ANTHROPOLOGY

12,000-Year-old Aboriginal rock art from the Kimberley region, Western Australia

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The Kimberley region in Western Australia hosts one of the world's most substantial bodies of indigenous rock art thought to extend in a series of stylistic or iconographic phases from the present day back into the Pleistocene. As with other rock art worldwide, the older styles have proven notoriously difficult to date quantitatively, requiring new scientific approaches. Here, we present the radiocarbon ages of 24 mud wasp nests that were either over or under pigment from 21 anthropomorphic motifs of the Gwion style (previously referred to as "Bradshaws") from the middle of the relative stylistic sequence. We demonstrate that while one date suggests a minimum age of c. 17 ka for one motif, most of the dates support a hypothesis that these Gwion paintings were produced in a relatively narrow period around 12,000 years ago.

INTRODUCTION

Constraining the age of rock art older than ~6 thousand years (ka) has remained a largely intractable scientific problem, particularly for rock engravings and for paintings where the paint no longer contains any original organic material (*1*–*4*). Although Pleistocene ages have been determined for exceptionally well-protected rock art paintings in limestone caves, quantitative age constraints for only a very small number of earlier Holocene or Pleistocene motifs in open rock shelters have been obtained (*5*, *6*).

In many of the world's major rock art regions, the relative timing of different art "styles" or iconographies has been proposed on the basis of analysis of motif superimpositions, weathering, and subject matter (*7*–*11*). However, until the ages of individual style phases within a rock art sequence are quantitatively dated, it is not possible to incorporate this powerful evidence of past human activity into the archeological, paleoenvironmental, and, sometimes, ethnographic record with confidence. The definition of a style, and the proposed stylistic sequences themselves, may be disputed as it can be difficult to verify the analysis on which they are based (*9*, *11*–*13*). Consequently, quantitative, radiometric dating of many stylistically distinct motifs is required both to confirm, or to refine, the proposed sequences and to constrain the absolute age intervals over which particular styles were produced (*14*).

A well-defined stylistic sequence for Aboriginal rock art in the Kimberley region of Western Australia has been developed and comprehensively documented by researchers over the past 40 years (*8*, *15*–*19*), and ongoing research continues to refine this sequence. Apart from the most recent Wanjina phase, very few motifs from the earlier art periods have absolute age constraints. Only two Kimberley rock art motifs have provided age estimates older than the mid-Holocene (*20*, *21*), and only one of these can be attributed to an identified style, but even this date has been the subject of much debate (*5*, *22*). Notwithstanding this lack of direct evidence, it has long been thought that the older styles in the Kimberley sequence date back to the Pleistocene [e.g., (*23*, *24*)]. Here, we report on radiocarbon dating of mud wasp nests, overlying (thereby providing minimum ages) or underlying (providing maximum ages) Kimberley rock art motifs, allowing this hypothesis to be thoroughly tested.

The development of the method to confidently date mud wasp nests is fully described elsewhere (*25*). This method relies on the identification of possible sources of carbon contamination in the environment of Kimberley rock shelters and pretreatment methods to remove them. This research also analyzed newly constructed mud wasp nests to understand their initial carbon composition and identified charcoal as the target compound for accelerator mass spectrometry (AMS) dating. The inbuilt or inherited age of the different sources of carbon was measured, and while not trivial, it can be accommodated within the accuracy sought from this method.

In this study, we use 24 wasp nest dates to estimate the age of a renowned anthropomorphic style from one of the relatively older periods of the Kimberley rock art stylistic sequence. These 24 nests were either under or over motifs originally referred to as "Bradshaw" paintings but which are now generally referred to as "Gwion" figures (*24*, *26*) while acknowledging that different Traditional Owner groups have their own preferred names (including Gwion Gwion, Kiro Kiro, or Kujon). The Gwion style is dominated by finely painted human figures in elaborate ceremonial dress (*27*, *28*) including long head-dresses and accompanied by material culture including boomerangs and spears (e.g., Fig. 1).

RESULTS

Age constraints for Gwion motifs

As part of a larger multiyear rock art dating project (*24*, *25*), nest samples associated with 21 different motifs of the distinctive Gwion style are reported here. All samples were obtained with Traditional Owner consent and participation. The motifs were identified as belonging to the Gwion style by P.H. and C.M. (see Materials and Methods). Detailed results are listed in table S1, and specific details of radiocarbon pretreatments are listed in table S2. Each age measurement is given a qualitative "Reliability Score" [described in detail elsewhere (*25*)] based on the carbon mass analyzed, the physical

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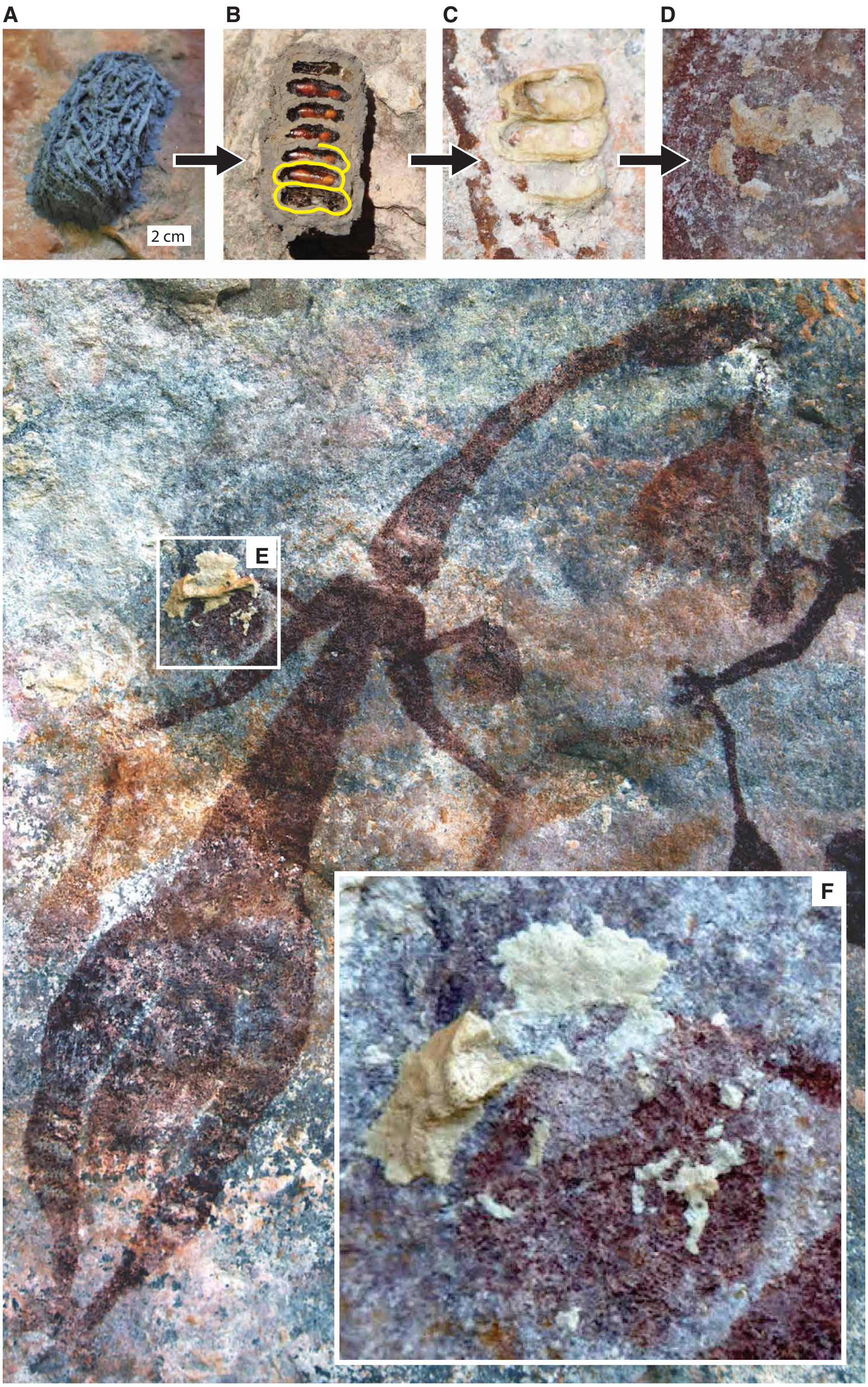

Fig. 1. Mud wasp nest samples and their development sequence. (**A**) A recently constructed *Sceliphron laetum* mud wasp nest. (**B**) Underside of the nest after removal from the rock surface with basal nest structure highlighted to show (**C**) the characteristic oval shape evident in weathered nests, leaving (**D**) just a remnant of mineralized mud over time. (**E**) A typical remnant mud wasp nest (DR006_03-1) overlying pigment from a Gwion motif before removal and (**F**) the remainder with pigment revealed underneath. Photo credit: Damien Finch.

cleaning of the sample, and the chemical pretreatment applied. The reliability score is a relative measure that communicates the susceptibility of the age measurement to potential sources of contamination. Ages with scores of 3 or less are, thus, less reliable than the most robust measurements associated with scores of 8 or more. Most samples fall into the middle reliability range (4 to 7).

Usually, only a single dated nest was associated with a particular motif, but one motif, DR015_01, had two overlying nests dated and another, DR015_07, had two overlying and one underlying nest dated. Where there was more than one overlying nest on a motif, only the oldest is included in the subsequent analysis as its age will be closer to that of the motif. For the other 19 motifs, 6 had nests underlying pigment and 13 had nests overlying pigment. Figure S2 provides photographs and interpretative illustrations for the dated motifs.

The calibrated ages of the 12 oldest wasp nests overlying art are mostly in the range from 4.5 to 12.1 ka [median calibrated years before the present (median cal BP)] with one nest (DR006_03) significantly older at 16.6 ka (median cal BP), with a reliability score of 5 out of 10 (Fig. 2) (*25*). Five of the six nests underlying pigment were dated to between 13 and 15 ka (median cal BP). The remaining nest, DR013_10-1, was dated to 6.9 ka (median cal BP) but with a low reliability score of 3. The low score reflects both the small mass of carbon measured (23 μg) and the small size of the sample pieces that restricted the potential for thorough cleaning of external surfaces. Given the potential for younger carbon contamination, this age is treated as an outlier. Uniquely, one motif, DR015_07, had one nest underlying and two nests overlying pigment. The dates on these three nests together provide an age bracket of 11.3 to 13.0 ka (cal BP, 95% probability) (Fig. 2).

DISCUSSION

Theoretical determination of art periods

Dated wasp nests, over or under pigment, provide only minimum or maximum age limits for individual motifs. How then can these individual age limits be used to estimate the age range of the stylistic periods of Kimberley rock art?

Weathering of the initially large surface area of mud wasp nests gives results in a rapid reduction in nest volume until the nest is reduced to a stump (Fig. 1) (*25*). Hence, the age distribution of all nests is likely to be broadly exponential, with most nests being young and the probability of nests being preserved diminishes as age increases. Although it is possible that nest production rates fluctuated in response to changing environmental conditions over the past 30,000 years, the almost continuous sequence of ages measured on Kimberley wasp nests reported elsewhere (*25*) suggests a quasi-continuous nest production through time (fig. S1A).

If the age distribution of all wasp nests is exponential or at least monotonically decreasing with time, then the age of the nests overlying rock art will be biased toward younger values. The most probable age for any "over-art" nest is, therefore, one that is closer to year 0, and the least probable ages for overlying nests are those closer to the

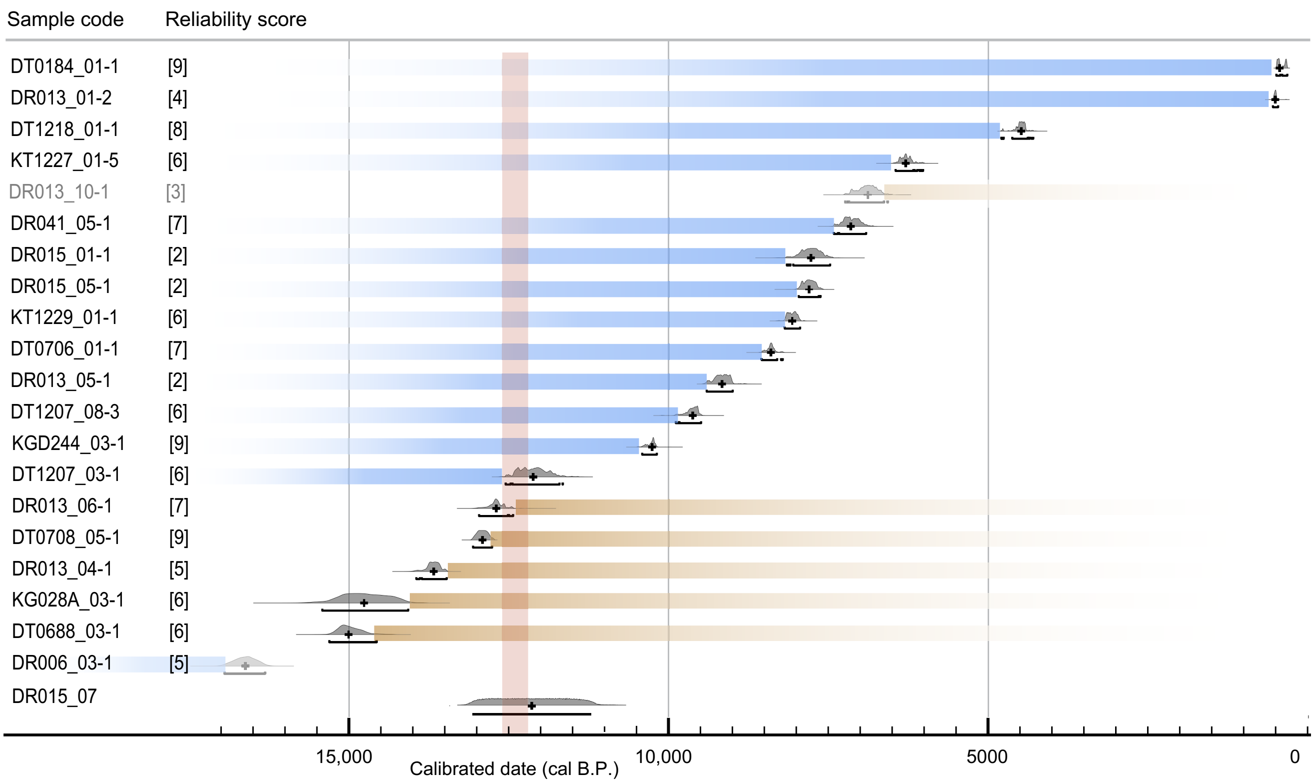

Fig. 2. Summary of Gwion-related ages. Calibrated dates for the oldest wasp nests and the associated reliability score (10 is the most reliable, and 1 is the least). The bar underneath each probability distribution plot indicates the 95% probability range, with the median marked with a cross. The minimum age constraints provided by overlying nests (indicated with blue bars, starting just beyond the 95% probability range for the nest) and the maximum age constraints from underlying nests (brown bars) together with the age bracket for DR015_07 suggest a narrow age range for production of most of these Gwion motifs around 12,400 years ago (cal B.P.) (red vertical bar), apart from DR013_10-1 and DR006_03-1.

age of the motif (fig. S1B). The opposite is true for nests underneath rock art in that the most likely nests are those closer in age to the age of the motif. With experience, it is often possible to identify and avoid more modern nests, thereby increasing the probability that the over-art sample age will be closer to the age of the motif. In general, however, an under-art nest is more likely to be closer in age to that of the motif (although it could sometimes be substantially older).

Only very occasionally will an individual motif have more than one overlying or underlying nest. It is, thus, rare to find multiple nests that will provide a narrow age bracket for a single figure, although one such motif is reported here. Consequently, a different methodology is required to constrain the age of a particular period. The approach taken here is to consider the ages of all nests associated with all motifs of a single style to estimate the time span for that graphic tradition.

Assuming, at one extreme (Fig. 3, scenario 1), that motifs of a given style were all painted within a narrow age range, e.g., 3000 ± 100 years ago, then the expected age of nests overlying these motifs will be as illustrated by the blue triangles and the ages of underlying nests by the brown triangles (Fig. 3A). The bars to the left or right of each nest age (triangle) indicate the possible age range for the associated motif. In this case, there can be minimal overlap (<200 years) in the age ranges for overlying and underlying nests. The difference between the age of the oldest overlying nest and the age of the youngest underlying nest provides a useful estimate of when motifs in this style were painted.

At the other extreme, in scenario 2, we assume that motifs in this style were painted over a more extended period between 2000 and 4000 years ago (Fig. 3B). Here, the ages of the overlying and underlying nests may overlap significantly by up to 2000 years. The age difference between the oldest over-art nest and the youngest under-art nest still provides an estimate of the time span for the style. As the number of dated nests increases, the statistical distribution of the ages will provide a more precise and robust time span estimate for a given style phase.

The summed probability functions for all the over-art nests (blue curves in Fig. 3, C and D) show the probability that a motif has a minimum age of less than x years. Similarly, for under-art nests, the brown curves show the probability that the maximum age of a motif is greater than x years (see Materials and Methods).

Age range hypothesis for the Gwion style

The lack of significant overlap between the probability distributions for maximum and minimum ages on 21 Gwion motifs (Fig. 2)

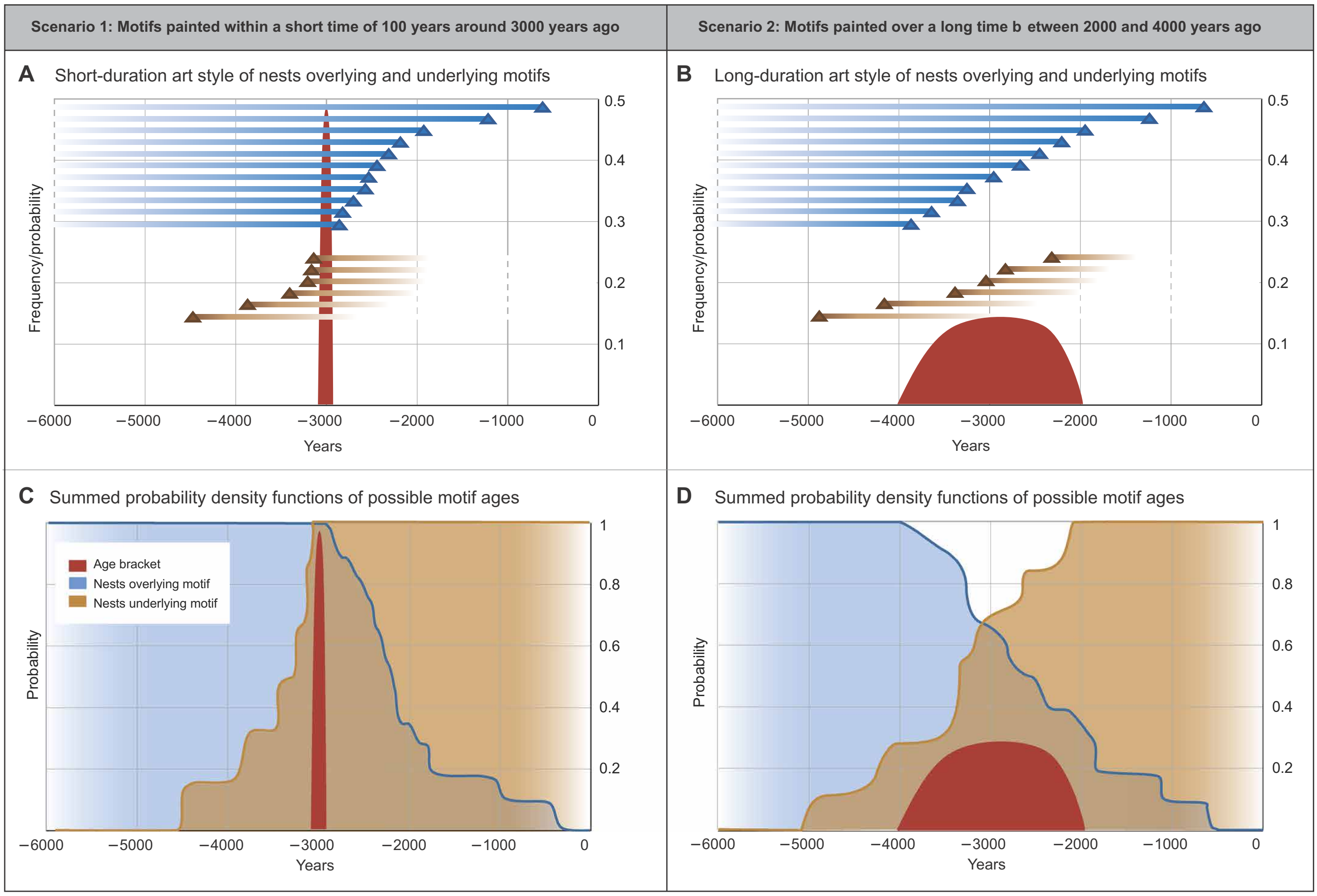

Fig. 3. Hypothetical ages of nests overlying (blue triangles) and underlying (brown triangles) motifs. Blue (brown) horizontal bars show the possible age range for the associated motif over (under) the nest. Scenario 1 (**A**): All motifs were painted in a short period permitting no major overlap between the ages of underlying and overlying nests. Scenario 2 (**B**): Motifs were painted between 2000 and 4000 years ago so the ages of underlying and overlying nests will overlap significantly. The probability functions in (**C**) and (**D**) are the sum of the possible age ranges for motifs from overlying (blue curve) and underlying (brown curve) nests.

suggests that they were painted over a short duration as modeled in Fig. 3A rather than a long duration as in Fig. 3B. All but one of the over-art nest ages are consistent with a hypothesis that Gwion motifs are older than ~12 ka cal B.P. (Fig. 4A), at least in the area studied. The under-art nest ages (excluding DR013_10) are consistent with a hypothesis that Gwion motifs are younger than ~13 ka cal B.P. (Fig. 4B). The median of the age bracket for DR015_07 falls between these two limits (Fig. 4C), supporting the proposition that the Gwion motifs in this study were painted between 12 and 13 ka cal B.P.

While the 16.3 to 17.0 ka cal B.P. age for the nest overlying DR006_03 has a mid-range reliability score of 5, we allow that although the rest of the data suggest a short period of production of Gwion motifs around 12.4 ka cal B.P., it is possible that some Gwion motifs may be more than 4000 years older.

The summed probability functions of the minimum ages (blue) and the maximum ages (brown) are plotted in Fig. 5. As the two outliers, DR013_10 and DR006_03, are included, the overall shape of these curves is less like the short-duration scenario depicted in Fig. 3C than it would be if they were excluded.

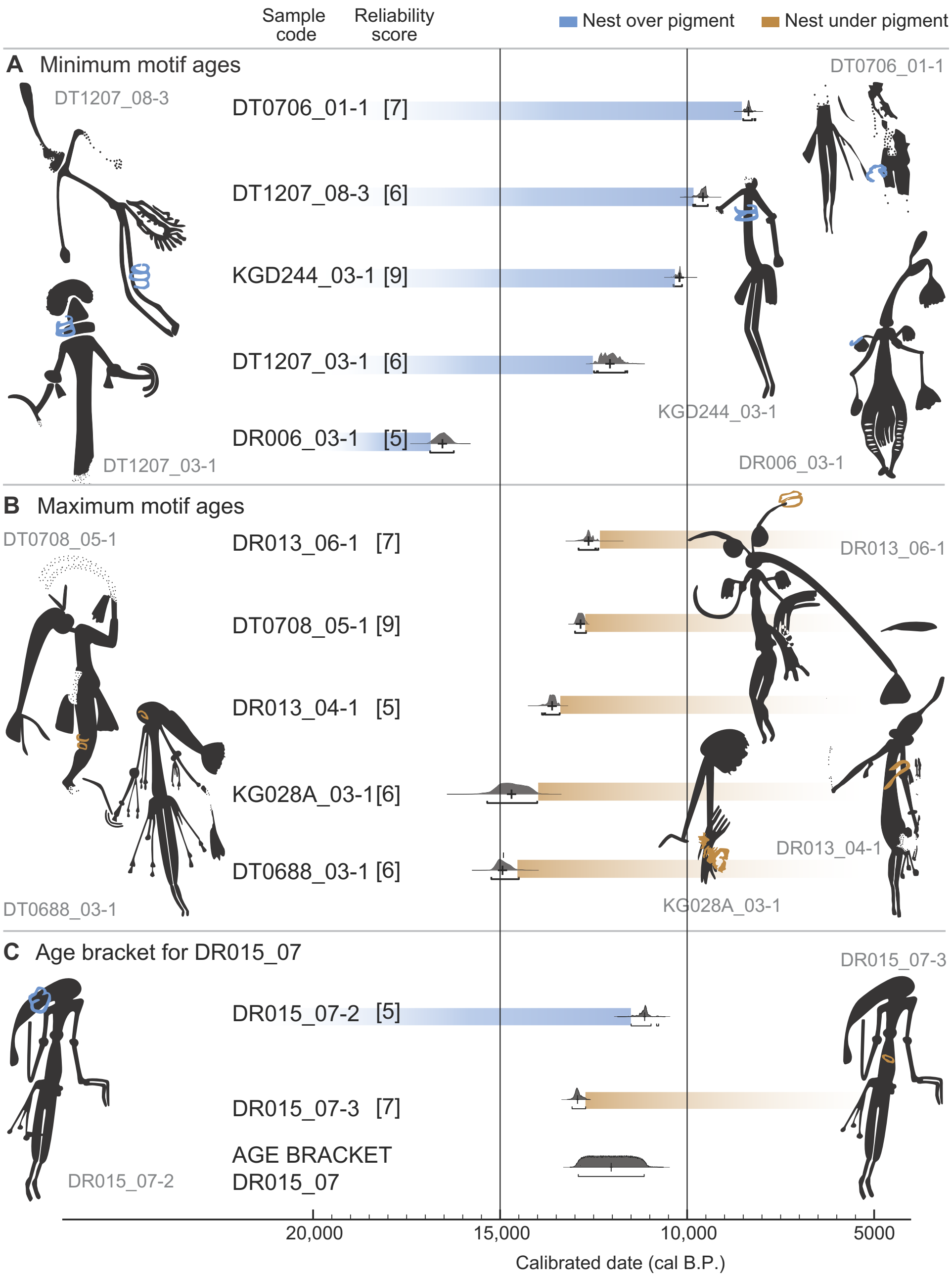

Fig. 4. Motif age ranges. Calibrated dates for the oldest wasp nests with a reliability score of at least 5. (**A**) Nest over motif: Nest sample locations are indicated in blue on the black figures. (**B**) Nest under motif: Nest sample locations are indicated in brown. (**C**) Nests under and over the same motif DR015_07 and the calculated age bracket for motif DR015_07 using the OxCal 4.3.2 software (*36*, *40*) and the code listed in text S1. Illustrations: Pauline Heaney.

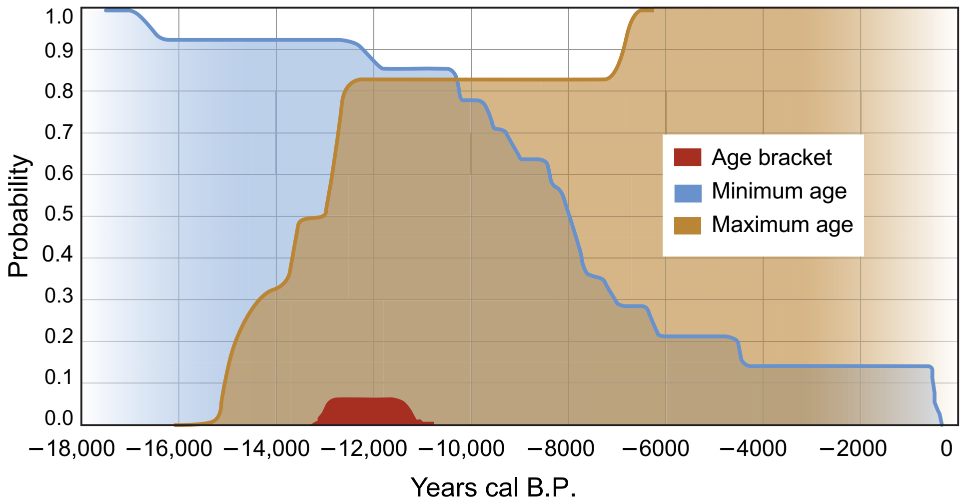

Fig. 5. Probability distributions for the age constraints for Gwion motifs. Sum of the cumulative probability density functions for the ages of nests over (blue) and under (brown) pigment and the age bracket for motif DR015_07 (red). The intersection of the blue and brown areas then represents the probability distribution for the age of Gwion motifs. The outliers, DR013_10 and DR006_03, are included.

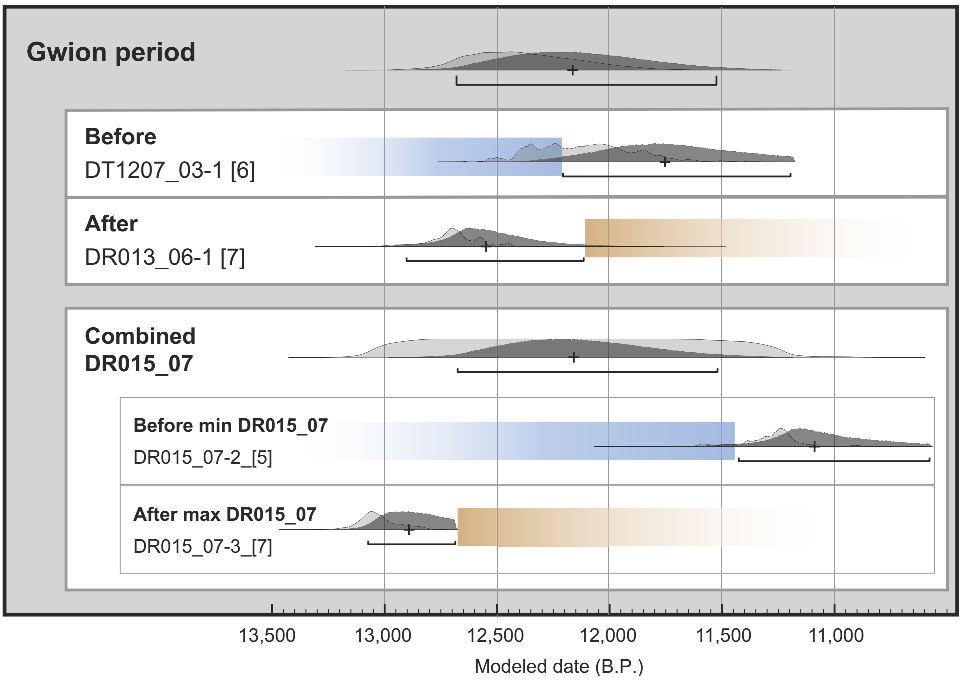

Fig. 6. Hypothesized age range for the Gwion style (top graph), with (dark gray) and without (light gray) a correction for inbuilt charcoal age. Excluding the two possible outlier dates for DR013_10 and DR006_03, the Gwion style is defined temporally by combining the age distributions for the oldest over-art nest (DT1207_03), the youngest under-art nest (DR013_06), and the age bracket for DR015_07. The bar under the curve is the 95% probability range, and the cross marks the median of the corrected distribution. Modeled using OxCal v4.3.2 (*40*); r:5 SHCal13 atmospheric curve (*35*) and the code listed in text S1.

Even this unprecedented sample of ages on 21 Gwion motifs, collected from sites up to 100 km apart, may not fully represent the diversity present across the full geographic range of this style. The hypothesized age range for Gwion production is heavily influenced by a small number of age determinations, with only one nest dated in the critical period from 10.5 to 12.5 ka. Nonetheless, this analysis serves to demonstrate how the theoretical model is applied. Additional samples from the earliest subphases in the Gwion style period and from the western half of the Kimberley will be sought in future studies. Many more nests, both over and under Gwion motifs, will need to be dated before the true age distribution of paintings in the Gwion style and substyles can be stated with greater confidence.

Allowance for inbuilt age of charcoal

The main source of carbon in old mud wasp nests is from charcoal fragments in the mud collected by wasps at the time of nest construction (*25*). Frequent Kimberley bushfires burn relatively short-lived vegetation (especially grasses), such that most wasp nests do not contain very old charcoal when they are built. However, some recently constructed (i.e., modern) nests did contain charcoal up to

~1000 years old. Analysis of charcoal samples from nine modern nests suggests a mean inbuilt age of 255 years (*25*), although the majority (six) contained only modern carbon.

If no correction is made for this inbuilt carbon age, then when the probability density functions for the maximum and minimum (excluding DR006_03) age limits and the age bracket are combined, the implied duration of the Gwion period is 11,850 to 12,810 cal B.P. with a median of 12,400 cal B.P. (95% probability) (Fig. 6, light gray curves). This assumes that the oldest of the overlying nests (DT1207_03) defines the minimum age for these Gwion paintings, and the youngest under-art nest (DR013_06) defines the maximum age. While the age range is calculated from just two dates, these particular dates are end points in age distributions, and it is the distributions (with a large number of samples, indeed the largest such sample ever dated for older Kimberley rock art) that provide confidence in the range calculated. If any one date was significantly removed from others (i.e. an outlier), then that would normally call for further evidence to support it.

The impact of old charcoal can be modeled assuming the inbuilt age follows an exponential distribution, with a mean of 255 years and a maximum possible value of 4000 years (Fig. 6, dark gray curves) (*29*). The effect is to shift the hypothesized age range of the Gwion style from 11,850 to 12,810 cal B.P. (median, 12,400) to 11,520 to 12,680 cal B.P. (median, 12,160).

Results in context

The aim of this research was to demonstrate how multiple dates on mud wasp nests overlying and underlying rock art motifs of a particular style within a region can be used to estimate the age span of that style. A first estimate for an age span of Gwion style paintings (previously known as Bradshaw paintings) is derived from radiocarbon age determinations on 24 mud wasp nests that were either under or over 21 motifs from 14 sites. If Gwion motifs were continually produced over a period of many thousands of years, then we would expect the ages of wasp nests under pigment to overlap significantly with those of nests on top of pigment. However, we found no overlap between the median calibrated ages of 13 overlying nests and 5 underlying nests, implying that most of these Gwion motifs were painted over a relatively narrow time span between 11,500 and 12,700 years ago. The closely bracketed age for motif DR015_07 supports this hypothesis, its age being constrained by two overlying and one underlying nest to be between 11.3 and 13.0 ka cal B.P.

However, two further results are outliers that do not support this hypothesis. The younger of these (DR013_10) can be discounted as being of low reliability, but the other (DR006_03) is of mid-range reliability and less readily discounted. The only other old minimum age determination on a proposed Gwion motif, reported in 1997 but still much debated, is also closer to 16 ka (16.4 ± 1.8 ka) (*21*), so it is certainly possible that the initial depiction of Gwion motifs date from this period but that their production as the dominant anthropomorphic style proliferated by c. 12,000 B.P. It has also been suggested that the anthropomorphic Datu Saman figures from Borneo are "notably similar" to Gwion motifs (*30*). While there is only a single minimum age of 13.6 ka reported on one of these figures, it is a little older than the age suggested here for Gwion motifs but of the same order.

Most of the results presented here support a hypothesis that motifs of the Gwion rock art style of Australia's north Kimberley were produced around 12,000 years ago, with the proliferation of this phase likely occurring within a millennium; however, one result points to the possibility that some motifs may be more than 4000 years older. These results confirm that rock art was being produced in the Kimberley during the terminal Pleistocene. Notably, as the Gwion paintings are not the oldest in the relative stylistic sequence for this area, earlier styles must have an even greater antiquity.

MATERIALS AND METHODS

Sample collection

Remnant mud wasp nest samples related to Gwion style paintings were collected from 14 different rock art sites up to 100 km apart in the Drysdale River and King George River catchments (*31*) between 2015 and 2017. The median sample size of all samples collected is c. 250 mg. In keeping with the wishes of the Traditional Owners, the site locations are not disclosed here but have been fully documented in an access-controlled database (*31*). Sampling was approved on site by relevant local Traditional Owners who participated in this fieldwork and under research permits from the Kimberley Land Council/ Balanggarra Aboriginal Corporation and the Western Australian Department of Planning Lands and Heritage (formerly Department of Aboriginal Affairs).

All samples were photographed (including high-resolution macroimaging) before and after they were removed to record the context of the sample in relation to the rock art. As others have noted [e.g., (*14*, *22*)], it is critical to establish a clear relationship between the art and the sample, but this is often challenging. Head-mounted, binocular magnifying glasses of varying magnification (×1.5 to ×2.5) and bright light sources were particularly useful. Digital microscopes were also used, but the limited depth of field restricted their application on irregular rock surfaces. For nests overlying pigment, the expectation is that more pigment will be revealed when the sample is removed (see Fig. 1F). Commonly, however, part of the nest will remain adhered to the rock surface, so it may not be absolutely clear that paint once overlay the nest and has simply weathered away. If there was any doubt, then the remaining nest was carefully abraded until pigment was revealed to confirm the inferred relationship.

Where approval was granted to remove samples underneath pigment, a different set of contextual challenges apply. In particular, it was necessary to establish that it was not possible for material younger than the nest to have been trapped in or behind the nest. Infrequently, signs of biogenic activity were evident when these samples were carefully inspected. These occur as thin, dark lines or accretions, usually between nest and rock surface. The introduction of modern carbon, following construction of the nest, can invalidate maximum age estimates; therefore, if this material could not be removed during physical pretreatment, then the sample was rejected. A motif may have been repainted (rarely) or painted over by a separate motif (more commonly) after a nest was constructed over it, resulting in pigment both over and under the nest. In all cases, careful field observations were recorded photographically on a custom field recording database and in field notes and discussions to confirm the relationships between the art and the sample.

Typically, only part of the nest occurs directly over or under pigment. Usually, only that part of the nest unambiguously in contact with the art was removed. However, when the available sample was small, the nest was critically examined to determine whether more of the nest could be included in the sample. The color, texture, and morphology of the nest were used to verify that it was all constructed at the same time (i.e., a single generation nest), with the practice progressively refined as hundreds of nests of all ages were studied (*25*). Given that new material can be added by wasps at the edge, or over an existing nest, only that part of the nest directly under the pigment or unequivocally part of the same construction episode was relied on.

Radiocarbon age measurements

Initially (laboratory codes in the range OZT444 to OZU730), all stages of pretreatment were conducted using the Australian Nuclear Science and Technology Organisation (ANSTO) Radiocarbon Chemistry laboratory. Subsequently, samples with laboratory codes from OZU776 to OZW426 underwent physical pretreatment and part of the chemical pretreatment at the University of Melbourne. Complete details of the pretreatment methods are described elsewhere (*25*). All sample combustion and graphitization were carried out at ANSTO. All samples were measured using the 10MV ANTARES (Australian National Tandem Research Accelerator) or 2MV STAR AMS at ANSTO. Although the mass of carbon analyzed was mostly in the range of 20 to 70 μg (up to 159 μg), even the smallest samples (13 to 14 μg) are within the analytical capability previously established for this facility over the past 20 years, with dedicated quality control procedures in place to monitor contamination in processing and possible fractionation in measurements (*32*–*34*). In our measurements, we have followed the protocols described in these papers. The carbon concentration of old wasp nests varies greatly but is c. 0.22% before radiocarbon pretreatment (*25*). $\delta^{13}C$ determinations were not performed for these samples because there was insufficient material. The typical charcoal value for $\delta^{13}C$ (−25 ‰) was assumed. All radiocarbon ages were calibrated using SHCal13 (*35*) in OxCal v4.3.2 (*36*).

Motif classification

Radiometric methods that quantitatively date older rock art almost always provide a maximum or minimum age for a single motif at a time. To determine the duration of Kimberley rock art styles or periods, we needed to classify motifs into a particular defined style. While objective classification is possible through attribute analysis, it is often a largely subjective decision, so it requires both expert opinion and an estimate of uncertainty.

Some motifs have the form and many of the elements that characterize a particular style and can be correctly and certainly classified by someone with minimal familiarity with Kimberley rock art typology. At the other extreme, some complete motifs were unable to be classified with any certainty because they lack clear defining characteristics. The most experienced observers can be expected to be able to classify a greater percentage of motifs, with a higher level of confidence, than those with less experience. However, even those with the greatest experience will be more or less confident in classifying a specific motif depending on the state of preservation and presence of defining characteristics. Notwithstanding the subjective component of the process, P.H. and C.M. classified 75 motifs into one of the six major Kimberley styles and nominated the level of confidence associated with each classification.

The claim to expertise in classifying Kimberley rock art is based on extensive field research, locating and recording rock art in field expeditions over a combined total of 27 years. P.H. and C.M. have contributed to the recording and digital cataloging of more than 6000 Kimberley rock art sites and more than 90,000 rock art images over the past 30 years, as well as academic publications (*24*, *37*).

Each person classified a motif to one of the six main Kimberley rock art styles and nominated the probability that their decision was correct. Levels of confidence used in the classifications are as follows: "certain" to indicate a probability of at least 99%, "highly likely" for at least 90%, "likely" for 70%, "possible" for 50%, "uncertain" for 35%, or "unknown." This terminology borrows from research into perceptions of probability terminology [e.g., (*38*)] and standard terms used by the Intergovernmental Panel on Climate Change (*39*). So, if a motif is classified as highly likely to be a Gwion, then the expectation is that this interpretation would be correct for 90% of motifs of this form, with this set of characteristics.

All 21 Gwion motifs in this study were classed as "Gwion-certain" by both P.H. and C.M. (table S2). Four further motifs were classed as Gwion by just one person and at a lower confidence level. They have, therefore, been excluded from this analysis. At the time of classification, neither person had knowledge of the age of the wasp nests related to the motifs.

Probability functions for motif ages

The possible age range for a motif was determined from the age of a nest that is either over or under the motif. This possible motif age range can be statistically expressed as a probability density function (PDF). For wasp nests overlying pigment, the PDF of the minimum age of the motif is the cumulative value of the PDF of the nest age, with a probability of 0 that the motif is older than ~50 ka (minimum age for the first arrival of people in Australia) and a probability of 1 that it is older than 0 years. Conversely, for wasp nests underlying pigment, the PDF of the maximum age of the motif is the cumulative value of the PDF of the nest age, with a probability of 1 that the motif is younger than 50 ka and a probability of 0 that it is younger than 0 year.

For each wasp nest dated, the OxCal (*36*) calibration program was used to generate a table showing the probability of the calibrated nest age at intervals of 5 years. To calculate the PDF for the minimum age of a motif, these values were accumulated (added), starting at a probability of 0 at 50 ka. For maximum age estimates, they were accumulated starting at a probability of 0 at 0 year.

All the minimum motif age PDFs were then summed to derive the blue curves shown in Figs. 3 (C and D) and 5. Similarly, the maximum motif age PDFs were summed to derive the brown curves.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/6/eaay3922/DC1

Fig. S1. Relationship between age of nest and associated motif.

Fig. S2. Photograph and illustrative interpretation of dated Gwion motifs.

Text S1. Calibrated age modeling code.

Table S1. Radiocarbon age determinations on wasp nests associated with Gwion motifs.

Table S2. Radiocarbon pretreatment methods and age determinations (uncalibrated) on wasp nests associated with Gwion motifs.

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Acknowledgments: We acknowledge and thank Balanggarra and Dambimangari Aboriginal Corporations, rangers, and Traditional Owners for permission to work on their country and for the support during fieldwork. In particular, we thank A. Unghango and family, the Waina family, A. Chalarimeri on Balanggarra land, and D. Woolagoodja, K. Woolagoodja, and W. Oobagooma on Dambimangari land. 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 laboratory support from the Australian Nuclear Science and Technology Organisation 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. **Funding:** This research was funded by Australian Research Council Linkage Projects LP130100501 and LP170100155 with funding partner the Kimberley Foundation Australia, with in-kind support from Dunkeld Pastoral Co. Pty Ltd. and Balanggarra Aboriginal Corporation especially for fieldwork. D.F. is supported by an Australian Postgraduate Award and an AINSE Post Graduate Research Award. The Kimberley Foundation Australia also provided a grant to D.F. to establish the radiocarbon pretreatment facility at the University of Melbourne. **Author contributions:** This research is part of the multidisciplinary Kimberley Rock Art Dating project conceived and led by A.G., who, with J.H. and V.A.L., supervised this work as part of D.F.'s PhD research project. Motif classification was by P.H. and C.M. D.F. collected and pretreated the samples, designed and performed the experiments, and analyzed and interpreted the results. Fieldwork was carried out by D.F., P.H., S.H., S.O., P.V., C.M., A.G., and H.G. Illustrations were drawn by P.H. V.A.L. conducted radiocarbon measurements and raw data analyses. D.F. wrote the manuscript draft with key editing from J.H. and A.G., with further input from all authors. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. OxCal code is included in the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 14 June 2019
Accepted 22 November 2019
Published 5 February 2020
10.1126/sciadv.aay3922

Citation: D. Finch, A. Gleadow, J. Hergt, V. A. Levchenko, P. Heaney, P. Veth, S. Harper, S. Ouzman, C. Myers, H. Green, 12,000-Year-old Aboriginal rock art from the Kimberley region, Western Australia. *Sci. Adv.* **6**, eaay3922 (2020).

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Sci Adv **6** (6), eaay3922.
DOI: 10.1126/sciadv.aay3922

Science Advances (ISSN 2375-2548) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science Advances* is a registered trademark of AAAS.

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advances.sciencemag.org/cgi/content/full/6/6/eaay3922/DC1

Supplementary Materials for

12,000-Year-old Aboriginal rock art from the Kimberley region, Western Australia

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Published 5 February 2020, *Sci. Adv.* **6**, eaay3922 (2020)
DOI: 10.1126/sciadv.aay3922

This PDF file includes:

Supplementary Materials

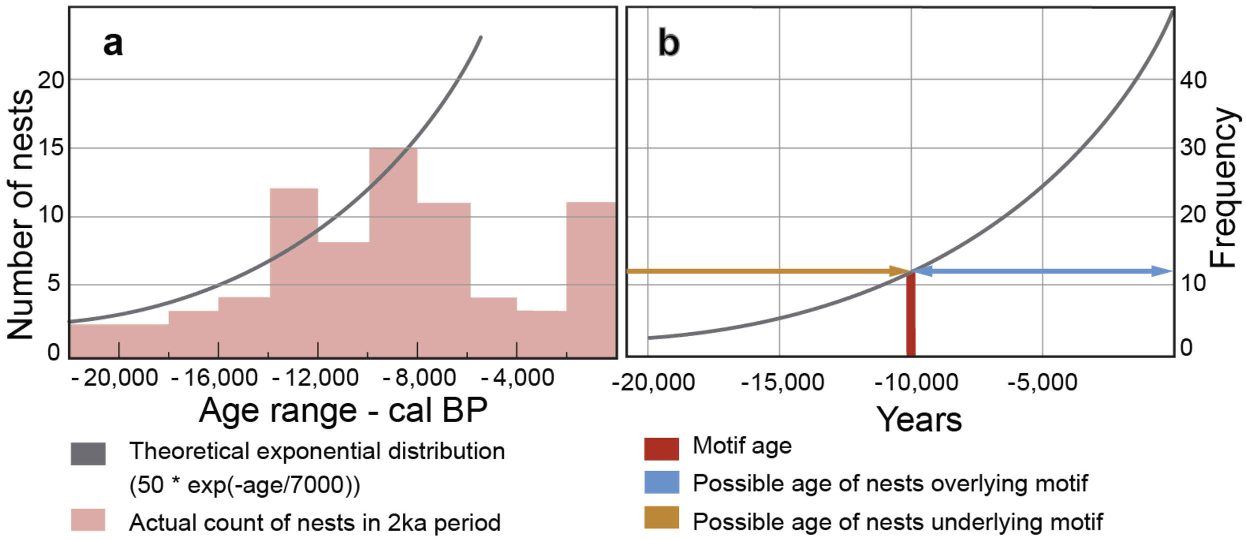


Fig. S1. Relationship between age of nest and associated motif. (a) Histogram of ages of 75 mud wasp nests from Finch et al. (25) in 2ka intervals with a theoretical exponential age distribution for comparison. Note that the significantly fewer nests recorded from this study in the 2 - 6 ka period represents deliberate sampling bias towards the earliest surviving examples (b) Hypothetical age distribution of all possible nests overlying and underlying a 10,000-year-old motif.

Text S1. Calibrated age modeling code.

The age bracket for motif DR015_07 is calculated as follows. The calibrated ages of the overlying nests are used to define the distribution of possible ages for the motif using the BEFORE function in OxCal version 4.3.2 software (*29,30)*. Similarly, the calibrated age of the underlying nest (DR015_07-3) uses the AFTER function to specify the maximum age range. The possible age range for the motif is then defined by applying the statistical COMBINE (or AND) function to the Before and After probability distributions. The motif's minimum age is solely constrained by nest sample DR015_07-2 as nest DR015_07-5 is younger. The OxCal code used to generate parts of Figures 2 and 4 is listed below:

```
Options()
 { Curve="SHCal13.14c";
  BCAD=FALSE; };
 Plot()
 {Combine("DR015_07")
   {Before("Min DR015_07")
     {R_Date("DR015_07-2_[5]", 9875, 85);
       R_Date("DR015_07-5_[5]", 8094, 70);};
     After("Max DR015_07")
     {R_Date("DR015_07-3_[7]", 11220, 71);{}};
   }; };
```

The OxCal code used to generate Figure 6, showing the hypothesised Gwion period age range, with and without a correction for inbuilt charcoal age, is listed below. The code applies a charcoal outlier model to each date (*34)*.

```
Options()
 {Curve="SHCal13.14c";
  BCAD=FALSE;};
 Plot()
 {Outlier_Model("Charcoal",Exp(255,-4000,0));
  { Combine("Gwion")
    { Before() { R_Date("DT1207_03-1 [6] Min", 10353, 107) {Outlier("Charcoal",1);};};
       After() { R_Date("DR013_06-1 [7] Max", 10818, 120) {Outlier("Charcoal",1);};};
       Combine("DR015_07")
         {Before("Min DR015_07") {R_Date("DR015_07-2_[5]", 9875, 85)
                   {Outlier("Charcoal",1);};};
           After("Max DR015_07") {R_Date("DR015_07-3_[7]", 11220, 71)
                   {Outlier("Charcoal",1);};};};
   }; }; };
```

DR006_03-1

SAMPLE CODE: **DR006_03-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **13,790 ± 80 (1σ)**
RELIABILITY SCORE: **5**

CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
16,950	**16,310**	**95.4**	**16,620**

DR013_04-1

SAMPLE CODE: **DR013_04-1**
AGE: **MAXIMUM**
^{14}C YEARS BP: **11,900 ± 80 (1σ)**
RELIABILITY SCORE: **5**

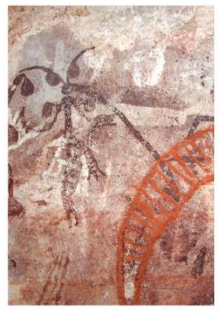
CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
13,950	**13,890**	**2.7**	**13,670**
13,860	**13,470**	**92.7**	

DR013_05-1

SAMPLE CODE: **DR013_05-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **8,240 ± 80 (1σ)**
RELIABILITY SCORE: **2**

CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
9,410	**9,000**	**95.4**	**9,170**

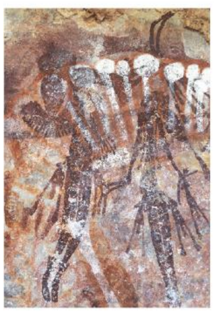
DR013_06-1



SAMPLE CODE: **DR013_06-1**
AGE: **MAXIMUM**
^{14}C YEARS BP: **10,820 ± 120 (1σ)**
RELIABILITY SCORE: **7**

CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
12,970	**12,510**	**90.8**	**12,700**
12,500	**12,430**	**4.6**	

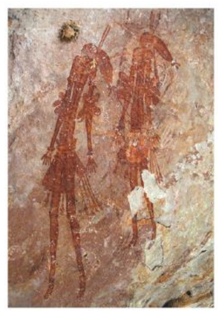
DR013_10-1



SAMPLE CODE: **DR013_10-1**
AGE: **MAXIMUM**
^{14}C YEARS BP: **6,070 ± 110 (1σ)**
RELIABILITY SCORE: **3**

CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
7,240	**7,200**	**1.1**	**6,890**
7,180	**6,630**	**94.3**	

DR015_01-1



SAMPLE CODE: **DR015_01-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **6,970 ± 170 (1σ)**
RELIABILITY SCORE: **2**

CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
8,150	**8,130**	**0.4**	**7,780**
8,119	**8,090**	**0.2**	
8,060	**7,470**	**94.9**	

DR015_07-2

SAMPLE CODE: **DR015_07-2**
AGE: **MINIMUM**
^{14}C YEARS BP: **9,870 ± 80 (1σ)**
RELIABILITY SCORE: **5**

CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
11,620	**8,640**	**94.5**	**11,270**
10,920	**10,890**	**0.9**	

DR015_07-3

SAMPLE CODE: **DR015_07-3**
AGE: **MAXIMUM**
^{14}C YEARS BP: **11,220 ± 70 (1σ)**
RELIABILITY SCORE: **7**

CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
13,180	**12,830**	**95.4**	**13,040**

DR015_05-1

SAMPLE CODE: **DR015_05-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **7,010 ± 90 (1σ)**
RELIABILITY SCORE: **2**

CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
7,970	**7,650**	**95**	**7,800**
7,640	**7,620**	**0.4**	

DR041_05-1

SAMPLE CODE: **DR041_05-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **6,290 ± 100 (1σ)**
RELIABILITY SCORE: **7**

CALIBRATED DATE CAL BP			
FROM	TO	%	MEDIAN
7,420	**7,350**	**4.1**	**7,150**
7,340	**6,910**	**93.3**	

DT0688_03-1

SAMPLE CODE: **DT0688_03-1**
AGE: **MAXIMUM**
^{14}C YEARS BP: **12,680 ± 80 (1σ)**
RELIABILITY SCORE: **6**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
15,310	**14,560**	**95.4**	**15,000**

DT0706_01-1

SAMPLE CODE: **DT0706_01-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **7,640 ± 60 (1σ)**
RELIABILITY SCORE: **7**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
8,550	**8,300**	**94.6**	**8,400**
8,240	**8,220**	**0.8**	

DT0708_05-1

SAMPLE CODE: **DT708_05-1**
AGE: **MAXIMUM**
^{14}C YEARS BP: **11,090 ± 50 (1σ)**
RELIABILITY SCORE: **9**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
13,060	**12,770**	**95.4**	**12,910**

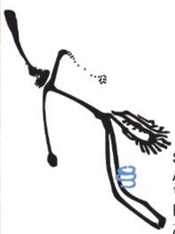
DT1207_03-1

SAMPLE CODE: **DT1207_03-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **10,350 ± 110 (1σ)**
RELIABILITY SCORE: **6**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
12,550	**12,470**	**2.6**	**12,120**

DT1207_08-3



SAMPLE CODE: **DT1207_08-3**
AGE: **MINIMUM**
^{14}C YEARS BP: **8,680 ± 70 (1σ)**
RELIABILITY SCORE: **6**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
9,890	**9,840**	**2.8**	**9,620**
9820	**9,490**	**92.6**	

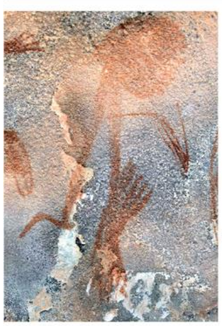
DT1218_01-1

SAMPLE CODE: **DT1218_01-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **4,060 ± 40 (1σ)**
RELIABILITY SCORE: **8**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
4,790	**4,760**	**2**	**4,490**
4,630	**4,400**	**92.7**	
4370	**4,350**	**0.3**	

KG028A_03-1



SAMPLE CODE: **KF028A_03-1**
AGE: **MAXIMUM**
^{14}C YEARS BP: **12,0590 ± 190 (1σ)**
RELIABILITY SCORE: **6**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
15,420	**14,070**	**95.4**	**14,760**

KGD244_03-1

SAMPLE CODE: **KGD244_03-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **9,150 ± 50 (1σ)**
RELIABILITY SCORE: **9**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
10,410	**10,190**	**95.4**	**10,260**

KT1227_01-5

SAMPLE CODE: **KT1227_01-5**
AGE: **MINIMUM**
^{14}C YEARS BP: **5,540 ± 70 (1σ)**
RELIABILITY SCORE: **6**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
6,460	**6,170**	**90.8**	**6,290**
6,160	**6,110**	**2.8**	

KT1229_01-1

SAMPLE CODE: **KT1229_01-1**
AGE: **MINIMUM**
^{14}C YEARS BP: **7,280 ± 70 (1σ)**
RELIABILITY SCORE: **6**

CALIBRATED DATE CAL BP

FROM	TO	%	MEDIAN
8,190	**7,950**	**95.4**	**8,070**

Fig. S2. Photograph and illustrative interpretation of dated Gwion motifs. Showing sample location (blue for nests over pigment, brown for nests under pigment, in the illustrations). Four overlying nests, less than 1000 years old, are not shown, nor, therefore, is motif DR013_01 as the data indicates, trivially, only that this motif is older than ~500 years. Photo Credit: Damien Finch. Illustrations: Pauline Heaney.

Table S1. Radiocarbon age determinations on wasp nests associated with Gwion motifs. The Sample Code is constructed from a short site identifier, followed by a number to identify the painted motif and then the number of the sample collected (on that motif, at that site) in the format “SITE_MOTIF-NEST”. The “Min or Max age constraint” indicates the nest sample was respectively, either over or under the motif. For a complete description of the Pretreatment Sequence, Fractions, and Reliability Score refer (25). Calibrated using SHCal13(32) in OxCal v4.3.2 (29).

Sample Code	Laboratory Code	C mass (μg)	^{14}C years BP	Error (1σ) ± (yrs)	Calibrated date cal BP (95% probability range) (years)				Reliability Score	Min or Max age constraint for motif
					from	to	%	Median		
DR006_03-1	OZT791	58	13,790	80	16950	16310	95.4	16,620	5	Min
DR013_01-2	OZT787	41	510	40	560	470	95.4	510	4	Min
DR013_04-1	OZT775	24	11,900	80	13950 13860	13890 13470	2.7 92.7	13,670	5	Max
DR013_05-1	OZT776	22	8,240	80	9410	9000	95.4	9,170	2	Min
DR013_06-1	OZU776U1	27	10,820	120	12970 12500	12510 12430	90.8 4.6	12,700	7	Max
DR013_10-1	OZT462	23	6,070	110	7240 7180	7200 6630	1.1 94.3	6,890	3	Max
DR015_01-1	OZT477	13	6,970	170	8150 8110 8060	8130 8090 7470	0.4 0.2 94.9	7,780	2	Min
DR015_01-2	OZT492	14	740	110	900 810	860 510	2.2 93.2	660	1	Min*
DR015_05-1	OZT779	24	7,010	90	7970 7640	7650 7620	95.0 0.4	7,800	2	Min
DR015_07-2	OZT781	55	9,870	80	11620 10920	11080 10890	94.5 0.9	11,270	5	Min
DR015_07-3	OZW367	39	11,220	70	13180	12830	95.4	13,040	7	Max
DR015_07-5	OZW377	30	8,090	70	9140	8640	95.4	8,920	5	Min*
DR041_05-1	OZW368	28	6,290	100	7420 7340	7350 6910	4.1 91.3	7,150	7	Min
DT0184_01-1	OZW371	159	410	20	500 410	430 320	55.4 40.0	450	9	Min
DT0688_03-1	OZW421U2	34	12,680	80	15310	14560	95.4	15,000	6	Max
DT0706_01-1	OZW416U2	31	7,640	60	8550 8240	8300 8220	94.6 0.8	8,400	7	Min
DT0708_05-1	OZW392	70	11,090	50	13060	12770	95.4	12,910	9	Max
DT1207_03-1	OZW418U2	22	10,350	110	12550 12450	12470 11710	2.6 92.8	12,120	6	Min
DT1207_08-3	OZW386	22	8,680	70	9890 9820	9840 9490	2.8 92.6	9,620	6	Min
DT1218_01-1	OZW372	36	4,060	40	4790 4630 4370 4330	4760 4400 4350 4300	2.0 92.7 0.3 0.4	4,490	8	Min

Sample Code	Laboratory Code	C mass (µg)	^{14}C years BP	Error (1σ) ± (yrs)	Calibrated date cal BP (95% probability range) (years)				Reliability Score	Min or Max age constraint for motif
					from	to	%	Median		
KG028A_03-1	OZU785U1	25	12,590	190	15420	14070	95.4	14,760	6	Max
KGD244_03-1	OZW414U2	60	9,150	50	10410	10190	95.4	10,260	9	Min
KT1227_01-5	OZW420U2	36	5,540	70	6460 6160 6080 6050	6170 6110 6060 6020	90.8 2.8 0.6 1.3	6,290	6	Min
KT1229_01-1	OZW419U2	25	7,280	70	8190	7950	95.4	8,070	6	Min

Table S2. Radiocarbon pretreatment methods and age determinations (uncalibrated) on wasp nests associated with Gwion motifs. All motifs in this table were classified as "Certain" Gwion motifs by both PH and CM. The "Fraction" column indicates where Heavy Liquid Separation was used to separate the sample into low density (Light) and higher density (Heavy) fractions with "All" indicating the sample was not separated. The $\delta^{13}C$ of all samples was not able to be reliably measured but is assumed to be -25‰ for the isotopic correction, based on an average for other similar samples. For a complete description of the Pretreatment Sequence, Fractions, and Reliability Score refer Finch et al. (25)

Sample Code	Laboratory Code	Pretreatment Sequence	Fraction	C mass (µg)	^{14}C years BP	Error (1σ) ± (yrs)	Reliability Score
DR006_03-1	OZT791	ABA	All	58	13,790	80	5
DR013_01-2	OZT787	ABA	All	41	510	40	4
DR013_04-1	OZT775	ABA	All	24	11,900	80	5
DR013_05-1	OZT776	ABA	All	22	8,240	80	2
DR013_06-1	OZU776U1	A-HLS-BA(8M)	Light	27	10,820	120	7
DR013_10-1	OZT462	ABA	All	23	6,070	110	3
DR015_01-1	OZT477	ABA	All	13	6,970	170	2
DR015_01-2	OZT492	ABA	All	14	740	110	1
DR015_05-1	OZT779	ABA	All	24	7,010	90	2
DR015_07-2	OZT781	ABA	All	55	9,870	80	5
DR015_07-3	OZW367	ABA(8M)	All	39	11,220	70	7
DR015_07-5	OZW377	ABA(8M)	All	30	8,090	70	5
DR041_05-1	OZW368	ABA(8M)	All	28	6,290	100	7
DT0184_01-1	OZW371	ABA(8M)	All	159	410	20	9
DT0688_03-1	OZW421U2	AB-HLS-A(16M)	Heavy	34	12,680	80	6
DT0706_01-1	OZW416U2	AB-HLS-A(16M)	Heavy	31	7,640	60	7
DT0708_05-1	OZW392	A-HLS-BA(8M)	Heavy	70	11,090	50	9
DT1207_03-1	OZW418U2	AB-HLS-A(16M)	Heavy	22	10,350	110	6
DT1207_08-3	OZW386	A-HLS-BA(8M)	Heavy	22	8,680	70	6
DT1218_01-1	OZW372	ABA(8M)	All	36	4,060	40	8
KG028A_03-1	OZU785U1	A-HLS-BA(8M)	Light	25	12,590	190	6
KGD244_03-1	OZW414U2	A-HLS-BA(8M)	Heavy	60	9,150	50	9
KT1227_01-5	OZW420U2	A-HLS-BA(16M)	Heavy	36	5,540	70	6
KT1229_01-1	OZW419U2	A-HLS-BA(8M)	Heavy	25	7,280	70	6