Direct Dating Indicates a Mid-Holocene Age for Archaic Rock Engravings in Arid Central Australia

M. A. Smith,[1]* A. Watchman,[2] and J. Ross[3]

[1]*Centre for Historical Research, National Museum of Australia, Canberra, ACT 2601, Australia*
[2]*Midasco Uranium LLC, 140 East Main St., Naturita, Colorado 81422, USA*
[3]*Department of Archaeology and Palaeoanthropology, School of Humanities, University of New England, Armidale, NSW 2351, Australia*

Archaic rock engravings are found widely across the arid interior of Australia and are thought to represent an early pan-continental tradition. A late Pleistocene age is assumed because of extensive weathering, but attempts to test this by direct dating have been unsuccessful. We use AMS ^{14}C dating of calcium oxalate skins covering archaic engravings at two rock shelter sites in Central Australia (Wanga East and Puritjarra), constrained by ^{14}C dates of charcoal in sedimentary layers beneath the same engraved slabs, to show this rock art is mid-Holocene in age. Despite a limited range of simple geometric designs and uniformity across the arid interior, this corpus of rock art is not associated with the initial peopling of the Australian desert, but is a later development reflecting the dynamics of established desert societies. © 2009 Wiley Periodicals, Inc.

INTRODUCTION

Arid central Australia has a distinctive suite of early rock engravings characterized by a limited range of pecked motifs, mainly bird and macropod tracks (often in track series), plain and concentric circles, arcs, pecked pits, and lizards (in plan view). This graphic tradition of tracks and non-figurative designs, sometimes referred to as the Panaramittee style (Maynard, 1979), is striking for its uniformity across 2.5 million km^2 of the desert interior (Edwards, 1966; Layton, 1992; Franklin, 2004). It is widely thought to be late Pleistocene in age (e.g., Basedow, 1914; Edwards, 1971; Maynard, 1979; Morwood, 2002:40, 57–58; Franklin, 2004:141) because (1) many of the rock art surfaces are fractured and deeply patinated, (2) some motifs may represent extinct species, and (3) similar engravings occur in Tasmania, which was isolated by the post-glacial rise in sea level. The geographic uniformity of the art has been taken as evidence that Pleistocene groups maintained open extensive social networks, important for small, mobile foraging populations (Morwood, 1984). Some regional variability in this rock art is evident (Rosenfeld, 1991; Franklin, 2004),

*Corresponding author; E-mail: m.smith@nma.gov.au

Geoarchaeology: An International Journal, Vol. 24, No. 2, 191–203 (2009)
© 2009 Wiley Periodicals, Inc.
Published online in Wiley Interscience (www.interscience.wiley.com). DOI:10.1002/gea.20262

but how much of this is due to later developments is unclear because temporal frameworks are so poor.

Despite 40 years of research, it has been difficult to directly date these engravings and doubts about their antiquity have persisted (David, Chant, & Flood, 1992; Layton, 1992:221). Broken sections of engraved panels are rarely found in archaeological deposits. The few examples date to the mid- to late-Holocene but in most cases are so fragmentary that cultural assignment is uncertain. Panels of engravings buried by archaeological deposits have been found in tropical northern Queensland and radiocarbon dated to 15.7 ka[1] (Rosenfeld, Horton, & Winter, 1981) and 9.0 ka (Morwood, 2002:235–242) and in temperate Tasmania, where the engravings date to ~1.4 ka (Brown, 1991). However, these represent different rock art traditions, with differences in motifs and composition that set them apart from archaic desert engravings. Initial attempts to directly date engraved rock surfaces using ^{14}C assay of calcium carbonate deposits intercalated within laminated rock varnish (Dragovich, 1984, 1986) did not resolve questions about the relationship between varnish layers and the rock engravings, and were invalidated when later work showed that pedogenic carbonates did not give reliable radiocarbon ages. Cation-ratio (CR) dating of rock varnish, which assumes time-dependent leaching of mobile elements (Ca and K) relative to Ti, has been applied to varnishes covering archaic desert engravings (Dorn, Nobbs, & Cahill, 1988) but floundered on the difficulty of calibrating cation ratios against known-age samples, observed variability in cation ratios across individual varnish layers, and because further research showed that the initial ratio of Ca + K:Ti was not constant (Reneau, Oberlander, & Harrington, 1991; Watchman, 2000). AMS ^{14}C dating of organic carbon inclusions within laminated rock varnish has also been attempted (Dragovich, 2000), but it is now evident that varnishes are remobilized and reworked and some have been shown to contain carbon of widely different ages (Dragovich, 2000; Watchman, 2000).

AMS ^{14}C dating of oxalate skins on rock surfaces avoids these problems as oxalate minerals provide a closed system for carbon and are stable and insoluble once formed (Watchman, 2001). However, oxalate minerals appear to be uncommon in arid environments. In Australia they are mainly found in humid to sub-humid tropical regions where mean annual rainfall is >700 mm (Watchman, 1991). It is only recently that rock art surfaces with oxalate skins have been identified in arid Central Australia.

STUDY AREA

Our work focused on two rockshelter sites, on the rim of the Amadeus basin in Central Australia (Figure 1), where archaic rock engravings are overlain by thin (<1 mm) laminated glossy brown oxalate skins: Wanga East (24°19′ 30′′S, 131° 40′24′′E) and Puritjarra (23°49′ 23′′S, 130°51′18′′E). At both sites archaic engravings occur on the upper surfaces of rock slabs that have fallen from the ceilings of the shelters, overlying archaeological deposits, allowing ^{14}C dating of charcoal preserved

[1] All ages calibrated years B.P.

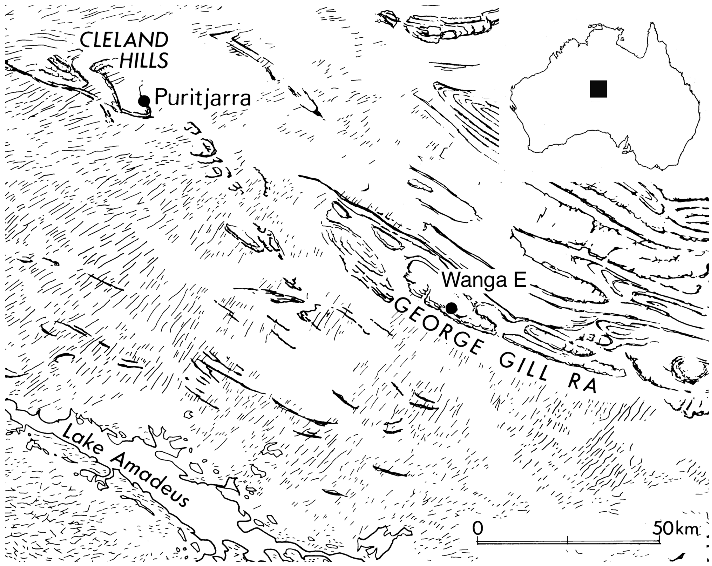

Figure 1. Map of western Central Australia, showing places mentioned in the text and regional topography of linear sand dunes, salt lakes, and sandstone ranges.

beneath the slabs to provide a *terminus post quem* for both the rock fall and the engravings. At both sites, therefore, the maximum age of the engravings could be bracketed by dating rock fall episodes, and the minimum age by dating calcium oxalate skins overlying the engravings.

We also chose panels of rock engravings that on *a priori* grounds were of similar relative age and which had previously been assigned to the earliest phase of the regional rock art sequence. In central Australia, differential patination of engravings at individual sites indicates punctuated bursts of rock art production. Combined with analyses of superposition, this allows a relative rock art sequence to be established (Ross, 2003). The earliest engravings are predominately small ($<$150 mm) plain circles with broad, fully pecked outlines, irregular concentric circles, and intaglio bird and macropod tracks, showing anatomical details of heel and toe, and arranged in single tracks or short series of tracks. Later engravings have a wider range of motifs, often have long track meanders, and are more schematized, with only narrow pecked lines. In this context, the engravings at Puritjarra and at Wanga East are representative of the earliest phase of rock engraving in Central Australia (Rosenfeld, 1990, 2002; Rosenfeld & Smith, 2002).

Wanga East

Wanga East is a long, narrow rock shelter on the Watarrka plateau, a low sandstone plateau whose southern margin forms the George Gill Range (Figure 1), an area known for its shady gorges, springs, and waterholes. The rockshelter is formed

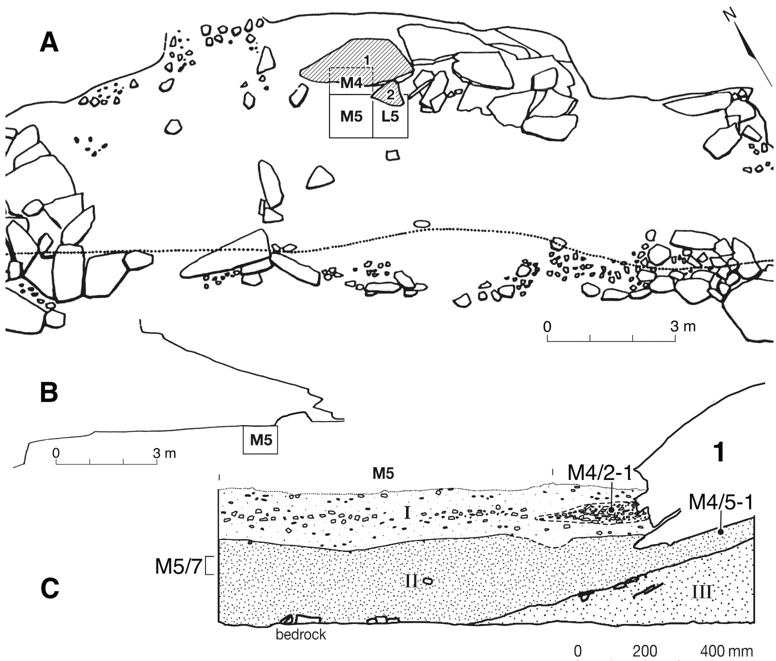

Figure 2. Plan (a) and profile (b) of Wanga East rock shelter, showing the layout of excavation trenches (M4–5, L5) in relation to engraved rock slabs 1 and 2. Stratigraphic section (c) shows the position of ^{14}C samples (charcoal) in relation to slab 1. Layer I is fine-grained pale brown sand, with abundant organic material (nuts, bone, charcoal pieces to 50 mm), bands of ash, and intact hearths (M4/2-1). Layer I rests unconformably on II, which is homogeneous fine-grained black silty sand with finely comminuted wood charcoal. Slabs 1 and 2 fell during the accumulation of layer II, and are partly buried by it. III is coarse-grained orange sand representing decomposed rock from an earlier rock fall at the rear of the shelter. Both II and III rest on a bedrock shelf.

in Palaeozoic Mereenie Sandstone. Periodic collapse of the sandstone ceiling has left a series of rock slabs overlying archaeological deposits at the rear of the rock shelter (Figures 2a, b). These have oxalate-encrusted archaic engravings on their upper surfaces (Figure 3), representing a single phase of pecked engraving with style and motifs typical of the earliest phase of rock art in this region: small plain circles, concentric circles, lines, pecked pits, bird tracks, and track series. Excavation of deposits beneath the west end of this rock fall (slabs 1 and 2) showed this occurred during the accumulation of layer II and that further build-up of sediments buried the lower part of these slabs (Figure 2c). Although no engravings extend below modern ground level, they could not have been made before the rock fall, as this created the surfaces used for engraving. Relatively large fragments of wood charcoal (~15 mm) are preserved beneath these slabs at the interface with the deposits, indicating the rock fall protected friable material on sedimentary surfaces from disintegration, and that slabs 1 and 2 fell on what was then a young surface. We collected M4/5-1 *in situ* directly beneath slab 1 to provide a maximum age for this rock fall

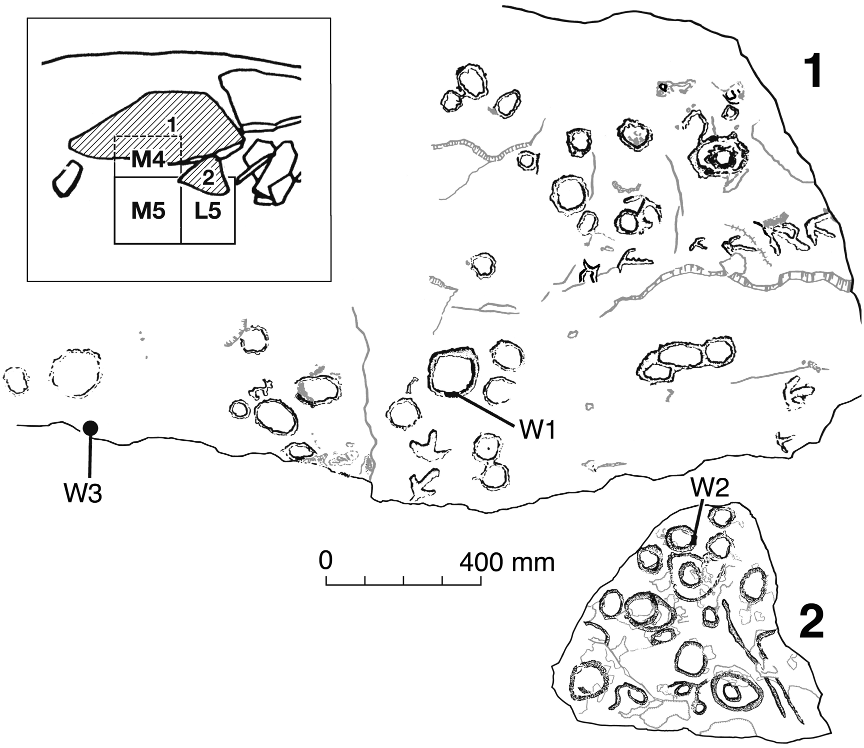

Figure 3. Rock slabs 1 and 2, Wanga East, showing engravings and location of oxalate samples (W1–W3).

event, M5/7 (detrital charcoal from excavated sediments) to date layer II sediments burying the base of slab 1, and M4/2-1 (*in situ* charcoal from an intact hearth) from the overlying layer as a crosscheck. The ^{14}C results (Table I) show that shortly after layer II began to accumulate, the rock fall occurred (~9.3 ka). Wk19122 (M5/7) confirms that slabs 1 and 2 were in place before ~5.7 ka. Analysis of archaeological remains from layers I and II (Table II) is consistent with the radiocarbon chronology, indicating two phases of occupation separated in time: Layer I has late Holocene tool types (geometric microliths and a seed grinder), small stone artifacts, and more use of chert; II has larger artifacts, amorphous retouched implements, less use of chert, and no grindstones, consistent with mid- to early Holocene assemblages in this region.

Puritjarra

Puritjarra is a large, open rock shelter, formed in Mereenie Sandstone, in the Cleland Hills (an outlying sandstone range set in sand hill country west of the George Gill Range). The site has a long record of late Pleistocene and Holocene occupation (Smith, Prescott, & Head, 1997; Rosenfeld & Smith, 2002). The shelter has 400 m^2 of

Table I. Radiocarbon ages bracketing archaic rock engravings, Central Australia.

Sample*	Lab Code	Age B.P.	Age Cal B.P.†	$\Delta^{13}C$ ‰#	Association	Material‡
Wanga East (W04)						
M4/2-1	Wk20451	320 ± 35	284–453	−24.0	Layer I sediments covering base of Slabs 1 and 2	Charcoal
W1 and W2 Top	NZA27886	1443 ± 25	1286–1347	−9.9	Final phase of oxalate formation within engravings W1 and W2	Oxalate
W1 Base	NZA27392	3820 ± 30	4006–4246	−10.2	Base of oxalate in engraved circle W1	Oxalate
W2 Base	NZA27393	4362 ± 30	4840–4965	−11.6	Base of oxalate in engraved circle W2	Oxalate
M5/7	Wk19122	5021 ± 44	5604–5888	−22.7	Layer II sediments covering base of Slabs 1 and 2	Charcoal
W3 Base	NZA27388	7271 ± 40	7970–8161	−7.9	Initiation of oxalate on rock surface	Oxalate
M4/5-1	Wk19121	8385 ± 50	9133–9452	−22.8	Sedimentary surface beneath Slab 1	Charcoal
Puritjarra						
P1 and P2 Top	NZA27555	542 ± 30	502–549	−12.9	Final phase of oxalate formation within engravings P1 and P2	Oxalate
P1 Base	NZA27391	2258 ± 30	2152–2327	−11.8	Base of oxalate in engraved circle P1	Oxalate
P2 Base	NZA27387	2613 ± 30	2512–2758	−12.1	Base of oxalate in engraved circle P2	Oxalate
ST5/10-3	ANU7460	13570 ± 100	15,659–16,555	—	Sedimentary surface under Block D	Charcoal

*Oxalate samples from the top of the crust (W1, 2; P1, 2) were combined for AMS ^{14}C. P3, an off-art sample to date initiation of oxalate formation on rock surfaces at Puritjarra, was not suitable for dating and is not shown.

†Radiocarbon ages (age B.P.) are calibrated with Calib 5.0.1, using SHcal04 for ages <1000 B.P., and Intcal04 for ages >1000 B.P. (with input corrected for Southern Hemisphere offset, 40 ± 13 yrs) (Stuiver & Reimer, 1993). Calibrated age intervals are 2-sigma.

#$\Delta^{13}C$ is relative to PDB. Not measured for ST5/10-3.

‡Archaeological samples were charcoal pieces: M5/7 (~6 mm); M4/5-1 (~15 mm), M4/2-1 (10–40 mm; from hearth), ST5/10-3 (3–10 mm). Charcoal received acid-base-acid pretreatment with ^{14}C assay of the insoluble fraction. For oxalate samples, see text.

Table II. Differences between excavated assemblages in mid- and late-Holocene units at Wanga East (W04).

Layer	Charcoal Density[a] g/10 kg	Chipped Stone Artifacts Density[a] #/10 kg	Mean Wt. (g)	Chert[b] %	Geometric Microliths #	Grindstones #
I Brown sand	374	4.0	1.4	25	3	3[c]
II Black unit	14	4.2	3.7	14	—	—

Note: Pits M4–M5 and L5 combined.
[a]Standardized by weight of excavated sediment.
[b]Number of chert artifacts as % stone artifacts in layer.
[c]Includes one muller, one amorphous grindstone, and one undiagnostic grindstone fragment.

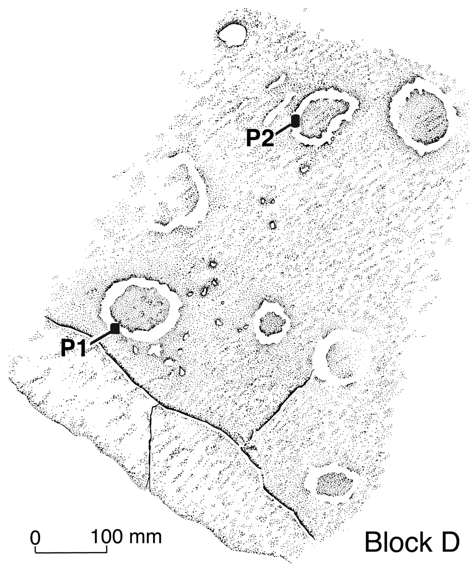

Figure 4. Block D, Puritjarra, showing detail of engraved panel and location of oxalate samples (P1–P2). This block has 6 plain pecked circles and traces of a seventh circle (not all shown).

floor area divided into northern and southern sectors by a cluster of large sandstone boulders that have detached from the rear wall or roof of the shelter. These have oxalate-encrusted archaic engravings on their upper surfaces and sides; all are small, plain circles, representing a single phase of engraving (Figure 4) (Rosenfeld & Smith, 2002). Excavation of Pits QR9 and ST5 showed that the engraved boulders rest in the upper part of layer II (Figure 5), in levels dating to the late Pleistocene (Smith, Prescott, & Head, 1997). ST5/10-3 consisted of large charcoal pieces (*Callitris* sp.) preserved directly beneath Block D (Figure 5) and provides a maximum age of ~16.1 ka for the block fall (Table I). Engravings on the upper surface of D (Figure 4) are on a surface created when the block detached from the rear wall of the rock shelter,

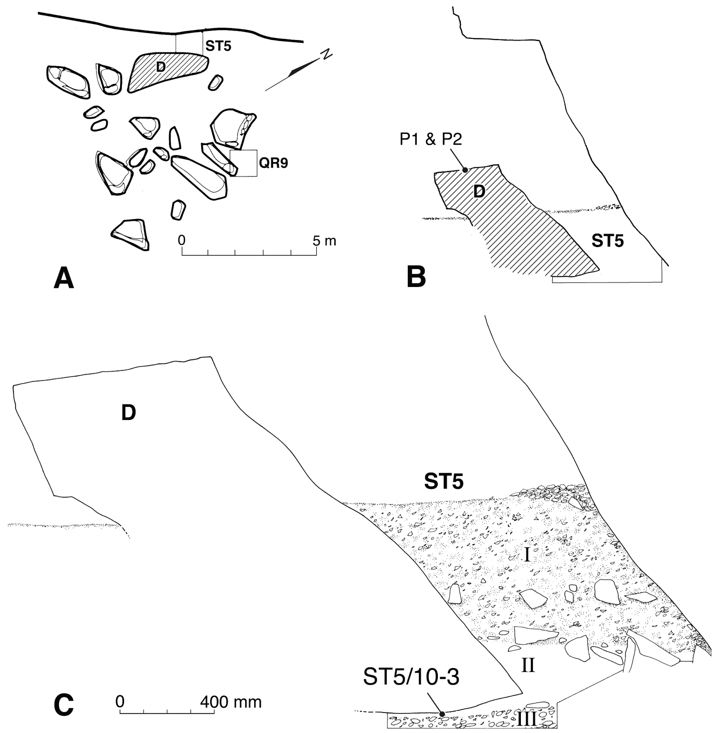

Figure 5. Plan (a) and profile (b) of northern sector of Puritjarra rock shelter, showing the position of Pit ST5 in relation to Block D. Stratigraphic section (c) shows the position of ANU-7460. The sampled engravings are on the upper face of the block (shown in b). Site plans, description of engraved blocks, and ^{14}C chronology have been previously published (Smith, Prescott, & Head, 1997; Rosenfeld & Smith, 2002).

leaving a prominent step (Figure 5b) and must therefore be younger than ANU-7460. Comparison with changes in sedimentation in the rockshelter, and inferred shifts in microclimate and weathering towards more humid conditions within the shelter, indicate that ~8.3 ka is a maximum upper age limit for formation of the oxalate skin covering the surface of Block D (Rosenfeld & Smith, 2002).

BACKGROUND AND METHODS

At Wanga East and Puritjarra, the oxalate skins are thin (<1 mm) compared to those in northern Australia (>1.5 mm) and are restricted to sheltered, sub-horizontal rock surfaces at the rear of these rockshelters. Oxalate skins form where microorganisms, mainly lichen, fungi, or cyanobacteria, excrete oxalic acid ($H_2C_2O_4$), which reacts with calcium in the substrate or in aerosols to form insoluble calcium oxalate CaC_2O_4 (Wiedemann & Bayer, 1988; Pinna, 1993; Monte, 2003). Moisture and temperature regimes control the mineral phase of the precipitate, either monohydrate whewellite ($CaC_2O_4 \cdot H_2O$) or polyhydrate weddellite ($CaC_2O_4 \cdot (2 + x)H_2O$) (Wiedeman & Bayer, 1988). Identification of whewellite in the crusts at Wanga East and Puritjarra was confirmed by XRD.

Strong sunlight and direct sunlight exposure of rock surfaces limits the extent of oxalate formation. On siliceous substrates, the availability of Ca is an additional limiting factor, and wind-blown gypsum ($CaSO_4 \cdot 2H_2O$) is important in the formation of oxalates from oxalic acid ($H_2C_2O_4$). Both Wanga East and Puritjarra are formed in Palaeozoic Mereenie Sandstone, deficient in Ca but open to fine gypsum dust derived from the deflation of an extensive chain of playas to the south (in the center of the Amadeus Basin), transported by seasonal southeastern winds.

Field Sampling

At each site, we sampled oxalate skins within several rock engravings to provide a minimum age for major engraved panels (Figures 3, 4). Because engravings may have been cut through existing oxalate skins. We also sampled rock surfaces away from engravings to establish the age of initiation of oxalate formation at these sites. Each sample was removed by using a diamond-coated tungsten carbide dental drill burr to grind progressively and remove the oxalate from an area 100–400 mm^2. Successive layers were removed separately and the micro-excavated powder was collected on aluminum foil.

Source of Oxalate Carbon

Microcolonial fungi are common on rock surfaces in arid Australia and are the most likely source of the oxalates at Puritjarra and Wanga East (Staley, Palmer, & Adams, 1982). An indirect source of oxalic acid in rainwater can be discounted, as these rock surfaces are not exposed to direct rainfall. Their sheltered position also rules out other common producers of oxalic acid: Cyanobacteria need liquid water for photosynthesis; lichens can use water vapor for photosynthesis but require adequate light and are not found in heavily shaded sites in central Australia. Most desert algae are photobionts in lichens, except where there is standing water. Other bacteria are only minor producers of oxalic acid. No microfossil structures resembling lichen thalli or fungal hyphae were found in the oxalate crusts at Wanga East or Puritjarra.

Unlike lichens and cyanobacteria, fungi rely on carbon fixed by other organisms for metabolism rather than photosynthesis and require an external source of nutrients. This is supplied in this case by a fine film of organic material from seasonal grass and shrub fires, which accumulates on sheltered rock surfaces. At Wanga and Puritjarra, $\Delta^{13}C$ analyses confirm a biological origin of the oxalate. The isotopic composition of oxalates depends on the carbon source utilized by the microorganism and biological fractionation associated with synthesis of oxalic acid. The $\Delta^{13}C$ of biologically derived oxalates should reflect the carbon isotopic signature of the ambient vegetation (a mix of C3 shrubs and

C4 grasses), corrected for growth-dependent fractionation for saprotrophic fungi (6.5‰). Fungal metabolic processes are associated with significant growth-dependent isotopic fractionation, especially in saprotrophic fungi. Fungal biomass is enriched in $\Delta^{13}C$ compared to substrate by 4.6–6.9‰ (during the exponential growth phase), with an average enrichment of 6.8‰ (Henn & Chapela, 2000; Henn, Gleixner, & Chapela, 2002). Exponential growth is sustained only while nutrient levels allow and then declines. Oxalic acid is only produced during the exponential growth phase, and so $\Delta^{13}C$ reflects fractionation during the growth phase. Only minor additional fractionation (0.03–0.6 ‰) takes place in the conversion of oxalic acid to calcium oxalate (Watchman, 2001). Observed $\Delta^{13}C$ values of the oxalate skins at Wanga East and Puritjarra (Table I) range from −7.9‰ to −12.9‰, consistent with this source of carbon.

Radiocarbon Dating

Provided that carbon-bearing phases associated with the oxalate are isolated during pretreatment, oxalate dates have been shown to yield ages that are conformable with other dating methods (Watchman, O'Connor, & Jones, 2005). We used established protocols to selectively target the carbon in the oxalates for radiocarbon assay (Gillespie, 1997; Watchman, 2001; Watchman, O'Connor, & Jones, 2005). For oxalate samples, carbonates and soluble organics were removed by acid hydrolysis. Rapid acidified permanganate oxidation was then used to decompose the oxalate, leaving more slowly oxidizing compounds and detrital charcoal unaffected. The resultant CO_2 was collected, reduced to graphite, and ^{14}C dated using AMS.

RESULTS

Timing of Oxalate Formation

At Wanga East, oxalate had started forming on slab 1 (W3) by ~8.1 ka (Table I). Allowing for time-averaging of our samples due to low rates of skin formation (<0.25 mm/ky), the oxalate on slab 1 started to form as soon as this surface was exposed (~9.3 ka). Dates for the upper part of oxalate skins at both sites (~1.3 ka at Wanga East; ~0.5 ka at Puritjarra) suggest that oxalate continued to form during the last millennium, and is probably forming at these sites today (under a mean rainfall of 250–270 mm p.a.). The formation of oxalate skins in arid Central Australia throughout the Holocene indicates that a high humidity regime is not required for formation of oxalate minerals (for a review of palaeoclimates in arid Australia, see Hesse, Magee, & van der Kaars, 2004). In xeric environments this may depend more on the microorganism involved and supply of gypsum dust in aerosols (Hess et al., 2008; Russ et al., 1996).

Age of the Rock Engravings

AMS ^{14}C dating of the base of oxalate skins formed within the engravings indicates that the engravings at Wanga East were made before ~5.0 ka (differences between W1 and W2 reflect the effects of small differences in time-averaging of samples), with the rock fall event providing an upper age bracket of ~9.3 ka.

Comparison of basal ages for W3 and W1-W2 indicates that engravings were cut into a surface with an existing oxalate skin, perhaps to highlight the engraved motifs. As oxalate was actively forming at this time, the true age of the Wanga East engravings must be ~5–6 ka (allowing for time-averaging of basal oxalate samples).

At Puritjarra, the engravings on Block D were made before ~2.6 ka. As the oxalate skin at this site is thinner (< 0.5 mm) than at Wanga East, time-averaging effects are greater, so we infer that the basal age of the oxalate may be greater than this, with a true age ~4–5 ka. A maximum age limit is provided by the block fall at ~16.1 ka; and if oxalate had been forming (continuously) since that time, then a thick crust should have formed over the entire rock, but this is not observed. The initiation of oxalate formation on the unengraved rock surfaces could not be determined at Puritjarra because of the thin coating and small sample size (Table I) but is unlikely to be >8.3 ka (Rosenfeld & Smith, 2002). If oxalate was actively forming on Block D from 8.3 ka, the actual age of the engravings will be close to the basal age of the oxalate in P1 and P2 (~4–5 ka).

CONCLUSIONS

In a review of the chronological relationships of Australian rock engravings, Franklin (2004: 138) identified Central Australia as a critical area for testing the age of Panaramittee-style engravings. Our results show that the archaic desert engravings at two sites in Central Australia are mid-Holocene in age. Despite a limited range of simple geometric designs and uniformity across the arid interior, this corpus of rock art is not necessarily a late Pleistocene pancontinental tradition but may be a later development reflecting the dynamics of established desert societies. Rather than open social networks, the production of archaic engravings at Wanga East and Puritjarra coincides with population growth in the arid interior around 5 ka and may therefore reflect increasing territoriality amongst hunter-gatherer groups in this marginal environment (Smith et al., 2008). Age estimates for rock engravings in other regions also form a cluster around this time, perhaps indicating a widespread phase of rock art production in the mid-Holocene (e.g., at Ingaladdi at 4.9–6.8 ka; Mulvaney, 1975:188; Franklin, 2004:138). Whatever the case, the relationship between archaic desert engravings and other rock art traditions, including earlier rock engravings in northern Australia (e.g., at Early Man rockshelter; Rosenfeld, Horton, & Winter, 1981), should now be reassessed.

We thank A. Rosenfeld, W. Mumford, and K. Dancey for assistance with rock art drawings and site plans. We especially thank Andrée for access to her earlier work at Wanga East and for her encouragement for this project. Puritjarra rock shelter was excavated by M.A. Smith between 1986 and 1990. Wanga East rock shelter was excavated in May 2006 by M.A. Smith and J. Ross. Our research at Wanga East was supported by AIATSIS Grant G2005/7067 and ARC Grant DP346246, with additional funding from the National Museum of Australia.

Dedication: In memory of Andrée Rosenfeld (1934–2008), friend, mentor, and doyenne of rock art research.

REFERENCES

Basedow, H. (1914). Aboriginal rock carvings of great antiquity in South Australia. Journal of the Royal Anthropological Institute of Great Britain and Ireland, 44, 195–211.
Brown, S. (1991). Art and Tasmanian prehistory: Evidence for changing cultural traditions in a changing environment. In P. Bahn & A. Rosenfeld (Eds.), Rock art and prehistory (pp. 96–108). Oxbow Monograph 10. Oxford: Oxbow Books.
David, B., Chant, D., & Flood, J. (1992). Jalijbang 2 and the distribution of pecked faces in Australia. Memoirs of the Queensland Museum, 32, 61–77.
Dorn, R.I., Nobbs, M., & Cahill, T.A. (1988). Cation-ratio dating of rock-engravings from the Olary Province of arid South Australia. Antiquity 62, 681–689.
Dragovich, D. (1984). Minimum age for desert varnish in the Broken Hill area, NSW: A preliminary estimate. Search, 15, 113–115.
Dragovich, D. (1986). Minimum age of some desert varnish near Broken Hill, New South Wales. Search, 17, 149–151.
Dragovich, D. (2000). Rock engraving chronologies and accelerator mass spectrometry radiocarbon age of desert varnish. Journal of Archaeological Science, 27, 871–876.
Edwards, R. (1966). Comparative study of rock engravings in south and central Australia. Transactions of the Royal Society of South Australia, 90, 33–38.
Edwards, R. (1971). Art and Aboriginal prehistory. In D.J. Mulvaney & J. Golson (Eds.), Aboriginal man and environment in Australia (pp. 356–367). Canberra: Australian National University Press.
Franklin, N.R. (2004). Explorations of variability in Australian prehistoric rock engravings. Oxford: British Archaeological Reports, International Series S1318.
Gillespie, R. (1997). On human blood, rock art and calcium oxalate: Further studies on organic carbon content and radiocarbon age of materials relating to Australian rock art. Antiquity, 71, 430–437.
Henn, M.R., & Chapela, I.H. (2000). Differential C isotope discrimination by fungi during decomposition of C4- and C4-derived sucrose. Applied and Environmental Microbiology, 66, 4180–4186.
Henn, M.R., Gleixner, G., & Chapela, I.H. (2002). Growth-dependent stable carbon isotope fractionation by Basidiomycete fungi: ^{13}C patterns and physiological processes. Applied and Environmental Microbiology, 68, 4956–4964.
Hess, D., Coker, D.J., Loutsch, J.M., & Russ, J. (2008). Production of oxalates in vitro by microbes isolated from rock surfaces with prehistoric paints in the lower Pecos region, Texas. Geoarchaeology, 23, 3–11.
Hesse, P.P., Magee, J.W., & van der Kaars, S. (2004). Late Quaternary climates of the Australian arid zone: A review. Quaternary International, 118–119, 87–102.
Layton, R. (1992). Australian rock art: A new synthesis. Cambridge: Cambridge University Press.
Maynard, L. (1979). The archaeology of Australian Aboriginal art. In S.M. Mead, (Ed.), Exploring the visual art of Oceania (pp. 83–110). Honolulu: University Press of Hawaii.
Monte, M. (2003). Biogenesis of oxalate patinas on marble specimens in fungal culture. Aerobiologia 19, 271–275.
Morwood, M.J. (1984). The prehistory of the central Queensland highlands. Advances in World Archaeology, 3, 325–380.
Morwood, M.J. (2002). Visions from the past: The archaeology of Australian Aboriginal art. Crows Nest, NSW: Allen and Unwin.
Mulvaney, D.J. (1975). The prehistory of Australia, rev. ed. Ringwood, Victoria: Penguin Books.
Pinna, D. (1993). Fungal physiology and the formation of calcium oxalate films on stone monuments. Aerobiologia, 9, 157–167.
Reneau, S.L., Oberlander, T.M., & Harrington, C.D. (1991). Accelerator mass spectrometry radiocarbon dating of rock varnish: Discussion and reply. Geological Society of America Bulletin, 103, 310–314.
Rosenfeld, A. (1990). Rock art in Watarrka National Park: Report on fieldwork in the Watarrka National Park 1990. Unpublished report to the Conservation Commission of the Northern Territory, Alice Springs.
Rosenfeld, A. (1991). Panaramittee: Dead or alive? In P. Bahn and & A. Rosenfeld (Eds.), Rock art and prehistory (pp. 136–144). Oxbow Monograph 10. Oxford: Oxbow Books.

Rosenfeld, A. (2002). Rock-art as an indicator of changing social geographies in Central Australia. In B. David & M. Wilson (Eds.), Inscribed landscapes: Marking and making place (pp. 61–78). Honolulu: University of Hawaii Press.

Rosenfeld, A., & Smith, M.A. (2002). Rock-art and the history of Puritjarra rock shelter, Cleland Hills, Central Australia. Proceedings of the Prehistoric Society, 68, 103–124.

Rosenfeld, A., Horton, D., & Winter, J. (1981). Early man in north Queensland. Canberra: Terra Australis 6, Australian National University.

Ross, J. (2003). Rock art, ritual and relationships. Unpublished Ph.D. thesis, University of New England, Armidale, NSW, Australia.

Russ, J., Palma, R.L., Loyd, D.H., Boutton, T.W., & Coy, M.A. (1996). Origin of the Whewellite-rich rock crust in the lower Pecos region of southwest Texas and its significance to palaeoclimate reconstructions. Quaternary Research, 46, 27–36.

Smith, M.A., Prescott, J.R., & Head, M.J. (1997). Comparison of ^{14}C and luminescence chronologies at Puritjarra rock shelter, Central Australia. Quaternary Science Reviews, 16, 299–320.

Smith, M.A., Williams, A.N., Turney, C.S.M., & Cupper, M.L. (2008). Human-environment interactions in Australian drylands: Exploratory time-series analysis of archaeological records. The Holocene, 18, 397–409.

Staley, J.T., Palmer, F., & Adams, J.B. (1982). Microcolonial fungi: Common inhabitants on desert rocks. Science, 215, 1093–1095.

Stuiver, M., & Reimer, P.J. (1993). Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon, 35, 215–230.

Watchman, A.L. (1991). Age and composition of oxalate-rich crusts in the Northern Territory, Australia. Studies in Conservation, 36, 24–32.

Watchman, A. (2000). A review of the history of dating rock varnishes. Earth Science Reviews, 49, 261–277.

Watchman, A. (2001). Dating oxalate minerals in rock surface deposits. In M. Jones & P. Sheppard (Eds.), Australasian connections and new directions: Proceedings of the 7th Australasian Archaeometry Conference (pp. 401–411). Auckland: University of Auckland, Research Papers in Anthropology and Linguistics 5.

Watchman, A., O'Connor, S., & Jones, R. (2005). Dating oxalate minerals 20–45 ka. Journal of Archaeological Science, 32, 369–374.

Wiedemann, G., & Bayer, G. (1988). Kinetics of the formation of whewellite and wedderlite by displacement reactions. Journal of Thermal Analysis, 33, 707–718.

Received 30 April 2008
Accepted for publication 21 October 2008
Scientific editing by Marshall Weisler