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ABSTRACT

Understanding how lithic raw materials were procured and managed by past stone toolmakers is a central component in reconstructing mobile hunter-gatherer lifeways. Yet, this is often approached through single rock shelter sequences that capture diachronic change in raw material preferences but provide limited insight into how these behaviours articulated with the wider landscape. The Tankwa Karoo, situated in the Doring River catchment in South Africa, preserves an extensive, multi-period surface archaeological record spanning the Middle and Later Stone Ages (MSA, LSA), providing an opportunity to observe such patterns at a broader spatial scale. This study examines raw material use at open-air localities distributed across adjacent Cape and Karoo geological contexts, comparing assemblage composition through time and space, and assessing transport and curation behaviours of key raw material types: silcrete and cryptocrystalline silicate (CCS, chert). Results show that while locally available lithologies were generally preferred, raw material selection was not determined solely by proximity to source. MSA assemblages show a stronger emphasis on local procurement, whereas LSA assemblages display a consistent preference for Karoo-derived rocks irrespective of bedrock geology. Patterns of raw material transport indicate that, alongside a strong regional focus on the Doring River, additional riverine corridors structured movement along a west–east axis, giving hunter-gatherers access to different resources. These results complement and extend existing models of raw material transport in the Doring catchment into adjacent Karoo landscapes, highlighting the importance of landscape-scale datasets for understanding mobility systems beyond single site sequences.

KEYWORDS

Middle Stone Age, Later Stone Age, lithic raw materials, mobility, South Africa

COMPETING INTERESTS

The author declares no competing interests.

AVAILABILITY OF DATA AND MATERIALS

All supporting material, including data and R script to replicate the analyses, are available from an external repository: https://osf.io/5ebam/

ETHICS APPROVAL

Not applicable.

CLINICAL TRIAL NUMBER

Not applicable.

Introduction

Access to flakeable stone raw material was a major factor that structured the lives of past stone toolmakers. In many landscapes, lithic resources are unevenly distributed and vary in their physical properties; therefore, understanding decisions about how stone was procured, transported, and managed is essential for reconstructing technological organisation and patterns of landscape use (Andrefsky, 1994a). Southern Africa has a deep prehistory of stone toolmaking, with preferences for certain stone types observed from the Earlier Stone Age (ESA) (Caruana & Mtshali, 2018; Mesfin et al., 2021; Sherwood, 2021). However, specific selection and transport behaviours became more pronounced in the Middle Stone Age (MSA) (Wilkins, 2017; Will et al., 2026), with long-distance movement and sophisticated raw material management strategies interpreted as signs of modern human behaviour or increasing adaptive flexibility (Kandel et al., 2016; Minichillo, 2006). Across the transition from the Middle to the Later Stone Age (LSA), further shifts in raw material choices are associated with toolkit miniaturisation, favouring fine-grained rocks in smaller package sizes (Pargeter & Shea, 2019).

The factors that drive lithic foraging behaviours are closely intertwined with other dimensions of hunter-gatherer life, reflecting trade-offs in how time and energy are allocated to acquiring necessary resources (Torrence, 1983, 1989). The spatial distribution of stone resources strongly influences mobility strategies, structuring whether raw material procurement was embedded within everyday foraging rounds, or obtained through targeted logistical visits to source locations over greater distances (Binford, 1979; Gould & Saggers, 1985). The transport costs incurred could require steps to increase efficiency, such as the removal of cortex to reduce mass (Dibble et al., 2005), or prolonging the use-life of tools through curation (Bamforth, 1986). In contexts where access to suitable raw material was restricted in space or time, additional strategies ensured individuals had access to functional tools when they were needed, through the provisioning of people or places (Binford, 1980; Kuhn, 1995). Within these constraints, the suitability of different raw materials for particular knapping strategies also influenced their selection, based on package size and shape (Andrefsky, 1994b), physical properties such as homogeneity and fracture predictability (Brantingham et al., 2000), and functional properties related to tool use and maintenance (Bamforth, 1986).

Despite the abundance and durability of lithic evidence, accessing these behaviours in the archaeological record presents several challenges. First, it depends on knowing the geological distribution of available stone sources across the landscape. Some rock types, such as obsidian and silcrete, can be geochemically fingerprinted to specific locations, allowing potential pathways of movement to be reconstructed (Nash et al., 2013, 2016, 2022; Shackley & Sahle, 2017). However, other materials cannot be provenanced so specifically, relying instead on geological surveys to determine potential primary and secondary sources (Bader et al., 2025; Gregory et al., 2023; Porraz et al., 2008; Wilkins, 2017). This is further complicated by geomorphic, hydrological, and sea level changes which may expose or cover these sources, meaning that modern distributions do not necessarily reflect past availability (Nash et al., 2016; Wilkins et al., 2017).

Second, the evidence for lithic behaviour is highly fragmented, preserving different stages of raw material procurement, reduction, and tool maintenance variably across the landscape (Dibble et al., 2017; Turq et al., 2013). Yet, the most commonly investigated Palaeolithic or Stone Age settings are cave and rock shelter sites, which represent only a subset of mobile hunter-gatherer life across the wider landscape (Hallinan, 2022a). Nevertheless, these serve as fixed points around which the geological distribution of raw materials is relatively stable, with diachronic changes in lithic procurement and management reflecting wider reorganisation of mobility and foraging activities in response to shifting environmental conditions. Deep sequence MSA and LSA sites, such as Diepkloof Rock Shelter, Sibhudu Cave and Umhlatuzana Rock Shelter, therefore offer long archives of behavioural change, showing marked variability in how local and non-local stone was used, giving insights into local adaptations through time (Porraz et al., 2013; Schmid et al., 2026; Will et al., 2014).

An alternative approach is to prioritise spatial variability over temporal control, considering hunter-gatherer movement between multiple sites across a region (Oestmo et al., 2014; Nash et al., 2022; Schoville et al., 2022). This has been explicitly addressed in recent work in South Africa's Western Cape region. In the Olifants, Varsche and Doring River catchments, landscape-scale studies have examined changes in lithic provisioning, tool design, raw material transport and management to gain diachronic perspectives on land use strategies (Hallinan & Parkington, 2017; Mackay et al., 2018; Shaw et al., 2019). Research in the Doring River area in particular has taken varied approaches, including comparing contemporaneous shelter and open-air site assemblages (Low & Mackay, 2018; Watson et al., 2020), measuring transport through cortex ratios (Lin et al., 2016), and spatial modelling of raw material transfers and mobility systems (Mackay et al., 2022; O'Driscoll & Mackay, 2024).

The Tankwa Karoo (**Figure 1**) falls within the Doring River catchment and has also been the focus of intensive surveys recording open-air lithic scatters (Hallinan, 2021, 2022a, 2022b). While previous work has highlighted changing landscape use patterns between the ESA, MSA and LSA, this paper specifically examines raw material use as a proxy for mobility. The study area extends 100 km from west to east and spans three geological formations with distinctive lithologies, providing a rare opportunity to track raw material transport at spatial scales relevant to mobile hunter-gatherers. Using data from surface stone artefacts, this study combines assemblage composition, transport distance, and reduction intensity to identify how raw material management strategies varied between the MSA and LSA, and how these relate to differences in raw material availability and movement across the Tankwa Karoo landscape.

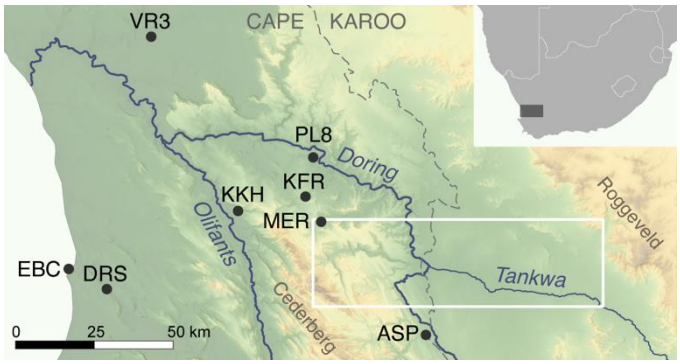


Figure 1. Location of the study area in South Africa. Regional rock shelter sites: ASP, Aspoort Cave; DRS, Diepkloof Rock Shelter; EBC, Elands Bay Cave; KFR, Klipfonteinrand; KKH, Klein Kliphuis; MER, Mertenhof Rock Shelter; PL8, Putslaagte 8; VR3, Varsche Rivier 3. Grey dashed line indicates the boundary between Cape and Karoo Supergroup geologies. White box outlines the survey area.

Raw material transport

Interpreting variation in raw material use requires a framework for understanding how transport and reduction are represented in lithic assemblages, drawing on ethnographic and theoretical models. In a neutral (Brantingham, 2003) or embedded procurement (Binford, 1979) model of stone acquisition, the 'least effort' assumption is that where local materials are available, these will be preferred over stone that requires greater energetic investment to procure (Bamforth, 1986; Torrence, 1983). Thus, the proportions of raw materials in an assemblage can be expected to show predominantly locally available rocks (<5 km) contributing the highest proportion (60–80%), with distance-related 'decay' reducing this to very small quantities (1–2%) derived from distant sources (>20 km) (Brantingham, 2003; Féblot-Augustins, 1993). However, an alternative model is that certain rock types have favourable properties that make the additional procurement costs worthwhile (Beck & Jones, 1990; Gould & Saggers, 1985; Wilson, 2007).

The parameters used to define 'local' and 'non-local' (or distant or exotic) raw materials vary in the southern African archaeological literature, and are highly context dependent (Ambrose, 2006). In their synthesis Kandel et al. (2016) distinguish between local (0–5 km) rocks that could be easily collected

in short walks from a site, regional (6–20 km) rocks that could be gathered during longer foraging rounds, and supra-regional (>20 km) rocks that might require longer logistical forays or interaction with other groups. Will (2021) applies a more spatially conservative framework, introducing an "ultra-local" (<1 km) class to account for rocks procured directly at a site (Rios-Garaizar, 2016), then distinguishing local (1–10 km), and non-local (>10 km) sources. More moderate distances of ">25 or 50 km" (Minichillo, 2006: 360) and 40 km (Ambrose, 2002, 2006; Porraz et al., 2008) have been applied elsewhere. From the perspective of the Kalahari, Nash et al. (2022) regard silcrete transport over 7–55 km across the Ntwetwe pan landscape as within a local range, since in a regional context transport up to 295 km is documented (Nash et al., 2013, 2016). Given this variability, minimum transport distances based on geological availability are used in this study as a comparative measure, rather than imposing *a priori* 'local' and 'non-local' categories.

While archaeologists generally conceptualise raw material transport in minimum (Euclidean) distances, it is unlikely that many raw material movements were made in a single straight-line transfer (Brantingham, 2006; Close, 2000). Rather, stone procurement is part of a wider mobility system that combines short daily foraging ranges with longer-distance movements, either as a specialised logistical trip, or in the course of successive residential moves (Binford, 1980). Ethnographic data indicate that, in general, hunter-gatherer daily foraging radii range around 6–10 km from residential camps (Kelly, 1995). In highly seasonal savanna environments, Pumé (Venezuela) average daily travel distances were ~7.6 km, meaning that the furthest point could not be more than 3.8 km from the camp (Greaves, 2006), while Hadza (Tanzania) women walk an average of 5.5 km and men 8.3 km on a daily round (Marlowe, 2010). In the Kalahari, Ju/'hoansi travel up to 9.6 km (Lee, 1979), meaning that 10 km is often used as a daily foraging radius in archaeological site catchment analysis, though this should be considered a maximum range (Kelly, 2013: 284). However, daily rounds are part of a broader system of mobility that sees successive placement of camps within a wider home range. The average distance of a residential camp relocation may be only 2.1 km (Pumé; Greaves, 2006) or 8–12 km (Hadza; O'Connell, et al. 1988; Marlowe, 2010), but as much as ~25 km (/Gwi and Ju/'hoansi, Kalahari; Lee, 1979; Silberbauer, 1981; Tanaka, 1980) or ~30–50 km (Ngadadjara, Australia; Gould, 1980: 64). More specific information on the distances of a single raw material transport journey is limited, but 40 km is documented in the Australian Western desert (Gould, 1980: 145). These ethnographic examples demonstrate that raw material transport is situated within larger-scale mobility systems, meaning that archaeological transport distances should be regarded as cumulative behaviours rather than discrete events. The lateral variation of the adjacent geological zones of the Tankwa Karoo study area allows overall patterns of raw material movement to be assessed through source-to-discard distances, while recognising that the specific dynamics of transport are likely to have been more complex.

Archaeologists apply a range of quantitative measures to lithic assemblages to interpret raw material procurement, management and mobility strategies, such as flake to core ratios (Holdaway et al., 2004), cortex and volume ratios (Dibble et al., 2005; Lin et al., 2016; Davies et al., 2018), and non-cortical to cortical artefact ratios (Dibble et al., 1995; Holdaway et al., 2004). Cortex is the weathered exterior surface of a stone raw material, indicative of whether it derives from primary geological outcrop or secondary fluvial source. The percentage of cortex remaining on lithic artefacts serves as a proxy for reduction intensity and the curation of artefacts (Dibble et al., 2005; Douglass et al., 2008). The expectation is that less cortex will be present on artefacts that have been transported over greater distances from their sources, mirroring the distance-decay relationship proposed for non-local raw materials. Given the range of lithic technologies and variation in raw material package size in the study area, cortex percentage is treated independently of artefact size or assemblage composition, allowing reduction intensity to be assessed in conjunction with transport distance.

Research questions

Applying this framework to the context of the Tankwa Karoo, this study addresses the following questions:

(1) How does raw material use vary across space (between geological zones) and time (between the MSA and LSA)?
(2) Were some raw materials preferentially transported and curated over others?
(3) Can raw material use and transport offer insights into how people occupied and moved across the landscape?
(4) How do raw material management and land use strategies in the Tankwa Karoo compare with broader regional patterns for the MSA and LSA?

Study area and raw material availability

Geology

The Tankwa Karoo is a lowland basin situated on the provincial border of the Western and Northern Cape, bounded geographically by the Cederberg and Bokkeveld Mountains to the west, and the Roggeveld Mountains to the east (**Figure 1**). These are geologically and orogenically distinct; the western mountains of the Cape Fold Belt comprise Ordovician to Carboniferous formations of the Cape Supergroup, while the elevated Great Escarpment plateau of the subcontinental interior is composed of Permian formations of the Karoo Supergroup (Partridge et al., 2010).

The Cederberg in the western part of the study area is formed of the Cape Supergroup, including erosion-resistant quartzitic sandstones of the Table Mountain Group, overlain by softer Bokkeveld Group shales and mudstones, and Witteberg Group sandstones (Quick & Eckardt, 2015). These lithologies produce a complex topography of steeply incised river valleys caused by extensive folding and faulting, forming both shallow overhangs and deeper rock shelters. The principal primary raw material available is quartzite, which varies in colour, grain-size and inferred knapping quality (**Figure 2A and B**). Within the Table Mountain Group, conglomerates of the Nardouw Formation contain small but abundant quartz pebbles and, less commonly, various types of chert. Silcrete forms on quartz-rich substrates in the Cape geological zone, although its distribution is patchy and dependent upon localised environmental conditions (Nash & Ulyott, 2007; Roberts, 2003).

The central and eastern parts of the study area comprise lower units of the Karoo Supergroup. The Dwyka Group is a glacial tillite containing diverse rock types from across the subcontinent within a fine-grained matrix. These deposits form prominent ridges flanking the Tankwa River and include boulder-rich diamictites, as well as horizons with smaller cobble- and pebble-sized clasts, including quartzite, lava, gneiss, quartz breccia, chert and jasper (Blignault & Theron, 2012; Visser & Hall, 1985) (**Figure 2C and D**). Overlying this, the Ecca Group consists of layers of shales and mudstones deposited as submarine fans, forming an undulating topography with pronounced ridges. The lowest exposed units in the study area include narrow bands of Prince Albert, Collingham and Whitehill Formations, whose shales and carbonates yield localised types of chert (Viljoen 1994).

The Karoo landscape is dissected by intrusive igneous dolerite that forms sills (horizontal features) and dykes (linear features), as well as kimberlite pipes of volcanic breccia (Rogers et al., 2014). Differential weathering of dolerite and surrounding sedimentary rocks produce distinctive landforms of mesa-like plateaux and inselbergs (Holmes, 2012). Contact metamorphism between dolerite intrusions and shale produces hornfels, outcropping along dykes (**Figure 2E**).

Hydrology

The region today falls within the winter-rainfall zone, with annual rainfall ranging between 400 mm in the eastern Cederberg and less than 100 mm in the eastern Tankwa basin. The Doring is highly seasonal, fed by run-off from the Cape Fold Belt mountains to the west and the Tankwa Karoo plains to the east. Although dry for about 150 km of its upper course across the plains, this area is prone to extreme flash-flooding after heavy rainfall. Karoo-derived rocks enter the Doring in its upper reaches, including hornfels and chert cobbles, alongside quartzite and silcrete from Cape sources. The Biedouw and Tra-Tra Rivers are seasonal but presently retain water year-round, carrying quartzite cobbles of varying size and quality, as well as quartz and conglomerate-derived pebbles. The Tankwa

River has a wide floodplain and is highly ephemeral today, receiving run-off from the Roggeveld Mountains to the east. It carries hornfels cobbles as well as other Karoo-derived lithologies (**Figure 2F**). Its main tributary, the Renoster, is also fed by Roggeveld run-off and contains extensive cobble beds of fine-grained sandstones and siltstones (**Figure 2G**).



Figure 2. Geology and available lithologies in the study area: (A) Witteberg Formation quartzite outcrops, (B) primary exploitation of fine-grained quartzite bedrock in the Tra-Tra River Valley, (C) Dwyka tillite boulders, (D) smaller clasts within the Dwyka tillite, (E) hornfels outcrop on a dolerite dyke at Oudebaaskraal, (F) cobble beds of the Tankwa River at Tweefontein, (G) Renoster River cobble beds

Archaeology

Only two dated, excavated rock shelter sites are present in the study area: Mertenhof Rock Shelter falls within the survey zone (Will et al., 2015, 2024) and Aspoort Cave is ~20 km to the south (Smith & Ripp, 1978). The Mertenhof sequence spans the Early MSA to Robberg (MIS 6–2) with a Final LSA occupation, while Aspoort contains LSA from the early to late Holocene. The abundant surface lithic record of the study area represents ESA, MSA and LSA occupation phases. ESA artefacts were largely restricted to Cape geology, making use of locally-occurring quartzite; therefore, this period will not be discussed specifically here (see Hallinan, 2021). The MSA and LSA span approximately 300,000 years and are subdivided into successive technocomplexes with regionally variable characteristics (Lombard et al., 2022). In this study, the broad temporal categories of MSA (~300–40 ka) and LSA (~40–0.2 ka) are used to identify macro-level, landscape-scale trends. However, certain technocomplexes of the later MSA are well represented locally, including the post-Howiesons Poort (early MIS 3). Within the LSA, most assemblages in the study area are likely dated to the mid to late Holocene (Wilton and Final LSA), although late Pleistocene (Robberg) and terminal Pleistocene/early Holocene (Oakhurst) may be represented at some localities.

Materials and methods

Survey and sampling methods

Fieldwork took place over four field seasons between 2013 and 2015, employing an off-site approach designed to capture variation in artefact density across the landscape (Foley, 1981; Hallinan, 2022a). Over 20,300 flaked stone artefacts were recorded in 213 high-density localities (sites), with a further 90 low-density 'off-site' scatters (Hallinan, 2019). Survey areas and walk-paths aimed to encompass the full range of topographic variation on offer to past humans, balancing representative sampling with logistical feasibility in a complex and heterogeneous landscape (Hallinan & Parkington, 2017). Survey paths were recorded with Garmin eTrex H units and individual artefacts were documented in the field by GPS points and digital photos with attributes recorded on annotated sheets. Attributes included descriptive and categorical data, such as artefact type, raw material, cortex type and coverage. Under South African heritage legislation, a permit is only required where artefacts are collected, displaced or destroyed; in this project, all artefact analysis was carried out *in situ* and artefacts were returned to their original position after recording. Further methodological details are provided in previous publications (Hallinan, 2021, 2022a, 2022b), and the full artefact attribute dataset is available from the accompanying repository (https://osf.io/5ebam/).

The principal sampling method recorded all artefacts observed along a survey walk-path; however, where artefact density was too high for complete recording to be feasible, a selective strategy was employed. This prioritised artefacts made of silcrete and CCS (cryptocrystalline silicate; fine-grained chert-like rock), while also recording any retouched or diagnostic pieces in other raw materials. In particularly dense and spatially focused assemblages, the most effective strategy was to record all artefacts within one or more 1×1 m sample squares. Alternative sampling and recording methods were employed at the site Tweefontein where different research questions were addressed (Hallinan & Shaw, 2020; Hallinan et al., 2026).

Analytical approach

For analyses of raw material transport and management, the 1×1 m sample squares provide comparable measures of raw material proportions across locations spanning different geological zones. Since silcrete and CCS artefacts were recorded comprehensively when encountered, these data are suitable for density-based analyses. Given that specific raw materials in the study area are associated with distinct geological sources, spatial analyses (e.g. intersect and proximity) allow the assessment of minimum transport distances and wider movement across the landscape. Assessing how distance from source is related to the proportion of cortex retained on artefacts provides a further indicator of transport and curation strategies.

Spatial and statistical analyses
Spatial analyses were carried out using the ESRI ArcGIS ArcMap (intersect and proximity data extraction) and QGIS platforms (density and map visualisation), with statistical analyses conducted in R (R Core Team, 2026). Intersect (i.e. where does an artefact of a certain raw material overlap with its potential primary bedrock source?) and proximity (i.e. how far is an artefact of a certain raw material from a primary geological or secondary fluvial source?) analyses were used to determine 'local' stone procurement and minimum (Euclidian) transport distances. Open-source spatial data were obtained from the Council for Geoscience, South Africa (1:1 000 000 geological data), and Department of Water and Sanitation, South Africa (1:500 000 rivers data).

In comparing data from 1×1 m sample squares, PERMANOVA (R package: *vegan*; Oksanen et al., 2026) was used to test differences in raw material composition against temporal and geological variables. Non-parametric tests (Kruskal-Wallis for geology, and Wilcoxon rank sum for period) were then used to examine patterning within raw material categories, with p-values adjusted for multiple comparisons using the Benjamini-Hochberg correction. Specific raw material patterns for individual samples were visualised using Non-metric Multidimensional Scaling (NMDS; R package: *vegan*), a non-parametric ordination method based on a Bray-Curtis distance matrix.

Density maps were produced in QGIS by superimposing an arbitrarily placed grid of 500×500 m cells over the study area and calculating the number of artefacts located within each cell, for the whole population, and specific raw materials (silcrete and CCS). To visualise a heat-map of relative densities, Jenks natural breaks were calculated in R (R package: *classInt*; Bivand, 2024) for greater replicability than the inbuilt QGIS function. All data and R script are provided in the accompanying repository (https://osf.io/5ebam/).

Methodological considerations
A limitation in identifying statistical patterning from survey data is that geological formations and landscape settings were not sampled uniformly across the study area. In addition, lithic raw material identification was based on macroscopic observations rather than petrographic or geochemical analyses, which would allow more precise identification of ambiguous types (Bader et al., 2025; Sifogeorgaki et al., 2023; Wilkins, 2017). For example, distinguishing quartzite from quartz or sandstones using macroscopic characteristics alone is not always reliable (Abrunhosa et al., 2023; Howard, 2005; Prieto et al., 2019; Tarriño et al., 2023), with similar observations made for hornfels and dolerite (Wadley & Kempson, 2011). However, a key strength of the methodology was the integration of archaeological and raw material surveys, allowing the types of stone used for artefacts to be directly contextualised within the surrounding geological landscape. Raw materials were classified using a descriptive approach based primarily on colour, grain and cortex type, with informal sub-categories capturing finer-grained variation observed in the field (see **Table S1** for full descriptions).

Results
A total of 20,346 flaked stone artefacts were recorded in landscape-wide surveys, including all sampling strategies and time periods (ESA, MSA and LSA) (Hallinan, 2019). These were distributed roughly equally between Cape (47.6%) and Karoo (52.4%) geological contexts (**Table 1**). Hornfels was the dominant lithology overall (31.5%), followed by quartzite (23.8%). Dolerite, silcrete and CCS each contributed around 11%, with the remainder comprising quartz (7.4%) and various other rocks (4.3%). The principal raw material type in each geological zone was broadly consistent with locally available rocks: quartz (81.4%), quartzite (59.3%) and silcrete (61.9%) were most common on Cape bedrock, and dolerite (95.6%) in the easternmost Karoo region, where dolerite sills cap rocks of the Ecca Group. Hornfels presents a more complex pattern, whereby 41.3% occurs on Cape geology and 31.6% in the east where dykes (primary sources) occur. Cortex was present on 33.3% (n=2132) of hornfels artefacts, indicating that it was predominantly sourced from fluvial cobbles (76.8%, n=1637), with only 23.2% (n=495) deriving from outcrop sources. This pattern is especially strong in the Cape

zone, where 99.4% of cortex derives from river cobbles, likely collected from the Doring River gravels. Silcrete and CCS can be traced to geologically restricted sources, therefore patterns in their usage warrant separate discussion (see below).

CCS is a heterogeneous raw material category in southern African lithic studies, encompassing fine-grained rocks such as chert, chalcedony, agate, jasper and opaline. The varied geological formations of the Tankwa Karoo region result in a wide range of CCS types being used for toolmaking. These were classified into sub-categories based on abundance (C1 and C2 being the most common), or likely source geology (Table Mountain Group or Karoo).

Lithologies classified as quartzite included quartzitic sandstones of Cape geological formations (**Figure 2A–B**), but localised types also occurred in Dwyka and Ecca contexts, present as clasts within the tillite or as metamorphosed or quartz-rich sandstones. These showed strong bedrock-related relationships: 97.1% of very fine-grained translucent 'Dwyka type' (**Figure S1A**) quartzite occurred on or within 5 km of Dwyka geology (n=825 total), and all but one of 'Ecca type' (**Figure S1B**) was associated with the Prince Albert Formation (n=106 total). Quartz was separated into opaque white quartz (66.2%), derived from conglomerate pebbles or hydrothermal veins (**Figure S1C**), and translucent or crystal quartz (33.8%), observed as cobbles in the Tankwa River (**Figure S1D**), but likely available from other sources as well. 'Other' raw material types included brecciated quartz (n=314) observed as seams of brightly coloured blocks (red, purple, grey) on Dwyka geology and knapped close to the source (**Figure S1E–F**), miscellaneous Dwyka rocks (n=110) derived from the glacial tillite (**Figure S1G**), chalcedony (n=87) occurring predominantly near a source on Ecca geology, fine-grained sedimentary rocks including mudstone, shale and siltstone (n=71) across all geologies but most common in Ecca contexts, an indeterminate CCS/shale rock type (n=53) found in two localised Ecca clusters, and iron-rich rock classified as banded ironstone, haematite and ferricrete (n=43) observed across all geological zones. The remaining 203 artefacts were classified as 'uncertain', often with multiple artefacts of a certain type found in one locality.

Raw material	**Total** N *(%)*	**Cape** N *(%)*	**Dwyka** N *(%)*	**Dwyka*** N *(%)*	**Ecca** N *(%)*
All artefacts	20346	9677 *(47.6)*	5259 *(25.8)*	3380 *(16.6)*	5410 *(26.6)*
Hornfels	6411 *(31.5)*	2645 (*41.3*)	1737 *(27.1)*	1311 *(20.4)*	2029 *(31.6)*
Quartzite	4833 *(23.8)*	2865 (*59.3*)	1474 *(30.5)*	1398 *(28.9)*	494 *(10.2)*
Silcrete	2345 *(11.5)*	1447 *(61.7)*	853 *(36.4)*	144 *(6.1)*	45 *(1.9)*
CCS	2190 *(10.8)*	1355 *(61.9)*	480 *(21.9)*	378 *(17.3)*	355 *(16.2)*
CCS: C1 type	1289 *(6.3)*	898 *(69.7)*	228 *(17.7)*	167 *(13.0)*	163 *(12.6)*
CCS: C2 type	470 *(2.3)*	207 *(44.0)*	119 *(25.3)*	101 *(21.5)*	144 *(30.6)*
Dolerite	2177 *(10.7)*	15 *(0.7)*	80 *(3.7)*	33 *(1.5)*	2082 *(95.6)*
Quartz	1513 *(7.4)*	1231 *(81.4)*	105 *(6.9)*	105 *(6.9)*	177 *(11.7)*
Other	877 *(4.3)*	119 (*13.6*)	530 *(60.4)*	512 *(58.4)*	228 *(26.0)*

Table 1. Raw material frequencies and proportions by geological zone. *Dwyka totals excluding intensive samples at TWEE5

How does raw material use vary across space and time?

To systematically examine assemblage-level raw material patterning, 41 1×1 m squares were sampled at five MSA and fourteen LSA sites where assemblages were particularly dense (**Figure 3**). These are not evenly spaced across the landscape, but they illustrate how raw material use changes from west to east across the three main bedrock geologies (Cape, Dwyka and Ecca) for the MSA and LSA (**Figure 4, Table 2**). Descriptions of each site and the techno-typological characteristics of each assemblage are provided in supplementary information **Table S2**.

Site	N squares	Geology	*Quartzite*	*Silcrete*	*CCS*	*Hornfels*	*Quartz*	*Other*	*Dolerite*	Total artefacts	Average per square
MSA											
TRA9CD	2	Cape	80.9	8.5	2.1	6.4	2.1	0.0	0.0	94	47
KOB20	3	Cape	26.6	56.0	4.1	10.1	2.6	0.0	0.6	493	164
MOR4	10	Cape	85.3	7.5	3.3	3.3	0.3	0.3	0.0	361	36
TWEE5_M	1	Dwyka	5.4	5.4	2.7	79.5	0.0	1.7	5.4	297	297
RWF1	2	Ecca	1.2	0.0	1.2	9.6	0.0	0.0	88.0	83	42
LSA											
KRAAI1	2	Cape	9.6	1.3	17.2	54.1	17.2	0.6	0.0	157	79
AGT12	3	Cape	4.8	0.0	14.3	49.0	19.7	12.2	0.0	147	49
AGT11	2	Cape	28.0	4.0	4.0	44.0	18.0	2.0	0.0	50	25
AGT11*	6	Cape	23.7	5.1	8.5	50.0	10.2	2.5	0.0	118	20
TRA14A	2	Cape	11.8	0.0	9.6	56.7	21.9	0.0	0.0	178	89
MOR2	2	Cape	2.6	3.9	29.5	26.5	36.6	0.7	0.0	535	268
MOR1	1	Cape	1.7	29.8	15.7	23.6	27.7	1.7	0.0	242	242
EVLEI2	1	Dwyka	1.4	0.0	24.6	58.0	15.9	0.0	0.0	69	69
BONTE2	1	Dwyka	41.7	2.8	13.9	23.6	13.9	4.2	0.0	72	72
TWEE3	1	Dwyka	9.5	0.0	50.0	32.1	1.2	7.1	0.0	84	84
TWEE5_L	2	Dwyka	4.6	2.0	11.7	65.0	14.2	1.5	1.0	197	99
TWEE10	1	Dwyka	12.5	0.0	4.2	72.2	9.7	0.0	1.4	72	72
GANS4A	2	Ecca	7.4	0.9	20.9	38.7	29.1	1.7	1.3	230	115
PDK4	2	Ecca	0.0	0.0	2.6	95.7	0.9	0.9	0.0	117	59
RWF4	1	Ecca	20.9	0.0	3.6	59.1	3.6	0.0	12.7	110	110

Table 2. Sample square raw material percentages, ordered from west to east by time period.
*AGT11 including four additional samples (see text)

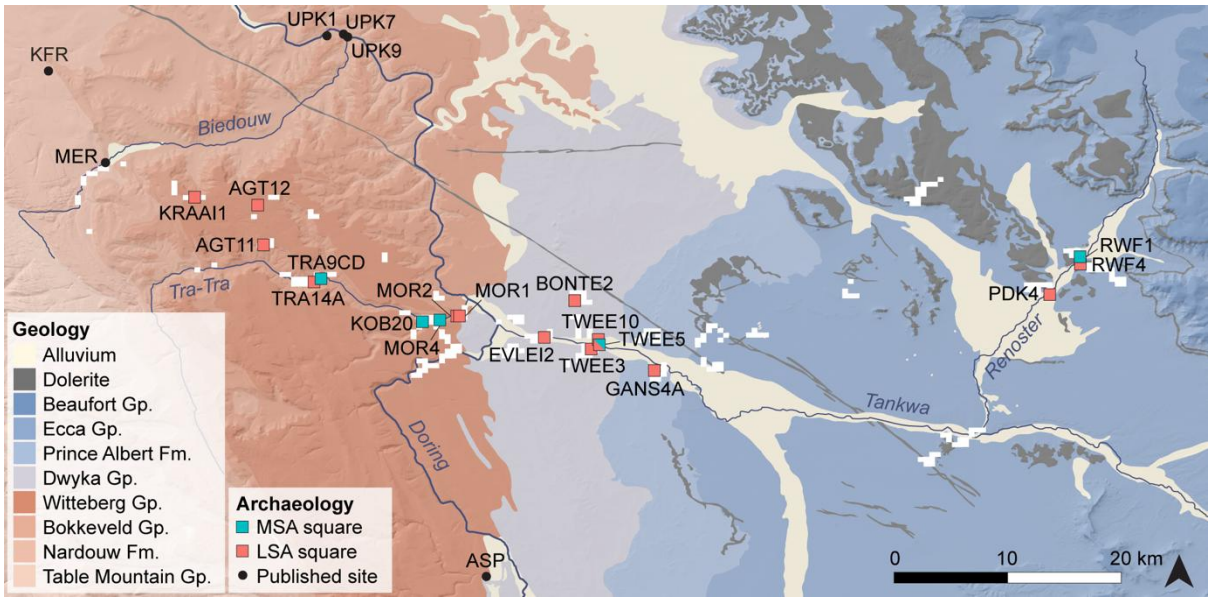


Figure 3. Geological map of the study area showing MSA and LSA sample square locations, and other regional archaeological sites (ASP, Aspoort; KFR, Klipfonteinrand; MER, Mertenhof; UPK, Uitspankraal 1, 7 and 9). Surveyed areas are indicated in white.

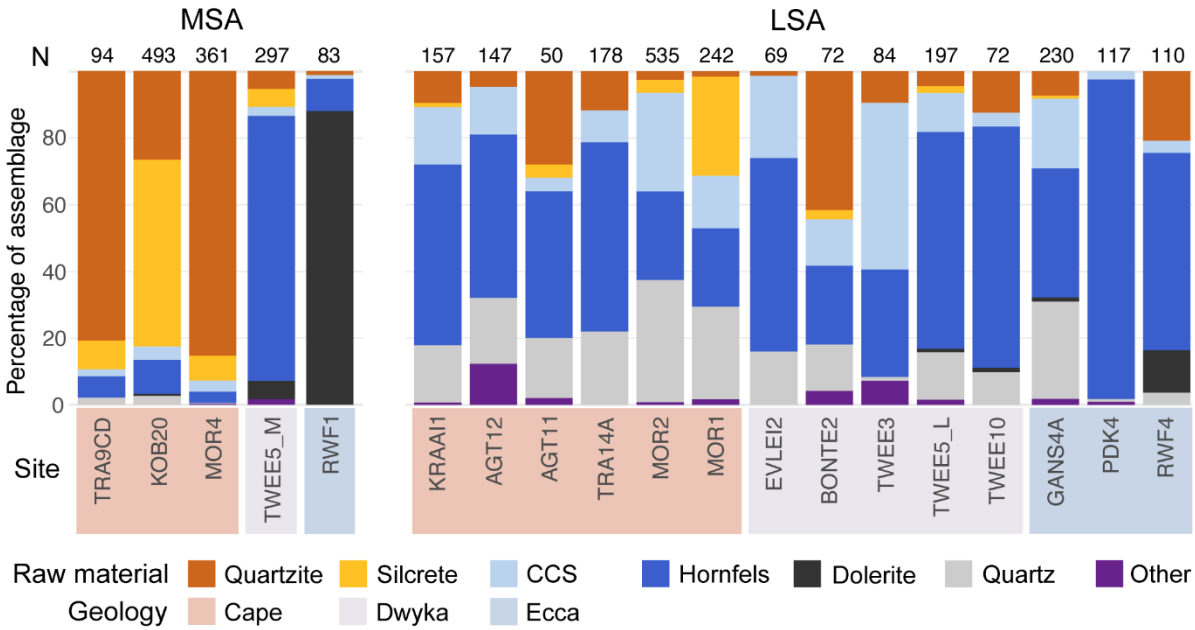


Figure 4. Percentage frequencies of raw material use in MSA and LSA sample squares, ordered from west to east by time period

MSA sample squares were located along the Tra-Tra River on Cape geology (TRA9CD, KOB20, MOR4), on Dwyka geology at Tweefontein (TWEE5), and on Ecca geology at Roodewerf (RWF1) (**Figure 3**). Locally available raw materials comprised over 80% of the assemblage at all MSA sites. The dominant raw material for samples on Cape geology was quartzite, with the exception of KOB20 where silcrete was most prevalent (56%) (**Figure 4, Table 2**). On Karoo geology, hornfels was predominant at TWEE5 (Dwyka) and dolerite at RWF1 (Ecca). Artefact density and overall raw material diversity were greatest at KOB20 (mean n=164 per square) and TWEE5 (n=297), both attributed to the post-Howiesons Poort based on the characteristic artefact types of unifacial points and Nubian Levallois cores (Hallinan, 2021; Hallinan & Shaw, 2020). Elevated silcrete use, including heat-treatment, is also noted to be a regional feature of the post-Howiesons Poort (Schmidt & Mackay, 2016; Will et al., 2015).

The setting of LSA sample squares was more varied, including rock shelters on the elevated Agtersfontein plateau (KRAAI1, AGT12, AGT11) and along the Tra-Tra River valley on Cape geology (TRA14A, MOR2, MOR1), and open-air localities on Dwyka (EVLEI2, BONTE2, TWEE3, TWEE5, TWEE5A, TWEE10) and Ecca geology (GANS4A, PDK4, RWF4) (**Figure 3**). Many Karoo LSA scatters were also associated with (semi-)circular stone structures, tentatively interpreted as windbreaks (Hallinan, 2019; Sampson 1968; Smith & Ripp 1978).

Hornfels was the dominant raw material in most LSA samples, comprising 44–57% of assemblages, including those on Cape geology where there are no local outcrops (**Figure 4, Table 2**). In contrast, use of locally available quartzite and silcrete was generally low in the Cape zone, although AGT11 is an exception (28% quartzite; 4% silcrete). Due to low artefact counts in two sampled squares (n=50), four additional samples were recorded (within a ~1 m radius), producing similar proportions (24% quartzite; 5% silcrete; n=118). Samples from the talus slopes of shelter sites MOR2 (mean n=268) and MOR1 (n=242), located near the confluence of the Tra-Tra and Doring Rivers, yielded the highest overall artefact densities. These were also the only Cape geology LSA sites where hornfels was not the principal raw material. At MOR2, CCS dominated one square (35%, n=215 total artefacts), and quartz was most common in the second square (45%, n=320 total). At nearby shelter MOR1, silcrete was predominant (30%), contrasting with its minimal use at other LSA sites (<4%). On Dwyka geology, hornfels was again the main raw material with two exceptions. At BONTE2, a fine-grained translucent variety of quartzite was preferred, occurring locally as clasts in the Dwyka tillite, while at TWEE3, CCS made up half of the raw materials, mostly using the Prince Albert

Formation 'C2' type (see below). On Ecca geology, raw material proportions at GANS4A show some similarities with MOR2, with high levels of CCS (21%) and quartz (29%), alongside substantial hornfels (39%). While lacking the high number of bipolar cores that characterise MOR2, GANS4A was also a dense assemblage (mean n=115), associated with a circular stone structure with extremely large quantities of ostrich eggshell fragments, including two bead preforms.

Beyond these localised differences between individual sites, PERMANOVA was used to evaluate whether raw material composition varied significantly by time period and geological context (**Table 3**). When considered independently, only period shows a significant effect ($R^2 = 0.293$; $p = 0.003$), whereas geology alone is not significant ($R^2 = 0.167$; $p = 0.124$), indicating that assemblages do not simply reflect local raw material availability. However, the combined model of both factors explains a substantial proportion of variation ($R^2 = 0.436$; $p = 0.001$), and the interaction between period and geology is also significant ($R^2 = 0.219$; $p = 0.001$), explaining 22% of variation between sites. This accords with broader spatial patterning indicating different landscape zone usage between the MSA and LSA: LSA archaeology is more prevalent on Cape geology in the west, while MSA becomes increasingly abundant on Karoo geology to the east (Hallinan, 2021, 2022a, 2022b).

Model	DF	Residual	SS	R^2	F	P
Period	1	17	0.892	0.293	7.051	0.003 **
Geology	2	16	0.509	0.167	1.607	0.124
Period + Geology	3	15	1.328	0.436	3.872	0.001 ***
Period * Geology	2	13	0.667	0.219	4.139	0.01 **

Table 3. PERMANOVA results for period and geology. DF = degrees of freedom, SS = sum of squares, R^2 = coefficient of determination, F = Goodall's F-statistic, P = significance levels: $P < 0.001$ (***), $P < 0.01$ (**)

When raw material composition is visualised using NMDS ordination, LSA sites cluster more tightly than MSA even though there are more samples overall (**Figure 5**). The specific raw material types driving these patterns were confirmed through non-parametric tests (**Table S3**), showing significant differences by period for quartz and CCS (adjusted $p = 0.017$), reflecting elevated usage in the LSA. Weaker, non-significant trends are seen in silcrete and hornfels (adjusted $p = 0.076$), likely driven by specific MSA sites (KOB20 and TWEE5 respectively).

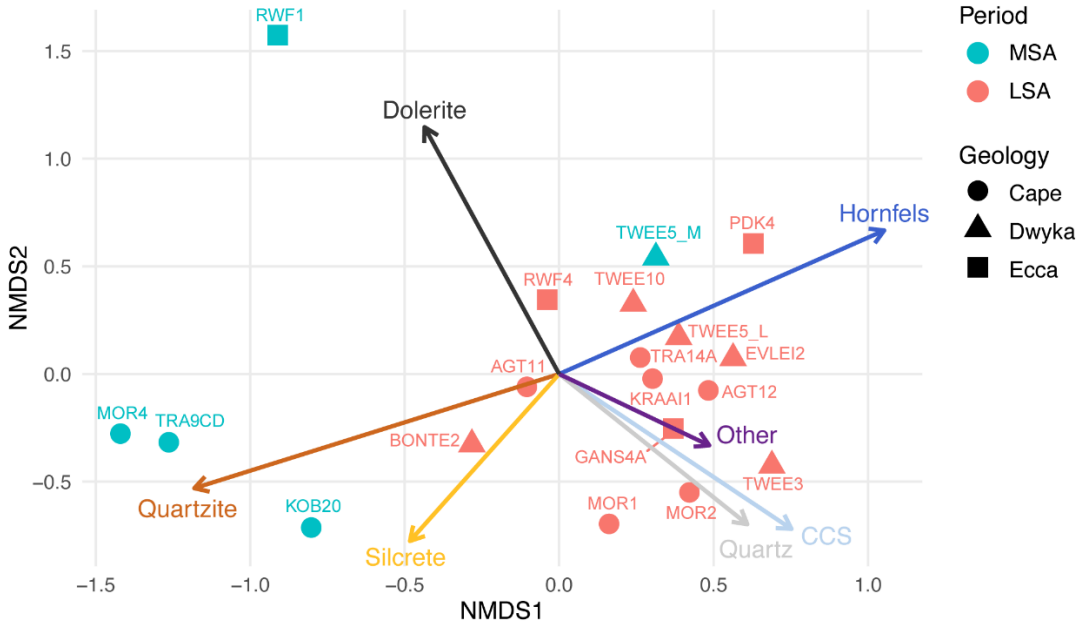


Figure 5. Non-metric Multidimensional Scaling ordination of raw material composition in MSA and LSA sample squares. Vectors indicate the direction and strength of relationships between each raw material and variation among sites.

Were some raw materials preferentially transported and curated over others?

While quartzite (Cape), hornfels and dolerite (Karoo) are abundant across large parts of the study area, other raw material types have more geologically restricted sources, and show strong temporal patterning in their usage. Two raw materials are of particular interest: silcrete and CCS. These are fine-grained raw materials, generally suggested to have desirable fracture properties (Luedtke, 1992; Will & Mackay, 2017; Wragg Sykes & Will, 2017). In the wider southern African record, elevated silcrete use is associated with later parts of the MSA (Will & Mackay, 2017), and CCS is common in the LSA (Deacon, 1984; Mitchell, 2000; Parkington et al., 1988). Considering the total population of artefacts recorded in the survey area (n=20,346), analyses sought to understand where these raw materials came from (minimum transport distance), the type of source (primary or secondary) and degree of curation (cortex proportion). Distance-decay expectations are that artefacts transported over a greater distance will be more highly reduced (low cortex presence), whereas pieces reflecting local procurement will show lower reduction (high cortex presence).

Silcrete is a duricrust that forms on quartz-rich bedrock through the dissolution of silica by percolating water and its subsequent reprecipitation as cemented nodules and crusts (Nash & Ulyott, 2017; Roberts, 2003). In the Western Cape region, sources of silcrete are documented in the bedrock terraces of the upper reaches of the Olifants River and along the west coast (Porraz et al., 2008, 2013; Roberts, 2003), but were presumed to be absent to the east of the Cederberg (Smith & Ripp, 1978; Wiltshire, 2011). However, outcrops in the study area were observed on Witteberg Group bedrock, with a sheet-like duricrust exposure identified on the Agtersfontein plateau (**Figure 6A**). Elsewhere nodules up to 30 cm were observed on the land surface along the lower Tra-Tra River, and above the Doring River at Brakfontein, but similar occurrences are likely to be more widespread (**Figure 6B–D**). A further regional source is noted east of the Doring River at Swartvlei, where ~10 cm nodules may represent a fragmented crust formed on Bokkeveld Group geology (Schmidt & Mackay, 2016). Secondary context river cobbles were observed in the Doring River at Brakfontein and, though infrequent, are noted to the north (Mackay et al., 2014).

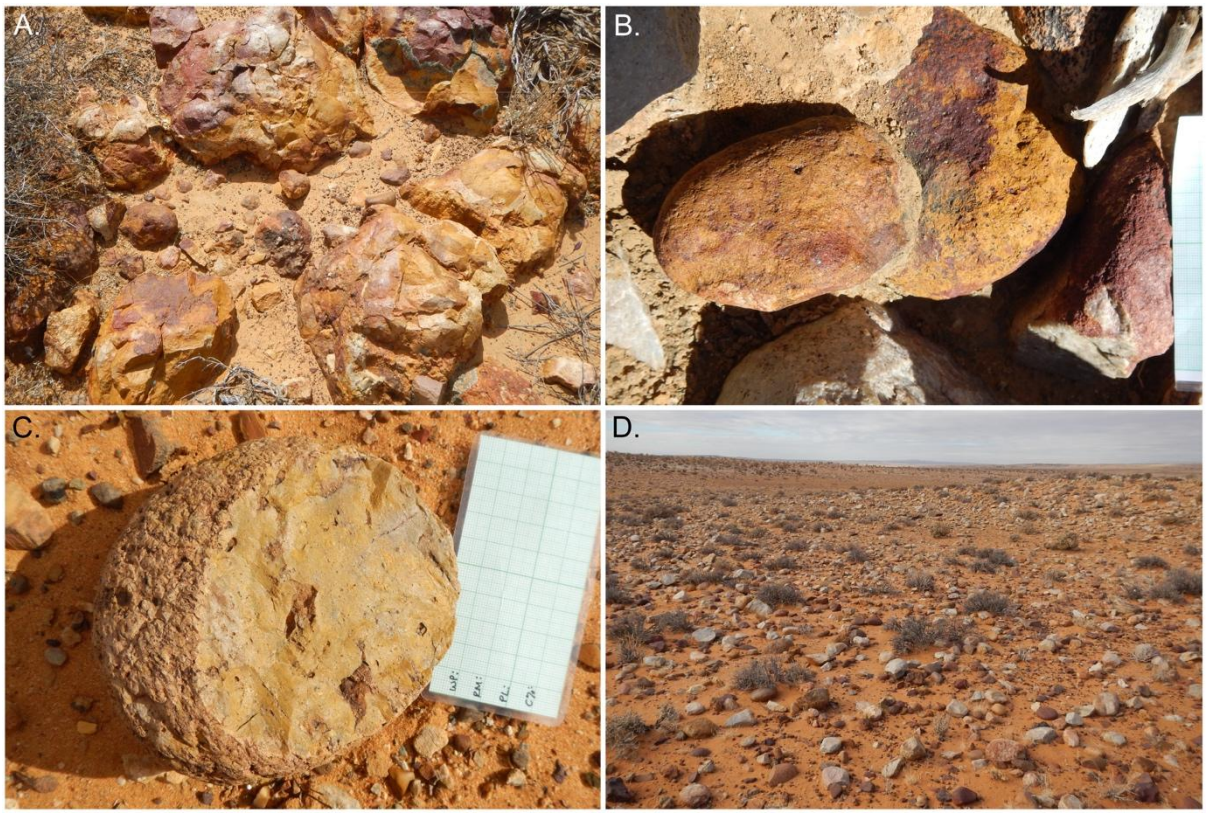


Figure 6. Silcrete sources: (A) primary outcrop at AGT2 on the Agtersfontein plateau, (B) localised cluster of nodules on the cliff top above the southern bank of the Doring River, (C–D) widespread nodules across the landscape at Brakfontein between the Doring and Tra-Tra.

The two most abundant sub-types of CCS identified are examined specifically. The dominant type ‘C1’ is a cryptocrystalline light-grey-blue material with tiny pits throughout (**Figure 7**). Cortex is typically white or orange and the material sometimes contains dark-grey or black patchy (manganese?) inclusions. Variations in colour and inclusions were identified as C1V, and patinated artefacts classified as C1P had a white to orange matt, weathered texture. Primary sources of C1 in the study area are uncertain but the material compares well to CCS from the Matjiesfontein Chert Member, a rock band that lies between the Whitehill and Collingham Formations within the Ecca Group (Cole & Basson, 1991; Parkington et al., 2026; Smith &Ripp, 1978; Viljoen, 1994) (note that available geological maps and GIS shapefiles for the region group the Whitehill and Collingham Formations with the Prince Albert Formation). A primary nodule was noted in the Tankwa River at Ganskop near to where these lithologies may outcrop (**Figure 7A**). Most C1 artefacts recovered had secondary cobble cortex which would accord with the material entering the Doring River 40–60 km south of the study area, where it intersects Whitehill and Collingham geology, and large cobbles were observed. The largest C1 cobbles observed near the Doring were around 10 cm, and many show raw material testing (**Figure 7C**).

The second most common CCS type, ‘C2’ occurs as globular nodules of cryptocrystalline material within a fine-grained mudstone-like matrix. These spherical nodules can be small and thinly distributed in the matrix but knappable CCS is formed when these nodules cluster together in a mass (**Figure 8**). Its colour is variable, ranging from black to red-brown with yellow or olive mottled patches. Sources of C2 appear to be related to the Prince Albert Formation, with outcrops of blocks observed at Spitzkop and intersecting the Tankwa River at Ganskop (**Figure 8A**).

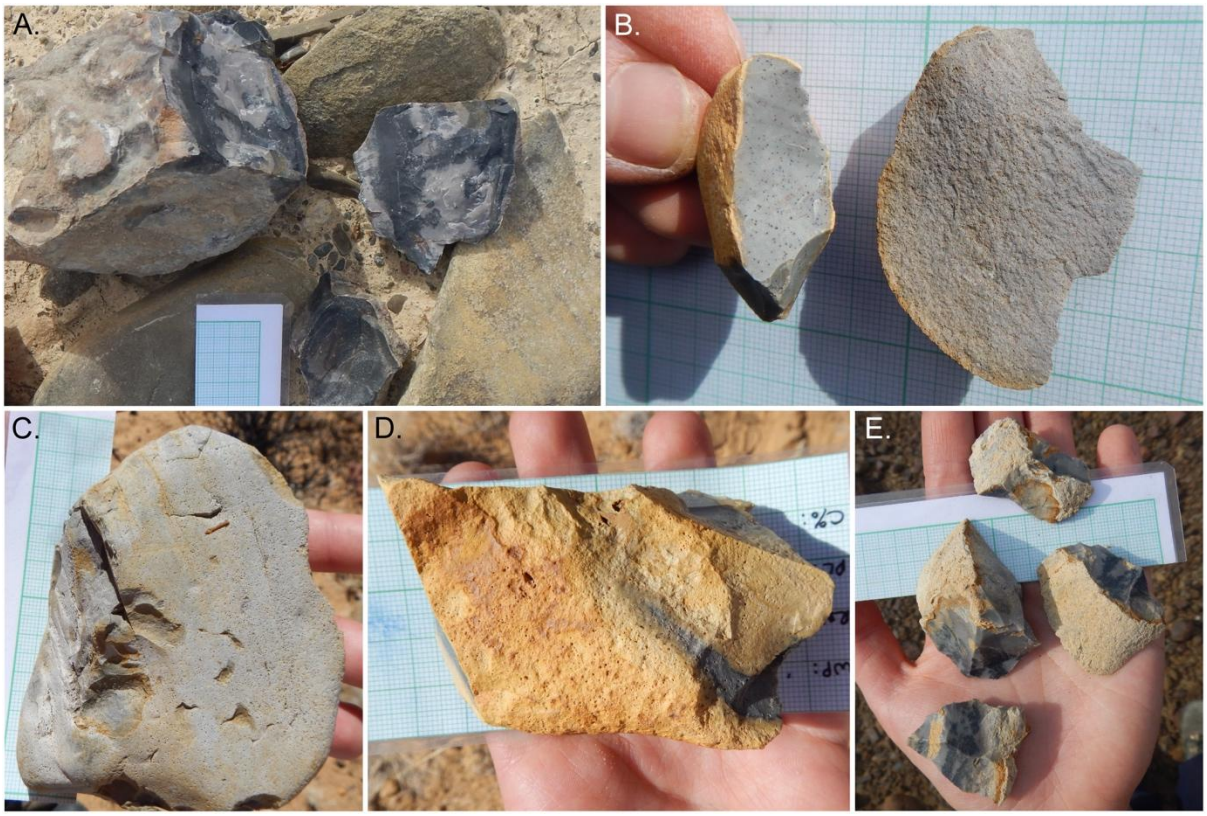


Figure 7. C1 CCS sources: (A) outcrop nodule in the Tankwa River at Ganskop, (B) unweathered and weathered C1 artefacts, (C) cobble from a sandy terrace near the Doring River, (D) chunk with probable outcrop cortex from near the Doring River, (E) cluster of flakes from the same transported nodule

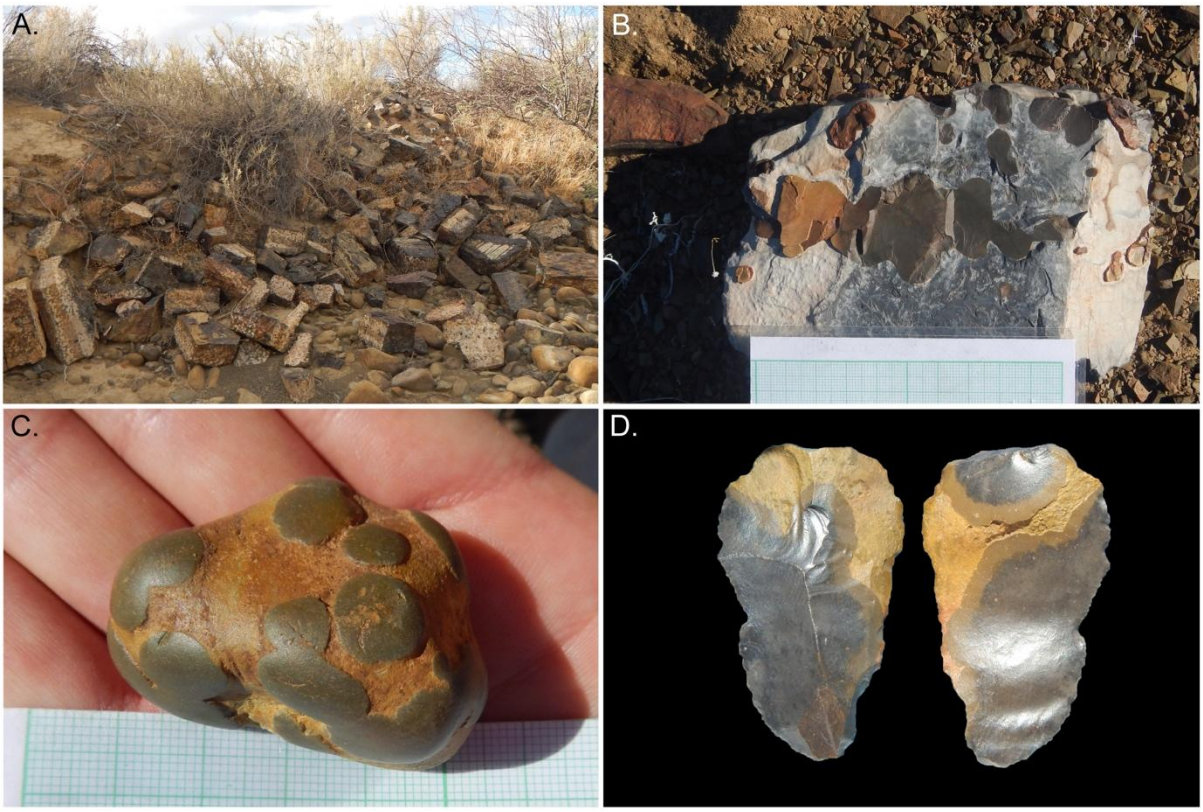


Figure 8. C2 CCS sources: (A) outcrop exposed in the Tankwa River at Ganskop, (B) outcrop chunks at Spitzkop, (C) cobble from near the Doring River, (D) point knapped from C2 CCS from TWEE5

Raw material	Total	Outcrop N *(%)*	Cobble N *(%)*	Indeterminate N *(%)*	No cortex N *(%)*
Silcrete	2345	785 *(33.5)*	71 *(3.0)*	12 *(0.5)*	1477 *(63.0)*
CCS: C1 type	1289	28 *(2.2)*	736 *(57.1)*	41 *(3.2)*	484 *(37.5)*
CCS: C2 type	470	65 *(13.8)*	136 *(28.9)*	21 *(4.5)*	248 *(52.8)*

Table 4. Raw material cortex type frequencies for silcrete and CCS

A total of 2345 silcrete artefacts were recorded, accounting for 11.5% of all raw materials (**Table 1**). Cortex is present on 37.0% of artefacts, most of which derives from outcrop sources (33.5%) (**Table 4**). The majority of silcrete occurs on Cape geology (61.7%), corresponding with the location of primary sources and demonstrating a strong procurement preference. Silcrete is also common on Dwyka geology (36.4%), although most of these artefacts come from a single site, Tweefontein (TWEE5) (n=729, 85.5% of the Dwyka total), which skews the expected distance-decay distribution by producing a frequency spike 10–20 km from Cape geology and 1–10 km from the Doring River (**Figure 9A–B, Table S4**). When this site is excluded, silcrete comprises only 5.3% of raw materials in the Dwyka zone, transported up to 10.5 km from primary (Cape geology) or 9 km from secondary (Doring River) sources—broadly within a local range. The systematic transport of silcrete to Tweefontein displays a trend observed regionally in the post-Howiesons Poort and is highly curated within the assemblage (Hallinan & Shaw, 2020; Hallinan et al., 2026). Silcrete use declines considerably on Ecca geology (1.9%), with minimum transport distances ranging between 15 and 52 km. Overall, silcrete displays a strong distance-decay pattern for raw material transport in terms of artefact frequency, while there is some variation in the percentage of cortex retained (**Figure 9C, Table S5**). Twenty-four silcrete artefacts (23 flakes, two cores) were transported over 50 km to the Roodewerf area, but unexpectedly for artefacts transported such a distance, five retain 25–50% cortex and one flake fragment has 100% dorsal cortex (although of indeterminate type). More broadly, among artefacts with cortex, the dominant coverage category is 25–50%, representing 43% of artefacts from both primary and secondary sources. This is slightly higher than expected, compared with 34–37% of artefacts in the 1–25% cortex range, and is observed across most distance ranges

(**Figure 9C, Table S5**). The fact that outcrop cortex is present on transported pieces indicates that silcrete reduction continued away from immediate sources. The low incidence of cobble cortex (3%), coupled with a rapid decline in its presence and coverage with distance from the Doring River, suggests that where used, decortication of river cobbles occurred close to the source. This pattern accords with observations elsewhere in the Doring River catchment, where fluvial cortex is rare at Doring terrace sites (6.3% of cortical pieces) and absent in transported contexts, indicating a wider preference for outcrop sources (Low & Mackay, 2018; Mackay et al., 2022; Shaw et al., 2019).

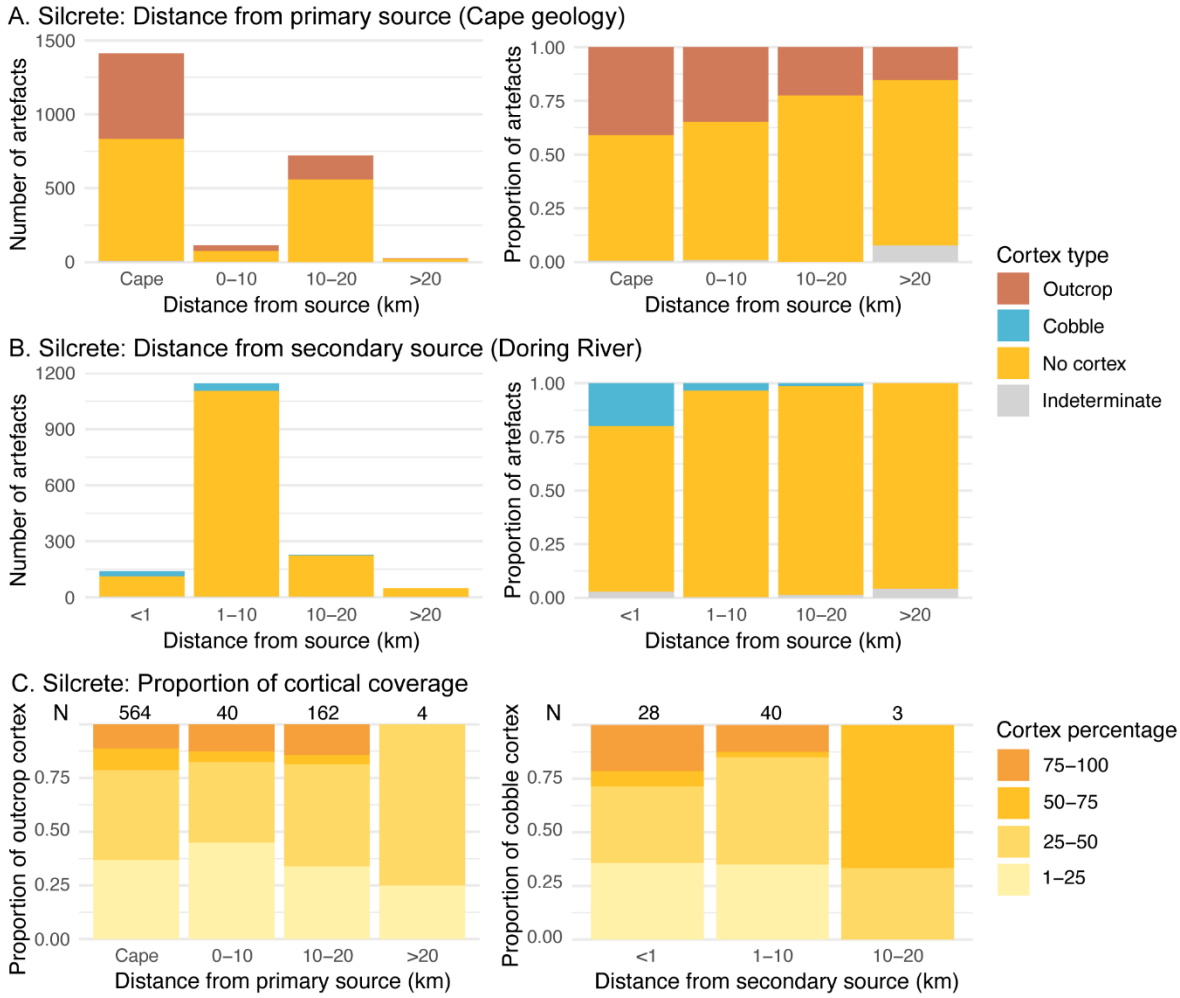


Figure 9. Silcrete transport distance and cortex presence: (A) distance from primary source, (B) distance from secondary source, (C) proportion of cortical coverage

Light-grey C1 type CCS was represented by 1289 artefacts, comprising 58.9% of all CCS (n=2190) and 6.3% of all raw materials (**Table 1***)*. Cortex is present on 61.9% of artefacts, identified as primary outcrop cortex on 2.2% and secondary cobble cortex on 57.2%. This pronounced difference indicates that outcrops are not the principal source of C1 exploited in the study area, supported by the absence of a clear spatial relationship between C1 artefacts and Whitehill/Collingham Formation geology. Instead, the Doring River appears to be the most likely C1 source, corroborated by the largest cobbles being identified on its terraces. While the Tankwa River downstream of the Whitehill/Collingham Formations could potentially contain C1 cobbles, the high-energy Doring (where cobbles were observed) is a more likely source. In support of this, artefacts with high proportions of cobble cortex were most abundant within 1 km of the Doring (**Figure 10C**).

C1 CCS shows a strong distance-decay relationship only from Doring River sources, consistent with the high incidence of cobble cortex (57.2%) (**Figure 10, Tables S6–7**). The majority of artefacts (58–68%) in all but the >20 km distance category preserve cobble cortex, with similar proportions (~40%)

of cortical pieces falling within the 1–25 and 25–50% categories. These patterns are expected given the small package size and high surface area to volume ratio of small cobbles, suitable for transport and complete reduction away from source areas (e.g. **Figure 7E**). This is also reflected in a high proportion (though a low absolute number, n=10) of artefacts with outcrop cortex transported 17–25 km eastwards to Ecca geologies (**Figure 10C**). Compared with silcrete, many more cores and chunks are present in transported contexts (19% artefacts >20 km from the Doring River), further supporting the transport of unreduced nodules.

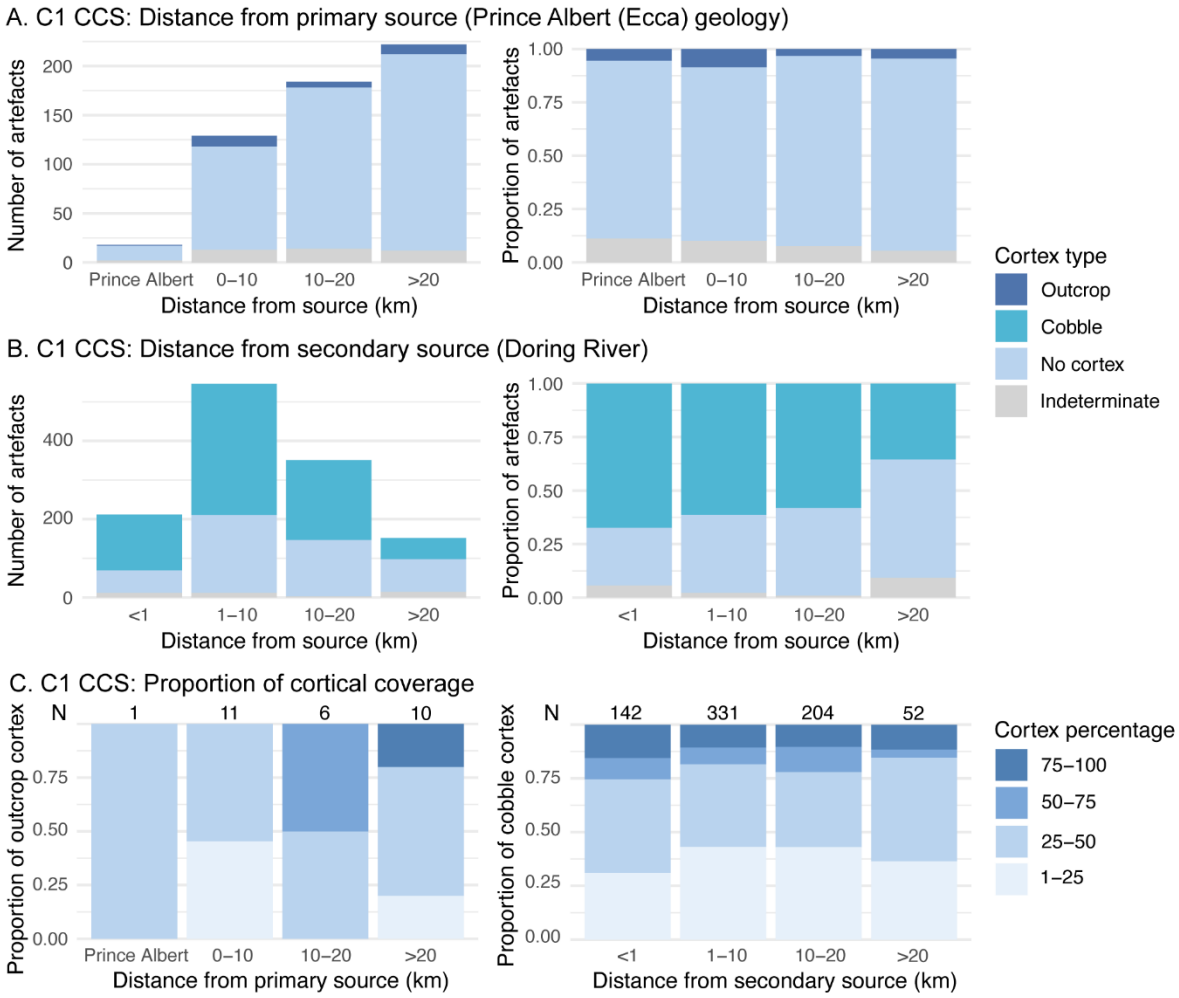


Figure 10. C1 CCS transport distance and cortex presence: (A) distance from primary source, (B) distance from secondary source, (C) proportion of cortical coverage

A total of 470 CCS artefacts were identified as C2 type, representing 21.4% of CCS and 2.3% of all raw materials (**Table 1**). Cortex was observed on 46.1% of artefacts, 28.9% of which was cobble and 13.8% outcrop (**Table 4**). The majority of C2 artefacts were found on Cape geology (44.0%), with cobble cortex on 47.3% of these artefacts suggesting the Doring River as the main source. On Ecca geology, 70.1% of C2 artefacts were found in areas underlain by the Prince Albert Formation, of which 27.7% preserve primary context cortex. Artefacts in this zone account for 21.5% of the total number of C2 artefacts in the study area. Frequencies on Dwyka geology are higher than expected (25.3%), likely reflecting its position between (and roughly equidistant from) both outcrop and Doring River sources.

While the overall artefact sample is lower than silcrete and C1 CCS, the distance-decay pattern for C2 CCS is relatively weak, with no consistent decline in artefact frequency or cortex presence across distance categories (**Figure 11A–B, Table S8**). Cortex frequencies decrease across the 1–10 and 10–20 km distance brackets for both primary and secondary sources, but increase again in the >20 km

category for both. Among artefacts with cortex, patterns are relatively consistent across both primary and secondary contexts, with the 1–25 and 25–50% categories dominating at all distances (**Figure 11C, Table S9**). However, there is no clear relationship between cortical coverage and transport distance, in contrast to the more structured patterns observed for silcrete and C1 CCS. Overall, C2 CCS shows mixed strategies of procurement and reduction intensity that are not closely tied to distance from source, and may reflect more localised or site-specific behaviours influenced by a small number of high-density assemblages (discussed below).

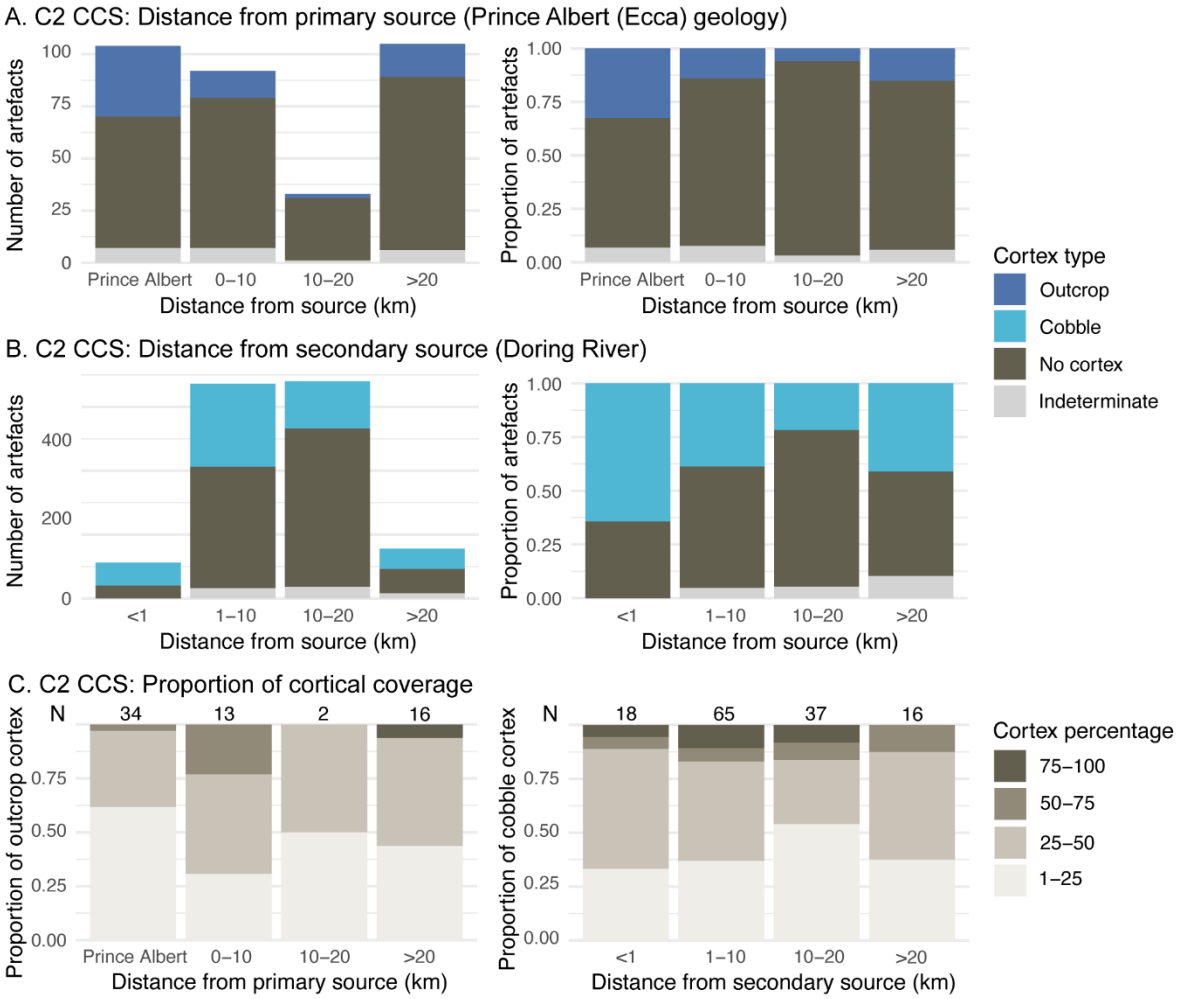


Figure 11. C2 CCS transport distance and cortex presence: (A) distance from primary source, (B) distance from secondary source, (C) proportion of cortical coverage.

Can raw material use and transport offer insights into how people occupied and moved across the landscape?

For the three categories of raw material considered in detail, transfers of over 10 km were relatively common, reflecting widespread circulation of stone across the study area. At a landscape scale, human activity was strongly concentrated along the major river courses of the region (**Figure 12A**) (Hallinan, 2021; see also Hallinan & Parkington, 2017). Building on the broad transport and reduction patterns outlined above, density analyses highlight more spatially discrete concentrations of activity, allowing temporally specific patterns of occupation and movement to be identified.

Much of the silcrete use in the study area is associated with the MSA; 23.2% silcrete artefacts show techno-typologically diagnostic MSA characteristics (n=540), although more artefacts without specific features are present in associated assemblages. By contrast, explicit LSA use of silcrete is

comparatively marginal (n=51, 2.2%), also evident in the 1×1 m sample squares. Although prevalent on Cape geology (61% of raw materials), its distribution suggests that sources are highly localised. Silcrete artefacts are uncommon in the westernmost Cape geology region (Biedouw River) where LSA rock shelter-associated assemblages are most common, only increasing on the Agtersfontein plateau at AGT1, where two MSA bifacial points were observed within a silcrete-rich assemblage (Hallinan, 2021) (**Figure 12B**). Only one duricrust outcrop of silcrete was observed at AGT2 despite wider survey across the Cape geological zone. The highest concentration of silcrete use is around the confluence of the Doring and Tra-Tra River where silcrete nodules are common (**Figures 12B and 6C–D**). In this area, the open-air site of KOB20 and the talus of the shelter site MOR1 are particular hotspots, with artefact types attributed to the post-Howiesons Poort at KOB20 and, potentially, Robberg, at MOR1 (Hallinan, 2021, 2022b; Hallinan & Shaw, 2020) (see Discussion below). Besides Tweefontein, in the easternmost part of the study area, RWF1 and RWF3 contain clusters of silcrete artefacts in association with Nubian cores over 50 km from Cape geology, with an additional silcrete point from a Nubian core at REN1 (40 km). These all lie along the Renoster River which joins the Tankwa to the south, suggesting that at least during the post-Howiesons Poort (early MIS 3), these ephemeral rivers may have formed a conduit for human movement across the Karoo zone towards the more reliable water of the Doring.

C1 is more widely transported across the study area than silcrete (**Figure 12C**), which may relate to its availability as small portable cobbles, and its use in both the LSA (n=826, 64.1%) and MSA (n=141, 10.9%). The highest density of C1 CCS was on the talus of shelter MOR2 (2 km from the Doring), with a C1 CCS and quartz-dominated assemblage. A further high-density assemblage is the LSA site of TRA3 on the Tra-Tra River (13 km from the Doring River), which had large numbers of scrapers (n=20) and small flaking debitage, with elevated quartz use including bipolar cores. Hotspots were also recorded just above the Doring River at BRAK7, a small overhang underneath a boulder, with roughly equal CCS and hornfels use, and on a sandy terrace of the Tra-Tra River, KOB22 (3 km from the Doring), where pottery fragments may indicate a post-2 ka assemblage component (Hallinan, 2022b). MSA usage of C1 CCS was infrequent compared to the LSA; however, like silcrete, its frequency is elevated at the post-Howiesons Poort assemblages of Tweefontein and RWF1, with cortex mostly indicating acquisition from secondary sources.

Most of the C2 artefacts in the study area that could be assigned to a broad time period were LSA (n=301, 64.0%), with only a small number of diagnostic MSA artefacts recorded (n=18, 3.8%), mostly from Tweefontein (TWEE5). Its usage in the far western Cape geology region of the study area was low, clustered at two LSA shelter sites (MER12 and HEUNR4), ~20 km west of the Doring (**Figure 12D**). The highest densities of C2 usage were on Prince Albert Formation geology at two LSA ridge-top sites, GANS1 and GANS4A. This raw material type accounted for 66.7% of CCS artefacts at the extensive scatter GANS1, where diagnostic artefacts were primarily bladelet cores and thumbnail scrapers. At the nearby stone circle GANS4A, 72.4% of CCS artefacts were C2 type, although very few diagnostic artefact forms were recorded in any raw material. Its other main hotspot was the LSA scraper-production site of TRA3 where cobble cortex was most common, and a small but dense LSA scatter at the highest point of the ridge south of Tweefontein, TWEE3, where outcrop was the main cortex type (3 km from Prince Albert geology). Elevated C2 was also noted at the boulder overhang BRAK7 and MOR2 shelter talus, showing overlap with high C1 use. In the east, C2 was the most common CCS type at REN2, a concentrated LSA scatter near the Renoster River, with both outcrop (n=8) and cobble (n=4) cortex present, 21 km and 40 km from primary and secondary (Doring) sources respectively. At a landscape-scale, assemblages with a high incidence of C2 occur along the Tra-Tra and Tankwa River channels on either side of the Doring, suggesting regular movement in both directions along a west–east axis.

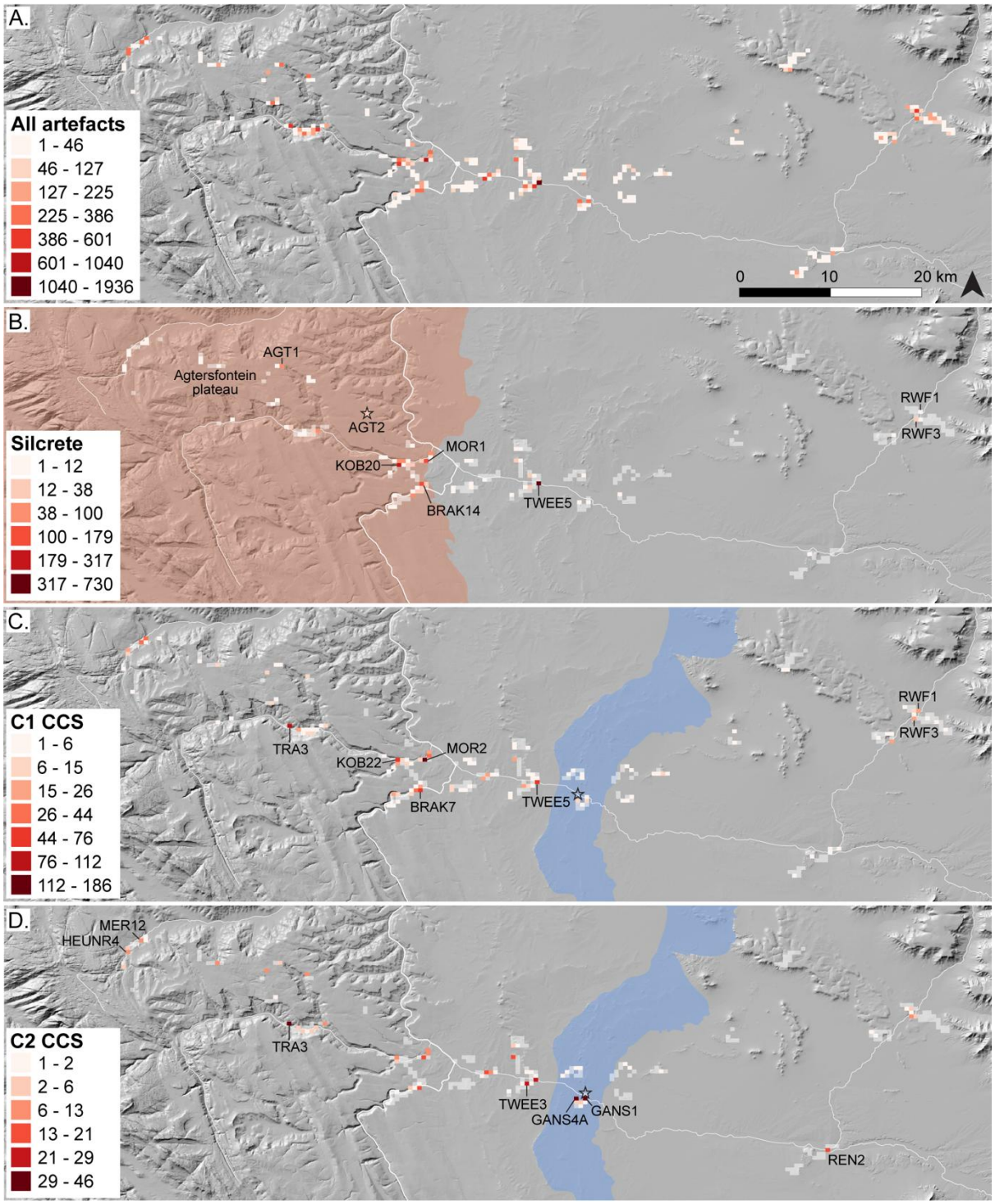


Figure 12. Artefact densities per 500×500 m grid cell: (A) all artefacts, (B) silcrete, (C) C1 CCS, (D) C2 CCS. Potential geological sources are indicated by shaded areas: in (B) orange indicates Cape geology, in (C–D) blue indicates Prince Albert geology. Identified primary sources are marked by a star. Named sites are referred to in the text.

Discussion

The Tankwa Karoo provided past toolmakers with an abundant and wide range of flakeable stone, with distinct raw material preferences observed between the MSA and LSA. However, raw material use in both periods shows that local availability was not always the primary driver of stone selection, reflecting deliberate preferences or procurement strategies. Three raw material types are particularly informative in both the study area and regional record: silcrete, available from Cape geology, and

CCS and hornfels, available from Karoo geology and the Doring River. Variable investment in procuring these rocks through time and across space may reflect changes in mobility and access to toolstone, as well as changes in the functional requirements of different stone types.

How do raw material management and land use strategies in the Tankwa Karoo compare with broader regional patterns for the MSA and LSA?

Within the regional context of the Doring River catchment, other studies have identified strong patterning in silcrete and hornfels transport in particular, deriving primarily from outcrop (silcrete) and fluvial (hornfels) sources (Lin et al., 2016; Low & Mackay, 2018; Mackay et al., 2020, 2022; Schmidt & Mackay, 2016; Shaw et al., 2019; Watson et al., 2020). This area is of significant comparative value to the Tankwa Karoo study since it combines both chronologically anchored rock shelter occupation with temporally discrete open-air scatters on terraces of the Doring River (Mackay et al., 2023; Shaw et al., 2019, 2026). Rock shelters are scarce in Karoo geologies west of the Doring River, whereas they are common along the smaller, steeply incised tributaries in the Cederberg Mountains, where water may be more reliable but the range of locally available raw material is more limited. Existing work has integrated the rock shelter and open-air site records to gain landscape-level insights into MSA and terminal Pleistocene LSA raw material transport and land use dynamics within the region (e.g. Low & Mackay, 2018; O'Driscoll & Mackay, 2024; Watson et al., 2020). Raw material transport has also played a pivotal role in regional discussions of Holocene LSA hunter-gatherer mobility systems (Parkington, 1972, 1987; Smith & Ripp, 1978). Parkington proposed that Karoo-derived rocks present in Cederberg assemblages were evidence of movement between the areas (Parkington, 1972, 1987; Parkington & Poggenpoel, 1971; Parkington et al., 1988). This was later tested through the investigation of Aspoort Cave near the Doring River, where four excavated LSA levels yielded ages that span the early to late Holocene (Parkington & Hall, 1987; Smith & Ripp, 1978). Results from the Tankwa Karoo broaden these perspectives into a contrasting geological setting, allowing patterns of raw material transport and land use to be evaluated across both Cape and Karoo landscapes.

Based on currently available comparative data, the majority of MSA activity in the Tankwa Karoo is likely to date to MIS 6–5 and MIS 3 (Hallinan, 2021). Sampson (1968, 1986) proposed that MSA assemblages in the interior Karoo were associated with humid episodes of MIS 5 or MIS 3 (see also Carr et al., 2023; von der Meden et al., 2022), but precisely when, together with finer-grained technological signatures, remains unresolved. Only a few bifacial points of potentially Still Bay age were observed in the study area, and no backed artefacts or characteristic blade cores of the Howiesons Poort. This stands in contrast to the presence of MIS 4 Still Bay and Howiesons Poort occupations in regional rock shelters and (Still Bay) open-air sites (Mackay et al., 2018), though is consistent with their absence from the interior Karoo region in general (d'Errico et al., 2017; Hallinan, 2026; Sampson et al., 2015). The post-Howiesons Poort (>50 ka) is well-represented regionally in both dated rock shelters and open-air contexts (Hallinan & Shaw, 2020; Mackay, 2011; Will et al., 2015). However, a major challenge is that many surface assemblages, especially those in the easternmost Ecca zone, show 'generic MSA' radial and preferential Levallois cores, unretouched and unifacially retouched points, and blade production which cannot be tied to a specific period (Hallinan, 2021). This means that most MSA behavioural interpretations for the Tankwa Karoo area are currently restricted to the post-Howiesons Poort.

Early MSA (MIS 6–5) assemblages are difficult to identify given their heterogeneous features but may be recognised through prepared cores, blade production, and generally expedient tools comprising denticulates, notches and scrapers (O'Driscoll & Mackay, 2023, 2024; Schmid et al., 2016). Locally, MSA assemblages dated to MIS 5 and 6 at Mertenhof and Klipfonteinrand 1 show a strong preference for local quartzite and sandstone, including "ultra-local" direct flaking of a roof-fall block at the latter site (O'Driscoll & Mackay, 2023, 2024) (**Figure 13**). This behaviour can also be observed on the local landscape, particularly where Witteberg Group quartzites outcrop and MSA surface scatters show the large-scale exploitation of fragmented quartzite bedrock that litters the

landscape, such as MOR4 (**Figure 2A**), as well as direct flaking of finer-grained outcrops along the cliff walls of the Tra-Tra River (**Figure 2B**).

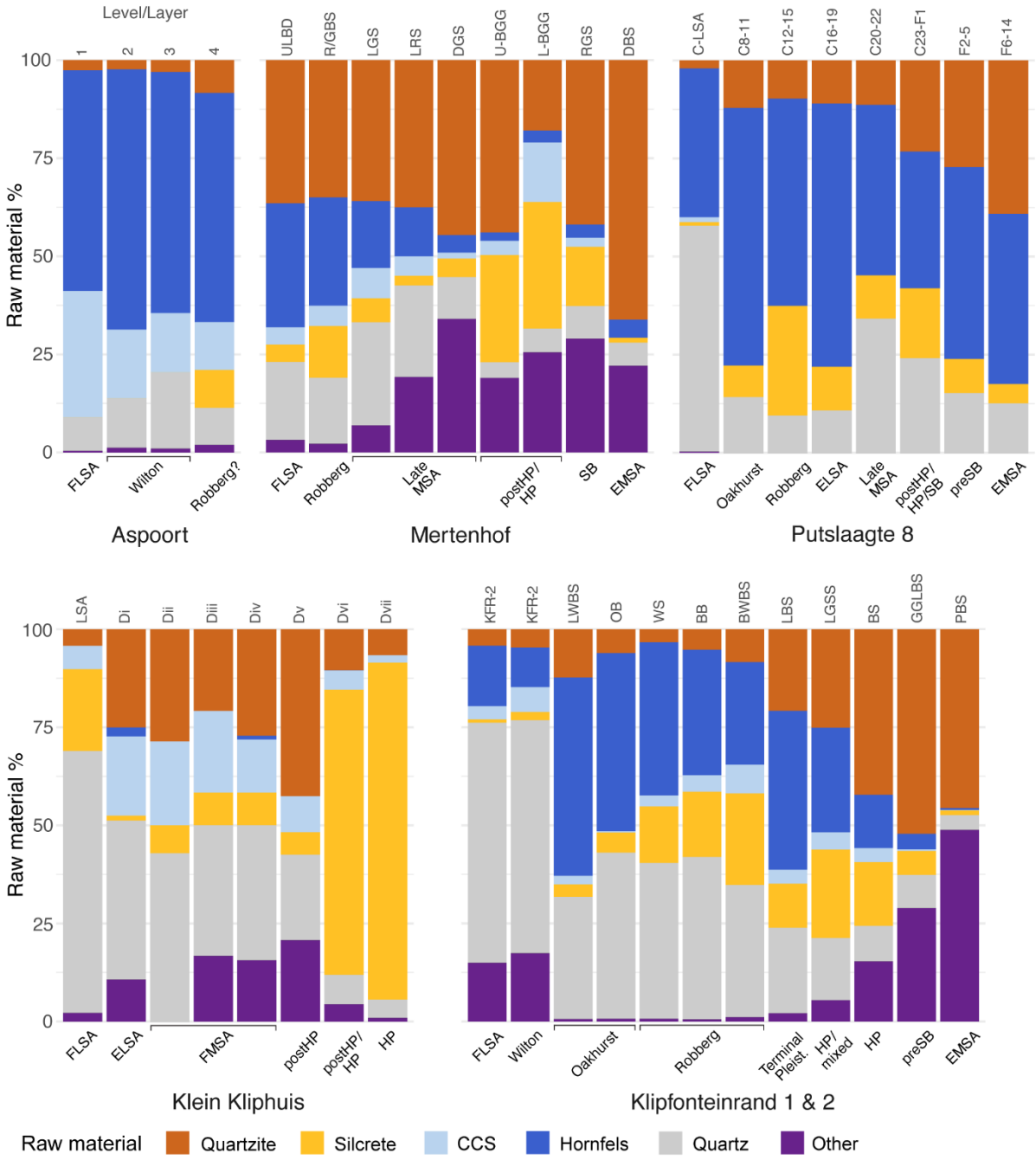


Figure 13. Raw material frequencies in LSA and MSA occupations at regional rock shelter sites. Full data and references are provided in **Table S10**. See **Figure 1** for site locations.

Post-Howiesons Poort (early MIS 3) assemblages in the region have unifacial points as the dominant tool form (Mackay, 2011; Porraz et al., 2013), and locally show novel modes of Levallois point production using the Nubian method (Hallinan & Shaw, 2020; Will et al., 2015). Silcrete use is elevated during the Howiesons Poort and post-Howiesons Poort at Klein Kliphuis and Mertenhof (**Figure 13**), with an emphasis on silcrete also seen at the Doring River open-air site of Uitspankraal 7 (Will et al., 2015) as well as at Tweefontein (TWEE5) and KOB20 in the study area (Hallinan & Shaw, 2020). While KOB20 is very close to primary silcrete nodules, Tweefontein is located over 10 km from observed and potential sources. Nubian cores at Tweefontein made from silcrete show high levels of reduction intensity in both core size and shape (Hallinan & Shaw, 2020; Hallinan et al.,

2026), reflecting an expected curation signal for transported raw material. Mertenhof is located 20–25 km from known silcrete sources, yet this raw material represents ~20–30% of the assemblage in the post-Howiesons Poort and Howiesons Poort (Schmidt & Mackay, 2016). Heat-treatment of silcrete was employed as a strategy to increase its fracture predictability, making it more 'chert-like' in its flaking properties (Schmidt & Mackay, 2016). At Mertenhof, silcrete heat-treatment is most common in the post-Howiesons Poort (87% of silcrete), when chert and hornfels use are lowest and local quartzite use is relatively high (Schmidt & Mackay, 2016). In the preceding Howiesons Poort, silcrete use is high but signs of heat-treatment are less common (37–43%), while relative proportions of chert and hornfels are higher and quartzite use is low. The increase in local raw materials and silcrete heat-treatment in the post-Howiesons Poort at Mertenhof is interpreted as reflecting more restricted mobility, employing strategies to prolong the use-life of stone that required transport at least ~20–25 km (Schmidt & Mackay, 2016). This stands in contrast to the post-Howiesons Poort in the Tankwa Karoo where both systematic transport of silcrete to Tweefontein and occasional long-distance (>50 km) movement of silcrete is observed. This may indicate differences in how activities at rock shelter and open-air sites were organised, with Tweefontein interpreted as a 'gearing up' site for large-scale production of Levallois points from Nubian cores that were used to provision individuals moving more widely across the landscape (Hallinan, 2021; Hallinan & Shaw, 2020).

Following the post-Howiesons Poort, assemblages attributed to late MIS 3 show a shift in raw material use and procurement strategies. The open-air Doring terrace site of Putslaagte 1 may reflect a further 'gearing up' locality, making use of locally available hornfels cobbles (Mackay et al., 2014). A substantial cortex deficit in relation to the volume of knapped hornfels at the site suggests that large flakes were transported away (Lin et al., 2016). The Putslaagte 1 assemblage is composed mostly of informal flakes and cores with an absence of formal tools, making it difficult to recognise its wider landscape signature or determine where these large flakes were transported to. One possibility is illustrated in the short, punctuated occupations during mid MIS 3 at Mertenhof, which show higher hornfels proportions than earlier in the MSA, coupled with an under-representation of cortical pieces (Will et al., 2024) (**Figure 13**). Mid MIS 3 pulses are also observed at Putslaagte 8 Shelter (Mackay et al., 2015), which together suggest that open-air localities played an important role in wider settlement systems—a component that may be represented by some of the 'generic MSA' Tankwa Karoo assemblages.

MIS 2 occupation in the region encompasses the Early LSA, Robberg and Oakhurst, with a particularly strong Robberg signal in shelter and open-air contexts (Low et al., 2017; Low & Mackay, 2018; Mackay et al., 2020; Watson et al., 2020). Robberg assemblages (locally ~22–16 ka) are characterised by the production of bladelets from volumetric single platform cores, alongside bipolar technology and few retouched tools (Deacon, 1984), with a particular emphasis on silcrete in the Doring catchment, and cryptocrystalline raw materials more widely (Bousman, 2005; Mitchell, 2000). Robberg assemblages at Mertenhof, Putslaagte 8 and Klipfonteinrand 1 provide grounds for attributing the silcrete-rich (30%) shelter talus assemblage at MOR1 to the Robberg (**Figure 13**). This includes seven single platform cores with bladelet removals made from silcrete and varied types of CCS, alongside quartz and CCS bipolar cores, and three thumbnail (small convex) scrapers in quartz and CCS. Most flakes were fragmentary, which may account for why blades and bladelets were not observed in the 1×1 m sample square. A further potentially Robberg occupation locally is in the lowest layer at Aspoort Cave—the only level to contain silcrete (Smith & Ripp, 1978) (**Figure 13**). While this is associated with a radiocarbon date of 10.7 ka (uncalibrated age: 9420±160, sample: PTA-2250; Parkington & Hall, 1987), there is currently insufficient technological information available to confirm whether the assemblage has Robberg or Oakhurst technological characteristics. Silcrete is present in reduced quantities in the Oakhurst at Klipfonteinrand and Putslaagte 8 (~16–13 ka) (**Figure 13**), but the period's diagnostic artefacts are tabular short-axis cores and large scrapers or 'naturally backed knives' typically made on hornfels, alongside macrolithic flake production (Mackay et al., 2015, 2020; Sampson, 1985). These artefact types are especially common around the terraces of the Doring River where hornfels was readily available in tabular cobble form (Hallinan, 2022b; Shaw et al., 2019). Although in the interior Karoo, Oakhurst or Lockshoek activity is widespread (Sampson, 1985), its markers were uncommon east of the Doring River in the study area. However, increased use

of (non-local) hornfels in the Oakhurst at Elands Bay Cave on the west coast may indicate regional mobility towards the coast rather than further inland (Orton, 2006; Parkington, 1987; Parkington et al., 1988). The regional Holocene sequence begins in the Wilton, represented only at Aspoort (~8–6 ka) and, potentially, Klipfonteinrand 2, where the LSA is divided into pre- and post-2 ka components (i.e. without and with pottery) (Nackerdien, 1989; Smith & Ripp, 1978) (**Figure 13**). The closest comparable LSA assemblage in the Tankwa Karoo is at MOR2, which like Aspoort Levels 2–3 comprises roughly equal proportions of CCS and quartz, alongside bipolar technology and tools with backing and scraper retouch (Deacon, 1984). LSA assemblages are abundant in the wider Tankwa Karoo landscape, showing diverse raw material preferences even within geological contexts (**Figures 4–5**) and often lacking in retouched tools, therefore determining their specific chronology is challenging (Hallinan, 2022b).

The regional Final LSA (>2 ka) at Putslaagte 8, Klipfonteinrand 2 and Klein Kliphuis show a strong predominance of quartz, but this is more muted at Mertenhof and Aspoort, situated closer to the Tankwa Karoo (**Figure 13**). At the sampled LSA sites, pottery fragments were present at KRAAI1, AGT12, TRA14A, PDK4 and RWF4, all of which are dominated by hornfels and mostly have low CCS usage. Pottery is generally infrequent in the study area (Hallinan, 2022b), clustering strongly around major water courses (Tra-Tra, Doring and Renoster Rivers), or within 1 km of a spring on the Agtersfontein plateau. Pottery is entirely absent from LSA sites along the main Tankwa River channel (Dwyka and Prince Albert geology) where assemblages occur at elevated points in the landscape, often associated with a small circular stone structure. While this may reflect behaviour from a chronologically restricted period, it may also relate to site function as ephemeral camps or hunting blinds (Brooks, 1978; Crowell & Hitchcock, 1978; Jacobson, 2004; Parsons, 2004, 2005; Sampson, 1985), where pottery was not required and raw materials were procured from targeted sources in the immediate surrounds; for example, translucent quartzite at BONTE2, and C2 CCS at TWEE3.

Mobility—and thus access to stone—is only one dimension in understanding why certain raw materials were selected over others, with choices also linked to the physical properties of stone and their suitability to given technological systems (Schmidt et al., 2024). The qualities of knappable stone can be assessed in terms of both flaking predictability and edge durability as finished tools. Materials with fine-grained, homogeneous (isotropic) internal structures, such as chert or CCS, tend to fracture predictably, making them well-suited to complex reduction sequences (Brantingham et al., 2000) and fine retouch (Orton, 2008). However, these are often comparatively brittle, producing sharp but less durable edges. By contrast, coarser-grained rocks such as quartzite require greater force to fracture, but produce edges that are more resistant to abrasion and mechanical stress (Braun et al., 2009; Schmidt et al., 2024).

In southern Africa, CCS (chert) is not widely available as extensive deposits (Will, 2021; cf. Bader et al., 2025) and instead occurs primarily as small cobbles or pebbles in fluvial contexts that were often transported over substantial distances (Bousman, 2005). In the Tankwa Karoo, despite the expected geological potential for obtaining CCS from primary Karoo geological contexts (e.g. Schmidt & Mackay, 2016; Will et al., 2024), only limited use of outcrop sources was reflected by cortex type. Instead, procurement was principally as secondary cobbles (<10 cm) of light grey pitted C1 type that were transported widely, particularly to the Cederberg in the west. However, a localised primary source of brown C2 type on the Prince Albert Formation was exploited at nearby Holocene LSA sites, although cortex suggests that cobbles from the Doring River were used and transported more widely. The small size and portability of complete CCS pebbles, combined with their fine-grain and predictable fracture, made this material suitable for small flake and bladelet production knapped from unprepared freehand or bipolar cores.

Silcrete is generally a fine-grained rock capable of producing sharp edges. Its fracture predictability can be improved through heat-treatment (Brown et al., 2009; Schmidt et al., 2013), but with the trade-off that heat-treated silcrete requires more force for edge-chipping (i.e. retouch) than in its unheated state (Schmidt et al., 2024). Macroscopic changes to the material can be observed on heat-treated artefacts (e.g. Schmidt & Mackay, 2016), though these were not systematically recorded and as such

the use of heat-treatment in the Tankwa Karoo is currently unknown. The long-distance transport of silcrete from source locations supports arguments that it was a highly desirable stone during the MSA (Deacon & Wurz, 1996; Nash et al., 2013; Will & Mackay, 2017), with these behaviours also observed in the Tankwa Karoo. Numerous primary sources with varying nodule size and quality were available to the west of the Doring River, with evidence in the post-Howiesons Poort for structured transport to 'gearing up' locations as well as movement over distances >50 km to the east, exhibiting strong curation and distance-decay. This suggests that the mechanical properties of silcrete were sufficient to offset the cost of transport within broader mobility systems. Silcrete was used for a range of high-investment technologies, such as Levallois cores, Levallois and retouched points in the MSA, with more limited use in the LSA where other fine-grained rocks fulfilled toolmakers' needs.

Hornfels presents a contrasting case, requiring comparatively low knapping force but exhibiting reduced fracture predictability and limited resistance to edge abrasion (Schmidt et al., 2024). It was used for a range of technologies, including both preferential Levallois point reduction and expedient large flake production. In the Tankwa Karoo, the most common morphology of hornfels was as tabular blocks, providing flat platforms and 90-degree knapping angles that did not require prior preparation, incorporated into localised technologies in both the MSA and LSA (Hallinan, 2022b; Hallinan et al., 2026; Mackay et al., 2015; Shaw et al., 2021). Although primary sources were available from dolerite dykes in the eastern Karoo, none were observed to yield large or high-quality pieces or reflect intensive use as 'quarrying' sites (Sampson, 1985; Will et al., 2026), and fluvial cobbles were still a persistently exploited source. In Karoo geological contexts, dolerite provides an alternative to quartzite as a hard and durable raw material (Wadley & Kempson, 2011). Hornfels and dolerite have also been shown to possess similar hardness and stiffness values, suggesting they were equally suited to certain technologies, such as blade manufacture (Fratta et al., 2026). For the MSA in the eastern Ecca zone of the study area, both materials were selected and knapped in a similar manner, including centripetal Levallois flake (radial core) and blade reduction, as well as producing Levallois and unifacial points. However, hornfels was always selected over dolerite for Nubian Levallois point cores, implying desirable knapping qualities beyond availability alone.

Conclusion

The rich, multi-period surface archaeological record of the Tankwa Karoo provides a rare opportunity to examine lithic raw material transport across adjacent geological zones with distinct lithological potentials for past stone toolmakers. The wider Doring River catchment has been the subject of comparative studies that connect movement and behaviour between rock shelters, open-air sites and raw material sources across the region. However, the Doring River itself has formed a delimiting boundary to these discussions, with mobility models largely oriented towards the Cederberg Mountains to its west. The Tankwa Karoo data extend this perspective eastwards onto Karoo geologies, where alternative raw materials (CCS, hornfels and dolerite) are available from primary sources. Results show that while the Doring River was a key focal point, both as a source of water and fluvial cobbles, additional riverine corridors on a west–east axis played an important role in structuring habitual movement, reflected in raw material transport.

Assemblages from the MSA show a preference for locally available stone, although during the post-Howiesons Poort silcrete was selected and transported over greater distances, suggesting that its desirability as a raw material offset procurement costs within broader mobility systems. By contrast, LSA assemblages display a consistent emphasis on Karoo-derived rocks irrespective of local bedrock geology. CCS was acquired from both the Doring River and, less frequently, localised Prince Albert outcrops, with small, portable nodules serving as suitable raw material packages for microlithic production.

In wider regional context, Doring River catchment sites show inverse raw material frequencies to those in the Olifants River catchment to its west (Parkington, 1980; Hallinan & Parkington, 2017; Porraz et al., 2013), where silcrete is locally available from raft-like outcrops whereas hornfels

cobbles must be obtained from the Doring—accessible either by crossing the Cederberg Mountains, or at its confluence with the Olifants (**Figure 1**). While raw material transfers from the Karoo have long been hypothesised within wider hunter-gatherer mobility between the west coast and interior (Mackay, 2016; Parkington, 1972, 1987; Parkington & Poggenpoel, 1971; Parkington et al., 1988), investigation has so far remained restricted to Cape geological contexts. The Tankwa Karoo data provide the first empirical support for these connections, establishing a foundation for future work extending models of landscape use further east into the interior Karoo, and demonstrating the value of open-air records for reconstructing mobility systems beyond individual site sequences.

DECLARATIONS

Ethical approval

Not applicable

Competing interests

The author declares no competing interests.

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Availability of data and materials

Supporting material, including data and R script to replicate the analyses, are available from an external repository: https://osf.io/5ebam/. Spatial data are withheld to protect site locations but are available from the author upon request.

Supplementary Information

SI1. Supplementary Figure S1 and Tables S1–10

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References

Abrunhosa, A., Santonja, M., Pérez-González, A., Panera, J., Méndez-Quintas, E., Rubio-Jara, S., Aubry, T., dos Anjos Ribeiro, M. & Dimuccio, L. A. (2023). Quartz and quartzite lithic raw material studies: problems and challenges. *Proceedings of the 2022 IMEKO TC4 International Conference on Metrology for Archaeology and Cultural Heritage*, 149–153. https://doi.org/10.21014/tc4-arc-2022.029

Ambrose, S. H. (2002). *Small things remembered: origins of early microlithic industries in sub-Saharan Africa*. In R. G. Elston & S. L. Kuhn (Eds.), *Thinking Small: Global perspectives on microlithization* (pp. 9–29). Archeological Papers of the American Anthropological Association, No. 12.

Ambrose, S. H. (2006). Howiesons Poort lithic raw material procurement patterns and the evolution of modern human behavior: A response to Minichillo (2006). *Journal of Human Evolution*, *50*(3), 365–369. https://doi.org/10.1016/j.jhevol.2005.12.006

Andrefsky Jr., W. (1994a). Raw-material availability and the organization of technology. *American Antiquity*, *59*(1), 21–34.

Andrefsky Jr., W. (1994b). The geological occurrence of lithic material and stone tool production strategies. *Geoarchaeology*, *9*(5), 375–391.

Bader, G. D., Sommer, C., Linstädter, J., Masia, D. P., Blessing, M. A., Forrester, B. & MacDonald, B. L. (2025). Decoding hunter-gatherer-knowledge and selective choice of lithic raw materials during the Middle and Later Stone Age in Eswatini. *Journal of Archaeological Science*, *180*, 106302. https://doi.org/10.1016/j.jas.2025.106302

Bamforth, D. B. (1986). Technological efficiency and tool curation. *American Antiquity*, *51*(1), 38–50.

Beck, C. & Jones, G. T. (1990). Toolstone selection and lithic technology in early Great Basin prehistory. *Journal of Field Archaeology, 17*(3), 283–299. https://doi.org/10.1179/009346990791548240

Binford, L. R. (1979). Organization and formation processes: Looking at curated technologies. *Journal of Anthropological Research*, *35*(3), 255–273.

Binford, L. R. (1980). Willow smoke and dogs' tails: hunter-gatherer settlement systems and archaeological site formation. *American Antiquity*, *45*(1), 4–20.

Bivand, R. (2024). *classInt: Choose Univariate Class Intervals*. R package version 0.4-11, https://github.com/r-spatial/classInt/

Blignault, H. J. & Theron, J. N. (2012). Modes of sedimentation and glaciological aspects of the Permo-Carboniferous Dwyka Group in the Elandsvlei-Elandsdrif area, South Africa. *South African Journal of Geology*, *115*(2), 211–224. https://doi.org/10.2113/gssajg.115.2.211

Bousman, C. B. (2005). Coping with risk: Later stone age technological strategies at Blydefontein Rock Shelter, South Africa. *Journal of Anthropological Archaeology*, *24*(3), 193–226. https://doi.org/10.1016/j.jaa.2005.05.001

Brantingham, P. J. (2003). A neutral model of stone raw material procurement. *American Antiquity*, *68*(3), 487–509.

Brantingham, P. J. (2006). Measuring forager mobility. *Current Anthropology*, *47*(3), 435–459. https://doi.org/10.1086/503062

Brantingham, P. J., Olsen, J. W., Rech, J. A. & Krivoshapkin, A. I. (2000). Raw material quality and prepared core technologies in northeast Asia. *Journal of Archaeological Science*, *27*(3), 255–271. https://doi.org/10.1006/jasc.1999.0456

Braun, D. R., Plummer, T., Ferraro, J. V., Ditchfield, P. & Bishop, L. C. (2009). Raw material quality and Oldowan hominin toolstone preferences: evidence from Kanjera South, Kenya. *Journal of Archaeological Science*, *36*(7), 1605–1614. https://doi.org/10.1016/j.jas.2009.03.025

Brooks, A. S. (1978). A note on the Late Stone Age features at ≠Gi: analogies from historic San hunting practices. *Botswana Notes and Records*, *10*, 1–3.

Brown, K. S., Marean, C. W., Herries, A. I. R., Jacobs, Z., Tribolo, C., Braun, D., Roberts, D. L., Meyer, M. C. & Bernatchez, J. (2009). Fire as an engineering tool of early modern humans. *Science*, *325*(5942), 859–862. https://doi.org/10.1126/science.1175028

Carr, A. S., Chase, B. M., Birkinshaw, S. J., Holmes, P. J., Rabumbulu, M. & Stewart, B. A. (2023). Paleolakes and socioecological implications of last glacial "greening" of the South African interior. *Proceedings of the National Academy of Sciences*, *120*(21), e2221082120. https://doi.org/10.1073/pnas.2221082120

Caruana, M. V. & Mtshali, S. P. (2018). Assessing the durability of Oldowan stone tools in South Africa: Implications for quartz selectivity and use. *Lithic Technology*, *43*(4), 245–254. https://doi.org/10.1080/01977261.2018.1516721

Close, A. E. (2000). Reconstructing movement in prehistory. *Journal of Archaeological Method and Theory*, *7*(1), 49–77. https://doi.org/10.1023/a:1009560628428

Cole, D. I. & Basson, W. A. (1991). Whitehill Formation. *Catalogue of South African Lithostratigraphic Units*, *3*, 51–52.

Crowell, A. L. & Hitchcock, R. K. (1978). Basarwa ambush hunting in Botswana. *Botswana Notes and Records*, *10*, 37–51.

d'Errico, F., Banks, W. E., Warren, D. L., Sgubin, G., van Niekerk, K., Henshilwood, C., Daniau, A.-L. & Sánchez Goñi, M. F. (2017). Identifying early modern human ecological niche expansions and associated cultural dynamics in the South African Middle Stone Age. *Proceedings of the National Academy of Sciences*, *114*(30), 7869–7876. https://doi.org/10.1073/pnas.1620752114

Davies, B., Holdaway, S. J. & Fanning, P. C. (2018). Modeling relationships between space, movement, and lithic geometric attributes. *American Antiquity*, *83*(3), 444–461. https://doi.org/10.1017/aaq.2018.23

Deacon, J. (1984). *The Later Stone Age of Southernmost Africa*. British Archaeological Reports International Series 213.

Deacon, H. J. & Wurz, S. (1996). Klasies River main site, cave 2: a Howiesons Poort occurrence. In G. Pwiti & R. Soper (Eds.), *Aspects of African Archaeology: Papers from the 10th Congress of the PanAfrican Association for Prehistory and Related Studies* (pp. 213–218). University of Zimbabwe.

Dibble, H. L., Roth, B. & Lenoir, M. (1995). The use of raw materials at Combe-Capelle Bas. In H. L. Dibble & M. Lenoir (Eds.), *The Middle Paleolithic Site of Combe Capelle Bas (France)* (pp. 259–287). University of Pennsylvania Museum.

Dibble, H. L., Schurmans, U. A., Iovitá, R. & McLaughlin, M. V. (2005). The measurement and interpretation of cortex in lithic assemblages. *American Antiquity*, *70*(3), 545–560.

Dibble, H. L., Holdaway, S. J., Lin, S. C., Braun, D. R., Douglass, M. J., Iovita, R., McPherron, S. P., Olszewski, D. I. & Sandgathe, D. (2017). Major fallacies surrounding stone artifacts and assemblages. *Journal of Archaeological Method and Theory*, *24*(3), 813–851. https://doi.org/10.1007/s10816-016-9297-8

Douglass, M. J., Holdaway, S. J., Fanning, P. C. & Shiner, J. (2008). Assessment and archaeological application of cortex measurement in lithic assemblages. *American Antiquity*, *73*(3), 513–526. https://doi.org/10.1017/S0002731600046849

Féblot-Augustins, J. (1993). Mobility strategies in the late Middle Palaeolithic of central Europe and western Europe: Elements of stability and variability. *Journal of Anthropological Archaeology*, *12*(3), 211–265. https://doi.org/10.1006/jaar.1993.1007

Foley, R. A. (1981). *Off-site Archaeology and Human Adaptation in Eastern Africa*. British Archaeological Reports International Series 97.

Fratta, V., Conard, N. J. & Schmidt, P. (2025). A single test for raw material properties: hardness and stiffness of tools-stones from Sibhudu. *Archaeological and Anthropological Sciences*, *18*(1), 6. https://doi.org/10.1007/s12520-025-02358-5

Gould, R. (1980). *Living Archaeology*. Cambridge University Press.

Gould, R. A. & Saggers, S. (1985). Lithic procurement in central Australia: A closer look at Binford's idea of embeddedness in archaeology. *American Antiquity*, *50*(1), 117–136.

Greaves, R. D. (2006). Forager landscape use and residential organization. In F. R. Sellet, R. Greaves & P. L. Yu (Eds.), *Archaeology and Ethnoarchaeology of Mobility* (pp. 127–52). University Press of Florida.

Gregory, A., Mitchell, P. & Pargeter, J. (2023). Raw material surveys and their behavioral implications in Highland Lesotho. *Journal of Paleolithic Archaeology*, *6*(1), 18. https://doi.org/10.1007/s41982-023-00138-y

Hallinan, E. S. (2019). *Variation and modernity in Middle Stone Age landscape use in the Western and Northern Cape, South Africa*. [Doctoral Dissertation, University of Cambridge].

Hallinan, E. (2021). Landscape-scale perspectives on Stone Age behavioural change from the Tankwa Karoo, South Africa. *Azania: Archaeological Research in Africa*, *56*(3), 304–343. https://doi.org/10.1080/0067270x.2021.1960675

Hallinan, E. (2022a). “A survey of surveys” revisited: Current approaches to landscape and surface archaeology in southern Africa. *African Archaeological Review*, *39*(1), 79–111. https://doi.org/10.1007/s10437-021-09469-z

Hallinan, E. (2022b). Landscape-scale perspectives on Later Stone Age settlement in the Tankwa Karoo, South Africa. *Azania: Archaeological Research in Africa*, *57*(4), 419–462. https://doi.org/10.1080/0067270x.2022.2152990

Hallinan, E. (2026). The Southern African Stone Age Site Index (SASSI): A spatial, chronological and contextual resource for archaeological research. *Journal of Open Archaeology Data*, *14*, 2. https://doi.org/10.5334/joad.186

Hallinan, E. & Parkington, J. (2017). Stone Age landscape use in the Olifants River Valley, Clanwilliam, Western Cape, South Africa. *Azania: Archaeological Research in Africa*, *52*(3), 324–372. https://doi.org/10.1080/0067270x.2017.1365438

Hallinan, E. & Shaw, M. (2020). Nubian Levallois reduction strategies in the Tankwa Karoo, South Africa. *PLoS ONE*, *15*(10), e0241068. https://doi.org/10.1371/journal.pone.0241068

Hallinan, E., Shaw, M., Shaw, C. & Samawi, O. (2026). The Nubian spectrum: 3D geometric morphometric perspectives on Levallois core reduction at Tweefontein, South Africa. *Journal of Paleolithic Archaeology*, *9*(10). https://doi.org/10.1007/s41982-025-00244-z

Holdaway, S. J., Shiner, J. & Fanning, P. C. (2004). Hunter-gatherers and the archaeology of discard behavior: an analysis of surface stone artifacts from Sturt National Park, western New South Wales, Australia. *Asian Perspectives*, *43*(1), 34–72.

Holmes, P. J. (2012). Lithological and structural controls on landforms. In P. J. Holmes & M. E. Meadows (Eds.), *Southern African Geomorphology: Recent trends and new directions* (pp. 25–39). Sun Press.

Howard, J. L. (2005). The quartzite problem revisited. *The Journal of Geology*, *113*(6), 707–713. https://doi.org/10.1086/449328

Jacobson, L. (2005). Comments of stone circles in the Bloubos landscape, Northern Cape. *Southern African Humanities*, *17*, 153–156.

Kandel, A. W., Bolus, M., Bretzke, K., Bruch, A. A., Haidle, M. N., Hertler, C. & Märker, M. (2016). Increasing behavioral flexibility? An integrative macro-scale approach to understanding the Middle Stone Age of southern Africa. *Journal of Archaeological Method and Theory*, *23*(2), 623–668. https://doi.org/10.1007/s10816-015-9254-y

Kelly, R. L. (1995). *The Foraging Spectrum: Diversity in hunter-gatherer lifeways*. Smithsonian Institution Press.

Kelly, R. L. (2013). *The Lifeways of Hunter-Gatherers: The foraging spectrum.* Cambridge University Press.

Kuhn, S. L. (1995). *Mousterian Lithic Technology: An ecological perspective*. Princeton University Press.

Lee, R. B. (1979). *The !Kung San: Men, women, and work in a foraging society.* Cambridge University Press.

Lin, S. C., Douglass, M. J. & Mackay, A. (2016). Interpreting MIS3 artefact transport patterns in southern Africa using cortex ratios: an example from the Putslaagte valley, Western Cape. *South African Archaeological Bulletin*, *71*(204), 173–180.

Lombard, M., Bradfield, J., Caruana, M. V., Makhubela, T. V., Dusseldorp, G. L., Kramers, J. D. & Wurz, S. (2022). The Southern African Stone Age sequence updated (II). *South African Archaeological Bulletin*, *77*(217), 172–212.

Low, M., Mackay, A. & Phillips, N. (2017). Understanding Early Later Stone Age technology at a landscape-scale: evidence from the open-air locality Uitspankraal 7 (UPK7) in the Western Cape, South Africa. *Azania: Archaeological Research in Africa*, *52*(3), 373–406. https://doi.org/10.1080/0067270x.2017.1343431

Low, M. & Mackay, A. (2018). The organisation of Late Pleistocene Robberg blade technology in the Doring River catchment, South Africa. *Journal of African Archaeology*, *16*(2), 168–192. https://doi.org/10.1163/21915784-20180014

Luedtke, B. E. (1992). *An Archaeologist’s Guide to Chert and Flint*. Institute of Archaeology, University of California.

Mackay, A. (2011). Nature and significance of the Howiesons Poort to post-Howiesons Poort transition at Klein Kliphuis rockshelter, South Africa. *Journal of Archaeological Science*, *38*(7), 1430–1440. https://doi.org/10.1016/j.jas.2011.02.006

Mackay, A. (2016). Three arcs: observations on the archaeology of the Elands Bay and northern Cederberg landscapes. *Southern African Humanities*, *29*, 1–15.

Mackay, A., Sumner, A., Jacobs, Z., Marwick, B., Bluff, K. & Shaw, M. (2014). Putslaagte 1 (PL1), the Doring River, and the later Middle Stone Age in southern Africa's Winter Rainfall Zone. *Quaternary International*, *350*, 43–58. https://doi.org/10.1016/j.quaint.2014.05.007

Mackay, A., Jacobs, Z. & Steele, T. E. (2015). Pleistocene archaeology and chronology of Putslaagte 8 (PL8) Rockshelter, Western Cape, South Africa. *Journal of African Archaeology*, *13*(1), 71–98. https://doi.org/10.3213/2191-5784-10267

Mackay, A., Hallinan, E. & Steele, T. E. (2018). Provisioning responses to environmental change in South Africa's Winter Rainfall Zone: MIS 5-2. In E. Robinson & F. Sellet (Eds.), *Lithic Technological Organization and Paleoenvironmental Change* (pp. 13–36). Springer International. https://doi.org/10.1007/978-3-319-64407-3_2

Mackay, A., Cartwright, C. R., Heinrich, S., Low, M. A., Stahlschmidt, M. C. & Steele, T. E. (2020). Excavations at Klipfonteinrand reveal local and regional patterns of adaptation and interaction through MIS 2 in southern Africa. *Journal of Paleolithic Archaeology*, *3*(3), 362–397. https://doi.org/10.1007/s41982-019-00040-6

Mackay, A., Ames, C. J. H., McNeil, J.-L. & Shaw, M. (2022). Reconstructing Middle Stone Age mobility patterns from raw material transfers in South Africa's Still Bay (77–70 ka) technocomplex. *Archaeological and Anthropological Sciences*, *14*(1), 14. https://doi.org/10.1007/s12520-021-01484-0

Mackay, A., Ames, C. J., Low, M. A., McNeil, J.-L., O'Driscoll, C., Phillips, N., Saktura, R. B., Shaw, M. & Watson, S. (2023) Doring River Catchment, South Africa. In A. Beyin, D. K. Wright, J. Wilkins & D. I. Olszewski (Eds.), *Handbook of Pleistocene Archaeology of Africa*. (pp. 1403–1858). Springer. https://doi.org/10.1007/978-3-031-20290-2_90

Marlowe, F. W. (2010). *The Hadza: Hunter-gatherers of Tanzania*. University of California Press.

Mesfin, I., Lotter, M. G. & Benjamim, M. H. (2021). A new approach to quantifying raw material selectivity in the African Acheulean: Perspectives from Angola and South Africa. *Journal of African Archaeology*, *19*(2), 205–234. https://doi.org/10.1163/21915784-20210013

Minichillo, T. (2006). Raw material use and behavioral modernity: Howiesons Poort lithic foraging strategies. *Journal of Human Evolution*, *50*(3), 359–364. https://doi.org/10.1016/j.jhevol.2005.08.013

Mitchell, P. J. (2000). The organization of Later Stone Age lithic technology in the Caledon Valley, southern Africa. *African Archaeological Review*, *17*(3), 141–176. https://doi.org/10.1023/A:1006606204287

Mucina, L. & Rutherford, M. C. (Eds.) (2006). *Vegetation atlas of South Africa, Lesotho and Swaziland*. South African National Biodiversity Institute, Strelitzia 19.

Nackerdien, R. (1989). *Klipfonteinrand 2: a sign of the times*. [Honours dissertation, University of Cape Town].

Nash, D. J. and Ulyott, J. S. (2007). Silcrete. In D. J. Nash & S. J. McLaren (Eds.), *Geochemical Sediments and Landscapes* (pp. 95–148). Blackwell.

Nash, D. J., Coulson, S., Staurset, S., Ullyott, J. S., Babutsi, M., Hopkinson, L. & Smith, M. P. (2013). Provenancing of silcrete raw materials indicates long-distance transport to Tsodilo Hills, Botswana, during the Middle Stone Age. *Journal of Human Evolution*, *64*(4), 280–288. https://doi.org/10.1016/j.jhevol.2013.01.010

Nash, D. J., Coulson, S., Staurset, S., Ullyott, J. S., Babutsi, M. & Smith, M. P. (2016). Going the distance: Mapping mobility in the Kalahari Desert during the Middle Stone Age through multi-site geochemical provenancing of silcrete artefacts. *Journal of Human Evolution*, *96*, 113–133. https://doi.org/10.1016/j.jhevol.2016.05.004

Nash, D. J., Ciborowski, T. J. R., Coulson, S. D., Staurset, S., Burrough, S. L., Mothulatshipi, S. & Thomas, D. S. G. (2022). Mapping Middle Stone Age human mobility in the Makgadikgadi Pans (Botswana) through multi-site geochemical provenancing of silcrete artefacts. *Quaternary Science Reviews*, *297*, 107811. https://doi.org/10.1016/j.quascirev.2022.107811

O'Connell, J. F., Hawkes, K. & Jones, N. G. B. (1988). Hadza scavenging: implications for Plio/Pleistocene hominid subsistence. *Current Anthropology*, *29*(2), 356–363. https://doi.org/10.1086/203648

O'Driscoll, C. A. & Mackay, A. (2024). Middle Stone Age technological organisation from MIS 5 at Mertenhof Rockshelter, South Africa. *Quaternary Science Advances*, *16*, 100243. https://doi.org/10.1016/j.qsa.2024.100243

O'Driscoll, C. A. & Mackay, A. (2023). Middle Stone Age technology from MIS 6 and MIS 5 at Klipfonteinrand 1, South Africa. *Quaternary Science Reviews*, *318*, 108289. https://doi.org/10.1016/j.quascirev.2023.108289

Oestmo, S., Schoville, B. J., Wilkins, J. & Marean, C. W. (2014). A Middle Stone Age paleoscape near the Pinnacle Point caves, Vleesbaai, South Africa. *Quaternary International*, *350*, 147–168. https://doi.org/10.1016/j.quaint.2014.07.043

Oksanen, J., Simpson, G., Blanchet, F., Kindt, R., Legendre, P., Minchin, P., O'Hara, R., Solymos, P., Stevens, M., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Borman, T., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., Evangelista, H., FitzJohn, R., Friendly, M., Furneaux, B., Hannigan, G., Hill, M., Lahti, L., Martino, C., McGlinn, D., Ouellette, M., Ribeiro Cunha, E., Smith, T., Stier, A., Ter Braak, C. & Weedon, J. (2026). *vegan: Community Ecology Package*. R package version 2.8-0, https://vegandevs.github.io/vegan/

Orton, J. (2006). The Later Stone Age lithic sequence at Elands Bay, Western Cape, South Africa: raw materials, artefacts and sporadic change. *Southern African Humanities*, *18*(2), 1–28.

Orton, J. (2008). A useful measure of the desirability of different raw materials for retouch within and between assemblages: the raw material retouch index (RMRI). *Journal of Archaeological Science*, *35*(4), 1090–1094. https://doi.org/10.1016/j.jas.2007.08.002

Pargeter, J. & Shea, J. J. (2019). Going big versus going small: Lithic miniaturization in hominin lithic technology. *Evolutionary Anthropology: Issues, News, and Reviews*, *28*(2), 72–85. https://doi.org/10.1002/evan.21775

Parkington, J. E. (1972). Seasonal mobility in the late stone age. *African Studies*, *31*(4), 223–244. https://doi.org/10.1080/00020187208707386

Parkington, J. E. (1980). Time and place: some observations on spatial and temporal patterning in the Later Stone Age sequence in southern Africa. *South African Archaeological Bulletin*, *35*(132), 73–112.

Parkington, J. E. (1987). Changing views of prehistoric settlement in the Western Cape. In J. E. Parkington & M. Hall (Eds.), *Papers in the Prehistory of the Western Cape, South Africa* (pp. 4–23). British Archaeological Reports International Series 332 (ii).

Parkington, J. E. & Poggenpoel, C. (1971). Excavations at De Hangen, 1968. *South African Archaeological Bulletin*, *26*(101/102), 3–36.

Parkington, J. E. & Hall, S. L. (1987). Patterning in recent radiocarbon dates from South Africa as a reflection of prehistoric settlement and interaction. *Journal of African History*, *28*(1), 1–25.

Parkington, J. E., Poggenpoel, C., Buchanan, B., Robey, T., Manhire, A. & Sealy, J. C. (1988). Holocene coastal settlement patterns in the western Cape. In G. N. Bailey & J. E. Parkington (Eds.), *The Archaeology of Prehistoric Coastlines* (pp. 22–41). Cambridge University Press.

Parkington, J. E., Milton-Deam, S., Christowitz, A., Wessels, S. G., Poggenpoel, C. & Horwitz, L. K. (2026) The archaeological landscape of Wolwekraal Nature Reserve (South Africa). *Antiquity: Project Gallery,* https://doi.org/10.15184/aqy.2026.10293

Partridge, T. C., Dollar, E. S. J., Moolman, J. & Dollar, L. H. (2010). The geomorphic provinces of South Africa, Lesotho and Swaziland: A physiographic subdivision for earth and environmental scientists. *Transactions of the Royal Society of South Africa*, *65*(1), 1–47. https://doi.org/10.1080/00359191003652033

Parsons, I. (2004). Stone circles in the Bloubos landscape, Northern Cape. *Southern African Humanities*, *16*, 59–69.

Parsons, I. (2005). Reply to comments on stone circles by Jacobson. *Southern African Humanities*, *17*, 155–156.

Porraz, G., Texier, P.-J., Rigaud, J.-P., Parkington, J. E., Poggenpoel, C. & Roberts, D. L. (2008). Preliminary characterization of a Middle Stone Age lithic assemblage preceding the 'classic' Howieson's Poort complex at Diepkloof Rock Shelter, Western Cape Province, South Africa. *South African Archaeological Society Goodwin Series*, *10*, 105–121.

Porraz, G., Texier, P.-J., Archer, W., Piboule, M., Rigaud, J.-P. & Tribolo, C. (2013). Technological successions in the Middle Stone Age sequence of Diepkloof Rock Shelter, Western Cape, South Africa. *Journal of Archaeological Science*, *40*(9), 3376–3400. https://doi.org/10.1016/j.jas.2013.02.012

Prieto, A., Yusta, I. & Arrizabalaga, A. (2019) Defining and characterizing archaeological quartzite: Sedimentary and metamorphic processes in the lithic assemblages of El Habario and El Arteu (Cantabrian Mountains, Northern Spain). *Archaeometry*, *61*, 14–30. https://doi.org/10.1111/arcm.12397.

Quick, L. J. & Eckardt, F. D. (2015). The Cederberg: A rugged sandstone topography. In S. W. Grab & J. Knight (Eds.), *Landscapes and Landforms of South Africa* (pp. 85–93). Springer International Publishing. https://doi.org/10.1007/978-3-319-03560-4_10

R Core Team (2026). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rios-Garaizar, J. (2016). Early Middle Palaeolithic occupations at Ventalaperra cave (Cantabrian Region, Northern Iberian Peninsula). *Journal of Lithic Studies*, *3*(1), 161–183. https://doi.org/10.2218/jls.v3i1.1287

Roberts, D. L. (2003). *Age, Genesis and Significance of South African Coastal Belt Silcretes*. Council for Geoscience.

Rogers, J., Smith, G. & Engelbrecht, W. (2014). *Around the Tankwa Karoo National Park: A field guide to the geology and landscape*. Bright Brown.

Sampson, C. G. (1968). *The Middle Stone Age Industries of the Orange River Scheme Area*. National Museum, Bloemfontein Memoir No. 4.

Sampson, C. G. (1985). *Atlas of Stone Age Settlement in the Central and Upper Seacow Valley*. Memoirs of the National Museum Bloemfontein.

Sampson, C. G., Moore, V., Bousman, C. B., Stafford, B., Giordano, A. & Willis, M. (2015). A GIS Analysis of the Zeekoe Valley Stone Age Archaeological Record in South Africa. *Journal of African Archaeology*, *13*(2), 167–185. https://doi.org/10.3213/2191-5784-10277

Schmid, V. C., Parkington, J. E., Texier, P.-J. & Porraz, G. (2016). The 'MSA 1' of Elands Bay Cave (South Africa) in the context of the southern African Early MSA technologies. *Southern African Humanities*, *29*, 153–201.

Schmid, V. C., Sifogeorgaki, I., Abruzzese, T., Blik, S., Huang, L. & Dusseldorp, G. L. (2026). Wind(ow) of change: The end of the Middle Stone Age and the beginning of the Later Stone Age at Umhlatuzana rockshelter showcasing concurrent technological and techno-economic shifts. *Quaternary Science Reviews*, *377*, 109806. https://doi.org/10.1016/j.quascirev.2026.109806

Schmidt, P., Porraz, G., Slodczyk, A., Bellot-gurlet, L., Archer, W. & Miller, C. E. (2013). Heat treatment in the South African Middle Stone Age: temperature induced transformations of silcrete and their technological implications. *Journal of Archaeological Science*, *40*(9), 3519–3531. https://doi.org/10.1016/j.jas.2012.10.016

Schmidt, P. & Mackay, A. (2016). Why was silcrete heat-treated in the Middle Stone Age? An early transformative technology in the context of raw material use at Mertenhof Rock Shelter, South Africa. *PLoS ONE*, *11*(2), e0149243. https://doi.org/10.1371/journal.pone.0149243

Schmidt, P., Pappas, I., Porraz, G., Berthold, C. & Nickel, K. G. (2024). The driving force behind tool-stone selection in the African Middle Stone Age. *Proceedings of the National Academy of Sciences*, *121*(10), e2318560121. https://doi.org/10.1073/pnas.2318560121

Schoville, B. J., Brown, K. S. & Wilkins, J. (2022). A lithic provisioning model as a proxy for landscape mobility in the southern and middle Kalahari. *Journal of Archaeological Method and Theory*, *29*(1), 162–187. https://doi.org/10.1007/s10816-021-09507-9

Shackley, M. S. & Sahle, Y. (2017). Geochemical characterization of four quaternary obsidian sources and provenance of obsidian artifacts from the Middle Stone Age site of Gademotta, Main Ethiopian Rift. *Geoarchaeology*, *32*(2), 302–310. https://doi.org/10.1002/gea.21579

Shaw, M., Ames, C. J. H., Phillips, N., Chambers, S., Dosseto, A., Douglas, M., Goble, R., Jacobs, Z., Jones, B., Lin, S. C., Low, M., McNeil, J.-L., Nasoordeen, S., O'Driscoll, C. A., Saktura, R. B., Sumner, T. A., Watson, S., Will, M. & Mackay, A. (2019). The Doring River Archaeology Project: approaching the evolution of human land use patterns in the Western Cape, South Africa. *PaleoAnthropology*, 400–422. https://doi.org/10.4207/pa.2019.art138

Shaw, M., McNeil, J.-L., O'Driscoll, C. A., Ames, C. J. H. & Mackay, A. (2021). Characterising Middle Stone Age core forms along the Doring River, South Africa, and their implications for past technological organisation. *South African Archaeological Bulletin*, *76*(215), 151–162.

Shaw, M., Phillips, N., Ames, C. H. J. & Mackay, A. (2026). Spatial and temporal scales of patterning in open-air surface scatters along the Doring River, South Africa. *Journal of Archaeological Method and Theory*, *33*(1), 3. https://doi.org/10.1007/s10816-025-09736-2

Sherwood, N. L. (2021). Lithic quality comparisons between Sterkfontein and Swartkrans in the Oldowan and Early Acheulean, South Africa. *South African Archaeological Bulletin*, *76*(215), 93–108.

Silberbauer, G. B. (1981). *Hunter and Habitat in the Central Kalahari Desert*. Cambridge University Press.

Sifogeorgaki, I., Schmid, V. C., Os, B. van, Fratta, V., Huisman, H. & Dusseldorp, G. L. (2023). Two methods on one stone: Integrating visual and analytical techniques to clarify lithic raw material utilization in the Middle and Later Stone Age at Umhlatuzana rockshelter (South Africa). *Journal of Archaeological Science: Reports*, *48*, 103890. https://doi.org/10.1016/j.jasrep.2023.103890

Smith, A. B. & Ripp, M. R. (1978). An archaeological reconnaissance of the Doorn/Tanqua Karoo. *South African Archaeological Bulletin*, *33*(128), 118–133.

Tanaka, J. (1980). *The San Hunter-Gatherers of the Kalahari: A study in ecological anthropology*. University of Tokyo Press.

Tarriño, A., Ábalos, B., Puelles, P., Eguiluz, L. & Díez-Martín, F. (2023). The crystalline quartz-rich raw material from Olduvai Gorge (Tanzania): why is it called quartzite when it should be called quartz? *Archaeological and Anthropological Sciences*, *15*(6), 78. https://doi.org/10.1007/s12520-023-01774-9

Torrence, R. (1983). Time budgeting and hunter-gatherer technology. In G. Bailey (Ed.), *Hunter-Gatherer Economy in Prehistory: A European Perspective* (pp. 11–22). Cambridge University Press.

Torrence, R. (1989). Retooling: towards a behavioral theory of stone tools. In R. Torrence (Ed.) *Time, Energy, and Stone Tools* (pp. 57–66). Cambridge University Press.

Turq, A., Roebroeks, W., Bourguignon, L. & Faivre, J.-P. (2013). The fragmented character of Middle Palaeolithic stone tool technology. *Journal of Human Evolution*, *65*(5), 641–655. https://doi.org/10.1016/j.jhevol.2013.07.014

Viljoen, J. H. A. (1994). Sedimentology of the Collingham Formation, Karoo Supergroup. *South African Journal of Geology*, *97*(2), 167–183.

Visser, J. N. J. & Hall, K. J. (1985). Boulder beds in the glaciogenic Permo-Carboniferous Dwyka Formation in South Africa. *Sedimentology*, *32*(2), 281–294. https://doi.org/10.1111/j.1365-3091.1985.tb00510.x

Meden, J. von der, Pickering, R., Schoville, B. J., Green, H., Weij, R., Hellstrom, J., Greig, A., Woodhead, J., Khumalo, W. & Wilkins, J. (2022). Tufas indicate prolonged periods of water availability linked to human occupation in the southern Kalahari. *PLoS ONE*, *17*(7), e0270104. https://doi.org/10.1371/journal.pone.0270104

Wadley, L. & Kempson, H. (2011). A review of rock studies for archaeologists, and an analysis of dolerite and hornfels from the Sibudu area, KwaZulu-Natal. *Southern African Humanities*, *23*, 87–107.

Watson, S., Low, M., Phillips, N., O'Driscoll, C., Shaw, M., Ames, C., Jacobs, Z. & Mackay, A. (2020). Robberg material procurement and transport in the Doring River catchment: Evidence from the open-air locality of Uitspankraal 9, Western Cape, South Africa. *Journal of African Archaeology*, *18*(2), 209–228. https://doi.org/10.1163/21915784-20200013

Wilkins, J. (2017). Middle Pleistocene lithic raw material foraging strategies at Kathu Pan 1, Northern Cape, South Africa. *Journal of Archaeological Science: Reports*, *11*, 169–188. https://doi.org/10.1016/j.jasrep.2016.11.002

Wilkins, J., Brown, K. S., Oestmo, S., Pereira, T., Ranhorn, K. L., Schoville, B. J. & Marean, C. W. (2017). Lithic technological responses to Late Pleistocene glacial cycling at Pinnacle Point Site 5-6, South Africa. *PLoS ONE*, *12*(3), e0174051. https://doi.org/10.1371/journal.pone.0174051

Will, M. (2021). The role of different raw materials in lithic technology and settlement patterns during the Middle Stone Age of southern Africa. *African Archaeological Review*, *38*(3), 477–500. https://doi.org/10.1007/s10437-021-09446-6

Will, M., Bader, G. D. & Conard, N. J. (2014). Characterizing the Late Pleistocene MSA lithic technology of Sibudu, KwaZulu-Natal, South Africa. *PLoS ONE*, *9*(5), e98359. https://doi.org/10.1371/journal.pone.0098359

Will, M., Mackay, A. & Phillips, N. (2015). Implications of Nubian-Like core reduction systems in southern Africa for the identification of early modern human dispersals. *PLoS ONE*, *10*(6), e0131824. https://doi.org/10.1371/journal.pone.0131824

Will, M. & Mackay, A. (2017). What factors govern the procurement and use of silcrete during the Stone Age of South Africa? *Journal of Archaeological Science: Reports*, *15*, 630–645. https://doi.org/10.1016/j.jasrep.2016.11.046

Will, M., Jacobs, Z. & Mackay, A. (2024). No one home? New evidence for MIS 3 occupations in the Western Cape (South Africa) from Mertenhof Rock Shelter. *Journal of Paleolithic Archaeology*, *7*(1), 34. https://doi.org/10.1007/s41982-024-00199-7

Will, M., Sommer, C., Möller, G. H. D., Botha, G. A., Blessing, M. A., Msimanga, L., Mazel, A., Val, A., Venditti, F. & Riedesel, S. (2026). Specialised and persistent raw material procurement by humans in the Middle Pleistocene. *Nature Communications*, *17*(1), 2702. https://doi.org/10.1038/s41467-026-70783-8

Wilson, L. (2007). Understanding prehistoric lithic raw material selection: Application of a gravity model. *Journal of Archaeological Method and Theory*, *14*(4), 388–411. https://doi.org/10.1007/s10816-007-9042-4

Wiltshire, N. (2011). *Spatial analysis of archaeological sites in the Western Cape using an integrated digital archive*. [Masters dissertation, University of Cape Town].

Wragg Sykes, R. M. & Will, M. (2017). Guest editorial – Silcrete as a lithic raw material in global context: Geology, sourcing and prehistoric techno-economics. *Journal of Archaeological Science: Reports*, *15*, 492–499. https://doi.org/10.1016/j.jasrep.2017.08.010

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