


Examining the distribution of Middle Paleolithic Nubian cores relative to chert quality in southern (Nejd, Dhofar) and south-central (Duqm, Al Wusta) Oman

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Abstract

Lithic raw material properties are often invoked to explain the presence, absence, form, or ontogeny of Paleolithic stone tools. Here, we explore whether the frequency of the Middle Paleolithic Nubian core form and core-reduction systems co-varies with toolstone quality in two neighboring regions in Oman: the southern region of Nejd, Dhofar, and the south-central region of Duqm, Al Wusta. Specifically, we predicted that if raw material differences were influencing the distribution of Nubian cores, the chert would be of higher quality in the southern region, where Nubian cores were frequent, and of lower quality in the south-central region, where they were scarce. We tested this prediction by collecting 124 chert samples from 22 outcrops and then quantitatively assessed two geochemical variables that are widely thought to influence knapping: impurity amount and silica content. We also examined the mineralogical composition, and the crystallite size and lattice strain for quartz (crystalline α -SiO₂) of representative chert samples. Our results suggest that the cherts in the two regions are similar, which is not consistent with the hypothesis that lithic raw material quality contributed to Nubian core spatial distribution in Oman. We discuss potential alternative hypotheses to explain Nubian core geographic patterning, and provisionally suggest that the scarcity of Nubian cores in south-central Oman may be due to a concomitant scarcity of toolmakers, given a lack of water availability.

KEYWORDS

geochemistry, lithic raw materials, Middle Paleolithic, Nubian, Oman

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1 | INTRODUCTION

A fundamental aim of archaeological research is to understand the factors that influence past technologies' spatial distribution and chronological range (Lycett, 2015, 2022; Meltzer, 1993, 2002, 2021, 2024). In Paleolithic research, this topic often involves questions regarding the geo-temporal distribution of knapped lithic artifacts. Why was a particular lithic technology culturally transmitted generation after generation? Was a lithic technology carried into a region during a dispersal? Did it diffuse across distinct populations or was it independently invented (convergence)? And what factors contributed to the *absence* of a lithic technology beyond a particular geo-temporal boundary: an environmental barrier that prevented hominin dispersal, a disruption in cultural transmission, a failure of invention, or a taphonomic process? Or is the "absence" of a lithic technology in a region merely an illusion cast by a dearth of fieldwork?

A classic investigation of Paleolithic artifact distribution involves the so-called "Movius Line" (Lycett, 2007; Lycett & Bae, 2010; Lycett & Gowlett, 2008; Lycett & Norton, 2010; Norton et al., 2006; Norton & Bae, 2009; Norton & Lycett, 2010; see also Brumm & Moore, 2012; Dennell, 2016; Forestier, 2020; Petraglia & Shipton, 2008). This line, first recognized by Movius (1948, 1969; see also Coon, 1965), originally represented a strict prehistoric cultural boundary between modern-day India and East/Southeast Asia. Sites possessing bifacial tool technologies like handaxes and prepared cores like Levallois fell west of the line in western Europe, the Levant, Africa, and India; sites lacking these technologies fell east of the line in East and Southeast Asia (Lycett & Bae, 2010, p. 522). Yet, decades of fieldwork in East and Southeast Asia have revealed the occasional presence of bifacial technologies in these regions (e.g., Brantingham et al., 2000; Derevianko et al., 2018; Hu et al., 2019, 2023; Li et al., 2014; Norton et al., 2006; Wang et al., 2012, 2014; Yamei et al., 2000), and today, archaeologists refer to this cultural boundary as the "Movius Line *sensu lato*." The latter is based on four observations:

- (1) a lower frequency of handaxe sites in eastern Asia;
- (2) a lower percentage of handaxes at sites in eastern Asia compared with many coeval Acheulean sites in Africa, western Asia, and Europe;
- (3) the presence of morphological differences between East Asian handaxes and classic Acheulean examples, especially those of Middle Pleistocene age; and
- (4) in line with the original observations of Movius, a paucity of Levallois (prepared core) technologies in eastern Asia (Lycett & Bae, 2010, p. 525–526).

Archaeologists have proposed and investigated several explanations for the Movius Line's artifact distribution patterning, including the isolation of pre-Acheulean hominins in East and Southeast Asia (Toth & Schick, 1993); the production and use of bamboo tools over bifacial lithic implements (Bar-Yosef et al., 2012; Brumm, 2010; West & Louys, 2007); demographic and social transmission considerations (Lycett & Norton, 2010); and—with respect to our central interest in

the present manuscript—lithic raw material constraints (Bar-Yosef et al., 2012; Gao & Norton, 2002; Toth & Schick, 1993).

The notion that "poor-quality" or "poorer-quality" lithic raw materials constrained the kinds of knapped technologies that past peoples produced is often invoked to explain the geo-temporal patterning of artifacts and their morphological differences (see discussions and references in Brantingham et al., 2000; Braun et al., 2009; Browne & Wilson, 2011; Clarkson, 2010; Egeland et al., 2019; Eren, Lycett, et al., 2011; Eren, Roos, et al., 2014; Gregory et al., 2023; Lewis, Williams, et al., 2022; Lycett & von Cramon-Taubadel, 2015; Sharon, 2008; Suga et al., 2022, 2023; Williams et al., 2019; Wilson et al., 2016, 2018; Wilson & Browne, 2014). There are two hypotheses that potentially explain how lithic raw material influences stone tool patterning and morphology (Costa, 2010; Eren, Roos, et al., 2014; Lewis, Williams, et al., 2022; Sharon, 2008; de la Torre, 2011). The first, referred to as "natural forces" (de la Torre, 2011), states that a toolstone possesses properties that automatically and unavoidably determine whether, or what kind of, stone tools can be produced. The second hypothesis, referred to as "artificial forces" (de la Torre, 2011), alternately states that lithic raw material can potentially influence stone tool patterning and morphology via the interaction of toolstone properties with other knapping variables, such as craftsperson skill or time constraints, but there is nothing inherent to the raw material that inevitably dictates knapping outcomes. The first hypothesis is relatively straightforward to test via experimental archaeology or geochemical methods (Bar-Yosef et al., 2012; Braun et al., 2009; Eren, Roos, et al., 2014; Eren, Lycett, et al., 2011; Lewis, Williams, et al., 2022; Williams et al., 2019), the second hypothesis less so, given that variables like prehistoric knapping skill or time constraints do not preserve in the archaeological record. Accordingly, our present study will focus on the "natural forces" hypothesis.

With respect to the Movius Line, Movius (1944) himself suggested that 'poor' raw materials in the form of "low-quality" quartz and quartzite prevented hominins in East and Southeast Asia from knapping lithic technologies more complex than pebble-core-chopper industries (see also Gao & Norton, 2002; Norton et al., 2006; Toth & Schick, 1993). Yet, archaeological and geological evidence, as well as experimental testing, are not consistent with this hypothesis (Lycett & Bae, 2010). With respect to the archaeological and geological evidence mentioned above, bifaces and Levallois-like technologies have been documented in East and Southeast Asia (see references above), and "high-quality" knapping toolstone is present in the region (Schick, 1994). With regard to experimental testing, experimental knapping has demonstrated that even on so-called "poor" East Asian raw materials, handaxes, and Levallois cores can be produced (Bar-Yosef et al., 2012; Schick, 1994).

Here, we investigate the possible relationship between Middle Paleolithic artifact spatial patterning with lithic raw material constraints on the Arabian Peninsula. In Oman, two decades of fieldwork have revealed the abundance of Nubian cores (Figure 1) on the Nejd plateau in Dhofar, the southern region (Rose et al., 2023), and a scarcity (but not total absence, Beshkani et al., 2017) of this core type throughout the rest of the country. While the rarity of raw

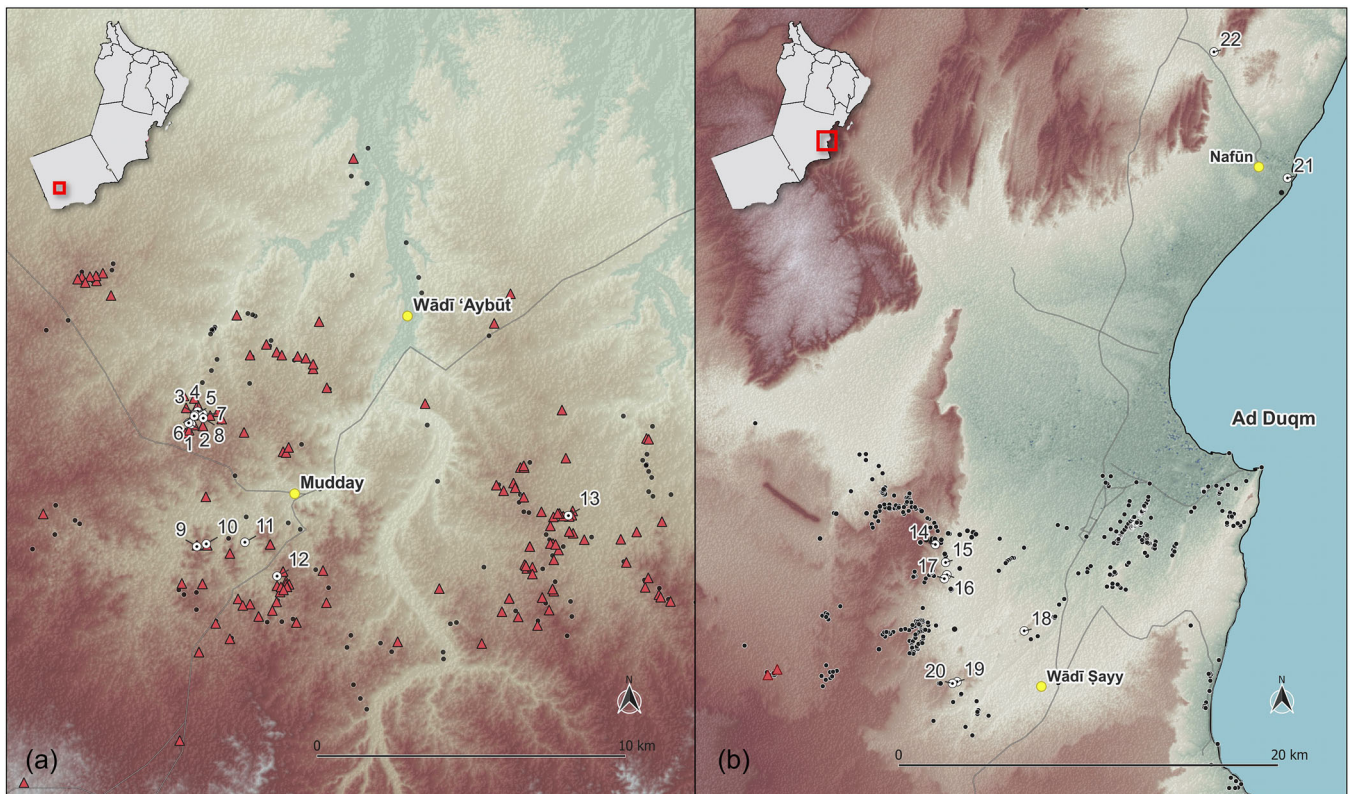


FIGURE 1 Location of the two study areas (southern region, left; south-central region, right) and their chert outcrops (indicated by numbers). Black dots = archaeological sites; red triangles = Middle Paleolithic sites. Note the lack of red triangles in the south-central region.

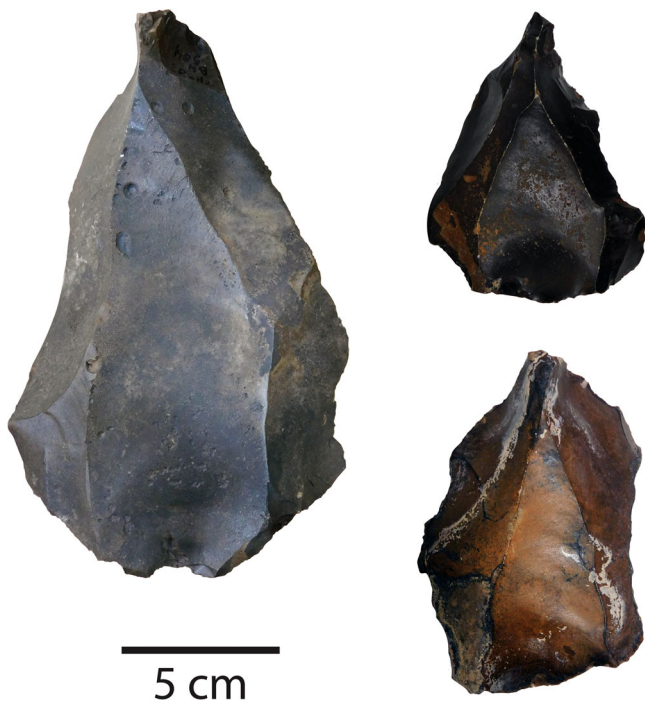


FIGURE 2 Examples of Nubian cores from the southern region: left, from site TH383; upper right, from site TH 143; lower right, from site TH143.

materials may explain the absence of Nubian technology elsewhere in Oman, the neighboring south-central area of Duqm, Al Wusta region, is rich in chert, yet is virtually absent in Nubian core technology (Figure 2). Given that Nubian cores, like many Middle Paleolithic core types, are relatively complex to knap (e.g., Eren, Bradley, et al., 2011; Hilbert et al., 2016, p. 19–20; Muller et al., 2017, 2022), we ask whether differences in locally available lithic raw materials in either region can potentially explain the Nubian core geographic distribution in Oman. Specifically, if raw material constraints influenced the distribution of Nubian cores, we predict that the south-central region possesses “poorer-quality” raw materials compared to those in the southern region.

1.1 | Nubian cores

Nubian cores are the discarded by-products of a lithic reduction sequence that, among other products, resulted in the production of pointed, elongated blanks, which potentially served as weapon tips or knife blades (Figure 2) (Groucutt, 2020a; Groucutt & Rose, 2023; Hallinan, Barzilai, Beshkani, et al., 2022; Hallinan & Marks, 2023; Oron et al., 2024; Van Peer, 1992; Rose et al., 2011; see also Bonilauri et al., 2023; Rots et al., 2011). Nubian cores have been found in varying frequencies in Africa (e.g., Chiotti et al., 2009;

Foley et al., 2013; Guichard & Guichard, 1965; Hallinan & Shaw, 2020; Kurashina, 1978; Marks, 1968; Olszewski et al., 2005, 2010; Van Peer et al., 2003; Smith et al., 2007; Tryon et al., 2012; Will et al., 2015), Arabia (e.g., Beshkani et al., 2017; Crassard & Hilbert, 2013; Hilbert et al., 2016, 2017; Rose et al., 2011, 2019; Usik et al., 2013), the Levant (Goder-Goldberger et al., 2016, 2017; Munday, 1976; Oron et al., 2024; Vermeersch, 2001), and possibly South Asia (Blinkhorn et al., 2015). The few numeric ages associated with Nubian cores suggest a time frame spanning MIS 5 and MIS 4, approximately 130,000 to 59,000 years ago (Masojć et al., 2017; Mercier et al., 1999; Oron et al., 2024; Van Peer & Vermeersch, 2007; Van Peer et al., 2010; Rose et al., 2011; Schmidt et al., 2015).

While there is agreement that Nubian cores are, broadly, a Middle Paleolithic phenomenon, questions abound regarding which hominins knapped Nubian cores, their chronological range, their geographic and cultural origin, and the contemporaneity of Nubian cores in different regions (Blinkhorn et al., 2021, 2022; Groucutt, 2020a; Hallinan, Barzilai, Beshkani, et al., 2022; Hallinan, Barzilai, Bicho, et al., 2022; Hallinan & Marks, 2023). Nor can we robustly assess whether *all* Nubian cores are Middle Paleolithic in age, or whether they represent a unified cultural transmission or dispersal of technology, as opposed to individual instances being the result of convergence, possibly in pre- or post-Middle Paleolithic contexts (e.g., Groucutt, 2020a; Oron et al., 2024; Scerri et al., 2021; Will et al., 2015; see also Eren, Meltzer, et al., 2021; Eren et al., 2013, 2018; Eren, Patten et al., 2014; Groucutt, 2020b; O'Brien et al., 2018; Scerri, 2012). Discussion regarding whether Nubian technology is part of a broader "Nubian complex" cultural unit is also beyond the scope of the present manuscript.

1.2 | Chert geology and geography in south and south-central Oman

Our focus here involves, (1) in Southern Oman, the elevated highlands of the Nejd plateau, north of the drainage divide, inland from Salalah along the north and northeast dipping Arabian Plate with elevations around 500–700 m and (2) in south-central Oman, the rough nearshore terrains from Duqm with low ground elevations of up to about 100 m. Chert-rich sediments are distributed over the larger part of the Arabian Peninsula (with the exception of the central Rub Al Khali), most frequently from the Cretaceous period to the Eocene epoch. In both the Nejd and Duqm areas, the combined thickness of these formations reaches over 1000 m (Béchenec et al., 1993). The chert occurrences in the area of interest (AOI) are exclusively restricted to marine sediments, which have been uplifted in connection with the opening of the Red Sea and Gulf of Aden (Stockli & Bosworth, 2019) and consequently exposed by erosion from the Late Tertiary until recently. In the Nejd area (southern Oman), only Paleocene to Eocene strata of the Lower Tertiary are exposed at the surface and are represented by extensive platform carbonates, structurally only marginally deformed and largely flat

lying, while in the Duqm area (south-central Oman), additionally, Cretaceous cherts are available in a structurally more complex geological setting (Béchenec et al., 1993). All three formations of the Lower Tertiary from the Paleocene to the Eocene (Umm Er Radhuma, Rus, and Damman) are extremely rich in chert-layers of various morpho-types (nodular, platy, and slabs) and dimensions, usually with diameters in the range of decimeters for individual nodules. Spectacular "chert-sculptures" have been discovered in a valley about 10 km WSW of Duqm, where individual chert "nodules" reach diameters of several meters, weighing up to more than 10 tons, belonging stratigraphically to the Damman formation of Middle Eocene (Lutetian). In this area, an incised (Middle to Late Eocene) canyon has been observed during the fieldwork in 2023, suggesting the possibility of a nearby fluvial incursion into the platform with the potential input of siliceous enriched waters. An additional explanation for the genesis of such unusually large chert concretions could be abiotic processes related to the input of nearby silica, potentially from submarine volcanic exhalations resulting in hydrothermal chert genesis, as inferred for the Precambrian Xionger Group in China (Luo et al., 2014). Potential origin mechanisms of the various cherts in the AOI have not been studied in detail yet, but some samples from Cretaceous formations in the northeastern Oman (Wang et al., 2024) have been analyzed and documented in the Global Chert Database (GCDB).

1.3 | Assessing lithic raw material quality

Different lithic raw materials can impart different advantageous or disadvantageous qualities to stone tool production and function (Brantingham et al., 2000; Braun et al., 2009; Lewis, Williams, et al., 2022). Our focus in this study is on *fracture predictability* or the raw material properties that would influence flaking (Braun et al., 2009; Crabtree, 1967; Doelman et al., 2001; Domanski et al., 1994; Eren, Roos, et al., 2014; Lewis, Williams, et al., 2022; Luedtke, 1992; Williams et al., 2019, p. 314). While several variables can potentially influence the fracture predictability of knappable rocks (e.g., Brown et al., 2009; Eren, Roos, et al., 2014; Mraz et al., 2019; Namen et al., 2022; Pargeter & Schmidt, 2020; Suga et al., 2022, 2023), we first assess two proposed key variables: impurity content and silica (silicon dioxide, SiO₂) content. Cherts that fracture predictably possess fewer impurities (e.g., carbonates, oxides, clays, or organic matter content) that could potentially interfere with conchoidal fracture propagation, and more silica, the latter being the primary constituent of chert (Brantingham et al., 2000; Braun et al., 2009; Domanski & Webb, 1992; Stout et al., 2005; Whittaker, 1994). It follows then that a "higher-quality" toolstone—in terms of fracture predictability—is one that possesses relatively fewer impurities and more silica, thus fracturing more predictably when compared to a "lower-quality" toolstone (Brantingham et al., 2000; Braun et al., 2009; Lewis, Williams, et al., 2022). We then also assess the following (Bustillo et al., 2009; Ichinose et al., 2023): the mineralogical composition, and the crystallite size and lattice strain for quartz (crystalline α-SiO₂) using



FIGURE 3 Examples of chert outcrops: From left to right, outcrops #1, #9, #13, #17, and #18.

available representative chert samples over a range of impurity and silica contents.

Thus, in sum, our analyses of raw materials aim to assess whether cherts in south-central Oman, where Nubian cores are scarce,¹ possess more impurities or less silica than cherts in southern Oman, where Nubian cores are common. We aim to assess whether there are differences in the mineralogical composition, crystallite size, and lattice strain among representative samples from the two regions that might potentially explain geographic patterning of Nubian cores. However, we feel that it is important to emphasize that the variables we assess here are by no means the only ones that are potentially relevant to assessments of raw material “quality.” Nodule size and shape, cortex amount, the number of natural cleavages and internal fractures, and texture, among several other potential variables, could be of analytical consequence (see Eren, Lycett, et al., 2011; Eren, Roos, et al., 2014; see also discussions in Lewis, Williams, et al., 2022). Future work should aim to not only replicate our research here but to also expand upon it by assessing other aspects of lithic raw material quality in Oman.

2 | MATERIALS AND METHODS

2.1 | Fieldwork and specimen collection

In February 2023, M. R. B. and M. I. E. surveyed 22 chert outcrops in southern and south-central Oman, from which they collected 124 chert samples (Figure 3). The survey occurred via pedestrian reconnaissance and resulted in 87 samples from the southern region and 37 samples from the south-central region (Table S1; see also Data S1). An effort was made to collect a variety of chert colors and surface textures from each outcrop. Each chert specimen was bagged, cataloged, weighed, and photographed (Data S1).

¹Co-authors (R. G., D. C.) report the first discovery of Nubian Levallois cores near Duqm (Chlachula et al., n.d.); however, the overall frequency of Nubian surface scatters in southern versus south-central Oman remains higher by a factor of 200.

2.2 | Bulk elemental composition of chert samples

Before elemental analysis, loss on ignition (LOI) was used as a proxy for organic matter content or the presence of other volatile impurities that could potentially influence fracture predictability (Dean, 1974; Konen et al., 2002) following a previously established procedure (Williams et al., 2012; see also Williams et al., 2019 and Lewis, Williams, et al., 2022 for archaeological applications). A weighed mass of subsample with a target mass of 2.5 g was placed in ceramic crucibles with lids and brought to 550°C using a Thermo Fisher Thermolyne muffle furnace for 1 h, and then allowed to cool before being reweighed. Bulk elemental composition was determined by X-ray fluorescence using a PANalytical Epsilon 3XLE Series XRF, where accuracy and precision were monitored using NIST soil standards 1646a, 2586, and 2587. The analytical error for Si was ± 0.32 wt%. Pellets were made by mixing 11 g of milled soil and 1.2 g of cellulose binder (SPEX 3642) and then pressed to 20 tons of pressure twice for 1 min using a Carver 3664 pellet press.

2.3 | Bulk X-ray diffraction

Representative samples based on silica content as determined by X-ray fluorescence (XRF) were analyzed by bulk X-ray diffraction (XRD) to determine bulk mineralogical composition, and the crystallite size and lattice strain for quartz (crystalline α -SiO₂). The milled samples were loaded and lightly pressed into sample disks and analyzed using a Rigaku Miniflex 6G Diffractometer. Scans were conducted at 40 kV and 15 A from a 2θ angle range of 3.0°–90.0°. Rigaku's PDXL software, with the whole pattern powder fitting method using a Rietveld Refinement, connected to the International Centre for Diffraction Data) database, was used in the determination of mineralogical presence and relative abundance.

2.4 | Statistical analysis

We conducted two sets of statistical analyses to assess our central question of interregional chert quality differences. First, we compared

the 86 chert samples from southern Oman to the 37 chert samples from south-central Oman in terms of LOI. We could not record data from sample #32 from southern Oman. Because the LOI values do not conform to an underlying normal distribution (Shapiro–Wilk W for southern region = 0.386, south-central region = 0.705; $p < 0.0000$ for both regions), we used a nonparametric Mann–Whitney test to compare the medians of the two sample groups. We used a Fligner–Killeen test to investigate statistical differences in the coefficient of variation for both sample groups.

Second, we compared 61 chert samples from southern Oman to 32 from south-central Oman in terms of the Euclidean distance that each sample strayed from a theoretically “perfect” chert, that is, a chert with a value of 0 LOI and 100% SiO₂ content (Lewis, Williams, et al., 2022; Williams et al., 2019). The sample sizes for this analytical comparison were smaller than for the first because some chert samples were too small to record elemental data. We statistically compared the Euclidean scores between samples collected from the two different regions. Again, because the Euclidean scores were not normally distributed (Shapiro–Wilk W for southern region = 0.814, south-central region = 0.614; $p < 0.0000$ for both regions), we used the nonparametric Mann–Whitney test to compare the two sample groups.

We also conducted two supplementary analyses to assess interregional differences in chert composition. Our first supplementary analysis was a trace element composition analysis of cherts from southern versus south-central Oman. We used two multivariate statistical methods to examine differences in the trace element composition of the cherts from the two regions. The first method is varimax-rotated principal components analysis (VPCA), which was performed using the IBM SPSS version 28 software. VPCA was used as an exploratory technique to investigate the multivariate structure of these data. VPCA has previously been applied to derivative transformed reflectance data obtained from powdered samples of chert stone tools to help identify provenance (Lewis, Simone, et al., 2022). Here, we applied VPCA to the elemental data measured as oxides for the chert samples studied. We excluded sparse variables and samples with most of their measurements below the detection limit, leaving a small number of missing values in the subsample data set. Analysis of the data set was done with and without the remaining missing values filled. Multivariate unmixing was then conducted on the correlation matrix using PCA, and the resulting components with eigenvalues greater than 1 were extracted and varimax-rotated to maximize the orthogonal separation between components, yielding the final VPCA solution (Lewis, Simone, et al., 2022; Ortiz, 2011). Use of the correlation matrix as the basis for the elemental decomposition reduces the influence of the dominant oxides present, allowing the differences in trace elements to provide greater sensitivity between samples for provenance studies (Ortiz, 2011).

The second method is nonlinear discriminant analysis (NDA). NDA is used to classify observations into predefined groups based on predictor variables. Here, we use the cherts from the two regions, the southern and south-central regions, and the 32 measured trace elements as predictor variables. Unlike linear discriminant analysis,

NDA does not assume a linear relationship between predictors and the log-odds of group membership, making it suitable for nonlinear relationships. Because several chert samples were not subject to trace element analysis, we used a subset of samples for the analysis, which includes 61 samples from the southern region and 32 samples from the south-central region. We used the “nnet” package in R to carry out the NDA and we trained the model using 10-fold cross-validation using the “multinom” function in the “nnet” package.

Our second supplementary analysis was a comparative assessment of chert quality between cherts from Oman and cherts from the state of Ohio, USA.

All data, and the R script for the NDA analysis, are available in the Data S1 and Text S1.

3 | RESULTS

We measured the LOI and the weight percentage of SiO₂ and other major and minor elements for 123 geological chert samples from Oman. A total of 86 specimens were tested from the southern region and 37 specimens from the south-central region. While the south-central sample group is smaller than the southern one, there is still a substantial amount of overlap between regions, which is visible in the bivariate plot of SiO₂ and LOI (Figure 4).

3.1 | Comparing southern versus south-central Omani cherts via LOI

The Mann–Whitney test indicates that there is no significant difference in LOI values between regions ($U = 1264.5$; $z = 1.8$; $p = 0.07$). A Fligner–Killeen test for differences in the coefficient of variation shows that there also is no statistical difference in variation among the regional sample groups ($z = -0.694$, $p = 0.244$).

3.2 | Comparing southern versus south-central Omani cherts via the Euclidean distance from theoretically “perfect” chert

Next, we produced Euclidean scores of material quality for each of the geologic specimens. We did this by converting the SiO₂ and LOI values into a Euclidean distance measure of each specimen to the theoretically “perfect” chert specimen, comprised of 100% SiO₂ and 0 LOI. Thus, the Euclidean distance of material quality represents the distance between each specimen plotted in Figure 4 to the far-right bottom of the graph. We statistically compared these Euclidean scores from samples collected from the two different regions. The Mann–Whitney test demonstrates that there is no significant difference in the Euclidean distance measures between regions ($U = 756$; $z = 1.78$; $p = 0.076$).

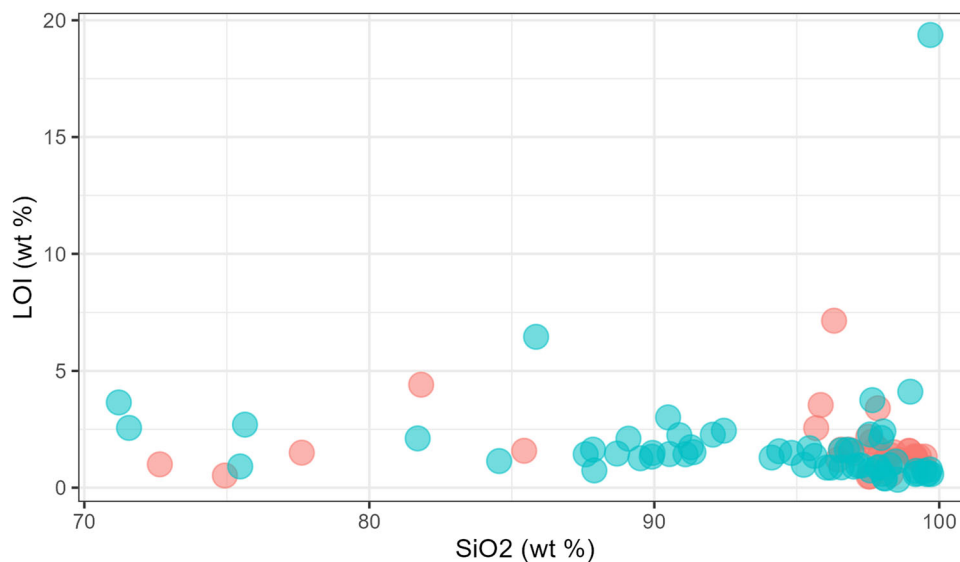


FIGURE 4 Geological chert-quality ranges for chert specimens from Oman. Specimens from southern Oman ($n = 86$) are turquoise and specimens from south-central Oman ($n = 37$) are light red. The theoretically "perfect" chert sample (composed of 100% SiO_2 and no impurities or 0% loss on ignition) is located at the far-right bottom of the figure.

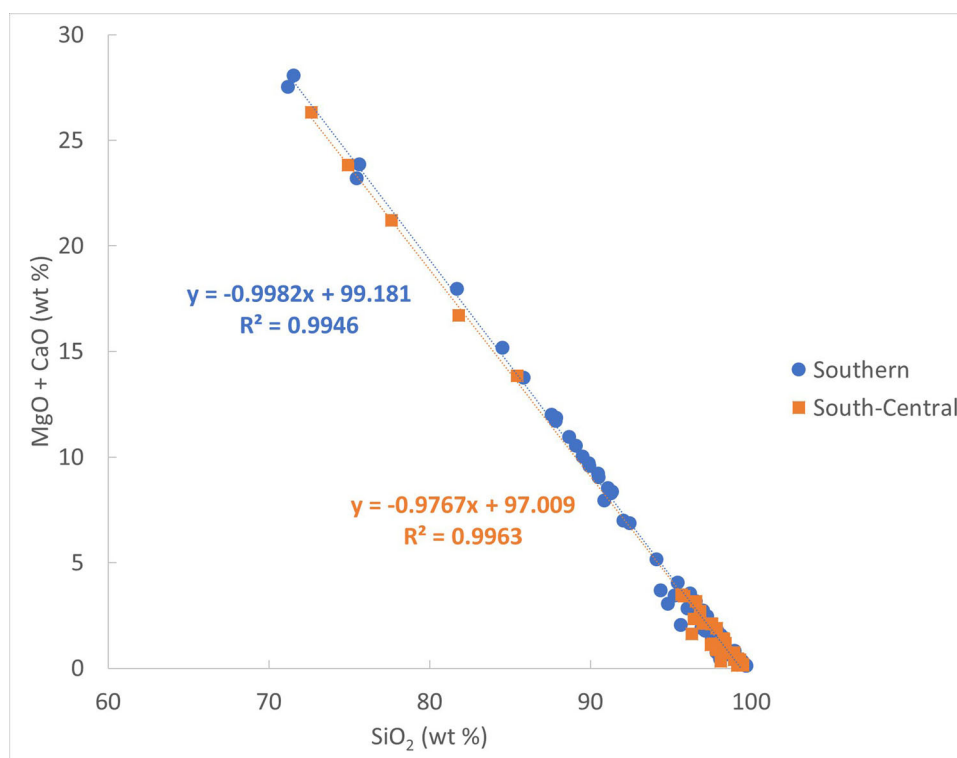


FIGURE 5 Comparison of the silica content versus the sum of MgO and CaO for the southern cherts (blue circles) and south-central cherts (orange squares), with linear regressions and equations (blue and orange text and dashed lines, respectively).

The main impurities in the cherts were Mg and Ca, which showed a strong linear negative correlation with silica content (Figure 5). The relationship between impurity content and silica content was essentially identical between the two chert populations, with slope (m) values of -0.998 and -0.977 and R^2 values of 0.995 and 0.996 for the southern and south-central cherts, respectively.

3.3 | Bulk mineralogy

Bulk XRD analyses indicated that the chert samples are dominated by crystalline quartz (Figure 6 and Table 1; see also Figures S1–S6), and samples with nearly pure silica content, as determined by XRF, were determined to be 100% quartz. Chert

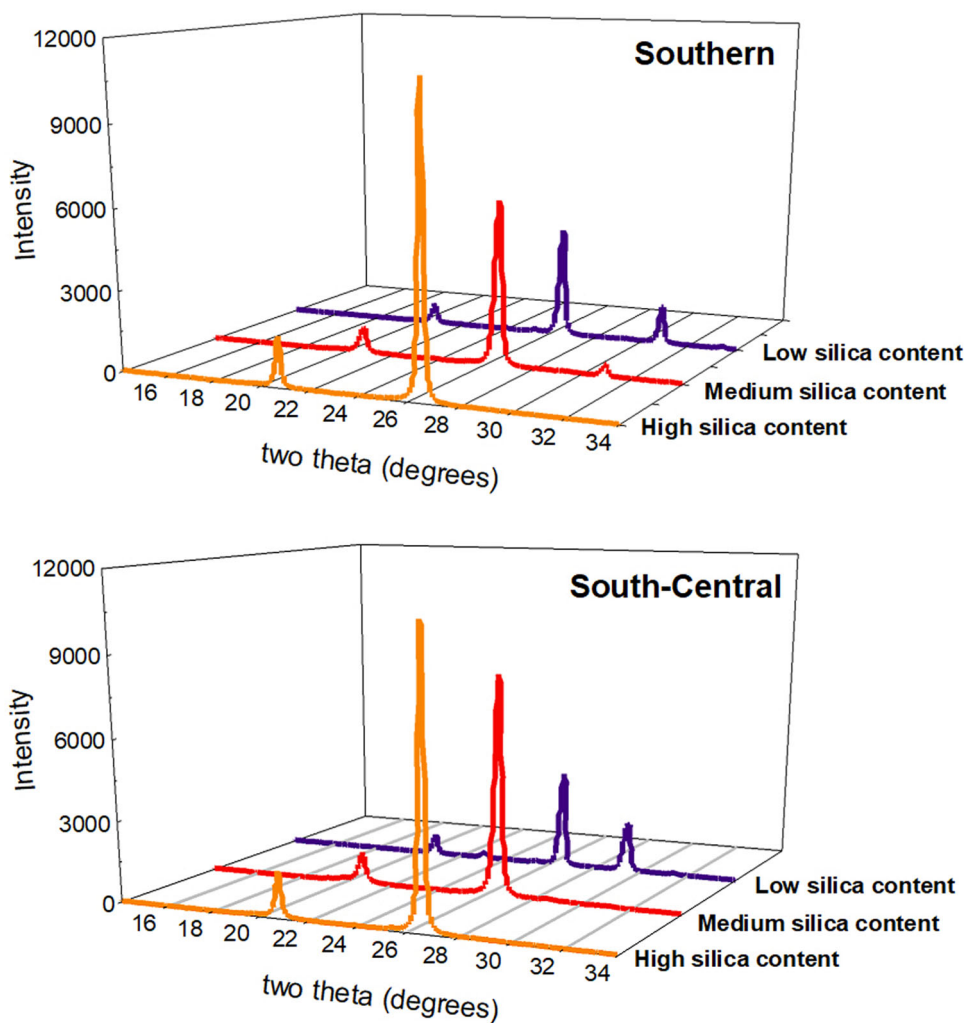


FIGURE 6 Representative bulk X-ray diffraction patterns of chert samples from the southern (top) and south-central locations and chosen based on silica content as determined by X-ray fluorescence (high, orange; medium, red; and low, purple). The medium silica content samples also have higher Fe_2O_3 content. The primary diffractions peaks are labeled for quartz (q), dolomite (d), and calcite (c). Full patterns and fits for the six samples are shown in the Supporting Information document.

TABLE 1 Representative bulk solid phase characterization results from XRF (percent SiO_2 , Fe_2O_3 , and $\text{CaO}+\text{MgO}$) that were used to choose three representative samples from both sites across a range of bulk compositions.

Sample no.	Southern			South-Central		
	30	6	8	55	64	50
% SiO_2 (from XRF)	99.67	94.12	75.47	99.28	98.48	72.68
% Fe_2O_3 (from XRF)	0.06	0.32	0.06	0.09	0.24	0.05
% $\text{CaO}+\text{MgO}$ (from XRF)	0.12	0.12	23.19	0.41	0.73	26.32
% Quartz	100	97.8	72.7	100	100	84.1
% Dolomite	0	2.2	27.3	0	0	0
% Calcite	0	0	0	0	0	15.9
Quartz crystallite size (nm)	28.2	19.1	23.1	16.7	22.8	29.9
Quartz crystallite strain (%)	0.1	0.2	0.2	0.3	0.2	0.1
<i>Rwp</i>	11.8	12.7	13.5	15.5	12.4	12.7
<i>Rp</i>	8.5	9.5	9.5	11.6	9.1	8.7
<i>Re</i>	9.1	9.5	10.8	8.9	9	10.9

TABLE 1 (Continued)

Sample no.	Southern			South-Central		
	30	6	8	55	64	50
S	1.3	1.3	1.3	1.7	1.4	1.2
c^2	1.7	1.8	1.6	3	1.9	1.2
Max shift/e.s.d.	0.008	0.083	0.069	0.074	0.084	0.098

Note: Bulk XRD results include mineral abundances (of quartz, dolomite, and calcite), the quartz crystallite size (nm) and lattice strain (percent), and fitting parameters for the Rietveld refinements (R_{wp} , R_p , R_e , S , and max shift/e.s.d.).

Abbreviations: e.s.d., estimated standard deviations; XRF, X-ray fluorescence; XRD, X-ray diffraction.

samples with a higher abundance of calcium and magnesium were found to contain either the carbonate minerals dolomite $[(Ca,Mg)CO_3]$ or calcite ($CaCO_3$), with maximum percent abundances (~25%) consistent with the CaO+MgO content. Similar to the bulk XRF results, the XRD results indicated that there was a range of carbonate mineral impurities within the cherts from each site, with a similar range for both sites. Further, the amount of carbonate mineral impurities did not affect quartz crystallinity, as the quartz crystallite size (which ranged from 16 to 30 nm) and percent lattice strain (which ranged from 0.1% to 0.3%) did not vary as a function of carbonate mineral content. Chert samples with higher Fe_2O_3 content as determined by XRF (up to 0.3 wt%) did not contain carbonate minerals, consistent with low CaO+MgO content. The higher Fe abundance did not affect quartz crystallinity.

3.4 | Supplementary analysis #1: Comparing trace element composition of southern versus south-central Omani cherts using VPCA and NDA

The VPCA analysis enables evaluation of the impurities present in the chert samples based on their relative oxide concentrations. By comparing VPC scores between the southern and south-central regions, we can elucidate whether they are derived from the same or different populations. A total of 93 samples, 61 from the southern sites and 32 from the south-central sites, were analyzed. The VPCA was based on analysis of 13 oxides (Table 2) measured in 93 samples. A total of 40 missing out of 331 oxide values (12% of the observations) that were below detection were filled with zeros for analysis. Comparison of the communalities and structure of the leading components for filled versus unfilled missing values did not appreciably alter the VPCA results (not shown).

The leading component (24.6% variance) represents a contrast between the dominant silica in the chert and sediment impurities derived from the local mafic to ultramafic volcanic rocks (Table 3). The second component (19.5% variance) has high loadings in CaO, SrO, and SO_3 and likely represents sedimentary carbonate impurities incorporated into the chert. The third component (14.8% variance) is rich in TiO_2 and Fe_2O_3 and may represent desert varnish, while the fourth component (11.2% variance) is dominated by Cl and Cr_2O_3 and may represent residual salts or heavy metals derived from sea water during chert formation.

TABLE 2 Oxide statistics for samples in the VPCA analysis.

Oxide	Mean (%)	SD (%)	Analysis N
MgO	2.18	3.08	93
SiO_2	93.90	7.09	93
SO_3	0.20	0.25	93
Cl	0.04	0.05	93
CaO	3.24	4.92	93
TiO_2	0.006	0.004	93
Cr_2O_3	0.009	0.004	93
Fe_2O_3	0.11	0.06	93
CuO	0.003	0.0003	93
SrO	0.01	0.02	93
SnO_2	0.01	0.004	93
TeO_2	0.01	0.001	93
WO_3	0.03	0.03	93

Abbreviation: VPCA, varimax-rotated principal components analysis.

TABLE 3 Varimax-rotated component loadings for the oxide data.

Oxide	Communality	VPC 1	VPC 2	VPC 3	VPC 4
MgO	0.84	0.85	0.04	0.09	-0.32
SiO_2	0.91	-0.75	-0.55	0.00	0.20
SO_3	0.77	0.01	0.87	0.08	-0.07
Cl	0.50	0.07	-0.02	-0.03	0.71
CaO	0.87	0.56	0.73	-0.11	-0.10
TiO_2	0.79	-0.12	0.02	0.88	0.07
Cr_2O_3	0.66	-0.09	-0.01	0.27	0.76
Fe_2O_3	0.85	-0.01	-0.07	0.92	0.03
CuO	0.37	0.30	0.12	0.42	0.29
SrO	0.82	0.11	0.89	-0.02	0.12
SnO_2	0.61	0.64	-0.26	-0.21	0.29
TeO_2	0.67	0.81	0.12	0.02	0.06
WO_3	0.46	-0.63	-0.21	-0.01	-0.15

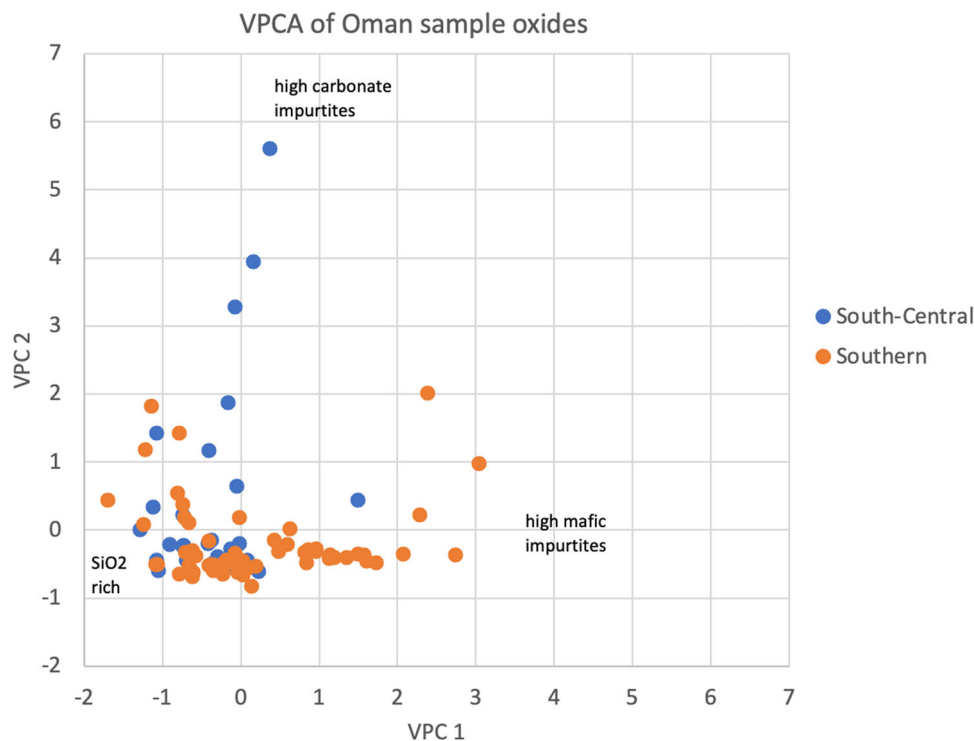


FIGURE 7 Bivariate plot of varimax-rotated principal component 1 representing 24.6% of the variation in the data set versus varimax-rotated principal component 2 comprising 19.5% of the variation in the data set. The specimens are colored by region (turquoise = southern region; light red = south-central region).

Comparison of the first and second components demonstrates that there is considerable overlap between the chert samples from the southern and south-central regions, particularly for samples with $VPC1 < 0$ and $VPC2 < 2$ (Figure 7). Samples with higher values for $VPC1$ trend off away independently from $VPC2$ in the southern region, while samples with higher values for $VPC2$ covary with $VPC1$ in the south-central region. This indicates that volcanogenic-derived impurities are more important for some of the southern, rather than the south-central samples, while carbonate-derived impurities show a weak correlation in the two locations, reaching higher values in the south-central region. Some samples from the southern region plot closest to samples from the south-central region, while one sample from the south-central region plots closest to southern samples, indicating that there is considerable heterogeneity in the incorporation of impurities in the chert. High scores in $VPC1$ (to the right on the x-axis) are driven by $MgO\%$ (0.85), TeO_2 (0.64), and SnO_2 (0.64), in contrast to low values of $SiO_2\%$ (-0.75) and $WO_3\%$ (-0.63). On the other hand, high scores on the $VPC2$ axis (up on the y-axis) are driven by $SrO\%$ (0.89), $SO_3\%$ (0.87), and $CaO\%$ (0.73). The region of overlap between the southern and south-central samples with $VPC1 < 0$ and $VPC2 < 2$ indicates that samples rich in $SiO_2\%$ have low values in $VPC1$ and $VPC2$ because $SiO_2\%$ loads negatively on $VPC1$ (-0.75) and $VPC2$ (-0.55).

The NDA is also used to determine if the chert sample groups from the two regions can be statistically differentiated from one another. The results of the NDA separating specimens from the southern and south-central regions of Oman using trace element composition show that cherts from the different regions can be separated at a cross-validated

rate of 95.7% (95% CI: 0.89–0.99). The confusion matrix classifies 60 of the 61 chert samples from the southern region correctly, while 29 of the 32 chert samples from the south-central region are classified correctly. A resulting p value of $2.233e-12$ indicates an extremely small probability that the observed accuracy of the NDA model is due to chance, assuming that the null hypothesis is true. In this case, it suggests that the model's accuracy is significantly higher than the "no information rate" (the accuracy achieved by always predicting the majority group, thus defining the baseline accuracy), with very strong statistical significance.

3.5 | Supplementary analysis #2: Comparing quality of Omani cherts versus Ohio cherts

Seventeen geological samples of chert from Ohio were collected and analyzed (see Williams et al., 2019) using the same techniques and measures used for the Oman samples. We compared LOI values for the Ohio and Oman sample groups and then plotted SiO_2 and LOI for the three sample groups (Ohio, southern Oman region, and south-central Oman region).

The LOI values for the Omani cherts remain significantly different from an underlying normal distribution, while the Ohio sample group is normal. We carried out a nonparametric Kruskal–Wallis test to determine if the three sample groups differed in median LOI values. The results indicate that no statistical difference among the three sample groups could be discerned ($H = 0.71$, $p = 0.700$). In addition, we

conducted a permutation multivariate analysis of variance and tested for differences among the three sample groups for both LOI and SiO₂. The results similarly show no significant difference (permutations = 9999; $F = 0.576$, $p = 0.599$). Both nonsignificant results suggest that more data, particularly from Ohio, are needed for future analyses. Interestingly, the Ohio sample group of chert has a strong negative correlation ($r = -0.90$, $r^2 = 0.81$, $p < 0.000$), whereas both the south-central ($r = -0.02$, $r^2 < 0.00$, $p = 0.915$) and southern ($r = -0.07$, $r^2 < 0.00$, $p = 0.618$) regions have nonsignificant correlations.

4 | DISCUSSION

Lithic raw material quality differences are often invoked to explain, in part or in full, the presence or absence of stone tool types, and/or their technological or morphological differences. Here, we assess whether there are differences in chert quality between two regions of Oman where Nubian cores are frequent (southern region) or rare (south-central region). If our analysis had uncovered quality differences in the form of poorer-quality raw materials in the south-central region, then raw material constraints could have been considered as a potential factor in the absence of Nubian cores there. However, following approaches used previously (Lewis et al., 2022; Williams et al., 2019; see also Brantingham et al., 2000; Braun et al., 2009), our XRF results suggested no chert quality differences between the two regions, which is instead consistent with the hypothesis that raw material constraints *alone* (i.e., the “natural forces” hypothesis) cannot explain the dearth of Nubian cores in the south-central region. This result with respect to quality is all the more interesting because, according to our NDA analysis, southern and south-central cherts could be distinguished geochemically. This may have resulted from the ability of NDA to observe nonlinear relationships within the data as the linear VPCA decomposition still observed overlap, although our assessment was based on qualitative comparison of only the leading two VPCA components. Some researchers have used the quartz crystallinity index (Murata & Norman, 1976) to evaluate the relationship between variability in the crystallite size and crystal structure and cherts used for stone tools (Bustillo et al., 2009; Ichinose et al., 2023). In the current work, there was no evidence in XRD patterns for a poorly crystalline and/or amorphous phase based on the flat diffraction backgrounds. Further, given the presence of carbonate mineral impurities in some of the chert samples, a full pattern fitting procedure (i.e., a Rietveld refinement) was warranted to determine quartz crystallinity properties. However, given that we only assessed available representative chert samples with XRD, further work is needed to more robustly compare quartz content and crystallinity as a function of impurity content across the regions that we analyzed.

Our results conform to several other previous findings. The widespread occurrence of Nubian cores geographically—from Africa to Arabia to the Levant—in and of itself suggests that Nubian core technology can be knapped on a wide variety of lithic raw materials (e.g., Hallinan & Shaw, 2020; Kurashina, 1978; Marks, 1968; Usik et al., 2013). Along these lines, Hilbert et al. (2016) compared chert

and quartzite Nubian assemblages from Oman and Saudi Arabia, respectively. They found that Nubian cores “in both regions show comparable traits” and that “no regional patterning could be observed,” indicating that “different raw materials used in assemblages more than 1000 km [apart] had little effect on the application of Nubian technology” (Hilbert et al., 2016, p. 18). While their results do not support the “natural forces” iteration of the raw material constraints hypothesis, they did document more of what they interpreted as “knapping mistakes” in the Saudi quartzite assemblage. This latter result might potentially be consistent with the “artificial forces” iteration of the raw material constraints hypothesis, although it is equally plausible that the Nubian knappers in Saudi Arabia simply possessed less skill (e.g., novice knappers) or were knapping under some time constraint (e.g., Schillinger et al., 2014), relative to the Nubian knappers in Dhofar, and raw material did not play a role in those mistakes (but see discussion in Hilbert et al., 2016, p. 19–20).

Although we did not quantitatively assess the size or shape of chert nodules in the field, we can confirm from our observations that both the southern and south-central regions possessed a variety of sizes as well as shapes (e.g., tabular, pebble, etc.). Moreover, Nubian core forms can be knapped on relatively small chert nodules (Usik et al., 2013), so even if chert size differences were present between the two regions, such differences would not necessarily impede production. The same can be said for Levallois core forms more generally (Dibble & McPherron, 2006).

If indeed Nubian core reduction falls into the Levallois “family” of knapping, then there may be further reason to doubt that raw material constraints—even if they had been present—can fully explain the scarcity of Nubian cores in south-central Oman. This is because Levallois knapping has been proposed to be, in some instances, innovated and/or selected by hominins as a response to “poor” raw material quality, as Brantingham et al. (2000, p. 269) suggested for the significant innovations in Levallois-like prepared core technology at Tsagaan Agui, Mongolia. Brantingham et al.’s (2000) suggestion is supported by a 20-month experiment conducted by Eren, Lycett et al. (2011) involving preferential Levallois flake (PLF) production. Eren knapped two batches of PLF cores. The first batch, knapped at the start of Eren’s PLF technology learning, was on a “higher quality” lithic raw material consisting of standardized large flakes knapped on a fine-grained silicious sedimentary rock from the Cretaceous-aged Upper Greensand, located in the chalk cliffs of the South Devon coast, UK (referred to as a “Greensand silicate”). The second batch, knapped after Eren mastered PLF reduction, was on a chert from the Cretaceous-aged Fredericksburg Group (Fredericksburg variety of Texas chert) that occurred as irregular, cortical nodules as replacement features within the Edwards limestone and varied tremendously in texture and internal cleavages. Skill level markers were designed to measure Eren’s ability to achieve a series of goals, all quantified and subjected to statistical testing. In all but one test, significant increases in skill could be detected from the earlier to the later batch of reductions, *despite* the drop in toolstone quality. In other words, the switch to the more challenging raw material of “poorer

quality” offered no obvious impediment to Eren's rising Levallois skill (Eren, Lycett, et al., 2011, p. 2738).

In sum, the results that we present here, especially when considered in light of previous archaeological and experimental work, strongly suggest that raw material constraints cannot be invoked to explain the scarcity of Nubian cores in south-central Oman, and that other hypotheses might be more parsimonious. We explore the following alternative hypotheses to explain the limited distribution of Nubian technology in Oman:

1. Culture—Distinct Middle Paleolithic populations existed in southern and south-central Oman, who did not culturally transmit Nubian technology between them.
2. Taphonomy—The landscapes in south-central Oman have been heavily modified by high-energy surface runoff since the Late Pleistocene, removing most Middle Paleolithic archaeological remains.
3. Hydrology—There were insufficient freshwater sources in south-central Oman to support a substantial Middle Paleolithic population.
4. Geography—The >300 km long Jiddat al Harassis plain separating southern and central Oman is a biogeographic barrier.
5. Ecology—Different plant and animal species have produced different regional adaptations.
6. Epistemology—Insufficient fieldwork in south-central Oman relative to Dhofar.

We can discard the notion of insufficient fieldwork, as several systematic surveys have been conducted throughout south-central Oman over the past two decades (e.g., Garba, 2021; Genchi et al., 2017; Jagher, 2009; Jagher & Pümpin, 2010; Maiorano et al., 2023; Rose, 2006) (see also Figure 1). These surveys have mapped hundreds of prehistoric sites, with virtually no evidence of Nubian core technology, nor any diagnostic Middle Paleolithic technology for that matter. This also calls into question the cultural explanation, as there presently does not appear to be a Middle Paleolithic population in south-central Oman that is coeval with Nubian toolmakers in the south—there are no dated assemblages from this period and no tool types or core technologies have been found that are associated with any known Middle Paleolithic industry. Regarding taphonomy, the scarcity of both Lower and Middle Paleolithic assemblage types, in contrast to the frequency of Upper/Late Paleolithic sites, may support post-depositional disturbance to explain the absence of Nubian cores in south-central Oman. If the density of Middle Paleolithic sites had been similar to Dhofar in antiquity, however, at least a modicum of evidence would be expected within drainage channels or on high terraces, as it does in Dhofar.

Considering the ecologies of southern versus south-central Oman, both regions belong to the same phytogeographic zone, alternately classified as Somalia-Masai or Sudanian-Zambezi-Sindian endemic zones (Al-Nafie, 2008; Radcliffe-Smith, 1980; Raffaelli & Tardelli, 2006). The mountains of Dhofar are distinguished by their tall-grass savannah, which are described as “an impoverished outlier of the East African savannah” (Patzelt, 2011, p. 301). Between south and south-central

Oman, the same medium- and large-sized game populate both regions, including oryx, ostrich, gazelle, and ibex (Harrison & Bates, 1991; Jennings, 1986). Therefore, it is doubtful that fauna can explain the absence of Nubian technology in south-central Oman. We are left with hydrology and geography to explain this phenomenon. Southern Oman is uniquely impacted by the Indian Ocean Monsoon and, as a result, the Nejd plateau is incised by several large interior-draining river systems that house freshwater springs. South-central Oman, conversely, does not receive monsoon rainfall and is marked by a single coastal-draining river system. Hence, there are major differences in access to fresh water between Dhofar (southern region) and Duqm (south-central region). Moreover, between the easternmost drainage system in Dhofar and southern Duqm lies a 300 km plain devoid of drainages or springs, which forms a biogeographic boundary that may have restricted or blocked contact between regions. Taking all these factors into consideration, we suggest that the availability of water—in the form of precipitation, activated drainage systems, and artesian springs—was a limiting factor in the distribution of Middle Paleolithic Nubian toolmakers across southern Arabia. A lingering question remains, however, as to why Upper/Late Paleolithic sites are so frequent in south-central Oman during a more arid climatic phase. Or are they rather associated with Early/Middle Holocene? These blade sites represent a large portion of lithic scatters in Duqm (Jagher & Pümpin, 2010). So far, the very first absolutely dated stratified lithic material in Duqm comes from the Neolithic rock shelter dated 5984–5370 cal. B.C.E. (Maiorano et al., 2023).

Our two supplementary analyses have implications for future research on the Paleolithic of Oman and on chert studies. Regarding the former, we note that, to our knowledge, geochemical sourcing of lithic raw materials is not as commonly done in Oman as it is in some other parts of the world (e.g., Barrientos et al., 2023; Boulanger et al., 2015, 2021, 2022; Eren, Bebbler, et al., 2021; Hoard et al., 1992; Lewis, Simone, et al., 2022; Milne et al., 2009, 2011; Nash, Coulson, Staurset, Smith, et al., 2013; Nash, Coulson, Staurset, Ulyott, et al., 2013; Nash et al., 2016; Newlander & Lin, 2017; Parish, 2016; Parish et al., 2013; Parish & Werra, 2018; Sherman et al., 2023; Speer, 2014a, 2014b; Speer & Jennings, 2019). Thus, our supplementary analysis involving chert trace element data is an important first step. That cherts in southern and south-central regions of Oman seem to be statistically distinguishable geochemically is an interesting result and one that, if repeated in future tests, may be useful for understanding past land use, mobility, and trade in the Omani Middle Paleolithic and beyond, both temporally and spatially. All the trace element data analyzed in the present study are available in Data S1 for researchers who wish to build upon our initial results.

Our second supplementary analysis, which compared the quality of Omani cherts versus those in Ohio, USA, yielded two noteworthy results. First, despite the vast geographic distance between Oman and Ohio, there were no differences in impurity amount and silica amount. This result suggests that these aspects of chert formation are broadly similar regardless of geography. Second, although we found no difference between Omani and Ohio cherts in terms of impurity amount and silica amount, our analyses suggest that *the relationship* between impurity amount and silica amount is

different for the sample groups. Specifically, Williams et al. (2019) previously found a statistically significant inverse relationship between LOI and SiO₂ in Ohio cherts. Yet, we documented no relationship between impurity content and SiO₂ in Omani cherts. The reason for this prominent difference in Omani and Ohio cherts requires further research and could very well be due to the Ohio chert's smaller sample sizes or due to differences in the mechanisms by which the cherts form in both locations.

5 | CONCLUSION

Over 20 years ago, Holdaway and Stern (2004, p. 55) noted that "few studies... actually document the impact of the properties of raw materials on the way in which particular tool types were produced." Their observation was important, because lithic raw material quality, constraints, and differences have regularly been uncritically offered as explanations for past technologies' spatial distribution, chronological range, form, or ontogeny (see discussion and references in Eren, Roos, et al., 2014). Here, we examined whether the presence of a Middle Paleolithic core form—the Nubian core—covaried with chert quality. We explicitly defined quality as "fracture predictability" and quantitatively assessed this quality via the measurement of impurities and silica content. Our results suggested that the quality of cherts in the two regions was similar, even though they could be distinguished geochemically. As such, the presence of Nubian cores in southern Oman, and their absence in south-central Oman, cannot currently be attributed to differences in lithic raw material quality. Instead, this pattern may be a function of hydrology and differences in the availability of freshwater sources between the two regions. We provisionally suggest that the line separating regions with Nubian cores from those without Nubian cores be referred to as the "No-bian Line."

AUTHOR CONTRIBUTIONS

Metin I. Eren: Conceptualization; investigation; funding acquisition; writing—original draft; writing—review and editing; project administration. **Michelle R. Bebbler:** Conceptualization; investigation; funding acquisition; writing—original draft; writing—review and editing; project administration. **David Singer:** Investigation; funding acquisition; writing—original draft; writing—review and editing; methodology; formal analysis; supervision; resources. **Chloe Pearson:** Methodology. **Joseph D. Ortiz:** Investigation; funding acquisition; writing—original draft; methodology; writing—review and editing; formal analysis; supervision; resources. **Briggs Buchanan:** Funding acquisition; investigation; writing—original draft; writing—review and editing; formal analysis. **Amir Beshkani:** Writing—original draft; writing—review and editing; investigation. **Dominik Chlachula:** Investigation; writing—original draft; writing—review and editing. **Rudolf Dellmour:** Investigation; writing—original draft; writing—review and editing. **Roman Garba:** Investigation; funding acquisition; writing—original draft; writing—review and editing; project administration. **Anthony E. Marks:** Investigation; writing—original draft; writing—review and editing; funding acquisition.

Vitaly Usyk: Investigation; writing—original draft; writing—review and editing. **Jeffrey I. Rose:** Investigation; funding acquisition; writing—original draft; writing—review and editing; project administration.

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DATA AVAILABILITY STATEMENT

The data presented are available online in digital form in the Supporting Information.

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