robe Range III only contains a population of high D/L values, most likely representing carbonate production close to the time of deposition (MIS 5c; 105 ka), with the possibility that some of the foraminifera are actually older and reworked from the Last Interglacial Woakwine Range (MIS 5e; 125 ka), although these may not be statistically resolved. The extent of AAR in whole-rock aeolianite samples from the coastal barriers Robe III and Woakwine I, for example, revealed that the extent of leucine racemization (total hydrolysable amino acids measured by gas chromatography) in skeletal carbonate sand (63–500 µm) were not significantly different (Robe III – D/L 0.453 ± 0.005 cf. Woakwine I – D/L 0.451 ± 0.099; Murray-Wallace et al., 2001). This observation highlights that amino acid racemization does not have the age-resolving power to distinguish MIS 5e from 5c.

The broad spread in D/L values from Robe Range (blue dots in oval 3) is attributed to two factors. Firstly, the rate of aspartic acid racemization slows significantly in its later kinetic history as seen in Late Pleistocene fossils (Murray-Wallace et al., 2010), such that the acid does not discriminate time as well as for Holocene or earliest Late Pleistocene fossils. Secondly, the parabolic nature of racemization kinetics, means that fossils of MIS 5 age *sensu lato*, cannot be distinguished (i.e. the various sub-stages within MIS 5 cannot be identified due to the age-resolving power of the AAR method as outlined above). It is possible that some of the D/L values for *L. dimidiatus* from Robe Range, shown within the right-hand most side of oval 3 relate to MIS 5e rather than 5c. The Woakwine Range, however, did not experience substantial erosion following its formation, as the seaward side of the structure remains well preserved, apart from the region to the north of Guichen Bay (i.e. between northern-most Guichen Bay to Cape Jaffa; Fig. 1). Further south, however, between Robe and Beachport (Fig. 1), subdued, calcreted beach ridges on the immediate seaward side of the Woakwine Range, attest to a high level of preservation of this

dune range and minimal sediment input to the formation of Robe Range. Finally, relative sea level was some 9–20 m below present sea level during the two Late Pleistocene phases in the development of Robe Range. Accordingly, the hinterland extending up to the Woakwine Range was not inundated by marine waters during MIS 5c and 5a.

5.1. Implications for sediment budgets and taphonomy

Determining the relative proportion of reworked skeletal carbonate grains and biogenic constituents included in relict foredune deposits in this region, advances the understanding of sediment sources for shoreline progradation over the Holocene. At Guichen Bay, and Rivoli Bay to the south, the rapid phase of shoreline progradation before 5000 years ago was likely due to significant volumes of sediment derived from the marine erosion of Robe Range, available for onshore transport and foredune building (Oliver et al., 2020). Samples of the Holocene dune sands > 5000 years old would therefore be expected to contain a greater population of reworked benthic foraminifera derived primarily from Robe and possibly from the Woakwine Range, compared with younger beach and dune sediments. The results of this study suggest that it may be possible to test this hypothesis.

AAR analyses of single foraminifera will also provide the opportunity to delineate the timing and frequency of convulsive events within depositional systems, such as the effects of tsunami and high intensity storms in coastal regions and submarine mudslides in continental shelf and slope environments (Nitttrouer et al., 2007; Terry and Goff, 2012). Large and robust species of benthic foraminifera such as *L. dimidiatus* and *Elphidium macelliforme* will be most suited for AAR analyses to ensure sufficient sample mass for reverse phase, high performance liquid chromatography (Kaufman and Manley, 1998). As a taphonomic tool, the AAR method can identify reworked foraminifera based on the magnitude of D/L values, as well as establishing the time-equivalence of fossils. The technique can also distinguish the taphonomically active zone (Mixed layer) subject to continued bioturbation and sediment reworking by episodic storm events, from more deeply buried Historical layers (Martin, 1998). The AAR analysis of foraminifera will increase the spatial resolution in stratigraphical investigations and refine questions that may be addressed resulting from a higher density of sampling.

6. Conclusions

The extent of amino acid racemization in single tests of the benthic foraminifer *Lamellodiscorbis dimidiatus*, measured by reverse phase, high performance liquid chromatography, represents a valuable tool for identifying reworked specimens within Holocene temperate carbonate sediments. The tests of *Lamellodiscorbis* sp., are sufficiently robust to withstand sediment recycling associated with discrete episodes of coastal erosion accompanying glacio-eustatic sea-level changes. The data reveal that individuals derived from the erosion of Robe Range III, and possibly Robe Range II, were incorporated within late Holocene relict foredune and modern foreshore sands. This letter highlights the potential of AAR to identify unambiguously remanié fossils within temperate carbonate sediments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project was funded in part by an Australian Research Council Discovery Program grant (DP150101936).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.margeo.2019.106096>.

References

- Belperio, A.P., Hails, J.R., Gostin, V.A., Polach, H.A., 1984. The stratigraphy of coastal carbonate banks and Holocene sea levels of northern Spencer Gulf, South Australia. *Mar. Geol.* 61, 297–313.
- Blakemore, A.G., Murray-Wallace, C.V., Westaway, K.E., Lachlan, T.J., 2015. Aminostratigraphy and sea-level history of the Pleistocene Bridgewater Formation, Mount Gambier region, southern Australia. *Aust. J. Earth Sci.* 62, 151–169.
- Boreen, T., James, N., Wilson, C., Heggie, D., 1993. Surficial cool-water carbonate sediments on the Otway continental margin, southeastern Australia. *Mar. Geol.* 112, 35–56.
- Bourman, R.P., Murray-Wallace, C.V., Harvey, N., 2016. Coastal Landscapes of South Australia. University of Adelaide Press, Adelaide. (405 pp.).
- Boutakoff, N., 1963. The geology and geomorphology of the Portland area. Victoria, Geological Survey, Memoir 22. (172 pp.).
- Brooke, B.P., 2001. The distribution of carbonate eolianite. *Earth Sci. Rev.* 55, 135–164.
- Cann, J.H., Murray-Wallace, C.V., 2012. Interstadial age (MIS 5c) beach-dune barrier deposits in the Coorong Lagoon, South Australia. *Aust. J. Earth Sci.* 59, 1127–1134.
- Colwell, J.B., 1979. Heavy minerals in the late Cainozoic sediments of southeastern South Australia and western Victoria. *BMR J. Aust. Geol. Geophys.* 4, 83–97.
- Davies, J.L., 1973. Geographical Variation in Coastal Development. Hafner Publishing Company, New York. (204 pp.).
- Dougherty, A.J., Thomas, Z.A., Fogwill, C., Hogg, A., Palmer, J., Rainsley, E., Williams, A.N., Ulm, S., Rogers, K., Jones, B.G., Turney, C., 2019. Redating the earliest evidence of the mid-Holocene relative sea-level highstand in Australia and implications for global sea-level rise. *PLoS One* 14 (7), 30218430.
- Hansen, H.J., Revets, S.A., 1992. A revision and reclassification of the Discorbidae, Rosalinidae and Rotaliidae. *J. Foraminif. Res.* 22, 166–180.
- Hearty, P.J., O'Leary, M.J., 2008. Carbonate eolianite, quartz sands and Quaternary sea-level cycles, Western Australia: a chronostratigraphic approach. *Quat. Geochronol.* 3, 26–55.
- Hossfeld, P.A., 1950. The Late Cainozoic history of the South-East of South Australia. *Trans. R. Soc. S. Aust.* 73, 232–279.
- Huntley, D.J., Hutton, J.T., Prescott, J.R., 1994. Further thermoluminescence dates from the dune sequence in south-east South Australia. *Quat. Sci. Rev.* 13, 201–207.
- James, N.P., Bone, Y., 2011. Neritic Carbonate Sediments in a Temperate Realm – Southern Australia. Springer, Dordrecht. (254 pp.).
- James, N.P., Bone, Y., Borch, C.C., Gostin, V.A., 1992. Modern carbonate and terrigenous clastic sediments on a cool water, high energy, mid-latitude shelf: Lacedpede, southern Australia. *Sedimentology* 39, 877–903.
- Kaufman, D.S., Manley, W.F., 1998. A new procedure for determining enantiomeric (D/L) amino acid ratios in fossils using reverse phase liquid chromatography. *Quat. Sci. Rev.* 17, 987–1000.
- Lachlan, T.J., 2011. Aminostratigraphy and Luminescence Dating of the Pleistocene Bridgewater Formation, Kangaroo Island, South Australia: An Archive of Long Term Climate and Sea-level Change Unpublished PhD Thesis. University of Wollongong. (711 pp.).
- Lewis, S.E., Sloss, C.R., Murray-Wallace, C.V., Woodroffe, C.D., Smithers, S.G., 2013. Post-glacial sea-level changes around the Australian margin: a review. *Quat. Sci. Rev.* 74, 115–138.
- Martin, R.E., 1998. One Long Experiment – Scale and Process in Earth History. Columbia University Press, New York. (262 pp.).
- Murray-Wallace, C.V., 2018. Quaternary History of the Coorong Coastal Plain, Southern Australia: An Archive of Environmental and Global Sea-Level Changes. Springer International Publishing, Cham. (229 pp.).
- Murray-Wallace, C.V., Brooke, B.P., Cann, J.H., Belperio, A.P., Bourman, R.P., 2001. Whole-rock aminostratigraphy of the Coorong Coastal Plain, South Australia: towards a 1 million year record of sea-level highstands. *J. Geol. Soc. Lond.* 158, 111–124.
- Murray-Wallace, C.V., Banerjee, D., Bourman, R.P., Olley, J.M., Brooke, B.P., 2002. Optically stimulated luminescence dating of Holocene relict foredunes, Guichen Bay, South Australia. *Quat. Sci. Rev.* 21, 1077–1086.
- Murray-Wallace, C.V., Bourman, R.P., Prescott, J.R., Williams, F., Price, D.M., Belperio, A.P., 2010. Aminostratigraphy and thermoluminescence dating of coastal aeolianites and the later Quaternary history of a failed delta: the River Murray mouth region, South Australia. *Quat. Geochronol.* 5, 28–49.
- Nicholas, W.A., Lachlan, T., Murray-Wallace, C.V., Price, G., 2019. Amino acid racemization and uranium-series dating of a last interglacial raised beach, Kingscote, Kangaroo Island, Southern Australia. *Trans. R. Soc. S. Aust.* 143, 1–26.
- Nitttrouer, C.A., Austin, J.A., Field, M.E., Kravitz, J.H., Syvitski, J.P.M., Wiberg, P.L. (Eds.), 2007. Continental Margin Sedimentation: From Sediment Transport to Sequence Stratigraphy. In: Special Publication Number 37, International Association of Sedimentologists. Blackwell Publishing, Malden. (549 pp.).
- Oliver, T.S.N., Murray-Wallace, C.V., Woodroffe, C.D., 2020. Holocene shoreline progradation and coastal evolution at Guichen and Rivoli Bays, southern Australia. The Holocene (in press). doi:10.1177/0959683619875815.

- Schwebel, D.A., 1984. Quaternary stratigraphy and sea-level variation in the southeast of South Australia. In: Thom, B.G. (Ed.), Coastal Geomorphology in Australia. Academic Press, Sydney, pp. 291–311.
- Short, A.D., 2000. The distribution and impact of carbonate sands on southern Australian beach-dune systems. In: Magoon, O.T., Robbins, L.L., Ewing, L. (Eds.), Carbonate Beaches. pp. 236–250.
- Short, A.D., 2010. Sediment transport around Australia—sources, mechanisms, rates, and barrier forms. *J. Coast. Res.* 263, 395–402.
- Short, A.D., 2019. Australian Coastal Systems – Beaches, Barriers and Sediment Compartments. Springer, Cham. (2 Vols, 1256 pp.).
- Sprigg, R.C., 1952. The geology of the South-East province, South Australia, with special reference to Quaternary coastline migrations and modern beach developments. Geological Survey of South Australia, Bulletin 29.
- Sprigg, R.C., 1979. Stranded and submerged sea-beach systems of southeast South Australia and the aeolian desert cycle. *Sediment. Geol.* 22, 53–96.
- Terry, J.P., Goff, J. (Eds.), 2012. Natural Hazards in the Asia – Pacific Region: Recent Advances and Emerging Concepts. In: Geological Society, London, Special Publications, 361. (225 pp.).
- Thom, B.G., Bowman, G.M., Gillespie, R., Temple, R., Barbetti, M., 1981. Radiocarbon Dating of Holocene Beach-ridge Sequences in Southeast Australia. 11. University of New South Wales, Department of Geography. Monograph. (36 pp.).