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

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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

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

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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

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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, climate 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

Fig. 1 Location map of the Doring River and Biedouw confluence and recorded open-air and rock shelter localities mentioned in-text. Modified from Will et al. (2015) (N.B. since this publication, the far eastern scatter of UPK 7 has been assigned the new locality name 'UPK 9')

Fig. 2 Location map of late Pleistocene LSA sites from open-air (white circular markers) and rock shelter (black-white circular markers) contexts. Digital elevation model sourced from Jarvis et al. (2008). Sites numbered as follows: 1. Apollo XI, **2. Appleboskraal**, 3. Blydefontein, 4. Boomplaas, 5. Border Cave, 6. Buffelskloof, 7. Bushmans Rock Shelter, 8. Byneskranskop 1, 9. Cave James, 10. Dikbosch, **11. Elands Bay Cave**, 12. Equus Cave, 13. Erfkroon, **14. Faraoskop**, 15. Gobabeb, 16. Ha makotokoto, 17. Heuningneskrans, 18. Highlands Rock Shelter, 19. Kangkara, 20. Kathu Pan 5, **21. Klein Kliphuis**, 22.

Klipfonteinrand, 23. Lion Cavern, 24. Matjies River, 25. Melikane, 26. Melkhoutboom, 27. Nelson Bay Cave, 28. Ntloana Tsoana, 29. Pockenbank, 30. Pomongwe (not depicted), **31. Putslaagte 8**, 32. Ravenscraig, 33. Rose Cottage Cave, 34. Sehongong, 35. Shongweni, 36. Sidebe, 37. Siphiso, 38. Spitzkloof, 39. Strathalan B, **40. Uitspankraal 7**, **41. Uitspankraal 9**, 42. Umhlutuzana, 43. White Paintings Shelter (not depicted), 44. Wonderwerk, 45. Zebra River. Sites in bold are regionally proximate to our study area

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 Putslaagte 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 Parkington 2017; Mackay et al. 2018). Assemblages from both technocomplexes are found in rock

shelter contexts throughout this region, but to varying degrees (compare Högberg 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 unretouched 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 Putslaagte 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 bladelet 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; Forssman and Pargeter 2014; Kuman 1989; Moeyersons 1978; Oestmo et al. 2014; Pargeter and Bradfield 2012). This contrasts extensive research on open-air post-deposition and formation in Central, East and North Africa (e.g. Barich et al. 2006; Benito-Calvo and de la Torre 2011; Hassan 1997; Haynes 2001; Koopman et al. 2016; Kuper and Kröpelin 2006; Schild and Wendorf 2001a, b; Stern 1994; Stern et al. 1993; Wright et al. 2017), and globally, in Europe and Asia (e.g. Benito-Calvo et al. 2009; Bertran and Texier 1995; Enloe 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. Araujo and Feathers 2008; Araujo et al. 2013; Bettis and Mandel 2002; Dunnell and Simek 1995; Ozán 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;

Fig. 3 Examples of bladelets and blades (**a, b**) from Uitspankraal 9 and freehand bladelet cores from Uitspankraal 9 (**c**) and Appleboskraal (**d**) surface scatters. Note the diversity in fine-grained raw materials and dimensions

Nielsen 1991; Pargeter and Bradfield 2012; Shea and Klenck 1993; Toth 1987). Of the few experimental studies that examine displacement, fewer still assess surface assemblage disaggregation in arid environments (e.g. Eren et al. 2010; Forssman and Pargeter 2014; Ozán 2017; Pargeter and Bradfield 2012; Rick 1976; Schick 1986).

Objectives

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,

271 vegetation, Fig. 4) (Favier Dubois 1998; Martin 2006; Ozán
 272 et al. 2015). The surface morphology is defined by a ridge
 273 and two opposed slopes of different average gradients (north
 274 [$\sim 9^\circ$] and south [$\sim 11^\circ$], Fig. 4). The south slope is more rilled
 275 and therefore more uneven than the north slope (Fig. 4), which
 276 may increase flow velocity, increasing the force available to

277 cluster objects initially and subsequently shift larger objects
 278 downslope (e.g. cores, Ozán (2017) and citations therein).

279 The size of the study area available determined the sample
 280 size of the experimental assemblage. A total of 409 experi-
 281 mental lithics (freehand cores = 29, bipolar cores = 30,
 282 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 modelling 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

Fig. 6 Experimental dacite lithic assemblage (from top left): **a** freehand cores ($n = 29$), **b** bipolar cores ($n = 30$) and **c** flakes ($n = 350$)

351 analogous to the fine-grained raw materials that were
 352 used by LSA hunter-gatherers. Dacite glass is a fine-
 353 grained volcanic rock that is both chemically and visibly
 354 discernable from raw material found in the western Cape.
 355 Its mineral composition provides a signature for detecting
 356 and distinguishing our experimental lithics from the land-
 357 scape's raw and archaeological material.
 358 To explore whether the technological contrasts between
 359 rock shelter and open-air lithic assemblages result from post-
 360 depositional attrition of specific technological classes in open-
 361 air contexts, we based the production parameters for our rep-
 362 licated assemblage on the technological composition of late
 363 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 exper-
 imental and archaeological assemblages. Statistical compar-
 isons of the core size variables also show no significant differ-
 ences between the assemblages (Table 1). Flake size compar-
 isons 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

Fig. 7 Box/whisker plot comparisons of core size (maximum length, width and log weight) between the Klipfonteinrand, Sehonghong and experimental assemblages

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

Fig. 8 Box/whisker plot comparisons of flake size (maximum length, width and thickness, and log weight) between Klipfonteinrand, Sehonghong and the experimental assemblage

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 ANOVA test comparisons for core length, width and weight between the two archaeological assemblages and the experimental assemblage

Comparisons	Df	Sum sq	Mean sq	F value	Pr(>F)	Cohen's f effect size
Core length by assemblage type	2	67	33.71	0.428	0.653	0.0652
Residuals	201	15,845	78.83			
Core width by assemblage type	2	83	41.59	0.629	0.534	0.079
Residuals	201	13,296	66.15			
Core weight by assemblage type	2	7.7	3.853	1.72	0.182	0.1311
Residuals	201	448.1	2.241			

Table 2 ANOVA test comparisons for flake length, width and weight between the two archaeological assemblages and the experimental assemblage

Comparisons	<i>Df</i>	Sum sq	Mean sq	<i>F</i> value	Pr(> <i>F</i>)	Cohen's <i>f</i> effect size
Flake length by assemblage type	2	17,815	8908	161.8	< 0.0001	0.53
Residuals	1139	62,724	55			
Flake width by assemblage type	2	20.45	10.225	50.44	< 0.0001	0.29
Residuals	1139	230.51	0.203			
Flake thickness by assemblage type	2	8.4	4.221	12.78	< 0.0001	0.14
Residuals	1139	376.1	0.33			
Flake weight by assemblage type	2	282.5	141.27	67.92	< 0.0001	0.34
Residuals	1139	2366.9	2.08			

Texier 1995; Dibble et al. 1997; Enloe 2006; Lenoble and Bertran 2004; Lotter et al. 2016; McPherron 2005, 2018; Oestmo et al. 2014; Ozán 2017; Sitzia et al. 2012; Wright et al. 2017; Zwyns et al. 2014). We collected individual lithic orientations to examine their arrangement in response to non-cultural processes. There are mixed perspectives on the use of size and shape cut-offs when recording orientation (cf. McPherron 2005). The experimental assemblage is composed of miniaturised lithics, with a high proportion of blades and bladelets. Being an assemblage of miniaturised lithics, dimensions often fall below the recommended size limit (> 20 mm) for lithic fabric analysis (e.g. Lenoble and Bertran 2004). Over one third ($n = 153$) of our assemblage measures less than 20 mm in length. However, over half of these lithics are elongated (length/width ratio > 1.6, $n = 83$). Therefore, we recorded orientations for all lithics that had a discernible longitudinal axis and assess their fabric strength with dimensional susceptibility in mind.

Brunton compass bearings were corrected for magnetic declination and logged to observe how assemblage orientation changed at each recording series. Average dip/slope of the north and south slopes represents lithic plunge. Rose diagrams are used to plot north and south slope orientations. Although not always the case (see Oestmo et al. 2014), statistically random orientations are traditionally considered indications of knapping or discard behaviour rather than secondary, non-cultural processes. This 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)).

Table 3 Statistical comparisons of archaeological bipolar and freehand cores from Sehonghong and Klipfonteinrand

	<i>Df</i>	Sum sq	Mean sq	<i>F</i> value	Pr(> <i>F</i>)	Cohen's <i>f</i> effect size
Core weight by technology	1	2861	2860.6	27.064	< 0.0001	0.93
Core weight by site	1	433	432.8	4.095	0.0449	0.06
Residuals	141	14,903	105.7			
Core length by technology	1	2199	2198.6	31.96	< 0.0001	0.57
Core length by site	1	20	19.9	0.29	0.591	0.08
Residuals	142	9768	68.8

Fig. 9 Box/whisker plot comparisons of bipolar and freehand core weight and length for Klipfonteinrand and Sehonghong assemblages

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 outnumber 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

t4.1 **Table 4** Class type counts by slope and attrition per recording series

t4.2	Class type	Series															Series total attrition
t4.3		1			2				3				4				
t4.4		Count		Loss	Count		Loss	Count		Loss	Count		Loss				
t4.5		South	Total		North	South	Total	North	South	Total	North	South	Total				
t4.6	Bipolar core	30	30	0	6	18	24	− 6	4	19	23	− 1	2	15	17	− 6	− 13
t4.7	Freehand core	29	29	0	5	22	28	− 1	5	22	27	− 1	3	20	23	− 4	− 6
t4.8	Flake	350	350	0	126	224	350	0	130	203	333	− 17					− 17
t4.9	Total	409	409	0	137	264	402	− 7	139	244	383	− 19	5	35	40	− 10	− 36

539 slopes (Fig. 11), followed by freehand cores (Figs. 11 and 12).
540 Despite their spread of distance values, flake counts appear
541 relatively well constrained around their median for series 2
542 and 3, on both the north and south slopes (Fig. 11). On aver-
543 age, 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

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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)

Fig. 11 Box and whisker plot showing interactions between lithic movement and lithic class, slope and series for the series 2 and 3 data

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 modelling 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 GALMSS package in R which allows greater flexibility when working with highly skewed response variables.

Fig. 12 Box and whisker plot showing interactions between lithic movement and lithic class, slope and series for the cores in series 2, 3 and 4

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

Fig. 13 Histograms of log-transformed predictor variables. Horizontal movement is shown in its untransformed state to illustrate its patterning

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

Table 5 Summary statistics for linear model assessing lithic size as a predictor of lithic movement (response variable)

Series	Predictor	Estimate	Std. error	<i>t</i> value	Pr(> <i>t</i>)
2	Weight	−0.25	0.30	−0.85	0.40
	Length	0.07	0.44	0.16	0.87
	Width	0.63	0.36	1.74	0.08
	Thickness	−0.91	0.34	−2.69	0.01
3	Weight	−0.54	0.33	−1.66	0.10
	Length	0.44	0.48	0.91	0.36
	Width	0.45	0.35	1.29	0.20
	Thickness	−0.61	0.39	−1.57	0.12

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

Series	Predictor	Estimate	Std. error	<i>t</i> value	Pr(> <i>t</i>)
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

t7.1	Table 7 Generalised r^2 values (sensu Nagelkerke 1991) describing the practical significance of the shape and size predictor sets on tool movement	Series	Predictor set	Generalised r^2
t7.2				
t7.3		2	Shape	0.12
t7.4		3		0.10
t7.5		2	Size	0.15
t7.6		3		0.20

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 ($\chi^2 [4, N = 199] = 0.8844$, $p = 0.9268$). Similarly, cores show no significant differences between series 2, 3 and 4 ($\chi^2 [3, N = 199] = 0.6908$, $p = 0.8754$, 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 emulates 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 we 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

t8.1	Table 8 Summary statistics for ANOVA model with lithic movement as the response variable and series, class (bipolar core, freehand core, flake), slope (north/south), climate (wet/dry) and their interactions as predictors. Data are for cores and flakes in series 2 and 3 combined	Predictor	Df	Sum sq	Mean sq	F value	Pr(>F)	Cohen’s f effect size
t8.2								
t8.3		Series	1	2.4	2.4	2.139	0.1441	0.05
t8.4		Class	2	33.8	16.9	15.194	< 0.0001	0.19
t8.5		Slope	1	448.7	448.7	403.141	< 0.0001	0.72
t8.6		Slope:climate interaction	1	0.5	0.5	0.434	0.5102	0.02
t8.7		Series:class interaction	2	0.3	0.2	0.149	0.862	0.01
t8.8		Class:slope interaction	2	7.4	3.7	3.342	0.0359	0.09
t8.9		Residuals	768	854.8	1.1			

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

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

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 down-slope ("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).

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

t10.1 **Table 10** Permutation tests
t10.2 statistics estimated by Monte
t10.3 Carlo simulation comparing lithic
t10.4 orientation and plunge by series,
t10.5 slope and lithic class

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

743 Figure 18 summarises the results of our first lithic simula-
744 tion model in which lithics moved on a cumulative unidirec-
745 tional basis (model 1 in Fig. 17). The model outputs in
746 Table 13 show that 15 lithics lie beyond the 5-m experimental
747 boundary after 10 simulated lithic movement events (each
748 accounting for a 12-month period). After 100 events
749 (100 years), this number jumps to 180 lithics, and after 1000
750 events, the assemblage has moved well beyond the experi-
751 mental boundary. The data show that a degree of assemblage
752 structure is maintained throughout the movement simulations,
753 driven by the fact that our model did not account for variations
754 in lithic coordinates. The model also fails to account for sig-
755 nificant predictors of movement like flatness which will ho-
756 mogenise movement patterns across the population. Future
757 simulation work will focus on including these complicating
758 factors.
759 Figure 19 summarises the results of our second lithic
760 simulation model, in which lithics moved in both nega-

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

Fig. 15 Bar plot showing lithic counts in series 1, 2 and 3

Table 11 Summary statistics for chi-square comparisons of lithic loss between series 2 and 3 (cores and flakes) and series 2, 3 and 4 (cores)

Comparison	Chi-square	Df	p value
Series 1, 2 and 3	0.8844	4	0.9268
Series 1, 2, 3 and 4	0.6908	3	0.8754

Discussion

Predictors of miniaturised lithic movement

Our experiment addresses a fundamental question in archaeology: Does the technological structure of open-air lithic assemblages represent behavioural variability and/or preservation bias? In this experiment, we tested for movement against rainfall and slope (gravity), predicting that increased overland flow together with slope gradient would catalyse movement of smaller, lighter lithics downslope, south of the study area's ridgeline. Rather than rainfall, our results show that the strongest predictor of a lithic's movement was the slope onto which it was originally placed, even at low angles, reflecting observations made in other arid to semi-arid conditions (see Bertran et al. 2012; Fanning and Holdaway 2001; Nash et al. 1987; Schick 1986). However, counter to our preliminary predictions, more initial movement occurred on the northern slope, not the southern (steeper) slope. This involved rapid assemblage disaggregation between flakes and cores within the first 7 months of discard, slowing after this time. A similar pattern of initial, rapid movement has been noted in other movement experiments (e.g. Forssman and Pargeter 2014). However, over time, we observed that lithics placed on the steeper south slope eventually moved more extensively than lithics on the north slope.

Counter to our own and published expectations, lithic size (maximum width, length, thickness and weight) and shape proved to be poor practical predictors of movement. Smaller, lighter tools did not move more extensively than larger tools. Elongation, one of the key axes of technological variability in late Pleistocene LSA lithic assemblages, played a minimal role in predicting lithic movement. During the first 7 months of exposure, flatter lithics moved more. However, between 7 and 12 months of exposure, elongation shows increased influence on lithic movement, possibly with the added influence 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

Table 12 Odds ratio values describing the odds of lithic loss for lithics in the two chi-square tests. Bipolar cores are the comparison class in each test, and as such, they do not have odds ratio confidence intervals

Comparison	Variable	Odds ratio	Lower 95%	Upper 95%
Series 1, 2 and 3	Bipolar core	1	NA	NA
	Freehand core	1.21	0.57	2.55
	Flake	1.25	0.72	2.19
Series 1, 2, 3 and 4	Bipolar core	1	NA	NA
	Freehand core	1.21	0.57	2.55

Fig. 16 Bar plot showing core counts in series 1, 2, 3 and 4

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

Fig. 17 A basic overview of our two lithic movement simulation models

Fig. 18 Simulation model outputs from model #1 in which lithics moved in a positive only direction. Red line indicates the extent of the experimental area

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.

Table 13 Model outputs showing the number of simulation runs and lithic movement beyond the 5-m experiment zone

Model	Interactions	Artefacts beyond 5 m boundary
Positive movement	10	15
	100	180
	1000	409
	10,000	409
Positive/negative movement	10	14
	100	172
	1000	314
	10,000	361

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

Fig. 19 Simulation model outputs from model #2 in which lithics moved in both positive and negative directions. Red line indicates the extent of the experimental area

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 availability 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 extensive, 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 experimental lithics relocated within the 5-m boundary zone. Forssman and Pargeter (2014) note similarly high lithic recovery rates in their open-air trampling and preservation study.

Using an exponential decay equation, they estimated that under the conditions of their experiment, > 99% of lithic material would be winnowed downslope within 500 years. Our attrition profile did not follow an exponential decay pattern and so we decided to employ a simulation study to examine the attrition 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 clustered 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 archaeological 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 archaeology, 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.

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AUTHOR QUERIES

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- Q1. Please check article title if presented correctly.
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- Q3. The symbol “<=” was changed to “□”. Please check if appropriate.
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- 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)”.