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A 47,000 year archaeological and palaeoenvironmental record from Juukan 2 rockshelter on the western Hamersley Plateau of the Pilbara region, Western Australia

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ABSTRACT

Archaeological and palaeoenvironmental investigations at Juukan 2 rockshelter have yielded new information on the ancient Aboriginal occupation of the Pilbara uplands in northwest Australia. Using multiple lines of evidence, including lithic, faunal, pollen, ancient DNA, radiocarbon dating, optically stimulated luminescence, and Bayesian chronological modelling, we show that Aboriginal people occupied the western Hamersley Plateau as early as 47,000 years ago (47 ka). Late Pleistocene populations utilised a diverse range of tool technologies, including bone points, grindstones, and flaked stone artefacts. Palaeoclimatic conditions at Juukan 2 rockshelter varied greatly over the past 47 ka, with repeated site visits by people, including during the peak hyper-arid phase of the Last Glacial Maximum (LGM) c. 21 ± 2 ka. Ancient starch analyses of the ground stone artefacts show the processing of *Ipomoea* (Bush Potato) from around 42 ka to the present day. Pronounced increases in the discard of stone artefacts and bone in the last 3500 years are interpreted to be the result of increased frequency of site use. A braided hair fragment dated to this period has demonstrated genetic links between the earlier rockshelter occupants and contemporary Puutu Kunti Kurrama and Pinikura peoples, who have maintained strong cultural connections to the area.

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1. Introduction

The Pilbara region of Western Australia contains an extensive record of Late Pleistocene Aboriginal settlement extending from the coast to the uplands of the Hamersley Plateau (Bird and Rhoads, 2015; Hughes et al., 2011; Law et al., 2010; Cropper and Law, 2018; Marsh et al., 2018; Marwick, 2002; Morse et al., 2014; Reynen, 2019; Reynen et al., 2018; Slack et al., 2009, 2017, 2018, 2020) (Fig. 1). Along the Pilbara coast, evidence for a human presence has been detected from approximately 51,000 years ago at Boodie Cave on Barrow Island, and from 40,000 years ago at Cape Range (Ditchfield, 2017a; Morse, 1993; Veth et al., 2017a, 2017b). Up to 500 km further inland, the rockshelter sites of Yurlu Kankala and Kariyarra (Cropper and Law, 2018; Marsh et al., 2018; Morse et al., 2014; Reynen et al., 2018; Slack et al., 2018, 2020) and Watura Jurnti (Marsh et al., 2018) date to 45,000 years ago, while investigations at Karnatukul (Serpents Glen) (McDonald et al., 2018) on the edge of the Little Sandy Desert report a modelled age of 50,010 cal BP - 45,190 cal BP, which is consistent with other sites across the region, such as Parnkupirti on the edge of Lake Gregory, Great Sandy Desert (Veth et al., 2009). There is increasing evidence to support the proposition that initial human settlement of the Australian interior, including the arid rangelands, occurred rapidly and commenced well before 45, 000 years ago.

The timing of settlement on the Hamersley Plateau has long been discussed in the archaeological literature, with suggestions that the montane biogeography of this region may have been a ‘refuge’ for people during periods of extreme aridity during the Last Glacial Maximum (LGM), c. 21 ± 2 ka (e.g., Williams et al., 2009). The argument has been that occupation at this time was concentrated on the eastern part of the plateau. The oldest published archaeological sites for the Hamersley Range: Newman Rockshelter (including PAD10-17), and Newman Orebody XXIX (Slack et al., 2018, 2020), and Djadjiling, Jundaru, HS-A1 and HD07-3A-PAD13 (Cropper and Law, 2018; Law et al., 2010; Slack et al., 2018) (see Fig. 1), cluster near the eastern plateau margins, with sequences dated to between 45,000 and 40,000 years ago. These investigations, therefore, have established human occupation of the region >40,000 years, but thus far no archaeological sites of similar antiquity have been reported for the western plateau.

For the western Hamersley Plateau, three archaeological sites contain cultural materials >30,000 years in age: Mesa J24, Juukan 1, and Juukan 2 (Slack et al., 2009; Hughes et al., 2011, Fig. 1). The presence of artefacts below the oldest radiocarbon determination of 29, 301 - 27,657 cal BP (WK-2514) at Mesa J24 led Hughes et al. (2011) to argue for an initial human presence prior to 29,000 years ago. Like other archaeological sites of this age or older (e.g., Devils Lair, Turney et al., 2001), the lowest stratigraphic levels of the sequence yielded very few artefacts, in this case fewer than ten. Previous excavations at Juukan 1 and Juukan 2 suggested an older and better-preserved archaeological record than that identified at Mesa J 24, although further work was required to better understand the temporal limits of the Late Pleistocene archaeological sequence at these sites (Slack et al., 2009).

This paper presents the results of the 2014 investigations at Juukan 2 rockshelter, combining the archaeological and palaeoenvironmental analyses with the results of the previously published 2008 study (Slack et al., 2009). A new and revised chronology for a human presence on the western Hamersley Plateau is reported and situated in the context of other studies for the region; implications of the findings for our understanding of the timing and process of the peopling of Sahul are discussed.

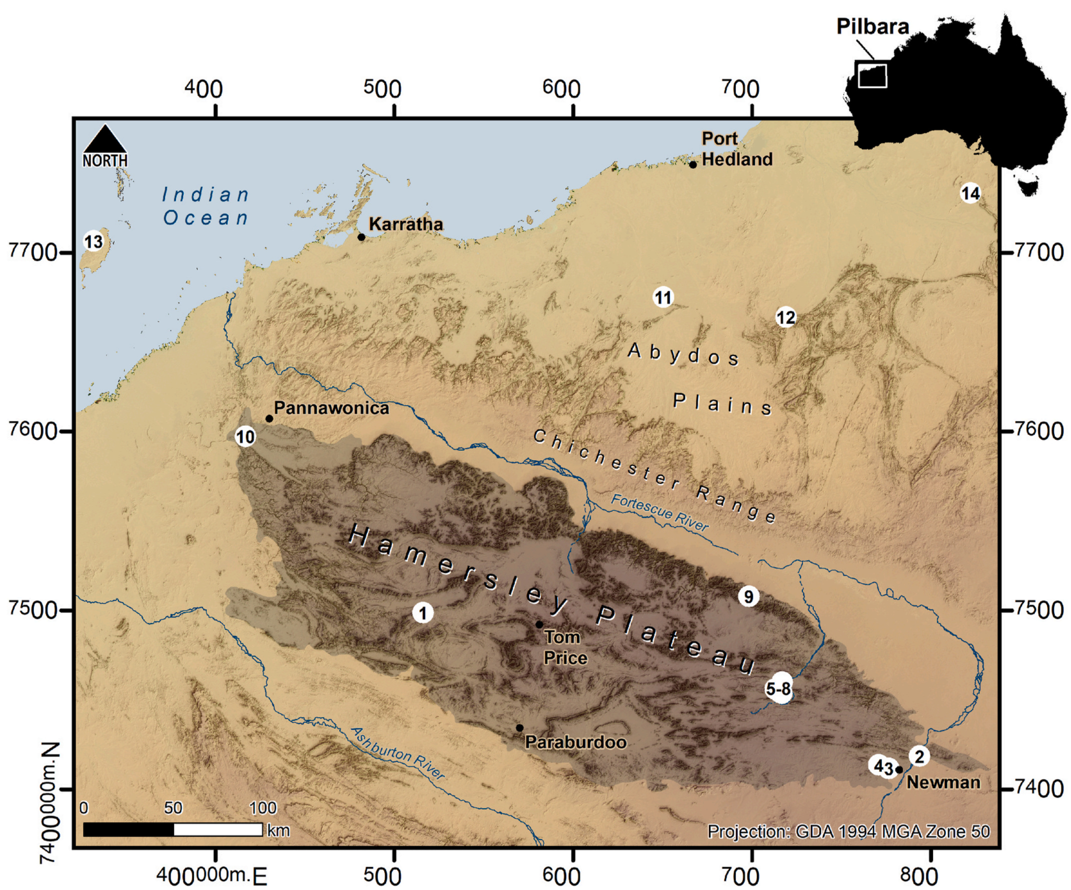

Fig. 1. Map of the Pilbara region and Hamersley Plateau showing key regional Pre-LGM archaeological sequences: **1.** Juukan 1 & 2; **2.** Newman Rockshelter; **3.** Newman Orebody XXIX; **4.** PAD10-17; **5.** Djadjiling; **6.** Jundaru (Malea); **7.** HS-A1; **8.** HD07-3A-PAD13; **9.** Milly’s Cave; **10.** Mesa J-24; **11.** Kariyarra Rockshelter; **12.** Yurlu Kankala Cave; **13.** Boodie Cave; **14.** Watura Jurnti.

2. Regional setting

The project area is in the western ranges of the Hamersley Plateau, a prominent area in the southern Pilbara biogeographic region of Western Australia (Thackway and Cresswell, 1995). The area is a montane desert landscape, nestled between the Fortescue and Ashburton River Basins (Fig. 1). The Hamersley Plateau is a visually spectacular landform, with rugged upland topography (relief up to 450m amsl) that distinguishes it from the surrounding sand plains and stony lowlands. The plateau is incised with deep gullies and drainages that have formed through millions of years of weathering and erosion of the underlying ironstone. Juukan 2 rockshelter formed in such erosional contexts.

The regional climate is arid/semi-arid, dominated by hot and dry conditions with variable rainfall that includes extensive droughts and occasional floods (Van Vreeswyk et al., 2004). There is little surface water present for most of the year other than small ephemeral pools. Vegetation is dominated by hummock grasses, including the hard spinifex *Triodia* varieties and *Wiseana wiseana, Wiseana brizoides*, and *Wiseana plurinervata*. Less frequently, an overstorey of scattered shrubs and trees of *Acacia* and *Senna* spp (Payne, 2004) also occur. Patches of *Eucalyptus leucophloia* (snappy gum) occur infrequently, typically confined to hill slopes, ridges, and minor drainages.

2.1. Palaeoclimatic evidence

Palaeoclimate and palaeoenvironmental modelling of the Abydos Plain from 125 ka to 0 ka has been undertaken by Whitley et al. (2023). Although focused on the coastal parts of the Abydos Plain, the reconstructions provided by Whitley et al.'s model (and references therein) can be applied to the Hamersley Range, especially those western parts of the ranges.

125 ka marked the last high sea level stand globally, and both the climate and the map of the Pilbara at this time would have been much like this region is today. By the time humans occupied the continent at 65 ka (Clarkson et al., 2017), sea level had dropped dramatically and the expanded Abydos Plain would have been dominated by grasslands, scrub, some coastal forest and riverine woodland.

When the earliest known occupation of the Pilbara and Hamersley Ranges occurred around 50 ka, the coastline was still well beyond current limits. Climates were warmer and wetter than today, and lowland semi-open woodland extended into the interior, with eucalypt forests and wetlands along ephemeral drainage systems (Whitley et al., 2023:739).

By 35 ka climates began to dry and sea level began its decline to LGM lows. The forest and woodland environments were gradually replaced by scrublands and grasses, and the previous ephemeral drainage systems would have dried into occasional waterholes. By the peak of the LGM the Abydos Plain would have been a very arid grassland dominated by tussock grasses, spinifex, and blue mallee (Whitley et al., 2023).

Rapid sea level rise and a return of the monsoon occurred after 15 ka, and this change re-established drainage systems and brought a return of more treed vegetation. After 10 ka, shorelines came close to their present positions, estuaries formed, and waterholes became more reliable. Vegetation density increased and coolabah and other large eucalypts dominated the area around water sources (Whitley et al., 2023). Modern coastlines and plains vegetation were established by around 4 ka (Whitley et al., 2023).

2.2. Aboriginal occupation of the Pilbara through time

As described above, Aboriginal occupation of the Pilbara region commenced before 45,000 years ago. In the early days of archaeological exploration of the arid zone, it was assumed that most of the arid interior would have been abandoned at the height of the cold/dry LGM (c.29 ka to 15 ka), apart from a few refugia (Slack et al., 2009; Veth, 1993). However, as research into arid zone occupation began to fill in archaeological gaps, the complexity of arid zone occupation was revealed (Law et al., 2021; Veth et al., 2017a). It is true that several sites from the Pilbara interior that were originally occupied prior to the LGM were abandoned with the onset of the harsh conditions of the LGM. At Milly's Cave (Marwick, 2002; see Fig. 1), for example, there were very low rates of occupation between 30 ka and 21 ka, and even less discard between 21 ka and 14 ka. Milly's Cave did not exhibit evidence for increased occupation until the very end of the LGM. It is a similar story for Newman Rockshelter, Newman Orebody XXIX and Jundaru (Slack et al., 2009; see Fig. 1), in the inland Pilbara, and Noala Cave in the Montebello Islands, close to the LGM coastline (Manne and Veth, 2015). But there are other places that remained occupied, or at least used, right through this period. Closer to the edge of the exposed continental shelf, for example, Barrow Island (Boodie Cave) was regularly visited throughout the Pleistocene and into the early Holocene, after which time islandisation and isolation from the mainland lead to rapid abandonment (Veth et al., 2017b). To the north of the Hamersley Plateau, Watura Jurnti and Yurlu Kankala rockshelters were occupied throughout the LGM, with abandonment, or at least a pronounced reduction in material and sedimentological deposition, from the end of the LGM to the recent past, c. 15 ka (Marsh et al., 2018; Morse et al., 2014).

On the Hamersley Plateau itself, four rockshelters on the eastern edge of the massif have also yielded Pleistocene occupation evidence: Jundaru, HD07-3A-PAD13, HS-A1 and Djadjiling (Cropper and Law, 2018). Each of these shelters demonstrate early Aboriginal occupation well prior to the onset of the LGM, followed by some LGM occupation, although probably ephemerally (Cropper and Law, 2018). Many of the Pilbara sites were abandoned after the LGM or early in the Holocene, with re-occupation occurring in some sites in the last 4000 to 1000 years.

Juukan 2 rockshelter is important in reinforcing these patterns of early inland occupation, and extending evidence from the eastern Hamersley Plateau to the western extremity of the ranges. Juukan 2 is also significant in that this site differs from many others in the region by demonstrating evidence for continued use from 47,000 years ago, through the height of the LGM, and throughout the Holocene, right up to present times.

3. Juukan 2 rockshelter

Juukan 2 rockshelter was located within the Puutu Kunti Kurrama and Pinikura Native Title Determination area of the Pilbara. It was a large rockshelter situated within a small ironstone gorge, near an ephemeral watercourse known as Purlykuti Creek (Fig. 2). The site is 75 km from the nearest substantial (albeit ephemeral) watercourse: the Ashburton River. In May 2020, the rockshelter was extensively damaged with explosives as part of an expansion for a mine, resulting in international media coverage and condemnation. Further excavation work and rehabilitation at Juukan Gorge began in 2022 to remediate Country under the direct guidance of Traditional Owners. Results of these recent excavations will be the subject of a future publication.

Juukan 2 had two south facing chambers: a large western chamber, and a small unprotected eastern chamber with a bare rock floor. Archaeological investigations were focussed on the larger chamber (Figs. 2 and 3). This chamber was 10 m wide and 10 m deep, with a 10 m high cavernous roof space. The height at the dripline was about 8 m. There were three general spaces within the main chamber; a scoured and rocky area with some low vegetation in the western side where a hole in the roof allowed rain to enter; a central area where large roof fall has acted as a sediment trap, and where the main archaeological deposits were found; and a raised area at the eastern rear of the site where bedrock is about 1.5 m higher than in other areas, with negligible sediment accumulation.

Fig. 2. North facing Juukan 2 rockshelter with excavations in progress in 2014.

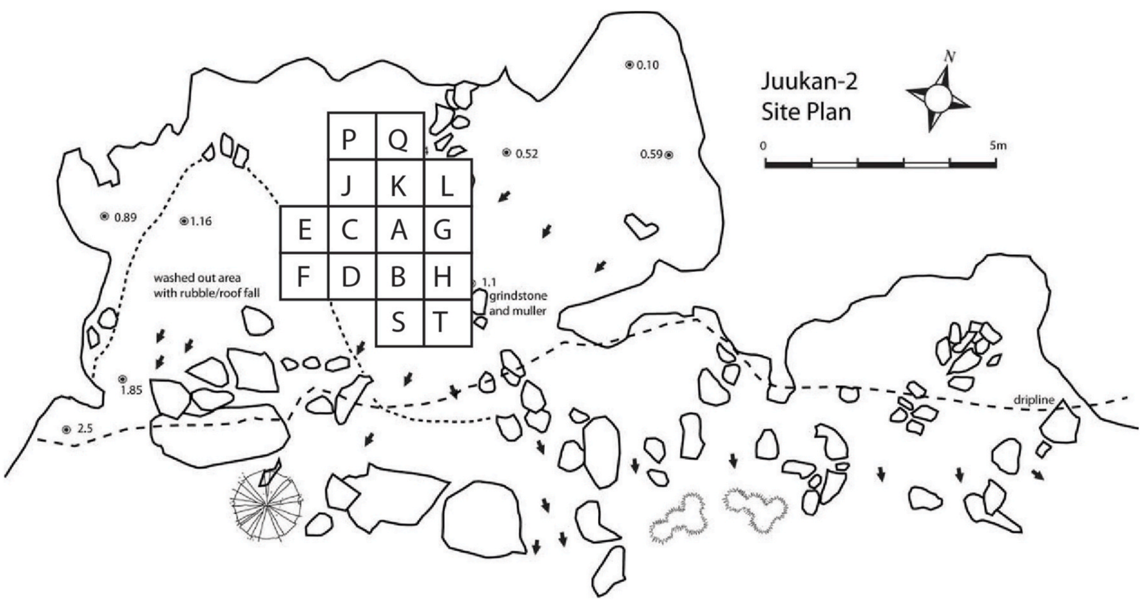

Fig. 3. Plan of Juukan 2 showing the location of the 2008 test pit (square A) and the 2014 excavation squares.

3.1. Excavation

Excavation of a 1 m × 1 m test pit was undertaken in 2008 as part of a cultural heritage assessment of the Rio Tinto Brockman 4 mining tenement (Slack et al., 2009). This test pit reached a depth of approximately 105 cm below surface (bs). Large pieces of roof fall prevented further excavation.

In 2014, a salvage excavation was undertaken to expand the previous 2008 investigations (square A, Fig. 3). A total of fifteen 1 × 1 m squares was excavated, with nine squares terminating on bedrock (A, B, C, D, E, J, K, P, Q; see Fig. 3). The remaining squares (F, G, H, L, S and T) were subjected to limited excavation, either to provide bench access to the lower deposit, or they were abandoned due to time constraints. Squares F and T were excavated from approximately 130 cm to bedrock, specifically to expand the Pleistocene layer during the final days of excavation, with the upper material discarded. A total of c. 22 cubic metres (m^3) of sediment was excavated. This paper provides the results of these pre-destruction excavations.

4. Methods

4.1. Excavation

Both the 2008 and 2014 excavations were undertaken using standard archaeological methods of hand trowelling site sediments, and removing deposits in 5 cm excavation units (XU) within stratigraphic units (SU). Any features (such as hearths) were excavated separately from the surrounding SU and were recorded separately. All sediment was dry sieved using 2 mm and 4 mm mesh stacked sieves.

4.2. Chronology

Chronology of the site was undertaken using radiocarbon assessment of charcoal particles recovered from hearths and other carbonised elements in the site, and OSL dating of quartz grains buried in the sediments. The results from the radiocarbon and the OSL dating were subjected to a Bayesian analysis to model the chronology for the site, to check for consistency of results, and to ensure that no intra-site movement of dated materials had occurred. Methods used for the Bayesian analysis are presented in section 6.4, since the methods are integral to the presentation and discussion of results.

4.2.1. Radiocarbon assessment

Charcoal samples were collected from a range of hearths and other carbonised features excavated from the deposits. The charcoal particles were analysed using standard Accelerator Mass Spectrometry (AMS) at Beta Analytic, Florida and the radiocarbon dates were calibrated using the ShCal20 curve (Hogg et al., 2020).

4.2.2. OSL dating

OSL dating is a technique that can estimate when quartz grains were last exposed to light, thus indicating when they were last buried (Huntley et al., 1985; Rhodes, 2011). OSL samples were collected by hammering opaque plastic tubes (5 cm diameter) into exposed sections along the north wall near to the junction of squares A and C (refer Fig. 4). Quartz grains of 180–212 μm diameter were extracted from sediment samples under red-light conditions using standard OSL dating procedures (Gliganic et al., 2017). A detailed description of preparation and measurement conditions is provided in Supplementary Data.

4.3. Palaeoenvironmental reconstruction

The results of the 2008 excavation demonstrated that Juukan 2 is a deep and very productive site. Preservation was excellent. As a consequence, the 2014 excavation targeted the retrieval of sediment samples, alongside pollen, and carbonised particles that could be used to expand investigations into the deep time history of the site and develop an understanding of the site's changing landscape and surroundings through time. This was done via the collection of bulk sediment samples from every second XU of square C.

4.3.1. Particle size analysis

Particle size analysis was undertaken to characterise likely sediment sources and transport processes contributing to sediment accumulation in the rockshelter (see section 7.1). Laser analysis of the <2 mm fraction of the bulk sample was undertaken using the Malvern Mastersizer 2000 housed at the University of Western Australia in Perth (UWA).

4.3.2. Pollen and micro-charcoal analysis

The palaeoenvironmental sequence for the site was enhanced by the collection of pollen and carbonised particles from 5 g samples collected from the bulk sediment samples taken from square C (see section 7.2). Sample processing followed the methods described in Moss (2013). Soil samples were sieved using a combination of 125 μm (to remove the sand component) and 8 μm (to remove clay fraction) mesh. A heavy liquid (sodium polytungstate with a specific gravity of 1.9) treatment separated the organic fraction (containing pollen and micro charcoal) from the minerogenic component. Pollen and micro-charcoal particles (> 11 μm) were counted at ×400 magnification using a Leica DM2500 compound microscope.

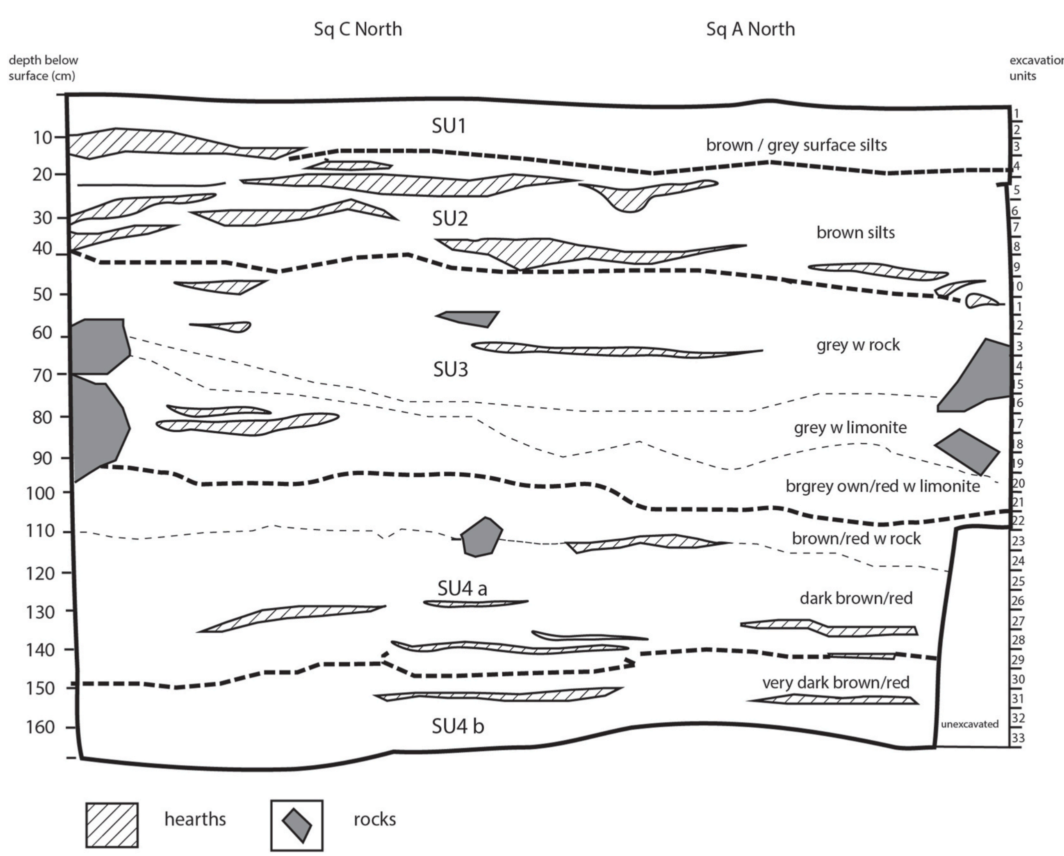

Fig. 4. Stratigraphy of the Juukan 2 deposit, squares A and C.

4.4. Cultural material

Cultural material was collected and bagged on encounter, or when recovered from the sieves. Cultural material was analysed in two main categories: stone artefacts and faunal remains.

4.4.1. Stone artefacts (flaked and ground stone)

The Juukan 2 lithic assemblage consists of 7309 flaked artefacts and six ground stone artefacts, representing one of the largest excavated assemblages in the Pilbara (after Cropper, 2018; Cropper and Law, 2018). Detailed technological analysis of the entire Juukan 2 assemblage has been completed (Reynen, 2019) and will be reported separately; however, some of the broad chronological trends and technological characteristics are presented here (see section 8.1). To better understand changes in artefact abundance and raw material use over time, the deepest contiguous excavation squares, square C (n = 680) and square D (n = 751), were examined for temporal trends in artefact discard (total = 1431, 19.5%). Technological characteristics of the assemblage are inferred through an analysis of raw materials and retouched artefacts (such as retouched flakes, backed artefacts, tula adzes, and burrens), which was extended to the entire assemblage to improve sample size.

The six ground stone artefacts were sampled for use-related residues, specifically starchy plants (see section 8.2). Methods used to extract starch grains followed standard techniques as described by Field (2018); Coster and Field, (2015; 2018); Field et al. (2020) ; Owen et al. (2019)). In brief, samples were extracted from smoothed surfaces by partial or complete submersion of the artefacts in an ultrasonic bath for 2 min. Starch and phytoliths were isolated by a heavy liquid separation in sodium polytungstate (Specific Gravity 2.35) (see Owen et al., 2019; Field et al., 2020) and mounted on glass slides with water and sealed with nail polish. Microscopic examination of the slides using a Zeiss Axioskop II brightfield microscope fitted with Nomarksi optics identified starch grains and other morphological features such as fissures, facets, and lamellae, all of which were recorded, and then geometric and morphometric measures of the grains were calculated. Details of methods used for starch grain identification are provided in Supplementary Data.

4.4.2. Faunal remains

Faunal remains were recovered from 13 of the excavated squares (B, C, E, F, G, H, J, K, L, P, Q, S, T). Analysis of these remains provided a NISP (Number of Identified Specimens) of 7697 for all bone, and a total weight of 1320 g (see section 8.3). For analytical purposes the stratigraphic sequence for Juukan 2 was split into five temporal units: 'Late Pleistocene' (SU4b); 'Pre-LGM' (SU4a); 'LGM' (SU3); 'Early – Mid-Holocene' (SU2); and 'Late Holocene' (SU1) (see section 5). Bones were identified to broad taxonomic categories of mammal, bird, reptiles and indeterminate.

4.4.3. Human hair belt

Excavations recovered a human hair belt was at 18 cm depth, and it has been dated to c. 3.5 ka (section 8.4). Ancient DNA (aDNA) analysis of the hair was conducted by Prof. Dave Lambert at the Australian Research Centre for Human Evolution at Griffith University (see also Supplementary Data). Approximately 0.08 g of the hair sample was processed in accordance with standard aDNA extraction protocols (Wright et al., 2018; Wasef et al., 2020). The aDNA from the hair sample was then sequenced using a HiSeq 4000 Sequencing System (Illumina) at the Danish National High-Throughput DNA Sequencing Centre in Copenhagen. The sequences were mapped against the rCRS human mitochondrial reference genome and a Consensus mitogenome was generated, producing a low-coverage, partial mitochondrial genome. A haplotype was assigned using the online HaploGrep 2.0 software (Weissensteiner et al., 2016) and checked manually using the Samtools tview command (Li and Durbin, 2009).

5. Stratigraphy

Thirty-five distinct lenses and features were recorded during the two excavation seasons, including hearths and preserved organic lenses (e.g., grasses and paperbark) (Fig. 4). Hearths varied from 2 to 10 cm in thickness and included thick layers of ash up to 2 cm in depth. The deposit was divided into four main stratigraphic units (SU) based on changes in sedimentary texture, colour, and particle-size. Colour changes (and pH) correlated to goethite, kaolinite and limonite concentrations. These units are as follows.

5.1 Stratigraphic Unit 1 (SU1 0-15 cm depth) comprised the uppermost unit and consisted of loose topsoil and brown (7.5 YR 4/3) silty sands extending to a depth of 15 cm. This unit graduated into SU2.

5.2 Stratigraphic Unit 2 (SU2, 15–40 cm depth) was a compact light brown unit (7.5 YR 4/2). Organic material (including paperbark, grasses) and hearth features were identified in this unit. Bioturbation, in the form of rats' nests, was observed across square P at the rear of the shelter, and over a limited 1 m × 1 m area.

5.3 Stratigraphic Unit 3 (SU3, c. 40–90 cm depth) was a compacted and rocky (40%) unit, dark brown (7.5 YR 3/3) to brown (7.5 YR 4/3, 7.5 YR 4/2) in colour, with discontinuous grey lenses (inferred to be hearths). The boundary between SU2 and SU3 was distinct and marked by a clear change in sediment colour with an increase in SU3 of boulders and cobbles indicative of rockfall. SU3 was noticeably greyer than all other units and many combustion features within this unit presented as disc shaped, consistent with a hearth. The sediments surrounding these features were also rich in loose charcoal and ash.

5.4 Stratigraphic Unit 4 (separated into SU4a from 90-150 cm depth; and SU4b from c. 150 cm to bedrock) was characterised by loose and fine-grained reddish-brown sediments (5 YR 4/4, 5 YR 4/3, 7.5 YR 4.3). Few cobbles and medium-coarse gravels (>2 cm) occurred throughout SU4. Towards the base of the unit, roof fall fragments increased, along with weathered bedrock. Concentrated charcoal and ash (approximately 100 g/50 L of sediment) occurred throughout SU4, varying between 1 cm and 5 cm thick. A substantial increase in silt ~150 cm corresponds with a chronological discontinuity (see section 6.3), which defined the separation of subunit SU4a from subunit SU4b (Fig. 4).

6. Chronology

Three AMS radiocarbon determinations were obtained on charcoal from XUs 2, 12 and 17 in square A, excavated in 2008 (Slack et al., 2009), resulting in the following calibrated ages (SHCal20).

- 7 cm, XU2: 470 ± 40 years BP; 540 – 328 cal BP (Beta-247330);
- 51 cm, XU12: 16,160 ± 80 years BP; 19,585 – 19,175 cal BP (Beta-247331); and
- 90 cm, XU17: 20,090 ± 100 years BP; 24,287 – 23,835 cal BP (Beta-247332) at the base of excavations where roof fall precluded further excavation.

It was these ages that first indicated the potential that Juukan 2 might be significantly older than had been at first realised, and which encouraged the 2014 salvage excavation.

6.1. Radiocarbon dating

A series of in situ charcoal samples for dating were collected in 2014 from contexts in association with combustion (hearth) features and/or nearby lithic material. Most samples were selected from square C (n = 9), with one sample each from squares D and E. This is in addition to the three dated samples from square A collected in 2008. The results of radiocarbon dating, including calibrated results, are summarised in Table 1. The lowest excavated level from square C that featured well-preserved charcoal was XU27. A sample of charcoal derived from a hearth spread across both squares C (115–120 cm depth) and D, and

Table 1
All radiocarbon determinations for Juukan 2. The samples/results from square A derive from the earlier excavations (Slack et al., 2009). All ^{14}C ages are AMS on single fragments of charcoal. Calibrated ages are modelled using OxCal v4.4 (ShCal20).

Lab ID	SQ	SU	XU	Depth (cm bs)	d13C	^{14}C Age (BP)	Error	Age Range cal BP (95.4% C.I.)	Median Age cal BP	D14C	D14C (σ)	Context
Beta-247330	A	1	2	7	−23.5	470	40	540–328	489	−56.8	4.7	in situ hearth
Beta-432028	C	2	4	19	−22.4	3330	30	3588–3401	3515	−339.4	2.5	in situ hearth
Beta-432029	C	2	6	24	−23.1	6790	30	7674–7520	7611	−570.6	1.6	in situ hearth
Beta-432030	C	3	9	42	−21.8	14220	50	17,385–17,077	17,227	−829.7	1.1	in situ hearth
Beta-432031	C	3	12	51	−23.8	16340	50	19,855–19,535	19,699	−869.2	0.8	in situ hearth
Beta-247331	A	3	12	51	−22.9	16130	80	19,585–19,175	19,422	−865.7	1.3	in situ hearth
Beta-432032	C	3	14	70	−23.5	18070	60	22,153–21,786	21,983	−894.5	0.8	XU sediment
Beta-432033	C	3	16	76	−22.5	18210	70	22,310–21,970	22,136	−896.4	0.9	in situ hearth
Beta-432034	C	3	18	87	−24.1	19570	80	23,787–23,268	23,516	−912.5	0.9	in situ hearth
Beta-247332	A	4a	17	90	−22.4	20090	100	24,287–23,835	24,055	-918.0	1.0	sediment
Beta-432035	C	4a	20	97	−22.6	21270	90	25,797–25,286	25,593	−929.2	0.8	in situ hearth
Beta-432036	C	4a	22	107	−23.6	21230	70	25,734–25,285	25,539	−928.8	0.6	sediment
Beta-432037	C	4a	24	114	−22.5	22560	80	27,126–26,453	26,858	−939.7	0.6	likely hearth
Beta-383965	C	4a	27	133	−22.4	24410	110	28,898–28,263	28,629	−952.1	0.7	in situ hearth
Beta-432027	E	4b	32	155	−23.8	38020	400	42,590–41,940	42,266	−991.2	0.4	XU sediment
Beta-383966	D	4b	32	157	−24.1	38620	430	42,862–42,170	42,489	−991.8	0.4	XU sediment

closely associated with stone artefacts, returned a date of 27,126–26,453 cal BP (Beta 432037). Deeper in situ charcoal was recovered from features from squares D and E. One sample, recovered adjacent to a bone implement from square E (XU32:SU4b; 155 cm), returned a date of 42,590–41,940 cal BP (Beta-432027).

The earliest radiocarbon date for the Juukan 2 sequence comes from SU4b, square D (XU32). This date of 42,862–42,170 cal BP (Beta-383966) is associated with three flaked artefacts and overlies six further artefacts including an ironstone core 3 cm below (XU33). In the adjacent square E there were a further 52 flaked stone artefacts (XU32) at the same depth below surface.

6.2. Optically stimulated luminescence (OSL) dating

Five sediment samples were collected to provide quartz grains for OSL dating. Results, summarised in Table 2 demonstrate a high level of agreement with the radiocarbon dating results in Table 1. Importantly, the OSL date of 39.8 ± 3.2 ka comes from a depth of 153 cm (XU30) and is underlain by about 10 cm of cultural deposit. See Supplementary Data for a thorough discussion of OSL results (Table S1; Fig. S1).

6.3. Radiocarbon and OSL interpretation

Radiocarbon determinations and OSL dates were grouped based on stratigraphic units. The results show a stratigraphically consistent chronology where the radiocarbon ages and OSL dates are in general agreement for both age and depth across the squares, with consistent age estimates at 51 cm for squares A and C. The results indicate that net sedimentation accumulation is relatively consistent across the rock-shelter, with charcoal from hearths indicative of former surfaces. The

Table 2
OSL dating results (dose rate, equivalent dose, and age data) for samples from Juukan 2.

Sample	Depth (cm bs)	SU	Water content (%)	Dose rate data (Gy/ka)				De data			
				Gamma	Beta	Cosmic	Total dose rate[a]	n = [b]	CAM De (Gy)	CAM OD (%)	Age (ka)
BR21–5	22	2	0.96	0.45 ± 0.01	0.94 ± 0.05	0.034 ± 0.003	1.46 ± 0.07	170	16.0 ± 0.4	24 ± 2	11.0 ± 0.6
BR21–4	50	3	1.97	0.42 ± 0.01	0.73 ± 0.04	0.033 ± 0.003	1.21 ± 0.06	126	25.9 ± 0.7	24 ± 2	21.4 ± 1.3
BR21–3	117	4a	1.77	0.47 ± 0.01	0.90 ± 0.05	0.030 ± 0.003	1.44 ± 0.07	81	34.9 ± 1.3	29 ± 3	24.3 ± 1.5
BR21–2	143	4a	2.26	0.48 ± 0.01	0.82 ± 0.04	0.029 ± 0.003	1.36 ± 0.06	71	40.0 ± 1.4	23 ± 3	29.4 ± 1.8
BR21–1	153	4b	2.09	0.34 ± 0.01	0.58 ± 0.03	0.029 ± 0.003	0.99 ± 0.05	85	39.3 ± 1.1	21 ± 2	39.8 ± 2.3

[a] Includes an internal dose rate of 0.3 ± 0.1 Gy/ka based on measurements made on Australian quartz (Bowler et al., 2003).
[b] Number of grains for each sample accepted (out of 400 measured).

rate of net sediment accumulation averages around 4 cm/ka, decreasing steadily through the LGM unit (SU3) to around 2.9 cm/ka, but increases in the top 20 cm to range between 5 and 15 cm/ka. The chronology indicates a relatively steady accumulation of sediments from the earlier Pleistocene units (SUs 4a and 4b), through the LGM (SU3), and terminal Pleistocene (SU2). However, there are some chrono-stratigraphic discontinuities worth exploring.

A stratigraphic discontinuity is inferred between SU3 and SU2, with approximately 20 cm of sediment accumulated between OSL sample BR21-5 (11 ± 0.6 ka) at 22 cm and ^{14}C sample Beta-432030 (17,385–17,077 cal BP) at 42 cm. The distinct lithological change between these depths (SU2 and SU3; see Fig. 4) and increase in boulders and cobbles is interpreted to be associated with sediment destabilisation, possibly a result of the reintroduction of the northern summer monsoon cycle after 14 ka (Wyrwoll and Miller, 2001).

Similarly, a chronological discontinuity occurs in SU4, where less than 10 cm of sediment separates the deepest OSL sample BR21-1 (39.8 ± 2.3 ka) at 153 cm and BR21-2 (29.4 ± 1.8 ka) at 143 cm depth. This discontinuity correlates with a substantial increase of silt in the deepest site deposits, below 150 cm. The cause of the discontinuity is unknown, but it is more likely to have been caused by erosion or other sedimentological factors than by an absence of people c. 40-30 ka. To account for the chronological disparity, SU4 has been divided into sub-units SU4a and SU4b.

6.4. Bayesian Analysis

A Bayesian analysis of dates has become common practice in archaeological analysis (Ramsey, 2009). A Bayesian sequence depositional model (Bronk Ramsey, 2008, 2009a) was constructed for Juukan 2 using prior chrono-stratigraphic information to determine model design (Ditchfield, 2017b). Age determinations were entered into the model in order of their depth (i.e., from deepest to shallowest). Within the model, the dates were ordered by a series of identified phases that are separated by boundaries. In a Bayesian model, phases assume that the age determinations they contain are uniformly distributed with no order (Bronk Ramsey, 1998). This is appropriate for Juukan 2, because while we cannot categorically rule out any intra-strata movement in dated materials/sediments, we are confident that there is little inter-strata (or inter-phase) movement, particularly considering that the dates are in stratigraphic agreement. The phases for Juukan 2 reflect the stratigraphic units identified at the site.

The modelled Juukan 2 sequence uses both continuous and sequential boundaries (see Bronk Ramsey, 2009a). Sequential boundaries represent some kind of discontinuity between phases while continuous boundaries represent an unbroken transition from one stratum to the next. With reference to the Juukan 2 chrono-stratigraphy, sequential boundaries were placed between SU2 and SU3 and between SU4a and SU4b. The remainder are continuous. In order to assess the likelihood of any one sample being an outlier, a General t-type Outlier Model was inset into the sequence model (Bronk Ramsey, 2009b). All

Table 3
Bayesian analysis results for Juukan 2. Modelled ages are presented as cal BP.

Name	Modelled ages (68.2%)		Modelled ages (95.4%)		Summary statistics			Indices		
	from	to	from	to	μ	σ	median	Agreement Index	Outlier Posterior	Convergence
Boundary: SU1 Top	400	140	400	20	220	110	220	100		100
Phase: Late Holocene										
Beta-247330	520	450	540	320	470	60	490	97.7		100
Boundary: SU2/SU1 Transition	2120	340	3410	340	1590	920	1360			99.6
Phase: Early - Mid-Holocene										
Beta-432028	3570	3450	3620	3400	3510	50	3510	100.7	96.4	99.9
BR21-5	11490	10250	12100	9620	10850	640	10860	98.9	95	99.9
Beta-432029	7660	7570	7680	7510	7610	40	7610	101.2	96.5	100
Boundary: SU2 Base	14130	10780	16300	10250	12910	1630	12660			99.3
Boundary: SU3 Top	17300	16010	17380	14050	16240	980	16550			99.4
Phase: LGM										
Beta-432030	17340	17130	17400	17070	17240	90	17240	100.3	95.9	99.9
BR21-4	22640	20160	23630	18960	21290	1210	21340	103.3	95.3	100
Beta-247331	19540	19310	19600	19160	19410	130	19420	100.6	95.6	99.7
Beta-432031	19820	19560	19860	19530	19690	100	19700	100.9	95.9	99.9
Beta-432032	22080	21900	22170	21770	21970	100	21980	100.8	95.8	99.9
Beta-432033	22230	22040	22320	21960	22140	90	22140	101	96	99.9
Beta-432034	23610	23320	23780	23220	23480	150	23470	99.7	95.7	99.7
Boundary: SU4a/SU3 Transition	24010	23560	24200	23360	23790	230	23790			99.9
Phase: Pre-LGM										
Beta-247332	24220	23940	24450	23820	24110	240	24090	97.6	94.8	99.6
Beta-432035	25750	25350	25810	25280	25560	150	25590	100.7	95.7	99.8
Beta-432036	25700	25350	25740	25270	25530	140	25540	100.7	95.7	99.7
Beta-432037	27090	26490	27130	26450	26800	230	26860	100.3	95.4	99.6
BR21-3	25760	23890	27260	23560	25200	1010	25040	107.9	95.2	99.9
Beta-383965	28770	28470	28910	28140	28570	210	28610	96.9	94.9	99.7
BR21-2	29410	26900	30830	25240	28120	1310	28200	98.4	95.2	100
Boundary: SU4a Base	30260	28520	32830	28210	29870	1380	29460			98.4
Boundary: SU4b Top	42500	40160	42620	34730	40390	2480	41440			97.2
Phase: Pleistocene										
BR21-1	42990	41120	43870	38200	41730	1340	42160	89.3	95.2	99.9
Beta-432027	42440	42140	42600	41960	42290	160	42290	102.6	95.8	99.8
Beta-383966	42600	42280	42820	42140	42460	170	42450	102.9	95.7	99.8
Boundary: SU4b Base	43640	42260	47130	42140	43630	2000	42960			91.1

dates were assigned a prior outlier probability of 0.05. An Agreement Index (A-index) was also used to support the outlier analysis. This index indicates a 'goodness-of-fit' for individual dates and for the whole model at a 60% threshold value (Bronk Ramsey, 1998). SHCal20 was used to calibrate the model (Hogg et al., 2020). All modelled dates were appropriately rounded following Stuiver and Polach (1977).

At 95.4% probability, the Bayesian model estimated that the earliest Juukan 2 deposits began accumulating at 47,130 to 42,140 cal BP (at the base of SU4b), coincident with the first discard of artefacts (Table 3). The modelled ages for the discontinuity between SU4a and SU4b suggest that this discontinuity began at 42,620–34,730 cal BP, before SU4a reinitiated at 32,830–28,210 cal BP (Table 3), which also coincides with a previously noted stratigraphic and sedimentary change in SU4. The model indicates that SU4a is indeed pre-glacial, and SU3 is largely representative of LGM deposits, beginning at 24,200–23,360 cal BP and finishing at 17,380–14,050 cal BP. While the model indicates that the base of SU2 may be as old as 16,300 cal BP, the pollen record and environmental context (see discussion below) suggest that it is more likely to be closer to 10,250 cal BP in age. Only one Late Holocene date occurs in SU1 and, as a result, the modelled age for the transition to SU1 is 3410 to 340 cal BP. The SU1 top boundary was constrained with a uniform distribution representing the past 400 years. No outliers were returned in the model and all dates have a less than 12% probability of being an outlier. All individual dates also return Agreement Index results above the threshold value (60%) while the model as a whole has high Agreement Indices (A_{model} = 100.7, $A_{overall}$ = 100.3) (See Fig. 5)

7. Palaeoenvironmental reconstruction

The dry sediments of Juukan 2 have ensured that data relating to palaeoenvironmental reconstruction have been able to be collected from the site. Square C has been used as a representative sample of the sediments of the site, and bulk samples were collected from every second XU throughout this square.

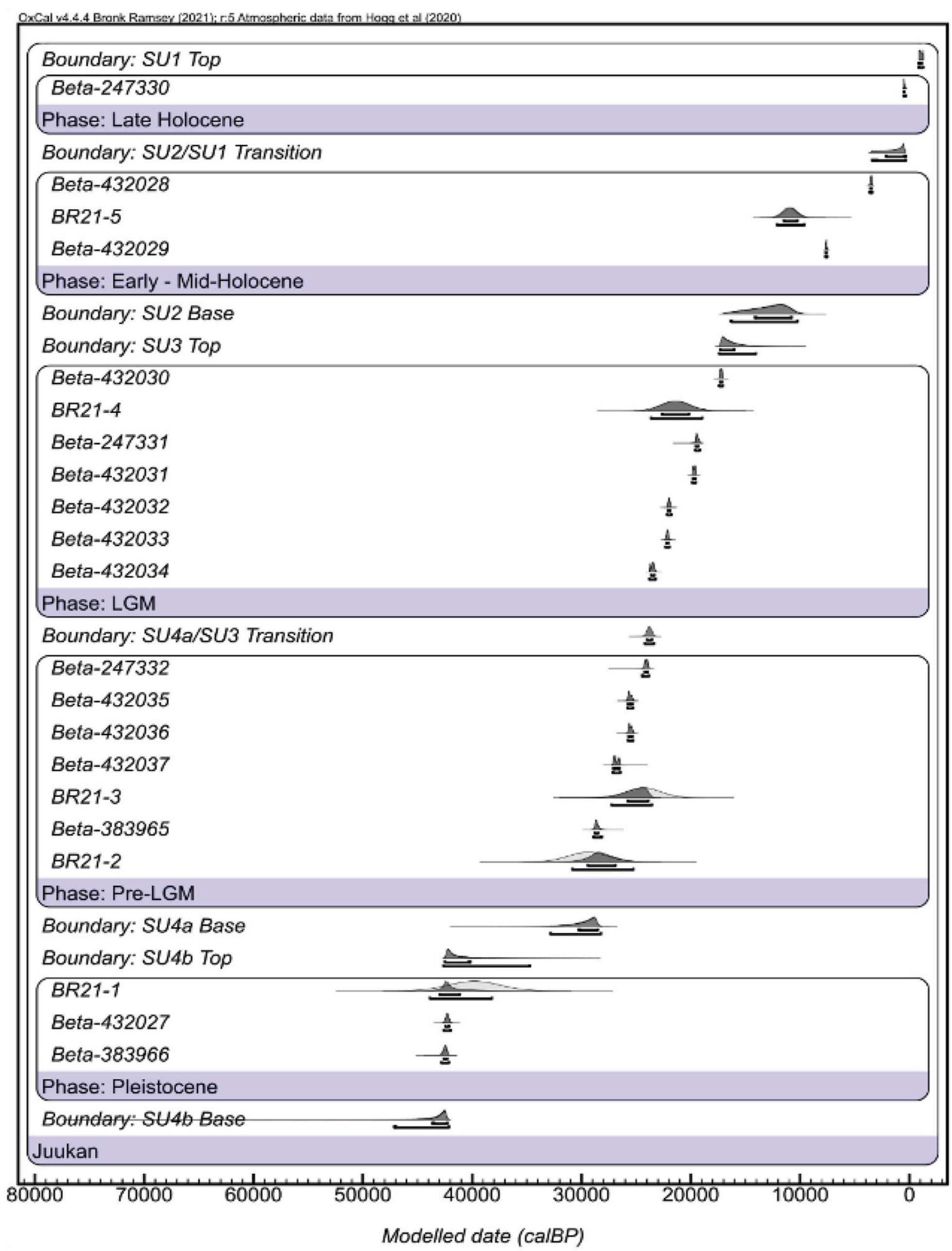

Fig. 5. Bayesian Analysis of all ages from Juukan 2 showing four clear phases of occupation.

7.1. Particle size analysis and interpretations

Particle size analyses indicated that sediment sizes were bimodal throughout, comprising a dominant coarse sand (620–800 μm) and a less dominant silt (50–75 μm) fraction (Fig. 6). The coarsest sediments were from XU24 (~115–120 cm) and XU33 at the base of the excavation, and coincide with the presence of rubble or rock-fall at these levels. Minerals in the coarse fraction were predominantly ironstone, quartz, feldspar and organic matter (charcoal) and some bone. The coarse quartz grains are moderately rounded suggesting they have been transported by water, in contrast to the feldspar which is more angular, and implies a more local source.

The fine fraction is dominated by quartz and degraded ironstone. These silt deposits were predominantly found in deeper levels of the site (XUs16-18: 80–90 cm and XU30: 150 cm). The higher relative proportion of silt at these depths indicates a local or regional change in sediment source and/or lower energy regime, which at 150 cm, corresponds well to the observed discontinuity between SU4a and SU4b in the excavation profile.

7.2. Pollen and micro-charcoal analysis and interpretations

Pollen and carbonised particles provide data that can be used in the reconstruction of local and regional palaeoenvironments through time. For Juukan 2, pollen sum consisted of at least 300 pollen and carbonised particle grains, which have informed the creation of a pollen diagram (Fig. 7), created using the Tilia program (Grimm, 2004). The plant taxa are divided into arboreal taxa, herbs and wetland taxa (both aquatics and pteridophytes). Pollen and micro-charcoal concentrations (particles <125 μm) are also shown in the diagram, along with age/depth and cm bs.

Micro-charcoal was present throughout the sequence while pollen preservation occurred from 120 cm (~28,000 years ago) in SU4a (Fig. 7). Two samples from SU4b (at 165 cm and 155 cm) contain micro-charcoal, with values between 31,555 particles/cm^3 and 208,080 particles/cm^3. The lack of preserved pollen at these levels suggests that oxidation of the sediments has occurred, a process that generally destroys palynomorphs and can reflect seasonal drying (Newsome, 1999). The fact that micro-charcoal is still found in the sediments indicates that vegetation is still present in the vicinity of the site and providing a sufficient biomass to burn, even though there is no pollen preservation.

The transition from SU4b to SU4a at 145 cm is marked by a sharp peak in micro-charcoal (to nearly 600,000 particles/cm^3) followed by a decline at 135 cm, to ~140,000 particles/cm^3. Pollen is preserved in the sediment at 120 cm (SU4a, c. 26 ka) in low concentrations (~420 grains/cm^3) and is characterised by a high abundance of Poaceae (grasses, ~80%). The presence of aquatic taxa (mainly Cyperaceae), suggests wetter, anaerobic conditions at or near the site, while the dominance of grass pollen reflects an open and arid landscape more broadly at this time. Lower micro-charcoal values (generally <50,000 particles/cm^3) in SU4a suggest less burning, and correlate to lower fuel loads. Grass values decline to 55% in SU4a, with a corresponding increase in daisy (Asteraceae) pollen, Brassicaceae (herbaceous taxa) and eucalypts. The changes may reflect a shift from predominantly summer rainfall to winter rainfall, as detected in a marine record off the northwest Australian coast (van der Kaars and De Deckker, 2002).

SU3 encompasses the LGM and following deglacial period, and initially records an increase in Asteraceae (daisy) pollen (60–90 cm). A peak in charcoal particles and Poaceae (grass) pollen at 90 cm most probably reflects increased aridity (more open landscape) associated with the LGM, as observed in marine pollen records (van der Kaars et al., 2006).

From around 20,000 to 14,000 years ago (60–50 cm) there is a marked decline in Asteraceae, coinciding with a decrease in grass pollen followed by a sustained increase in eucalypt, sedge (Cyperaceae) and pteridophyte (vascular plants that produce spores) representation. These changes most likely represent the return of summer rainfall dominance linked to the return of the Australian monsoon (Wyrwoll and Miller, 2001), as has been observed in the Kimberley records to the north (Field et al., 2017, 2018), as well as regional marine records (van der

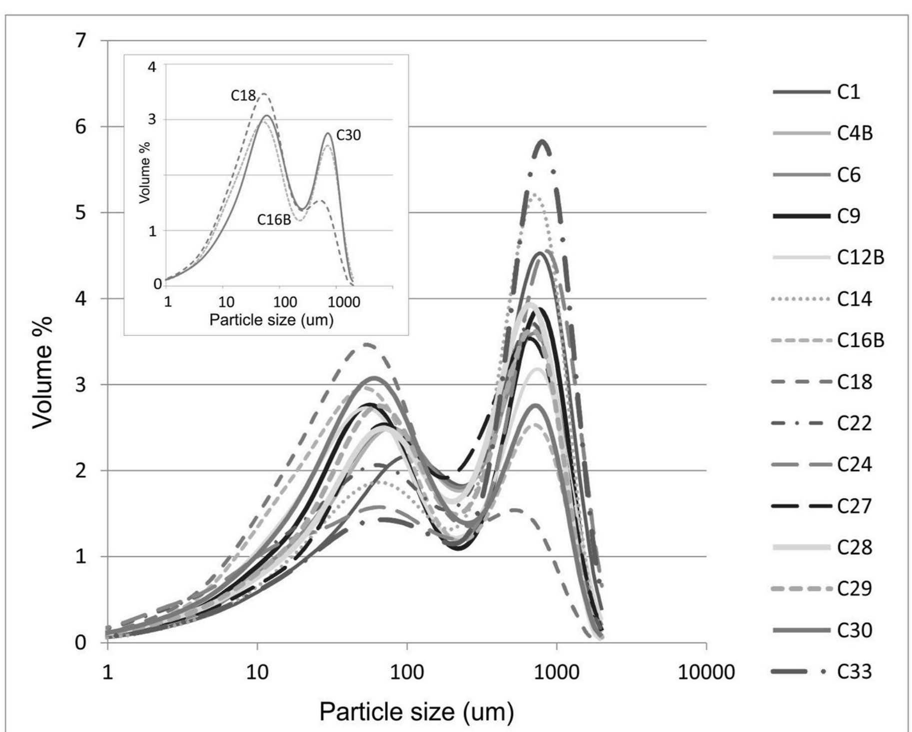

Fig. 6. Particle Size Analysis (PSA) of the Juukan 2 square C deposit showing predominantly bimodal sediments of coarse sand and silt. The silt component dominates in XUs 16, 18 and 30 (inset).

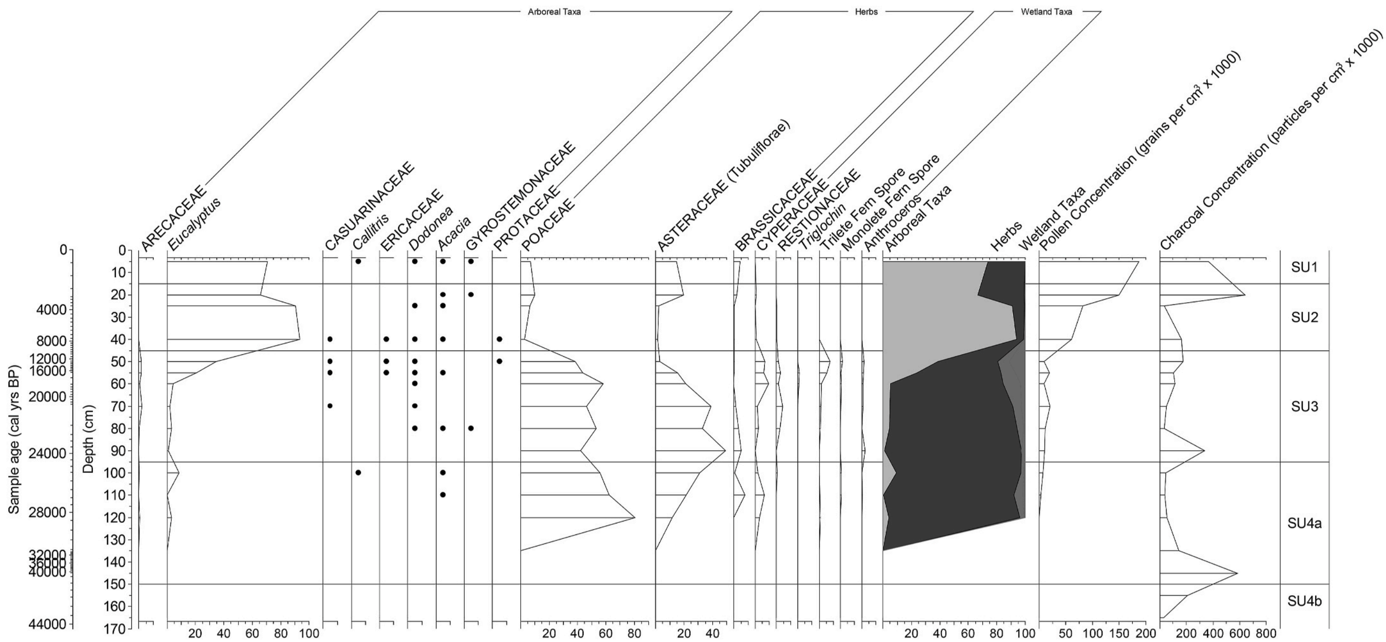

Fig. 7. Pollen diagram and macrocharcoal analysis for Juukan 2.

Kaars, 1991; van der Kaars et al., 2000; van de Kaars and De Deckker, 2002).

The Early to Mid-Holocene (SU2; 40 cm and 25 cm) is marked by the dominance of eucalypt forest, with *Eucalyptus* pollen making up 80% of the pollen sum, associated with a dramatic decline in grass and daisy pollen, and aquatic taxa. These levels most likely reflect the intensification of the Australian monsoon and may be the wettest period in the record. The marked increase in pollen concentration (to above 100,000 grains per cm^3) may also be a consequence of wetter conditions at the site and improved preservation conditions. Other Holocene palynology records across the northwest Western Australian region also reflect wetter conditions (van der Kaars and De Deckker, 2002; Haberle, 2005; Haberle et al., 2018; McGowan et al., 2012; Field et al., 2017, 2018; Rowe et al., 2019).

The pollen and charcoal data from the top of the record (20 cm and 5 cm) represent the Late Holocene. Drier conditions are indicated by a clear decline in eucalypt pollen representation (to 60% of the pollen sum), and an increase in herbaceous taxa, particularly Asteraceae. Corresponding dramatic rises in micro-charcoal values (~400,000 to 600,000 particles/cm^3) possibly reflect increased burning associated with greater aridity, a trend observed in other regional palynological records (van der Kaars and De Deckker, 2002; McGowan et al., 2012; Field et al., 2017; Field et al., 2018; Rowe et al., 2019). One explanation for the drier trends at this time is that the records reflect a decline in the intensity of the Australian monsoon, linked to the increased importance of winter rainfall, and perhaps slightly cooler temperatures during the Late Holocene (van der Kaars et al., 2006). However, cultural burning may also be a factor in the increase in micro-charcoal during this period, with evidence for a marked increase in human populations over the last 4000 years across Australia (Williams, 2013). Field et al. (2018) have suggested that increased soil erosion and fungal activity in the Kimberley may correlate with population increases. Williams et al. (2015) have also argued that periods of climatic variability promoted higher Indigenous fire use to increase landscape productivity.

8. Cultural materials

The range of cultural material recovered from Juukan 2 is extensive. As with most Australian archaeological sites, flaked stone artefacts dominate, but grindstones, faunal remains, and even a human hair belt have also been found. We present summary information on all these different cultural materials.

8.1. Flaked stone artefacts

The Juukan 2 lithic assemblage comprises 7309 flaked stone artefacts and six ground stone artefacts. The Holocene and terminal Pleistocene units (SU1 and SU2) yielded more lithic material than the LGM and Late Pleistocene units (SU3, SU4a, SU4b), which is consistent with other Pilbara rockshelter records (Marwick, 2009; Cropper and Law, 2018; Slack et al., 2017, 2018; but see Morse et al., 2014; Reynen et al., 2018). The abundance and distribution of flaked stone artefacts by XU and SU for squares C and D is shown in Fig. 8, with the lowest in situ flaked stone artefacts associated with a maximum Bayesian modelled age range of 47,130 to 42,140 cal BP (Table 3). Intermittent visits to the site prior to and during the early transition to the LGM are reflected in the low artefact discard during SU4a and SU4b, with a subsequent pulse in artefact discard rates followed by an increase during the LGM and post-LGM (SU3). The frequency of artefact discard then decreases and remains relatively constant during the remainder of the terminal Pleistocene before slowly rising through the Early to Mid-Holocene (SU2). Stone artefact numbers increase markedly in the last few thousand years, which suggests that people visited the rockshelter more frequently during the Late Holocene (SU1) than during any prior period (Fig. 8).

Stone artefacts were manufactured from a range of raw materials, including Banded Ironstone Formation (BIF), chert, quartz and chalcedony. Although specific stone raw material locations were not identified for this assemblage, most raw materials can be found locally as cobbles in the nearby creeks and on the floodplain within a few hundred metres of the rockshelter. Broad temporal changes in the use of raw materials throughout the sequence are evident (Table 4). BIF (n = 653, 45.7%), chert (n = 577, 40.4%), and quartz (10.1%) are the most commonly knapped raw materials, with chalcedony selected for artefact manufacture much less frequently (n = 55, 3.8%). A substantial increase in the relative proportion of BIF occurs during and after peak LGM conditions, Bayesian modelled as being from 24,200 to 14,050 cal BP (SU3) (Table 3), with a concomitant decrease in chert at this time (Table 4). After c. 13,000 years ago (SU2), fine grained materials such as chert and quartz become increasingly dominant, while BIF declines

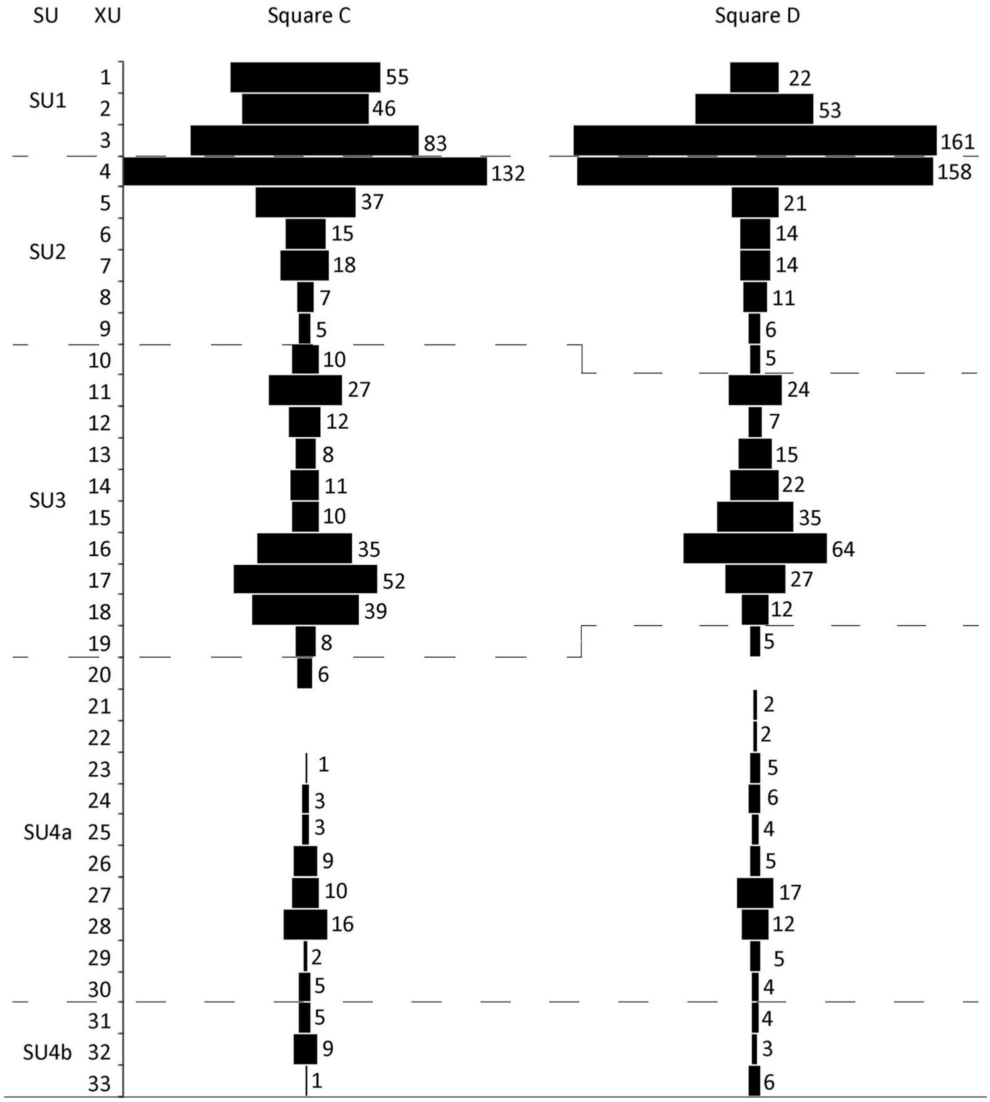

Fig. 8. Juukan 2 artefact abundance by XU for excavation squares C and D. SU divisions denoted by dashed line.

Table 4
Juukan 2 stone artefact abundance by raw material and stratigraphic unit for squares C and D, presented by stratigraphic unit.

Raw Material	SU1		SU2		SU3		SU4a		SU4b	
	n	%	N	%	n	%	n	%	n	%
BIF	89	21.2	206	47.6	290	67.9	50	41.3	18	62.1
Chalcedony	16	3.8	25	5.8	4	0.9	8	6.6	2	6.9
Chert	225	53.7	166	38.3	122	28.6	58	47.9	6	20.7
Quartz	89	21.2	36	8.3	11	2.6	5	4.1	3	10.3
TOTAL	419	100	433	100	427	100	121	100	29	100

(Table 4).

Retouched flakes and formally manufactured implements comprise between 2.7% and 3.8% of the overall assemblage for each phase (Reynen, 2019: 172). The highest frequency of retouched materials occurs in SU1 (n = 125; 3.7%), and the total number of retouched artefacts decreases with depth: SU2 (n = 55; 3.1%), SU3 (n = 43, 3.8%), SU4a (n = 19; 3.5%), and SU4b (n = 5; 2.7%). Flake retouch is strongly correlated with the knapping quality of the lithic raw material. Fine-grained raw materials (e.g., chert and chalcedony) dominate the retouched flake assemblage and coarse-grained materials such as BIF exhibit less retouch.

A total of 89 backed artefacts were recovered from the Juukan 2 excavations, as well as four burren adzes and ten tula adzes (Reynen, 2019: 171). The earliest backed artefact was manufactured from BIF. It was recovered while sieving excavated sediments removed between 35 and 38 cm below surface from square K-XU8 (SU2) (Reynen, 2019: 169). The specimen is bracketed by median age estimates of 7611 cal BP (Beta-432029; 24 cm) and 17,227 cal BP (Beta-432030; 42 cm) (Table 1). The precise age of the backed artefact could not be determined because 18 cm of sediment, including a stratigraphic change at 40 cm, separates these ^{14}C samples. As all other backed artefacts (n = 88) from Juukan 2 are associated with Holocene-aged sediments, we estimate it is likely to be of similar age. We note, however, that backed artefacts have been reported from other Pleistocene contexts elsewhere in the arid zone (see Slack et al., 2004; Hamm et al., 2016; McDonald et al., 2018).

Twenty-four stone artefacts were submitted for usewear and residue analysis (Connell, 2017); nine had clearly been used, with three showing evidence for potential use. Ten artefacts had evidence of hafting, including one backed artefact with intact hafting resin (Fig. 9). Usewear analysis suggests backed artefacts were multifunctional, with uses including cutting, scraping and even projective/chopping activities (Connell, 2017). The most common function identified for this artefact type was plant processing. There are multiple instances where a backed artefact had been used for cutting plant fibres, but the worked material was indeterminate.

8.2. Ground stone artefacts (including ancient starch studies)

Six ground stone artefacts were recovered, either as surface finds or from excavated sediments, and were sampled for use-related residues (see Supplementary Data; Field, 2018). Five of the six ground stone artefacts yielded starch grains (Fig. S2) and phytoliths were also present in most of the samples. Twenty-one starch grains were recovered from Artefact K31 A001 (square K at a depth of 153 cm [XU31; Fig. 10), which also yielded a large number of phytoliths and reddish plaques that may represent ochre. Of the remaining five artefacts, 30 grains were recovered from surface A019 and 23 grains from square B9 Sieve A001. Less than ten grains were found on the remaining three artefacts: square K-XU4 A001 – 6 grains; square S4 A075 – two grains; and square K-XU3 B A161 – no grains.

To identify which starchy plants were being processed with these pounding/grinding stones, a reference set (based on the reference collection held by the University of New South Wales [UNSW]) of widely known economic plant taxa with starchy roots, fruits or seeds was compiled (Table S2). It has been observed that plants exploited for their seeds or fruits in one place may not be similarly exploited elsewhere (e.g. Nardoo [*Marsilea drummondii*]), and we were careful to avoid inclusion of unlikely contributing species. The reference set used in this study includes those plant taxa reported in various publications (e.g. Juluwarlu Aboriginal Corporation, n.d.; Hayes and Hayes, 2007; Young and Vitenbergs, 2007). Not all known economic plants are in the UNSW collection, and this may have constrained our ability to obtain confident identifications in some cases.

Several unknown starch grains were identified in this study. These most closely align with *Ipomoea* sp. (Bush Potato) samples (Fig. 11). There were two *Ipomoea* species included in the analysis: *Ipomoea costata* and *Ipomoea muelleri*, both of which were initially identified as being present in the region (AVH and Buurabalayjii Thalanyji Association Inc., 2007). Recent advice, however, (S. van Leeuwen, pers. comm., 2020) excludes *I. costata* as present on the Hamersley Plateau. As a consequence, the finding of *I. costata* amongst the starch grains in our study is interesting, and can be interpreted in one of two ways: 1. *Ipomoea costata is* present on the grinding stones, having been brought to the site from elsewhere; or 2. *I. costata* is *not* the species present, but instead represents a different species of *Ipomoea*. The starch grains were clearly separated from those of *I. muelleri* but broad similarities across this genus were noted. We have attributed to these grains a putative identification of *Ipomoea* sp. for a cobble located on the surface of the site (surface A01), for a fragment of ground stone from square B9 A001, and for a cobble fragment from square K31 A001. The identification of Bush Potato points to *Ipomoea* as an important starchy food since first settlement of the region. The ground cobble fragment (K31 A001) as shown in Fig. 10 currently represents one of the earliest examples of a grindstone with use related residues in the Pilbara, estimated to have been discarded nearly 42,000 years ago (see Table 3, Beta 432027).

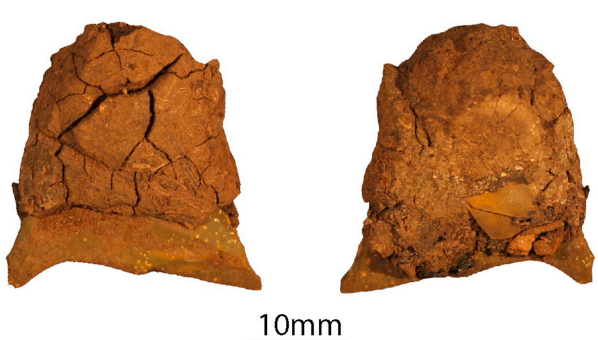

Fig. 9. Backed artefact from Holocene sediments at Juukan 2 square J-XU3 affixed with molded spinifex resin.

8.3. Fauna

Faunal remains were recovered from 13 of the excavated squares (B, C, E, F, G, H, J, K, L, P, Q, S, T). Counts of specific bone parts provided a NISP (Number of Identified Specimens) of 7697, with the bone weighing a total of 1320 g (Table 5). The majority of the bone was located in SUs 1–3: LGM and through the Holocene (Garvey, 2016), with the highest percentage recorded during the LGM (SU3).

The distribution of the major groups of animals per stratigraphic unit indicates that mammals were the largest group representing between 22 and 50% of the identifiable taxa per stratigraphic unit (Table 5). This group includes unidentified mammals (those that could not be assigned to taxon). The results indicate that there is an increase in faunal diversity towards the top of the Juukan 2 sequence, in SUs 1 and 2 (Holocene deposits). Of the mammals, small mammals (particularly murids such as native mice and rats), are the most common (Table 6). Given the small size and relative completeness of these bones, it is probable that these animals entered Juukan 2 via owl predation and not human activity.

It is interesting to see echidna amongst the mammalian fauna from Juukan 2. Bones from the echidna are rarely found in Australian archaeological assemblages, despite the species being regarded as a favoured food by many Aboriginal groups across Australia.

Macropods (kangaroos and wallabies) remain the most common human prey throughout the sequence. Humans are likely to have been the primary contributors of the medium and large mammal remains at Juukan 2 (Table 5) as evidenced by the patterns of body part representation, the nature of bone breakage—consistent with systematic processing of the limb bones to access the highly nutritious bone marrow—and the recovery of a manufactured bone point from XU28 in square K (134 cm) dating to approximately 28,910–28,140 cal BP (Table 3, Beta 383965; square C-XU27 at 133 cm) (section 8.3.2).

The presence of emu (*Dromaius novaehollandiae*) was only recorded from eggshell, occurring at depths between 5 and 25 cm (SUs 1 and 2) (dating to the Holocene) (indicated as part of the bird material in Table 5). Emu bones are rare in the archaeological record, so it is not surprising that none were recorded at Juukan 2. Emus are seasonal breeders with females laying eggs between November and March, so the presence of eggshell suggests spring to summer occupation by people in Juukan 2, at least when they were collecting and consuming emu eggs.

8.4. Usewear and residue study of a bone point

The bone point (mentioned above) was excavated from XU28 in square K (134 cm) and dates to approximately 28,910 to 28,140 cal BP (Table 1). It was manufactured from the right proximal shaft of a macropod (kangaroo) fibula and is 126.47 mm in length, 8 mm in width, and weights 5.5 gm. The bone has been modified into a point, with the functional end of the tool rounded and notched (Fig. 12). It has a concave shaft with damage evident on the lateral margin. The base (proximal) of the bone has been broken, excluding the possibility of any assessment of symmetry of the element.

Under low magnification (3× and 50X), horizontal striations that extend from the tip to the shaft are apparent on the pointed tool. The tip

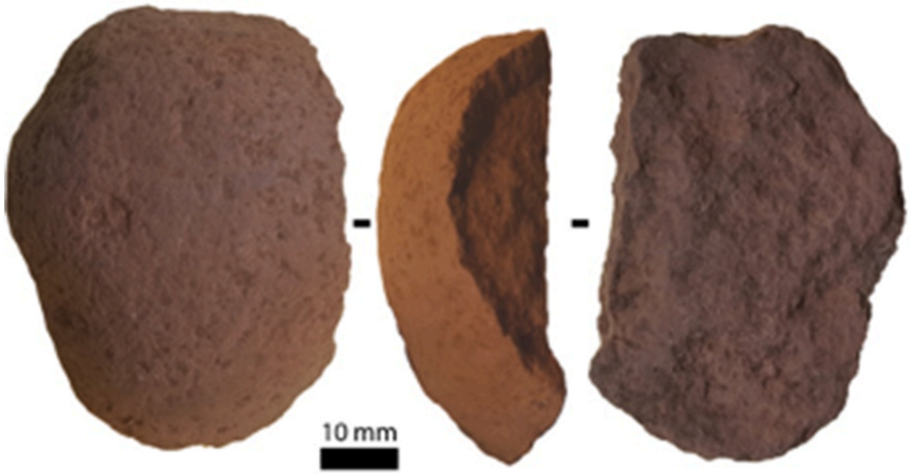

Fig. 10. Macroscopic photograph of the grinding stone cobble K31 A001 (Photo J. Field).

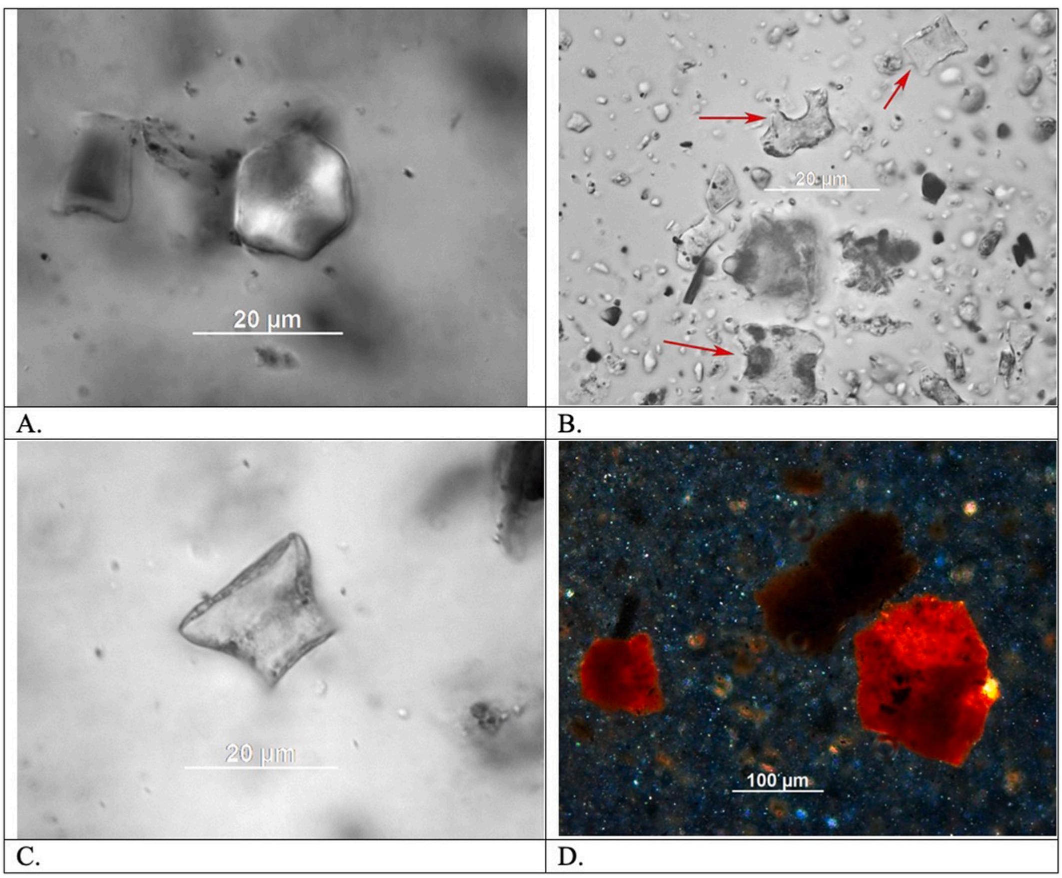

Fig. 11. Attributed starch grain identifications for grinding stone cobble square K31 A001. A. Unknown starch grain. B. Starch grain from *Ipomoea costata*-2; C. Unknown starch grain; D. Starch grain from *Ipomoea costata*-1.

Table 5
The NISP and weight (gm) of the total animal bone per stratigraphic unit.

Taxon	SU1		SU2		SU3		SU4a		SU4b	
	NISP	**%**	**NISP**	**%**	**NISP**	**%**	**NISP**	**%**	**NISP**	**%**
Mammal	677	44.7	1092	50.5	1039	34.1	212	32.6	74	22.6
Bird	41	2.7	12	0.6	13	0.4	0	0	0	0
Reptile	20	1.3	22	1.0	15	0.5	2	0.3	0	0
Indeterminate	777	51.3	1035	47.9	1976	65.0	436	67.1	254	77.4
TOTAL	1515	100	2161	100	3043	100	650	100	328	100

Table 6
Distribution of mammals per stratigraphic unit.

Taxon	SU1		SU2		SU3		SU4a		SU4b	
	NISP	**%**	**NISP**	**%**	**NISP**	**%**	**NISP**	**%**	**NISP**	**%**
Small dasyurid *(Antechinus/Sminthopsis)*	3	0.5	5	0.5	4	0.4	1	0.5		
[a]**Bandicoot**	1	0.2	1	0.1	2	0.2				
[a]**Bettong sp.**	2	0.3	1	0.1	1	0.1				
[a]**Brushtail Possum (*Trichosurus vulpecula*)**			1	0.1	1	0.1				
[a]**Echidna (*Tachyglossus aculeatus*)**	120	18.5	3	0.3						
[a]**Macropod**	70	10.8	77	7.3	87	8.4	30	14.2	17	13.8
[a]**Red kangaroo (*Macropus rufus*)**			2	0.2	2	0.2	3	1.4		
Murid	112	17.3	201	19.0	277	26.7	33	15.6	7	5.7
Native mice ***Pseudomys/Notomys***	20	3.1	4	0.4			1	0.5		
Indeterminate mammal	319	49.3	765	72.2	662	63.9	144	67.9	99	80.5
Total NISP	**647**	**100.0**	**1060**	**100.0**	**1036**	**100.0**	**212**	**100.0**	**123**	**100.0**
TOTAL of likely cultural origin	**193**		**85**		**93**		**33**		**17**	

[a] denotes those that are likely to have a cultural origin.

Fig. 12. A bone point made on the proximal end of a macropod right fibula from square K, XU28 and estimated to be around 28,600 years old. Scale = 3 cm (Photo: Jarrad Paul).

shows minor scratching on the surface with no formal pattern, and no discernible striations on laterals. At higher magnification (200×), red areas are visible, the result of likely stains from pigment use. The presence of red staining indicates that the tool is more likely to be attributed to use during symbolic markings (or as a nose-bone, see Langley et al. 2016) rather than as an awl for hide preparation. Functional attributes of the tool however should be understood with caution due to the multitude of uses bone tools can attain during their use life.

At an age of c. 28 ka, this bone point is an early example of worked bone technology from Sahul. Current research regarding bone tool technology in Australia (Langley et al., 2016; Langley, 2018) has pushed the date of the oldest implements to at least 47 ka in the Kimberley region, an area previously thought to be devoid of this technology during the period. The oldest example from Carpenter's Gap 1 (Langley et al., 2016) also provides a comparative example to one in the present study: both are made from kangaroo fibula bones, are of similar length (129. 7 mm), and the presence of red ochre likely relate to their functional use. As such, the bone point from Juukan 2 adds to the growing literature of the worked bone studies and provides evidence for the diverse toolkit utilised in the Pilbara during the Pleistocene.

8.5. Human hair and DNA analysis

A small woven or plaited bundle of human hair, about 10 cm long and consisting of approximately 30 strands, was recovered from 18 cm (square B-XU4) and dates to c. 3500 years ago. It has been interpreted by PKKP Traditional Owners as being part of a hair belt, and with their permission the sample was submitted for Ancient DNA (aDNA) analysis. The aDNA sequence generated showed that the mitochondrial consensus sequence produced for this sample was aligned to other previously published Aboriginal Australian mitochondrial genomes (Tobler et al., 2017; Nagle et al., 2017; Wright et al., 2018; Wasef et al., 2020). The mitochondrial sequence was used to construct a phylogenetic tree (Kozlov et al., 2019). Although the aDNA was highly degraded with a very minute amount of endogenous DNA that could be detected, the results revealed that the ancestral remains belong to the human mitochondrial haplogroup R*. Further haplogroup analyses showed that the hair sample (SA_hair) with the haplogroup R* is highly likely to be for an Aboriginal Australian individual, who is closely related to nine contemporary individuals from Western Australia who carry the Australian haplotype R12. Two of those nine individuals are from the Pilbara area (Yinhawangka and Banjima) (Wright et al., 2018).

9. Discussion

Systematic archaeological excavations at Juukan 2 have revealed a rich paleo-environmental and archaeological history. The archaeological sequence commences between 47,130 and 42,140 cal BP (i.e., the lower modelled Bayesian age estimate for base of deposit) and continues into the recent past. Importantly, it documents repeated visits to the rockshelter during the peak of the LGM, providing new detail on human movements in a place where previously held views were of a hiatus in human occupation over this time (e.g., Hiscock, 1988; Veth, 1993; Thorley, 2001; O'Connor, 1995; 1999; O'Connor and Veth, 2006; O'Connor et al., 1998 Przywolnik, 2005a). At least for parts of the Hamersley Plateau, there is now a growing body of archaeological evidence supporting intermittent visits by Aboriginal people during the LGM (Cropper and Law, 2018; Marwick, 2002; Morse et al., 2014; Reynen, 2019; Reynen et al., 2018; Slack et al., 2017; Slack et al., 2018). Recent reconstructions of LGM palaeoenvironmental conditions further support this interpretation, showing substantial climatic variability and periodic improvements in water availability across inland Australia (De Deckker et al., 2020). Water accessibility is inextricably linked to foraging opportunities in the arid zone, contributing to an uneven patchwork of resource-rich and resource-poor environmental conditions, even within ostensibly similar land systems (Law et al., 2021). Thus, at times during this much colder and drier period, Pleistocene populations could have feasibly occupied the arid interior and sustained themselves on inland waters (De Deckker et al., 2020).

The pollen record shows a strong correlation with more general regional climate changes (Williams et al., 2009) and forms a backdrop to the formation of the archaeological record. From 47,000 years, the local environment was dominated by Poaceae (grasses) with the presence of aquatic taxa, suggesting wetter conditions. Changes in pollen frequencies during the pre LGM likely reflect a shift from predominantly summer rainfall to winter rainfall and drying. The LGM features an increase in Asteraceae pollen and charcoal particles reflecting increased aridity associated with the peak of the LGM. From around 14,000 years ago there is likely a return of summer rainfall dominance linked to the Australian monsoon.

During the earliest occupation phase (from 47,130 to 34,730 cal BP), discard of cultural material is low (SU4b), consistent with infrequent visitation, similar to other proposed patterns of use in the eastern

Hamersley Plateau (Cropper and Law, 2018; Law et al., 2010; Slack et al., 2018, 2020). First human settlement occurred during a period of higher rainfall when the local environment around the rockshelter was dominated by Eucalypt woodland. Functional analyses of artefacts, along with bone, charcoal, and other organic finds preserved in these levels have demonstrated the early appearance of important technologies: bone tool and grinding stones. The material record indicates that people were equipped with diverse and complex toolkits.

Throughout the LGM (SU3), the region was arid, particularly c. 28,000 years ago. Between c. 23,000 to 19,000 years ago, hyper-arid conditions prevailed, and arid conditions persisted until the end of the glacial cycle. The vegetation history shows a marked change around Juukan 2 at this time with spinifex grasslands replacing the Eucalypt woodlands. Greater site use is correlated with increased artefact discard during the LGM, the peak period of aridity. The flaked stone is dominated by locally available BIF rather than more distantly sourced raw materials such as chert and quartz.

The Early to Mid-Holocene (SU2) coincides with climatic improvements indicated by the increases in *Eucalyptus* pollen and the re-initiation of the Indo-Australian monsoon cycle c. 14,000 years ago (Wyrwoll and Miller, 2001). At Juukan 2 there is a steady and then substantial increase in the discard of cultural material, particularly after c. 3500 years. An increase in retouch occurs from the start of the Holocene and includes a backed artefact discarded prior to c. 7600 years. Usewear has identified hafting and processing of plants. Increased bone discard is also indicative of greater site use, and summer use of the cave is signalled by the presence of emu eggshell from c. 3500 years. The uppermost sediments at Juukan 2 (SU1) date to the Late Holocene and feature a substantial accumulation of cultural material including retouched artefacts and bone, as well as paperbark sheets.

A backed artefact affixed with spinifex resin (square J-XU3 A24) is one of only two known such finds from the Pilbara, the other reported from Newman rockshelter (Troilett, 1982; Slack et al., 2020). Recent usewear and residue studies of backed artefact assemblages from the eastern Hamersley Range suggest that hafting backed artefacts in spinifex resin may have been a feature of this region (Cropper and Law, 2018; Fullagar, 2018). The Juukan 2 evidence adds to discussions concerning the function of hafted backed artefacts across Australia, with some researchers arguing that hafting of backed artefacts may be more widespread than previously reported (McDonald et al., 2007; Fullagar et al., 2009; Robertson, 2011; Fullagar, 2018).

The significant new finds from the expanded 2014 excavations included human hair, ochre, a bone point and grinding stones. A plait of human hair, dated to c. 3500 cal BP was identified as part of a belt and ancient DNA mitochondrial results indicate it is highly likely to be associated with the contemporary Pilbara people. Importantly, the DNA results confirm their cultural continuity and long-term connection to the site and area. The bone point (c. 28,000 cal BP) is one of the oldest examples of this form of technology in Australia (Langley, 2018). Ochre residue hints at the decorative nature of the Late Pleistocene toolkit and the cultural complexity of groups in this region.

The excavations (15 m^2) have yielded a rich and complex record including flaked and ground stone artefacts, bone implements, human hair and other important materials such as spinifex resin and ochre. Together, the material record indicates that the earliest peoples inhabiting the interior of the western Hamersley Plateau were equipped with diverse and complex toolkits. First settlement of this region occurred during a period of higher rainfall when the local environment around the rockshelter was dominated by Eucalypt woodlands.

The presence of (putative) *Ipomoea* sp. (Bush Potato) tuber starch grains on the surface of artefacts from three levels of the site, indicates not only continuity of use through time, but perhaps the earliest evidence for use of *Ipomoea* currently known. A ground cobble fragment, estimated to have been discarded nearly c. 42,000 years ago, has yielded residues from the processing of roots and seeds. While *I. costata* is known to have been widely used and in some places traded in Australia/Sahul (Latz, 1996; O'Connell et al., 1983), it's presence at Juukan 2 appears to be somewhat problematic. The question remains as to whether conditions in the distant past may have been conducive to an *I. costata* presence in this area. *I. costata* has been reported in the region (Australiasian Virtual Herbarium; Hayes and Hayes, 2007), the accuracy of these reports have been questioned (S. van Leeuwen, pers comm. 2020). We have observed a significant overlap in morphologies between the various *Ipomoea* species in our collection, of which all have starchy tubers/roots and are generally regarded as an important staple (see Sweeney, 1947; O'Connell et al., 1983; Cane and Stanley, 1985; Low, 1991). A number of *Ipomoea* species (including *I. costata)* can be widely available and are potentially exploited year-round. Both seeds and tubers of some species appear to have been exploited, and in the case of *I. costata* large tubers can be found up to 1 m underground (see Meggitt, 1957). *Ipomoea muelleri* has quite a different habit: a trailing vine with weak stems. It's leaves and stems are toxic to sheep but it is not clear if the roots were also toxic. *I. muelleri* is more likely to be a drought food (see Latz, 1996). The presence of starch from *I. muelleri* on the pounding/grinding stones indicates they were pounded in preparation for consumption (Meggitt, 1957; Latz, 1996). As observed in other contexts (e.g. Field et al., 2020), some plant parts, especially if they are fibrous will be pounded or ground to render them edible, and sometimes they are pounded for the old and the very young.

While significant advances in our understanding of plant use over time have been made through the study of macrobotanical remains (e.g. Dilkes-Hall et al., 2019), microfossils such as starch have been notoriously difficult to confidently attribute to plant taxa. As we advance new methodologies for the identification of starch, it is ever more important to have an understanding of habitat and range of the possible contributing species and together they will improve our understanding of plant use over time generating important insights to subsistence strategies and landscape use by people in marginal environments. The discovery of ground stone artefacts at Juukan 2 adds to similar evidence for the early emergence of grindstones in Sahul and their associated function of preparing starchy plant foods (Field et al., 2006; Clarkson et al., 2017).

Dating studies and Bayesian modelling at Juukan 2 support visitation of the site during the height of the LGM and refute the commonly held view that there was a hiatus in occupation in the semi-arid and arid zones of Sahul at this time (e.g. Hiscock, 1988; Veth, 1993; Thorley, 2001; O'Connor, 1999; O'Connor et al., 1998; Marwick, 2002; O'Connor and Veth, 2006; Przywolnik, 2005a; Morse et al., 2014; Cropper and Law, 2018; Slack et al., 2017, 2018; Reynen et al., 2018). A distinct stratigraphic change at 24,200–23,360 cal BP, tightly bracketed by radiocarbon dates on in situ charcoal, along with the lithics, bone discard and combustion features supports a human presence at peak glacial aridity. Stratigraphic studies and Bayesian modelling show that there is no evidence for LGM discontinuities as seen at many other southern hemisphere arid zone sites (e.g. Barberena et al., 2017; Woods et al., 2016).

10. Conclusions

The expanded Juukan 2 sequence provides significant new information on the activities and longevity of people on the Hamersley Plateau during the Pleistocene and Holocene. The high-resolution chronology, LGM occupation sequence and large excavation area (15 m^2) indicates an LGM presence at a time when other areas appear abandoned. The stone and bone assemblages have presented an opportunity to examine subsistence strategies including technological change and raw material use over time. The starch record documents the processing of *Ipomoea* (Bush Potato), which continues from the earliest levels until the recent past. The Holocene levels are characterised by the appearance of formal stone tool types (e.g. backed artefacts, burrens, and tula adze), a shift to fine grained stone raw materials, as well as evidence for the hafting of backed artefacts with spinifex resin). The Holocene sequence is consistent with observations from other Pilbara archaeological sequences (see Marwick, 2009; Cropper and Law, 2018; Slack et al., 2020) and continues to build a picture of landscape use by Aboriginal people over time.

The Juukan 2 sequence reveals that the frequency and duration of rockshelter occupation has varied through time, with evidence of low site visitation during the beginning of the LGM c. 28,000 years ago. Juukan 2 site was occupied during the extreme hyper-arid phase of the LGM, c. 23,000 to 19,000 years ago, demonstrating that early peoples successfully adapted to the variable climatic conditions.

Juukan 2 rockshelter is the only mainland northern Australian Pleistocene aged site with faunal remains in unequivocal association with stone tools. Faunal remains are rarely preserved in Pleistocene-aged archaeological contexts in arid northern Australia. The combined evidence from Juukan 2 has provided a unique window on the archaeology of the Hamersley Plateau during a period of climatic variability and apparently marginal environmental conditions. The presence and persistence of people here during these times attests to their adaptability and dynamism during periods of significant change.

The early use of ground stone tools and bone points offers glimpses of the complexity of Pleistocene Aboriginal lifeways and provides a better understanding of their technological potential. Moreover, the excellent organic preservation has shown rarely preserved details of Holocene technological innovation, including a well-preserved example of a resin-affixed backed artefact, a 'belt' woven from human hair and likely use-related food residues. In spite of the poor preservation of genomic material in the hair sample, the analysis of the partial mitochondrial DNA of the hair provides evidence for the possibility of long-term genetic connection between contemporary Indigenous peoples and Juukan 2, showing their long-term connection to country**.** The Juukan 2 sequence confirms a human presence across the Hamersley Plateau, while adding to our knowledge and understanding of settlement histories across the Pilbara region, beginning between 50,000 and 45,000 cal ka BP (Cropper and Law, 2018; Marsh et al., 2018; McDonald et al., 2018; Morse et al., 2014; Slack et al., 2018, 2020).

11. Summary of contributions

All of the authors have made substantial contributions to this paper. Slack devised the project, led the excavations, analysed most of the archaeological material and drafted the manuscript. Law assisted with the excavations, analysis and was thoroughly involved in the manuscript drafting. Coster completed the residue analysis and was involved in the manuscript drafting. Ditchfield completed the Bayesian analysis and manuscript drafting. Field completed residue analysis and was involved in the manuscript drafting. Garvey completed the faunal analysis and was involved in the manuscript drafting. Gliganic completed the OSL analysis and was involved in the manuscript drafting. Moss completed the pollen analysis and was involved in the manuscript drafting. Paul completed usewear analysis and was involved in the manuscript drafting. Reynen completed lithic analysis and was involved in the manuscript drafting. Ward completed sediment analysis and was involved in the manuscript drafting. Wasef completed the DNA analysis and was involved in the manuscript drafting. The Puuntu Kunti Kurrama and Pinikura Aboriginal Corporation assisted with the excavations, assisted with manuscript drafting and editing. All authors have approved this final copy of the manuscript for review.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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Postscript: Juukan 2 rockshelter was destroyed on the first Sunday of NAIDOC week (May 21, 2020) by RIO Tinto as part of its development of the Brockman 4 Iron Ore Mine under permits issued by the Western Australian Government.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2024.108823.

References

Barberena, R., McDonald, J., Mitchell, P.J., Veth, P., 2017. Archaeological discontinuities in the southern hemisphere: a working agenda. J. Anthropol. Archaeol. 46, 1–11.
Bird, C., Rhoads, J.W., 2015. Rock shelters as indicators of mobility patterns in the inland Pilbara. Archaeol. Ocean. 50, 37–46.
Bowler, J.M., Johnston, H., Olley, J.M., Prescott, J.R., Roberts, R.G., Shawcross, W., Spooner, N.A., 2003. New ages for human occupation and climatic change at Lake Mungo, Australia. Nature 421, 20–23.
Bronk Ramsey, C., 1998. Probability and dating. Radiocarbon 40, 461–474.
Bronk Ramsey, C., 2008. Deposition models for chronological records. Quat. Sci. Rev. 27, 42–60.
Bronk Ramsey, C., 2009a. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.
Bronk Ramsey, C., 2009b. Dealing with outliers and offsets in radiocarbon dating. Radiocarbon 51 (3), 1023–1045.
Cane, S., Stanley, O., 1985. Land Use and Resources in the Desert Homelands. Northern Australia Research Unit. Australian National University, Darwin.
Clarkson, C., Jacobs, Z., Marwick, B., Fullagar, R., Wallis, L., Smith, M., Roberts, R.G., Hayes, E., Lowe, K., Carah, X., Florin, S.A., 2017. Human occupation of northern Australia by 65,000 years ago. Nature 547 (7663), 306–310.
Connell, K., 2017. Usewear Analysis of Juukan-2. Unpublished manuscript prepared for Scarp Archaeology Pty Ltd, Sydney, NSW.
Coster, A., Field, J., 2015. What starch grain is that? - A geometric morphometric approach to determining plant species origin. J. Archaeol. Sci. 58, 9–25.
Coster, A., Field, J., 2018. The Shape of Things to Come—Using Geometric and Morphometric Analyses to Identify Archaeological Starch Grains. In: Anderssen, R., Broadbridge, P., Fukumoto, Y., Kajiwara, K., Simpson, M., Turner, I. (Eds.), Agriculture as a Metaphor for Creativity in All Human Endeavors (FMfI 2016) Mathematics for Industry, 28. Springer, Singapore, pp. 1–6.

Cropper, D., 2018. Excavations at Jundaru (HN-A9) rockshelter. In: Cropper, D., Law, W. B. (Eds.), Rockshelter Excavations in the East Hamersley Range, Pilbara Region. Oxford: Archaeopress, Western Australia, pp. 91–170.
Cropper, D., Law, W.B. (Eds.), 2018. Rockshelter Excavations in the East Hamersley Range, Pilbara Region. Oxford: Archaeopress, Western Australia, p. 454.
De Deckker, P., Moros, M., Perner, K., Blanz, T., Wacker, L., Schneider, R., Barrows, T.T., O'Loingsigh, T., Jansen, E., 2020. Climatic evolution in the Australian region over the last 94 ka - spanning human occupancy -, and unveiling the Last Glacial Maximum. Quat. Sci. Rev. 249, 106593.
Dilkes-Hall, I.E., O'Connor, S., Balme, J., 2019. People-plant interaction and economic botany over 47,000 years of occupation at Carpenter's Gap 1, southcentral Kimberley. Aust. Archaeol. 85 (1), 30–47.
Ditchfield, K., 2017a. Pleistocene — Holocene Coastal Mobility Patterns in the Carnarvon Bioregion, North-Western Australia. Unpublished PhD thesis. University of Western Australia.
Ditchfield, K., 2017b. Bayesian Analysis of Juukan-2. Unpublished report prepared for Scarp Archaeology Pty Ltd, Sydney.
Field, J., 2018. Ancient starch analysis of six grinding/pounding stones from the site brockman 21 (Juukan-2). Unpublished report prepared for Scarp Archaeology 10.
Field, E., McGowan, H., Moss, P.T., Marx, S.K., 2017. A late Quaternary record of monsoon variability in the northwest Kimberley, Australia. Quat. Int. 449, 119–135.
Field, J., Summerhayes, G., Luu, S., Coster, A., Ford, A., Mandui, H., Fullagar, R., Hayes, E., Leavesley, M., Lovave, M., Kealhofer, L., 2020. Functional studies of flaked and ground stone artefacts reveal starchy tree nut and root exploitation in mid-Holocene highland New Guinea. The Holocene 30 (9), 1360–1374.
Field, E., Tyler, J., Gadd, P.S., Moss, P., McGowan, H., Marx, S., 2018. Coherent patterns of environmental change at multiple organic spring sites in northwest Australia: evidence of Indonesian-Australian summer monsoon variability over the last 14,500 years. Quat. Sci. Rev. 196, 193–216.
Fullagar, R., 2018. Usewear and residues on stone tools from PAD 3, djadjiling, and Jundaru rockshelters, east Pilbara, western Australia. In: Cropper, D., Law, W.B. (Eds.), Rockshelter Excavations in the East Hamersley Range, Pilbara Region. Oxford: Archaeopress, Western Australia, pp. 409–420.
Fullagar, R., McDonald, J., Field, J., Donlon, D., 2009. Deadly weapons: backed microliths from narrabeen, New South Wales. In: Haslam, M., Robertson, G., Crowther, A., Nugent, S., Kirkwood, L. (Eds.), Archaeological Science under a Microscope: Studies in Residue and Ancient DNA Analysis in Honour of Thomas H. Loy. ANU E Press, Canberra, pp. 248–260.
Garvey, J., 2016. Brock-21 Faunal Analysis. Unpublished report prepared for Scarp Archaeology.
Gliganic, L.A., Cohen, T.J., Meyer, M., Molenaar, A., 2017. Variations in luminescence properties of quartz and feldspar from modern fluvial sediments in three rivers. Quat. Geochronol. 41, 70–82.
Grimm, E.C., 2004. TGView Version 2.0.2. Illinois State Museum, Springfield, IL, USA.
Haberle, S., 2005. A 23,000-yr pollen record from lake euramoo, wet tropics of NE Queensland, Australia. Quat. Res. 64, 343–356.
Haberle, S., Hopf, F., Roberts, P., 2018. Sedimentary, charcoal and palynological analysis of djadjiling (HD07-1A-04), HD07-3A-PAD12, HD07-3A-03, HS-A1, and Jundaru (HN-A9) rockshelters, Pilbara, western Australia. In: Cropper, D., Law, W.B. (Eds.), Rockshelter Excavations in the East Hamersley Range, Pilbara Region. Oxford: Archaeopress, Western Australia, pp. 385–400.
Hamm, G., Mitchell, P., Arnold, L.J., Prideaux, G.J., Questiaux, D., Spooner, N.A., Levchenko, V.A., Foley, E.C., Worthy, T.H., Stephenson, B., Coulthard, V., Coulthard, C., Wilton, S., Johnston, D., 2016. Cultural innovation and megafauna interaction in the early settlement of arid Australia. Nature 539, 280–283.
Hayes, A., Hayes, S., 2007. Ngambunyjarri : Thalanyjibarndi Yininyjarri Thalanyji Plant Names and Uses (Western Australia). South Hedland: Wangka Maya Pilbara Aboriginal Centre.
Hiscock, P., 1988. Prehistoric Settlement Patterns and Artefact Manufacture at Lawn Hill, Northwest Queensland. University of Queensland, Brisbane. Unpublished PhD thesis.
Hogg, A.G., Heaton, T.J., Hua, Q., Palmer, J.G., Turney, C.S.M., Southon, J., Bayliss, A., Blackwell, P.G., Boswijk, G., Bronk Ramsey, C., Pearson, C., Petchey, F., Reimer, P., Reimer, R., Wacker, L., 2020. SHCal20 southern hemisphere calibration, 0–55,000 Years cal BP. Radiocarbon 62, 759–778.
Hughes, P., Quartermaine, G., Harris, J., 2011. Pleistocene rockshelters J23 and J24, Mesa J, Pilbara, western Australia. Aust. Archaeol. 73, 58–61.
Huntley, D.J., Godfrey-Smith, D.I., Thewalt, M.L.W., 1985. Optical dating of sediments. Nature 313 (5998), 105–107.
Kozlov, A., Darriba, D., Flouri, T., Morel, B., Stamatakis, A., 2019. RAxML-NG: a fast, scalable, and user-friendly tool for maximum likelihood phylogenetic inference. bioRxiv 447110.
Langley, M.C., 2018. Establishing a typology for Australian pointed bone implements. Aust. Archaeol. 84 (2), 164–180.
Langley, M.C., O'Connor, S., 2016. A >46,000-year-old kangaroo bone implement from Carpenter's Gap 1 (Kimberley, northwest Australia). Quat. Sci. Rev. 154, 199–213.
Latz, P.K., 1996. Bushfires and Bushtucker, Aboriginal Plant Use in Australia. IAD Press, Alice Springs.
Law, W.B., Cropper, D.N., Petchey, F., 2010. Djadjiling rockshelter: 35,000 ^{14}C years of aboriginal occupation in the Pilbara, western Australia. Aust. Archaeol. 70, 68–71.
Law, W.B., Hiscock, P., Ostendorf, B., Lewis, M., 2021. Using satellite imagery to evaluate precontact Aboriginal foraging habitats in the Australian Western Desert. Sci. Rep. 11, 10755.
Li, H., Durbin, R., 2009. Fast and accurate short read alignment with Burrows–Wheeler transform. Bioinform. 25 (14), 1754–1760.
Low, T., 1991. Wild Plant Foods of Australia. Harper Collins, Sydney.
Manne, T., Veth, P., 2015. Late Pleistocene and early Holocene exploitation of estuarine communities in northwestern Australia. Quat. Int. 385, 112–123.
Marsh, M., Hiscock, P., Williams, D., Hughes, P., Sullivan, M., 2018. Watura Jurnti: a 42000-45000-year-long occupation sequence from the north-eastern Pilbara. Archaeol. Ocean. 53 (3), 137–149.
Marwick, B., 2002. Milly's cave: evidence for human occupation in the inland Pilbara during the last glacial maximum. In: Ulm, S., Westcott, C., Reid, J., Ross, A., Lilley, I., Pragnell, J., Kirkwood, L. (Eds.), Barriers, Borders, Boundaries: Proceedings of the 2001 Australian Archaeological Association Annual Conference. University of Queensland, St Lucia, pp. pp21–33.
Marwick, B., 2009. Change or decay? An interpretation of late Holocene archaeological evidence from the Hamersley Plateau, western Australia. Archaeol. Ocean. 44 (S1), 16–22.
McDonald, J., Donlon, D., Field, J.H., Fullagar, R.L.K., Coltrain, J.B., Mitchell, P., Rawson, M., 2007. The first archaeological evidence for death by spearing in Australia. Antiquity 81, 877–885.
McDonald, J., Reynen, W., Petchey, F., Ditchfield, K., Byrne, C., Vannieuwenhuyse, D., Leopold, M., Veth, P., 2018. Karnatukul (Serpent's Glen): a new chronology for the oldest site in Australia's Western Desert. PLoS One 13 (10), e0202511.
McGowan, H., Marx, S., Moss, P., Hammond, A., 2012. Evidence of ENSO mega-drought triggered collapse of prehistory Aboriginal society in northwest Australia. Geophys. Res. Lett. 39, L22702.
Meggitt, M.J., 1957. Notes on the vegetable foods of the Walbiri of Central Australia. Oceania 28, 143–145.
Morse, K., 1993. West Side Story: Towards a Prehistory of the Cape Range Peninsula, Western Australia. Unpublished PhD thesis. University of Western Australia, Perth.
Morse, K., Cameron, R., Reynen, W., 2014. A tale of three caves: new dates for Pleistocene occupation of the inland Pilbara. Aust. Archaeol. 79, 167–178.
Moss, P.T., 2013. 14.26 palynology and its application to geomorphology. In: Shroder, J. F. (Ed.), Treatise on Geomorphology. Academic Press, San Diego, USA, pp. 315–325.
Nagle, N., van Oven, M., Wilcox, S., van Holst Pellekaan, S., Tyler-Smith, C., Xue, Y., Ballantyne, K.N., Wilcox, L., Papac, L., Cooke, K., van Oorschot, R.A., McAllister, P., Williams, L., Kayser, M., Mitchell, R.J., Genographic, Consortium, 2017. Aboriginal Australian mitochondrial genome variation - an increased understanding of population antiquity and diversity. Sci. Rep. 7, 43041.
Newsome, J.C., 1999. Pollen–vegetation relationships in semi-arid southwestern Australia. Rev. Palaeobot. Palynol. 106 (1–2), 103–119.
O'Connor, S., 1995. Carpenter's gap rockshelter 1: 40,000 years of occupation in the Napier Ranges, Kimberley, W.A. Aust. Archaeol. 40, 48–49.
O'Connor, S., 1999. 30,000 years of Aboriginal occupation: Kimberley, north west Australia. In: Terra Australis, 14. Centre for Archaeological Research, Australian National University, Canberra.
O'Connor, S., Veth, P., Campbell, C., 1998. Serpent's Glen Rockshelter: Report of the first Pleistocene-aged occupation sequence from the Western Desert. Aust. Archaeol. 46 (1), 12–22.
O'Connell, J.F., Latz, P.K., Bamett, P., 1983. Traditional and modern plant use among the Alyawarra of Central Australia. Econ. Bot. 37, 80–109.
O'Connor, S., Veth, P., 2006. Revisiting the past: changing interpretations of Pleistocene settlement subsistence and demography in northern Australia. In: Lilley, I. (Ed.), Archaeology of Oceania. Blackwell Publishing, Victoria, pp. 31–48.
Owen, T., Field, J., Luu, S., People, K.A., Stephenson, B., Coster, A.C., 2019. Ancient starch analysis of grinding stones from Kokatha Country, South Australia. J. Archaeol. Sci: Reports 23, 178–188.
Payne, A.L., 2004. Land systems. In: Van Vreeswyk, A.M.E., Payne, A.L., Leighton, K.A., Hennig, P. (Eds.), An Inventory and Condition Survey of the Pilbara Region. Government of Western Australia, Western Australia, pp. 175–384. Technical Bulletin 92, Perth, Department of Agriculture.
Przywolnik, K., 2005. Long term transitions in hunter-gatherers of coastal northwestern Australia. In: Veth, P., Smith, M.A., Hiscock, P. (Eds.), Desert Peoples: Archaeological Perspectives. Blackwell, Melbourne, pp. 177–206.
Ramsey, C.B., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51 (1), 337–360.
Reynen, W., 2019. Rockshelters and Human Mobility during the Last Glacial Maximum in the Pilbara Uplands, North-Western Australia. Unpublished PhD thesis.. University of Western Australia, Perth.
Reynen, W., Vannieuwenhuyse, D., Morse, K., Monks, C., Balme, J., 2018. What Happened after the Last Glacial Maximum? Transitions in site use on an arid inland island in north western Australia. Archaeol. Ocean. 53 (3), 150–162.
Rhodes, E.J., 2011. Optically stimulated luminescence dating of sediments over the past 200,000 years. Annu. Rev. Earth Planet Sci. 39, 461–488.
Robertson, G., 2011. Changing Perspectives in Australian Archaeology, part VII. Aboriginal use of backed artefacts at Lapstone Creek rock-shelter, New South Wales: an integrated residue and use-wear analysis. Technical Reports of the Australian Museum, Online 23, 83–101.
Rowe, C., Brand, M., Hutley, L.B., Wurster, C., Zwart, C., Levchenko, V., Bird, M., 2019. Holocene savanna dynamics in the seasonal tropics of northern Australia. Rev. Palaeobot. Palynol. 267, 17–31.
Slack, M.J., Fullagar, R.L.K., Field, J.H., Border, A., 2004. New Pleistocene ages for backed artefact technology in Australia. Archaeol. Ocean. 39, 131–138.
Slack, M., Fillios, M., Fullagar, R., 2009. Aboriginal settlement during the LGM at brockman, Pilbara region, western Australia. Archaeol. Ocean. 44, 32–39.
Slack, M., Connell, K., Davis, A., Gliganic, L., Law, W.B., Meyer, M., 2017. Post-last glacial maximum settlement of the west angelas region in the inland Hamersley Plateau, western Australia. Aust. Archaeol. 83 (3), 127–142.

Slack, M.J., Law, W.B., Gliganic, L.A., 2018. Pleistocene settlement of the eastern Hamersley Plateau: a regional study of 22 rock-shelter sites. Archaeol. Ocean. 53 (3), 1–14.

Slack, M.J., Law, W.B., Gliganic, L.A., 2020. The early occupation of the Eastern Pilbara revisited: new radiometric chronologies and archaeological results from Newman Rockshelter and Newman Orebody XXIX. Quat. Sci. Rev. 236, 1–19.

Stuiver, M., Polach, H.A., 1977. Discussion reporting of 14C data. Radiocarbon 19 (3), 355–363.

Sweeney, G., 1947. Food supplies of a desert tribe. Oceania 17, 289–299.

Thackway, R., Cresswell, I.D., 1995. An Interim Biogeographical Regionalisation for Australia: A Framework for Establishing the National System of Reserves. Australian Nature Conservation Agency, Canberra, Version 4.0.

Thorley, P.B., 2001. Uncertain supplies: water availability and regional archaeological structure in the Palmer river catchment, Central Australia. Archaeol. Ocean. 36, 1–14.

Tobler, R., Rohrlach, A., Soubrier, J., Bover, P., Llamas, B., Tuke, J., Bean, N., Abdullah-Highfold, A., Agius, S., O'Donoghue, A., O'Loughlin, I., Sutton, P., Zilio, F., Walshe, K., Williams, A.N., Turney, C.S.M., Williams, M., Richards, S.M., Mitchell, R. J., Kowal, E., Stephen, J.R., Williams, L., Haak, W., Cooper, A., 2017. Aboriginal mitogenomes reveal 50,000 years of regionalism in Australia. Nature 544 (7649), 180–184.

Troilett, G., 1982. Report on Ethel Gorge Salvage Project, Unpublished Report to Mt Newman Mining Co. Department of Aboriginal Studies, Western Australian Museum, Perth.

Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C.E., Grun, R., Lawson, E., Ayliffe, L.K., Miller, G.H., Dortch, J., Cresswell, R.G., 2001. Early human occupation at Devil's Lair, southwestern Australia, 50,000 years ago. Quat. Res. 55, 3–13.

van der Kaars, W.A., 1991. Palynology of eastern Indonesian marine piston-cores: a Late Quaternary vegetational and climatic record for Australasia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 85, 239–302.

van der Kaars, S., De Deckker, P., 2002. A Late Quaternary pollen record from deep-sea core Fr10/95, GC17 offshore Cape Range Peninsula, northwestern Western Australia. Rev. Palaeobot. Palynol. 120, 17–39.

van der Kaars, S., Wang, X., Kershaw, P., Guichard, F., Setiabudi, D.A., 2000. A Late Quaternary palaeoecological record from the Banda Sea, Indonesia: patterns of vegetation, climate and biomass burning in Indonesia and northern Australia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 155, 135–153.

van der Kaars, S., De Deckker, P., Gingele, F.X., 2006. A 100 000-year record of annual and seasonal rainfall and temperature for northwestern Australia based on a pollen record obtained offshore. J. Quat. Sci. 21, 879–889.

Van Vreeswyk, A.M.E., Payne, A.L., Leighton, K.A., Hennig, P., 2004. Technical Bulletin 92: an Inventory and Condition Survey of the Pilbara Region, Western Australia. Department of Agriculture, Government of Western Australia, Perth, Australia, pp. 1–423.

Veth, P., 1993. Islands in the interior: the dynamics of prehistoric adaptations within the arid zone of Australia. In: International Monographs in Prehistory, Archaeological Series, 3. Michigan, Ann Arbor.

Veth, P., Smith, M., Fitzsimmons, K., Williams, A., Hiscock, P., 2009. Excavations at Parnkupirti, Lake Gregory, Great Sandy Desert: OSL ages for occupation before the last glacial maximum. Aust. Archaeol. 69, 1–10.

Veth, P., Ward, I., Ditchfield, K., 2017a. Reconceptualising Last Glacial Maximum discontinuities: a case study from the maritime deserts of north-western Australia. J. Anthropol. Archaeol. 46, 82–91.

Veth, P., Ward, I., Manne, T., Ulm, S., Ditchfield, K., Dortch, J., Hook, F., Petchey, F., Hogg, A., Questiaux, D., Demuro, M., Arnold, L., Spooner, N., Levchenko, V., Skippington, J., Byrne, C., Basgall, M., Zeanah, D., Belton, D., Helmholz, P., Bajkan, S., Bailey, R., Placzek, C., Kendrick, P., 2017b. Early human occupation of a maritime desert, Barrow Island, North-West Australia. Quat. Sci. Rev. 168, 19–29.

Wasef, S., Wright, J.L., Adams, S., Westaway, M.C., Flinders, C., Willerslev, E., Lambert, D.M., 2020. Insights into aboriginal Australian mortuary practices: perspectives from ancient DNA. Frontiers in Ecology and Evolution 8, 1–10.

Weissensteiner, H., Pacher, D., Kloss-Brandstätter, A., Forer, L., Specht, G., Bandelt, H.J., Kronenberg, F., Salas, A., Schönherr, S., 2016. HaploGrep 2: mitochondrial haplogroup classification in the era of high-throughput sequencing. Nucleic Acids Res. 44 (W1), 58–63.

Whitley, T.G., Berry, M., Clayton Martinez, L., 2023. Application of spatial-analytical tools and current climate/sea-level models to visualise the changing landscapes of Murujuga. In: McDonald, J., Mulvaney, K. (Eds.), Murujuga: Dynamics of the Dreaming. UWA Publishing, Crawley, pp. 727–758. CRAR+M Monograph 2.

Williams, A.N., 2013. A new population curve for prehistoric Australia. In: Proceedings of the Royal Society B: Biological Sciences, 280, pp. 1–9.

Williams, M., Cook, E., van der Kaars, S., Barrows, T., Shulmeister, J., Kershaw, P., 2009. Glacial and deglacial climatic patterns in Australia and surrounding regions from 35 000 to 10 000 years ago reconstructed from terrestrial and near-shore proxy data. Quat. Sci. Rev. 28 (23–24), 2398–2419.

Williams, A.N., Ulm, S., Turney, C.S., Rohde, D., White, G., 2015. Holocene demographic changes and the emergence of complex societies in prehistoric Australia. PLoS One 10 (6), 1–17.

Woods, R., Jacobs, Z., Vannieuwenhuyse, D., Balme, J., O'Connor, S., Whitau, R., 2016. Towards an accurate and precise chronology for the colonization of Australia: the example of riwi, Kimberley, western Australia. PLoS One 11 (9), e0160123.

Wright, J.L., Wasef, S., Heupink, T.H., Westaway, M.C., Rasmussen, S., Pardoe, C., Fourmile, G.G., Young, M., Johsnon, T., Slade, J., Kennedy, R., Winch, P., Pappin, M., Wales, T., Bates, W., Hamilton, S., Whyman, N., van Holst Pellekaan, S., McAllister, P.J., Tacon, P.S.C., Curnoe, D., Li, Ruiqiang, Millar, C., Subramanian, S., Willersley, E., Malaspinas, A., Sikora, M., Sikora, M., Lambert, D.M., 2018. Ancient nuclear genomes enable repatriation of Indigenous human remains. Sci. Adv. 4, 1–12.

Wyrwoll, K.H., Miller, G.H., 2001. Initiation of the Australian summer monsoon 14,000 years ago. Quat. Int. 83–85, 119–128.

Young, L., Vitenbergs, A., 2007. Lola Young: Medicine Woman and Teacher. Fremantle Arts Centre Press. Fremantle, W.A.