Regional Variability in Lithic Miniaturization and the Organization of Technology in Late Glacial (~18 – 11 kcal BP) Southern Africa

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Abstract

Miniaturized stone tools made by controlled fracture are reported from nearly every continent where archaeologists have systematically looked for them. While similarities in technology are acknowledged between regions, few detailed inter-regional comparative studies have been conducted. Our paper addresses this gap, presenting results of a comparative lithic technological study between Klipfonteinrand and Sehonghong – two large rockshelters in southern Africa. Both sites contain Late Glacial (~18 – 11 kcal BP) assemblages, though are located in regions with different geologies, climates and environments. Results demonstrate that lithic miniaturization manifests differently in different regions. Both assemblages provide evidence for small blade production, though key differences exist in terms of the specific technological composition of this evidence, the raw materials selected, the role played by bipolar reduction and the manner in which lithic reduction was organized. Patterned variability of this nature demonstrates that humans deployed miniaturized technologies strategically in relation to local conditions.

Keywords: lithic miniaturization, organization of technology, Late Glacial, southern Africa

Introduction

Lithic miniaturization, systematically producing and using small stone tools by controlled fracture, is among hominin lithic technology's most distinctive characteristics (Pargeter and Shea 2019). Assemblages containing detached flakes, retouched tools, and cores less than 25 – 50 mm long occur from >2 mya (million years ago) but become widespread globally by about 40 thousand years. Miniaturized toolkits proliferate in Upper Paleolithic, Late Pleistocene Later Stone Age (LSA) and Holocene contexts across Eurasia and Africa and later in the Americas and Australia (e.g. Ambrose 2002; Doelman 2008; Elston and Brantingham 2002; Kuhn 2002; Clarkson et al. 2009). While small stone artefacts are found throughout the Stone Age, their presence in contexts of lithic miniaturization is recognised to be the result of more systematic methods of production suggestive of intent rather than accidental (Pargeter 2016, 221). We emphasize that systematic lithic miniaturization can be distinguished from unintentional small debris production by focussing on raw material contexts around sites, evidence for core reduction and/or management on even the smallest flakes and nodules, and by seeking evidence for the use of small flakes (cf. Pargeter & Shea 2019).

Archaeological data show how Late Pleistocene *Homo sapiens* pioneered efforts to rapidly generate novel solutions for survival in diverse, environments, exhibiting remarkable adaptive plasticity (e.g. Barker et al. 2007; d'Errico and Stringer 2011). Among such systems are miniaturized lithic technologies, including small cores and flakes, blades (sometimes referred to as bladelets), small backed and retouched tools, which provide several benefits such as raw material economy, functional flexibility, and replaceability (e.g. Elston and Kuhn 2002; Pargeter and Shea 2019). These economic benefits would have direct payoffs in environments where suitable raw material was scarce, where knappable rock occurred in small package sizes, or where groups had to maintain high levels of mobility/technological readiness (Kuhn 1995). Archeologists increasingly observe variable patterns of lithic miniaturization through time and across space (Ambrose 2002), suggesting that it was not an inevitable consequence of human tool use, but more likely a strategic behavior deployed in specific environments and periods (Mitchell 1988).

Yet, many discussions of miniaturized technologies are based on an 'a priori' assumption that such technological systems are structurally 'uniform', or at least similar enough to warrant broader synthesis into categories such as 'microliths' and processes such as ‘microlithization’. John Goodwin (1953, 87), a founding figure in South African archaeology, once marveled at the “clear conservatism of the great microlithic spread … Everywhere there is remarkably little variation in either type or technique.” Goodwin’s ideas still pervade contemporary thinking on lithic miniaturization. However, a significant degree of variation is possible when it comes to miniaturized technological systems with popular terms such as ‘microlithic’ becoming catch-all categories “…for a wide range of miniature tool production strategies” (Pargeter and Redondo 2016, 31). For example, North Africa’s ‘microlithic’ Iberomaurusian assemblages (<22 kcal BP) show backed bladelets, burin cores, and end scrapers (Olszewski et al. 2011; Sari 2014), while similarly dated ‘microlithic’ assemblages from the other end of the continent in southern Africa show few retouched tools and higher rates of bipolar reduction (Mitchell 1988; Porraz et al. 2016a; Low and Mackay 2016). When referring to ‘microliths’, archaeologists are clearly not always referring to the same thing, either typologically or technologically (Elston and Kuhn 2002; Hiscock et al. 2011; Pargeter and Redondo 2016).

Several hypotheses have been advanced to explain this variability including models focused on cultural choices, population demography and group mobility, and adaptations to environmental change (Mitchell 1988; Belfer-Cohen and Goring-Morris 2002; Ambrose 2002; Bleed 2002; Bousman 2005; Costa et al. 2005; Fisher 2006; Doelman 2008; Petraglia et al. 2009; Fullagar et al. 2009; Roberts et al. 2015; Goldstein and Shaffer 2016; Low and Mackay 2016; Porraz et al. 2016a; Clarkson et al. 2018; Chase et al. 2018). Tryon and Faith (2016), for example, argue increasing site occupation intensity at Nasera rockshelter in Tanzania ~40 ka resulted in decreased access to raw materials and increased reliance on local rocks. These demographic processes placed greater pressure on humans to conserve raw material by using increasingly bipolar dominated miniaturized lithic reduction strategies (cf. Shott 1989). Their model links increased site occupation intensity with resource scarcity and greater lithic miniaturization (small core reduction). It also finds that more efficient technologies (i.e. bipolar reduction related to bladelet production) manifest at times of increased site occupation intensity (cf. Eren et al. 2013). In the context of Late Pleistocene southern Africa, Mitchell (1988) argued that Pleniglacial (including the Late Glacial period) humans faced diminished environments and time stress on resource procurement resulting in greater efforts to develop and maintain more efficient technologies using smaller tools. Mitchell’s hypothesis implies factors affecting lithic miniaturization’s structure were widespread; as suggested by models to explain other shifts in southern Africa's Late Pleistocene lithic technologies (e.g. Mackay et al. 2014).

Ambrose's (2002) summary of the African Middle Stone Age (MSA) and Later Stone Age (LSA) evidence for lithic miniaturization shows how small blades, backed tools, and unretouched flakes vary across sub-Saharan Africa. He argues that these different elements should be conceptualized as separate phenomena. Pargeter and Shea (2019) argue that several factors might explain the ebb and flow of these various miniaturized toolkit components including the invention of composite hafted tools, new lithic production strategies, lightweight projectiles, for weapon systems, increased group mobility or some combination of these factors. Therefore, we should not expect the specific tactics by which prehistoric toolmakers achieved lithic miniaturization to have remained fixed and unvarying. Nor should we expect morphological variability among miniaturized stone tools to be a "monolithic" phenomenon over time and across space. Instead we should be asking how and why processes of lithic miniaturization vary and what this can tell us about prehistoric human behavioral variability.

The detailed inter-site and inter-region comparative analyses of miniaturized lithic assemblages necessary to uncover these processes are, however, rare (though see Mitchell 1988; Hiscock et al. 2011). One recent exception is Lewis' (2017) cross-continental study focused on documenting internal variability in Late Pleistocene miniaturized lithic assemblages from South Asia and southern Africa using quantitative attribute analyses. Her work documented how these region's lithic miniaturization strategies differ in the tools selected for retouch, the core reduction techniques, and the raw material choices. The results showed raw material variability played a minimal role in structuring technological differences, even toolmakers sharing the same raw material sources implemented different flaking strategies (Lewis 2017). Lewis' comparative study highlights the value in broad cross-continental scale comparisons of evidence for lithic miniaturization.

Lithic miniaturization: A southern African perspective

Southern Africa encompasses the modern political boundaries of South Africa, Lesotho, and Swaziland. This region benefits from a long lithic research history, well-dated and generally well-preserved Late Pleistocene archaeological sites, and lithic databases sharing a common focus on quantitative attribute approaches (e.g. Deacon 1984; Mitchell 1988; Wadley 1993;

Pargeter 2016; Mackay 2016; Low and Mackay 2016; Wilkins et al. 2017). These collective qualities make southern Africa the ideal context for inter-site comparative lithic studies.

Southern Africa provides some of the earliest evidence for systematic lithic miniaturization. Small backed tools and small blades occur by at least 70 ka at a suite of southern African Middle Stone Age (MSA) sites (Brown et al. 2012). The region's Howieson's Poort (HP) techno-complex, dated 64.8 – 59.5 ka, has the best known and studied small backed tools in Africa which link their production specifically to functional innovations (see Henshilwood 2012 and Wadley 2015 for recent reviews). The region's early and episodic increases in lithic miniaturization are followed by several shifts towards larger flake and blade production systems.

Late Marine Isotope Stage (MIS) 3 (c. 29 – 48 kcal BP) lithic assemblages show variable frequencies of miniaturized components with some assemblages containing small unretouched flakes and small blades, small flake and blade cores as well as high bipolar core frequencies (Mitchell 1988; Wadley 1993). At this time, those miniaturized lithic assemblages that are associated with MIS 3 are largely confined to the region's summer rainfall zone (SRZ; cf. Chase and Meadows 2007) implying possible environmental drivers (Mackay et al. 2014). Overall, however, Late MIS 3 lithic assemblages are noted for being heterogenous and technologically variable (Mackay et al. 2014, 13).

During MIS 2 (c. 29 – 12 kcal BP), a second pulse of lithic size reduction initiates across a wider swath of southern Africa's summer, winter, and year-round rainfall zones (Mackay et al. 2014). The best dated and longest records for this period are large rock-shelter sites such as Elands Bay Cave, Nelson Bay Cave, Boomplaas, Rose Cottage Cave, Sehonghong, and Umhlatuzana. Toolmakers used fine-grained local rocks to manufacture most MIS 2 lithic assemblages (e.g. Low and Mackay 2016). Cores are small, and toolmakers emphasize the production of miniaturized flakes and blades (Low and Mackay 2016). Bipolar reduction features prominently in these assemblages (Mackay et al. 2015; Porraz et al. 2016a).

In earlier MIS 2 (c. 29 – 18 kcal BP), archaeologists refer to lithic assemblages either as MSA/LSA transitional or as Early LSA, reflecting their 'mix' of so-called MSA and LSA technological features (Mitchell 1988, but see Low and Mackay 2016). At some sites, such as Umhlatuzana, MSA/LSA 'transitional' assemblages may genuinely represent a taphonomic mix of assemblages (Kaplan 1990). However, enough secure examples show the trend towards increased lithic miniaturization in MIS 2 was a real phenomenon in at least some areas of southern Africa (e.g. Low and Mackay 2016; Porraz et al. 2016b).

Small blades become the type fossil in later MIS 2 lithic assemblages (<25 kcal BP) and archaeologists refer to them collectively as the 'Robberg' techno-complex (Mitchell 1988). Frequent on-site reduction, local raw material use, and the relatively low frequencies (c. <1%) of artifact retouch suggest toolmakers' emphasis on disposable toolkits (Lombard et al. 2012). Sites with large and well-preserved faunal assemblages, such as Sehonghong and Boomplaas, emphasize the hunting of large- and medium-sized ungulates (Deacon 1984; Mitchell 1988). From these data, some archaeologists emphasize shared technological traditions and broadly similar behavioral responses across southern Africa (see Ambrose and Lorenz, 2009; Lombard et al., 2012), while others infer complex land-use systems involving variable group sizes, seasonal mobility, social connectivity, and functional flexibility (Carter et al. 1988; Mackay et al. 2014; Stewart and Mitchell 2018).

Variability in southern Africa's miniaturized MIS 2 lithic assemblages

Mitchell's (1988) study remains the most comprehensive and detailed comparative analysis of Late Pleistocene lithic miniaturization in southern Africa. He examined a range of MIS 2 lithic assemblages for evidence of synchronic and diachronic differences in raw material selection, tool function(s), and reduction strategies. He argued that typological similarities and technological variability were driven in part by the underlying geological constraints in different parts of southern Africa. At winter and year-round rainfall zone sites (i.e. Boomplaas and Nelson Bay Cave), Mitchell observed assemblages dominated by the use of local quartz, bipolar reduction and flake/informal blade production. Other archaeologists noted similar patterns at sites in southern Africa's summer rainfall zone (i.e. Heuningneskrans and Bushman rock-shelter) where quartz was the dominant local raw material (Deacon 1984; Clark 1999). Summer rainfall zone sites (i.e. Sehonghong and Rose Cottage Cave), where chert is the dominant rock, showed more formal blade production on pyramidal cores and greater core management through cresting techniques (Wadley 1993; Porraz et al. 2015). Mitchell (1988) argued that although the lithic assemblages from these different regions appeared distinct from one another, they were grounded in a similar emphasis on small blade production with the variable geological contexts and raw material access driving differences between the regions.

More recent studies have added complexity to Mitchell's observations. Low and Mackay (2016) show that in the Western Cape Region, toolmakers used bipolar reduction to miniaturize the reduction of small freehand quartz, hornfels, silcrete, and chert cores. They show sites in regions with quartz-rich surface geologies (e.g. Putslaagte 8) show low bipolar core frequencies. Using simulation studies and experimental archaeology in South Africa's Cederberg Mountains, Phillips et al. (2018) demonstrate that paucity of bipolar cores may have more to do with human behavioral variability at landscape scales rather than being related to underlying geological constraints. Low and Mackay's (2016) data also show temporal dimensions to this complexity with bipolar core frequencies fluctuating across time. The patterns suggest possible technological variability as a function of group mobility dynamics, foraging choices, social transmission biases, or a combination of these processes.

Other studies are contributing to a more complex view of southern Africa's Late Glacial miniaturized toolkits. Porraz and colleagues (2016a) demonstrate toolmakers at Elands Bay Cave truncated the base of cores to constrain blade size and morphology. This 'prepared core technology' constrains the form of the resultant blade prior to detachment. The observation at Elands Bay Cave is interesting considering that most archaeologists argue that prepared cores 'disappear' after the MSA (e.g. Mitchell 1988; Wadley 1993; McBrearty and Brooks 2000). At the lowland Lesotho site of Ntloana Tšoana, Pargeter (2016) notes a pattern of small bipolar core dominant lithic miniaturization adapted to the reduction of prismatic quartz crystals dated c. 12 – 14 kcal BP (Pargeter and Hampson 2019). Low and Mackay (2016) document a clear raw material shift from hornfels to silcrete and a decrease in blade size in Putslaagte 8's Robberg assemblage dated ~18 – 22 kcal BP. These results show that a uniform Late Pleistocene microlithic technology in southern Africa is unlikely (e.g. Wadley 1993; Mitchell 1995; Mackay et al. 2014).

Research

This study adds to previous quantitative comparative studies of lithic miniaturization (i.e. Mitchell 1988; Lewis 2017) by advancing an organization of technology approach to Late Glacial lithic assemblages. Organization of technology approaches weigh the design systems, costs, and benefits of stone-tool-making strategies in relation to specific archaeological contexts (Binford 1979; Bamforth 1986; Nelson 1991; Shot 2018; Bamforth and Bleed 1997; Torrence 1989; Bleed 1986, 2002). In emphasizing time, energy, and ecological factors, organization of technology approaches have had a great deal of success in explaining why toolkits vary across time and space (e.g. Low and Mackay 2018; Bleed 2002; Elston and Brantingham 2002; Goebel 2002; Lombard and Parsons 2008; Bousman 1993, 2005; Petraglia et al. 2009). Organization of technology approaches assume that prehistoric humans optimized their lithic technologies by minimizing the costs of having a readily available toolkit (extracting as many small flakes and blades from a core) while at the same time maximizing the benefits when deploying such a toolkit (having easily repaired multicomponent toolkits). Stone-tool technologies are rarely ever optimal, but by applying organization of technology models to behavior in the archaeological realm, archeologists hope to better evaluate and understand the contexts and decision-making processes governing miniaturized stone-tool technologies when models are falsified or fail to fully account for observed archaeological patterns.

Our aim is to better understand processes of lithic miniaturization by exploring regional variability and/or continuity associated with the miniaturization processes that occurred during MIS2 (i.e. commonly referred to as the Robberg Industry). Such assemblages have traditionally been considered as relatively uniform across the southern Africa. This study therefore uses quantitative descriptions of lithic attribute data to explore variability in MIS 2 lithic miniaturization processes at two large rockshelters from environmentally and geologically distinct regions: Klipfonteinrand (South Africa) and Sehonghong (Lesotho) (Fig. 1). The following questions are addressed:

1. How do the sites differ in terms of their miniaturized lithic systems?
2. How do the sites differ in terms of their structure and organization of blade-based miniaturized technologies?
3. To what degree does bipolar reduction contribute to each site's technological organization and lithic miniaturization?
4. To what extent are technological adjustments and lithic miniaturization interlinked?
5. To what degree are technological efficiency and reduction intensity similar at the two sites?

Methods

We begin by outlining our materials and methods starting with a summary of the archaeological and environmental backgrounds to the sites and samples chosen for analysis. We aggregate each site's sub-assemblage data into a Late Glacial sample defined chronologically as the interval between 18 and 12 kcal BP. This strategy allowed for broad comparisons between the two sites and regions as detailed comparisons of each site's sub-assemblages are published elsewhere (Mitchell 1995; Low 2019). Figure 2 compares the calibrated radiocarbon ages of the aggregated excavation units for Klipfonteinrand and Sehonghong illustrating the overlapping ages between the two sites.

Klipfonteinrand (Western Cape Province, South Africa)

Klipfonteinrand (KFR) is a large east facing rockshelter measuring ~18 meters along the entrance and ~13.5 meters from the dripline to the rear of the shelter. The rockshelter is situated in the arid interior east of the Cape Fold Mountain Belt in the eastern Cederberg and within the modern WRZ of the Western Cape Province in South Africa (Fig. 1). Geologically the site resides in the Table Mountain Sandstone Group though also borders the quartzite- and shale-dominant Bokkeveld Series of the interior. The Doring River is situated approximately 15 km to the north-east of the site with two of its highly seasonal tributaries, the Biedouw and Brandewyn Rivers, lying to the south and west respectively.

The site was first excavated by John Parkington and colleagues in 1969 who recovered archaeological material associated with the mid to late Holocene from the upper deposits of their trench and an undated MSA assemblage from the underlying lower units (Parkington 1977; Thackeray 1977; Volman 1981; Mackay 2009). The site was re-excavated under the direction of Alex Mackay in 2011/12 with extensions made to Parkington's original trench (resulting in the excavation of an additional 3 m x 1 m area) as well as the addition of a new trench (comprised of five squares) to the rear of the shelter. Specific details regarding the excavation procedure and dating program can be found in Mackay et al. (in review.) with only a brief overview provided here. Sediment was removed in excavation units of 30 mm or less guided by natural stratigraphy. Lithics >20 mm in addition to all cores, retouched flakes and potentially 'diagnostic' artefacts types (such as blades) regardless of size and faunal remains >30 mm were plotted using a total station. Sediment was dry-sieved using 3 mm and 1.5 mm mesh sieves.

Mackay’s excavations helped to refine Klipfonteinrand’s archaeological sequence revealing evidence for use of the rockshelter spanning >120 ka (Mackay et al. in review). While the front trench is predominantly associated with occupation during the MSA, the back trench is predominantly characterized by an LSA sequence. Mackay and colleagues recovered the material discussed in this paper from the rear trench during their more recent excavations. The stratigraphic aggregates relevant to this paper include from oldest to youngest: White Series (WS), Orange Band (OB) and the Laminated Brown and White Series (LWBS). Accelerated Mass Spectrometry radiocarbon ages bracket this material to ~16.9 – 14 kcal BP (Fig. 2).

Modern environment, vegetation, and the availability of knappable rocks

The Cederberg Mountains in which Klipfonteinrand is situated make up the northernmost range of the Cape Fold Mountain Belt in the southwest of the Western Cape province. The height of this mountain chain ranges from 1000 m - 2300 m and it acts as a topographical barrier that restricts precipitation to the mountain slopes on the range’s ocean side (Van Zyl 2003). Situated in the modern WRZ, the Cederberg experiences more than 66% of its mean annual rainfall (~200 mm) during the winter months between April and September (Chase and Meadows 2007; Chase et al. 2011). During these months temperatures often drop below zero degrees Celsius and snow is frequent on the higher ridges of the mountains with frost common at the lower levels (Quick and Echardt 2015).

Environmentally, the eastern Cederberg is situated within the Fynbos biome and borders the Succulent Karoo vegetation biome (Mucina and Rutherford 2006). The dominant Fynbos biome is a Mediterranean-type shrubland characterized by a high level of species richness (Linder 2003). The dominant vegetation follows the C3 photosynthetic pathway and includes *Restionaceae* flowering plants and shrubs of the *Proteaceae* and *Ericaceae* families (Cowling et al. 1997). The distinctive geology and soils of the Cederberg are largely responsible for the presence and distribution of Mountain Fynbos and the physical geography of the region influences both the area’s climate and environment.

Klipfonteinrand is situated within the Table Mountain Sandstone Group and borders the quartzite- and shale- dominant Bokkeveld Series of the interior. Such a geological background means that a range of flakeable raw materials were available to prehistoric toolmakers in the area. Quartz is ubiquitous within the landscape generally occurring as conglomerate pebbles associated with the Table Mountain and Nardouw formations and occasionally as rare veins in the sandstone. A range of FGS/CCS rock types including chert, jasper, and chalcedony are also present as conglomerate pebbles though their occurrence is much less common. Hornfels exists in the form of cobbles and pebbles among the cobble beds of the Doring River. Two primary sources of silcrete are also known (Swartvlei and Agtersfontein) both located over 30 km in a straight-line distance from Klipfonteinrand.

Sehonghong (eastern Lesotho Highlands, Lesotho)

Sehonghong (SEH) is a large roughly west facing rockshelter measuring ~86 meters across the front entrance and ~19 meters from the dripline to the rear of the shelter. The site is located 20 meters above the Sehonghong River in the Qacha's Nek District of Eastern Lesotho and within the modern SRZ (Fig. 1). The shelter is situated on the south side of the Sehonghong River, 3 km upstream from where the tributary joins the Orange River. The site is formed in outcropping sandstone and preserves a rich archaeological record extending to 57.6 ± 2.3 (Jacobs et al. 2008).

Following Pat Carter's pioneering work at Sehonghong in the 1970's, Mitchell undertook further excavations in 1992 to collect organic and inorganic materials related to the shelter's natural depositional history (e.g. Mitchell 1995, 1996a, 1996b; Plug and Mitchell 2008a, 2008b). Mitchell excavated a total of 161 stratigraphic units grouped together into ten layers across his 6 x 2 m excavation area. These excavations revealed a long sequence of Late Pleistocene and Holocene human occupations with the remains of abundant faunal, macro-botanical and freshwater aquatic resources. All excavated materials from the Late Pleistocene levels were dry sieved through 1.5 mm mesh. The stratigraphic layers from Mitchell's excavations of relevance to this paper include from oldest to youngest: RBL/CLBRF, RF and BARF with a combination of AMS and convention radiocarbon ages bracketing these assemblages to ~16 – 12 kcal BP (Pargeter et al. 2017).

Modern environment, vegetation, and the availability of knappable rock

Eastern Lesotho and the Thaba Tseka District, within which Sehonghong is situated, is one of southern Africa's most climatically extreme and variable regions (Stewart and Mitchell 2018). The area receives average annual rainfall of 620 mm (mostly in the summer), with a standard deviation of 115 around this mean (weather data for 1976 – 2004 from the Thaba Tseka weather station c. 28 km from Sehonghong) (Bawden and Carroll 1968).

Elevation and temperature gradients determine eastern Lesotho Highlands' vegetation patterns. The two major vegetation belts relevant to this project are the Senqu Montane Shrubland and Lesotho Highland Basalt Grassland (Moeletsi 2004). Senqu Montane Shrubland occurs along the Senqu River Valley and its tributaries at c. 1600 – 1900 m a.s.l. *Cymbopogon-Themeda-Eragrostis* C_4 grassland dominates alongside several tree and evergreen shrub species (Stewart and Mitchell, 2018). At medium elevations (c. 1900 – 2100 m a.s.l.) grasses are dominated by C_4 *Themeda triandra* (Mucina and Rutherford 2006). Lesotho Highland Basalt Grassland is a dense subalpine, C_4-dominated *Themeda-Festuca* grassland with patchy shrublands dominated by bushy *Passerina montana* between c. 1900 – 2700 m a.s.l. Above 2700 m *Themeda* gives way to less palatable C_3 *Festuca-Merxmuellera* grasses. Trees are mostly absent in Lesotho's Highland Basalt Grassland zone.

Sehonghong's surrounding geology provides toolmakers with a wealth of cryptocrystalline silicate (CCS) rocks such as chert, chalcedony, and agate (Fig. 3). The rocks occur as river-borne nodules and in veins and screes around the site (Mitchell 1996b). Cryptocrystalline silicate nodules occur in a range of sizes and morphologies; vein cherts occur in large package sizes (Fig. 3). Other local raw materials used for lithic production include dolerites and hornfels derived from eroding volcanic features (Fig. 3). The local volcanic rocks occur in larger package sizes, are tough to knap, but create tougher flake edges.

Lithic samples

Lithic samples were selected from two 1 m^2 excavation squares at Klipfonteinrand (squares 8/9) and Sehonghong (squares K12/K13). We chose the squares because they contain representative samples from each site's major stratigraphic layers and doing so allowed us to control to some degree the volume of excavated material in our comparisons. The analysis targeted a sample size of at least 300 flakes/layer (in layers with fewer than 300 lithics/layer, all were measured) and all cores were analyzed. This analysis included all flaked materials except small (<5 mm) flake fragments without platforms. A sample size of 300 flakes per aggregate and c. 20 – 100 cores per aggregate meets most social science disciplines' standards at the 95% confidence level (Agresti and Finlay 1986).

This sampling strategy assumes anthropogenic agency and unity for the sampled excavation layers and members. This may not always be the case, and the units could compress significant amounts of variability. However, because lithic miniaturization and its relationship to land-use strategies were processes unfolding over the *longue-durée* of southern African Late Pleistocene prehistory, it was essential to compromise between a narrow short-term and more expansive long-term sampling strategy. Too narrow a perspective would distort one's viewpoint of long-term human mobility and technological organization (Riel-Salvatore and Barton 2004). The excavation units from Klipfonteinrand and Sehonghong provided a satisfactory compromise between the long and short-term perspectives.

Lithic attributes and measurements

We used a standardized attribute-based framework focused on variables to track aspects of raw material selection and lithic reduction strategies. The variables also help clarify the relationship between the organization of technology and the size and shape of flakes. This framework allowed us maximum comparability between two sites excavated by different research teams. Attributes, measurements and indices used in this study are summarized in Table 1.

Basic assemblage descriptions are used as a starting point to characterize each sample and to explore potential variation in lithic provisioning systems employed at each site as well as discrepancies likely due to varying access to lithic types in the different geological settings. For each sample, we report on the frequency of technological classes (i.e. 'cores', 'flakes', 'retouched flakes', 'flake pieces'), the degree of fragmentation (recorded for cores as either 'complete' or 'fragment' and for flakes and retouched flakes as 'complete', 'proximal', 'mesial', 'distal', or 'marginal'), the raw material composition and the degree of cortex retention (recorded as ordinal categories including: 0%, 1-50%, 51-99% and 100%). We use the concept of a 'minimal flaked unit' comprising all flake fragments with proximal ends and all complete flakes. This allows for a more balanced representation of actual flakes in an assemblage.

Blade production

Small blades define many of southern Africa's Late Pleistocene lithic assemblages (Mitchell 2002; Lombard et al. 2012). For this reason, the next stage of our analysis focused on describing and contrasting the organization of blade production at each site. Following regional research trends (e.g. Deacon 1984; Mitchell 1988), we use the term 'blade' in a strict morphological sense to describe parallel sided flakes whose axial lengths are at least twice as long as they are wide. Blade cores must preserve evidence for the removal of at least one blade in the form of a flake scar with parallel scar ridges and a flake scar length at least twice as long as it is wide. We make no *a priori* distinction between blades and bladelets (Pargeter and Redondo 2016).

Soriano et al.'s (2007) blade classification scheme was used to identify, where possible, the stages of blade production represented in each assemblage and the degree of core preparation at each site. Complete blades in each assemblage were classified into one of three broad categories describing the stage of production: (a) the initial stage (crested or cortical blades), (b) main production phase (blades from the center or side of the debitage surface), or (c) core maintenance stage (crested blades from the second generation) (see Soriano et al. 2007, Fig. 4). Differences in the frequency of blades from each reduction stage are used to explore the degree of investment in production and potential differences in provisioning strategies. The absence of blades associated with the core maintenance stage, for instance, may indicate a scenario where toolmakers were less concerned with maximizing core reduction through systematic blade core maintenance. In terms of provisioning strategies, an under-representation of blades relating to the initial stage of production, for instance, may indicate earlier core removals occurred elsewhere in the landscape and/or that the initial stage of production did not involve the removal of crested or cortical blades. Blade to blade core ratios provide a measure of the differential staging of artifact production, artifact transportation and the nature of artifact provisioning strategies. Higher blade to blade core ratios would suggest greater on-site blade production and discard.

Bipolar technology

Bipolar technology occurs when a core is immobilised against an anvil or hard surface and a large hammer is used to apply axial-orientated blows (at near right-angle to the anvil) to remove flakes (Hiscock 2015, 4-5). Archaeologists have used variations in bipolar technology to help define spatial differences in blade-production systems across southern Africa (e.g. Mitchell 1988). This study therefore focused on assessing the role played by bipolar reduction techniques in the technological organization strategies across the two regions and the influence, if any, lithic raw material and/or core size might have on the choice to reduce cores using this strategy. Bipolar and freehand core/flake frequencies are used to explore the relative contribution of these reduction strategies in each assemblage.

Several macroscopic technological attributes were used to identify bipolar artefacts including: (1) crushing on opposed edges and/or compression ripples/waves extending towards one another from opposite directions suggestive of impact from two points of applied force; (2) contact surfaces that are typically rectilinear and smooth (often described as 'chisel-like in appearance); and (3) a bidirectional flaking pattern (Barham 1987; de la Peña 2015; Pargeter and de la Peña 2017; Pargeter and Eren 2017). For bipolar flakes, we focused on experimentally derived attributes shown to reliably distinguish bipolar flakes from freehand flakes in quartz and CCS (cf. Pargeter and de la Peña 2017; Pargeter and Eren 2017). These include rebound force scarring on the distal ends of flakes, the presence of axial, crushed, hinged, and splintered terminations, severely crushed flake platforms, and crushed and/or sheared bulbar surfaces. Recognising that at times it may be difficult to accurately identify an artefact as bipolar, particualry within the flake technological class, a conservative approach that erred on the side of caution was used when classifying artefacts as such. However, we emphasize that our experimentally driven approach is a more robust alternative in such cases.

A toolmaker's choice to use bipolar reduction may be influenced by a number of factors relating to the raw material (i.e. size of available nodules/blocks, scarcity or abundance of certain material types, quality and degree of structural imperfections of available materials), levels of mobility (i.e. influence how often toolmakers may have access to certain materials), scheduling of activities (i.e. resource procurement, manufacture and maintenance of tool kits, subsistence activities etc.) and/or individual preferences (i.e. preferred methods of initiating reduction, as a strategy maintaining cores as reduction progresses and/or as a production technique regardless of stage of reduction). Hiscock (2015) argues that bipolar reduction preformed a key role in immobilizing cores that were too small for freehand reduction. When there was strong directional selective pressure encouraging lithic miniaturization, the proportion of stone tool evidence referable to bipolar percussion should increase relative to evidence referable to freehand percussion.

This study focused on the relationship between core size and the choice to reduce materials using bipolar methods in addition to the relationship between bipolar reduction and different raw materials. To track these relationships, we recorded bipolar and freehand core mass and maximum core dimensions (length, width and thickness) in their respective raw material classes. Comparisons are made within each assemblage as well as between assemblages to explore the possible existence of a size-threshold for which bipolar techniques were implemented and to test the widely cited hypothesis that toolmakers used bipolar to increase small cores' use life (Hiscock 2015; Pargeter and Shea 2019; de la Peña 2015).

Technological change and the process of lithic miniaturization

Several attributes and measures were chosen specifically to test for relationships between technological organization and lithic miniaturization. If lithic miniaturization affected the organization of technological operations (or *vice versa*), we should see shifts in technological features (i.e. platform preparation frequencies and dorsal flake scar patterning) correlated with changes in artefact sizes. Platform preparation refers to the systematic process of small-scale flaking and abrasion intended to shape and isolate platforms that depends on a learning context conducive to the deliberate practice required for the individual mastery of such skills (Stout et al. 2014). The point to be taken here is that assemblage differences in platform preparation may thus be related to culturally specific differences in information acquisition strategies that indicate differences in skill-learning.

We compared the frequency of platform preparation and different dorsal scar patterns using standardized flake width and core mass quantile groups. This strategy allowed us to determine the relationship between lithic miniaturization and technological strategies while controlling for size differences in the two flake and core samples (Lin et al. 2016).

Technological efficiency and reduction intensity

Many archaeologists share the view that lithic miniaturization represents increased technological production economy and efficiency (e.g. Mitchell 1988; Hiscock 1994, 1996, 2015; Nuzhnyi 2000; Ambrose 2002; Belfer-Cohen and Goring-Morris 2002; Neeley 2002; Bleed 2002; Kuhn 2002; Elston and Brantingham 2002; Goebel 2002; Torrence 2002; Costa et al. 2005; Burdukiewicz 2005; Clarkson et al. 2009; Hiscock et al. 2011; Mackay and Marwick 2011). If these observations are correct, then we should find increased evidence for technological efficiency correlated with evidence for increased reduction intensity on smaller cores and flakes. We track technological efficiency and reduction intensity through three independent measures: cutting edge to mass ratio, assemblage reduction index (ARI), and cortex ratios.

The flake cutting to mass ratio is a widely used metric to trace lithic technological efficiency (e.g. Muller and Clarkson 2016; Stout et al. 2019). Measuring technological efficiency using flake cutting edge to mass rations are particularly relevant in a context associated with low frequencies of retouched tools and high frequencies of unretouched blades such as is the case with the Lake Glacial assemblages used in this study. We use the calculations in Mackay (2008) (*flake cutting edge=length+ maximum width+ maximum dimension*) and Braun and Harris (2003) (*flake cutting edge to mass=flake cutting edge/mass*^{3}) to calculate the flake cutting edge to mass ratios on our two assemblages. The second formula uses an exponent to account for the non-linear relationship between edge and weight. Flake length is measured from the point of initiation in the direction of percussion, maximum dimension is the longest distance across the ventral face of the flake, and maximum width is the widest point of the flake perpendicular to flake length. If smaller flakes and blades are more efficient technological strategies, we should see an increase in their flake cutting edge to mass values relative to larger flakes.

The ARI represents the ratio between average flake length and average core length used to gauge the intensity of raw material use and reduction (Olszewski et al. 2011). Lithic miniaturization is expected to occur more often in contexts with intensive core reduction (e.g. Tryon and Faith 2016). However, functional requirements might also compel toolmakers to produce smaller flakes irrespective of concerns about raw material conservation. The character of an assemblage and its degree of miniaturization may therefore not depend primarily on the economy of raw materials. The ARI provides a means of testing this hypothesis. The idea behind the measurement is that cores from which only few flakes have been struck should be larger (on average) than the flakes indicating a low reduction intensity (ARI <1). On the other hand, cores that have been heavily reduced on site will be smaller than the initial flakes (ARI >1) and, if reduction proceeded on site and was intensive enough, even smaller than the average size of flakes/blades. Comparisons of ARI indices between raw materials provides a measure of material specific reduction intensity.

Finally, we present summary data comparing the mass of cores versus flakes by raw material. More heavily reduced sub-assemblages should show lower core to flake mass ratios. Such data are used to explore potential differences in the degree of reduction for different raw materials.

Results

The study comprised 2836 flaked stone artifacts from Klipfonteinrand (n = 1382) and Sehonghong (n = 1125). Table 2 provides a general overview of the samples and the statistics for each assemblage based on technological artifact classes and artifact completeness while Tables 3 and 4 summarize the raw material proportions and cortex percentages respectively.

Cores are twice as common at Sehonghong (10%) than at Klipfonteinrand (5%) (Table 2). Although variable in their frequency, both sites exhibit similar rates of core fragmentation with the majority in both samples (i.e. >86%) representing complete cores (Table 2). Klipfonteinrand shows a higher frequency of minimally flaked units (complete flakes and proximal ends) (86%) compared to Sehonghong (63%). Retouched artifacts are more than three times as common at Sehonghong (2.9%) than Klipfonteinrand (0.7%). Klipfonteinrand's lower retouched tool frequencies approximate those in other Robberg lithic assemblages (~1%) (e.g. Kaplan 1989; Deacon 1978; Wadley 1996; though see Porraz et al. 2016a, 224).

The summary statistics presented in Table 3 show that the two assemblages are distinct in their raw material compositions, with results largely reflecting each site's local geological context. Raw material diversity calculated using Simpson's Index (Faith and Du 2018) shows higher values (0.65) at Klipfonteinrand compared with Sehonghong (0.45). The Sehonghong sample comprises predominantly CCS with this raw material making up ~82% of the site's cores and ~71% of its flakes. In contrast, the Klipfonteinrand assemblage comprises mostly quartz (~73% of cores and ~33% of flakes) and hornfels (~20% of cores and ~46% of flakes). Sehonghong is associated with high frequencies of cortex on ~87% of cores and over half of the flakes (Table 4). In contrast, the Klipfonteinrand sample contains a higher frequency of cores (31% vs. 13%) and flakes (56% vs. 46%) without cortex. At Klipfonteinrand, cores and flakes that do preserve cortex have less than 50% cortical coverage (Table 4). Sehonghong shows double the frequency of cores (41% vs. 19%) with higher amounts of cortical coverage (51-99%).

Blade production

Tables 5 and 6 summarize the number and frequency of blades versus flakes and blade cores versus flake cores for each site by raw material type. Overall, the Sehonghong sample comprises a higher frequency of blades (~40%, n = 142) and blade cores (~86%, n = 95) compared to Klipfonteinrand where blades (~30%, n = 397) and blade cores (30%, n = 20) represent a comparatively minor component. The considerably higher frequency of blade cores in the Sehonghong sample manifest in a much lower blade to blade core ratio of 1.5 compared to the markedly higher 19.8 blades per blade core at Klipfonteinrand.

At both sites, toolmakers made blades on specific raw materials with a prominent CCS/quartz blade component in the Sehonghong sample and a clear silcrete/quartz blade component in the Klipfonteinrand assemblage (Tables 5 and 6). In the Sehonghong assemblage, for example, over 80% of the CCS and quartz detached pieces are blades while in the Klipfonteinrand sample, blades represent one third of the silcrete detached pieces and ~30% of quartz detached pieces (Table 5). In contrast, hornfels appears largely associated with the production of flakes at both sites (Table 5). Similarly, ~88% of quartz cores and ~83% of CCS cores in the Sehonghong sample are associated with blade production (Table 6). In contrast, blade cores are largely under-represented in the Klipfonteinrand sample where they comprise less than a third of the cores in each raw material category (Table 6).

The discrepancy between blades and blade cores at Klipfonteinrand raises the possibility of variability in blade production staging between the two sites. To explore this idea further, blades from each site were classified using the Soriano blade scheme with results summarized in Fig. 4 by raw material types. In general, Klipfonteinrand has a higher frequency of blades associated with the initial stage of production (~12% of blades compared to <3% at Sehonghong). The frequency of initial stage blades is highest amongst the hornfels and quartz specimens in the Klipfonteinrand sample and quartz blades at Sehonghong (Fig. 4). Roughly 7% of the blades in the Sehonghong assemblage are associated with core maintenance (i.e. later stage production) showing signs of cresting) (Fig. 4). In contrast, core maintenance blades are completely absent from Klipfonteinrand.

Bipolar technology

Tables 7 and 8 display bipolar and freehand data for cores and flakes from Sehonghong and Klipfonteinrand. Examples of bipolar cores, freehand cores and bipolar and freehand flakes from each site are provided in Figs 5, 6 and 7. The data show that both sites have similar bipolar core frequencies representing ~41% and ~43% of the cores from Klipfonteinrand and Sehonghong respectively (Table 7). Bipolar flakes are more than twice as common at Sehonghong (10.6%; n = 107) compared to Klipfonteinrand (4.9%; n = 56) (Table 8). Despite the two site’s relatively similar bipolar core frequencies, differences are noted in the dominant raw materials associated with this reduction strategy. Toolmakers used quartz and hornfels to make the majority of Klipfonteinrand’s bipolar cores, whereas they used mostly quartz, hornfels, and CCS to produce bipolar cores at Sehonghong (Table 7). Despite Sehonghong’s relatively high CCS and hornfels bipolar core frequencies, only 8.5% of the site’s CCS flakes and 1.9% of its hornfels flakes show bipolar related damage (Table 8).

Figure 8 shows the relationship between core mass and bipolar reduction for all raw materials combined and for the dominant raw material associated with bipolar reduction at each site (i.e. CCS at Sehonghong and quartz at Klipfonteinrand). The later strategy helps control for potential raw material induced variability. The data show the size threshold at which toolmakers transitioned core technologies from freehand to bipolar (where one distribution overlaps with the other), sometimes referred to as the core ‘recycling window’ (Hiscock 2015). This cross-over value is higher at Sehonghong (~3.5 g) than at Klipfonteinrand (~2 g) when all raw materials are considered.

The Klipfonteinrand quartz sample shows a bipolar/freehand cross-over reminiscent of the one seen in the site’s larger raw material sample: the transition weight for the shift from freehand to bipolar remains at ~2 g. The data show that some of the site’s larger bipolar cores were made on non-quartz raw materials. Sehonghong’s CCS bipolar/freehand core masses show different patterning to the larger raw material sample, with the recycling window shifting from ~3.5 g to ~4 g indicating that tool-makers chose to reduce CCS cores using bipolar methods when they were ~30% larger than the remaining raw materials (mostly quartz) on which this strategy was used.

Technological change and the process of lithic miniaturization

Figure 9 illustrates the shift in core flaking directions (radial, multidirectional, unidirectional, and bidirectional) in terms of core mass quantiles. The data from both sites show that as core reduction became increasingly miniaturized, scar patterning became increasingly more unidirectional and bidirectional and less radial and sub-radial. The flake shape and technology data presented in Fig. 10 show that at both sites, toolmakers produced equally elongated flake products using both bipolar and freehand reduction. Figure 11 depicts the data on platform preparation compared across flake width quantiles. Both Sehonghong and

Klipfonteinrand show higher rates of platform preparation amongst the widest flakes decreasing in frequency as flakes became narrower and smaller.

Technological efficiency and reduction intensity

This section presents the results of our two flaking efficiency measures: flake cutting edge to mass and reduction intensity. Figure 12 shows the relationship between the flake width and the flake cutting edge to mass ratio for all raw materials. The data show a significant negative relationship between flake width and cutting edge to mass showing that narrower (smaller) flakes contain more cutting edge to mass and are a more economical reduction goal. The relationship between these two variables at the two sites is similar with complete overlap in both site's regression slopes and their 95% confidence intervals. Figure 13 shows this relationship for the dominant raw materials at each site (Klipfonteinrand = quartz, Sehonghong = CCS). These modified data show a better model with (improved r^2 values) and the same significant relationship between flake cutting edge to mass and flake size. The two regression slopes differ significantly (F [1,641] = 27.6, $p < 0.01$) in this comparison with Klipfonteinrand's quartz slope showing the stronger of the two relationships.

Figure 14 compares the assemblage reduction intensity (ARI) index between the two sites and across different raw materials. On average, Sehonghong's ARI index (0.85) is higher than Klipfonteinrand's (0.65) suggesting a greater overall reduction intensity of the former site's cores. Neither sites' ARI indices reach a value of 1 suggesting that cores were always on average larger than flakes. At Klipfonteinrand, all raw materials were reduced with approximately the same intensity except for hornfels which shows a relatively low ARI score. The pattern is different at Sehonghong where quartz was reduced more intensively than other rock types, which explains the site's higher overall ARI value. At both sites, hornfels shows relatively low reduction intensity values.

The data in Fig. 15 summarize the core mass to flaked mass ratios by raw material class. Values >1 indicate greater core mass than collective flake mass. At Sehonghong, these ratios largely reflect patterning in the ARI values (Fig. 14) suggesting that the most intensively reduced raw materials also contain the greatest collective cores masses (reflecting a greater number of cores) with CCS dominating the pattern. The trend at Klipfonteinrand is different, with a greater disparity between core mass/flake mass ratios compared to the ARI index. For example, quartz and silcrete show relatively similar ARI values, but the two raw materials have markedly different core mass/flake mass ratios. These differences suggest that toolmakers removed either quartz flakes or cores from the site thereby altering the core to flake mass ratios.

Discussion

Archaeologists have long emphasized the similarity of southern Africa's miniaturized lithic assemblages emphasizing their emphasis towards small blade and flake production (e.g. Lombard et al. 2012). Archaeologists have used evidence for technological uniformity to support arguments for the existence of long-distance connections, increased mobility and/or expanded territorial ranges across variable environments (e.g. Ambrose 2002, 21; Bousman 2005, 215; Ambrose and Lorenz 1990; Mitchell 2000, 2002; Barham and Mitchell 2008). Such inferences, however, are based on an 'a priori' assumptions that the technology dating to this period is 'uniform', or at least similar enough to warrant such interpretations justified. Just how similar the technology associated with the process of Late Pleistocene lithic miniaturization is across time and space, however, has rarely been tested.

By comparing data from Klipfonteinrand and Sehonghong we test how structurally similar the miniaturized technological systems at each site are considering their variable settings and the distance between them. Overall the assemblage comparisons demonstrate that lithic miniaturization expresses itself differently in different regions. While both assemblages appear superficially similar in their emphasis on the production of small blades, key differences exist in relation to the specific technological composition of each assemblage, the selection of raw materials, the role played by bipolar reduction and the way production was organized at a landscape scale including evidence for the variable transportation of different toolkit components.

Raw material patterning

Toolmakers largely took advantage of locally available raw materials (CCS at Sehonghong and quartz and hornfels at Klipfonteinrand). These patterns challenge the widely cited (though rarely validated) Late Glacial increase in humans' use of fine-grained, 'non-local' lithic sources (e.g. Ambrose 2002, 21; Bousman 2005, 215; Ambrose and Lorenz 1990; Mitchell 2000, 2002; Barham and Mitchell 2008). Archaeologists have linked greater local raw material exploitation to 'expedient' lithic technologies marked by irregular core morphologies, low frequencies of platform preparation in waste flake assemblages, a lack of evidence for the systematic rejuvenation of cores during reduction, short, squat flakes with length:breadth ratios around 1:1; and the frequent rejection of cores prior to exhaustion (Parry and Kelly 1987; McLaren 2011, 74). Our results contradict these observations with the Klipfonteinrand and Sehonghong assemblages showing signs of systematic core recycling, core rejuvenation, blade production, and platform preparation without extensive retouch. Klipfonteinrand and Sehonghong's shared emphasis on several of these features suggests that they are the product of organized approaches to core reduction challenging their previous classification as being 'informal' (Wadley 1993, 284). These patterns highlight the need for greater clarification in the use of terms such as local or non-local, expedient, and informal with reference to lithic systems.

In spite of these generalities, the two sites also show several interesting variations in their raw material sourcing and exploitation. Sehonghong shows a lower overall raw material diversity index and a greater exploitation of locally available CCS nodules whereas Klipfonteinrand's toolmakers exploited a wider range of rock types and to a lesser degree. Surveys around Sehonghong and Klipfonteinrand show that local rocks occur in a range of package sizes suggesting that raw material sizes did not necessarily drive lithic miniaturization (contra Wadley 1993, 271). Tool makers appear to have selected to produce small flakes and blades based partly on concerns over the functions of the tools rather than as a direct result of constraints posed by raw material package size. Processes governing bladelet production decouple from those governing small retouched tool (or 'microlith') production (sensu Pargeter and Shea 2019). Nevertheless, distinctive raw material patterning in the Klipfonteinrand assemblage does reveal differences in the staging of production between different artefact categories, a point we return to in more detail later when discussing the organization of such technological systems.

The organization of blade technology

Mobile populations faced regular trade-offs between the transport of tools and varying access to the raw materials necessary for their replacement (Bamforth 1986, 1991; Binford 1979, 1980; Kelly 1988, 1992; Kuhn 1995). In order to sustain a regular supply of stone tools to meet tasks under differing geological conditions, foragers could implement a range of non-exclusive strategies, including maintenance of transported tools (Bamforth 1986; Bleed 1986; Bousman 2005; Shott 1986), transport of lightweight, pre-prepared cores (Hiscock 2006), caching of tool-making potential for future use (Parry and Kelly 1987), and the situational use of locally-available resources (Binford 1979). The final composition of stone tool assemblages will be influenced in part by which of these strategies were implemented in the past.

Both Sehonghong and Klipfonteinrand provide clear evidence for the production of small blades while showing differences in their specific compositions of this evidence. Sehonghong shows a higher frequency of blades and blade cores whereas Klipfonteinrand's blade cores are largely underrepresented. At Sehonghong, CCS and quartz were preferred for blade production whereas silcrete and quartz dominate the Klipfonteinrand assemblage.

Overall, the results show broad differences in the blade production systems between the two sites. At Klipfonteinrand, hornfels and quartz blade cores were reduced on-site in contrast to silcrete where initial stages of reduction appear to have largely occurred off-site with minimal/no effort to maintain cores. In comparison, toolmakers at Sehonghong maximized output from CCS nodules during blade production by maintaining cores more formally at the site, while initiating hornfels core reduction processes off-site.

Differences in blade to blade core ratios between Sehonghong (1.4 blades per core) and Klipfonteinrand (19.8 blades per core), the two site's differences in cortex frequencies, and their sharp distinction in the frequency of initiation flakes indicates strong distinctions in the way blade technology was organized in relation to: (1) the staging of production; and (2) which stone artifact components formed regular parts of the transported toolkits. The high blade:blade core ratio at Klipfonteinrand, for instance, supports a scenario in which blade cores formed part of the transported toolkit with their discard taking place 'off-site'. This appears to be a central/defining feature of the organization of blade technology during the Late Pleistocene at several sites in the eastern Cederberg (Low and Mackay 2018). In contrast, Sehonghong's blade production occurred onsite and involved episodes of core maintenance and higher on-site core discard. The comparatively low blade:blade core ratio suggests that blades were frequently transported away from the site, that blade production occurred towards the end of a cores reduction history and/or that blade cores rarely formed a part of the typical transported toolkit in this region.

Bipolar technology and lithic miniaturization

Bipolar reduction's benefits in contexts of lithic miniaturization are well acknowledged (e.g. Ambrose 2002: 20; Eren et al. 2013; Pargeter and de la Peña 2017; Pargeter and Eren 2017). Bipolar technology allows toolmakers to reduce small nodules of rock, split open small round pebbles, conserve or economize on raw material usage, extend/prolong the use-lives of cores and retouched flakes (perhaps as a process of recycling), and to expediently produce flakes and blades while ultimately saving time and/energy in other areas such as the procurement of toolstone or the mastering of alternative reduction techniques. As such, it is perhaps unsurprising that bipolar technology forms a defining characteristic of miniaturized technological systems in a range of contexts spread across Europe, Africa, North America, Asia and Australia (Brantingham et al. 2004; de la Peña and Vega Toscano 2013; Goebel 2002; Ambrose 2002; Belfer-Cohen and Goring-Morris 2002; Hiscock 2002). Despite its widespread occurrences, theoretical work on bipolar technology are still dominated by several truisms. These include arguments that bipolar technology is an automatic response to quartz reduction and that bipolar technology reflects the use of small raw material package sizes and scarcity (e.g. Bousman 2005; Jeske 1992; Kaplan 1990; Shott 1989).

Our results shed new light on these issues. Bipolar reduction was used at both Sehonghong and Klipfonteinrand to reduce a range of raw materials with quartz well represented in each site's bipolar assemblages. Although this result provides some support for Mitchell's (1988) raw material providence model which hypothesises a link between quartz and bipolar reduction, the results show that sites in southern Africa's CCS dominant regions also show an emphasis on quartz bipolar reduction. Certain raw material types, however, were more frequently reduced using bipolar technology with the dominant bipolar-worked raw material types varying between the two sites. Sehonghong shows a pattern dominated by CCS and quartz whereas Klipfonteinrand's patterns were dominated by hornfels and quartz. Sehonghong's bipolar patterns show the shift from freehand to bipolar CCS reduction occurred when cores were larger than on other raw material types complicating its relationship with raw material package size. The data distributions also show that at Sehonghong's toolmakers used bipolar reduction more often to continue reduction of smaller freehand cores whereas at Klipfonteinrand toolmakers deployed this strategy on larger and smaller cores alike. That they did so with greater bidirectional flaking and bipolar reduction as cores became smaller suggests an effort to reduce the energy and costs of reduction intensification (i.e. using less demanding reduction strategies).

Our data show that Klipfonteinrand's toolmakers may have had a higher tolerance, if not a preference, for small freehand reduction than at Sehonghong and/or that other factors drove the use of bipolar reduction at the site. Possibilities include working with complex nodule geometries and variable internal raw material quality. Bipolar reduction provides toolmakers with a quick and efficient means to test the internal properties of a rock, which would have been especially useful in contexts where raw material packages are variable. Although fine-grained CCS nodules are locally available around Sehonghong, they are internally heterogeneous (see Fig. 3), with common internal flaws and inclusions, which, untested, can pose problems for toolmakers.

Differences in bipolar core and flake numbers compared across raw materials between Sehonghong and Klipfonteinrand suggest that: (1) bipolar reduction sequences were longer for some rocks than others, and/or (2) bipolar flakes were selectively removed from the sites. We argue for the second hypothesis where bipolar flakes/blades were produced at the rockshelter, selected for transportation, used and then discarded in the surrounding landscape. This interpretation is supported by the core mass to flaked mass ratios data organized by raw material class (Fig. 14). Moreover, results from an experimental study conducted in the eastern Cederberg suggest that the differential representation of bipolar artifacts in the landscape does not reflect preservation biases or variations in knapper skill levels, but rather behavioural factors such as the deployment of technologies strategically across landscapes (Phillips et al. 2018). Factors that could have influenced these landscape-wide technological patterns include responses to raw material availability and/or quality and task-specific activities in different areas.

Technological efficiency and reduction intensity

Our results demonstrate that the making of small tools represents an efficient use of raw material – the data show that narrower (smaller) flakes also have more cutting edge to mass. These patterns suggest that lithic miniaturization was directed towards conserving raw materials and in addition (possibly) to specific functional requirements for smaller tools. The functional requirements hypothesis will have to be tested in future work incorporating microwear, residue, and microfracture analyses of the tools.

The Sehonghong and Klipfonteinrand assemblages show different patterns of reduction intensity on locally available raw materials. The Sehonghong assemblage is associated with higher cutting edge to flaked mass ratios on CCS, the dominant locally available rock. This pattern matches with the site's high blade to blade core ratios and average reduction intensity index suggesting greater efforts at raw material reduction intensification through blade production. At Klipfonteinrand, in contrast, all raw materials show high cutting edge to mass ratios whereas hornfels, the dominant local raw material, showed lower cutting edge to mass values. This is perhaps not surprising considering the results from a previous study in the eastern Cederberg which found that with increasing distance from the Doring River (a likely source of hornfels), tool production was supplemented by the addition of other locally available materials such as quartz rather than by increasing the intensity of reduction of the hornfels material already present (Low and Mackay 2018). These differences in raw material reduction intensity are reflected in Klipfonteinrand's higher raw material diversity index. The data suggest that Klipfonteinrand's toolmakers drew on a wider raw material procurement network before reaching the site whereas Sehonghong's toolmakers mapped more onto local CCS raw material sources.

Technological change and the process of lithic miniaturization

Finally, the results of this study demonstrate that processes of lithic miniaturization impacted choices of technological strategies. Specifically, our results revealed similar patterning in the relationship between core size and flaking direction at both Sehonghong and Klipfonteinrand. Smaller cores show more unidirectional or bidirectional flake scars indicating a shift in core reduction systems towards greater single platform and bipolar approaches likely associated with the mechanics of reducing small cores. Interestingly, archaeologists have associated the shift from radial and prepared core technologies to pyramidal and bipolar based blade and small flake systems with the 'transition' from the Middle to Later Stone Ages in Africa (Clark 1997; Lombard et al. 2012; Wadley 2005). Some archaeologists argue that this process reflects demographic changes across the sub-continent (Bousman and Brink 2017). Our data show that similar technological shifts also occur as a result of efforts to intensify lithic reduction processes that may be linked to fracture mechanics as much as to these larger demographic processes.

Our results also point to important shared technological strategies across size classes at the two sites of the kind potentially relevant to processes of cultural learning and technological knowledge transmission. Both Sehonghong and Klipfonteinrand's data show toolmakers used platform preparation strategies on wider and larger flakes rather than on narrower and smaller flakes. Clarkson (2008, 288) argues that platform preparation strengthens a core's flake release surface when removing flakes from small cores with steeper platform angles. Considering the conflicting relationship between platform preparation and flake size identified at our two sites, the result suggests that toolmakers' use of platform preparation to strengthen small core edges was not universal and that patterned variation in this strategy could represent differences in culturally learnt and transmitted knapping strategies.

A more variable view of Late Glacial lithic miniaturization in southern Africa

Archaeologists have argued that technological strategies based on miniaturized technologies were advantageous in situations demanding more economical technologies including contexts where resources may have been restricted due to territorial controls brought on by increased population size and/or constraints posed by mobility (e.g. Belfer-Cohen and Goring-Morris 2002; Kuhn 2002, 84; Neeley 2002; Yesner and Pearson 2002, 150-151). Several archaeologists have invoked paleoenvironmental change to explain lithic miniaturization's variability (e.g. Elston and Kuhn 2002; Hiscock 1994; Lombard and Parsons 2008; Petraglia et al. 2009). The argument follows that erratic or especially harsh climatic episodes make resources less predictable.

Several authors have argued that southern African Late Glacial paleoenvironments provided relief from LGM foraging time-stresses that initiated the need for greater flaking efficiency through bipolar core reduction and an overall uptick in lithic miniaturization (Hiscock et al. 2011; Mackay and Marwick 2011; Mitchell 1988; Wadley 1993). However, such sweeping characterizations of paleoenvironmental conditions across southern Africa are inconsistent with a growing body of research highlighting substantial regional variation (e.g. Chase and Meadows 2007; Chase et al. 2018; Chevalier and Chase 2016; Faith 2013; Faith et al. 2019).

The dynamics of southern Africa's Late Glacial climatic and environmental change makes it challenging to draw simple correlations between broad environmental change and patterns of human behaviour and occupation (Gliganic et al. 2012; Eren et al. 2013, 253). This is partly because details of humans' use of lithic technologies intersect with behavioural adaptations at local scales. Unravelling these complexities necessitates detailed inter-site comparative analyses (see Bousman 2005). Only once such an understanding is gained can we attempt to explore how broader patterns of climatic and environmental change, operating at larger regional, continental or even global scales, may have interacted with human cultural choice and technological decision making. Comparisons between Klipfonteinrand and Sehonghong show toolmakers varied their use of bipolar reduction, local raw materials, technological scheduling across the landscape, reduction intensity, and the degree to which they invested in on-site core maintenance and repair. These variations almost certainly speak to the ways in which toolmakers managed tasks on the landscapes and the resources within them.

Traditional culture-historical taxonomies focused on measuring superficial similarities and differences among ‘microlithic’ industries and other archaeologically constructed entities overlook this behaviorally meaningful variability. Our data join analyses increasingly seeking to use lithics to better understand human behavioral evolution including such emphasis on settlement patterns, the organization of technology, and their relationships to larger evolutionary processes (Lycett and von Cramon-Taubadel 2015; O’Brien et al. 2016; Scerri et al. 2014). Such analyses will, we hope, allow southern African hunter-gatherer archaeology to contribute ever more strongly to building a more behaviorally focused perspective on lithic technology in general and lithic miniaturization more specifically and its relevance to understanding human evolution.

Conclusions

The systematic production of small stone artifacts by controlled fracture was a pervasive feature of Pleistocene lithic technology. While broad typological comparisons of ‘microlithic’ industries can potentially inform us about the history of these exceptional technological abilities, this potential is limited by the absence of detailed technological comparisons of relevant lithic assemblages. To address this, we adopt a comparative organization of technology approach, examining similarities and differences between two southern African Late Glacial lithic assemblages from Klipfonteinrand and Sehonghong. Our results show several key distinctions between the two assemblages in the ways toolmakers used locally available raw materials, the size thresholds at which they switched from freehand to bipolar reduction, the degree to which toolmakers intensified core reduction, and the use of platform preparation strategies to strengthen the margins on small cores. These data are useful for tracing inter-site technological patterns indicative of underlying behavioural processes of the kind potentially driving larger changes in southern Africa’s Late Glacial lithic record. Our results also provide a methodological benchmark for inter-site comparative lithic analyses by documenting the technological details required to capture particular aspects of change and variability in lithic miniaturization. For example, we have demonstrated that lithic assemblages recorded independently of one another can be accurately compared and contrasted using attribute-based approaches. This highlights the potential for future studies to consider the mechanisms underlying variability in lithic toolkits and the behavioral implications of miniaturized stone tools.

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Figure 1. Map of southern Africa showing the location of the two key sites featured in this study – Klipfonteinrand and Sehonghong – in association with their respective rainfall zones. Blue and brown shades indicate shifting mean annual rainfall gradients: blue = more summer rainfall, brown = less summer rainfall. For the purpose of this study, the modern rainfall zones as defined by Chase and Meadows (2007) are used as a general framework for making broad spatial comparisons across different regions. The winter rainfall zone (WRZ), therefore, encompasses the southwestern Cape which experiences more than 66% of its mean annual precipitation (~200 mm) during the winter months (April and September). The summer rainfall zone (SRZ) covers regions in the north, east and interior which experience more than 66% of mean yearly rainfall during the summer months (October and March).

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