Journal of the Royal Society of Western Australia, 99(1): 17–26, 2016

Chronostratigraphic context for artefact-bearing palaeosols in late Pleistocene Tamala Limestone, Rottnest Island, Western Australia

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Abstract

This paper presents absolute dates for artefact-bearing palaeosols intercalated with Tamala Limestone aeolianite successions on Rottnest Island (*Wadjemup*), Western Australia. The absolute chronology for the sub-aerial part of the island's constituent Tamala Limestone is based on 20 optically stimulated luminescence (OSL), two thermoluminescence (TL) age estimates, one U-series assay and three radiocarbon dates. The oldest of these estimates is an OSL age of 140 ± 14 ka at Fairbridge Bluff for the aeoliniate beneath the Rottnest Limestone member – a marine member of the Tamala Limestone succession. The palaeosols range in age from 49 to 10 ka. These age estimates provide, for the first time, a chronostratigraphic context for the isolated archaeological finds on the island as well as contributing to the timing and nature of late Quaternary sequences within the Tamala Limestone of the Perth Basin.

KEYWORDS: Rottnest Island, late Quaternary, Tamala Limestone, palaeosols, chronostratigraphy, luminescence dating

INTRODUCTION

Rottnest (or *Wadjemup*) is the largest of a chain of offshore islands and reefs composed of Tamala Limestone, the constituent rock of Quaternary age throughout the Perth Basin (Playford 1983, 1988, 1997) (Figure 1). Separating the sandy beaches around the island are aeolian calcarenite cliffs and headlands that formed when wide areas of the continental shelf was exposed and carbonate productivity was high – this is the Tamala Limestone (Playford 1988, 1997). These aeolianite successions comprise moderately cemented, fine to coarse bioclastic sands and shelly deposits, mainly in large scale cross bedded and planar bedforms (Hearty 2003). Intercalated within the aeolianite successions are moderately cemented calcretes and palaeosols (the "protosols" of Vacher & Hearty 1989), characterised by higher proportions of quartz and clay, calcified roots (rhizoliths), fossil land snails (mainly the gastropod *Austrosuccinea* sp.) and fossil weevil (*Leptopious* sp.) pupal cases (see also Playford 1997; Hesp *et al.* 1999).

It is within these palaeosol units that a number of isolated Eocene fossiliferous chert and calcrete artefacts are recorded at Bathurst Point, Little Armstrong Bay, Charlotte Point, Fish Hook Bay (Figure 1) along with seven other surface finds. Although few in number, the stone artefacts identified *in situ* within Tamala Limestone paleosols on Rottnest Is. (Dortch & Hesp 1994), along with a further nine found on Garden Island (Dortch & Morse 1984; Dortch 1991; Dortch & Hesp 1994; Dortch & Dortch 2012) indicate human presence on this part of the emergent continental shelf during the late Pleistocene and early Holocene. Minimal ages for these artefacts have been estimated from the time of the island's separation from the mainland around c. 6500 years ago (Churchill 1959; Playford 1997). This paper provides a more complete stratigraphic context and absolute chronology for the artefact-bearing palaeosols.

In situ artefact find sites and previous dating

The Tamala Limestone provides a register of Quaternary sea-level events (Teichert 1950; Fairbridge 1954, 1961; Playford 1988, 1997; Kenrick & Wyrwoll 1991; O'Leary *et al.* 2013; Brooke *et al.* 2014) and is also important from a regional archaeological perspective (see also Dortch & Dortch 2012). During the Last Interglacial (Marine Isotope Stage (MIS) 5), Rottnest lsland existed as shallow submerged shoals and reefs overlying Tamala Limestone, as evident from the Rottnest Limestone member at Fairbridge Bluff (Figure 2A). The reef/beach sequence here has been dated between 132 – 121 ka (MIS 5e) (Szabo 1979; Stirling *et al.* 1995, 1998; Price *et al.* 2001). Mean sea level (MSL) was about 3 – 4 m above present for much of this period, increasing to at least 8 m above present around 118 ka (O'Leary *et al.* 2013). This reef/beach sequence is capped by a reddish calcrete and *terra rossa* palaeosol with deep root casts filled with ferruginous, well-rounded, well-sorted quartz-rich dune sands (Figure 2A), indicating sub-areal weathering of the reef towards the end of MIS 5e (or possibly MIS ≤ 5d, Hearty 2003; Hearty & O'Leary 2008).

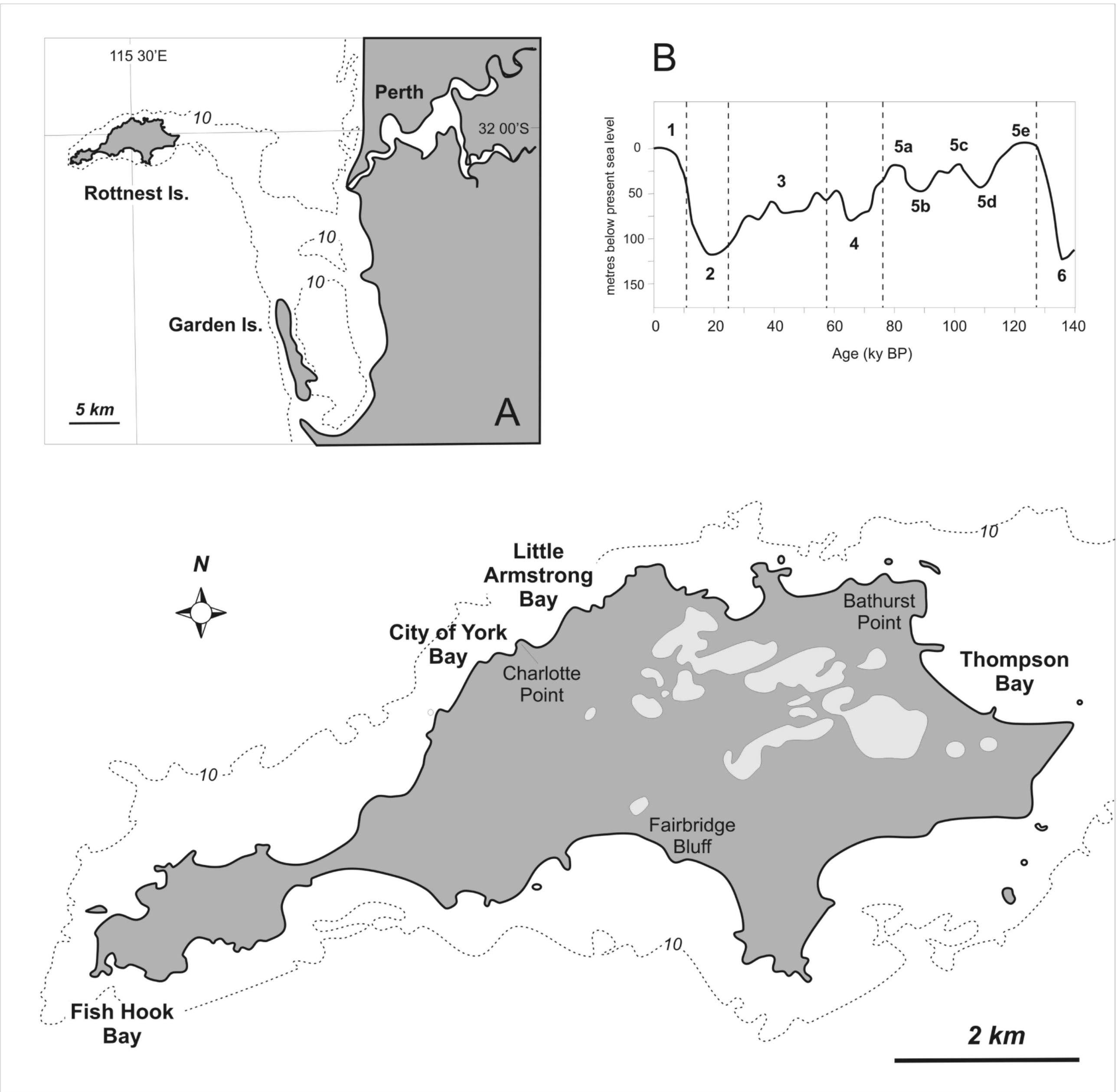

Figure 1. Rottnest Island map showing location of artefact-bearing palaeosols, including Bathurst Point, Little Armstrong Bay, Charlotte Point, City of York Bay and Fish Hook Bay. Inset A shows location of Rottnest Is. in relation to the Perth Metropolitan Region, central Swan Coastal Plain and Swan River/estuary. Inset B shows sea level curve showing major marine isotope stages (sourced from Waelbroeck *et al*. 2002).

Additional absolute ages relate to MIS 4 and are provided from Bathurst Point (Figure 1). Here four prominent stratigraphic units are observed – the first is a basal aeolianite unit 3 – 7 m ASL to below MSL, extending along the c. 500 m cliff length, dated by thermoluminescence (TL) at 67 ± 9 ka (Price *et al.* 2001) and by Optically-Stimulated Luminescence (OSL) dating to 77 ± 12 ka (Playford *et al.* 2013; Brooke *et al.* 2014). This unit is capped (trunctated?) by a massive calcrete/breccia calcrete unit (Figure 2B), defined by Hearty (2003) as a well-developed brecciated soil (rendzina) with abundant limestone clasts. Along parts of the eastern side of Bathurst Point, this calcrete/breccia unit can been seen to be overlain by a dark brown to nearly black silty sand (Figure 3). It is within this brecciated calcrete that a fossiliferous chert core was found (Dortch & Dortch 2012: their Figure 7), cemented and overlain by a thin layer (0.5 – 1 cm) of carbonate cement (see also Hearty 2003).

Overlying this calcrete/breccia unit is a younger aeolianite succession, exposed mainly on the western side of Bathurst Point, and dated by OSL to 27 ± 4.5 ka (Brooke *et al.* 2014) and 20 ± 2 ka by TL (Price *et al.* 2001) or MIS 2. This aeolinite unit is not present on the east side of Bathurst Point, at the find site of the chert artefact**.** Here the calcrete/breccia unit is immediately capped by a light brown (7.5 YR 5/3) rhyzolithic-rich palaeosol that

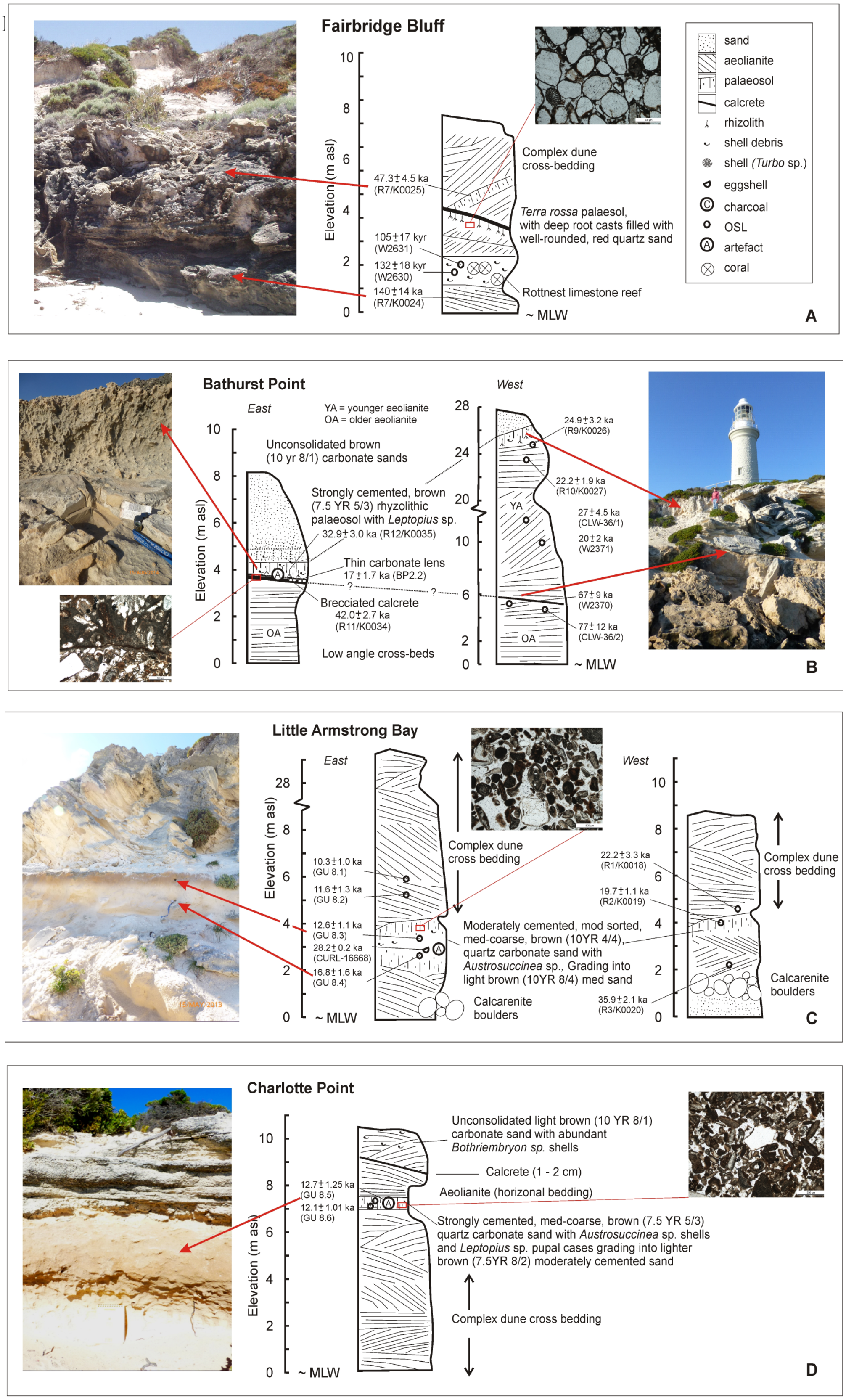

Figure 2. Schematic stratigraphic sections of Rottnest Island Eocene fossiliferous artefact find sites, including A. Fairbridge Bluff, B. Bathurst Point, C. Little Armstrong B and D. Charlotte Point. Inset petrographic photos show the quartz-rich (with inherited ferruginous rinds) *terra rossa* palaeosol at Fairbridge Bluff (A), the contrasting carbonate-rich palaeosol (with post-depositional ferriginisation) at Little Armstrong Bay (C) and Charlotte Point (D), and the sharp boundary created by the calcrete overlying the aeolianite unit at Bathurst Point (B) (scale bar is 500 µm).

Figure 3. Brecciated calcrete unit on the eastern side of Bathurst Point overlain by a dark brown silty sand and capped by a very thin carbonate lens (photo by IW).

can be traced through the largely vegetated dunes across to the western side of Bathurst Point where it overlies the younger aeolianite (Figure 2B). The succession is overlain by unconsolidated to lightly cemented Holocene dune sands containing abundant *Bothriembryon* and introduced land snail taxa (Hearty 2003).

A further two sites, Little Armstrong Bay and Charlotte Point (Figure 1), have each yielded a single *in situ* Eocene fossiliferous chert artefact from a Tamala Limestone palaeosol unit, previously described by Dortch and Hesp (1994). In contrast to the *terra rossa* palaesol at Fairbridge Bluff, these palaeosols are mainly composed of shelly carbonate, and the minor (5 – 10%) quartz that is present is more angular (Figure 2C and 2D) indicating a less distant source. The artefacts include a stone tool from the foot of sea-cliff on the western side of Little Armstrong Bay (LAB west) and a retouched tool, found half protruding from a prominent palaeosol on the eastern side of the bay (LAB east). The latter was associated with a tiny fragment of emu eggshell (*Dromaius novaehollandiae*) – the sole vertebrate fossil specimen known from the island. An earlier series of Amino Acid Racemisation (AAR) measurements, using the land snail *Austrosuccinea* sp. found *in situ* in palaeosols intercalated within aeolianite successions at three Rottnest Island sites – including Little Armstrong Bay, City of York and Fish Hook Bay – gave a provisional ages of > 50 ka (Hesp *et al.* 1999). However, these dates have been questioned by Brooke *et al.* (2014), and Hesp *et al.* (1999: 11) themselves regard their AAR dates as provisional due to “the paucity of amino acid data concerning the racemisation kinetics in [the genus] *Austrosuccinea*”.

A further two fossiliferous chert artefacts were found eroded from the summit of the cliffs at Fish Hook Bay, on the island’s south-west, and could have been derived from the deflation of the uppermost palaeosol and aeolianite units at the top of the cliff. The following presents new dates for Fish Hook Bay, City of York Bay and the artefact find sites at Bathurst Point, Little Armstrong Bay and Charlotte Point.

DATING METHODS

OPTICALLY STIMULATED LUMINESCENCE (OSL)

Aeolianite (7) and palaeosol (5) units were sampled (by EJR) in 2003 – 2004 at City of York, Fairbridge Bluff, Bathurst Point and Little Armstrong Bay. A series of small aliquot Optically Stimulated Luminescence (OSL) measurements were undertaken at the Australian National University (ANU), using a conventional SAR approach for small aliquots, and standard Risø equipment as described by Rhodes *et al.* (2010). High OSL sensitivity and favourable luminescence characteristics were observed, although some samples displayed relatively high over-dispersion (statistical scatter) between aliquots (up to 12%), possibly related to spatial variability in beta dose rate within the carbonate and quartz-rich aeolianite (Table 1). Dose rates were determined using NAA-measured radionuclide contents, along with in-field gamma spectrometry for gamma dose rate calculation.

The above ANU dates are complemented by single-grain OSL dating of palaeosols and aeolianites at Little Armstrong Bay and Charlotte Point (Table 1). These OSL measurements, undertaken at Griffith University, augment published OSL dating of samples collected at Bathurst Point by the same laboratory (Table 1; Brooke *et al.* 2014; Playford *et al.* 2013). The modified single aliquot regenerative dose protocol of Olley *et al.* (2004) was used on standard Risø equipment, as described in detail elsewhere (Olley *et al.* 2004; Pietsch *et al.* 2013; Brooke *et al.* 2014). Given over-dispersion values of 18 – 36% (Table 1), burial ages have been calculated using the minimum age model. Radionuclide contents for each GU sample were determined using Neutron Activation

Analysis (NAA - Becquerel Laboratories, Mississauga, Ontario, Canada), with lithogenic dose rates calculated using the conversion factors of Stokes *et al.* (2003); with β-attenuation factors taken from Mejdahl (1979) and cosmic dose rates calculated from Prescott & Hutton (1994) using our best estimate of a time weighted long term burial depth (Table 1) based on examination of the field stratigraphy.

Uranium-series (U-series)

Six small sub-samples of between 20 and 150 mg were cut using a hand-held dental drill from an 8 x 8 cm block of carbonate cement containing the fossiliferous chert core at Bathurst Point. The most indurated available material was targeted, with a preference for the lightest coloured. Analyses of six sub-samples followed the procedure of Hellstrom (2003) and Drysdale *et al.* (2012). Following Hellstrom (2006) an initial ^{230}Th/^{232}Th ratio of 3.51 ± 0.87 was found to bring the Th-corrected ages of all six analyses into agreement with respect to their uncertainties (i.e. Mean square weighted deviation (MSWD) = 1), meaning it is unlikely that the sample has been affected by uranium mobility since its deposition (Table 1).

Radiocarbon

Radiocarbon (Accelerator Mass Spectrometry (AMS)) radiocarbon dating of the emu eggshell fragment (*Dromaius novaehollandiae*) (CURL-16668) recovered from the palaeosol on the eastern side of Little Armstrong Bay was undertaken at the University of Colorado. In addition *in situ* charcoal fragments (Wk-37948) were collected from a palaeosol 150 m south east of the fossiliferous chert artefact find location and closely adjacent to OSL sample positions at Charlotte Point. The collective fragments were submitted to Waikato Radiocarbon Laboratory for AMS dating.

RESULTS OF THE DATING PROGRAM

FAIRBRIDGE BLUFF/CITY OF YORK

Two new OSL dates, not associated with artefacts, were obtained from Fairbridge Bluff. The oldest date of 140 ± 14 ka for sample R7/K0024 (Table 1, Figure 2A), produced using small aliquot OSL methods, is from an aeolianite sequence immediately overlying and broadly correlating with the Rottnest Limestone member (Figure 4). A second, younger age of 47 ± 4.5 ka (R6/K0023; Table 1), also obtained using small aliquot OSL methods, is from the palaeosol unit overlying the aeolianite.

Three other small aliquot OSL dates, not associated with artefacts, were obtained from City of York and include a palaeosol unit sandwiched between two aeolianite sequences (Figure 4). The palaeosol dated at 49 ± 3.3 ka (R5/K0022) and underlying aeolianite giving an equivalent age within uncertainties of 46 ± 2.9 ka (R6/K0023) (Table 1, Figure 4). Together these provide a weighted mean age of 48.1 ± 3.1 ka. The overlying aeolianite yielded an age of 36 ± 2.3 ka (R4/K0021).

Bathurst Point

The massive/breccia calcrete unit immediately underlying a cemented fossiliferous chert artefact is dated by small aliquot OSL to 42.0 ± 2.7 ka (R11/K0034), and gives a maximum age for the artefact. The U-series sample from the carbonate lens overlying and cementing the calcrete/breccia unit yielded a weighted average age of 17.1 ± 1.2 ka (Table 1). A second block sample cut into the top of rhyzolithic palaeosol unit is dated by small aliquot OSL to 32.9 ± 3 ka (R12/K0035) (Figure 2B). This date is discordant with both the U-series age estimate and the c. 20 ka inferred maximum age for the rhyzolithic palaeosol unit near the top of the section 60 m to the west (Figure 2B). Here, the rhyzolithic palaeosol unit rests directly on the underlying younger aeolianite dated by single aliquot

Figure 4. Tamala Limestone stratigraphical succession at City of York Bay (cf. Figure 1; photo by EJR).

Table 1. Age estimates for City of York Bay (COY), Fairbridge Bluff (FB), Charlotte Point (CP), Bathurst Point (BP) and Little Armstrong Bay (LAB) from Single-grain (SG) OSL estimates, single aliquot (SA) OSL age estimates, isotopic (U-series) age estimates (*2 sigma uncertainty) and radiocarbon dating (^{14}C). Water contents were in the range of 3 – 10%. Burial depth calculated as time weighted mean depth, i.e. the time-weighted average distance between the sampling point and the surface, based on our best estimate of the aggradation history at each site. Note, over-dispersion values for small aliquot (SA) OSL is expected to be significantly lower than for single grains (SG), owing to signal averaging effects. De is the dose (in Gy) of laboratory *b* irradiation equivalent to the dose received in the field from all sources (*a, b, g*, cosmic). s_d is the population overdispersion, it represents the degree of spread in the data beyond that which can be explained by known sources of uncertainty (*i.e.* measurement uncertainty on each individual single grain or single aliquot De). Non-zero s_d values are almost universally found for single grain dose distributions. The greatest component of this is traditionally attributed to partial bleaching (e.g. Olley *et al*. 2004) however there are other important contributors, most notably *b*-dose heterogeneity (Nathan *et al.* 2003) and variations in instrument uncertainty (Jacobs *et al.* 2006; Pietsch 2009). Radiocarbon dates are reported at 95.4% probability and calibrated using the SHCal13 curve (Hogg *et al*. 2013) in OxCal v.4.2.3 (Ramsey 2013).

Site	Lab code	Unit	Method	Depth (m)	De (Gy)	s_d	U (ppm)	Th (ppm)	K (%)	Dose rate (mGya^{-1})	Age (ka)
COY	R4/K0021	Upper aeolianite	SA OSL	4.0	8.82±0.24	4.2	0.740±0.002	0.440±0.022	0.081±0.001	0.28±0.02	36.3±2.3
COY	R5/K0022	Palaeosol	SA OSL	5.5	28.07±1.13	12	0.560±0.003	1.840±0.092	0.463±0.002	0.66±0.03	49.1±3.3
COY	R6/K0023	Lower aeolianite	SA OSL	7.5	23.72±0.84	9.6	0.610±0.003	1.420±0.071	0.410±0.002	0.60±0.03	46.2±2.9
FB	R8/K0025	Palaeosol	SA OSL	0.3	42.97±1.39	8.2	0.460±0.025	3.430±0.172	0.571±0.029	1.048±0.09	47.3±4.5
FB	R7/K0024	Aaeolianite	SA OSL	1.0	65.31±2.39	9.9	0.520±0.026	1.330±0.067	0.219±0.011	0.506±0.05	140.0±14.0
CP	GU8.5	Palaeosol	SG OSL	3.0	8.28±0.46	18	0.8±0.04	2.1±0.11	0.164±0.082	0.63±0.06	12.7±1.25
CP	GU8.6	Palaeosol	SG OSL	3.5	8.72±0.16	19	1.0±0.05	1.8±0.09	0.199±0.099	0.68±0.06	12.1±1.01
CP	Wk 37948	Palaeosol	AMS ^{14}C	2.0							10.3±0.06
BP (West)	R9/K0026	Aeolianite	SA OSL	3.0	6.31± 0.152	4.2	0.700 ± 0.001	0.450 ± 0.023	0.072 ± 0.001	0.294 ± 0.037	24.9 ± 3.2
BP (West)	R10/K0027	Aeolianite	SA OSL	4.5	6.2 ± 0.157	4.4	0.640 ± 0.001	0.380 ± 0.019	0.115 ± 0.001	0.324 ± 0.027	22.2 ± 1.9
BP (East)	R12/K0035	Palaeosol	SA OSL	3.5	7.71 ± 0.256	7.7	0.320 ± 0.016	0.690 ± 0.035	0.058 ± 0.003	0.270 ± 0.027	32.9 ± 3.0
BP (East)	R11/K0034	Palaeosol	SA OSL	4.0	11.36±0.271	2.9	0.420 ± 0.021	0.770 ± 0.039	0.066 ± 0.003	0.321 ± 0.037	42.0 ± 2.7
BP (East)	BP2.2	Calcrete	U-series	3.9							17.1 ± 1.7*
LAB (East)	GU8.1	Aeolianite	SG OSL	24.0	4.02±0.07	19	1.1±0.06	0.5±0.03	0.069±0.003	0.39±0.04	10.3±1.04
LAB (East)	GU8.2	Aeolianite	SG OSL	24.0	3.49±0.12	24	0.8±0.04	0.5±0.03	0.050±0.003	0.30±0.03	11.6±1.27
LAB (East)	GU8.3	Palaeosol	SG OSL	26.5	7.58±0.19	29	1.1±0.06	2.0±0.10	0.211±0.011	0.60±0.05	12.6±1.10
LAB (East)	GU8.4	Palaeosol	SG OSL	27.5	8.07±0.33	36	0.9±0.05	1.0±0.05	0.178±0.009	0.48±0.04	16.8±1.59
LAB (East)	CURL-16668	Palaeosol	AMS ^{14}C	27.5							28.2±0.18
LAB (West)	R1/K0018	Upper aeolianite	SA OSL	4.0	5.02±0.159	8.3	0.730±0.001	0.570±0.029	0.050±0.050	0.267±0.04	22.2±3.3
LAB (West)	R2/K0019	Palaeosol	SA OSL	4.5	8.08±0.221	1.4	0.850±0.003	1.630±0.082	0.194±0.001	0.475±0.02	19.7±1.1
LAB (West)	R3/K0020	Lower aeolianite	SA OSL	6.5	9.51±0.337	11.6	0.640±0.001	0.550±0.028	0.133±0.001	0.308±0.01	35.9±2.1

OSL to between 25 – 22 ka (Table 1). This age discrepancy may be explained by the presence, within the upper surface of the rhyzolithic palaeosol unit at Bathurst Point east (i.e. artefact find site), of large clasts of what may be older calcarenite. Hence the true age of the rhyzolithic palaeosol unit is considered to be < 20 ka.

Little Armstrong Bay

At Little Armstrong Bay (LAB) east, two single-grain OSL dates 12.6 ± 1.1 ka (GU8.3) and 16.8 ± 1.6 ka (GU8.4) pertain to samples taken just above, and at the same depth in this palaeosol, as the Eocene fossiliferous chert artefact and the emu eggshell fragment (Table 1). Significantly older than these age estimates is the calibrated radiocarbon date for the eggshell fragment at 28.2 ± 0.18 ka (CURL-16668). The discrepancy between it and the younger OSL dates from the same position in this palaeosol indicates that the eggshell fragment is probably re-worked from an older deposit – or recrystallised.

Two single-grain OSL dates of 10.3 ± 1.0 ka (GU8.1) and 11.6 ± 1.3 ka (GU8.2) were obtained from the aeolianite immediately overlying the fossiliferous chert artefact and emu eggshell-bearing palaeosol at LAB east (Figure 2C). These age estimates are much younger, but in chronological sequence, with the single-grain OSL date of 16.8 ± 1.6 ka for the palaeosol itself at LAB east and the single aliquot date of 19.7 ± 1.1 ka from the same palaeosol at LAB west (Table 1). The single aliquot OSL age estimate of 22.2 ± 3.3 ka, for the aeolianite overlying the palaeosol at LAB west (Table 1), is out of chronological sequence, indicating possible mixing of older grains in this sample. The single aliquot OSL age estimate of 35.9 ± 2.1 ka (R3/K0020) from the aeolianite below the palaeosol at LAB west provides a likely age for the corresponding aeolianite underlying the artefact-bearing palaeosol at LAB east (Figure 2C).

Charlotte Point

Two single-grain OSL dates (GU 8.5 and GU 8.6) from the artefact-bearing palaeosol at Charlotte Point give an absolute age of 12.7 – 12.1 ka (Table 1, Figure 2D). The palaeosol unit comprises a strongly cemented, brown (7.5 YR 5/3) medium-coarse grained quartz carbonate sand grading into a lighter brown (7.5 YR 8/2) and more loosely cemented quartz carbonate sand with *Austrosuccinea* sp. shells (Figure 2D). Charcoal from a pedogenically similar palaeosol 150 m south-east of the chert artefact find location, has yielded a slightly younger radiocarbon age of 10.3 ka (Wk 37948, Table 1). This date is however fully acceptable; together with the two OSL dates, it records the period through which the original sediments were deposited and developed into a soil.

DISCUSSION

DATED TAMALA LIMESTONE HISTORY FOR ROTTNEST ISLAND

A summary of the dated aeolianite sequences on Rottnest Is. is given in Figure 5. Eighteen previously unpublished OSL dates (Table 1) augment the absolute chronology for Rottnest Island's Tamala Limestone succession given by Price *et al.* (2001); Playford *et al.* (2013) and Brooke *et al.* (2014). The latter two papers note *three* major phases of dune deposition in the Tamala Limestone of Rottnest Island. A possible *fourth* or earlier phase of dune deposition is dated by single aliquot OSL to 140 ± 14 ka (MIS 6/5e), confirming Playford's (1997:725) suggestion that 'part of the Tamala Limestone near Fairbridge Bluff underlies the [Rottnest Limestone] reef, and must have formed a little earlier perhaps at about 135 – 140 ka'. Hence the major shoaling of Rottnest began during, or just after 125,000 yr ago (see also Hearty 2003).

A second major phase of dune deposition dates from around 77 ka (MIS 4) (Playford *et al.* 2013; Brooke *et al.* 2014). A third phase of dune deposition is dated to 49 – 36 ka (MIS 3) at Bathurst Point find site, City of York (Figure 4) and Little Armstrong Bay (Figure 2C). The final phase of aeolianite deposition represented at Bathurst Point and Fish Hook Bay broadly correlates with MIS 2 (27 – 23 ka), approximately the initial stages of the LGM (Andrews 2013; Clark *et al.* 2009). Thus the main periods of carbonate aeolianite deposition show a general younging seaward trend, dating to MIS 5e (~140 ka), MIS 5a (~80 ka), MIS 3 (~ 46 – 36 ka) and MIS 2 (~ 25 ka) on Rottnest Island and MIS 5e (~115 ka) and later on the mainland (Figure 5). Hearty (2003) adds a further two aeolinite stages on Rottnest Is. at MIS 5c (~100 ka) and MIS 1 (~15 ka). However, these latter dates are based on contestable amino acid racemisation (AAR) ages of 'whole-rock' biogenic samples, that likely date reworked calcareous marine invertebrates rather than the depositional age of the dunes (Dortch & Hesp 1994; Brooke *et al.* 2014). We would concur. Alongside Brooke *et al.* (2014), our OSL chronology indicate that coastal carbonate barriers and dune fields form very rapidly and under a wide range of climatic conditions and sea levels (*c.f.* Hearty 2003). Given the high potential for reworking of this shelf and coastal sediment prior to its final deposition and cementation, the data also show that OSL, especially single-grain OSL, is an effective and reliable method for dating these deposits (see also Playford *et al.* 2013).

Dated palaeosol history for Rottnest Island

According to Semeniuk (1986), fossil soils and calcretes in this region mark periods of local interruption in dune building during more humid periods of the Pleistocene, albeit with variable rates of lithification. Like the aeolianite sequences, the sometimes very thick (~ 1 – 2 m) palaeosol sequences on Rottnest Is. are laterally discontinuous and, from the chronology, appear to have formed in relative quick succession within the aeolianites but under a wide range of climatic conditions. The latter may well result in quite different palaeosol characteristics, as implied by the very preliminary analyses undertaken in this study.

A summary of the dated palaeosol sequences on Rottnest Is. is given in Figure 5, which indicate palaeosol units corresponding to MIS 3 (~ 49 – 33 ka) and MIS 2 (~ 17 – 10 ka) on Rottnest Island. The earliest of these date to 49 ± 3.3 ka and 47.3 ± 4.5 ka (MIS 3) at City of York Bay and Fairbridge Bluff respectively. Alongside the palaeosol units at Little Armstrong Bay and Charlotte Point, these two palaeosol units also contain significantly higher proportions of carbonate material than the older (MIS 5e/5d), almost pure quartz *terra rossa* palaeosol recorded

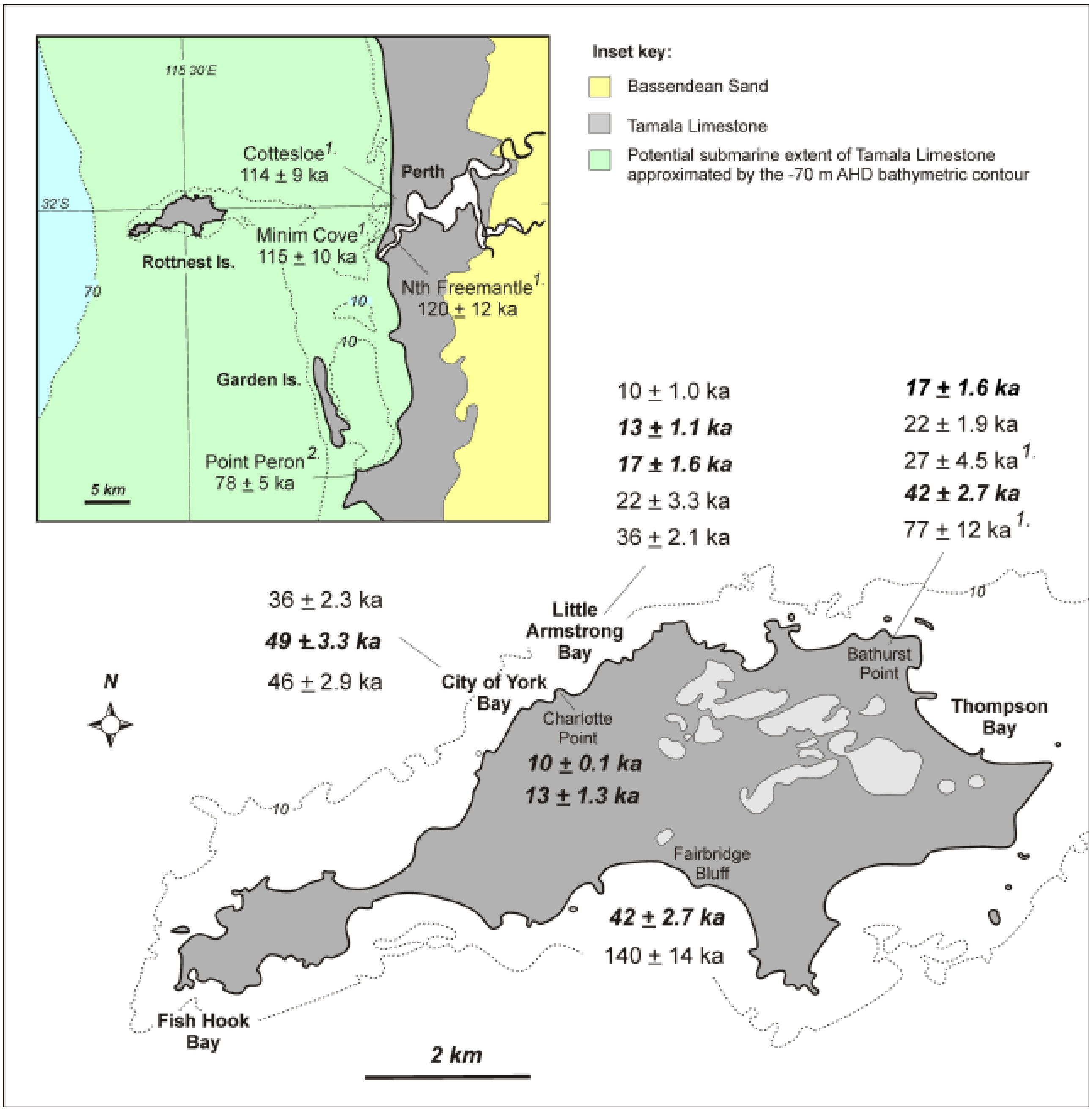

Figure 5. Summary of TL/OSL age estimates for aeolianite and palaeosol (in bold italics) sequences on Rottnest Is. and the adjacent mainland (inset figure), including previously published dates of 1. Brooke *et al.* (2014) and 2. Price *et al.* (2001). Inset figure also shows potential offshore extent of Tamala Limestone (after Smith *et al.* 2011).

at Fairbridge Bluff (Figure 2A), and also at Minim Cove and Cottesloe (Brooke *et al*. 2014). These contrasting carbonate-rich and quartz-rich palaeosols likely reflect the variable movement of mainland (westward) and exposed shelf (eastward) sediments across the shelf in association with changing sea level (Hearty & O'Leary 2008, 2010).

Other palaeosols, such as those at Charlotte Bay and Fish Hook Bay (Dortch and Hesp 1994), also contain variable amounts of charcoal (and fossil plant material) but this does not appear to be age-related. Likewise, although the palaeosols at the City of York Bay and Little Armstrong Bay and pedogenetically very similar, and their stratigraphic positions and heights above sea level are also much the same (Dotch and Hesp 1994: 26), nevertheless they yield different depositional ages (Figure 5). In contrast, the exposed palaeosol units on the east and west side of Little Armstrong Bay do show a similar age and pedogenic characteristics and hence likely belong to a single depositional unit. The palaeosol horizon at Charlotte Point also share similar sediment characteristics (albeit with inclusion of charcoal) and age to the Little Armstrong Bay. However, as indicated by Dotch and Hesp (1994), the palaeosols often cannot be traced laterally very far and caution should be taken before assuming any correlation between these.

The artefact-bearing palaeosols mainly date to the late (17 – 10 ka) stages of MIS 2 and possibly to MIS 3 if the oldest date of 42 ka for Bathurst Point is assumed. This brecciated calcrete/palaeosol unit forms partly as a result of mechanical fracturing by roots (see Arakel 1982), which are clearly evident in the overlying rhyzolithic palaeosol dated to around 17 ka (Figure 2B). Dissolution and re-cementation are common in such calcretes, as evident from the thin calcrete unit that caps the brecciated calcrete (Figure 3) and also in thin section (Figure 2B). Subsequent erosion of the rhyzolithic palaeosol, possibly as sea-level encroached Rottnest Is., may have resulted in exposure of the embedded artefact (see also Ward *et al.* 2016). Indurated palaeosols and duricrusts intercalated within Tamala Limestone aeolianite successions occur along many parts of the West Australian coastline (Playford *et al.* 2013, p.102) hence the possibility of other embedded artefacts being similarly exposed.

Palaeosols, occasionally featuring rhizotubules and *Leptopious* sp. pupal cases are revealed in many places along the littoral zone. At Little Armstrong Bay a massive, brown sandy palaeosol unit continues c. 200 m within the intertidal zone. Playford (1997) also describes root pipes in the Tamala Limestone extending below sea level at many localities around the coast (e.g. at Fairbridge Bluff). The luminescence dating of the ‘older aeolianite’ at Bathurst Point (Figure 2B) implies that some, perhaps even all of the palaeosol units exposed in the littoral are older than c. 77 – 66 ka (MIS 4). Correspondingly Smith *et al.* (2011) indicate the Tamala Limestone (and by implication intercalated palaeosol units) may extend as far as the -70 m bathymetric contour (Figure 5). However, no artefacts have been identified in any of these older or partially submerged palaeosol units exposed on Rottnest Island.

CONCLUSION

With an absolute chronology spanning MIS 6 to MIS 2 (~ 140 ka – 10 ka), Rottnest Island is today one of Australia’s best dated Late Quaternary localities and one of Western Australia’s most iconic geoheritage sites (Ward 2013). This secure chronology, particularly of the palaeosol units, is of great importance to further investigation of prehistoric archaeological sites as well as to other Quaternary field studies on the island. The artefact-bearing palaesol units mainly date to MIS 2 (17 – 10 ka). However, further dating and pedogenic characterisation of palaesol units around the island is needed before considering the possibility of a widespread distribution of one or more archaeologically significant palaeosol units (see Dortch and Hesp 1994). Similarly more detailed chronological studies – such as this one – are needed to further define dune-building and calcrete-forming episodes in the Tamala Limestone (Playford 1997). With continued evaluation of the Rottnest Island absolute chronology, the island will become an increasingly valuable site for Quaternary investigations.

ACKNOWLEDGEMENTS

I.W. and C.E.D. sincerely thank Perth Nyungar community elders who endorsed the archaeological investigations that resulted in the chronology reported here. They also thank staff of Cultural Heritage Services, Rottnest Island Authority (RIA) for the issuance of numerous ferry travel vouchers, and for contributing significantly to the project in many other ways. Many thanks to Phil Playford OA, who advised on Tamala Limestone geology and kindly arranged with WA Geological Survey for the sponsoring of charcoal 14C date (Wk 37948) reported here. The authors also thank the reviewers, Karl-Heinz Wyrwoll and David Haig. Lastly, thanks to Joe Dortch (UWA Archaeology) for his welcome comments on early versions of the text.

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