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ORIGINAL PAPER

Early silcrete heat treatment in Central Australia: Puritjarra and Kulpi Mara

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Abstract
Heat treatment of stone for tool making has important implications for our understanding of the early human history of the Australian continent. New data on the antiquity of Australian heat treatment and its evolution through time in different regions have posed questions about the origin and temporal stability of technical practices. In this paper, we present the first evolutionary sequence of the use of heat treatment in Central Australia, with a trend to lower levels of heat treatment over time. Different trends are found in other regions across Australia: on the eastern seaboard, heat treatment became more prevalent over time, while in the inland, semi-arid Willandra lakes region heat treatment gradually disappeared over time. In central Australia, the long-term trend is towards fewer heat-affected specimens over time, but this happens in a single transition from stable high levels in the Pleistocene to stable moderate levels in the Mid- to Late Holocene. These evolutionary trends are consistent with regional diversification, reflecting adaptations to local conditions, and are not consistent with technological uniformity across the continent.

Keywords Early Australian pyrotechnology · Modern behaviours · Lithic technology · Raw material transformation · Surface roughness analysis

Introduction

Stone heat treatment for tool knapping plays an increasingly important role in our understanding of early modern behaviours (Sealy 2009), technological complexity (Stolarczyk and Schmidt 2018) and cognitive processing (Wadley 2013). The earliest examples involve continental rock silcrete and date to the second half of the southern African Middle Stone Age (Brown et al. 2009; Schmidt et al. 2020). Silcrete is also an important rock for making artefacts in Australia and early silcrete heat treatment may be of similar importance there. While the research on heat treatment has a comparatively long history in Australia (see among others Flenniken and White 1983; Hanckel 1985), we still know relatively little about the evolution of its prevalence in different regions. Recently, two studies, on a 25-ka-long sequence in the Sydney area (Schmidt and Hiscock 2019) and on the ~40-ka-long sequence at Lake Mungo and the Willandra lakes (Schmidt and Hiscock 2020), uncovered an intriguing picture. On the eastern seaboard, the proportion of all silcrete artefacts that were heat-treated rose continuously from around 25 ka BP to its largest values in the terminal Holocene. The opposite happened in the semi-arid environment of the Willandra Lakes, where heat treatment in the oldest assemblages was prevalent and evolved continuously towards very low values through time. This observation reveals there is no continent-wide evolutionary trend, but instead a series of local ones, posing questions about how heat treatment evolved in other regions and what causes the different evolutionary pathways?

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To pursue these questions, we conducted a similar study on a third region, in Central Australia, where we examined two sites with long sequences: Puritjarra Rock Shelter and Kulpi Mara (locations in Online Resource Fig. S1). These two sites offer a key window onto the Pleistocene occupation of the arid centre of Australia.

Methods and materials

The Puritjarra deposits yielded three geological layers I, II and III, although only I and II produced artefacts (Smith 2006). Within those two layers, Smith (2006) constructed analytical units: 1a, 1b, 1c, 2a, 2b and 2c (2c represents the base of the sequence at > 32 ka BP). We only found silcrete artefacts in units 1a to 2a (ages summarised in Table 1). Of those, we inspected all > 3 mm from squares: M10, 11 and N5, 9, 10, 11, 12, 13, 18 (these are the squares that were excavated down through the site's entire sequence). We aimed to analyse 100 pieces per analytical unit, but we did not want to arbitrarily select the specimens for analysis, and so when an excavation bag contained more than 100 pieces, we analysed them all, producing slightly higher counts in the upper units. This did not occur in unit 1c and below as the lower units had fewer silcrete artefacts. At Kulpi Mara (KM) Rock Shelter 13, we analysed the three layers excavated by Thorley (1998). This sequence dates back to at least 30–35 kya, with much higher chronological resolution in the Pleistocene levels than in the Holocene (ages summarised in Table 1). All silcrete artefacts > 3 mm from KM 13 were analysed.

Methods used to assess the quantity of heat-treated artefacts are described in detail in Schmidt (2019) and in the Online Resource file. In brief, we employ two steps: (1) a visual classification of heating proxies distinguishing *pre-heating removal scars* (Fig. 1a, f), which are fracture scars resulting from knapping of unheated silcrete, from *post-heating removal scars* (Fig. 1b, e), which result from knapping of heat-treated silcrete. This distinction is based on identifying what we call *diagnostic pieces*, which are artefacts that contain pre- and post-heating scars documenting pre- and post-heating knapping on a single artefact. Artefacts that have only one type of scars are then compared with the known scars on diagnostic pieces to decide whether these are pre- or post-heating scars. The second step (2) consisted of making surface roughness measurements on some artefacts to verify the visual classification, using the replica tape method (Schmidt 2019). This non-destructive method produces quantitative values on the surface roughness of fracture scars, allowing to identify them as either pre- or post-heating scars. Graphs produced by replica tape roughness measurements display two statistics (extracted from the raw roughness data): natural logarithm of mean roughness Ln(Ra) and the information entropy (S) of the surface height distribution which expresses disorder in the roughness profile. Both values are displayed in plots so that rougher fracture scars from knapping unheated silcrete plot in the upper right corner and smoother scars from knapping of heated silcrete in the lower left (Fig. S2). This was done for 70 silcrete artefacts from analytical unit 1a at Puritjarra. If the results of our visual classification and replica tape measurement for this unit are comparable, we will conclude that our visual classification on our overall sample is likely to be robust with minimal misclassification.

Results and discussion

Our visual classification of heating proxies on silcrete artefacts reveals robust evolutionary trends in the use of heat treatment in Central Australia. The results are presented in Table 1, data on heat-treated flakes and retouched artefacts

Table 1 Relative prevalence of heat-treated silcrete in the analysed stratigraphic units at Puritjarra and Kulpi Mara, as determined by the visual determination of heating proxies. Percentages calculated as the piece count (*n*) divided by the total of all analysed pieces. Percentages in parenthesis are calculated to the base of all heat-treated pieces. Age estimates for units at Puritjarra from Smith (2006) and for layers at Kulpi Mara from Thorley (1998)

	Estimated age	Analysed pieces	Heat treated:		Not heated		Diagnostic pieces	
		n	*n*	%	*n*	%	*n*	%
Puritjarra unit 1a	~ 0–800 BP	108	52	48	56	51	24	22 (46.2)
Puritjarra unit 1b	~ 800–3500 BP	105	51	49	54	51	22	21 (43.1)
Puritjarra unit 1c	~ 3500–7500 BP	52	25	48	27	52	6	12 (24)
Puritjarra unit 2a	~ 7500–18,000 BP	31	23	74	8	26	8	26 (34.8)
Kulpi Mara layer 1	2580 ± 111 cal BP	61	33	54	28	46	12	20 (36.4)
Kulpi Mara layer 2	14,163 ± 407; 15,407 ± 667 cal BP	45	30	67	15	33	10	22 (33.3)
Kulpi Mara layer 3	28,322 ± 1484; 33,850 ± 322 cal BP	12	8	67	4	33	3	25 (37.5)

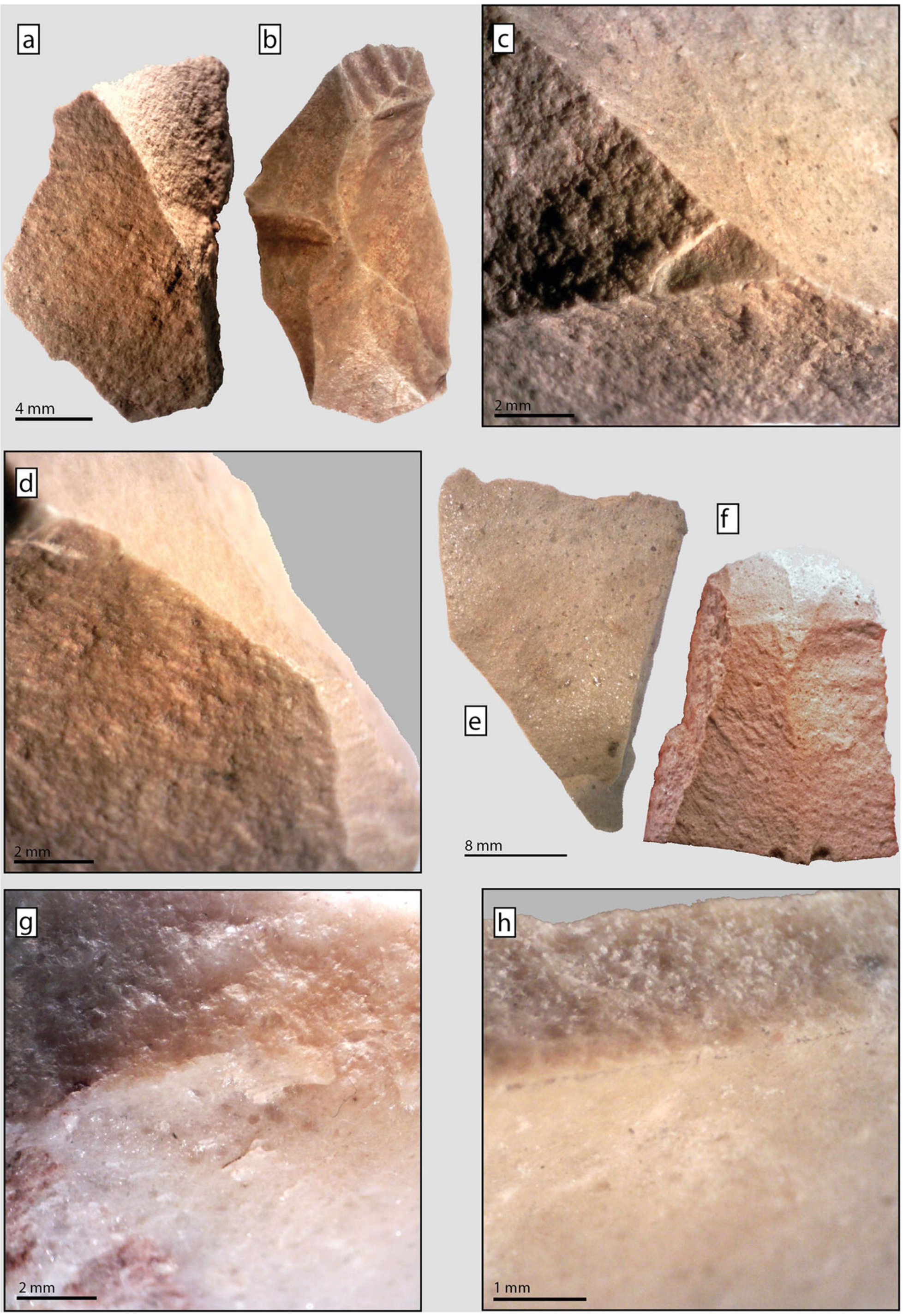

Fig. 1 Heat-treated and unheated silcrete artefacts from Puritjarra and Kulpi Mara. **a** Unheated flake Puritjarra unit 1a; **b** heat-treated flake Puritjarra unit 1a. 4 -mm scale bar only for those 2 photos. Note the difference in the smoothness of the fracture surfaces on both artefacts. **c**, **d** Details on 2 silcrete flakes showing roughness contrast between rough pre-heating scars and smoother post-heating scars, Puritjarra unit 1a. **e** Heat-treated flake from Kulpi Mara Split 27 of square B (layer 3); **f** unheated flake from Kulpi Mara Split 4 of square C (layer 1). 8-mm scale bar only for those 2 photos. **g**, **h** Details on 2 Kulpi Mara silcrete flakes showing roughness contrast: **g** split 10 of square A (layer 2) and **h** spit 1 of square A (layer 1)

are in the online resource file. Only a small proportion of specimens were indeterminate during visual inspection, 6% at Puritjarra (*n* = 18) and 15% at Kulpi Mara (*n* = 21). The relative abundance of diagnostic pieces in this analysis is comparable to previously published values from similar studies in Australia (Schmidt and Hiscock 2019; Schmidt and Hiscock 2020). An indicator of the quality of our visual classification comes from the replica tape analysis of 70 silcrete artefacts from Puritjarra unit 1a. Raw data obtained by this analysis are summarised in Table S1 of the Online Resource and graphically shown in Fig. 2. Of 70 specimens, 39 (55.7%) were found to be heat-treated, while 30 of 70 pieces (42.9%) were found to be unheated, with only 1 (1.4%) indeterminate. This is in agreement with our visual classification of heat-treated pieces in unit 1a that resulted in 48% heat-treated and 51% unheated pieces. Greater agreement between replica tape and

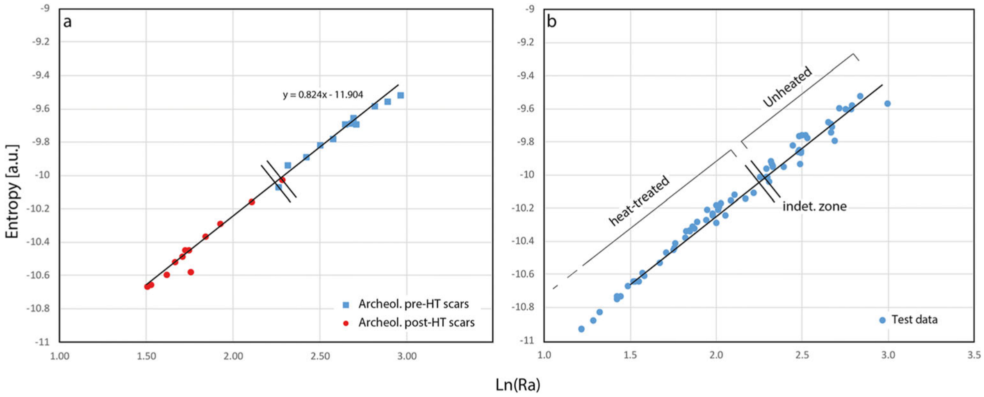

Fig. 2 Plots of the entropy *S* and logarithmic mean roughness Ra values of archaeological samples from Puritjarra unit 1a. **a** plot of 24 known pre- and post-heating surfaces on diagnostic artefacts and their linear best fit. Black lines mark the overlap zone in which pre- and post-heating scars plot. The lower and upper boundaries of the indeterminate zone [in Ln(Ra) at the intersection of the fitted function] are 2.26 and 2.28. Note that both pre- and post-heating surfaces can be distinguished at the two extremities of the scatter plot. **b** plot of 70 archaeological test samples onto the reference function and indeterminate zone of **a**

visual classifications was reported in previous studies (Schmidt and Hiscock 2019; Schmidt and Hiscock 2020) but our data from both approaches still agree within less than 10%. The quality of this replica tape roughness data is expressed by the mean distance of all test data dots from their fitted function in Euclidean distance in the scatter plot. It is 0.029. This value is in good agreement with previous studies (0.022 as recalculated from Schmidt (2019); 0.02 from Schmidt and Hiscock (2019) and 0.027 from Schmidt and Hiscock (2020)). Thus, our estimation of heat-treated pieces throughout the sequences at Puritjarra and Kulpi Mara can be regarded as correct within less than 10%.

An evolutionary trend in heat treatment of silcrete artefacts at Puritjarra and Kulpi Mara is clear (Fig. 3). Pleistocene assemblages consistently had higher levels of heat-treated artefacts than Holocene assemblages. The trend line is shown in Fig. 3b, with Pleistocene levels having 65–75% heat treated while later levels have 45–55% (a difference greater than the 10% measurement error). The frequency of heat treatment in these two time periods is significantly different ($t = 7.566$, d.f. = 5, $p = 0.001$), and within each period the frequencies display consistent levels of heat treatment: either high (in the Pleistocene or very early Holocene) or lower (in that later Holocene). We conclude that heat treatment was consistently used throughout the 35,000 years sequences available from Central Australia but was emphasised more in the Pleistocene. Declining rates of heat treatment are present and strong in both sequences, although the decline is slightly more pronounced at Puritjarra than at Kulpi Mara.

There are three noteworthy points about the evolution of silcrete heat treatment practices in Central Australia. The first is that the evolutionary trend in the Centre is not identical with those described from other regions within the continent, illustrating the local responsiveness of cultural systems in Australia to regionally different selective pressures. In Central Australia, the two long-term sequences we present here demonstrate persistent and moderately frequent use of heat treatment on worked silcrete for more than 35 ka, but they also reveal clear reduction over time in the use of heat treatment in stone working, from high to moderate levels of treated artefacts. However, the reduction over time in Central Australia, while statistically significant, is not as dramatic as it

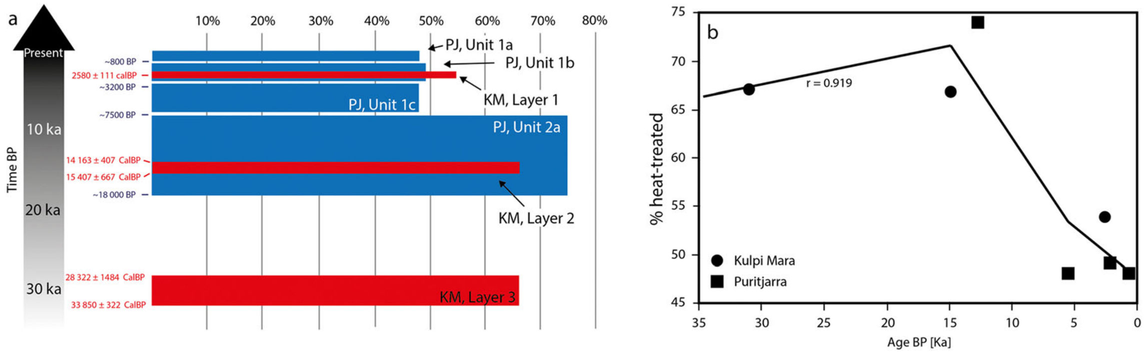

Fig. 3 Histogram (**a**) and plot (**b**) comparing the relative prevalence of heat treatment in the silcrete components of Puritjarra (PJ) and Kulpi Mara (KM) as a function of time from the oldest at the bottom to the youngest at the top. The thickness of the bars in **a** is not representative of duration or continuous occupation but of the uncertainty concerning the assemblages' age. The line of best fit in **b** is a lowess curve ($r^2 = 0.846$)

was in the semi-arid landscape of the Willandra Lakes, 750 km to the east. There, silcrete heat treatment frequencies reduced from similar Pleistocene rates to very low rates in the Holocene (at 42 ka, > 60% of the silcrete was heated, in the terminal Holocene < 10%, see Schmidt and Hiscock 2020). Hence, while Central Australia and the Willandra region shared a direction of evolutionary change, heat treatment remained a common practice in the centre of the continent, whereas in the Willandra, it became a rare element in the knapping repertoire. A quite different trend is evident on the south-eastern seaboard of Australia, where a sequence spanning over the past 25 ka documented an increasing prevalence of heat treatment through time (at 25 ka, 50% of all silcrete was heated; in the terminal Holocene > 80%, see Schmidt and Hiscock 2019). Variation in direction and magnitude between these regions demonstrates that there was no uniformity in the evolution of these practices over time, but rather there was geographical diversification in technological practices, from relatively similar heat treatment frequencies in the older periods (i.e. 25–35 ka) to extremely different rates of heat treatment in each region in the Late Holocene.

A second point about the heat treatment in Central Australia is that current data indicate two distinct phases, each varying little over time but with a small (though significant) change from one phase to another. Figure 3 b plots the regional sequence using the age mid-point of stratigraphic units, making the timing of assemblages appear precise, but the units in Puritjarra are not well defined chronologically (compare Fig. 3a). Hence, the boundary between the two phases is currently not well defined, largely because of uncertainty in dating unit 2a at Puritjarra. Our data do not preclude that the switch between phases might correspond to the Pleistocene/Holocene transition and be associated with economic shifts at that time. However, the evidence is not clear on that point.

Nevertheless, the evidence supports the idea that the evolutionary trend involved a single switch between technological systems that were stable over the long term. We suggest the selective context that elicited that state switch may have involved altered costs of raw material procurement, perhaps associated with alterations in the pattern or timing of foraging trips, or even altered tooling strategies. Similarly, there is no good evidence for an association between the trend in heat treatment and alterations in technology. In discussing Puritjarra, Smith (2006) argues that core reduction and flaking methods were similar throughout the sequence while he sees shifts in raw material procurement and implements typology only in the Late Holocene. A metrical study of retouching by Law (2009) concluded that reduction intensity also increased in the Late Holocene. None of those technological shifts correspond with the earlier state switch in heat treatment, indicating that heat treatment and specific technological patterns are not tightly associated in Central Australia. More economic and technological data from the region would be required to construct detailed models but current evidence indicates the evolutionary trend in Central Australian heat treatment is not simply linked to particular technological treatments.

The third point we can make is that it might be possible to explain at least some aspects of the heat treatment-related patterns in different regions by the availability of other raw materials. Besides silcrete, Puritjarra and Kulpi Mara yielded a consistent amount of chert throughout their sequences (Smith 2006; Thorley 1998). It has been argued that chert heat treatment requires different conditions than silcrete (compare Schmidt et al. 2017; Schmidt et al. 2016) but it is also possible that the presence of chert along with silcrete had an influence on the prevalence of silcrete heat treatment (this argument has been made in another context, see Schmidt and Mackay 2016). Furthermore, if chert was also heat treated in central Australia, changing silcrete heat treatment practices might be understood in the context of the procurement, heat treatment and usage of this material. When sorting artefacts from Puritjarra and Kulpi Mara, we observed the presence of heat-treated chert as well as silcrete (Fig. 4). We identified chert artefacts with diagnostic contrast between rough and smooth pre- and post-heating scars throughout the sequences at both sites, providing evidence that part of the chert component at both Central Australian sites was heat treated. This was unexpected, as none of the other two Australian sequences mentioned above (Schmidt and Hiscock 2019; Schmidt and Hiscock 2020) had provided evidence of chert heat treatment. The implications of this finding should be the subject of a dedicated study on chert heat treatment but it appears clearly that the cost of obtaining, and success in modifying, alternate lithic material will help us understand the economic context of silcrete heat treatment.

Conclusion and implications

In Central Australia, the reduction over time in the rate of heat treatment practices is a sequence that offers us new insights into technological evolution and regional diversification within Australia. In the past, models of technology in Australia commonly depicted uniformity and simplicity at earlier (Pleistocene) times, and regional differentiation in technology or culture was often understood as mid- or later Holocene (Hiscock 2008). While this may be true for heat treatment in some regions (see for example Maloney and Street 2020), our findings explore these concerns about uniformity, regionalism and chronology with surprising results. This paper reports on the third of three regional sequences of heat treatment spanning into the Pleistocene that is now known from Australia (Schmidt and Hiscock 2019; Schmidt and Hiscock 2020). We know that the sequence of heat treatment is different for each region, diverging over time, in response to differing

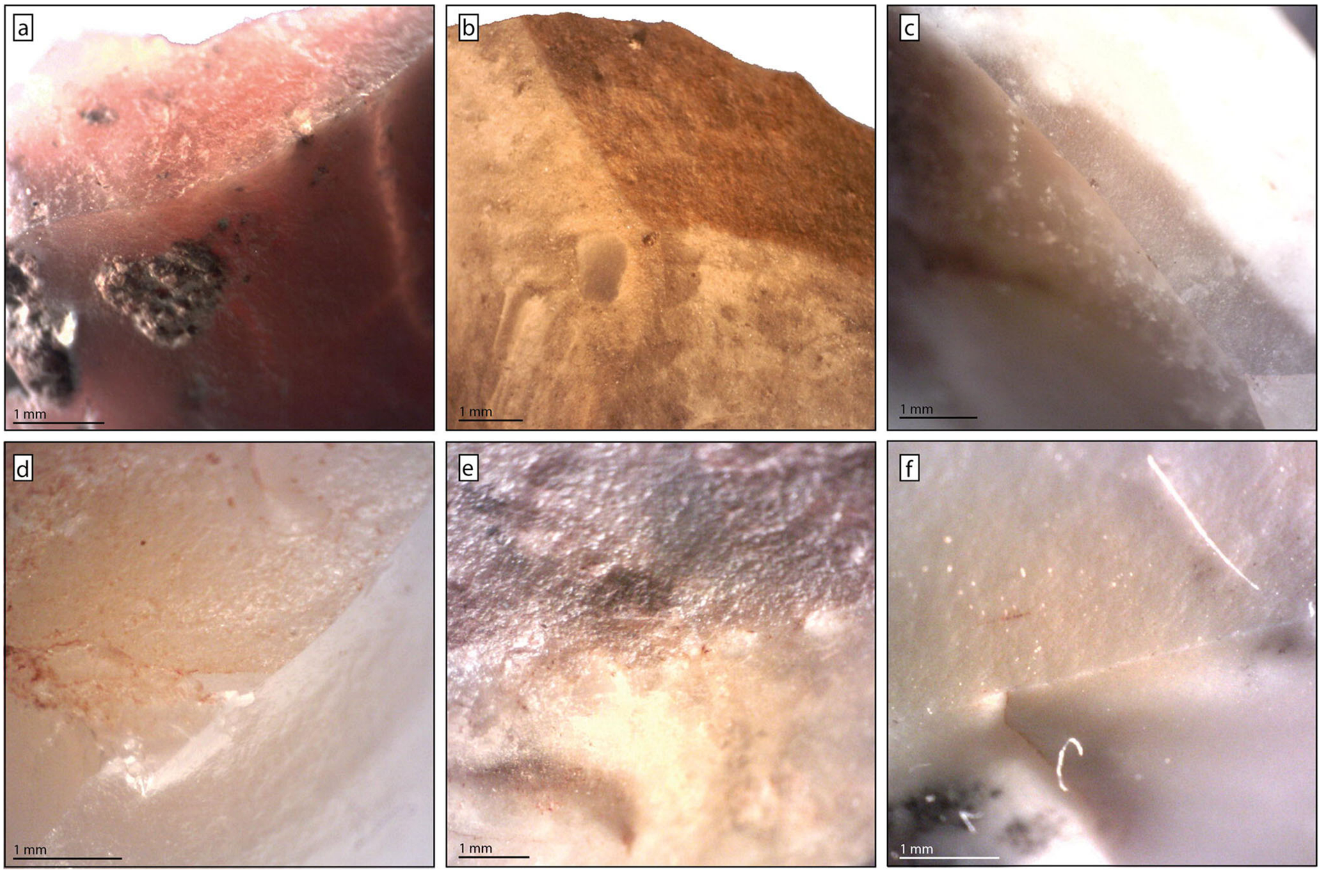

Fig. 4 Heat-treated chert lithics from Puritjarra and Kulpi Mara with roughness contrast. **a** Detail on a chert flake showing roughness contrast between rough pre-heating scars (top) and a smoother post-heating scar (bottom), Kulpi Mara Split 28 of square B (middle of layer 3 ~ 27–34 ka BP); **b** detail of roughness contrast on a flake from Kulpi Mara Split 3 of square B (middle of layer 1 ~ 2.4–2.7 ka BP) and **c** from Kulpi Mara Split 20 of square A (top of layer 3 ~ 27–34 ka BP); **d**, **e** detail of roughness contrast on flakes from Puritjarra unit 1a (~ 0–800 BP) and **f** from Puritjarra unit 1b (~ 0.8–3.5 ka BP)

conditions in each locality. Since the evolutionary trend in Central Australia is not identical with those described from other regions within the continent, we conclude there is no continental pattern shared by them. The regional patterns are distinct with heat treatment practices changing in opposite directions: increasing in some regions and decreasing in others. What is shared is that regional diversification in evolutionary trends was of substantial time depth, being initiated and distinct by the terminal Pleistocene at the very least. This indicates that technological reorganisation, and the development of different trajectories of technological evolution, was occurring over extended time periods. We have also shown that heat treatment practices in each region evolved at different rates, presumably in response to local selective pressures. While Schmidt and Hiscock (2019) showed that there was a reasonably continuous change on the eastern seaboard, this paper has demonstrated a stadial pattern in Central Australia, with current data indicating two distinct phases, each varying little over time but with a significant change from one phase to another. This reveals that not only is there evidence for long-term regional diversification of technology, in different directions and to different degrees but also that those evolutionary patterns happened at regionally different rates, implying not only different selective pressures but perhaps also different articulations of the technological systems in each region. These observations highlight the diversity of temporal trajectories of lithic technology in different regions across Australia. They call for more expansive investigations of other heat treatment-related behaviours on the continent, including research into the techniques that were used for heat treating rock and the relative costs and benefits of the investment it represented.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interests.

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