2018

Open-air preservation of miniaturised lithics: experimental research in the Cederberg Mountains, southern Africa

Natasha Phillips  
*University of Wollongong, np989@uowmail.edu.au*

Justin Pargeter  
*Stony Brook University, Emory University*

Marika Low  
*University of Wollongong, mal964@uowmail.edu.au*

Alex Mackay  
*University of Wollongong, amackay@uow.edu.au*

Publication Details

Open-air preservation of miniaturised lithics: experimental research in the Cederberg Mountains, southern Africa

Abstract
Open-air archaeology plays a limited role in southern African Late Pleistocene research, with most studies focused on rock shelter assemblages. Recently, archaeologists have noted discrepancies in the composition of Late Pleistocene lithic assemblages between some of the region's open-air and rock shelter sites. For example, although relatively abundant in rock shelters, Late Pleistocene Later Stone Age (LSA, c. 44-12 kcal. BP) bipolar cores are rare in open-air contexts. In this paper, we assess this discrepancy by testing for differential preservation of specific artefact classes and sizes in semi-arid open-air conditions. We placed a replicated assemblage of miniaturised cores and flakes on an archaeologically sterile sediment surface in the Doring River Valley (South Africa) and recorded their movements over 22 months. Our results indicate that bipolar and freehand cores moved comparable distances within the study interval and that surface slope is the strongest predictor of miniaturised tool movement. We also show that (1) relatively flat lithics move disproportionately more and (2) random artefact orientations do not preclude local (i.e. metre) scale artefact transport. In terms of the archaeology of our study area, the observed clustering of surface artefacts on sediment bodies likely results from their recent exposure. Our data suggest that the paucity of open-air bipolar artefacts in Late Pleistocene LSA assemblages may have more to do with human behavioural variability at landscape scales than differential preservation. Southern Africa's rich rock shelter record is, therefore, unlikely to represent the full suite of prehistoric hunter-gatherer behaviours.

Keywords
experimental, research, open-air, southern, lithics:, africa, mountains, miniaturised, preservation, cederberg

Disciplines
Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

This journal article is available at Research Online: http://ro.uow.edu.au/smhpapers/5314
Open-air preservation of miniaturised lithics: experimental research in the Cederberg Mountains, southern Africa

Natasha Phillips¹,² · Justin Pargeter³,⁴ · Marika Low¹,² · Alex Mackay¹,²

Received: 7 December 2017 / Accepted: 14 February 2018
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract
Open-air archaeology plays a limited role in southern African late Pleistocene research, with most studies focused on rock shelter assemblages. Recently, archaeologists have noted discrepancies in the composition of late Pleistocene lithic assemblages between some of the region’s open-air and rock shelter sites. For example, although relatively abundant in rock shelters, late Pleistocene Later Stone Age (LSA, c. 44–12 kcal. BP) bipolar cores are rare in open-air contexts. In this paper, we assess this discrepancy by testing for differential preservation of specific artefact classes and sizes in semi-arid open-air conditions. We placed a replicated assemblage of miniaturised cores and flakes on an archaeologically sterile sediment surface in the Doring River Valley (South Africa) and recorded their movements over 22 months. Our results indicate that bipolar and freehand cores moved comparable distances within the study interval and that surface slope is the strongest predictor of miniaturised tool movement. We also show that (1) relatively flat lithics move disproportionately more and (2) random artefact orientations do not preclude local (i.e. metre) scale artefact transport. In terms of the archaeology of our study area, the observed clustering of surface artefacts on sediment bodies likely results from their recent exposure. Our data suggest that the paucity of open-air bipolar artefacts in late Pleistocene LSA assemblages may have more to do with human behavioural variability at landscape scales than differential preservation. Southern Africa’s rich rock shelter record is, therefore, unlikely to represent the full suite of prehistoric hunter-gatherer behaviours.

Keywords Open-air surface archaeology · Formation processes · Late Pleistocene Later Stone Age · Lithic miniaturisation · Orientations · Experimental archaeology · GIS · R statistical platform

Introduction
Open-air research in southern Africa
Southern African open-air archaeology is abundant but often under-emphasised in archaeological studies, particularly in areas with numerous, long sequence rock shelter deposits. Open-air archaeology is typically found as surface artefact scatters formed to varying degrees by complex processes of post-depositional alteration and relocation. Archaeologists face considerable challenges in controlling for time and preservation in open-air contexts, deterring interest in these

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12520-018-0617-7) contains supplementary material, which is available to authorized users.

Natasha Phillips
np989@uowmail.edu.au

Justin Pargeter
justin.pargeter@gmail.com

Marika Low
mal964@uowmail.edu.au

Alex Mackay
amackay@uow.edu.au

¹ Centre for Archaeological Science, School of Earth and Environmental Sciences, University of Wollongong, Northfields Ave, Wollongong, NSW 2522, Australia
² Department of Archaeology, University of Cape Town, Beattie Building, 3rd Floor, University Avenue, Upper Campus, Rondebosch, South Africa
³ Department of Anthropology, Emory University Centre for Anthropological Research, 1557 Dickey Drive, Atlanta, GA 30322, USA
⁴ Department of Anthropology and Development Studies, University of Johannesburg, Auckland Park 2006, South Africa
settings. As a result, few late Pleistocene surface studies are carried out compared to other periods and parts of the world (e.g. Barton et al. 2002; Braun et al. 2016; Ebert 1987; Eren et al. 2010; Fanning et al. 2008; Holdaway et al. 2012; Koopman et al. 2016; Marks and McCall 2011; Marwick et al. 2017; Ozán 2017; Petraglia and Potts 1994; Schick 1986; Thompson et al. 2014; Wandsnider and Camilli 1992; Wells 2001). A few notable exceptions aside (e.g. Dietl et al. 2005; Fisher et al. 2013; Oestmo et al. 2014), there is also a lack of research engagement with the formation processes involved in the development of open-air contexts, despite this being a prerequisite to understanding the archaeological potential of such contexts for reconstructing past human behaviour (Schiffer 1987).

In this paper, we present the results of an experiment designed to explore the rate, scale and catalysing factors of lithic surface scatter movement and preservation. Our experiment examines the roles of lithic shape, size, climatic variability and land surface morphology on lithic movement and potential changes to assemblage composition. This study was conducted over a 22-month period using a replicated assemblage placed on an archaeologically sterile sediment surface in the Doring River Valley, South Africa—an area rich in both open-air and rock shelter assemblages (Fig. 1). We focus our attention on two questions of importance to the integrity of surface archaeology: (1) What is the rate at which initially coherent assemblages disaggregate? and (2) to what extent does movement/disaggregation effect different components of an assemblage? In particular, our interest is in changes in assemblages relating to the late Pleistocene Later Stone Age (LSA, c. 44–12 kcal. BP). In this period, archaeologists have recorded similar miniaturised stone lithic assemblages in the region’s rock shelter deposits and open-air contexts (Fig. 2), but with a persistent under-representation of small and most notably bipolar artefacts in the latter (e.g. Low and Mackay 2016; Low et al. 2017; Mackay 2010; Manhire 1993; Orton 2008; Porraz et al. 2016). While our results speak specifically to the local and regional archaeological records, they have broader implications for the preservation of miniaturised lithic assemblages in open-air settings throughout the world (e.g. Attenbrow et al. 2009; Hiscock 2015; Hiscock and Attenbrow 1998; Neeley 2002; Petraglia et al. 2009; Tang et al. 2013).

Contribution

Models of our species’ behavioural origins often extrapolate site-based evidence to landscape scale interactions (e.g. d’Errico et al. 2017; Mackay et al. 2014a; Marean 2010; McCall 2007; Porraz et al. 2013; Powell et al. 2009; Villa et al. 2010). Southern Africa’s documented late Pleistocene archaeological record mostly derives from rock shelters. While rock shelters provide micro-climatic conditions conducive to spatial and organic preservation, they comprise a small fraction of southern Africa’s terrain. Their evidence alone is insufficient to explain the human behavioural variability between regions and at landscape scales. This research bias raises the question: Are observed patterns of late Pleistocene...
behavioural change in rock shelters representative of broader events occurring across the southern African landscape? As is clear from ethnographic research on hunter-gatherers, humans deploy technology strategically across landscapes. Adaptations that work in one part of the landscape need not work in another.

Discrepancies between open-air and rock shelter contexts

Several examples within South Africa’s southern and western Cape region illustrate differences between rock shelter and open-air archaeological assemblages. Rock shelter sequences often show a decline or absence of occupation in the late Middle Stone Age (MSA, ~50–25 kcal BP) (Brown et al. 2012; Deacon 1995; Deacon and Thackeray 1984; Faith 2013; Jacobs 2010; Klein et al. 2004; Mackay 2010; Marean 2010; Wadley 1993). These patterns have been taken to suggest that humans abandoned the region during this time. However, sites like Putselaagte 1 document abundant late MSA occupation of open-air settings on the Doring River, within a catchment where comparable assemblages are absent from four excavated MSA rock shelters (Mackay et al. 2014b). Jerardino and Yates (1996) made comparable observations on the nearby west coast around Elands Bay. Periods in which large open-air shell middens accumulated showed relatively little occupation of common nearby rock shelters. Yet, these sites were well occupied both before and after.

Further contrasts are noted within the Cederberg region, in the differences between open-air and rock shelter artefact abundance assigned to two MSA technocomplexes, the Still Bay (identified through bifacial points and thinning flakes) and Howiesons Poort (small backed artefacts, notched pieces and blades) (e.g. Hallinan and Parkinson 2017; Mackay et al. 2018). Assemblages from both technocomplexes are found in rock
shelter contexts throughout this region, but to varying degrees (compare Högborg and Larsson 2011; Lombard et al. 2010; Mackay et al. 2015; Mourre et al. 2010; Porraz et al. 2013; Rigaud et al. 2006; Vogelsang et al. 2010; Will et al. 2015). Artefact discard rates for Howiesons Poort rock shelter assemblages are typically much higher than those from the Still Bay (Mackay et al. 2014b, 2018). This pattern is reversed at open-air localities, with Still Bay occurrences showing higher rates of manufacturing debris and discard rates indicative of manufacturing localities spread across multiple catchments (Hallinan and Parkington 2017; Mackay et al. 2010, 2018; Steele et al. 2012). So far, no comparable open-air Howiesons Poort scatters have been identified in the region (Mackay et al. 2018). Similar to the Howiesons Poort, archaeologists define late Pleistocene LSA assemblages by their miniaturised lithic production. In this case, assemblages are represented by untouched small flakes and bladelet production (Mitchell 1988). These products were made with a mix of bipolar and freehand flaking strategies. Frequent on-site reduction, local fine-grained raw material use and relatively low frequencies (c. < 5%) of artefact retouch suggest the importance of disposable toolkits (Low and Mackay 2016; Pargeter 2016). However, despite what late Pleistocene LSA assemblages ‘should’ look like, researchers working in several parts of southern Africa have noted lower occurrences of these assemblages at open-air localities (Fig. 2), with a low to absent bipolar component (Beaumont 1986; Churchill et al. 2000; Low et al. 2017; Mitchell 1988; Palmison 2014; Price-Williams and Barham 1982).

Low et al. (2017) noted the absence of bipolar cores and flakes during survey along the Doring River Catchment and analysis of late Pleistocene LSA scatters at the open-air site, Uitspankraal (UPK) 7 (Fig. 1). The general absence of bipolar cores contrasts with the general abundance of bipolar cores at the rock shelter Putslagte 8 (PL8), located 15 km to the northwest of UPK 7. They also detected a difference in raw material procurement and use between open-air localities and rock shelters within the broader Doring River Catchment (Fig. 1). While abundant hornfels river cobbles were sourced for the manufacture of artefacts along the river, the abundance of this raw material declines steeply with increasing distance from the Doring River. Away from the river, locally available quartz was preferentially selected for use at shelters such as PL8, including its use in bipolar reduction. These findings suggest that differential access to quartz and hornfels influenced the composition of late Pleistocene LSA lithic assemblages across the Doring catchment over distances of < 5 km (Low et al. 2017). In addition to this study, late Pleistocene LSA artefacts also occur in the Doring River Valley, as surficial scatters at Appleboskraal (ABK), and as more compositionally variable clusters in two exposed areas of UPK 9, located east of UPK 7 (Fig. 1, see Will et al. 2015). These artefacts occur on exposed surfaces in semi-arid, erosion-prone conditions. Both UPK 9 and ABK yield freehand bladdelet cores, without the clear presence of bipolar cores (Fig. 3).

Existing differences in the open-air and rock shelter occurrence of late Pleistocene LSA technological components may represent behavioural variability that manifests at landscape scales. However, like the Howiesons Poort, it is also possible that this compositional variance is due to differential preservation of artefacts of different sizes in different contexts. Bipolar reduction, in contexts of lithic miniaturisation, produces especially small cores that potentially preserve less often than larger freehand cores (Pargeter and Eren 2017). If the differential occurrence of bipolar and freehand cores is indeed due to their preservation and not their strategic deployment by people in the late Pleistocene, then we should expect patterns of lithic preservation, where freehand cores are preserved and bipolar cores are removed. These alternative proposals necessitate the experimental work outlined in this paper.

Despite the recurring issues surrounding control and preservation, only a few open-air studies in southern Africa are dedicated to systematically investigating post-depositional processes involved in the formation of archaeological deposits and surface scatters (Dietl et al. 2005; Fisher et al. 2013; Forsmann and Pargeter 2014; Kuman 1989; Moeyersons 1978; Oest m e et al. 2014; Pargeter and Bradfield 2012). This contrasts extensive research on open-air post-deposition and formation in Europe and Asia (e.g. Bertran and Texier 1995; Enlo e 2006; Guo et al. 2016; Sitzia et al. 2012; Wells 2001; Wilkinson 1999), Australia (e.g. Fanning and Holdaway 2001; Fitzsimmons et al. 2014) and North and South America (e.g. A raujo and Feathers 2008; A r a u j o et al. 2013; Bettis and Mandel 2002; Dunning and Simek 1995; Özän 2017; Rick 1976; Wells 2001). Here, we endeavour to help fill this southern African void using an experimental program designed to document bipolar and freehand miniaturised lithic patterns of horizontal displacement and assemblage disaggregation in open-air contexts.

Testing for open-air surface disaggregation: an experiment

Experimental studies are a useful approach to determining the various factors or catalysts involved in the post-discard alteration of open-air assemblages (Schiffer 1983, 1987). Formational experiments mainly focus on the systematics of lithic formation, reduction intensity, assemblage creation and discard patterns, use-wear and vertical displacement analyses from trampling experiments (e.g. Dibble and Rezek 2009; Douglass et al. 2017; Eren et al. 2010; Marwick et al. 2017; McBrearty et al. 1998; Newcomer and Sieveking 1980;
To investigate the contextual and compositional discrepancy apparent within late Pleistocene LSA lithic assemblages, we conducted an experiment over 22 months, assessing the degree and rate of surface disaggregation of miniaturised lithics in the Doring River Catchment. Our primary objective was to determine whether different elements of exposed surface assemblages, consisting of miniaturised cores and flakes, moved across a sloped surface in different ways and at different rates. We examined lithic movement in response to variance in lithic size and shape, technology (i.e. bipolar vs freehand cores), climate (rainfall) and gradient (slope).

We hypothesise that smaller cores and flakes will move further and at a faster rate from ‘point of last discard’ than larger cores and flakes due to overland flow following rainfall. Slope is expected to influence this movement response, where a slope with a higher angle will result in more downslope movement than one with a lower angle. Since bipolar cores are smaller than freehand cores, we predict different movement patterns and attrition rates in the two core classes. This result would support the proposition that technological discrepancies between open-air and rock shelter assemblages could be the result of preservation bias rather than the deployment of technological strategies at landscape scales.

Materials and methods

Experimental setting and controlling for movement

To compensate for potential variability in localised conditions (Schick 1986), we set the experiment in the semi-arid Doring River Valley, at the open-air locality of UPK 7 (Fig. 1). The selected area is ~65 m northeast of the river and ~50 m above river level. We chose a surface that is archaeologically sterile and mostly devoid of obstructing features that can inhibit lithic movement and recovery (e.g. structures, dune sands, colluvium, etc.).
vegetation, Fig. 4) (Favier Dubois 1998; Martin 2006; Ozán et al. 2015). The surface morphology is defined by a ridge and two opposed slopes of different average gradients (north \[\sim 9^\circ\] and south \[\sim 11^\circ\], Fig. 4). The south slope is more rilled and therefore more uneven than the north slope (Fig. 4), which may increase flow velocity, increasing the force available to cluster objects initially and subsequently shift larger objects downslope (e.g. cores, Ozán (2017) and citations therein).

The size of the study area available determined the sample size of the experimental assemblage. A total of 409 experimental lithics (freehand cores = 29, bipolar cores = 30, flakes = 350) were laid out in a line parallel to, and on the

**Fig. 4** Experimental setup (series 1), showing lithic arrangement on the slope south of the ridgeline with AM for scale. Detail is one of the 29 dacite freehand cores (scale bar = 1 cm). Depicted slope angles are averages of a series of dip readings taken in-field.
southern side of a central ridgeline, with the longest axis (if present) of each lithic placed perpendicular to this ridge (Fig. 4). This experiment was intended to assess non-cultural transforms on a known, standardised layout, and orientation of specific object types, sizes and forms on a known surface, and slope. For this reason, the starting distribution of our assemblage was deliberately arranged to deviate from ethnographic and experimental evidence for knapping distributions (e.g. Forssman and Pargeter 2014; Newcomer and Sieveking 1980). This is to test non-cultural transforms only, independent of single-event knapping.

For every recording series, we piece-plotted with a total station (Nikon 322-C-Series) the position of each experimental lithic, coding by lithic class (freehand cores = CF, bipolar cores = CB, flakes = F). The x, y, z positions recorded during setup were used as a starting reference line to compare against successive recording seasons (Fig. 4). Inter-series-linked unique identities were not allocated to individual lithics, so the tracking of individual lithic movements is outside the scope of this study. The extent of the experimental survey area was set at 5 m from the lithic start line, displayed as a buffer ring (4.8–5.2 m band) in Fig. 4. Topographic spot heights were recorded with a total station and used for surface modeling in ArcGIS (10.2, ESRI) to assess spatial patterning against slope. Due to its dip direction and micro-topography, we expected that lithics would move further on the southern than the northern slope. However, catalysing forces (e.g. overland flow from rainfall) would be needed to trigger lithic movement (see Bertran et al. 2012; Fanning and Holdaway 2001; Schick 1986) as both slope gradients are less than the critical slope angle of 16° (Rick 1976).

Climate and recording intervals

Recording intervals were planned around seasonal precipitation trends to assess the impact of wet and dry seasons on the experimental assemblage. We carried out spatial and attribute data collection for series 2 and 3 (2017) during the months before and after periods of potential rainfall (Fig. 5). Each series was then broadly linked to either wet (series 3 and 4) or dry (series 2) climatic categories. Recording intervals for series 2 and 3 were organised based on average monthly rainfall data collected over a 30-year period (1983–2013) by the Hough family, at Uitspankraal farm (Fig. 5). Due to funding and fieldwork logistics, data collection for series 4 occurred in mid-winter (June 2017), 22 months after initial setup. After series 3 recording, all flakes (and any experimental lithic that breached the study cut-off zone) were collected, bagged, tagged and removed from the study area. Freehand and bipolar cores were left in place for another 10 months, over the dry season and first half of the wet season (September 2016 to mid-June 2017) and their positions recorded during series 4.

Following series 4 data collection, all cores were left in place for future data collection in 2018. This subsequent period of exposure aims to assess whether the degree and rate of movement of freehand and bipolar cores increases compared to their earlier levels of disaggregation and attrition.

The experimental assemblage

JP manufactured the experimental assemblage according to technological patterns documented in southern African LSA assemblages dated to the late Pleistocene (Fig. 6). A narrow fronted marginal percussion strategy with a small hard hammer was used to produce the freehand assemblages. For the bipolar assemblages, a precision axial bipolar percussion method was used by employing the same small stone hammer. The overall goal in both the freehand and axial bipolar reduction experiments was to produce small, elongated flakes and bladelets and to reduce the cores until further flake production no longer proved possible. We used dacite, which is suitably.

![Fig. 5 Average monthly precipitation (mm) and series recording dates. Rainfall data was logged daily over 30 years (1983–2013) at Uitspankraal farm by the late Manus Hough](image-url)
Fig. 6  Experimental dacite lithic assemblage (from top left): 

- **a** freehand cores \((n = 29)\),
- **b** bipolar cores \((n = 30)\), and 
- **c** flakes \((n = 350)\)

To explore whether the technological contrasts between rock shelter and open-air lithic assemblages result from post-depositional attrition of specific technological classes in open-air contexts, we based the production parameters for our replicated assemblage on the technological composition of late Pleistocene LSA samples from Klipfonteinrand (Doring River Catchment) and Sehonghong (eastern Lesotho highlands) (sites 22 and 34 in Fig. 2). Both archaeological assemblages date to marine isotope stage (MIS) 2, between 26 and 12 kcal. BP (Mackay 2016; Mitchell 1995). They also emphasise bladelet and small flake production from small freehand and bipolar cores, made from fine-grained local raw materials. Figures 7 and 8 depict overall size differences between experimental and archaeological assemblages. Statistical comparisons of the core size variables also show no significant differences between the assemblages (Table 1). Flake size comparisons show more difference between the archaeological and experimental collections (Table 2). However, size statistics of these differences are low (Cohen’s \(f\) values ≤ 0.5), suggesting...
low practical significance to these results. Overall, this comparison demonstrates that the experimental assemblage is representative of both local and non-local late Pleistocene LSA assemblage size variability.

Data presented in Table 3 and Fig. 9 also show that bipolar and freehand cores from Klipfonteinrand and Sehonghong differ in weight and length within an archaeological assemblage. The size statistics for comparisons of core weight, length and technology show strong practical significance ($f$ values > 0.5) for these differences. Comparisons between core size and technology between the sites show weaker practical significance ($f$ values < 0.1). These data indicate that knappers at both sites adopted specific technological strategies to further extend core reduction and miniaturise flake production, supporting the notion that size differences are driven by technological choices and not differential preservation in rock shelter sites.

**Lithic size and shape**

Lithic attributes (i.e. dimensions [max length, max width and max thickness], weight and orientation) were recorded during each of the three recording series and joined to their spatial provenience in ArcMap. Size was measured based on maximum clast dimensions rather than percussion morphology. Digital scales and callipers were used to record weight, maximum length (first, longest axis), width (second longest axis, perpendicular to the first) and thickness (perpendicular to both the first and second longest axis). From these variables, we calculate flake and core volume (length * width * thickness). We measured flake and core shape using elongation (length/width) and flatness (width/thickness).

**Tracking lithic movement and loss**

**Distance**

We estimated distance travelled for individual lithics, for each recording event. Movement is approximated by the minimum distance between recovery location and the starting line, over set bins of time (7, 12 and 22 months). Without unique identities linking individual pieces between recording series, we used the Near tool in ArcMap to establish the shortest distance between a lithic and the start line. These measurements are treated as minimum distances covered by the experimental assemblage. The average distance overall and between slopes was assessed during attribute comparison and modelling (outlined below). Only downslope movement is trackable. We were unable to observe negative (upslope) movement towards start during their exposure. The inferred
exception to this is initial movement from south to north slope, which involved uphill movement until lithics crossed the ridgeline.

**Attrition**

Attrition is the process of lithic loss from the surface of the experiment’s arbitrarily defined survey area (> 5 m from survey zone, see Fig. 4). Attrition can result from natural causes (e.g. surface water and or debris runoff) resulting from surface movement, burial or removal by person or animal (e.g. baboons, farm stock). During the experiment, any dacite lithic found outside the 5-m cut-off zone was noted, included in the attrition count for the relevant series, collected and excluded from further recording. Lithics that were found broken during exposure were noted and removed to prevent skewing of lithic size and shape values.

**Lithic orientation**

Archaeologists typically use orientation and plunge to assess an assemblage’s spatial (re-) organisation (e.g. Bertran and

### Table 1

<table>
<thead>
<tr>
<th>Comparisons</th>
<th>Df</th>
<th>Sum sq</th>
<th>Mean sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
<th>Cohen’s f effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core length by assemblage type</td>
<td>2</td>
<td>67</td>
<td>33.71</td>
<td>0.428</td>
<td>0.653</td>
<td>0.0652</td>
</tr>
<tr>
<td>Residuals</td>
<td>201</td>
<td>15,845</td>
<td>78.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core width by assemblage type</td>
<td>2</td>
<td>83</td>
<td>41.59</td>
<td>0.629</td>
<td>0.534</td>
<td>0.079</td>
</tr>
<tr>
<td>Residuals</td>
<td>201</td>
<td>13,296</td>
<td>66.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core weight by assemblage type</td>
<td>2</td>
<td>7.7</td>
<td>3.853</td>
<td>1.72</td>
<td>0.182</td>
<td>0.1311</td>
</tr>
<tr>
<td>Residuals</td>
<td>201</td>
<td>448.1</td>
<td>2.241</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
experiment excludes cultural transforms as factors involved in lithic movement. Therefore, we expect to see uniform arrangement in lithic orientations in response to non-cultural processes, such as overland flow from rainfall. Rayleigh’s test (Watson 1982) was performed to assess the degree of uniformity of lithic orientations between slopes and series.

Statistical analyses

We use a combination of qualitative and quantitative approaches to compare, contrast and explore our experimental dataset. Linear models were used to assess the relationship between several predictor variables (i.e. lithic size, shape, technology, slope and climate) and our primary response variable: lithic movement. Further statistical details follow in each of the results sections below. All our quantitative analyses were performed using the R statistical platform (R Core Team 2015). Our analyses employ, with modifications, R code published by Marwick et al. (2017) in their experimental trampling study. Following recent calls for efforts to make scientific outputs more reproducible and transparent (Marwick et al. 2017), we include our modified R code and associated baseline datasets as supplementary materials (see Online Resources 1 and 2, covered by the Mozilla Public License 2.0), which are also available at the Open Science Framework (osf.io, see Phillips et al. (2018)).
Results/observations

Qualitative assessment of lithic class distributions and recovery

We mapped the series 2 lithic distributions in March 2016, 7 months after laying out the experimental assemblage. Between series 1 and 2, the assemblage was exposed to relatively dry conditions with low precipitation (< 10 mm average monthly rainfall, Fig. 5). We relocated and plotted 402 (98%) of the experimental lithics (Table 4 and Fig. 10b). Lithic distributions indicate minimal movement for all three technological classes on the south slope and relatively widespread dispersal of flakes on the north slope. The south slope retained most of the assemblage for all classes (n = 264, 66%) compared to the north slope (n = 137, 34%) and showed minimal movement from starting position, south of the central ridge. Of the 137 lithics that moved from the south to the north slope between series 1 and 2, 92% were flakes, and 8% were equal parts bipolar and freehand cores (Table 4). When compared to their respective class totals for series 2 (flakes = 350, bipolar cores = 24, freehand cores = 28), ~16% more flakes (36% of their class total) relocated to the north slope during the first exposure season than bipolar (20%) and freehand (21%) cores. One spatially anomalous and relatively large dacite freehand core (23.4 g, 295 cm²) shifted to a residual sediment mound, > 6 m upslope and to the east of the start line (0.7 m higher in elevation, Fig. 10b). Outside of the 5-m study boundary, this core was removed from further assessment and included in attrition counts for series 2 (Table 1).

Figure 10 depicts spatial distributions of series 1 to 4 lithic classes. Figure 10b presents a more dispersed assemblage of lithics across the north slope, whereas flakes on the south slope show some isotropic distribution, in linear downslope alignment, that appears to conform with the underlying surface topography. Initial dispersal between series 1 and 2 appears extensive, especially for flakes. However, series 3 spatial patterning appears to deviate little from series 2. Mapped cores for series 4 remain mostly clustered around the ridge. However, a number of bipolar and freehand cores have travelled beyond the 5-m survey zone. Both core types show similar degrees of movement.

Figures 11 and 12 present log movement of lithic classes by slope and series. Flakes greatly out-number bipolar and freehand cores (Table 4). They also present the greatest range in distance moved for both series 2 and 3 and north and south
slopes (Fig. 11), followed by freehand cores (Figs. 11 and 12). Despite their spread of distance values, flake counts appear relatively well constrained around their median for series 2 and 3, on both the north and south slopes (Fig. 11). On average, flakes moved more on the south slope than on the north but show little difference between series (cf. Fig. 10 and Fig. 11). This further indicates that lithic movement slows after initial dispersal, between series 1 and 2, onto both slopes.

Freehand cores moved more than bipolar cores after initial exposure (series 1 to 2, cf. Fig. 11 and 10b). However, bipolar

---

**Table 4** Class type counts by slope and attrition per recording series

<table>
<thead>
<tr>
<th>Class type</th>
<th>Series</th>
<th>Count</th>
<th>Loss</th>
<th>Count</th>
<th>Loss</th>
<th>Count</th>
<th>Loss</th>
<th>Count</th>
<th>Loss</th>
<th>Count</th>
<th>Loss</th>
<th>Series total attrition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td>3</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>Total</td>
<td>North</td>
<td>South</td>
<td>Total</td>
<td>North</td>
<td>South</td>
<td>Total</td>
<td>North</td>
<td>South</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Bipolar core</td>
<td>30</td>
<td>30</td>
<td>0</td>
<td>6</td>
<td>18</td>
<td>24</td>
<td>-6</td>
<td>4</td>
<td>19</td>
<td>23</td>
<td>-1</td>
<td>2</td>
</tr>
<tr>
<td>Freehand core</td>
<td>29</td>
<td>29</td>
<td>0</td>
<td>5</td>
<td>22</td>
<td>28</td>
<td>-1</td>
<td>5</td>
<td>22</td>
<td>27</td>
<td>-1</td>
<td>3</td>
</tr>
<tr>
<td>Flake</td>
<td>350</td>
<td>0</td>
<td>126</td>
<td>224</td>
<td>350</td>
<td>0</td>
<td>130</td>
<td>203</td>
<td>333</td>
<td>-17</td>
<td>-17</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>409</td>
<td>0</td>
<td>137</td>
<td>264</td>
<td>402</td>
<td>-7</td>
<td>139</td>
<td>244</td>
<td>383</td>
<td>-19</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 10** Panelled comparison of experimental lithic distributions mapped by class for each series: a Setup/series 1, b series 2, c series 3, d series 4. Lithic counts by class are included for each series. Freehand cores are represented by white squares, bipolar cores as blue hexagons, flakes as black triangles. Map b (series 2) depicts outlying freehand core, circled in red. The base map displays unmanned aerial vehicle (UAV) imagery of the surface topography, vegetation and colluvium. The survey boundary of 5 m is shown as a buffer ring around the white dashed start line. Grey contour lines are spaced at intervals of 0.25 m (see central legend for details).
cores overlap freehand core distance in series 3 (Fig. 12). With the exception of series 2 movement of freehand cores on the north slope, there is only minor difference between average distances moved by all classes shown for both north and south slopes (Fig. 11). Difference in median distance from log 0 decreases between series 2 and 3 (Fig. 11). The range of distances moved also decreases for cores on the north slope from series 2 to 3. However, this is followed by a range increase for freehand cores between series 3 and 4 (Fig. 12).

Quantitative assessments of lithic movement

While spatial patterning is apparent between series, it is difficult to say with certainty whether any single clast, technological or contextual variable is more likely the cause of this dispersal over the other. This section outlines the results of quantitative analyses assessing the relationship between several predictor variables (lithic size, shape, class, slope and climate) and lithic movement. We constructed linear models (i.e. ANOVAs and generalised linear models) to determine the relative role played by the various predictor variables. Differences between lithic orientation, recording series and slopes are also examined. Because lithic orientations are uniformly distributed, non-parametric permutation tests were carried out using the perm package in R to examine variance (Good 2013).

We determined each variable’s suitability for linear modeling by examining the data distributions for any assumption violations held by parametric linear models. Several of our predictor variables showed violations and were therefore log transformed before analysis (see Fig. 13). Our main response variable (lithic movement) is not normally distributed, and a log-normal conversion of the data failed to produce such a data distribution (Fig. 13, ‘Horizontal movement’). We compared this response variable to several theoretical distributions including the Weibull, exponential, log-normal and gamma distributions (Fig. S1, see Online Resource 3 for supplementary figures). The response variable shares the greatest structural similarity with the Weibull distribution (see Q-Q plot). Weibull distributions follow a power law and can capture data distributions with a large quantity of small observations, but relatively few larger ones. To model our response variable as a Weibull distribution, we used the GAMLSS package in R which allows greater flexibility when working with highly skewed response variables.
Lithic size and shape as predictors of lithic movement

We constructed two sets of generalised linear models, one for each recording session in which our data reflect the movement of cores and flakes. These model sets assess the respective roles of lithic size and shape in determining lithic movement (Figs. S2–5). Diagnostics plots show that the two sets of models perform well when fit to the experimental dataset, with roughly normal distribution for data residuals and good fit with normal Q-Q plot (Figs. S2–5).

Tables 5 and 6 present the lithic size, shape and lithic movement linear model results. The results show that lithic size is a poor predictor of lithic movement. Only lithic thickness showed a significant influence on lithic movement in series 2 (Table 5). Lithic shape, on the other hand, showed different patterns of significance across the series 2 and 3 data. In series 2, only flatness showed a significant relationship with lithic movement, while in series 3, both elongation and flatness showed such a relationship (Table 6). However, the shape model’s generalised $r^2$ values are relatively low (both < 0.2) suggesting a low practical significance to this pattern (Table 7).

Lithic class, slope and climate as predictors of lithic movement

Standard ANOVA models were used to compare the relative effects of several categorical variables (lithic class, climate, slope and recording series) and their possible influence on lithic movement. We built two sets of models: one for the core and flake data in series 2 and 3 and the other for the core data across series 2, 3 and 4.

Tables 8 and 9 present the results for both ANOVA models. The data in Table 8 show that lithic class ($F[2, 768] = 15.19, p < 0.0001, f = 0.19$) and slope ($F[1, 768] = 403.14, p < 0.0001, f = 0.72$) are the strongest predictors of lithic movement for the series 2 and 3 data. However, the effect size statistics for these results show that only slope has strong practical significance ($f$ value $> 0.5$) for determining lithic movement. This result is driven largely by differences in movement between bipolar cores on the north and south slopes and between freehand and bipolar core movement on different slopes (north vs south; see Table S1). There is no significant difference in movement between classes on the northern slope (Table S1). The southern slope shows a
significant difference in movement between flakes and free-hand cores (Table S1). Precipitation plays a minimal role in causing lithic movement under the conditions modelled in this experiment (Table 8).

The model representing the series 2, 3 and 4 core data shows lithic class (bipolar or freehand cores) to be of minor importance in determining lithic movement ($F[1, 131] = 3.02, p = 0.08$, $f = 0.17$) (Table 9). The cores’ movements are significantly different between the three recording series ($F[2, 131] = 5.61, p = 0.002, f = 0.26$), and slope remains a strong predictor of lithic movement ($F[1, 131] = 30.34, p < 0.0001, f = 0.56$) (Table 9). Of these two variables, only slope shows a strong practical significance ($f$ value > 0.5). Precipitation once again appears to play a minimal role in determining lithic movement (also see Table S1).

**Lithic orientation**

This section compares lithic orientations logged during each recording session. Figure 14 shows orientation comparisons as rose diagrams and mapped lithic bearings for series 2 and 3, and by slope. With slope direction in mind, series 2

| Series | Predictor | Estimate | Std. error | t value | Pr(>|t|) |
|--------|-----------|----------|------------|---------|----------|
| 2      | Weight    | −0.25    | 0.30       | −0.85   | 0.40     |
| 3      | Length    | 0.07     | 0.44       | 0.16    | 0.87     |
| 4      | Width     | 0.63     | 0.36       | 1.74    | 0.08     |
| 5      | Thickness | −0.91    | 0.34       | −2.69   | 0.01     |

**Table 6** Summary statistics for linear model assessing lithic shape as a predictor of lithic movement (response variable)

| Series | Predictor | Estimate | Std. error | t value | Pr(>|t|) |
|--------|-----------|----------|------------|---------|----------|
| 2      | Elongation| −0.28    | 0.24       | −1.18   | 0.24     |
|        | Flatness  | −1.08    | 0.19       | −5.74   | 0.00     |
| 3      | Elongation| −0.61    | 0.24       | −2.56   | 0.01     |
|        | Flatness  | −1.19    | 0.22       | −5.42   | 0.00     |
orientations show a NE-SW bearing tendency on the north slope and a WSW-ENE bearing tendency on the south slope (Fig. 14). However, there are no significant differences in mean orientations between series 2 and 3 and between the north and south slopes when tested for non-parametric permutations (Table 10). Series 3 orientations appear random for both slopes and have a wider distribution of flake orientation values than series 2 data (Fig. 14). Overall data distributions are not significantly different. There are also no significant differences in comparisons of flake orientations by lithic class (bipolar core, freehand core or flake; Table 10). Rayleigh tests also return no significant differences between the experiment’s lithic orientations and random lithic orientation patterns (Rayleigh Z = 0.0269, p = 0.6204).

Lithic attrition

Figures 14 and 15 show the lithic attrition rates across the different recording series (also see Table 4). Lithics were considered ‘lost’ once they crossed the 5-m experimental field recording boundary (see Fig. 10). Attrition results are considered conservative values due to the relatively small size of the study zone compared to archaeological exposures in the area. Recoverability proved remarkably high across the 7-, 12- and 22-month recording periods. In total, 8% (n = 36) of experimental lithics were ‘lost’ after 22 months of exposure, though this number includes those that were recovered in a fragmentary state (Table 4). Table 11 presents the results of chi-squares tests for the core and flake counts across series 2, 3 and 4. There were no significant differences between core and flake counts across series 2 and 3 (χ² [4, N = 199] = 0.8844, p = 0.9268). Similarly, cores show no significant differences between series 2, 3 and 4 (χ² [3, N = 199] = 0.6908, p = 0.8754, Table 11). The odds ratio (a measure of the relative effect of different groups in a chi-square test) demonstrates statistically similar probabilities of bipolar cores, freehand cores and flakes being ‘lost’ (odds ratios < 2, see Table 12). These results confirm our observations of inter-series lithic movement presented in the section “Qualitative assessment of lithic class distributions and recovery”, showing low or no practical significance (low effect size statistics) in the distances moved between different lithic classes.

Simulating lithic movement and loss over longer timescales

Our experiment extrapolates the degree to which an assemblage of discarded lithics might have disaggregated after 7 to 22 months of surface exposure. This timeframe falls short of the many millennia represented by our archaeological reference collections. This discord between archaeological and experimental timescales means archaeologists rely heavily on principles of uniformitarianism when comparing archaeological and experimental observations.

Simulation studies offer another set of methods for projecting experimental to archaeological timescales (Crema et al. 2014; Kovacevic et al. 2015). We employ a modified version of the lithic simulation model written by Marwick et al. (2017), who simulated the movement of lithics under trampling conditions. Our simulation resamples lithic movement values from those observed in the field as randomly determined incremented distances from original ‘discard’ position. Because our study found no significant differences in core and flake movement between the first (series 1 and 2) and second (series 2 and 3) periods of exposure, we pooled these movement results into a single dataset. Two simulation models were carried out (Fig. 16): model 1 considers forward movement away from start, model 2 accounts for potential negative movement back to start. Both simulations selected random movement values from the collective distance data bin to simulate new and hypothetical, but plausible, lithic movements. All lithics start with a position of 0 m. In model 1, the first iteration (or 12 months) involved adding randomly selected distance values from the pooled dataset to each lithic’s starting point (Fig. 17). This acts as position 1 for the simulated lithic. From here, the simulation randomly selects another distance value

| Predictor | Df | Sum sq | Mean sq | F value | Pr(>|F|) | Cohen’s f effect size |
|-----------|----|--------|---------|---------|---------|----------------------|
| Series    | 1  | 2.4    | 2.4     | 2.139   | 0.1441  | 0.05                 |
| Class     | 2  | 33.8   | 16.9    | 15.194  | <0.0001 | 0.19                 |
| Slope     | 1  | 448.7  | 448.7   | 403.141 | <0.0001 | 0.72                 |
| Slope:climate interaction | 1  | 0.5    | 0.5     | 0.434   | 0.5102  | 0.02                 |
| Series:class interaction | 2  | 0.3    | 0.2     | 0.149   | 0.862   | 0.01                 |
| Class:slope interaction | 2  | 7.4    | 3.7     | 3.342   | 0.0359  | 0.09                 |
| Residuals | 768| 854.8  | 1.1     |         |         |                      |
from the pooled movement data, adding this new value to position 1, resulting in a new position (2) and so on. Because our pooled series 2 and 3 lithic movement data were collected over a 12-month period, each simulated shift (randomly selected distance value added to previously held lithic position) represents possible movement over 1 year. Multiple iterations equal multiple years of movement (e.g. 10 iterations = 10 years). This model helps to determine the number of lithics lost beyond the 5-m experimental boundary over extended periods of exposure.

A lithic can move in multiple directions, not just downslope (‘forward’). However, individual lithic identities were not tracked across the recording series, and so it was not possible to record ‘negative’ movement of individual lithics. However, the simulation study allows us to speculate on this outcome. In simulation model 2, we applied a random sign flip, where sampled movement values could either be positive or negative at each movement interval (Fig. 17).

Table 9 Summary statistics for ANOVA model with lithic movement as response variable and series, class (bipolar core, freehand core), climate (wet/dry), slope (north/south) and their interactions as predictors. Data are for cores (not flakes) in series 2, 3 and 4 combined

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Df</th>
<th>Sum sq</th>
<th>Mean sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
<th>Cohen's f effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>1</td>
<td>1.98</td>
<td>1.98</td>
<td>1.813</td>
<td>0.18053</td>
<td>0.08</td>
</tr>
<tr>
<td>Series</td>
<td>2</td>
<td>12.25</td>
<td>6.13</td>
<td>5.61</td>
<td>0.002</td>
<td>0.26</td>
</tr>
<tr>
<td>Class</td>
<td>1</td>
<td>3.3</td>
<td>3.3</td>
<td>3.02</td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>Slope</td>
<td>1</td>
<td>33.13</td>
<td>33.13</td>
<td>30.34</td>
<td>&lt;0.0001</td>
<td>0.56</td>
</tr>
<tr>
<td>Series:slope interaction</td>
<td>2</td>
<td>4.35</td>
<td>2.17</td>
<td>1.99</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>Series:class interaction</td>
<td>2</td>
<td>1.17</td>
<td>0.58</td>
<td>0.54</td>
<td>0.59</td>
<td>0.09</td>
</tr>
<tr>
<td>Class:slope interaction</td>
<td>1</td>
<td>5.71</td>
<td>5.71</td>
<td>5.40</td>
<td>0.02</td>
<td>0.20</td>
</tr>
<tr>
<td>Residuals</td>
<td>131</td>
<td>143.03</td>
<td>1.09</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 14 Mapped lithic and related rose diagrams comparing orientations (180–360 axes only) from series 2 (light yellow lines) and 3 (black lines) north and south slope data. The base map displays UAV imagery of the surface topography, vegetation and colluvium. Grey contour lines are shown at intervals of 0.25 m.
Figure 18 summarises the results of our first lithic simulation model in which lithics moved on a cumulative unidirectional basis (model 1 in Fig. 17). The model outputs in Table 13 show that 15 lithics lie beyond the 5-m experimental boundary after 10 simulated lithic movement events (each accounting for a 12-month period). After 100 events (100 years), this number jumps to 180 lithics, and after 1000 events, the assemblage has moved well beyond the experimental boundary. The data show that a degree of assemblage structure is maintained throughout the movement simulations, driven by the fact that our model did not account for variations in lithic coordinates. The model also fails to account for significant predictors of movement like flatness which will homogenise movement patterns across the population. Future simulation work will focus on including these complicating factors.

Figure 19 summarises the results of our second lithic simulation model, in which lithics moved in both negative and positive directions depending on the random sign assignment of each movement value in each simulation run (model 2 in Fig. 17). Model 2 outputs show similar overall lithic attrition values as the first model, with 172 lithics ‘lost’ beyond the 5-m experimental boundary after 100 simulation events (Table 13). The difference in these two models is that with negative movement, lithics cluster around the 5-m experimental boundary to a greater degree than in the first model (cf. Figs. 18 and 19). After 10,000 simulation events, 361 lithics have moved beyond the 5-m experiment boundary (Table 13), but the majority remain clustered within a 50-m zone (Fig. 19). Negative movement produces a pattern in which low density scatters spread over a large area, while isolated lithics can end up over 200 m from their original location. In the second simulation, most lithics move quickly towards a modal spread pattern and change little in their position much after that.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Variant</th>
<th>Simulated p value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
<th>Monte Carlo replications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Slope</td>
<td>0.3086</td>
<td>0.2966</td>
<td>0.3205</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td>Series</td>
<td>0.7707</td>
<td>0.7596</td>
<td>0.7814</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Class</td>
<td>0.268</td>
<td>0.2565</td>
<td>0.2794</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 15 Bar plot showing lithic counts in series 1, 2 and 3
of exposure, flatter lithics moved more. However, between 7 months of exposure, the assemblage was subjected to the region’s lowest levels of annual precipitation (<10 mm) (Fig. 5). With low levels of rainfall, we expected to find equally low levels of movement in the experiment. However, series 2 shows the extensive movement of flakes dispersed with random orientations across the north slope and linear clustering along channels on the south slope. While the wet season has minimal influence on the change in lithic orientation between series 2 and 3, orientations are also randomly distributed despite the absence of anthropogenic discard behaviour influencing this pattern. This, together with initial movement and orientation of smaller flakes and bipolar cores on the northern slope, suggests the influence of factors beyond slope and surface water flow, such as animal or wind activity. While currently, no livestock roam this site, ostriches and baboons do frequent the river valley. There were no signs of ostrich activity at this locality during the experiment and so their impact on the site is difficult to determine. While baboon activity was more blatant, their engagement with the experimental lithics was selective, demonstrated by the removal of a large freehand core between series 1 and 2. Although not observed, animal ‘kicking’ resulting in the horizontal, rather than vertical, displacement of lithics (a mode of movement originally introduced by Barberena 2008; outlined in Ozán 2017) may have influenced north slope lithic dispersal. However, minimal breakage suggests that low levels of trampling occurred, and despite their combined arrangement of increased levels of precipitation (although see below). However, the practical significance of flatness and elongation in predicting movement is low relative to slope. Thus, while these results show that idiosyncrasies of lithic shape may influence which miniaturised lithics are preserved in open-air semi-arid conditions, slope plays a primary role in catalysing movement.

Wet-dry oscillations played less of a role in lithic movement than we initially predicted. Its effects may gather in magnitude with increased surface exposure times. Our results may also suggest that the ‘wet’ season did not reach predicted levels of precipitation as in previous years. Real-time local climatic records would provide more control and resolution regarding the interplay between lithic movement and shifts in different climatic conditions. This, however, does not change the unexpected results observed for series 2. Series 2 mapping was carried out 7 months after the experimental assemblage was laid out. During the preceding 7 months of exposure, the assemblage was subjected to the region’s lowest levels of annual precipitation (<10 mm) (Fig. 5). With low levels of rainfall, we expected to find equally low levels of movement in the experiment. However, series 2 shows the extensive movement of flakes dispersed with random orientations across the north slope and linear clustering along channels on the south slope.

While the wet season has minimal influence on the change in lithic orientation between series 2 and 3, orientations are also randomly distributed despite the absence of anthropogenic discard behaviour influencing this pattern. This, together with initial movement and orientation of smaller flakes and bipolar cores on the northern slope, suggests the influence of factors beyond slope and surface water flow, such as animal or wind activity. While currently, no livestock roam this site, ostriches and baboons do frequent the river valley. There were no signs of ostrich activity at this locality during the experiment and so their impact on the site is difficult to determine. While baboon activity was more blatant, their engagement with the experimental lithics was selective, demonstrated by the removal of a large freehand core between series 1 and 2. Although not observed, animal ‘kicking’ resulting in the horizontal, rather than vertical, displacement of lithics (a mode of movement originally introduced by Barberena 2008; outlined in Ozán 2017) may have influenced north slope lithic dispersal. However, minimal breakage suggests that low levels of trampling occurred, and despite their combined arrangement of increased levels of precipitation (although see below). However, the practical significance of flatness and elongation in predicting movement is low relative to slope. Thus, while these results show that idiosyncrasies of lithic shape may influence which miniaturised lithics are preserved in open-air semi-arid conditions, slope plays a primary role in catalysing movement.

Wet-dry oscillations played less of a role in lithic movement than we initially predicted. Its effects may gather in magnitude with increased surface exposure times. Our results may also suggest that the ‘wet’ season did not reach predicted levels of precipitation as in previous years. Real-time local climatic records would provide more control and resolution regarding the interplay between lithic movement and shifts in different climatic conditions. This, however, does not change the unexpected results observed for series 2. Series 2 mapping was carried out 7 months after the experimental assemblage was laid out. During the preceding 7 months of exposure, the assemblage was subjected to the region’s lowest levels of annual precipitation (<10 mm) (Fig. 5). With low levels of rainfall, we expected to find equally low levels of movement in the experiment. However, series 2 shows the extensive movement of flakes dispersed with random orientations across the north slope and linear clustering along channels on the south slope.
during setup, the relocation of more flakes than cores onto the north slope suggests that other processes influenced series 1 to 2 lithic dispersal. To date, precipitation is the principal climatic variable considered in archaeological formation research, with little research dedicated to investigating how wind can affect stone artefact movement. This alternative process would be worth testing if the initial upslope movement of lithics onto the north slope was indeed due to aeolian activity.

Our results also prompt us to question the value of lithic orientation as a measure of behavioural integrity in surface remains, especially with regards to miniaturised lithics. Traditionally, archaeologists have used random orientation...
among spatially clustered lithics to infer anthropogenic discard behaviour, either in the form of knapping or random provisioning and discard of lithics as individuals move across a landscape (cf. Lenoble and Bertran 2004; McPherron 2005; Oestmo et al. 2014). The results presented here demonstrate that haphazard orientation can also occur in response to redistribution by non-cultural processes.

Technological use and preservation in the open-landscape

Lithic technological categories (bipolar vs freehand cores or cores vs flakes) were shown to have low practical significance in determining a lithic’s movements. All the lithics moved over the course of a year, but they remained in close association with one another. This suggests that even at low frequencies, bipolar cores should be present when freehand cores are found in open-air miniaturised lithic scatters. This result has important implications for considering the structure of open-air sites in the Doring River Valley.

Archaeologists have puzzled over the low frequencies of miniaturised bipolar cores in open-air contexts along the Doring River Catchment (Low et al. 2017; Mackay et al. 2014b). The use and availability of anvils for bipolar reduction may be restricted to certain localities, influencing bipolar core discard across the landscape. While any large boulder may suffice as an anvil, ethnographic observations of stone tool using humans show anvils to be a selected, curated and sometimes transmitted component of the lithic toolkit (e.g. Weedman 2001; White 1968), where, in some cases, these
items are referred to as 'site furniture' (sensu Binford 1978).

The sporadic occurrence of bipolar technology may also be
the product of different activities that take place across the
open-landscape, possibly in response to raw material avail-
ability and/or quality. In terms of archaeological visibility,
different survey strategies can also affect the kinds of artefacts
identified during open-air data collection. Survey in the
Doring Catchment was carried out as either spatially exten-
sive, non-systematic field walking or intensive, cluster-
focused data collection. These possible factors for explaining
late Pleistocene LSA technological variability in the open-
landscape necessitate further experimental work and sampling
in this context.

**Preservation over time**

Our experiment resulted in high recoverability throughout the
22 months of open-air exposure, with 92% of the initial exper-
imental lithics relocated within the 5-m boundary zone.
Forssman and Pargeter (2014) note similarly high lithic recov-
er rates in their open-air trampling and preservation study.

Using an exponential decay equation, they estimated that un-
der the conditions of their experiment, > 99% of lithic material
would be winnowed downslope within 500 years. Our attri-
tion profile did not follow an exponential decay pattern and so
we decided to employ a simulation study to examine the attri-
tion profile of our lithics over longer periods of time. Our two
simulation models (one with negative lithic movement and the
other with only positive movement) show different outputs.
With negative movement, most lithics are 'lost' beyond our 5-
m experimental zone after 10,000 years, but they remain clus-
tered largely within a 50-m radius. Running the simulation for
500 years, we see that 14% of the tools remain within the 5-m
zone. Comparing these results to Forssman and Pargeter's
data, we see a greater retention of lithics after 500 years in
contexts akin to the Doring River Catchment because our data
are not in soft Kalahari sands and do not include the effects of
rapid downward trampling of lithics. These factors have a
strong influence on surface preservation at open-air archaeo-
logical sites. They suggest that the Doring River Catchment's
more consolidated soils may have been more ideal for tracking
open-air lithic scatters than softer, sandier environments.
Long-term simulations of the interaction between lithic movement and variables such as slope and artefact shape and size provide a useful heuristic tool for predicting what assemblage components might be expected at archaeological localities of differing ages. The archaeological scatters at UPK 7 range in age from the Holocene to at least the late Pleistocene (Low et al. 2017; Will et al. 2015). Our simulations predict the loss of an assemblage within the timespan of the Holocene (c. 10,000 years) suggesting that archaeological scatters thought to hold spatial integrity along the Doring River Catchment (i.e. Mackay et al. 2014b) may have only been exposed for short periods, despite its erosion-prone environment. This leads us to believe that processes involved in increasing the likelihood of preservation would benefit from further investigation.

Conclusion

Humans display a unique ability to modify their behaviour in response to and across varying landscapes. Rock shelters, although a seminal focus in southern African archaeological, provide only one perspective on late Pleistocene LSA human-landscape interaction. Open-air archaeology offers important insight into broader patterns of prehistoric human behaviour across space. Following archaeological observations at open-air localities along the Doring River Catchment (South Africa), our experimental study was designed to assess the differential preservation of miniaturised stone artefacts (cores and flakes) made using two different reduction strategies (bipolar and freehand) broadly representative of the late Pleistocene LSA in southern Africa. The study provides 22 months of observational data on the replicated lithic assemblage laid out in the Doring River Catchment, a region with an unusually high density of open-air archaeology. Our results show that surface slope is the strongest predictor of miniaturised tool movement. We observed similar movement patterns and attrition rates for both bipolar and freehand cores and flakes. The results provide minimal support for the idea that variation in the occurrence of bipolar technology between the catchment’s rock shelters and open-air scatters is due to differential preservation. The experiment demonstrates the necessity for assessing post-depositional effects on surface scatters in semi-arid open-air landscapes. While we present one possible scenario, it provides tangible insight into the various ways miniaturised lithics respond to exposed semi-arid conditions, bringing to the fore fundamental questions about the existence, spatial integrity and resilience of open-air lithic scatters.

Acknowledgements The authors would like to thank Ben Marwick for his help with the R code; the Department of Archaeology at the University of Cape Town for providing access to field equipment and storage space; Brian Jones for his analysis of our assemblage’s mineral composition; and Blair McPhee, Brian Jones, Aurore Val and Alex Blackwood for their assistance with the experiment’s data collection. A special thank you goes to the Pretorius family and Lilly Hough for their welcoming hospitality and land access in and around Uitspanskraal 7.

Funding information Funding for this research was provided by a University of Wollongong PhD Scholarship (Phillips), an Australian Government Research Training Program Scholarship (Low) and an Australian Research Council’s DECRA grant (Mackay, DE130100068).

References

Barich BE, Garcea EA, Giraudi C (2002) The effects of temporal and spatial patterns of human movement and variables such as slope and artefact shape and size provide a useful heuristic tool for predicting what assemblage components might be expected at archaeological localities of differing ages. Archaeol Anthropol Sci


Ebert JI (1987) Distributional archaeology: nonsite discovery, recording and analytical methods for application to the surface archaeological record


Favier Dubois M Dinámica sedimentaria y cambios ambientales en relación al registro arqueológico y tafonómico del cerro Cabeza de León Bahía San Sebastián (Tierra del Fuego, Argentina). In: Anales del Instituto de la Patagonia, Serie Ciencias Humanas, 1998, pp 137–152

Fisher E et al (2013) Archaeological reconnaissance for Middle Stone Age sites along the Pondoland Coast, South Africa. Paleo Anthropology 2013:104–137


innovations in South Asia ca. 35,000 years ago. Proc Natl Acad Sci
106:12261–12266
1312
Petraglia MD, Potts R (1994) Water flow and the formation of Early
1315
Paleolithic artifact sites in Olduvai Gorge, Tanzania. J Anthropol
1316
1317
Philips N, et al. Open-air preservation of miniaturised lithics: experimen-
1318
tal research in the Cederberg Mountains, Southern Africa (2018)
1319
Open Science Framework. https://doi.org/10.17605/OSF.IO/CXTA4
1320
Porraz G, Igreja M, Schmidt P, Parkinson JE (2016) A shape to the
1321
microlithic Robberg from Elands Bay Cave (South Africa). South
1322
Afr Humanit 29:203–247
1323
1324 (2013) The MSA sequence of Diepkloof and the history of southern
1325
1326
Powell A, Shennan S, Thomas MG (2009) Late Pleistocene demography
1328
Price-Williams D, Barham LS (1982) Swaziland archaeological research
1329 association. Nyame Akuma 21
1330
R Core Team (2015) R: a language and environment for statistical com-
1332 R-project.org/
1333
Rick JW (1976) Downslope movement and archaeological intrasite spa-
1334 tial analysis. Am Antiq 41:133–144
1335
1336 Stillbay et Howiesons Poort de l’abri Diekploof. Comptes Rendus
1337 Palevol 5:839–849
1338
Schick KD (1986) Stone Age sites in the making: experiments in the
1339 formation and transformation of archaeological occurrences. British Archaeological Reports Ltd, Oxford, England
1340
1341 Schiffer MB (ed) Formation processes of the archaeological record.
1342 University of Chicago Press, Chicago, p 117–139
1343
1345
1346 Schiffer MB (ed) Formation processes of the archaeological record.
1347
University of New Mexico Press, Albuquerque, NM, pp 265–303
1348
Schild R, Wendendorf F (2001a) Geoarchaeology of the Holocene climat-
1349 optimum at Nabta Playa, southwestern desert, Egypt. Geoa-
1350 rchaeology 16:7–28
1351
Schild R, Wendendorf F (2001b) Geomorphology, lithostratigraphy, geo-
1352 chronology and taphonomy of sites. In: Wendendorf F, Schild R (eds)
1353 Holocene settlement of the Egyptian Sahara: the archaeology of
1355
Shea JJ, Kleckner JD (1993) An experimental investigation of the effects
1356 of trampling on the results of lithic microwear analysis. J Archaeol Sci
1358
Sitjea L, Bertran P, Boulogne S, Bremet M, Cassard R, Delagnes A,
1359 Frouin M, Hatté C, Jaubert J, Khalidi L, Messager E, Mercier N,
1361 The paleoenvironment and lithic taphonomy of Shi’Bat Dhiya 1, a
1362 Middle Paleolithic site in Wadi Surdud, Yemen. Geoarchaeology 27:
1363 471–491. https://doi.org/10.1002/gea.21419
1364
Steele TE, Mackay A, Orton J, Schwartz S (2012) Varsche Rivier 003, a
1365 new Middle Stone Age site in southern Namaqualand. South Africa
1367
Stern N (1994) The implications of time-averaging for
1368 reconstructing the land-use patterns of early tool-using homo-
1370
Stern N, Bunn HT, Kroll EM, Haynes G, McBrearty S, Sept J,
1371 Willoughby PR (1993) The structure of the lower Paleolithic ar-
1372 cheological record: a case study from the Koobi Fora Formation.
1373 Curr Anthropol 34:201–225
1375 information at the entrance to the Northern Qingzang Plateau of the
1376 Kunlun Mountains of Qinghai. J Archaeol Anthropol Sci
1377 12266. https://doi.org/10.1016/j.jaas.2016.01.014
1378 Thompson JC, Mackay A, de Moor V, Gomani-Chindebu E (2014)
1379 Catchment survey in the Karonga District: a landscape-scale anal-
1380 ysis of provisioning and core reduction strategies during the Middle
1382 https://doi.org/10.1007/s10437-014-9167-2
1383 Toth N (1987) Behavioral inferences from Early Stone artifact
1385 https://doi.org/10.1016/0047-2484(87)90023-6
1387 and MSA III at Klases River main site, Cave 1A. J Archaeol Sci 37:
1389 Vogelsang R, Richter J, Jacobs Z, Eichhorn B, Linseele D, Roberts RG
1390 (2010) New excavations of Middle Stone Age deposits at Apollo
1391 Rockshelter, Namibia: stratigraphy, archaeology, chronology and
1394 River: J World Prehist 7:243–296
1395 Watkins L, Camilli EL (1992) The character of surface archaeological
1396 deposits and its influence on survey accuracy. J Field Arch 19:
1400 among the Gamo people of southern Ethiopia
1401 Wells LE (2001) A geomorphological approach to reconstructing ar-
1402 chaeological settlement patterns based on surficial artifact distribution.
1403 In: Earth sciences and archaeology. Springer, pp 107–143
1404 White JP (1968) Fabricators, Outils rcaillls or scalar cores? Aust J
1405 Anthropol 6:658–666
1406 Wilkinson TJ (1999) Holocene Valley fills of southern Turkey and
1407 northern Syria; recent geoarchaeological contributions. Quat Sci Rev
1410 reduction systems in southern Africa for the identification of early
1412 10.1371/journal.pone.0131824
1413 Wright DK, Thompson JC, Schilt F, Cohen AS, Choi JH, Mercader J,
1414 Nightingale S, Miller CE, Mentzer SM, Walde D, Welling M,
1415 Gomani-Chindebu E (2017) Approaches to Middle Stone Age
1417 https://doi.org/10.1016/j.jas.2016.01.014
1418 Zwyns N, Gladyshev SA, Gunchisuren B, Bolorbat T, Flas D,
1419 Dogandžić T, Tabarev AV, Gillam JC, Khatsenovich AM,
1420 McPherron S, Odsuren D, Paine CH, Pureykal JE, Stewart JR
1421 (2014) The open-air site of Tolbor 16 (northern Mongolia): prelimi-
1422 nary results and perspectives. Quat Int 347:53–65
1423
AUTHOR'S PROOF!

AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES.

Q1. Please check article title if presented correctly.
Q2. Please check affiliations if correctly modified and presented.
Q3. The symbol “<=” was changed to “≤”. Please check if appropriate.
Q4. Figures 9, 11-13, 17-19 contains text below the minimum required font size of 6pts inside the artwork, and there is no sufficient space available for the text to be enlarged. Please provide replacement figure file.
Q5. The occurrence of subpanel labels “a–c” in the citation of Fig. 11 found here was deleted as the corresponding artworks did not bear the said labels. Please check if appropriate.
Q6. The citation of Fig. 17 found here (“Simulating lithic movement and loss over longer time scales”, paragraph 2) was changed to Fig. 16 (originally not cited). Please check if appropriate.
Q7. Please check modifications made to the captions of Figs. 17–19 if appropriate.
Q8. Please check changes made here “even at low angles, reflecting observations made in other arid to semi-arid conditions” if appropriate.
Q9. Please provide complete bibliographic information for the reference entries “Ebert (1987)” and “Weedman (2011)”. 