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World's earliest ground-edge axe production coincides with human colonisation of Australia

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ABSTRACT
We report evidence for the world's earliest ground-edge axe, 44–49,000 years old. Its antiquity coincides with or immediately follows the arrival of humans on the Australian landmass. Ground/polished axes are not associated with the eastward dispersal of *Homo sapiens* across Eurasia and the discovery of axes in Australia at the point of colonisation exemplifies a diversification of technological practices that occurred as modern humans dispersed from Africa. Ground-edge axes are now known from two different colonised lands at the time humans arrived and hence we argue that these technological strategies are associated with the adaptation of economies and social practices to new environmental contexts.

ARTICLE HISTORY
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Introduction

We announce evidence of ground-edge axe production in northern Australia between 44,000 and 49,000 years ago. This is the earliest evidence of a ground-edge axe yet reported in the world, and the antiquity of axe production it reveals has implications for both the dispersion of modern humans out-of-Africa and the nature of the first human occupation of Australia.

Early manufacture of ground axes in Australia is challenging because Pleistocene Australian stone lithic industries have persistently been characterised as extremely and uniformly simple, comprising unstandardised, expedient, tools. This depiction of Antipodean technology prompted claims that humans dispersing from Africa carried with them an ancestral 'mode 3' or 'pre-blade' technology based on 'prepared' cores and flakes (Foley and Lahr 1997) or alternatively that the 'simple' technologies of early Australia resulted from a loss of technological diversity and complexity during the dispersal (Mellars 2006). Some recent models still accept the story of a 'simple' and unvarying technology in Pleistocene Australia and seek to explain it in terms of an unvarying narrow diet breadth by colonists (O'Connell and Allen 2012). And yet evidence for the production of expensive, long-lived/curated, hafted, polished, ground axes in Australia's Pleistocene shows that early lithic technological strategies cannot be characterised in this way (see Balme and O'Connor 2014; Balme et al. 2009; Hiscock 2008; Kamminga 1978; White 1977).

Previous research reported ground-edge axes across much of northern Australia during the terminal Pleistocene, at Widgingarri 1 and Carpenter's Gap 1 and 3 in the Kimberley region of Western Australia (O'Connor 1999; O'Connor et al. 2014), in western Arnhem Land at Malanangerr, Nauwalabila 1, Nawamoyn, and Nawarla Gabarnmang (Geneste et al. 2010; Jones 1985; Schrire 1982; White 1967), and at Sandy Creek on Cape York (Morwood and Trezise 1989) (see Figure 1). These Australian ground-edge axes were invented locally. Production of ground edge axes is absent in islands to the north of Australia until the Neolithic and there is no evidence that this technology was introduced to the continent. The questions that have been unanswered until now are when were axes invented, and how did that invention relate to the colonisation process? Here we present evidence for production of axes close in time to the colonisation of Australia.

Because axes are long-lived tools they are not abundant in assemblages. Thus the chronology of early axe production cannot be based solely on the recovery of whole axes, which are rare, and instead depends on the presence in well-dated excavations of flakes removed from the ground bevels of axes during the reshaping and repair of damaged and worn edges. This has been the basis for identifying axes dated to 35,000 BP in Australia (Geneste et al. 2010). Suggestions of the presence of even older axes at

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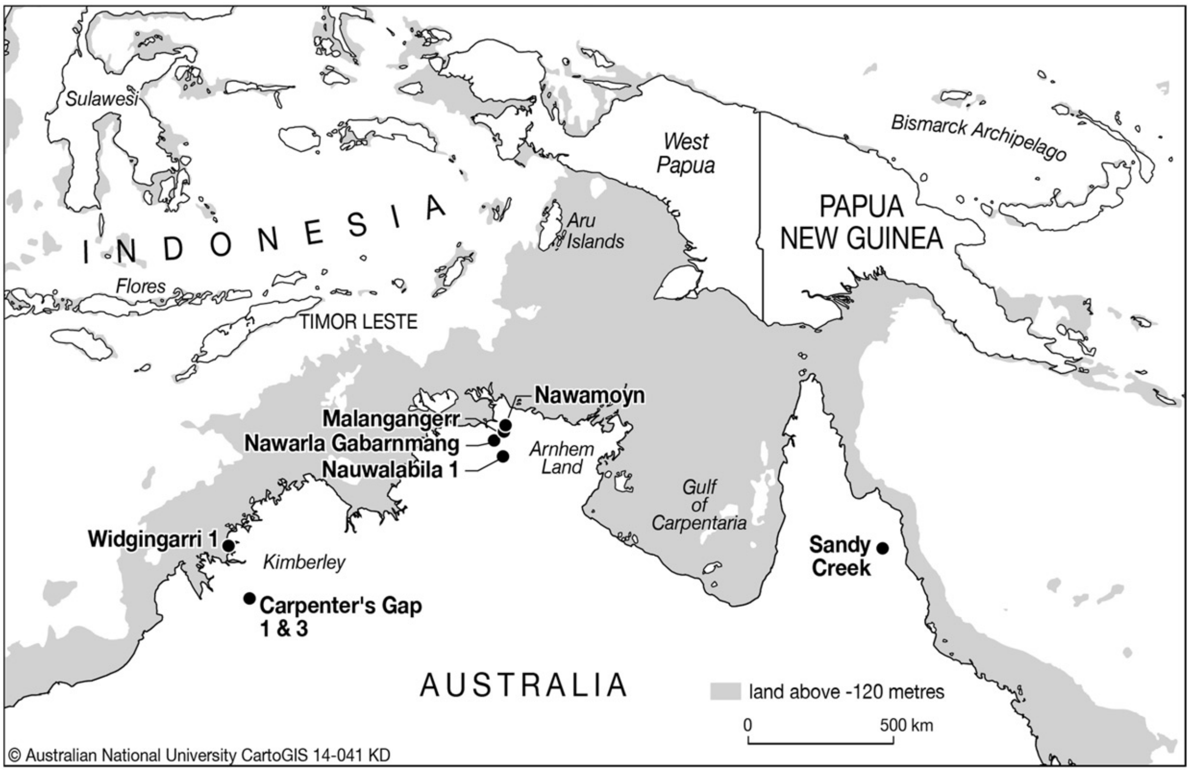

Figure 1 Map of northern Australia in its regional setting, showing the location of Carpenter's Gap 1 and other sites with Pleistocene axes.

Madjedbebe have been based on the presence of small flakes of volcanic material in sediments dated to more than 40,000 BP (Clarkson et al. 2015). However, we are cautious of this interpretation because the flakes do not have diagnostic ground bevels (Clarkson et al. 2015:173). Repair of a bevel often involved the removal of a number of flakes before the edge could be re-ground, and the repair cycle might be repeated several times, creating, by an order of magnitude more ground flakes than axes deposited into the archaeological record. Hence it is the polished bevel that defines specimens as ground-edged axes, and reshaping flakes that remove the bevel are as identifiable as the complete axe. The angle of ground bevels ranges between 60° and 100° (Dickson 1981:104), and edge characteristics can vary significantly during the life of the axe as multiple uses and repairs take place (Kononenko et al. in press). This range of angles overlaps with those produced in core reduction, making them unreliable as a sole diagnostic trait. The only morphological feature that is unique to axes is the highly polished ground surface. These smoothed surfaces are created by extensive abrasion with another rock and cannot be incidentally produced by other knapping actions such as platform preparation. Grinding basalt to a polished bevel has been experimentally shown to take 1.5–5 h depending on the character of the base stone and abrasive agent being used (Dickson 1980). Even in optimal conditions hundreds of forceful strokes are required to create the smoothed bevel. Our experiments and comparative measurements confirm this proposition and indicate that while ground surfaces vary in smoothness, they are always measurably far smoother than fracture surfaces (see below). We therefore use convergent bevels with high surface smoothness created by extensive abrasion as the key indicator of axes, and we apply this to the identification of small bevel reshaping flakes from axes.

In recent years, discoveries of such flakes have demonstrated that axes were made in Australia at least 30–35,000 years ago (Geneste et al. 2010; Jones 1985; Morwood and Trezise 1989; O'Connor 1999; O'Connor et al. 2014). However, evidence presented here from Carpenter's Gap Shelter 1 demonstrates that ground-edge axes were made in northern Australia more than ten millennia earlier. This is the earliest evidence of ground-edge axes yet reported in the world, and reveals that the first Australians were technological innovators who developed grinding and abrading as techniques with which to shape a range of new implements including hafted ground-edge axes. After describing the evidence from Carpenter's Gap 1 we argue that this kind of innovation arose as dispersing humans created regional traditions as part of their adaptations to new landscapes.

Carpenter's Gap Shelter 1

Carpenter's Gap 1 (CG1) is one of the oldest known habitation sites dated by the radiocarbon technique in Australia (Figure 2). It was first excavated over

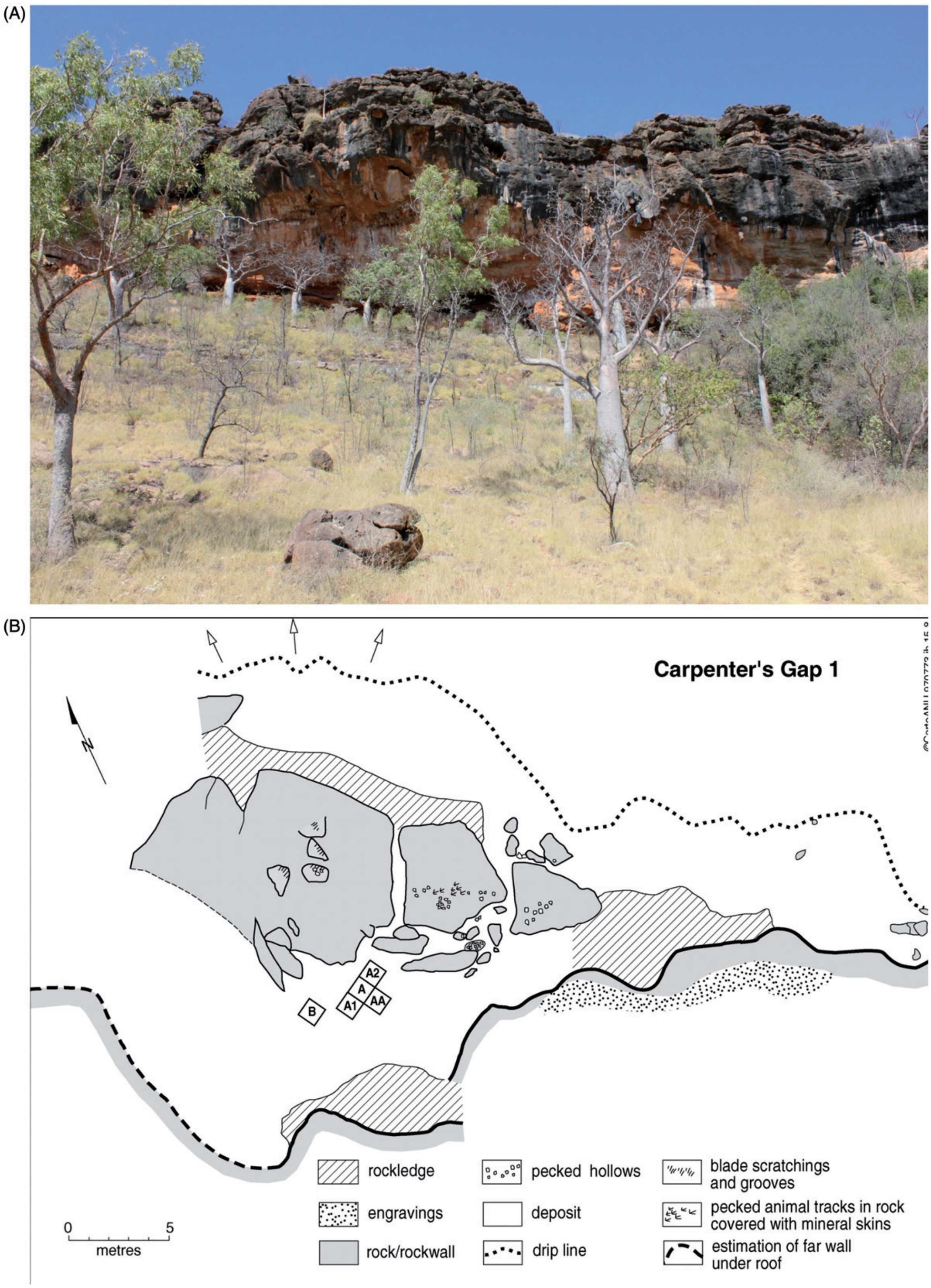

Figure 2 Carpenter's Gap 1. (A) Photograph of shelter. (B) Site plan showing the square A2.

two field seasons in 1992 and 1993 when five 1 m square test pits were dug to bedrock (Frawley and O'Connor 2010; O'Connor 1995). The artefactual material discussed in this paper comes from square A2, close to the large rockfall that has served to trap the deposit within the upper part of the shelter (Figure 2). In this site excavation units averaged 2 cm in depth but were dug within depositional units. For example, a hearth 10 cm in depth would be removed separately from other sediments, treated as one stratigraphic context, but would be subdivided into excavation units of 2 cm depth to enhance assessments of provenience.

The shelter contains an upper Holocene-aged deposit overlying Pleistocene-aged sediments dating from ∼49,000 cal. BP through to ∼18,000 cal. BP.

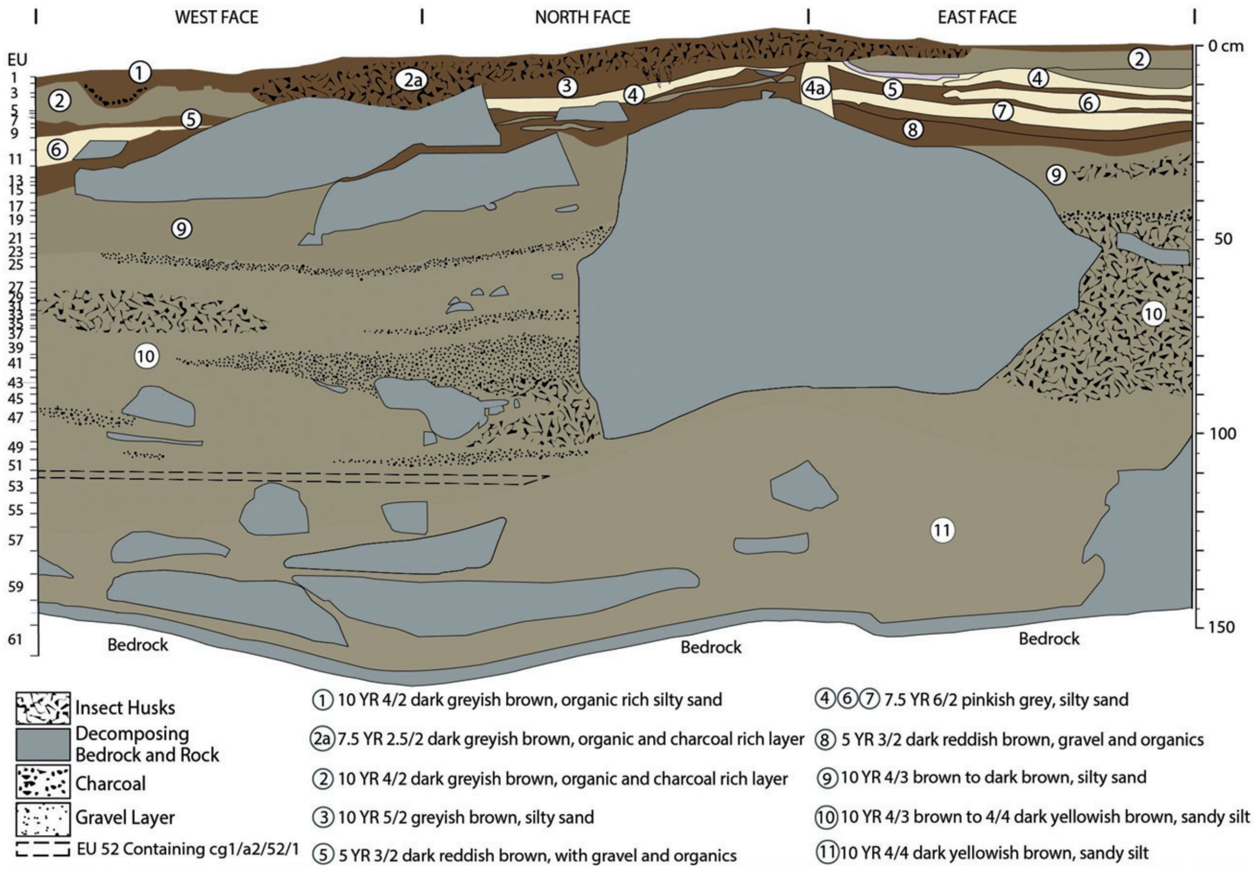

Figure 3 Stratigraphic section of Square A2 in Carpenter's Gap 1.

The sediments have accumulated primarily as a result of in situ weathering of layers of softer sedimentary rocks embedded in the limestone reef from which the shelter is formed, with the addition of an aeolian component (Vannieuwenhuyse et al. in press). Figure 3 presents the section drawing for square A2. Holocene assemblages are restricted to layers 1–4, and most of the deposit had accumulated before the LGM. Cultural material was deposited throughout, beginning in excavation unit 61, significantly below the 44–49,000 cal. BP date. The lowest axe fragment came from excavation unit 52, near the base of the cultural sequence.

The specimen recovered from unit 52 in Square A2 is designated cg1/a2/52/1 and referred to here as Carpenter's Gap Axe Flake 1. A charcoal sample from the same unit is dated to 48,875–43,941 cal. BP (WK-37976). We argue that the axe fragment and the dated charcoal fragment are stratigraphically associated and that this represents evidence of axe grinding technology being employed to manufacture axes at or immediately after the arrival of people in Australia.

The chronological integrity of early assemblages in Australia has been questioned by Allen and O'Connell (2003, 2014) and O'Connell and Allen (2004), who argue that post-depositional relocation of older specimens has placed them in a false association with early radiometric age-estimates. Although their critique is overdrawn (Hiscock 2013), the possibility of movement should be examined for each deposit. To evaluate whether the Pleistocene assemblages at CG1 were affected by vertical displacement we looked for size-sorting of artefacts within the lower deposit. This is a well-established test of post-depositional movement of materials within archaeological deposits, with a variety of processes acting to lower small specimens and/or raise larger ones (Bocek 1986; Cahen and Moeyersons 1977; Hofman 1986; McBrearty 1990; Schiffer 1987; Stockton 1973; Wood and Johnson 1978). We therefore predicted that, if there had been significant vertical movement that involved displacement of specimens into unit 52 from higher in the deposit, there would be smaller specimens in that and adjacent levels than in immediately higher ones. To this end we examined the relationship between depth and artefact size for specimens in excavation units 45-60, representing MIS3 – the period before the last glacial maximum. Using univariate GLM (General Linear Model) and non-parametric regression statistical tests we established that there is no significant relationship between depth and artefact mass ($F = 0.403$, d.f.=15, $p = 0.975$; $r_s = 0.011$, $p = 0.914$, $N = 100$), maximum artefact dimension ($F = 0.882$, d.f.=15, $p = 0.586$; $r_s = 0.079$, $p = 0.433$, $N = 100$) or flake percussion length ($F = 0.998$, d.f.=12, $p = 0.477$; r_s=-0.141, $p = 0.384$, $N = 40$). We view the failure to find size-sorting as a refutation of the hypothesis that there was persistent vertical movement of artefacts within

Figure 4 Photographs of cg1/a2/52/1. (A) Dorsal face. (B) Ventral face. (C) Close up of the ground bevel at the junction of platform and dorsal surfaces. (A) and (B) to the same scale, (C) to a different scale.

the oldest levels of the deposit. This conclusion is consistent with other lines of evidence. For instance, basalt flakes are common in excavation units 51–53 but rarer in higher levels (42–50) indicating that there is a minimal 'reservoir' of similar specimens from which the axe flake cg1/a2/52/1 could have derived. Furthermore, both small and large artefacts, including the ochre covered limestone plaque found at the base of the deposit (O'Connor and Fankhauser 2011), were found lying horizontally. None of these observations suggest regular displacement of material. Consequently we are confident that this specimen is stratigraphically and temporally associated with the radiocarbon sample in that excavation unit, and has an antiquity of 44–49,000 years cal. BP.

Demonstrating axe production

The interpretation we offer here relies not only on a reliable date through association but also a clear identification of the technological character of the specimen in question. We demonstrate that Carpenter's Gap Axe Flake 1 has been removed from a ground-edge axe with the following analysis.

The specimen is a left longitudinal cone split flake fragment made on basalt with platform and feather distal termination preserved (Figure 4A and B). The ventral surface shows morphological evidence of a hertzian fracture initiation, with a low but well-expressed bulb formed underneath the impact point. There are pronounced fracture fissures radiating out towards the lateral margin and distal end from the point of fracture initiation. The flake is small: 0.16 g in weight, 10.9 mm long (percussion length), 5.17 mm width (at mid-point of length), and 1.4 mm thick (at intersection of length and width).

The entire flake platform and a portion of the dorsal face have been smoothed by grinding, and the junction of those surfaces preserves a part of the gently rounded bevel abraded on the axe from which the flake was removed (Figure 4C). Grinding covers the whole platform surface and on the complete axe extended further from the bevel as the grinding surface was truncated by the fracture that created the flake. Obvious striae are linear and are oriented at approximately right angles to the platform edge. On the dorsal face a ground surface runs the length of the flake and was also truncated by the termination of the flake, as well as by a dorsal scar, thereby showing that the grinding preceded flake creation. Here too there are distinct linear striations oriented approximately 75° to the bevel. These striations are most distinct in the distal portion of the flake and less pronounced close to the platform. The ground surface is superimposed on a series of flake scars that shaped the axe. Away from the heavily abraded bevel it is the junctions of underlying scars that display the most smoothing and polishing. This observation that the polished surface was created by grinding on top of flake scars is singularly important because it demonstrates that the surface smoothing is not a relic natural surface (such as the outside of a water-rolled cobble), and that the abrading was applied after the specimen was shaped by flaking. This pattern is typical of flaked and ground axes throughout the Australian archaeological record.

The junction of the platform and dorsal face represents the ground bevel of the axe before flaking. The angle of the bevel is 75°+3° ($N=4$), a value similar to bevel angles from Northwestern Australia 78.5°+6.5° ($N=75$) in the samples Dickson (1981:106) measured ($t=-2.0867$, $p=0.0951$, d.f. $=4.6784$). Within 2 mm of the edge there are a number of microscopic bevels with different angles, relics of slightly different contact positions when the axe was ground against a grinding stone. These features are also typical of Australian axes in general and are unambiguous indications that the smoothed surfaces on the specimen were created by repeated abrading.

As argued earlier the only morphological feature that is unique to and distinctive of Australian axes is the bevel created by abrading the junction of two surfaces ground until they appear smooth and polished. Given the high antiquity of this specimen its capacity to unambiguously document edge-grinding technology is critical. We undertook two analyses to evaluate the status of Carpenter's Gap Axe Flake 1 as a piece of a ground-edge axe:

1. Experiments with modern materials to establish the amount of labour required to create surfaces with smoothness similar to that displayed on Carpenter's Gap Axe Flake 1.
2. Comparison of archaeological artefacts, axes and non-axes, to evaluate whether or not the abraded surfaces on Carpenter's Gap Axe Flake 1 are typical of axes.

In both analyses we quantified the roughness of ground artefact surfaces in both absolute terms and in comparison to the smoothest fracture surface. Employing a Hirox 8700 digital microscope and associated software we measured surface roughness with two indices. This instrument creates 3D images of objects by digitally synthesising multiple images captured at different field ranges for any given magnification. All 3D models used here were constructed at 80× (giving image intervals of 30 μm) in bright-field and automatic lighting settings.

Surface roughness was measured using the roughness parameters Ra and Rzjis. Ra is the arithmetical mean roughness and Rzjis is a 10-point mean roughness calculation. Both measures express roughness across a surface by removing surface topographic variation longer than a prescribed wave length (the tomographic curve) to give a measure of surface unevenness (a roughness curve) in a cross-section. On each specimen we measured 10 such cross-sections to assess lateral differences in roughness, and we employed these two roughness parameters as they are robust and little affected by atypical values. Ra is calculated by totaling absolute values of deviations from the corrected mean line and averaging them. Rzjis is obtained by totaling the average of absolute values of the five highest heights (Yp) above the removed mean line and the five highest heights below the line (Yv) and dividing by five. For both calculations lower values represent less pronounced variability in surface micro-topography and hence lower roughness. We measured these indices on all experimental specimens and on the sample of 50 archaeological artefacts, including Carpenter's Gap Axe Flake 1. On archaeological specimens these indices are highly correlated ($r=0.989$, $p\leq0.0001$, $N=50$).

In addition to the two direct indices of roughness, Ra and Rzjis, we calculated two further indices based on those measures. For each specimen with grinding we measured the Ra and Rzjis for the ground surface and on an unground fracture. Typical unground measurements were obtained from the ventral fracture surfaces on flakes and from flake scar surfaces on complete and broken axes. We then expressed the difference in roughness between those unground ventral surfaces and earlier surfaces. For unground flakes this was achieved by dividing average Ra and Rzjis values for the ventral surface by average Ra and Rzjis values for a portion of the dorsal surface, to express the typical roughness of outer surfaces relative to the freshest fracture surfaces on the specimen. For axes and flakes with grinding, we divided average Ra and Rzjis values for the ventral surface on flakes or negative scars on axes by average Ra and Rzjis values for one ground surface, to express the typical roughness of ground surfaces relative to the roughness of unground fracture surfaces on each specimen. Calculated values were multiplied by 100 to form what we term the 'Ra ratio' and 'Rzjis ratio'. The higher the value the greater is the smoothness of the early/ground surfaces relative to the roughness of unground fracture surfaces.

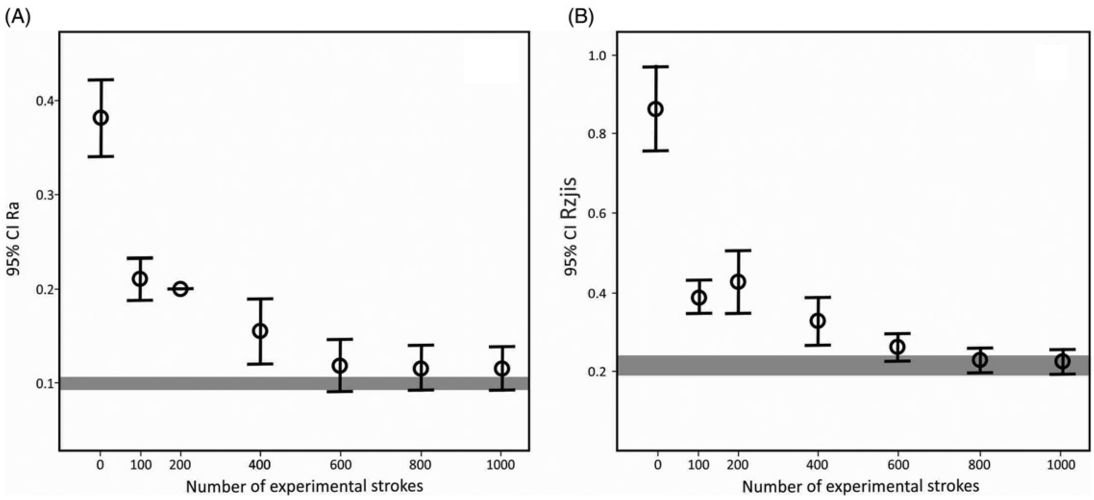

Figure 5 Summary of experiments. (A) Confidence intervals for mean Ra values of specimens subjected to varying amounts of experimental grinding, (B) confidence intervals for mean Rzjis values of specimens subjected to varying amounts of experimental grinding. In both cases, the grey band represents the value of cg1/a2/52/1.

Experiments

In our experiments we used basalt flakes struck from blocks obtained from the Carpenter's Gap region and identical in texture to the basalt specimens found in Carpenter's Gap 1. These specimens were abraded on a slab of fine sandstone (a commercially available paver of sawn Tuscan sandstone) using forceful strokes in which the flake was pushed 15 cm across the slab and drawn back the same distance. Abrasion in these two directions (away and back) constituted one stroke. Loading was constant for all strokes. No additional abrasive material or fluids were added. Specimens were abraded in this manner for 100, 200, 400, 600, 800 and 1,000 strokes, with four specimens for each treatment.

The smoothness on the bevel of Carpenter's Gap Axe Flake 1 required at least 600–800 long, force-full strokes on a sandstone slab (Figure 5). This exceeds any preparation known for basalt artefacts in Australian prehistory except for the manufacture of tools with ground edges. In Australia no platform preparation for core reduction ever involved such extensive smoothing. Hence Carpenter's Gap Axe Flake 1 can only have come from the edge of a beveled, ground artefact.

Archaeological comparison

Our comparative sample comprised 50 artefacts in three categories: (1) the specimen discussed in this paper Carpenter's Gap Axe Flake 1, (2) 11 axes and axe fragments from the Kimberley and adjacent regions, and (3) 38 unground basalt flakes from levels 48–52 of CG1. The third category included flakes with weathered and slightly patinated surfaces.

Mean values for Ra ratios and Rzjis ratios are significantly different for ground-edge axes and flakes of basalt without grinding (Ra ratio: $t = -3.810$, d.f. = 10, $p = 0.003$; Rzjis ratio: $t = -3.089$, d.f. = 10, $p = 0.011$). In contrast mean values for Ra ratio and Rzjis ratios are not significantly different for ground-edge axes and the specimen reported in this paper from excavation unit 52 from CG1 (Ra ratio: $t = -0.541$, d.f. = 10, $p = 0.601$; Rzjis ratio: $t = -0.542$, d.f. = 10, $p = 0.600$). These results are consistent with the proposition that the smoothing on the platform and dorsal face is unlike the surface of flaked or weathered basalt at Carpenter's Gap 1 and is indistinguishable from the ground faces of axes (Figure 6). Given that the morphology of the platform and its junction with the dorsal face on cg1/a2/52/1 is the same as typical bevels on axes, and that the extensive and laborious abrasion has smoothed the basalt to the same extent as observed on axes, we conclude that cg1/a2/52/1 (Carpenter's Gap Axe Flake 1) must be a flake removed from the polished edge of a ground axe.

Technological novelty and the colonisation of Australia

This age for ground axe production is close to, perhaps immediately after, the generally accepted age for colonisation of Sahul, the Pleistocene continent combining Australia and New Guinea (Hiscock 2008). It is now clear that the invention of ground-edge axes came shortly after landfall. Hence we have evidence of substantial technological innovation in the context of the colonising process. In a remarkable parallel, ground-edge tools also appeared when *Homo sapiens* entered the Japanese archipelago about 38,000 years

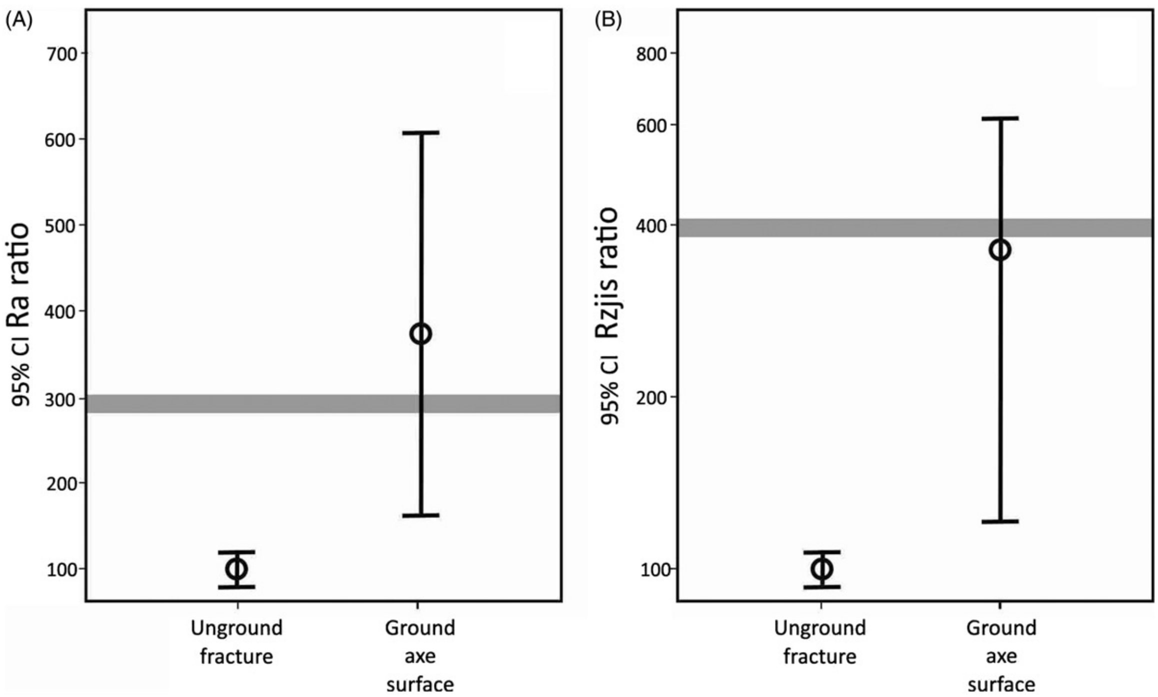

Figure 6 Summary of archaeological comparisons. (A) Confidence intervals for mean Ra ratio values of unground and ground surfaces of archaeological specimens, (B) confidence intervals for mean Rzjis ratio values of unground and ground surfaces of archaeological specimens. In both cases, the grey band represents the value of cg1/a2/52/1.

ago (Takashi 2012). Known Pleistocene Australian and early Japanese axes are distinctly different in size and shape and represent separate technical innovations, perhaps both building on pre-existing grinding applications such as hematite grinding for pigment or production of osseous tools. The timing of these innovations at the point of colonisation, in two separate lands, suggests that dispersing humans were often innovating as they entered new territories, rather than maintaining technologies that had been employed previously. This pattern of innovation facilitated adjustments to both provisioning and production systems that suited local materials and material availability/costs as well as the new economic and social systems that were serviced by these novel technologies in new landscapes. We can illuminate something of the magnitude and structure of technological experimentation and innovation in Australia by describing the growth of regional diversity in the production of ground-edge and waisted axes.

Technological diversity and regional traditions

Geographic variation and regional traditions of behaviour are evident in the technology of humans colonising Sahul. This is epitomized by the Pleistocene use of hafted ground-edge axes in northern Australia, and flaked/waisted unground axes in Papua New Guinea, but no axes at all in the southern two-thirds of Australia (Balme and O'Connor 2014; Geneste et al. 2010; O'Connor 1999; 18, Summerhayes et al. 2010). These divisions originated around the time of colonisation and persisted until the Holocene when axes began to be made in most southern parts of mainland Australia and polished adzes in Papua New Guinea. These regional distinctions lasted 40,000 years, presumably bolstered by distinctions in language and social views.

Our findings offer a new image of the dispersion of humans out-of-Africa. Cultural groups occupying new lands such as Australia/Sahul and Japan displayed flexible and novel adaptations, revealed archaeologically in the invention of new technological strategies such as hafted, ground-edge axes. These innovations helped construct cultural differences between groups in different regions, and in some instances the cultural distinctions created at colonisation were extremely long lasting. We conclude that dynamic adaptive modification of cultural systems occurred in conjunction with the dispersal of *H. sapiens* and played not only a significant role in the successful expansion of humans across the globe but also led to long-lasting differentiation of human societies.

Conclusion

In Australia, the antiquity of ground-edge axe production has progressively been pushed backwards, reflecting not only increasingly sensitive dating techniques but also the gradual accumulation of archaeological sample sizes. With our discovery of the specimen at Carpenter's Gap 1, dated to approximately 44–49,000 year BP, we can conclude that ground-edge axe production is broadly coincident with human colonisation of Australia. We suggest that axe production was probably invented within Australia shortly after people arrived, and we have noted two implications of this inference. First, the invention of ground-edge axes here exemplifies the emergence of novelty during the global dispersal of humans. As humans spread, technology was not merely losing the diversity it had evolved in Africa, it was also being transformed through invention of entirely novel varieties of tools. Second, the early invention of ground beveled edges on Northern Australian axes is a marker of long lasting regional distinctions in behaviour, documenting spatial differentiation in traditions and adaptive patterns from the earliest period of exploration and settlement. Technological elements of these regional distinctions lasted 40,000 years and indicate that these technological differences were part of deep social and linguistic distinctions within Sahul.

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