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This is a post-peer-review, pre-copyedit version of an article published in Nature Human Behaviour. The final authenticated version is available online at: https://doi.org/10.1038/s41562-020-01041-0

Ages for Australia's oldest *in situ* rock paintings

Damien Finch[1*], Andrew Gleadow[1], Janet Hergt[1], Pauline Heaney[2], Helen Green[1], Cecilia Myers[3], Peter Veth[4,5], Sam Harper[4], Sven Ouzman[4], Vladimir A. Levchenko[6]

1 The School of Earth Sciences, The University of Melbourne, Australia.

2 Lettuce Create, 16 Chaucer Parade, Strathpine, Queensland 4500, Australia.

3 Dunkeld Pastoral Co. Pty Ltd Theda Station, PMB 14, Kununurra, 6743 Western Australia, Australia.

4 M257, Centre for Rock Art Research + Management, University of Western Australia, 35 Stirling Highway, Crawley, 6009 Western Australia, Australia.

5 ARC Centre of Excellence for Australian Biodiversity and Heritage, University of Wollongong, NSW, Australia

6 Australian Nuclear Science and Technology Organisation, Locked Bag 2001, Kirrawee DC, NSW 2232, Australia

*Corresponding author: damien.finch@unimelb.edu.au

Abstract:

Naturalistic depictions of animals are a common subject for the world's oldest dated rock art, including wild bovids in Indonesia, and lions in France's Chauvet Cave. The oldest known Australian Aboriginal figurative rock paintings also commonly depict naturalistic animals but, until now, none had been quantitatively dated. Here we present 27 radiocarbon dates on mud wasp nests that constrain the ages of 16 motifs from this earliest known phase of rock painting in the Australian Kimberley region. These initial results suggest paintings in this style proliferated between 17,000 and 13,000 years ago. Notably, one painting of a kangaroo is securely dated to between 17,500 and 17,100 years based on the ages of 3 overlying and 3 underlying wasp nests. This is the oldest radiometrically dated *in situ* rock painting so far reported in Australia.

Introduction

Throughout the world, rock art records some of the earliest attempts at complex human communication. In regions where conditions do not favour preservation of organic material, evidence of past human activity is largely restricted to micromorphological evidence, stone tools and rock art. Stone tool usage is placed on the absolute timescale of human development using radiometric dating of the context where such material is found in the layers of an archaeological excavation[1-3]. Unfortunately, radiometric dating techniques are only rarely applicable to older rock art, so the age of this aspect of human creative expression is not as well constrained. Consequently, we cannot correlate records of changes in climate, sea-level, food sources, and population, for example, with the subjects that people chose to depict in their rock art, leaving the archaeological record incomplete.

In the absence of reliable methods to directly date rock art, researchers have used extensive observations of motif superimpositions and state of preservation to determine relative age sequences for groups of motifs that share common characteristics. In many of the major rock art regions, style and superimposition analysis have been used to hypothesise relative stylistic periods. However, stylistic groupings are not necessarily chronologically discrete. Furthermore, the practical difficulties in precisely defining particular styles and reliably determining superimposition sequences for the oldest, faded, pigments add uncertainty to this approach[4-7]. Absolute or well-constrained dates on individual motifs are essential to test these hypotheses and to confirm or refine the common characteristics used to define a given style.

With rare exceptions, for example in France where charcoal pigmented art is preserved in deep caves[8,9], the remaining pigment in paintings from the Pleistocene period (older than c. 11,500 years) contains no materials that can be dated directly. Occasionally, rock fragments

with some pigment on one surface are found in archaeological excavations with the stratigraphic context providing an age estimate for the time of burial. In Australia, two excavations have yielded such fragments, one estimated to be c. 28,000 years old[10] and the other c. 40 ka[11] but neither are unambiguously classified as painted rock art motifs[12] and, in any event, are unable to be classified to a particular style. In this study, we rely on the fortuitous occurrence of dateable mud wasp nests overlying or underlying rock art to provide minimum or maximum age limits for individual motifs. Such techniques, using wasp nests or surface mineral accretions, have provided Pleistocene age constraints for figurative rock paintings in Spain[13], Indonesia[12,14-16] and Australia[17-19]. Results from these limited examples support the proposition that 'realistic' paintings of animals dominate the oldest figurative rock art in different continents[8,9,14-16,20].

In two of the most extensive provinces for painted rock art in Australia, the Kimberley (Fig. 1) and Arnhem Land, naturalistic animals are the most common subjects in the oldest stylistic period[21-268] based on superimposition analysis, but there is debate about their antiquity and the adequacy of the definitions of these earliest styles[5,6,28,28]. The same or similar animals are also depicted in more recent art periods, but using different stylistic techniques (e.g. solid or regular infill rather than irregular infill and solid infill of the extremities of the head, tail and limbs), so further evidence is required to test these ideas as no old, radiometric, age constraints have been published for any of these motifs. In the Kimberley it is now known that paintings from the superimposed and inferred to be more recent Gwion stylistic period proliferated around 12,000 years ago[18] so the generally agreed relative rock art sequence predicts that the earlier paintings of naturalistic animals should be older than this.

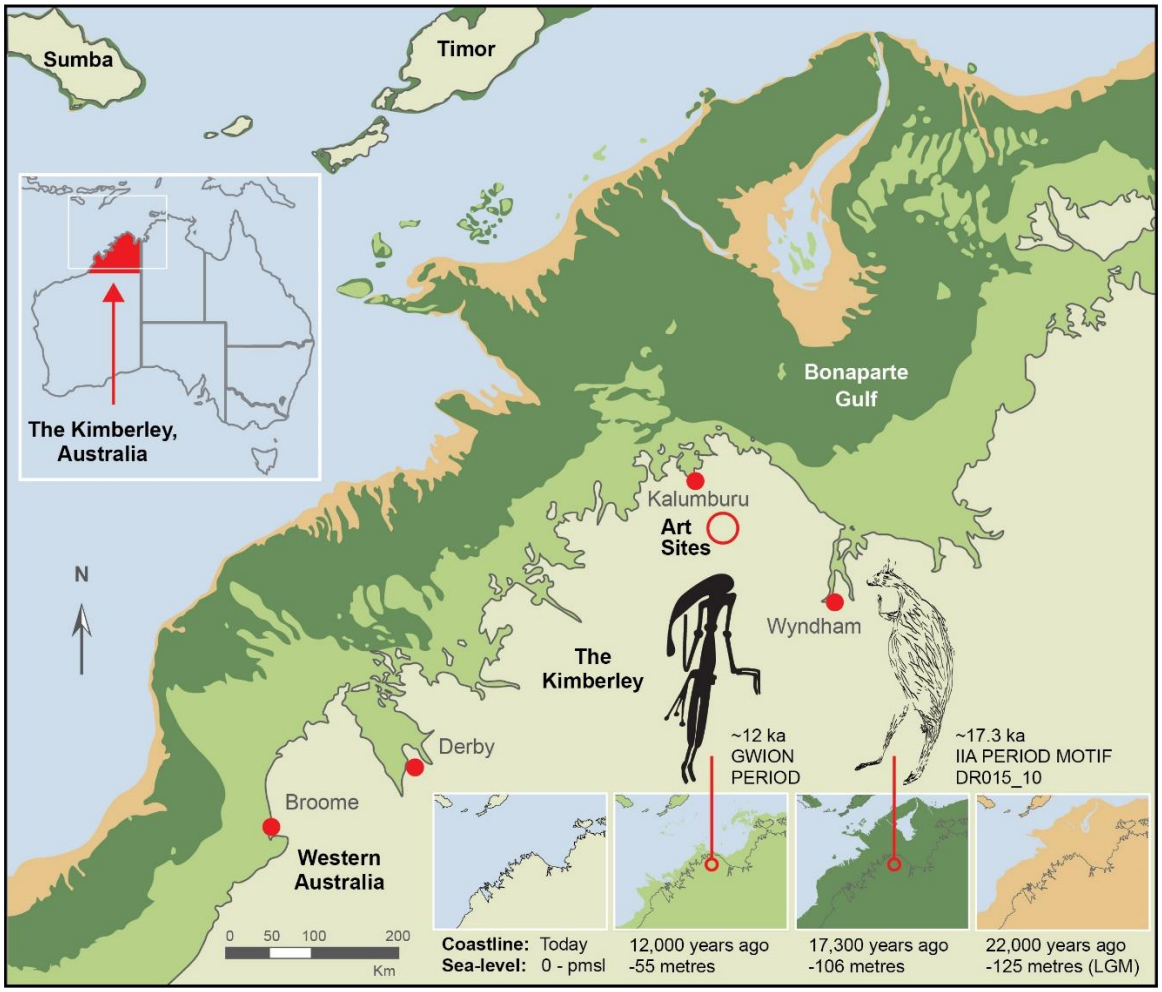


Figure 1. Map of Kimberley region in Western Australia. Shows general location of the 8 rock art sample sites and the coastline[38,43] at 12ka around the time of the Gwion period[18] and at 17.3 ka when IIAP motif DR015_10 was painted. The present mean sea level (pmsl) and the coastline during the Last Glacial Maximum (LGM) (125 m below pmsl at 22 ka) are shown for comparison. Illustrations: PH.

In the Kimberley rock art stylistic sequence these naturalistic animals belong to the earliest known phase of painted rock art, the Irregular Infill Animal Period (IIAP). Notwithstanding the abovementioned debate about the classification of similar motifs in the Arnhem Land region (some 700 km to the east), we adopt the comprehensive definition of the Kimberley IIAP by Walsh[22,29] and Welch[23,24] as a starting hypothesis. This definition of IIAP motifs includes some styles of hand stencils, hand prints, stencils of boomerangs and other objects,

and some freehand depictions of plants (e.g. yams), animals (particularly kangaroos but also echidna, birds, goannas, fish, and possum) and, more rarely, anthropomorphs (see Walsh[29] for examples). Here we report radiocarbon ages determined from 27 mud wasp nests, collected from 8 separate sandstone rock shelters (Fig. 1), that serve to constrain the ages of 16 IIAP motifs (Extended Data Figure 1). Fifteen nests overlay 10 IIAP motifs and six nests were underneath a further 5 motifs. Importantly, 3 overlying and 3 underlying nests were dated from one further IIAP motif, thereby providing a bracketed age constraint for that individual painting.

Results

As part of a broader multi-year program to date Kimberley rock art, a total of 75 remnant mud wasp nests either under or over pigment from north-east Kimberley rock art motifs of various styles have been radiocarbon dated[30]. Of these, 27 nests were in contact with 16 different rock art motifs that are classified as "Certain" or "Highly Likely" to be in the IIAP style (see Extended Data Figure 2). Other dated nests are associated with motifs that are less certainly IIAP, so they are not reported here.

Each age determination is given a Reliability Score (RS) in a range from 1 (least reliable) to 10 (most reliable) to communicate a qualitative assessment of several factors that can influence the accuracy of the result in addition to the analytical precision. The score is a relative measure based on the carbon mass of the sample measured, the degree to which physical cleaning was possible, and the chemical pretreatment applied. This approach is described in detail elsewhere[18,30] but it is worth noting here that even a sample with a very low score may still provide a useful age constraint for an underlying motif while one with a mid-range score may be rejected. For example, a mid-range score on a nest under a motif

may be rejected if it has a significant risk of modern carbon contamination even after pretreatment. Lower scores serve to identify samples where the sample context and the risk of any potential contamination may influence the accuracy of the age constraint inferred from the date of the nest sample. Another important conclusion was that any possible residual contamination risk would be from more modern rather than ancient carbon in this setting of ancient sandstones devoid of organic carbon or carbonates. Consequently, any age determinations impacted by contamination would represent a minimum age for nest construction.

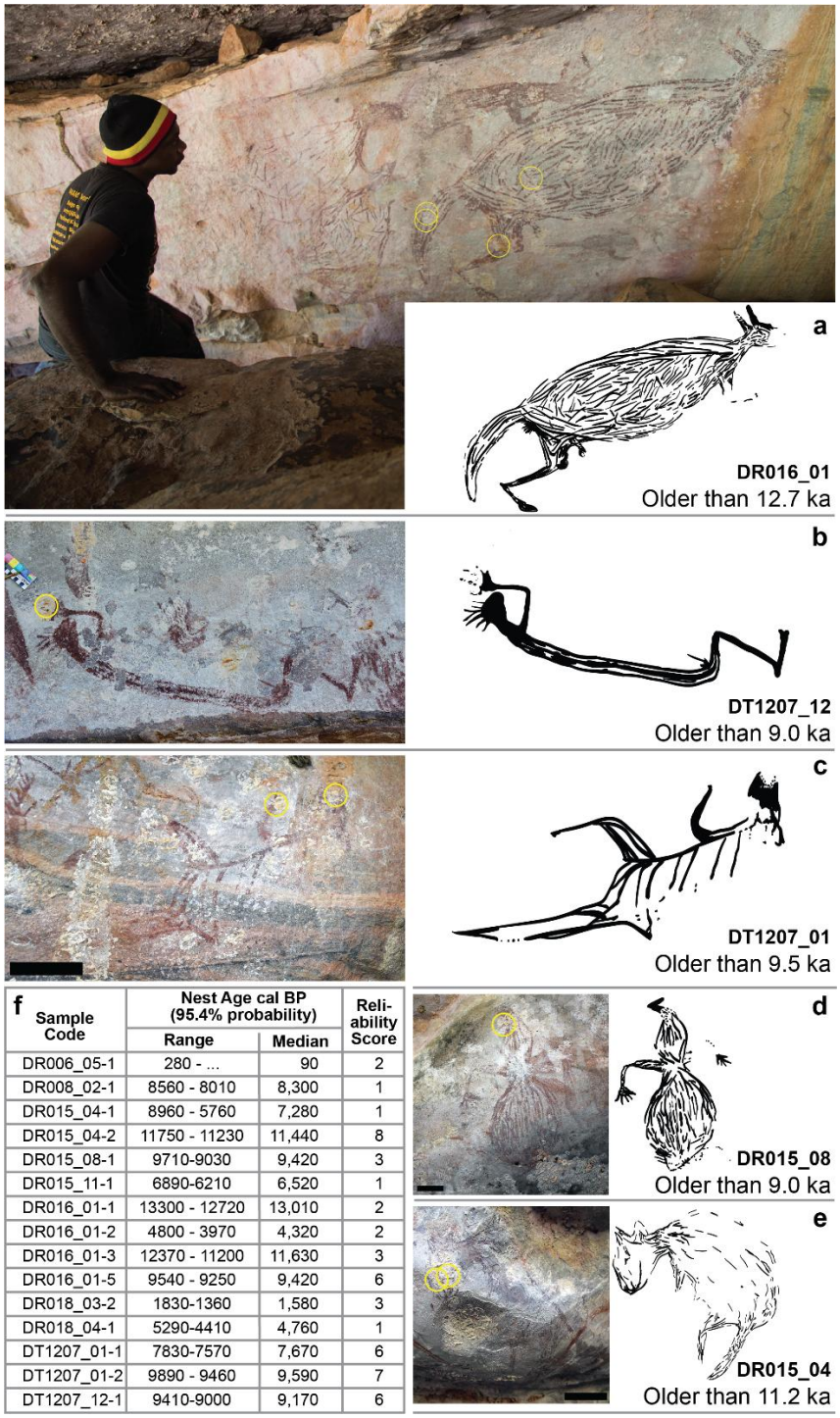
The results are presented below in three main sections beginning with the ages of nests overlying pigment giving minimum ages for the motifs, followed by a summary of the results for nests underlying pigment (maximum ages for the motifs), and finally, by a section detailing a single motif with both underlying and overlying nests.

Minimum age constraints

Calibrated ages for 15 wasp nests overlying pigment from 10 IIAP motifs ("Certain" or "Highly Likely"), from 6 different rock art sites, are summarized in Fig. 2 (details in Extended Data Figures 1 and 2). Three of the 10 motifs have more than one overlying wasp nest that has been dated. For nests overlying pigment, we take the younger limit of the 95.4% probability range for the calibrated age of the oldest overlying nest as the relevant minimum age constraint for the motif. So, for the macropod (i.e. kangaroo or wallaby) motif DR015_04 where there are two overlying nests with median ages of c. 7.3 ka and 11.4 ka, we determine the painting must be older than 11.2 cal kBP (being the lower end of the 95.4% probability, radiocarbon calibrated age in thousands of years Before Present, which is taken to be 1950 by convention). Another macropod motif, DR016_01, has 4 overlying nests, with median dates

of 4.3, 9.4, 11.6 and 13.0 cal kBP. While the oldest of these nests has a relatively low RS of 2, the age determination is credible given the other 3 dates on nests overlying the same motif. As noted above, the contamination risk reflected in the low RS for this sample is such that, if anything, the nest, and therefore the motif, would be even older than 13 cal kBP if so affected. The third motif with more than one overlying nest, DT1207_01 also depicts a macropod. The two overlying nests are of similar age and we conclude this motif is older than 9.5 cal kBP.

Of the other 7 motifs with overlying nests, 4 are at least of mid-Holocene age with minimum nest dates in the range 6.2 to 9.7 cal kBP (Fig. 2f). The other 3 dated nests are younger and therefore provide little by way of age constraints for the related motifs. The age of DR006_05-1, for example, indicates, only that the motif is older than c. 100 years.



f Sample Code	Nest Age cal BP (95.4% probability)		Reli-ability Score
	Range	Median	
DR006_05-1	280 - ...	90	2
DR008_02-1	8560 - 8010	8,300	1
DR015_04-1	8960 - 5760	7,280	1
DR015_04-2	11750 - 11230	11,440	8
DR015_08-1	9710-9030	9,420	3
DR015_11-1	6890-6210	6,520	1
DR016_01-1	13300 - 12720	13,010	2
DR016_01-2	4800 - 3970	4,320	2
DR016_01-3	12370 - 11200	11,630	3
DR016_01-5	9540 - 9250	9,420	6
DR018_03-2	1830-1360	1,580	3
DR018_04-1	5290-4410	4,760	1
DT1207_01-1	7830-7570	7,670	6
DT1207_01-2	9890 - 9460	9,590	7
DT1207_12-1	9410-9000	9,170	6

Figure 2. Minimum ages for 10 motifs from 15 overlying wasp nest ages. The five oldest motifs are illustrated: (a) (showing Traditional Owner Ian Waina inspecting motif DR016_01), (c), and (e) are interpreted as macropods, (b) as a rare depiction of an IIAP human figure reclining and (d) as a lizard-like figure. Scale bars, where shown, are 10 cm. Sample locations marked are with a yellow circle. See Extended Data Figure 1 for images of the other motifs. The Sample Code is constructed from a short site identifier, a number to identify the painted motif and the number of the sample collected from that motif, in the format "SITE_MOTIF-NEST". Full details of the radiocarbon dates are in Extended Data Table 1. Credits: Photos DF, PV, Illustrations PH

Maximum age constraints

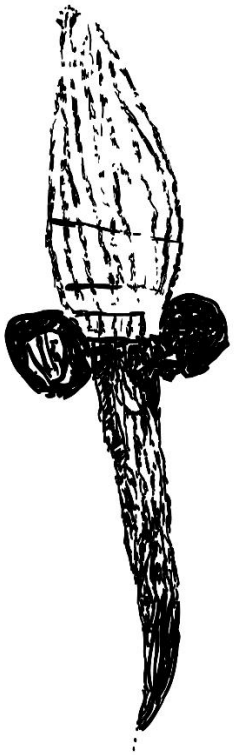
Calibrated radiocarbon ages measured for 6 mud wasp nests underlying 5 different motifs are summarized in Fig. 3 (see Extended Data Figure 1 for details). All motifs are classified as IIAP (Extended Data Figure 2) although DR006_08 may have been repainted, at least in the lower part (Fig. 3b), hence, conservatively, the age of the nest serves as a maximum age for the repainted section of 18.7 cal kBP.

The boomerang stencil motif, DR013_09, has two nests where paint spray was visible on the outer surfaces. The younger nest provides a maximum age of 13.1 cal kBP for this stencil. DR015_14, interpreted as a serpentine motif, had a single underlying nest providing a maximum age of 15.1 cal kBP.

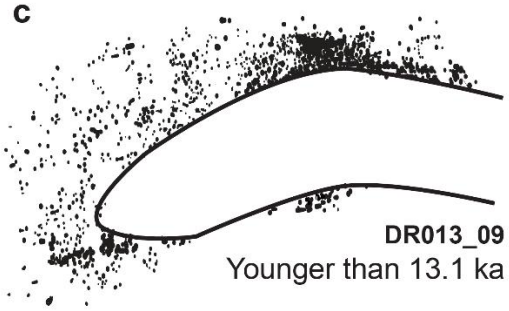
a

DR015_14
Younger than 15.1 ka

DR006_08
Younger than
18.7 ka



c



DR013_09
Younger than 13.1 ka

Sample Code	Nest Age cal BP (95.4% probability)		Reliability Score
	Range	Median	
DR006_09-1	1410 - 970	1,210	3
DR012C_02-1	10150 - 9480	9,700	4
DR013_09-1	20640 - 20070	20,370	7
DR013_09-2	13130 - 12790	12,990	8
DR015_14-4	15100 - 13990	14,490	5
DR006_08-1	18670 - 17870	18,260	4

b

d

Figure 3. Maximum ages for 5 motifs from 6 underlying was nest ages. Motifs with the three oldest dates are illustrated: (a) is interpreted as a snake, 3 m long, (b) is indeterminate, 1.1 m long, and (c) is a boomerang stencil (overpainted with Gwion then Wanjina motifs) with the illustration showing the interpreted position of the boomerang used to make the stencil (see Extended Data Figure 2). Sample locations marked are with a yellow circle. Credits: Photos DF, Illustrations PH

Reliability considerations

The 6 nests underlying 5 separate motifs have median ages in the range of 1.2 to 20.4 cal kBP. If all of these motifs are correctly classified as IIAP and the age estimates are all correct, then the youngest age of 1.2 cal kBP (DR006_09-1) implies at least some IIAP motifs may have been painted relatively recently. At the other extreme, the 18.3 cal kBP age for DR006_08-1 indicates others may be as much as 17 ka older, in which case motifs in this style may have been painted over almost 17,000 years. Critical to the interpretation of this age interval, however, is the observation that the two youngest nest ages are of comparatively low reliability. The reliability score is particularly important for under-art nests because, as noted earlier, the potential sources of contamination are more probably from more modern carbon. Hence the contamination risk for low reliability score under-art samples is such that the measured nest age may be younger, perhaps much younger, than the true age of construction, so any such results require further scrutiny.

Nest DR006_09-1, dated to c. 1.2 ka, underlies an animal motif with dotted infill (see Extended Data Figure 3). While the dotted infill is not common for IIAP motifs it has other attributes that make its IIAP classification "highly likely". Importantly, the IIAP motif is also superimposed by motifs that belong to the more recent Gwion stylistic period. A Gwion motif (DR006_03-1) from the same site has a measured minimum age of c. 16.3 ka and ages determined for other Gwion motifs are around 12 cal kBP[18]. Consequently, either the age of <1.2 ka for DR006_09-1 is incorrect, or the overlying Gwion motifs must also be anomalously young (<1.2 ka). The DR006_09-1 sample comprised a number of small, friable pieces with external surfaces that could not be thoroughly cleaned. As one of the samples processed in the first batch of wasp nests dated in 2016, it also had an early form of chemical pretreatment that may not have removed all contamination[30]. Both factors contribute to the relatively low Reliability Score of 3. The same limitations apply to DR012C_02-1; although

obvious contamination from debris built up behind the nest was removed prior to chemical pretreatment the presence of this debris represents a higher risk of contamination. These, and some other early inconsistent results, led to further experimentation and refinement of both sample selection and processing methods as described elsewhere[30]. Consequently, the results from DR006_09 and DR012C_02 are considered unreliable and are excluded from subsequent discussion.

The other 3 under-art samples underwent the more advanced pretreatment protocols and are considered more reliable. These nest dates suggest that a boomerang stencil (DR013_09) is younger than c. 13.1 cal kBP and that a snake motif (DR015_14) is younger than c. 15.1 ka.

Age bracket for macropod motif

The large IIAP macropod motif, DR015_10 was painted on the sloping ceiling in a rock shelter housing many thousands of fossilized mud wasp nests (Fig. 4). Three nests overlying the motif and a further three nests under the motif were radiocarbon dated with results summarized in Table 1 (for details, see Extended Data Figure 1). The six samples were

collected in 3 separate field trips in 2015, 2016 and 2017 and underwent pretreatment in 4 different batches at two different laboratories (at the University of Melbourne and ANSTO).

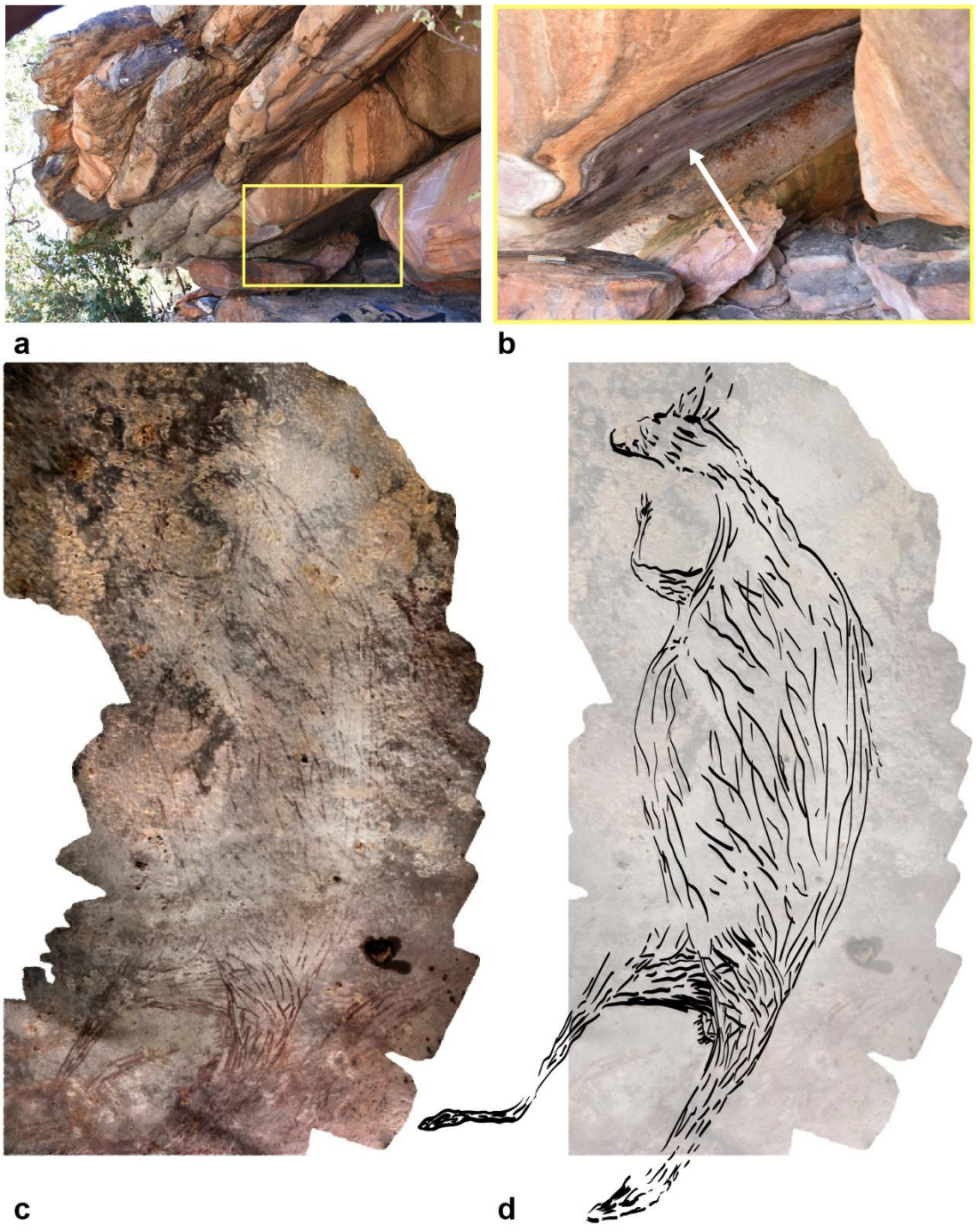


Figure 4. Macropod motif DR015_10 dated to c. 17,300 years. Showing (a) upper part of Site DRY015 with (b) the location of motif 10 on the ceiling as indicated by the arrow, (c) composite image of macropod motif from 39 photographs, and (d) motif illustration in same orientation as (c). The motif is c. 2 metres long. See Extended Data Figure 3 for sample locations and images. Credits: Photos DF, Illustration PH.

Two samples (10-7 and 10-2) were sufficiently large to use heavy liquid separation to produce "light" (density <2.2 g/cm^3) and "heavy" fractions (>2.2g/cm^3) (see [30] for details and rationale) both of which contained enough carbon for AMS measurement (Table 1). The ages determined for the two fractions of DR015_10-2 have high reliability scores and are both close to 17 cal kBP. The age on the heavy fraction of 17,790 – 17,160 cal BP (95.4% probability) provides a minimum age constraint of c. 17.2 cal kBP for the underlying painting (taking the youngest limit of the 95.4% probability range). However, the two fractions for sample DR015_10-7 are of very different ages (Light at c. 5.4 cal kBP and Heavy at 12.7 cal kBP) with lower reliability scores of 2 and 4. The outer surfaces of this sample were too small to be removed prior to chemical pretreatment so the young age for the light fraction most likely reflects the inclusion of more modern carbon in the mineral accretion coating the nest. This fraction also has an extremely low carbon mass (11µg) so even a tiny amount of modern carbon contamination will significantly reduce the measured age.

Table 1. Calibrated radiocarbon ages for macropod motif DR015_10

Sample Code	Laboratory Code	Fraction	Nest Age cal BP (95.4% probability)		Reliability Score	Over/ Under Pigment
			Range	Median		
DR015_10-7	OZW379	Light	5590 - 5050	5,380	2	Over
DR015_10-7	OZW380	Heavy	12740 - 12440	12,650	4	Over
DR015_10-3	OZW365	All	13570 - 13280	13,430	7	Over
DR015_10-2	OZU779U1	Light	17570 - 16870	17,230	9	Over
DR015_10-2	OZU779U2	Heavy	17790 - 17160	17,480	8	Over
DR015_10-1	OZT479U*	All	17450 - 16790	17,130	4	Under
DR015_10-4	OZW366	All	18970 - 18590	18,790	8	Under
DR015_10-6	OZW376	All	20980 - 20320	20,650	7	Under

The age of the oldest over-art nest (10-2) fraction implies the motif is older than c. 17.2 cal kBP and the age of the youngest under-art nest, DR015_10-1, (17,450 – 16,790 cal BP) implies it is younger than c. 17.5 cal kBP. While DR015_10-1 has a mid-range RS of 4 reflecting the less than ideal pretreatment, the higher than average carbon mass dated (37µg) means that it is somewhat less susceptible to significant contamination and is therefore

difficult to discount. The possible age range for the motif, modelled using OxCal radiocarbon calibration software[31,32] (Fig. 5, light gray probability distribution graphs), is in the range 17.5 – 17.1 cal kBP with a median value of 17.3 cal kBP (95.4% probability range).

It has been shown that charcoal incorporated into mud wasp nests may have a significant inherited or inbuilt age at the time of construction but, in our research area, the mean inbuilt age based on studies of modern nests is determined to be ~255 years[30]. The effects of any possible contamination of this kind can be accommodated when calculating the possible age range for this motif (see[18] and Methods). Applying a correction for an inbuilt charcoal age of this magnitude reduces the possible age of motif DR015_10 to be in the range 17.4 – 16.2 cal kBP with a median of 16.9 cal kBP (95.4% probability) (Fig. 5, dark gray probability distribution graph). However, based on the analysis of modern wasp nests[30], the uncorrected age bracket is likely to be more accurate.

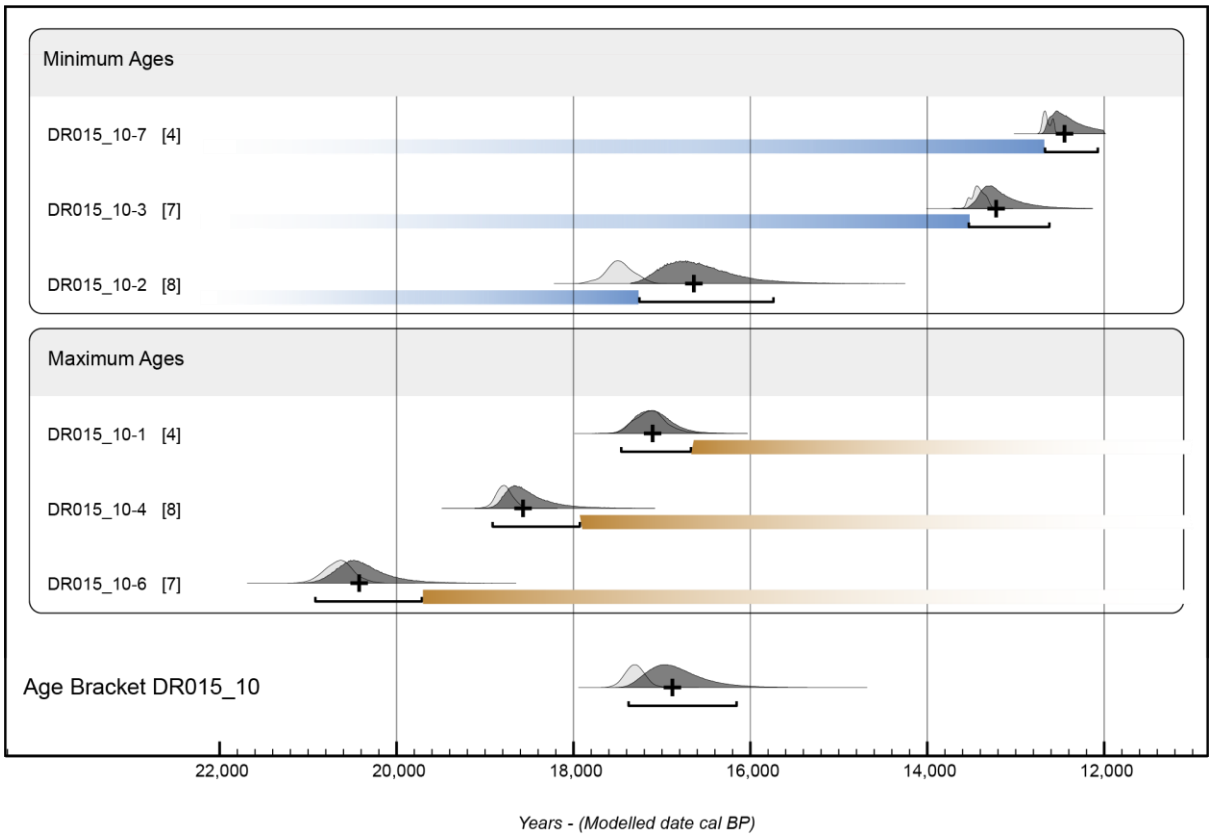


Figure 5. Calibrated ages for the 6 nests used to constrain an age range for motif DR015_10. Light and dark gray probability distribution graphs for each sample illustrate (i) the calibrated age range determined for the nest and (ii) the effect of the correction on that distribution for any potential inbuilt charcoal age, respectively. The bar under the dark gray curve shows the 95.4% probability range and the cross marks the median of the corrected distribution. The coloured horizontal bars, starting just beyond the 95.4% range (for clarity), show the possible age range for the motif. That is, art painted over the nest must be younger than the age of the nest (brown bars) and art underlying the nest must be at least as old as the nest (blue bars). The Age Bracket (lower graph) is constrained by nests underlying and overlying the motif and has been modelled using OxCal (v4.3.2[44]; r:5 SHCal13 atmospheric curve[45]) using the software code listed in Methods.

Hypothesised IIAP age range

Ultimately, the aim of the rock art dating program is to determine the age distribution for the different Kimberley styles described from numerous superimposition sequences and for sub-styles less amenable to superimposition analysis. In the case of the Gwion style, even with just 24 ages on wasp nests over or under 21 different motifs it was possible to justify an

initial hypothesis that paintings in this style proliferated around 12,000 years ago[18]. The age distribution for all but two nests associated with Gwion motifs revealed that 15 over-art nests are younger than c. 12 ka and do not overlap with ages of 6 under-art nests that are all older than c. 13 ka[18]. In contrast, the results presented here, for IIAP motifs, do not support a similar, relatively short period of proliferation. The overlapping ages between over- and under-art nest ages (Fig. 6) are more consistent with production over an extended period, as argued below.

The method developed to infer the chronology of rock art stylistic periods from maximum and minimum age constraints is described elsewhere[18]. An estimate for the extent of the art period is provided by the period between the age of the oldest over-art nest and the age of the youngest under-art nest[18]. Therefore, these data suggest that IIAP motifs were produced over the timespan from, at least, 17.2 to 13.1 cal kBP (using 95.4% probability ranges for calibrated age measurements).

This analysis, however, does not take into account the fact that some of the over-art and under-art nests relate to the same motif, DR015-10. The additional evidence provided by the age bracket for this macropod motif (17.5 – 17.1 cal kBP with a median age of 17.3 cal kBP (95.4% probability)) strongly supports a starting age of 17.2 cal kBP for the IIAP, at the latest. The end date of 13.1 ka is derived from the maximum age of the boomerang stencil DR013_09. In his first major publication on Kimberley rock art in 1994, Walsh[21] argues that some boomerang stencils are appropriately classified as IIAP motifs based on observed superimpositions of such motifs by tasselled human figures, generally accepted as the earliest of the Gwion style variants[23,24]. Lewis[28] disputed this classification, arguing that boomerang stencils were more likely to be contemporary with Gwion figures. Walsh subsequently published two further examples of tasselled Gwion motifs painted over boomerang stencils[22] (Plates 142 and 353/4) to support his inclusion of some boomerang stencils as IIAP motifs.

The stencil DR013_09 is another example that is overpainted by tassel Gwion motifs (see Extended Data Figure 5) and, as such, supports Walsh's argument. Nonetheless, the results so far are not definitive for all boomerang stencils. It is still possible that boomerang stencils are younger than other IIAP motifs and closer in age to Gwion motifs, but further dates are required to resolve the absolute chronology. If the DR013_09 stencil was not included as an IIAP motif then the estimated age range for the IIAP period would be reduced to 17.2 to 15.1 cal kBP.

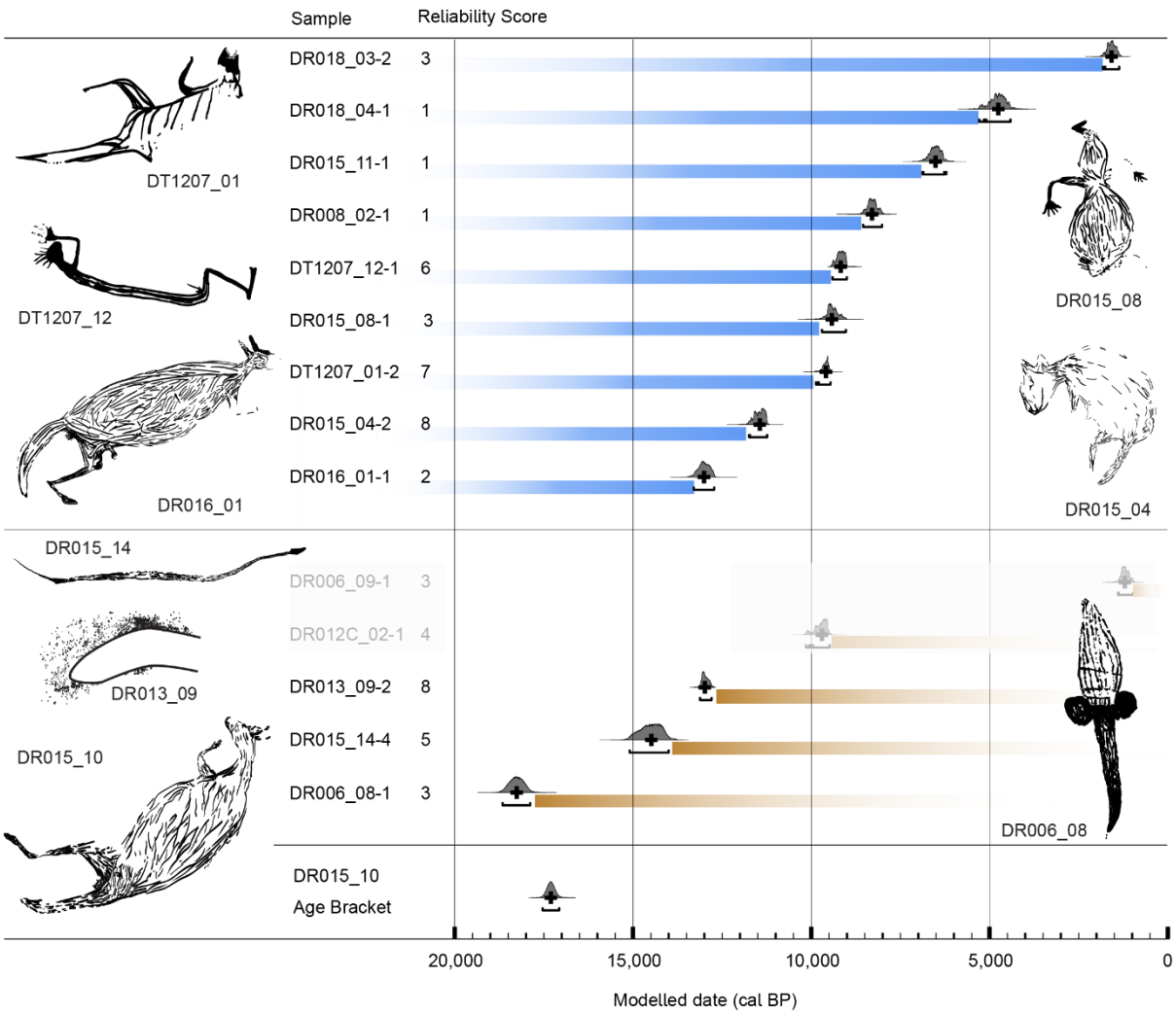


Figure 6. Age constraints for IIAP motifs. The top panel summarises the ages of nests that have been constructed over IIAP artwork. Thus, the ages of the IIAP motifs must be older (blue bars). The middle panel shows the ages of nests underlying IIAP motifs thereby requiring the artwork to be younger than the nest age (brown bars). The bottom panel identifies the age bracket derived from ages of three overlying and three underlying wasp nests from the single macropod motif DR015_10. For motifs with more than one nest dated, the oldest over-art nest age and/or the youngest under-art nest age are used. Illustrations: PH

Discussion

Kimberley IIAP motifs share similar stylistic characteristics (parsimonious infill, colour of pigment, anatomical detail, close to life-size figures) with naturalistic animal motifs elsewhere in the world[14,33-35]. Of the motifs that have been radiometrically dated, there is a

very wide spread of ages from less than 5,000 years (e.g. in China[36]), to the oldest dated figurative motifs from the Southeast Asian islands of Sulawesi (a pig motif, painted before 44 ka[15]) and Borneo (an unidentified animal, older than 40 ka[16]). Ages determined for similar European (mostly Franco-Cantabrian) figurative motifs suggest some may be as old as 35 ka but the directly dated charcoal drawings at Chauvet range in age from 34 – 29 ka[8] and throughout the period from 33 to 12 ka more generally in the region[13,37].

The age estimates for 27 mud wasp nests in contact with 16 different rock paintings of the Kimberley IIAP style suggest these motifs were painted between 17.2 and 13.1 cal kBP. The age of one IIAP macropod motif is well-constrained by six radiocarbon dates on three overlying and three underlying wasp nests to be between 17,500 and 17,100 years old, corresponding to the middle of the age range for the European figurative motifs.

This is a period when sea levels in the nearby Joseph Bonaparte Gulf began to rise from a low of ~125m below present sea levels during the Last Glacial Maximum (LGM) (21±3 ka) but mostly before the rapid rise in sea levels between 14.6 and 8 ka (Meltwater Pulse 1a)[38] (see Fig. 1). By 12 ka, the coastline to the north-west had advanced by around 300 km over the continental shelf toward the area in which our study was undertaken. Many generations of Kimberley coastal Aboriginal populations experienced continuing loss of territory over these millennia. At around the same time, from 14 to 13 ka, a paleoenvironmental record from a nearby mound spring and other Kimberley climate proxies indicate an improving climate with an increase in monsoonal activity and precipitation[39]. It was just after this time, 12,000 years ago, that paintings in the Gwion style proliferated in the northern Kimberley[18]. The dominant subjects in IIAP paintings are animals and, to a lesser degree, plants. This was replaced by an almost complete focus on decorated human figures during the Gwion

period[40,41]. The coincidence between these marked changes in painted rock art styles and prevailing environmental conditions suggests that the shift from the IIAP to the Gwion period may reflect social and cultural changes in the region. For example, the change in the style of artwork may have been a response to increasing territoriality and population growth supported by an improving climate[38].

These Pleistocene ages for naturalistic animal motifs from the earliest known period of Australian rock painting position this creative human activity at the end of the Last Glacial Maximum. The initial results from 8 rock art sites in the north-eastern Kimberley suggest an extended period for the Irregular Infill Animal style, from 17,000 to 13,000 years ago. Many more dates from this period are required before the full chronological extent of the paintings still visible today can be determined. For now, a robustly dated, c. 17,300-year-old painting of a kangaroo is the oldest *in situ* rock painting radiometrically dated in Australia.

Methods

The methodology developed to radiocarbon date mud wasp nests is described in Finch et al.[30]. Methods developed to derive estimates for the age of rock art stylistic periods are described in Finch et al.[18]. The following sections provide specific detail for the IIAP motifs.

The Balanggarra Aboriginal Corporation has reviewed a draft of this paper and has agreed that the images it contains can be published.

Sample Collection

Mud wasp nest samples related to IIAP paintings were collected between 2015 and 2017 from 8 rock art sites up to 16 km apart in the Drysdale River National Park, an area known to be particularly rich in IIAP paintings [24]. Sampling was approved on site with the consent and participation of local Traditional Owners and under research permits from the Kimberley Land Council/ Balanggarra Aboriginal Corporation, the Western Australian Department of Biodiversity and Attractions and Department of Planning Lands and Heritage (Section 16 Permits 558, 567). The Balanggarra Traditional Owners have requested that the site locations are not disclosed here but locations have been fully documented in an access-controlled database [42].

Motif Classification

The subject matter of most IIAP motifs, such as macropods and plants, also appear in later stylistic periods of the Kimberley rock art sequence. The classification of a motif as IIAP requires familiarity with the sometimes-subtle differences in the way such subjects are depicted in different periods. Given the subjective nature of the classification process, the most experienced researchers of Kimberley rock art can be expected to provide the most accurate classifications. The motif classifications reported here (Extended Data Figure 2) were determined by P.H. and C.M. whose qualifications are described elsewhere [18]. Only motifs "Highly Likely" or "Certain" to belong to the IIAP are reported here.

Sample Preparation and Age Measurement

Initially, mud wasp nest samples underwent all stages of pretreatment using the Australian Nuclear Science and Technology Organisation (ANSTO) Radiocarbon Chemistry laboratory (Laboratory Codes in the range OZT448 to OZT801). Subsequently, samples with Laboratory Codes from OZU777 to OZW417 underwent physical pretreatment and part of the chemical pretreatment at the University of Melbourne. Complete details of the preteatment methods are described elsewhere [30] but, in short, after mechanical cleaning, where possible, samples were ground before undergoing a version of the acid-base-acid (ABA) charcoal pretreatment protocol. Heavy liquid separation (HLS) was used on some of the larger samples to create fractions labelled as "Light" (density < ~2.0 g/cm^3) and "Heavy" (density > ~2.0 g/cm^3) in Extended Data Figure 1. Fractions labelled as "All" did not undergo HLS. All sample combustion and graphitisation was carried out at ANSTO. All samples were measured using the 10MV ANTARES (Australian National Tandem Research Accelerator) or 2MV STAR (Small Tandem for Applied Research) AMS at ANSTO. All radiocarbon ages were calibrated using SHCal13 [45] in OxCal v4.3.2 [32]

Statistical Model and Code

The radiocarbon calibration program, OxCal (version 4.3, SHCal13) was used to calibrate all carbon isotope measurements[31,32, 45]. The software code used to generate Fig. 5 is listed below:

```
Options()
 { Resolution=10;
   Curve="SHCal13.14c";
   BCAD=FALSE;  };
Plot()
```

```
{Outlier_Model("Charcoal",Exp(255,-4000,0));
 Combine("DR015_10")
{Before("Minimum Ages")
  {R_Date("DR015_10-7_[4]", 10730, 70){Outlier("Charcoal",1);};
   R_Date("DR015_10-3_[7]", 11640, 80){Outlier("Charcoal",1);};
   R_Date("DR015_10-2_[8]", 14390, 100){Outlier("Charcoal",1);};};
 After("Maximum Ages")
  {R_Date("DR015_10-1_[4]", 14130, 100){Outlier("Charcoal", 1);};
   R_Date("DR015_10-4_[8]", 15570, 90){Outlier("Charcoal", 1);};
   R_Date("DR015_10-6_[7]", 17160, 120){Outlier("Charcoal", 1);};};
};  };
```

Data availability: All data is available in the manuscript or the supplementary materials and two earlier publications [18,30]. At the request of Balanggarra Aboriginal Traditional Owners of the land where the samples were collected, the data does not include exact locations of rock art sites.

Code availability: the custom code used is listed in the Methods section

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Acknowledgements:

We acknowledge and thank the Balanggarra Aboriginal Corporation, Rangers and Traditional Owners for permission to work on their Country and for their support during fieldwork. In particular, we thank Augustine Unghango and family, the Waina family, and Ambrose Chalarimeri. Fieldwork support was provided by S Bradley, P Hartley, N Sundblom, R Maher, T Tan, M Maier and P Kendrick. The sites we visited were relocated and recorded over decades by Dunkeld Pastoral Co Pty Ltd and the Kimberley Visions Survey teams, J Schmiechen, and the late G Walsh. Radiocarbon measurements and laboratory support from the Australian Nuclear Science and Technology Organisation (ANSTO) was provided by A Williams, F Bertuch and B Yang. Financial support for the Centre for Accelerator Science at ANSTO was provided by the Australian National Collaborative Research Infrastructure Strategy. DF thanks AINSE Ltd for providing financial assistance through a Post Graduate Research Award to enable work on the radiocarbon analyses. This research was funded by an Australian Research Council Linkage Projects LP130100501 and LP170100155 with funding partners the Kimberley Foundation Australia (now Rock Art Australia), with in-kind support from Dunkeld Pastoral Co Pty Ltd and Balanggarra Aboriginal Corporation especially for fieldwork. DF is supported by an Australian Postgraduate Award. The Kimberley Foundation Australia also provided a grant to DF to establish the radiocarbon pretreatment facility at the University of Melbourne. The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript beyond that indicated above.

Author contributions:

This research is part of the multi-disciplinary Kimberley Rock Art Dating project conceived and led by AG who, with JH, supervised this work as part of DF's PhD research project. Motif classification was by PH and CM. DF collected and pretreated the samples, designed, and performed the experiments, and analysed and interpreted the results. Fieldwork was

carried out by DF, PH, SH, SO, PV, CM, AG and HG. Illustrations were drawn by PH. Radiocarbon measurements and initial data reduction were performed by VAL. DF wrote the manuscript draft with key editing from JH and AG with further input from all authors.

Competing interests: The authors declare that they have no competing interests.