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Life beyond the lakes: An analysis and implications of a Pleistocene combustion feature on the Pike River in South Australia

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ABSTRACT

The Pike River is an anabranch and palaeochannel of the Murray River located in South Australia's Riverland region, in the southwestern part of the Murray-Darling Basin. The floodplain contains abundant and varied archaeological evidence of Aboriginal life, including extensive deposits of shell midden exposed along the high cliff-line bounding the southeastern margin of the floodplain. The oldest of these deposits has been securely dated, so far, to ~29 ka cal BP. This article presents the results of chronological, micromorphological and sedimentary analyses of a combustion feature also located on this cliff-line. Based on our analysis and interpretation of the feature's stratigraphic context, in combination with ^{14}C and OSL dating, we argue that the feature is ~43 ka old. Whilst the combustion feature contains no associated cultural material (e.g. stone artefacts or faunal remains) we argue that a cultural origin is, nonetheless, supported given the feature's geometry, sedimentary structures, geochemistry and magnetic response. As such, we argue that the feature provides a rare glimpse into the earliest peopling of the Murray River corridor. Further, the feature is amongst some of the earliest pieces of evidence for human pyrotechnology in the Australasian region and only one of a few examples from an open-air site that is microstratigraphically (micromorphologically) contextualised. The preservation of combustion features of this antiquity in open-context sites is extremely rare, both in this region and globally.

1. Introduction

The record of Aboriginal occupation in Australia's Murray-Darling Basin (MDB) remains fundamental in understanding the processes and timing for the earliest peopling of Sahul, the palaeo-landmass that had incorporated mainland Australia, Tasmania and New Guinea (e.g. Bradshaw et al., 2021; Salles et al., 2024). Current evidence suggests that Aboriginal people were living in the central western MDB at the Willandra and Menindee lakes by ~50–45 ka, and possibly at Lake Tyrell to the south of the Murray River corridor by 44 ka (Allen and O'Connell, 2014; Bowler et al., 2003; Bradshaw et al., 2021; Cupper and Duncan, 2006; Hiscock, 2008; Hiscock and Wallis, 2005; O'Connell and Allen, 2015; Richards et al., 2007) (Fig. 1). Beyond these lakes, however, archaeological evidence of Aboriginal life in the MDB is lacking for this early period. Indeed, taken at face value, the dating evidence suggests a lag of ~20 ka between an early focus on lacustrine settlement and later movement into the riverine corridors extending throughout the broader MDB.

Here we report the results of a multi-parameter analysis of a combustion feature (sensu Mentzer, 2014:617) identified in profile on a cliff-line overlooking the Pike River, a palaeochannel and anabranch of the Murray River located downstream of Renmark in South Australia (SA) (Fig. 1). A combination of detailed field recording, microstratigraphic analysis (micromorphology), sedimentology, magnetic

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susceptibility as well as radiocarbon (^{14}C) and Optically Stimulated Luminescence (OSL) dating are employed to rigorously characterise, contextualise and establish a plausible chronology for the feature. Such thoroughness of investigation is required given the difficulties in unambiguously interpreting an anthropogenic source for fire in the absence of material culture items (Whitau et al., 2018:740; see also McNiven et al., 2018). Our analysis leads us to argue that the feature represents the controlled, anthropogenic use of fire at ~43 ka, potentially marking it amongst some of the earliest pieces of evidence for human pyrotechnology in the Australasian region (cf. Adeleye et al., 2024; Cupper and Duncan, 2006) and one of few examples of a combustion feature from an open air site that is microstratigraphically (micromorphologically) contextualised (cf. Friesem et al. 2014; Stahlschmidt et al., 2018). The preservation of combustion features of this antiquity in open-contexts is extremely rare, both in this region and globally (e.g. Friesem et al. 2014; Moreau et al., 2021; Roebroeks and Villa, 2011).

2. The study area and site description

The Pike River is a palaeochannel and anabranch of the Murray River that deviates east of the modern river course immediately downstream of Renmark (Fig. 1). The anabranch floodplain is contained within a broad, shallow valley ~9 km wide and incised to a depth of 30 m into a semi-arid plain mantled with dunes and sand sheets of the Woorinen Formation, a complex mid Pleistocene–Holocene aeolian sequence (Brown and Stephenson, 1991; Firman, 1971, 1972). Lomax et al. (2011) identified five distinct phases of dune activation within the Woorinen Formation in the south western MDB from late MIS 4 through to MIS 1–72–63 ka, ~38–25 ka, 25–18 ka, 14–12 ka and 8–5 ka, with each phase partitioned by regional paleosols (see also Bowler et al., 2006; Bowler and Magee, 1978; Bowler and Polach, 1971; Brown and Stephenson, 1991; Churchward, 1961, 1963; Fitzsimmons et al., 2013; Fitzsimmons et al., 2019; Gill, 1973a, 1973b; Lawrence, 1966; Pell et al., 2001; Twidale et al., 2007). This scenario of episodic aeolian activity is replicated in the Woorinen Formation along the Pike River cliff-line. The combustion feature described in this paper is situated in a palaeodune ridge that has been truncated along a high, almost sheer cliff-line overlooking the southeastern corner of the floodplain (Fig. 2).

Archaeological materials form a semi-continuous deposit along the Pike River cliff-line, characterised in large part by densely packed lenses of shell midden composed of freshwater mussel (*Alathyria jacksoni* and *Velesunio ambiguus*) and river snail (*Notopala sublineata*), hearths constructed from calcrete rubble heat retainers and a sparse selection of stone and bone artefacts. Similar deposits are observed along the Murray River cliff-lines throughout the broader Riverland (see Marquez, 2023; Westell et al., 2024; Westell et al., 2023). The combustion feature is situated in a site that was recorded initially by Wood and Westell (2016) and designated as PikeSP16_05.

Westell et al. (2020) reported a series of 14 ^{14}C ages returned on midden shell sampled from two archaeological sites (PikeAWE15_10 and PikeSP16_01) on the Pike River cliff-line approximately 3 km downstream of PikeSP16_05. All the dated samples were recovered from unconsolidated Woorinen Formation sediments stratigraphically above a carbonate palaeosol of sheet and pisolitic calcrete. The midden ages spanned the period 29.9–29.0 cal BP (OZX288) to 2.7–2.4 cal BP (Wk-48705). The ~29 ka age, and a similar age midden recorded at Lake Victoria in New South Wales (Abdulla et al., 2019), represent the earliest published archaeological evidence of Aboriginal life in the MDB beyond the Willandra, Menindee and Tyrell lake systems, to date (see Fig. 1).

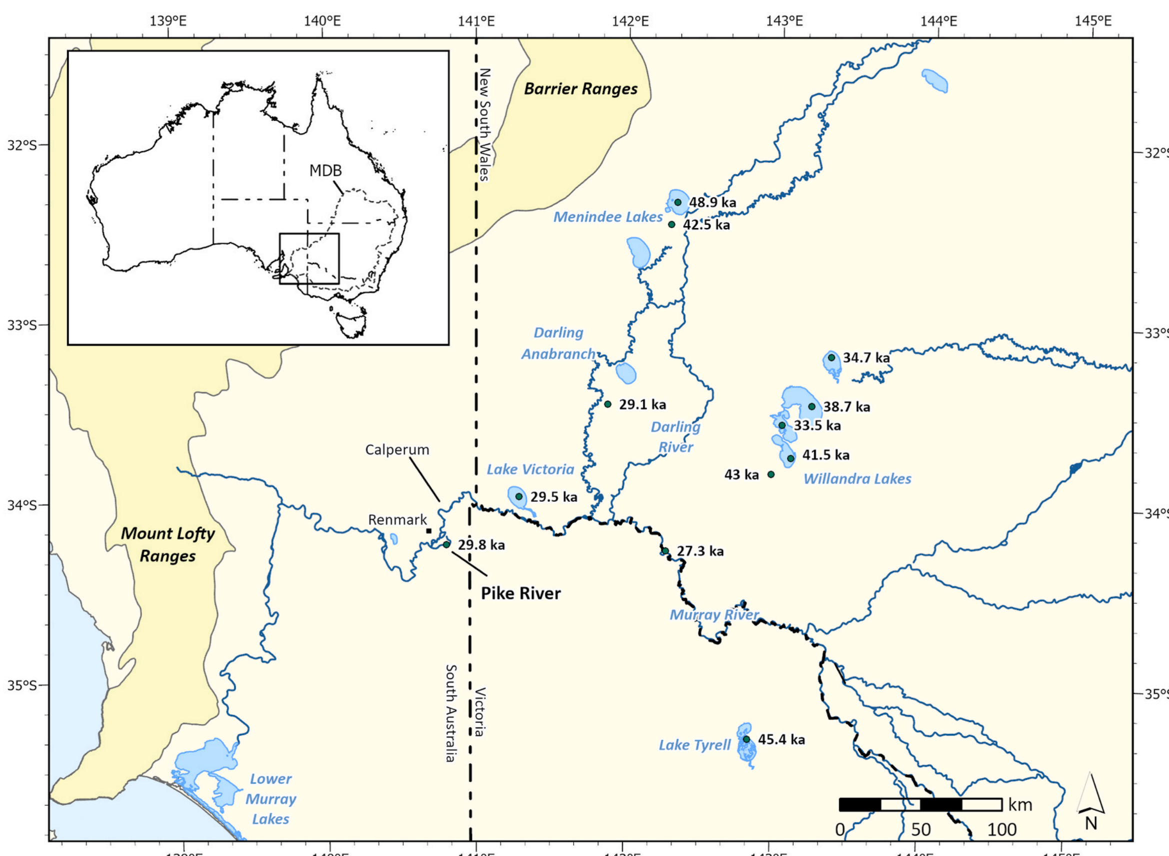

Fig. 1. The Pike River in relation to the south western portion of the Murray-Darling Basin (MDB) showing places mentioned in the text and locations where the maximum values in calibrated ^{14}C age ranges (as shown) returned on archaeological materials fall within MIS 3, i.e. 57–29 ka (^{14}C age ranges are based on Williams et al., 2014).

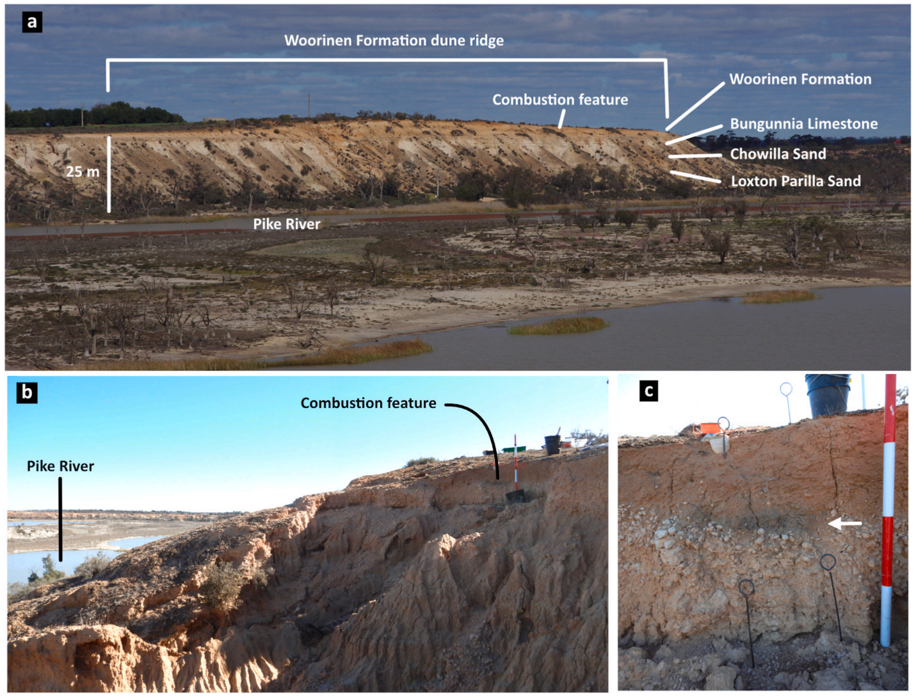

Fig. 2. Context images including (a) a view looking south east across the Pike River floodplain to the location of the combustion feature showing the geological setting, (b) a view looking north along the cliff in the immediate area of the feature, and (c) a view of the originally exposed feature indicated by arrow and with 20 cm increments shown on range pole.

The Pike River also defines the downstream limit of non-contentious Pleistocene archaeology recorded within the MDB (Westell et al., 2024).

The combustion feature had been truncated vertically by erosion along the cliff-line and was identified in section as a well-defined, lenticular exposure of dark sediment measuring ~45 cm in diameter and 9 cm thick (Fig. 2). The feature was contained in a thin unit of calcrete rubble formed directly over a palaeosol hardpan and situated below unconsolidated aeolian sand. The feature did not extend into the overlying sand. This stratigraphic context predates all other contexts that contain archaeological material along the Pike River cliff-line both within this site and the additional exposures investigated by Westell et al. (2020), including the 29 ka midden lens within site PikeAWE15_10.

3. Background to anthropogenic combustion features

The methods employed in this study sought to address criteria that researchers have previously used to determine whether or not 'evidence of fire clearly represents human action' (Stahlschmidt et al., 2015:182; see also Mallol et al., 2017; McNiven et al., 2018; Goldberg et al., 2017; Ward and Friesem, 2021), although we acknowledge that these criteria are not necessarily prescriptive. As Ward and Friesem (2021:20) argued, 'the presence of rubified sediment or fire-cracked rock, charcoal or articulated ash lenses can all be used to identify intact combustion structures or hearths but none are unequivocal indictors'. People lit fires for different purposes, they constructed and managed fire in a variety of ways and selected fuels based on preference and intent. For some purposes, there may not be other cultural materials deposited in direct association with a combustion feature (see summaries in Ward and Friesem, 2021; Whitau et al., 2018). These variables would necessarily manifest in a continuum of potential combustion features represented in the archaeological record (Mentzer, 2014:216–217).

While controlled, human-made fires may share some common traits with natural fires, it has been argued that the former are more likely to display the following attributes.

1. Demonstrate *in situ* burning (as opposed to in-washed sediments) and demonstrate evidence of thermal alterations (e.g. fractured stones, darkened stones, enrichment in ferromagnetic minerals, rubification of sediments) (Goldberg et al., 2017; McNiven et al., 2018:105, 110);
2. Be basin-shaped or lenticular in profile (up to ~15 cm) and sub-circular in plan view (Bellomo, 1993:550; McNiven et al., 2018:109, 110; Mentzer, 2014:633; Robins, 1996:34);
3. Occur in a concave feature, which is usually anthropogenic in origin (see summary in McNiven et al., 2018:109) but occasionally natural (Mentzer, 2014:633, 639);
4. Incorporate 'a basic stratification of ash-rich deposits often overlying a charcoal-rich layer with a basal layer of burnt sediments' (McNiven et al., 2018:109; also see Ward and Friesem, 2021:Table 1). Basal sediments may be rubified, but this will not always be the case particularly in limestone sands (Aldeias et al., 2016:71, 73; McNiven et al., 2018:109; Mentzer, 2014:636–639; Miller et al., 2010; Ward and Friesem, 2021:20), likely due to the low conductivity of carbonates;
5. Contain other cultural materials such as hearthstones and/or other heat retainer material, artefacts and faunal remains (McNiven et al., 2018:105; Ward and Friesem, 2021:20; Westell 2022); and
6. Be more commonly composed of multiple taxa of 'above-ground' tree wood as opposed to single taxon 'root-wood' charcoal (McNiven et al., 2018:107, 110).

4. Methods and materials

4.1. Field observations and sediment analyses

Field observations of the stratigraphy and sediments surrounding the feature noted the dimensions, texture, colour, compaction, content and the nature of interfaces separating each identified stratigraphic (lithological) unit (SU). The combustion feature was recorded, photographed and surveyed prior to the collection of samples.

Bulk sediment samples were collected for laboratory analyses in a vertical column in contiguous 2 cm increments (but respecting unit

Table 1
Grain statistics, radionuclide concentrations and dose calculations used on each OSL sample.

Sample	OD (%)	Grain diameter (μm)	Total grains	Depth (m)	U (ppm)	Th (ppm)	K (%)	H2O content (% dry weight)	Cosmic dose (Gy/ka)	Dose rate (Gy/ka)
AD20012	7	212–250	247	1.00	1.11 ± 0.08	5.13 ± 0.33	0.96 ± 0.04	2.2 ± 0.1	0.19 ± 0.02	1.7 ± 0.04
AD20013	12	250–300	351	0.45	0.81 ± 0.06	4.73 ± 0.31	0.83 ± 0.03	2.8 ± 0.1	0.21 ± 0.02	1.47 ± 0.04
AD20014	18	212–250	349	0.20	0.94 ± 0.07	4.73 ± 0.31	0.84 ± 0.03	4.3 ± 0.1	0.25 ± 0.02	1.53 ± 0.04

interfaces) from the natural ground surface down to a depth of 52 cm through the southern edge of the combustion feature (see Fig. 3). A suite of analyses on these sediments was chosen to provide additional information regarding the stratigraphic context of the feature and to test for characteristics that would be expected in a combustion feature, including evidence of heating and the presence of combustion residues.

Carbonate and organic content were measured following a standard Loss On Ignition (LOI) procedure as described by Heiri et al. (2001). Each 2 cm column sample was sub-sampled to ~10 g aliquots then heated in a Kanthal CF1200 Muffle Furnace to 100 °C and weighed to measure loss of moisture content, heated to 550 °C and weighed to measure the loss of organic content and reheated to 1000 °C and weighed to measure loss of carbonate content. The aim of the LOI analysis was to provide quantitative information to support the field characterisation of the sediments. Specifically, we aimed to determine the relative abundance of calcium carbonate across the section and evaluate the amount of organic material within the combustion feature.

Low and high frequency Magnetic Susceptibility (MS) measurements were taken using a Bartington MS3 with a MS2B dual frequency sensor. Samples of ~20 gm were measured for 5 s each, including a blank measurement before and after each sample and corrected for mass to determine χ and χfd% of each sample from the 2 cm interval column. As has been demonstrated in various studies, burning can lead to secondary enhancement in ferrimagnetic minerals reflected in an increase in χ and the percentage of superparamagnetic grains which can be reflected in an increase in χfd% (e.g. Aspinall et al., 2009; Barbetti, 1986; Cuenca-García et al., 2023; Dalan and Banerjee, 1998a; Dearing, 1999; Linford and Canti, 2001; Peters et al., 2000). Magnetic susceptibility techniques have been used in Australia to recognise burning and, by association, human occupation (e.g. Lowe et al., 2018; Lowe et al., 2016; Rosendahl et al., 2014) but have only rarely been applied to interrogate discrete combustion features (Moffat et al. 2008, 2010; Wallis et al., 2008).

Sediment grainsize was measured via an Endecotts laboratory test sieve pack comprising 1 mm, 0.5 mm, 0.25 mm, 0.125 mm and 0.063 mm aperture sieves that was vibrated for 5 min on an Endecotts Minor vibration device. These sieve fractions correspond to the very coarse sand, coarse sand, medium sand, fine sand, very fine sand and clay/silt grain sizes in the Wentworth scale (Wentworth, 1922), and again, sought to refine the field observations regarding the divisions between, and nature of, the stratigraphic units.

Elemental concentrations were measured from samples at 10 cm intervals along the sediment column following dissolution with Aqua Regia solution using an Agilent 8900 ICP-MS at Adelaide Microscopy. The results were calibrated against standards HPS-Q17617A and ICP-MS68A Solution B. Studies have found that the combustion process can influence the elemental concentrations of some elements, such as heavy metals (e.g. Monge et al., 2015; Pazalja et al., 2021).

4.2. Micromorphology

Micromorphological analyses of sediments which retain their original physical arrangements, can provide vital information about the origin and function of an archaeological feature or sediment body (e.g. Morley et al., 2017; Morley et al., 2019). This technique has proven to be a powerful tool in locating evidence of combustion and discriminating between naturally occurring and human-made fire (Goldberg et al., 2017; Karkanas et al., 2007; Mentzer, 2014; Ward and Friesem, 2021). Micro-contextual information can discern markers relating to potential hearths including depositional features, the presence of finer-grain content (e.g. ash, bone, shell and other residues), thermal alteration to sediments and other environmental processes and related taphonomic products that risk being overlooked at a macro (field) scale (Mentzer, 2014:616; Ward and Friesem, 2021:12; Whitau et al., 2018:714).

An intact, vertically orientated and undisturbed sediment block

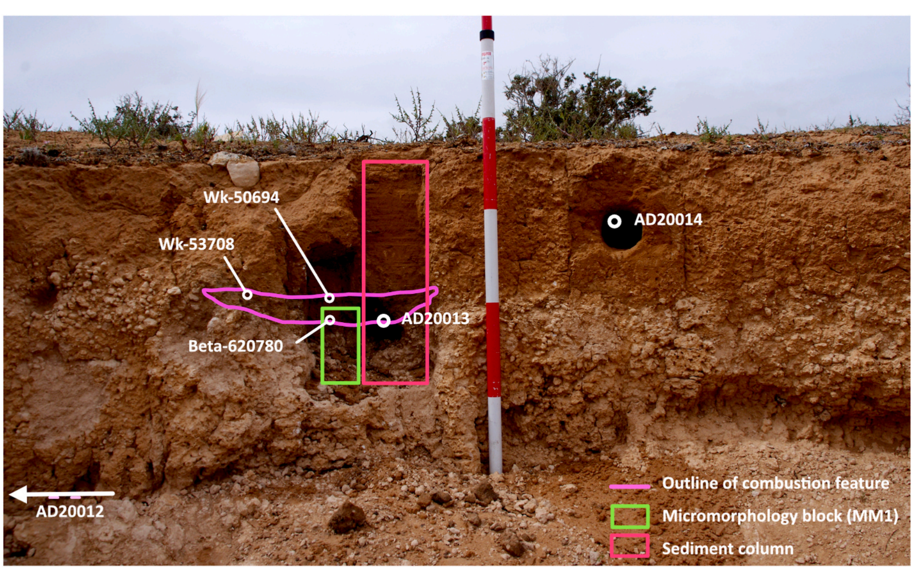

Fig. 3. The locations of ^{14}C (code prefixes Wk- and Beta-) and OSL (code prefix AD) sampling, the extracted micromorphology block MM1 and sediment column in relation to the combustion feature. OSL sample AD20012 was located approximately 7 m to the north of the feature. The increments shown on the range pole are 20 cm.

(MM1) measuring ~20x10x10 cm was recovered from the original cliff face incorporating the lower section of the feature from a point immediately below the location of the radiocarbon sample Wk-50694 (Fig. 3). The block straddled the base of the feature, a thin underlying unit of matrix supported calcrete gravel and the surface of a carbonate hardpan. The block was oven dried at 35 °C and then impregnated with Dalchem crystic polyester resin diluted with styrene and catalysed with methyl ethyl ketone peroxide at a ratio of 7:3:0.02 at the Flinders University Microarchaeology Laboratory. Following curing, the sample was trimmed to 50 × 75 mm wafers and sent to Adelaide Petrographics laboratories to be manufactured into 30 μm thin sections. A flatbed scanner was used to capture an overview of the general composition of the thin sections. Thin sections were analysed under plane and cross-polarised light using a Leica DM2700 polarising microscope at 8x to 200x magnification generally following the prescribed terminology of Stoops (2021).

To ascertain the micromorphological and compositional nature of the dispersed dark powdery sediment within the feature, the upper half of MM1 was subsampled into a smaller thin section MM1A (Fig. 6A) that captures the stratigraphic boundaries across the base of the feature. MM1A was also analysed using an energy dispersive x-ray (EDX) equipped ThermoFischer Phenom XL benchtop scanning electron microscope (SEM) at 550 to 21500x magnification. A representative sample of grains or fragments that appeared to be carbonised and were sufficiently large in size, were examined to determine whether material in the thin section was burnt or charred.

4.3. OSL dating

The collection of OSL samples, laboratory treatment and analyses followed standard methods for single grain OSL dating (see for instance Kreutzer et al., 2018; Kreutzer et al., 2012; Murray and Wintle, 2000; Prescott and Hutton, 1994). Three OSL samples were obtained from cleaned sections within well-defined stratigraphic units below (AD20012), within (AD20013) and above (AD20014) the feature (Fig. 3). Standard collection methods were employed whereby an opaque metal tube was hammered horizontally into each section, the tube was then removed and capped at both ends to minimise light exposure. *In situ* gamma spectrometry was obtained for each sampling location.

OSL ages were determined using Finite Mixed Modelling (Fmix) (see Arnold and Roberts, 2009; Galbraith and Green, 1990; Galbraith et al., 1999; Roberts et al., 2000), an approach that is particularly suited to aeolian landscapes where complex phases of deflation can complicate OSL signals beyond the intrinsic effects of bioturbation and soil development (Bateman et al., 2003; Roberts et al., 2000:460). In these instances, polymodal distributions in OSL signals can be generated as various grain histories are superimposed through a sediment column. The major components generated in the Fmix model are considered against the geomorphological context in interpreting the OSL age of the primary depositional unit at the point of sampling.

4.4. Radiocarbon dating

Three ^{14}C samples were obtained from the feature (see Fig. 3). Wk-50694 was recovered from the upper part of the feature during the removal of a thin wedge of sediment required to expose a fresh, vertical section. The excavated sediment was sieved through nested 5/2.5/1 mm screens with granules of gritty black sediment and several small charcoal fragments (~<2 mm diameter) able to be hand-picked with tweezers from the screens. All the recovered material was submitted for radiocarbon dating. No other archaeological materials were identified in this sediment. Sample Wk-53708 comprised a black sediment recovered from a bulk sample at the outer edge of the naturally exposed feature. Sample Beta-620780 also comprised a black sediment recovered after minimal sorting of residual sediment collected during the extraction of micromorphology block MM1.

AMS techniques were applied to all samples using standard pretreatment protocols (Petchey et al., 2017). Age determinations were returned as both Conventional Radiocarbon Ages (CRAs) (with 1 sigma errors) and calibrated age ranges using the SHCal20 atmospheric curve (Hogg et al., 2020) and the OxCal v4.3.2 program (Bronk-Ramsey, 2009). Calibrated ages are reported here as 95.4 % probability.

5. Results

5.1. Stratigraphic context

As described above, the combustion feature presented as a well-defined, lenticular unit of dispersed dark, fine-grained sediment measuring ~45 cm in diameter and 9 cm thickness (Figs. 2c and 4). No cultural materials were identified in direct association with the feature, despite repeated inspections over a period of two years. The feature contained no apparent heat retainers.

Field observations identified four stratigraphic (lithological) units (SU3–SU6) in the profile intersecting the feature (Figs. 4 and 5). Two additional units (SU2 and SU1) were noted above SU3 in the broader site area (see Westell 2022). The feature occupied a shallow basin in SU5, a thin (~10 cm) unit of coarse calcrete rubble that directly overlies a palaeosol hardpan (PS3) (see Figs. 2c, 4 and 5). PS3 had developed across the surface of SU6, i.e. aeolian sediment forming the palaeodune ridge. SU5 is interpreted as the eroded surface of PS3. SU4 and SU3 sit above SU5 and comprise yellowish-red, fine-medium quartz sand with calcrete clasts largely confined to SU4. Apart from the combustion feature, all other archaeological material identified in PikeSP16_05, e.g. heat retainer hearths, stone artefacts and midden lenses, are contained within unconsolidated aeolian sediments in SU3, SU2 and SU1.

Given the unstable nature of the cliff edge (see Fig. 2), no attempt was made to reveal the feature in plan view through excavation. It became apparent during subsequent sampling for OSL, micromorphology and sediment analyses, however, that the extant feature extended no more than ~15–20 cm into the cliff face. As such, our analysis is constrained to a partially preserved feature, which imposes limitations in interpreting the feature's original structure, contents and extent. Continuing erosion since the recording has also resulted in the partial collapse of this section of cliff, and at the time of writing, only a small section of the originally exposed feature remains intact.

The results of the laboratory-based sediment grain size, magnetic susceptibility and geochemical analyses are provided in the Supplementary Information and summarised in Fig. 5. These results support the field observations and provide further information about the sedimentary sequence, evidence of a combustion feature in this section and its context within the sequence. Key observations include the following.

- The grain size characteristics illustrate consistent grain size sorting properties across the section, with sediment comprising a very fine–fine sand with relatively minor medium grained sand and silt fractions, although with an observable decrease in coarser carbonate clasts up-section from SU6 to SU3.
- Other than the trend described above, there is no distinct change in grain size across the base of the feature.
- The smaller component of carbonate clasts in the upper units is reflected in a stepwise decrease in the LOI carbonate percentage from a peak of 13.6 % within SU6 to <3 % in SU3. The upper units are essentially a fine–very fine quartz sand. Organic material is consistently low (1–2 %) throughout the section, and, although it increases very slightly in the combustion feature, the increase is not significant.
- The highest peak (12.7 %) in χfd% corresponds with the combustion feature at a depth of 30–32 cm, suggesting the highest concentration of superparamagnetic grains at this level. The χfd% in the remainder of the section are high (10.9–12.5 %), all within the range which suggests that greater than 75 % of the magnetic mineral grains are

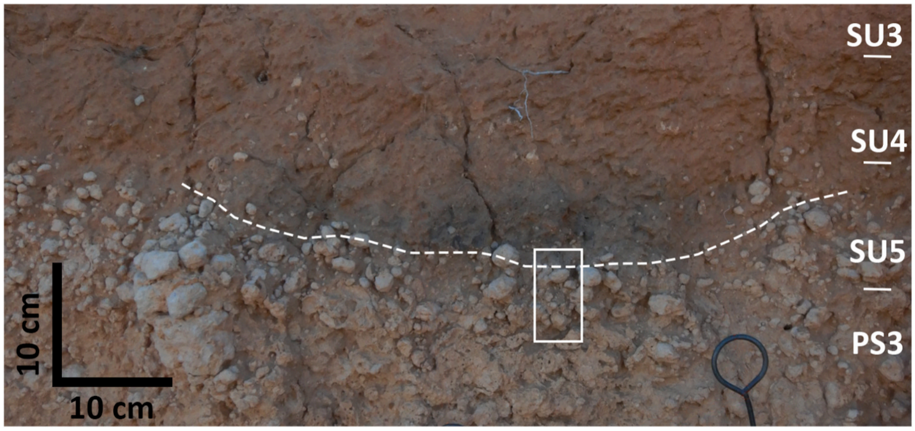

Fig. 4. The location of thin section MM1A (solid outline) in relation to the base of the feature (dotted line) and stratigraphic units (SU).

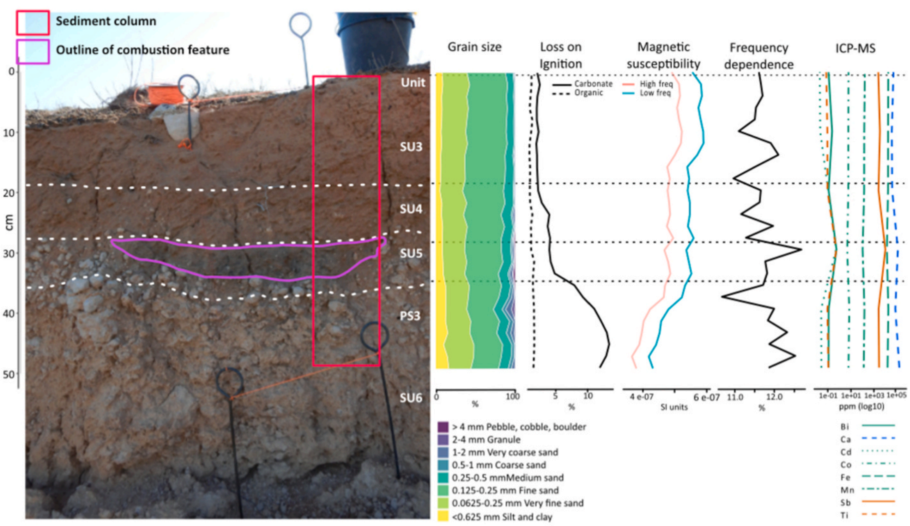

Fig. 5. The results of the various sediment analyses against an interpretation of the stratigraphy across the feature. Considering the difference in the resolution of each data set, the results of the analyses are provided in the Supplementary Data.

superparamagnetic (Dearing, 1999). χ values are highest in SU3, SU4 and SU5, decreasing significantly in SU6.

- Despite the lower resolution in the elemental assays, i.e. sampling at 10 cm increments rather than 2 cm, it is apparent that elemental values deviate most strongly at the combustion feature. Heavy metal concentrations are high in the sediment sample associated with the feature at 30 cm depth, with Bi, Ti, Sb and Cd being considerably more elevated at this level than at any part of the stratigraphic section. Mn, Fe and Co are lower at this stratigraphic level than anywhere else in the stratigraphic section. Ca concentrations are elevated below a depth of 30 cm, correlating well with field observations and the LOI results while the concentrations of all other elements are broadly consistent throughout the profile.

5.2. Micromorphology

Interpretation of the micromorphology was based on thin section MM1A (Fig. 6A), which was cut from the upper half of sample MM1 (Fig. 4), capturing the base of the combustion feature, the underlying unit SU5 and the upper surface of the palaeosol hardpan PS3 (Figs. 4, 5 and 6A). The upper surface of PS3 is typical of the undulating and fragmentary nature of this boundary in the vicinity of the combustion feature. The rounded to sub-rounded calcrete gravel clasts within SU5 are interpreted as having detached from the main body of PS3.

The fabric of the calcrete gravel, i.e. the sediment forming the original palaeodune ridge (SU6), comprises densely packed silt to fine sand-sized quartz grains, generally well sorted, ranging from angular to sub-rounded and suspended in a calcareous matrix. The calcite is very pure with <1 % accounted for by impurities/exotic mineral grains. Differential weathering is observed on the outer surfaces of clasts near the surface of PS3, with the presence of upward-orientated darker rinds and altered rims (see upper surface of clast in Fig. 6B) suggesting *in situ* weathering from above. These rinds are rotated to various orientations on the matrix-supported clasts in SU5, further illustrating the physical breakdown of the PS3 surface. Many of these clasts also exhibit a clay coating rich in organic silts (Fig. 6D).

Younger, finer grained sediments (clay, silt and fine sand) fill the void spaces between the gravel in SU5 (Fig. 6C). The gravel and this matrix are densely compact with only minor thin planar voids, usually around the margins of clasts, probably relating to shrink-swell processes. The gravel clasts within SU5 decrease in size and frequency up-profile and there is a marked change to a much darker colouration in the matrix associated with an increase in pedogenic clays and the inclusion of finely divided charcoal powder (Fig. 6E) that has filtered down from the base of the combustion feature proper.

The upper quarter of thin section MM1A sits entirely within the base of the combustion feature, defined by a significant increase in combusted material and related colour change (Fig. 6A). The fabric within

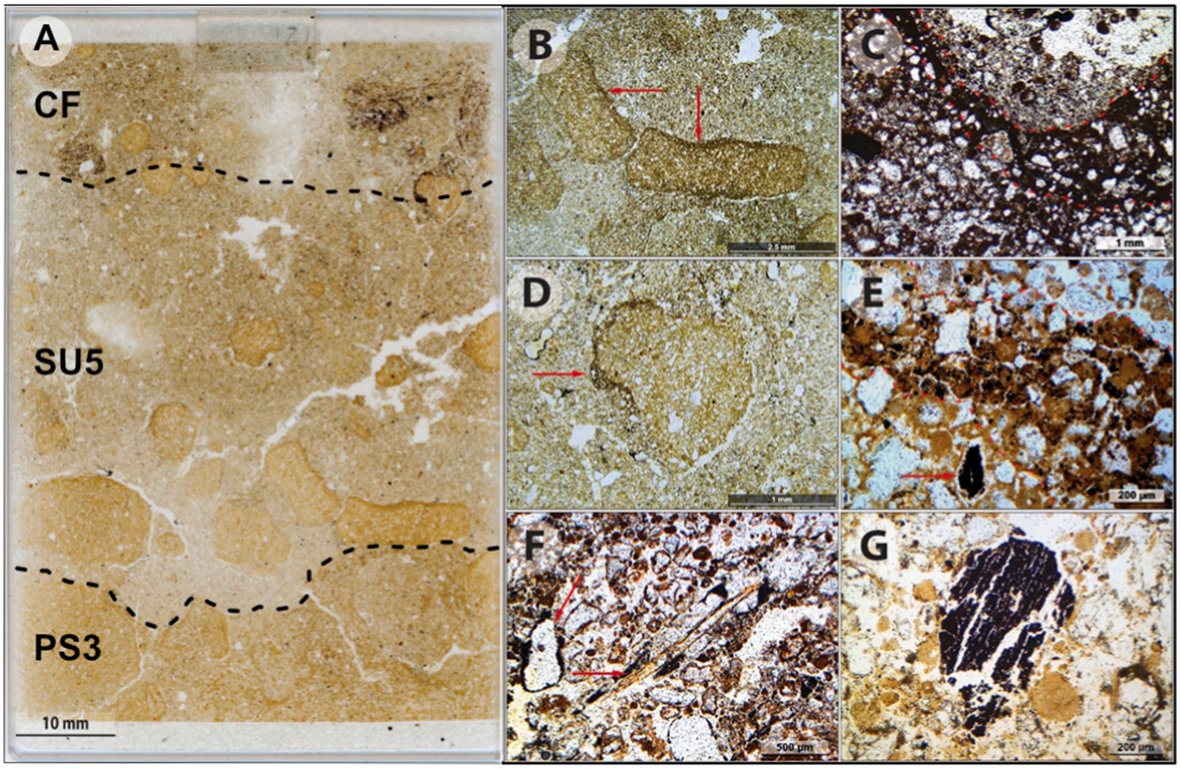

Fig. 6. *Thin section MM1A.* ***A)*** *Flatbed scan of thin section MM1A with the dashed lines demarcating the upper surface of PS3 and base of the combustion feature (CF).* ***B)*** *Rounded calcareous gravel of SU5, showing internal matrix consisting of quartz sand and fine clays/silts. Note the presence of the upward-facing altered rims (as pointed to by arrows) which likely reflect weathering.* ***C)*** *Clays filling interstitial void spaces within SU5.* ***D)*** *Calcrete gravel clast exhibiting similar weathering pattern as in panel B, but with clay coating rich in organic silts (as pointed to by arrows),* ***E)*** *Darker colouration in clays, suggesting its organic nature and a fragment of microcharcoal (as pointed to by arrows),* ***F)*** *Organic powders dispersed in the matrix and coating sand grains (upper arrow), and preserved plant vegetal matter in the area of the combustion feature (lower arrow), likely part of a relict soil associated with the surface in which the combustion feature was excavated in to,* ***G)*** *Fragment of charcoal. Note the dotted areas of partly preserved plant cellular structure within the fractured fragment.*

the feature is formed of silts and fine-grained quartz sand, with discontinuous clay micromass extending laterally across the thin section. This clay-rich fabric is associated with clay coatings on mineral grains, preserved vegetal matter and a generally poorly sorted coarse fraction (Fig. 6F), consistent with a weakly developed or incipient soil horizon (Fedoroff et al. 2018) that is stratigraphically equivalent to the feature. In the same level as this clay-rich horizon are dense accumulations of finely divided organic silts and occasional microcharcoal fragments, some of which preserve the original plant structure (Fig. 6G).

Organic silts in the thin section are generally comprised of carbon and oxygen at a ratio of ~6:4, respectively (Fig. 7B and D). The organic silts are characteristically homogenous and somewhat vitrified (Fig. 7B) or possessing a dendritic, internally fractured structure (Fig. 7C) that has been noted of charred plant materials (Li et al., 2022). Locally, the clay fabric and included microcharcoal are very densely packed, but void structures are observed elsewhere in the slide, a characteristic that is consistent with bioturbation.

5.3. Chronology

5.3.1. OSL

The grain statistics, radionuclide concentrations and dose calculations applied to the three OSL samples are summarised in Table 1. All three samples returned OSL signals with multiple populations that are best represented by the 5-component Fmix models summarised in Table 2. These populations are also shown on the Abanico diagrams in Fig. 8 alongside the ordinal Kernel Density Estimate (KDE) plots for each sample. The low percentage values of the youngest components offer support to the approach of using Fmix modelling and the adoption of major components in describing key sedimentary phases. There is also a clear accord between major components in the three OSL age distributions, illustrating a commonality and turn-over in the sediment column.

The sample taken from directly within the combustion feature (AD20013) has large grain populations equating to OSL ages of 27.6 ± 1.1 ka (35 %) and 43.7 ± 1.9 ka (33 %). The largest population in the sample taken stratigraphically below the combustion feature (AD20012) equated to an OSL age of 70.0 ± 2.2 ka (33 %). The sample taken stratigraphically above the combustion feature (AD20014) has the largest population at 6.4 ± 0.4 ka (32 %).

5.3.2. Radiocarbon

All three ^{14}C samples were characterised in the field as dark, gritty sediment. Fine charcoal fragments were also discernible in Wk-50694 both in the field sampling and Waikato Laboratory notes. Wk-53708 was described in the laboratory notes as mainly grit and soil. Similarly, Beta-620780 retained no discernible charcoal after laboratory pretreatments and was analysed as organic sediment. Both Wk-50694 and Wk-53708 had percentage values of carbon on combustion above the recommended minimum 50 %C used by the Waikato Laboratory as a quality control, however Wk-53708 only marginally met this threshold with a value of 51 %C. Wk-50694 returned a value of 64.4 %C and can, therefore, be considered the better 'quality' sample. No %C value was provided for Beta-620780. The age results are summarised in Table 3 and were 44.2–42.3 kcal BP (WK-50694), 36.7–35.8 kcal BP (Beta-620780) and 28.8–28.3 kcal BP (Wk-53708).

The wide discrepancy in the radiocarbon ages is reminiscent of the issues identified by Gillespie (1998) in dating 'black samples' of organic carbon from hearth features in the Willandra Lakes region where particulate charcoal was limited or absent in the extant features or following laboratory pretreatments. Gillespie (1998:176) suggested that

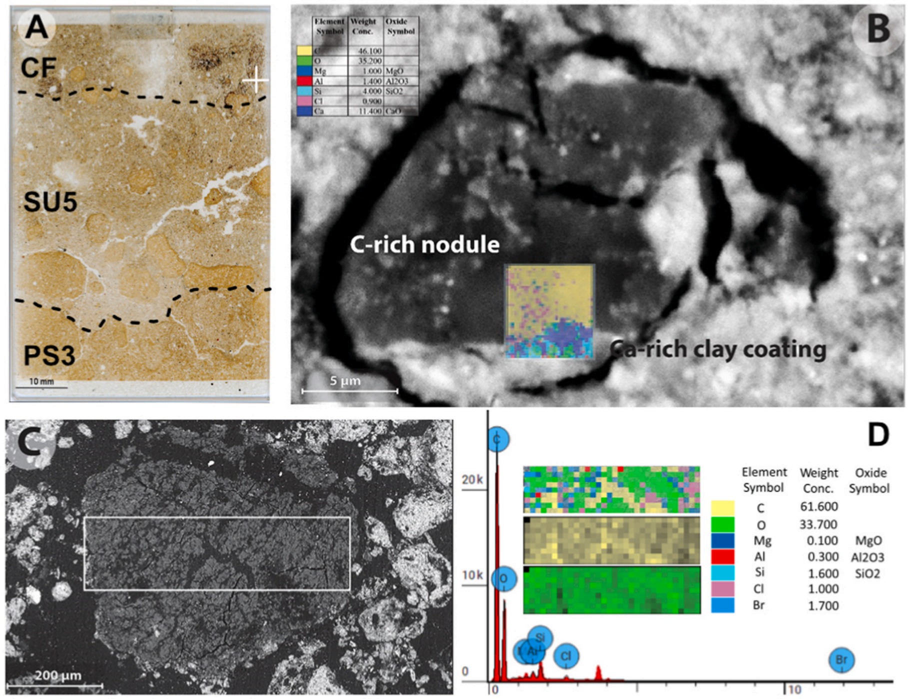

Fig. 7. Microstratigraphic results from SEM-EDX analysis. (**A**) Thin section MM1A with the white cross marking where SEM-EDX was performed within the combustion feature (CF). (**B**) Dark nodule within the general matrix in the area of interest in panel 'A'. Notice the high concentration of carbon and oxygen partly coated in calcium-rich clays. The elemental concentrations, general structure, and dark colour of the nodule suggests that this is charcoal, which is partly coated in clays. (**C**) Dark nodule within the same area of interest. Nodule has a more articulated woody structure. White box marks the area where EDX analysis was performed. (**D**) EDX analysis and map demonstrating high concentrations of carbon and oxygen, and areas (map) where these elements are concentrated respectively, suggesting that these nodules are microcharcoal within the substrate. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Fitting model, equivalent dose, population proportions and OSL ages for each component of each sample.

Sample	Fitting model	Population proportion (%)	Dose rate (Gy/ka)	Palaeodose (Gy)	Age (ka)
AD20012	Fmix (5)	3	1.7 ± 0.04	31.1 ± 2.8	18.3 ± 1.7
		17		64.9 ± 1.9	38.2 ± 1.5
		33		118.8 ± 2.4	70.0 ± 2.2
		25		220.6 ± 5.6	129.0 ± 5.0
		22		516.9 ± 12.9	305.0 ± 11.0
AD20013	Fmix (5)	10	1.47 ± 0.04	7.2 ± 0.3	4.9 ± 0.2
		10		17.2 ± 0.7	11.8 ± 0.5
		35		40.5 ± 1.2	27.6 ± 1.1
		33		64.1 ± 2.4	43.7 ± 1.9
		12		130.5 ± 5.7	89.0 ± 4.0
AD20014	Fmix (5)	16	1.53 ± 0.04	5.4 ± 0.3	3.5 ± 0.2
		32		9.7 ± 0.5	6.4 ± 0.4
		22		18.4 ± 0.8	12.0 ± 0.6
		22		46.8 ± 1.5	30.7 ± 1.2
		9		103.3 ± 5.1	67.6 ± 3.7

the alkaline environments created by wood ash in combination with calcrete enabled alkali-soluble humic acids to migrate into the hearth features from the surrounding sediments, introducing 'young-carbon' (see also Bird, 2013). In summarising, Gillespie (1998:176) argued that age determinations returned on anything other than recognisable charcoal fragments should be treated with caution as they are prone to erroneously young radiocarbon ages—smaller fragments of charcoal tend to be more prone to both contamination (higher % of contaminants relative to the sample size) and displacement (see also Bird et al., 2002).

6. Discussion

6.1. Evidence and nature of combustion

Micromorphological and compositional evidence confirms that the dark powdery fine silts that stain the sediment matrix of the combustion feature are finely divided charcoal powder and microcharcoal. The compact, dendritic and fractured structure of the microcharcoal is consistent with mechanical weathering and elemental exchanges consistent with concentrated and managed, high temperature (~300°–450°C) fires. This temperature presumably leads to the abundance of charcoal powder we observe in the micromorphology sections and the concomitant absence of ash (Li et al., 2022: Fig. 2). As demonstrated by Bellomo (1993:533), natural fires (e.g. tree stumps and grass

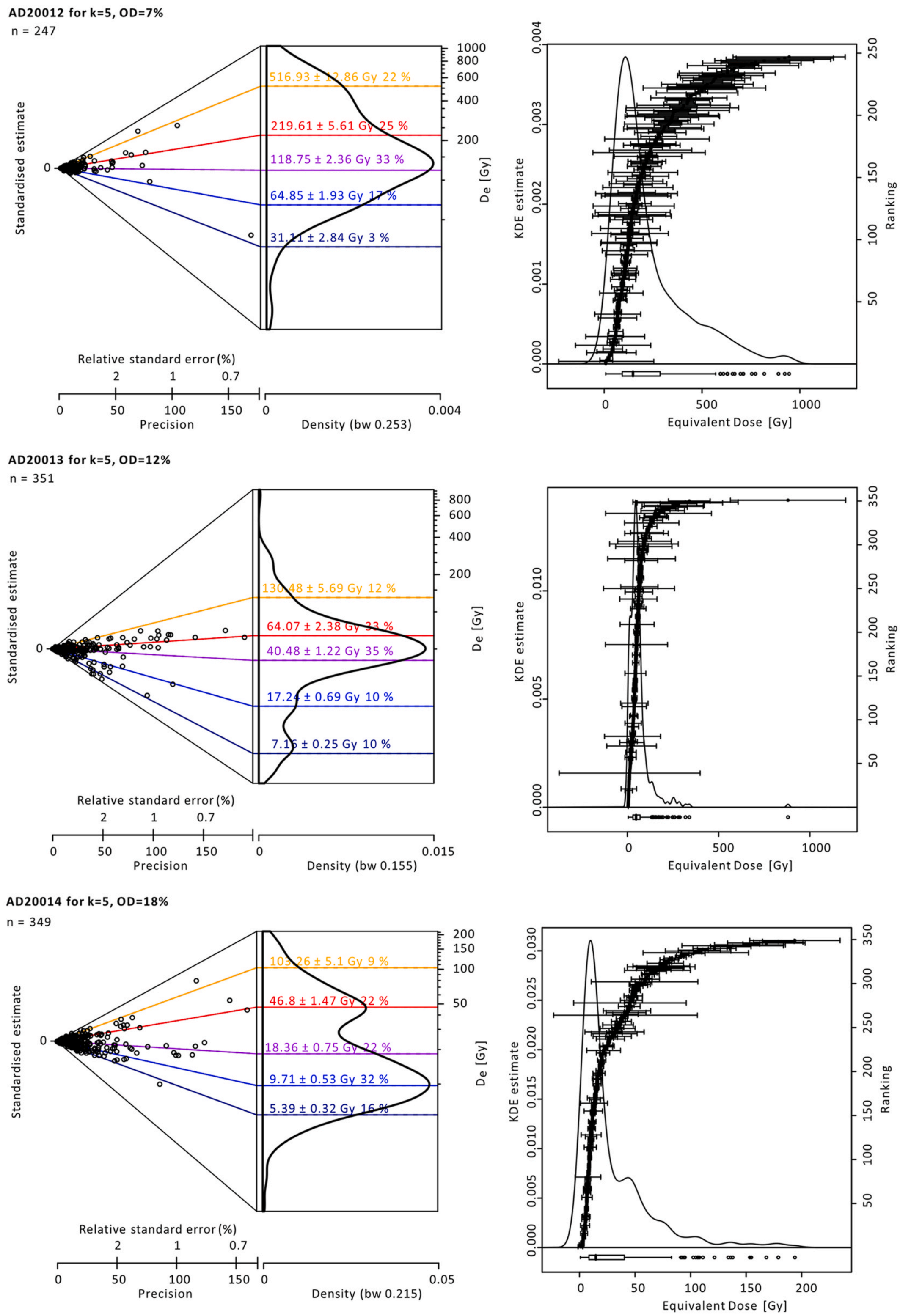

Fig. 8. Abanico diagrams showing the Fmix components and their grain percentages alongside the KDE estimate plots for the three OSL samples.

fires) tend to burn at high temperatures, but over relatively shorter time spans than managed fires.

The elevated values in χfd% measured in the combustion feature compared to the rest of the section also suggest the relative enrichment of superparamagnetic grains at this level and, as such, further evidence of combustion (e.g. Dalan and Banerjee, 1998b; Linford and Canti, 2001). The elevated values in χfd% associated with the feature are within or above the χfd% ranges interpreted as burning evidence in other archaeological contexts (Lowe et al. 2016, 2018; Lowe and Wallis, 2020; Peters et al., 2000; Rosendahl et al., 2014). We also note that high χfd% values are reported through the rest of the section, though these values correlate well with natural background measurements from the region (Hu et al., 2020). The source of elevated χfd% values in this part of the MDB is unclear but, given its interpreted wide geographic

Table 3
^{14}C age estimates returned on the combustion feature. Calibrated ranges are reported at 95.4 % probability.

Lab code	Material dated	Method	% modern C	CRA (BP)	Cal range (cal BP)
Wk-53708	Charcoal	AMS	4.8 ± 0.0	24,631 ± 83	28,780–28,290
Beta-620780	Organic sediment	AMS	1.9 ± 0.1	31,930 ± 200	36,717–35,752
Wk-50694	Charcoal	AMS	0.7 ± 0.1	39,309 ± 606	44,239–42,274

distribution (Hu et al., 2020:10), it is presumably geological in origin rather than a consequence of bushfires, as has been interpreted elsewhere (Blake et al., 2006; Oldfield et al., 1981). Determining whether χfd% can be used reliably as a standalone technique to determine the presence of anthropogenic burning in this region would require developing a more detailed understanding of the magnetic properties of these sediments and undertaking actualistic fire experiments (Linford and Canti, 2001). In our interpretation, we attribute the deviation in χfd% above the background level at the combustion feature to the effect of burning, which is supported by additional proxies, as described below.

Other studies have observed elemental concentration in heavy metals associated with combustion features (e.g. Monge et al., 2015; Pazalja et al., 2021). In this instance, we observe the most significant deviations in elemental concentrations across the feature relative to the rest of the section, with higher concentrations of the heavy metals Bi, Ti Sb and Cd, and lower concentrations of Mn, Fe and Co. As with the χfd%, this trend is spatially defined by the feature. The definitive interpretation of the source of this enhancement and depletion is complicated by a lack of similar studies, our relatively coarse vertical sampling increment (10 cm) and the lack of sampling from a control section away from the combustion feature. Future research addressing these deficiencies would provide the opportunity to better understand this and other interpreted combustion features in similar contexts.

The fundamental issue to consider is whether the evidence of combustion necessarily relates to a fire that was constructed and used by Aboriginal people, and here, we return to the criteria outlined in the methods section of this paper.

6.1.1. *Evidence of in-situ burning*

Whilst the feature contains combustion residues in the form of finely divided charcoal powder and microcharcoal, evidence of thermal alteration both within and below the feature, is ambiguous. We attribute the lack of definitive evidence, such as rubification or vitrification of the sediments (Mentzer, 2014; Röpke and Dietl, 2017), to the long exposure to bioturbation and pedogenic weathering. Combustion features of this antiquity in open-context sites are extremely rare, both in this region and globally (e.g. Friesem et al. 2014; Kuman et al., 1999; Moreau et al., 2021; Roebroeks and Villa, 2011:Dataset S1), and the integrity of the feature is undoubtedly compromised by its antiquity and context. Evidence of pedogenic alteration is, for instance, suggested in the association of combustion residues with a laterally discontinuous horizon of pedogenic clay and silt. It could also suggest that the combustion residues had accumulated on the margins of a fire away from the direct heat source, or alternatively, as a spread created through subsequent trampling or natural deflation (Miller et al., 2010; Whitau et al., 2018). We would expect a surface lit fire to be particularly prone to such post-depositional effects and the dispersal of combustion residues in intercalating lenses supports this hypothesis (see Mallol et al., 2007; Mentzer, 2014:Table 7; Shahack-Gross et al., 2004; Ward and Friesem, 2021; Whitau et al., 2018).

There is also no evidence in either the field observations or micromorphology to suggest that the microcharcoal was washed or blown in to its context. If this had been the case, we would expect the boundaries between the feature and SU5 to be more clearly defined, potentially marked with a distinct transitional unit and with depositional layering or distinctive grainsize sorting characteristics retained in, or at the base of, the feature. Similarly, the presence of microcharcoal that retains aspects of the original plant morphologies in MM1A, suggest that these fragments were not remobilised and transported over any considerable distance, as it has been observed that a broader dispersal can compromise the original plant morphology in charcoal fragments (Courty et al., 1989; Jha et al., 2021).

Given that the evidence for combustion (primarily charcoal) is highly localised and forms a lenticular feature ~45 cm in diameter and ~9 cm thick, it is highly unlikely that this represents a more widespread burning event which would be expected in a natural fire scenario. As Bellomo (1993) demonstrated, for instance, features produced through the burning of tree stumps or ground cover/grass fires are distinctly different from those produced through the (re)use of hearths. It would be expected that material washed or blown in would form a broader unit extending beyond this well-defined feature. Indeed, when all is considered, the image we draw is of combustion residues accumulating in a shallow, though well-defined basin, and percolating downward through interstitial gaps amongst the underlying gravel of SU5.

6.1.2. *Lenticular in profile and sub-circular in plan*

As noted above, the lenticular or basin-like profile, thickness and width of the extant feature are consistent with a managed fire (Bellomo, 1993:534). Indeed, Bellomo (1993:534, 537–539) concluded in experimental studies that it was only ‘multiple-burn campfires’ that produced ‘basin-shaped’ features—as opposed to grass or tree stump fires which produced no change or holes in the substratum, respectively. However, there is a caveat in that the feature had been vertically truncated by erosion and was only partially preserved in section view. The feature was not able to be exposed in plan view, though based on the excavation required for OSL and micromorphology sampling, the feature extended no more than ~20 cm into the cliff face. Extrapolating the full extent of the original feature is not possible.

6.1.3. *The use of an artificially constructed rather than natural concavity*

As observed in Figs. 2c and 4, the dark sediment defining the feature occupies a shallow concavity in the surface of SU5 with combustion materials having percolated downward form the base of this concavity into SU5. There was no suggestion in the field observations, sediment assay or micromorphology that the base of the feature rested on a definable contact that would be expected across a natural, pre-existing ground surface.

6.1.4. *Stratification of ash–charcoal–thermally altered sediments*

As above, fire temperature will influence the production and/or retention of ash (Li et al., 2022:Fig. 2) and it is notable that, in this instance, the combustion materials comprise finely divided charcoal powder and microcharcoal fragments, with no ash identified. Based on the micromorphological analysis, stratification within the feature is ostensibly limited to a charcoal-rich upper layer and a dark organic sediment filling the interstitial voids amongst the gravel below. The sediments are discontinuous and disturbed. This could potentially relate to weathering, erosion and/or bioturbation, something unsurprising given the antiquity of this feature and the dynamic nature of aeolian sedimentation across the cliff-line. As confirmed in the micromorphological analysis (see below), combustion residue has translocated downward into SU5 from the base of the feature, and it is possible that the underlying hardpan PS3 had prevented the complete leaching of the feature and added stability to its structure—a rare combination of circumstance required to preserve a feature of this antiquity within an otherwise dynamic and inherently destructive taphonomic environment.

The evidence of thermal alteration is, however, ambiguous. Whilst there is some vitrification of the microcharcoal fragments, we do not observe evidence of thermal alteration in the included sediment or some of the other classic microstructural evidence associated with hearths, although the feature does share some affinity with surface hearths, as described by Ward and Friesem (2021). However, elevated values in χfd % and deviations in heavy metal concentrations are spatially aligned with the feature.

6.1.5. Associated cultural materials

The feature is situated within a much larger archaeological complex which includes densely packed lenses of freshwater shell midden, hearths and stone and bone artefacts, albeit in significantly younger contexts than the combustion feature (Westell 2022). There were no cultural materials (macro or micro) directly associated with the feature itself.

6.1.6. Multiple taxa of 'above-ground' as opposed to single taxon 'root-wood' charcoal

Anthracology was not applied in this research due to the small size of the charcoal recovered. As previously noted, the Waikato Laboratory described Wk-50694 as containing only 'fine' charcoal fragments and Wk-53708 as being composed mainly of 'grit and soil', while Beta-620780 was analysed as organic sediment. The LOI results support the low overall percentage of charcoal in the sediments. Similarly, the results of the micromorphology revealed only finely divided charcoal powder and micro-charcoal which is generally less than 63 μm in size. Previous studies have indicated that the analysis of charcoal fragments <2 mm in size 'often do not permit secure botanical identification' (see Kabucku and Chabal, 2021:11) and some authors preference fragments >1.5 mm (Whitau et al., 2018:748). As such, we determined that anthracological analyses would not be viable for this study and we can make no comments concerning the nature of the wood used in the combustion feature.

6.2. A chronology

The dating conducted within the feature requires a consideration of a broad range of radiocarbon and OSL component ages. Major grain populations from OSL sample AD20013, taken directly within the feature, equate to OSL ages of 45.6–41.8 ka (33 %) and 26.5–28.7 ka (35 %), while the three ^{14}C ages returned on the feature were 44.2–42.3 kcal BP (Wk-50694), 36.7–35.8 kcal BP (Wk-53708) and 28.8–28.3 kcal BP (Beta-620780).

A consideration of the stratigraphic context of the feature is required in interrogating this range of ^{14}C and OSL ages. SU6 represents the upper unit of a dune ridge that was overprinted by palaeosol PS3, a deep pedogenic zone capped by a carbonate hardpan. The depositional age for SU6 at a sampling point approximately 50 cm below the base of the hardpan and 7 m to the north of the feature, is represented by a major component (33 %) in sample AD20012 that translates to an OSL age of 72.7–67.8 ka. PS3 postdates this age and SU5 had formed through the breakdown of the surface of PS3 prior to the combustion feature. SU5 is overlain by well-sorted brown to strong brown, fine-medium aeolian sand with two distinct units identified above the feature (SU4 and SU3). Westell (2022) suggested that two additional units (SU2, SU1) exist within this younger aeolian cover in the broader site area, i.e. that potentially four discrete phases of re-mobilisation of the dune surface are represented above SU5.

This scenario accords closely with a chronology proposed by Lomax et al. (2011) for the Woorinen Formation sequence within the south-western MDB, as outlined above. Based on the schema proposed by Lomax et al. (2011), together with OSL sample AD20012, the palaeosol PS3 is likely to have developed from c. 63 ka with the overlying gravel (SU5) having formed through the break-down of this soil. A younger cover of aeolian sand (SU4 and SU3) was deposited over multiple phases of dune (re)activation from ~38 ka. On this basis, the age of the feature falls somewhere between these two endpoints; it is younger than 63 ka but older than 38 ka. Given this, we argue that a large (33 %) grain population in OSL sample AD20013 equating to an age of 45.6–41.8 ka most likely provides a timing for the combustion event, either relating to the direct thermal bleaching of the quartz grains or the incorporation of sediment at this time. This OSL age is statistically equivalent to the calibrated ^{14}C range of 44.2–42.3 kcal BP (Wk-50694) returned on fine charcoal from the upper part of the feature. As above, this was also the best 'quality' of the three ^{14}C samples.

No other datable materials were identified in association with the feature or in the sedimentary profile intersecting the feature. However, Westell (2022) obtained 14 ^{14}C ages on samples of midden shell (13) and charcoal (1) in site PikeSP16_05 within sedimentary units SU3–SU1. These ranged from 4,869 to 4,728 cal BP (Wk-52035) to 14,912−14,298 cal BP (OZZ020). As discussed in the introduction, ^{14}C ages of c. 29 ka and 27 ka have also been reported by Westell et al. (2020) on a lens of *A. jacksoni* in site PikeAWE15_10 contained within unconsolidated aeolian sand above a hardpan surface. This age range provides a close match to a major component of 31.9–29.5 ka (22 %) in OSL sample AD20014 located at the boundary between SU4 and SU3 in the location of the combustion feature (see Fig. 3). In terms of the archaeological materials preserved along the Pike River cliff-line, the combustion feature occupies a unique stratigraphic context that pre-dates all other reported ages, including the c. 29–27 ka midden.

The micromorphology shows that combustion residues are associated with a partially preserved buried soil horizon represented by a laterally discontinuous horizon of pedogenic clay and fine silt, in which dense concentrations of charcoal powder and occasional microcharcoal are preserved (Fig. 9A and B). These structures suggest the feature was subject to weathering over an extended period and perhaps modified through natural deflation coeval with incipient soil development having occurred before the deposition of the overlaying aeolian cover.

A schematic interpretation of the stratigraphy in the area of the combustion feature is presented in Fig. 10 based on field observations, the analyses conducted during this research and the chronological data collected by Westell et al. (2020) and Westell (2022) from four archaeological sites along the Pike cliff-line. Also shown are the Fmix OSL age components for the three samples in PikeSP16_05.

7. Conclusions

The methods applied in this study aimed to analyse an apparent Pleistocene-age combustion feature through various scales of observation (geochemical, micro, macro, landscape) and employ a multi-parameter investigation of the chronology, structure, content and context of the feature. The research has involved the use of various field, radiometric, micromorphological and sedimentological analyses, and notably, represents one of few instances where microstratigraphy has been used in this region to investigate an archaeological feature.

The combustion feature does not satisfy all criteria identified in previous studies of anthropogenic hearths (e.g. Mallol et al., 2017; McNiven et al., 2018; Ward and Friesem, 2021; Whitau et al., 2018), on either a macro or micro-contextual scale. Notably, the feature does not retain stratified layers of ash and charcoal or thermally altered sediment, and there were no cultural materials associated with it. Conversely, the diameter and thickness of the extant feature, its lenticular profile, the slight concavity in the underlying substrate and the extensive quantities of dispersed charcoal powder and fragments, elevated χfd% values and anomalous heavy element concentrations, are all characteristics that are consistent with an anthropogenic combustion feature. There is no evidence to suggest that the combustion residues had washed or blown in to form this discrete feature. On balance, therefore, we need to consider the possibility that the feature relates to a managed fire used by Aboriginal people. In this case, the extant feature formed as an accumulation of combustion residues, potentially around the periphery of a heat source, either concurrently or through later deflation and/or trampling. The heat source, itself, has been lost through erosion of the cliff-line. An age of c. 43 ka for the feature is likely, based

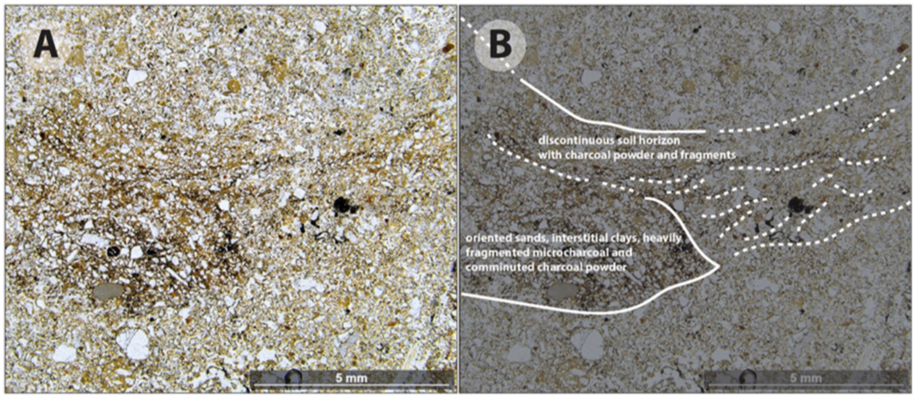

Fig. 9. Relict soil horizon associated with evidence for combustion. Notice the alternating bands of charcoal/clays/aligned and oriented sand grains within this feature.

on a consideration of the ^{14}C and OSL dating and the stratigraphic context.

There has been a renewed global impetus in incorporating open-context sites in valid interpretations of human activity in deep-time (e.g. Carlson and Bement, 2022; Jungnickel et al., 2024; Pineda and Saladié, 2022). It is inevitable, however, that the integrity of archaeological sites and materials within these settings is compromised by their direct exposure to the natural elements. While an understanding of early human occupation in the MDB has been framed around a set of open-context sites, these are reported specifically within lunette sequences where the incremental accumulation of sediments has provided a mechanism for long-term preservation (Bowler et al., 2003; Cupper and Duncan, 2006; Richards et al., 2007). The Pike cliff-line represents a very different taphonomic setting, being situated on the southern slope of a palaeodune that has been impacted by both periodic deflation and the relentless erosion of the cliff-line as the Murray River has migrated within the floodplain below. This context would be expected, under normal circumstances, to impact the preservation of burning evidence (Aldeias et al., 2016:65; Braadbaart et al., 2020), though in this instance, some fortuitous combination of factors such as topography, aspect, deflation/burial episodes along the dune and/or chemical environment, has provided the conditions for preservation over a period of 43,000 years. This result is significant, as it suggests that similar, deep-time evidence of human occupation may be preserved elsewhere in the MDB beyond the specific environmental context of lunettes. Furthermore, while MIS 3-age and older combustion features are more commonly reported from cave and rockshelter sequences, or are inferred from proxy evidence such as heat affected bone or stone, the retention of combustion residues within a preserved feature of a similar age in an open-context is extremely rare, both in this region and globally (e.g. Cupper and Duncan, 2006; Doboş and Trinkaus, 2012; Friesem et al. 2014; Garralda et al., 2014; Leierer et al., 2019; Moreau et al., 2021; Roebroeks and Villa, 2011; Walshe, 2012; Zieba et al., 2008).

There is obviously a limit to which a single feature can contribute to a narrative, and in this case, the feature offers few pointers to a social context. Nevertheless, the combustion feature currently represents the oldest archaeological evidence recorded in the MDB outside of the Willandra and Menindee Lake systems and indicates that the earliest phase of peopling in the MDB had projected into this downstream part of the basin—a new minimum age for Aboriginal lifeways in this riverscape. Unfortunately, the absence of any associated cultural materials in the analysed sediments makes further interpretation difficult and we can only speculate on the intent of the fire, whether for cooking, heating, lighting or some other cultural purpose (see a summary of fire functions in Ward and Friesem, 2021:12; Whitau et al., 2018:740). It does, however, allow us an opportunity to picture Aboriginal people in deep time, looking across a very different Murray River floodplain, navigating and living in a riverscape that they would potentially be the first to name, map and claim as their country, and that would become part of epic ancestral narratives (see Roberts et al., 2023).

In a practical sense, there is limited opportunity to revisit and conduct further analysis of the feature itself given its precarious condition, though further investigation of the Pike River cliff-line may provide a way forward in potentially identifying contemporaneous features and establishing a baseline for the geochemical and magnetic properties of Woorinen Formation sediments outside of the feature. This would provide a basis to further scrutinise the feature's properties and improve our understanding of its context.

CRediT authorship contribution statement

Craig Westell: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Amy Roberts:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation. **Mike W. Morley:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Ian Moffat:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Vito C. Hernandez:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Nigel A. Spooner:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Kathryn McDonnell:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Rachel Rudd:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Fiona Petchey:** Writing – original draft, Methodology, Investigation, Formal analysis.

Data availability

The data that support the findings of this study are included as part of the paper and the supplementary material file (SI Datafile-1_Sedimentary Analyses) and in the stated references.

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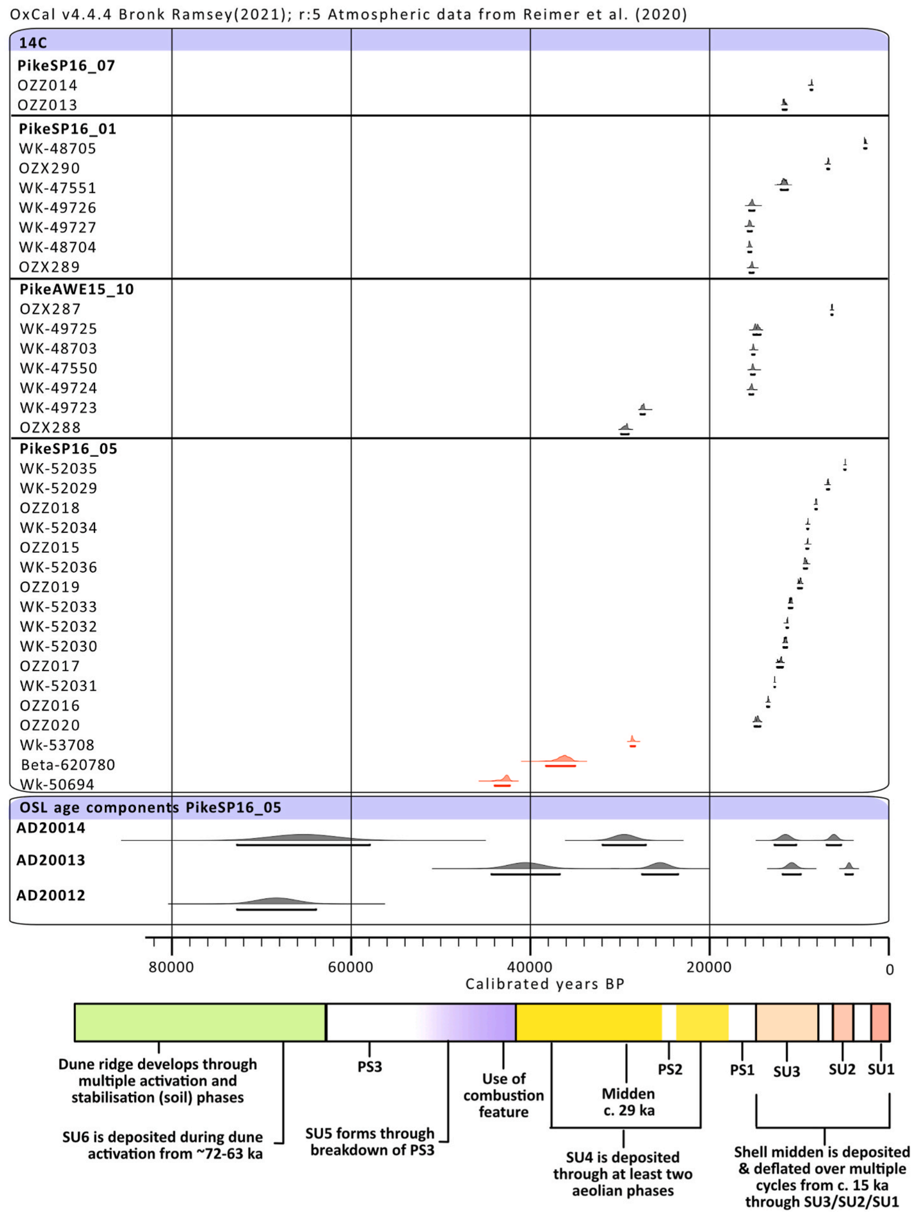

Fig. 10. (Top) Ordinal plot of ^{14}C ages reported on archaeological materials in sites along the Pike River cliff-line (the three ^{14}C ages returned on the combustion feature in PikeSP16_05 are highlighted in red) together with OSL Fmix model components from sampling conducted in PikeSP16_05 (ages results are summarised from Westell et al. [2020] and Westell [2022]). (Bottom) A schematic depositional model for aeolian sediments across the Pike River cliff-line and archaeological materials located within it. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Craig Westell reports financial support was provided by Australian National Collaborative Research Infrastructure Strategy. Amy Roberts reports financial support was provided by Australian Research Council. Ian Moffat reports financial support was provided by Australian Research Council. Mike Morley reports financial support was provided by Australian Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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