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Mapping lateral stratigraphy at Palaeolithic surface sites: A case study from Dhofar, Oman

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ABSTRACT

Open-air accumulations of chipped stone debris are a common feature in arid landscapes, yet despite their prevalence, such archives are often dismissed as uninformative or unreliable. In the canyonlands of Dhofar, southern Oman, lithic surface scatters are nearly ubiquitous, including extensive, multi-component workshops associated with chert outcrops. These sites typically display chronologically diagnostic features that correspond to distinct taphonomic states, which in turn appear linked to spatial distribution, with more heavily weathered artifacts often found farther from the chert outcrops. We propose that post-depositional modifications and spatial distributions of chipped stone artifacts reflect site formation processes and, under certain conditions, may provide relative chronological information when absolute dating methods are unavailable. Our study tests this hypothesis by mapping artifact distribution and lithic taphonomy across a series of surface sites in southern Oman, spanning the Lower, Middle, and Upper/Late Palaeolithic periods. The results largely support our model, offering valuable insights into surface site formation and technological change over time. While these findings serve as broad predictive markers for age, their applicability for analyzing finer-scale assemblage variability remains to be determined. Future taphonomic recording systems should aim to quantify surface modifications to enhance replicability for such studies.

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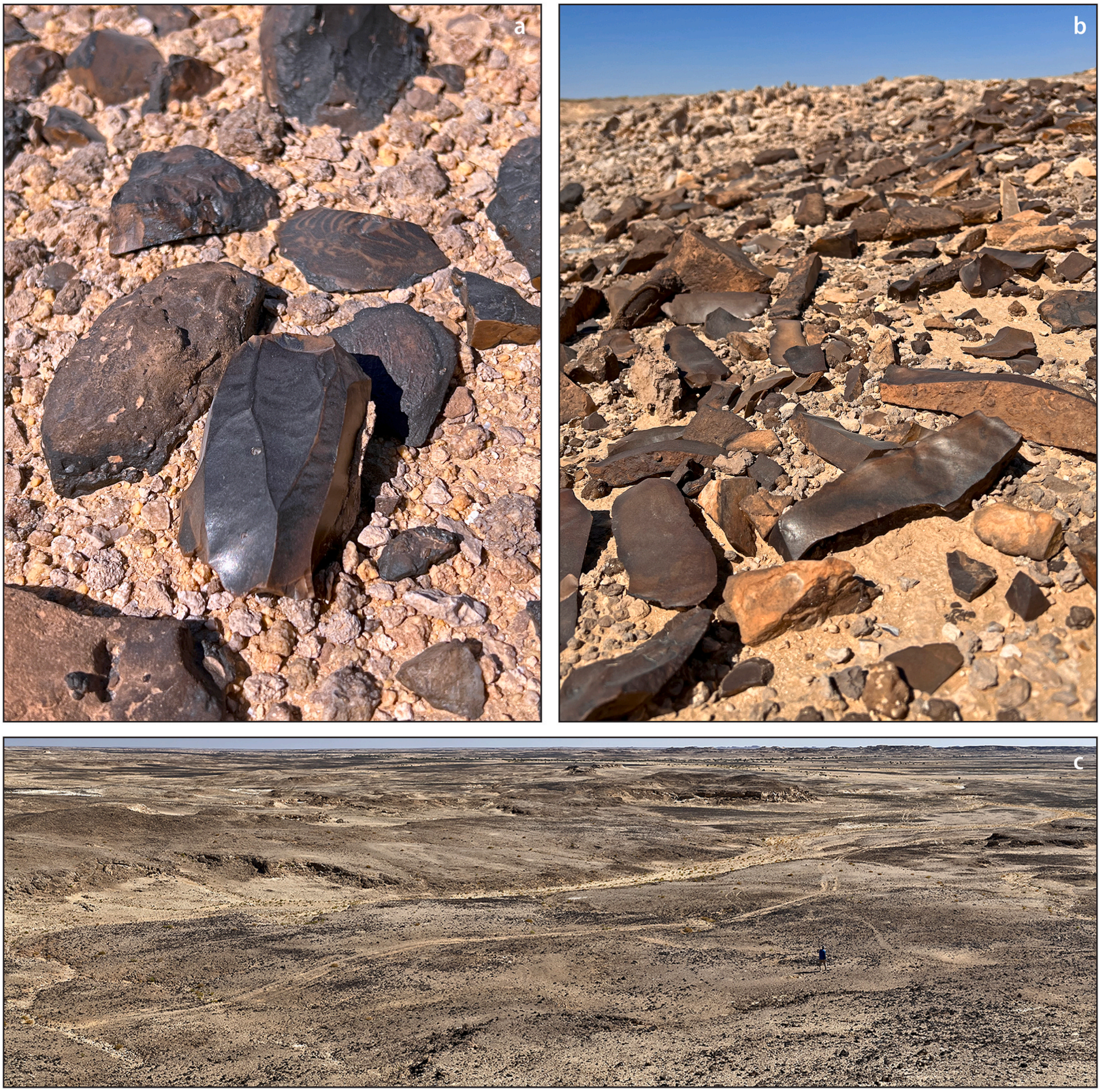

Fig. 1. (a) isolated core, (b) moderate density lithic scatter, (c) lithic landscape above Wadi Amut (Photos J. Rose).

1. Introduction

1.1. Surface sites

Every lithic scatter, at one point or another, has been a surface site. Surface sites, however, are commonly disregarded as unreliable archives of archaeological information, given their lack of spatial and chronological control compared to buried assemblages (Lewarch and O'Brien, 1981). Nevertheless, such findspots are often the only archaeological contexts in arid environments and, combined with appropriate methodologies, have been shown to yield important insights into past human behaviors (e.g., Fanning et al., 2009; Olszewski et al., 2010; Foley and Lahr, 2015; Hallinan, 2022; Oron et al., 2023; Douglass et al., 2023).

Erosional processes prevalent in arid landscapes lead to the formation of desert pavements, created by the aeolian deflation or accretion of fine sediments, resulting in an interlocking mosaic of stones (McFadden et al., 1987; Fanning and Holdaway, 2004; Goudie, 2008). These are long-lived, stable surfaces that can be used as surface-age indicators (Adelsberger and Smith, 2009; Matmon et al., 2009). Consequently, lithic artifacts that lie on top of, or are incorporated into the surface represent multi-phase, "time-averaged" archaeological palimpsests (Stern, 1994; Bailey, 2007; Coco and Iovita, 2020; Knight and Zerboni, 2018). This presents a major challenge, and unique opportunity, in arid regions with long occupation histories such as the Arabian Peninsula, where conflated surface scatters are extensive, diverse, and comprise the vast majority of Palaeolithic archaeological sites.

Various methods have been applied to overcome the limitations of conflated surfaces. It is possible to differentiate anthropogenic from geogenic deposits and multi-occupation palimpsests from single-event living floors (e.g., Malinsky-Buller et al., 2011; Hovers et al., 2014; Oron et al., 2023). In cases of sufficiently pristine preservation, lithic refitting can be used to link individual artifacts to a single knapping event, allowing for more precise reconstructions of toolmaking behavior (e.g., Volkman, 1983; Chiotti et al., 2007; Usik et al., 2013; Oron et al., 2024). The spatial integrity of surface scatters has been demonstrated (Bisson et al., 2014; Staurset et al., 2023), while acknowledging that there are predictable patterned changes, such as the loss of small artifact fractions from assemblages (Bertran et al., 2012; Adelsberger et al., 2013; Ugalde et al., 2015; Borrazzo, 2016).

Lithic artifacts, whether buried rapidly or exposed for long periods of time, are subject to chemical and mechanical weathering processes that alter their surface morphologies. These result in physical changes such

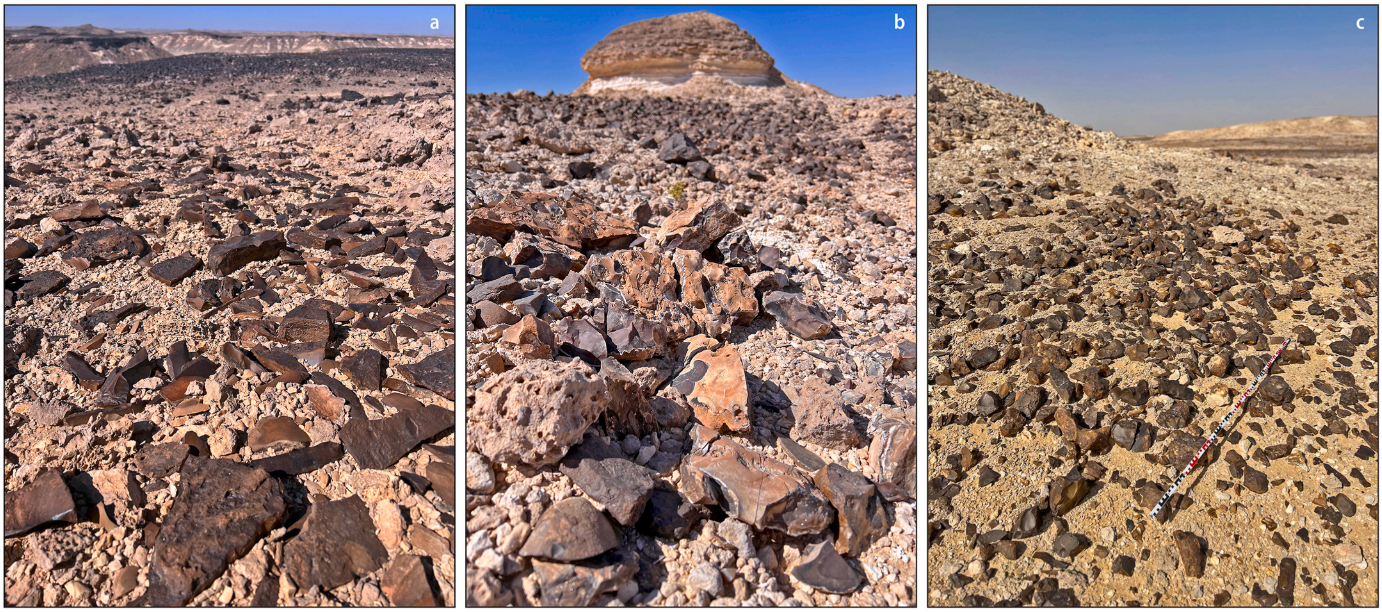

Fig. 2. (a) Jebel Sanoora chert outcrop near findspot TH.143, (b) Aybut plateau chert outcrop, (c) Aybut Hills chert outcrop near findspot TH.76 (Photos J. Rose).

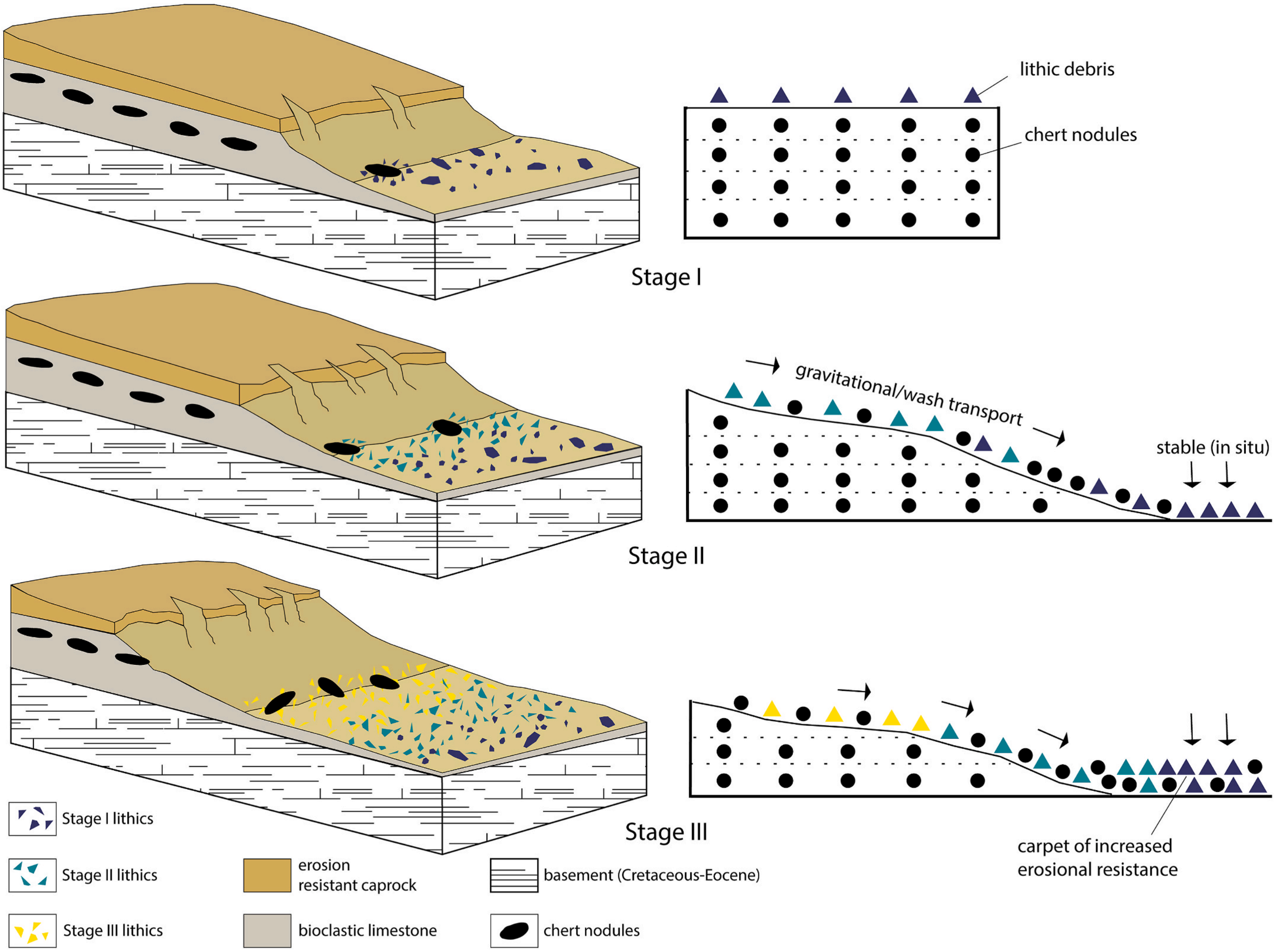

Fig. 3. (left) Surface site formation model showing development of lateral stratigraphy from early to mid to late stages of chert exposure at the edge of the scarp, (right) conceptual visualization of site formation process.

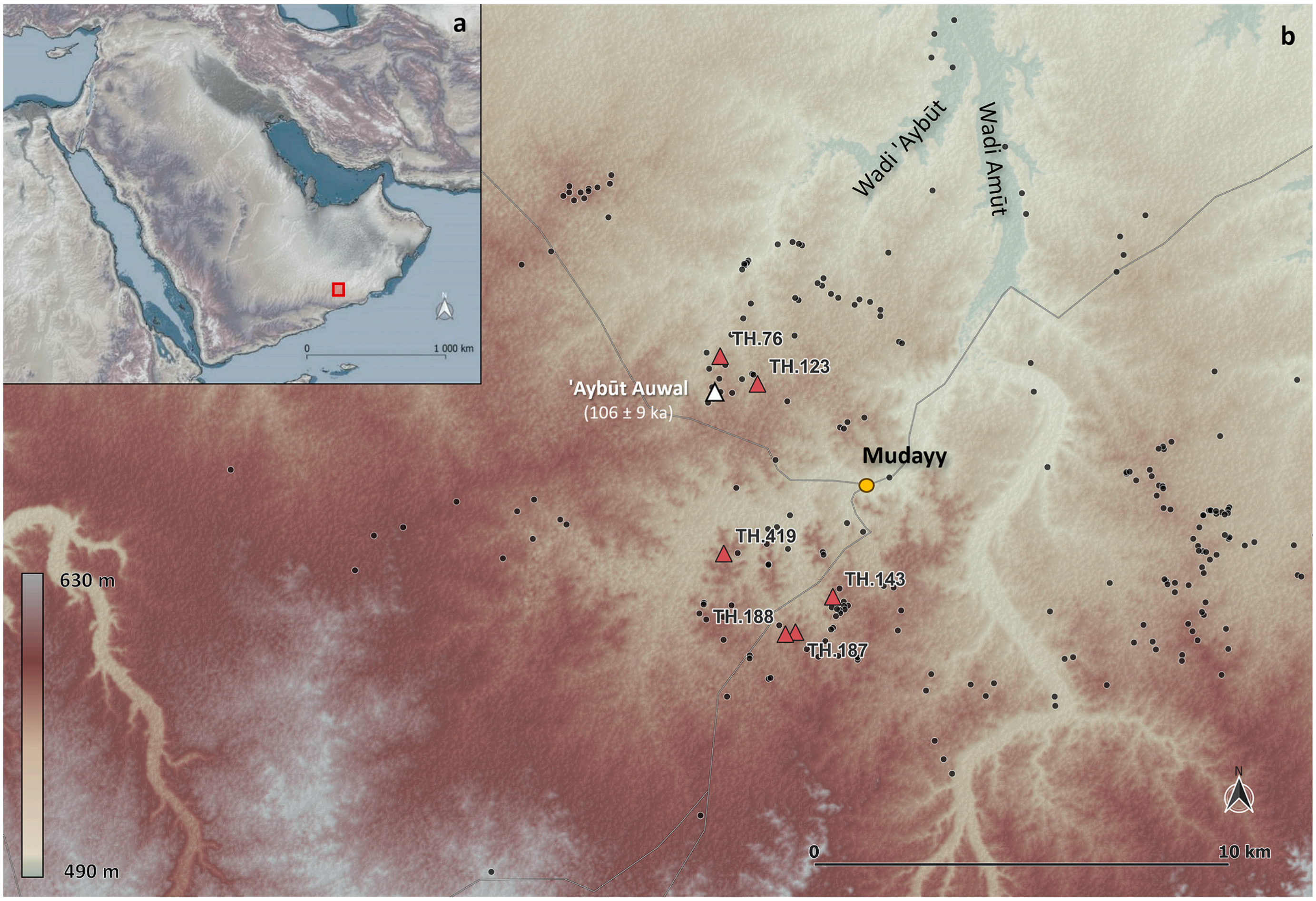

Fig. 4. (a) Map of the Arabian Peninsula showing study area; (b) Mudayy region. Red triangles = study sites with IDs. Black dots = all recorded lithic findspots. Data DEM source for (a) GEBCO 2022grid (http://gebco.net); (b) SRTM 1 Arc-Second, generated using QGIS v.3.26 Buenos Aires. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

as patination (Hurst and Kelly, 1961; Howard, 2002; Fernandes et al., 2007), dissolution (Thiry et al., 2014), abrasion (Burroni et al., 2002; Knight and Zerboni, 2018) and edge damage (McBrearty et al., 1998; Eren et al., 2011; McPherron et al., 2014; de la Peña and Witelson, 2018). Scholars have long theorized that lithic taphonomic features may potentially serve as relative chronological markers, based on the observation that older artifacts have been subjected to post-depositional surface modifications longer than younger ones (Seligman, 1921; Goodwin, 1960; Pawlikowski and Wasilewski, 2002). Systematic methods for quantifying lithic taphonomy, however, remain underdeveloped (see Gauthier and Burke, 2011; Ugalde et al., 2015; Caux et al., 2018; Bustos-Pérez et al., 2019; Berruti and Arzarello, 2020; Oron et al., 2023).

In this paper, we explore the relationship between lithic taphonomy and spatial distributions of artifacts at multi-occupation surface sites in the Dhofar region of Oman, where there is a plethora of open-air anthropogenic accumulations, yet a dearth of stratified contexts. Can lithic taphonomy be used to study site formation processes and relative changes in technology? If so, at what temporal scale can this approach be effective?

1.2. Regional context

The density of Palaeolithic surface scatters littering the Dhofar Nejd plateau of southern Oman is among the highest in the Arabian Peninsula (Zarins, 2001; Newton and Zarins, 2013; Rose et al., 2019a, 2023). They occur in a variety of settings and signal different human activities. In some cases, these are single discarded cores or isolated points, while others consist of vast accumulations of lithic debris that extend over hundreds of meters (Fig. 1), within which different archaeological phases are represented. Diagnostic elements include, among others, Lower Palaeolithic (LP) handaxes and radial cores, Middle Palaeolithic (MP) Nubian Levallois cores and products, and Upper/Late Palaeolithic (UP) blades and bifacial foliates. There is high archaeological visibility across the arid Nejd plateau, where most of these sites are found, while buried assemblages in datable contexts are exceedingly rare. Of the nearly 1000 mapped Palaeolithic findspots, there are currently just two sites with numeric ages: Aybut Auwal, a Nubian Levallois open-air deposit dated to <106 ka (Rose et al., 2011) and Matafah, an accretional terrace with UP blades and microliths dated to ~30 ka (Rose et al., 2019b). Consequently, there is little temporal control over the numerous surface scatters in Dhofar, hindering our understanding of Pleistocene population dynamics in a region that is theorized to have served as a critical demographic conduit between Africa and Eurasia (Fernandes et al., 2012, 2015; Rose and Marks, 2014; Vyas et al., 2016; Mineta et al., 2021).

Several factors coincide to produce such a dense and diverse archive of Palaeolithic surface sites in this region: 1) plentiful high quality raw material, 2) episodic precipitation during the Pleistocene that activated inland river systems and artesian springs, and 3) extensive landscape deflation, resulting in high archaeological visibility. Situated just north of the Intertropical Convergence Zone (ITCZ), periodic intrusions of the ITCZ brought pulses of precipitation, signaled by speleothem activation in the Dhofar mountains (Fleitmann et al., 2007), fluvial accretions on

Table 1
Total number of mapped artifacts at each site organized by class.

Site Code	Site Name	Cores	Tools	Debitage	Total	Diagnostics
TH.76	Aybut Hills 3	71	47	79	197	(126)
TH.123	Aybut Hills 4	41	9	68	118	(77)
TH.143	Jebel Sanoora 1	85	10	123	218	(147)
TH.187	Jebel Sanoora 2	66	5	63	134	(86)
TH.188	Jebel Sanoora 3	47	4	42	93	(67)
TH.419	Umm Mudayy 2	166	26	90	282	(219)

the Nejd plateau (Rose et al., 2011, 2019b), and palaeolake deposits in the southern Rub' al Khali desert (Matter et al., 2015).

The lithology of the Dhofar Nejd plateau consists of horizontally bedded, shallow marine Paleocene-Eocene carbonate layers (Platel and Roger, 1989; Roger et al., 1989). Throughout the Quaternary, fluvial and aeolian activity have eroded the soft bioclastic matrix of these strata, exposing chert nodules and tabular chert seams (Fig. 2). Around the village of Mudayy, which is the geographic focus of this study, exposures of the Umm Er Radhuma geological formation contain concentrations of chert with favorable flaking properties (Eren et al., 2024). It is here that lithic workshop sites are most common and exhibit the widest range of technological diversity (Rose et al., 2019a, 2023).

Over the course of several seasons of archaeological fieldwork, we observed that artifacts diagnostic of different periods tended to exhibit visible differences in surface modification. It was also noted that at some sites, the typologically oldest, most heavily weathered artifacts seemed to be located farthest from the present chert exposure, while typologically younger, less weathered artifacts appeared to be distributed closer to the outcrop. We posited that these patterns might be due to landscape erosion, surface creep, anthropogenic effects of quarrying, or a combination of variables, resulting in a kind of lateral stratigraphy (Fig. 3). Examining a series of primary workshop sites from the Nejd plateau, this paper tests the null hypothesis that variability in lithic taphonomy and spatial distribution of artifacts is arbitrary. We assess if spatial distribution and lithic taphonomy can be effective guides for determining relative chronologies at mixed surface sites, in instances where they occur within a discrete geomorphic zone sharing the same climate history and unified raw material properties.

2. Methods

2.1. Field collections

Our study was designed to explore correlations between lithic taphonomy and spatial distribution of artifacts. Six multiple-component sites were selected in the vicinity of Mudayy village (Fig. 4; Table 1). Sites were chosen based on the presence of at least two discernible Palaeolithic assemblage types (LP, MP, and/or UP) associated with an extant chert outcrop, where all artifacts were made on the same raw material. At each site, the survey transect was oriented perpendicular to an actively eroding linear chert outcrop and positioned to obtain a sample assemblage of all visible weathering stages. The length and width of each transect varied among sites, depending on the density and distribution of artifacts, with the aim of mapping and collecting the largest sample of artifacts practicably attainable.

Lithics were mapped in three-dimensional space using a total station (Fig. 5), which was positioned near the outcropping/least weathered chert nodules in order to calculate the distance of individual artifacts to the present chert exposure. Each site was given its own coordinate system. Artifacts chosen for study within the transects included: cores, tools, and intact debitage over 3 cm in maximum dimension (i.e., unbroken, identifiable platforms and dorsal surface). Unstruck nodules and

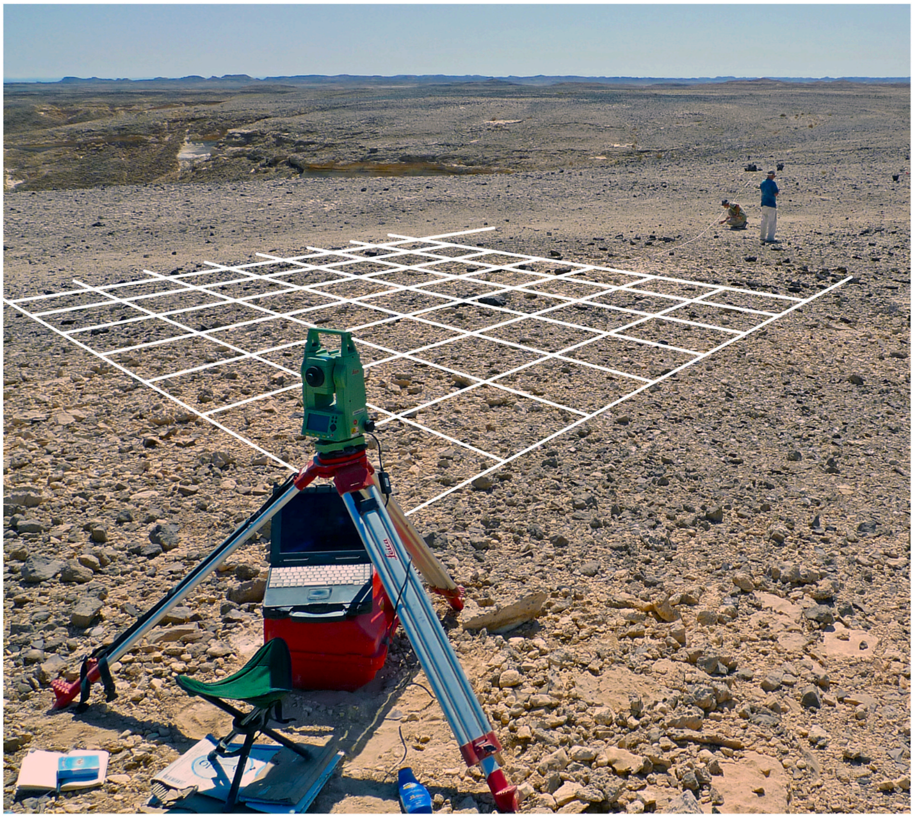

Fig. 5. Mapping grid at findspot TH.76 (Photo Y. Hilbert).

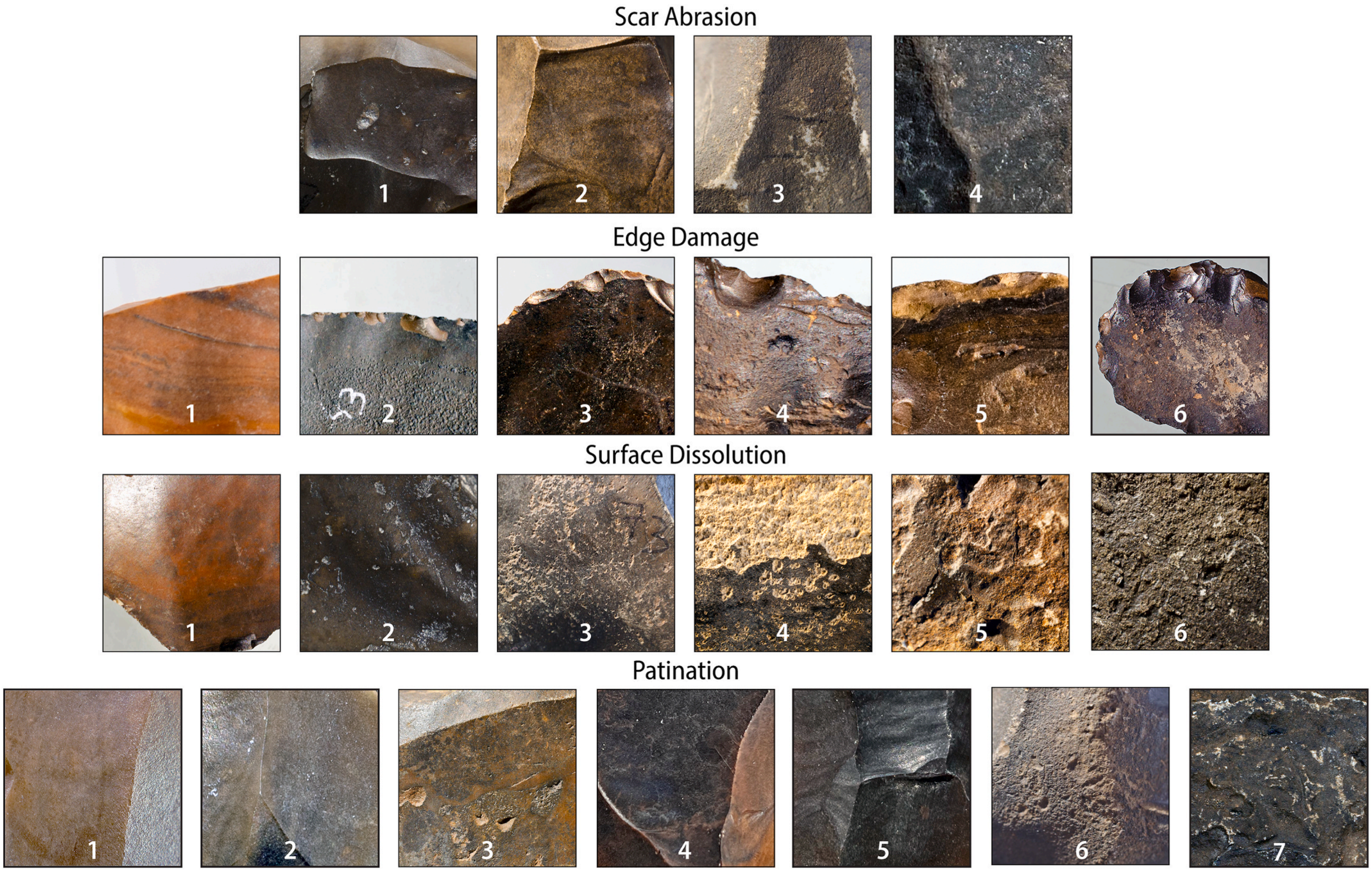

Fig. 6. Images of post-depositional surface modification variables (Photos J. Rose and A. Beshkani).

natural debris were present at all sites but not mapped, as these did not have an anthropogenically sheared surface 'zeroing' the taphonomic clock. After the lithics were mapped and collected, technological, metric, and taphonomic attributes were recorded. These included basic linear measurements – length, width, thickness, and platform dimensions – to explore correlations between reduction strategies, artifact proportions, and the amount of time exposed on the surface. The rubric for recording lithic weathering stages is described below.

2.2. *Lithic taphonomy*

In recording lithic taphonomy, we distinguished various mechanisms to test the utility of different types of weathering as relative markers. Surface modification of flaked chert objects proceeds by the interaction of (a minimum of) five separate processes: 1) mechanical damage of the edges from lateral transport, trampling, and vertical displacement, 2) aeolian and fluvial abrasion of the aretes, 3) chemical dissolution and leaching that leads to desilicification and pitting, 4) oxidation, hydration, microbial activity, and mineral accumulation that causes the development of a patina, and 5) mechanical weathering of individual crystals, creating a rough surface that diffusely reflects light and alters the color of the artifact (see Hurst and Kelly, 1961; Rottländer, 1975; Burroni et al., 2002; Howard, 2002; Fernandes et al., 2007; Thiry et al., 2014).

While we are uncertain regarding the specific properties of patina formation within the Umm er Radhuma chert outcrops of Dhofar, elemental analysis of chert nodules from various exposures in Dhofar indicate they are geochemically homogenous, forming a statistically distinct group when compared to cherts from the neighboring region (Eren et al., 2024). Given the similar geomorphic and climatic conditions affecting each workshop site in this study, all of which employ the same raw material—forming a unified taphonomic zone—it is

Table 2
Description of post-depositional surface modification variables.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
Scar Abrasion	none	mild	moderate	advanced			
Edge Damage	none	slight nibbling on one edge	continuous nibbling damage on one or more edges	discontinuous invasive damage on one edge	continuous nibbling/invasive damage on one or more edges	continuous invasive damage on two or more edges	
Surface Dissolution	0–10%	11–25%	26–50%	51–75%	76–90%	91–100%	
Patination	light tan/ whitish-gray; banding visible	tan/whitish-gray; banding faintly visible	darker tan/ orangish-yellow; banding no longer visible	brown/orangish-brown; surface often exhibits mixed colors	dark brown/black; orangish tint no longer visible	blackish-orange/ blackish-tan; surface color lightens as texture becomes coarser	brownish-orange/ brownish tan; desilicified surface now resembles cortex

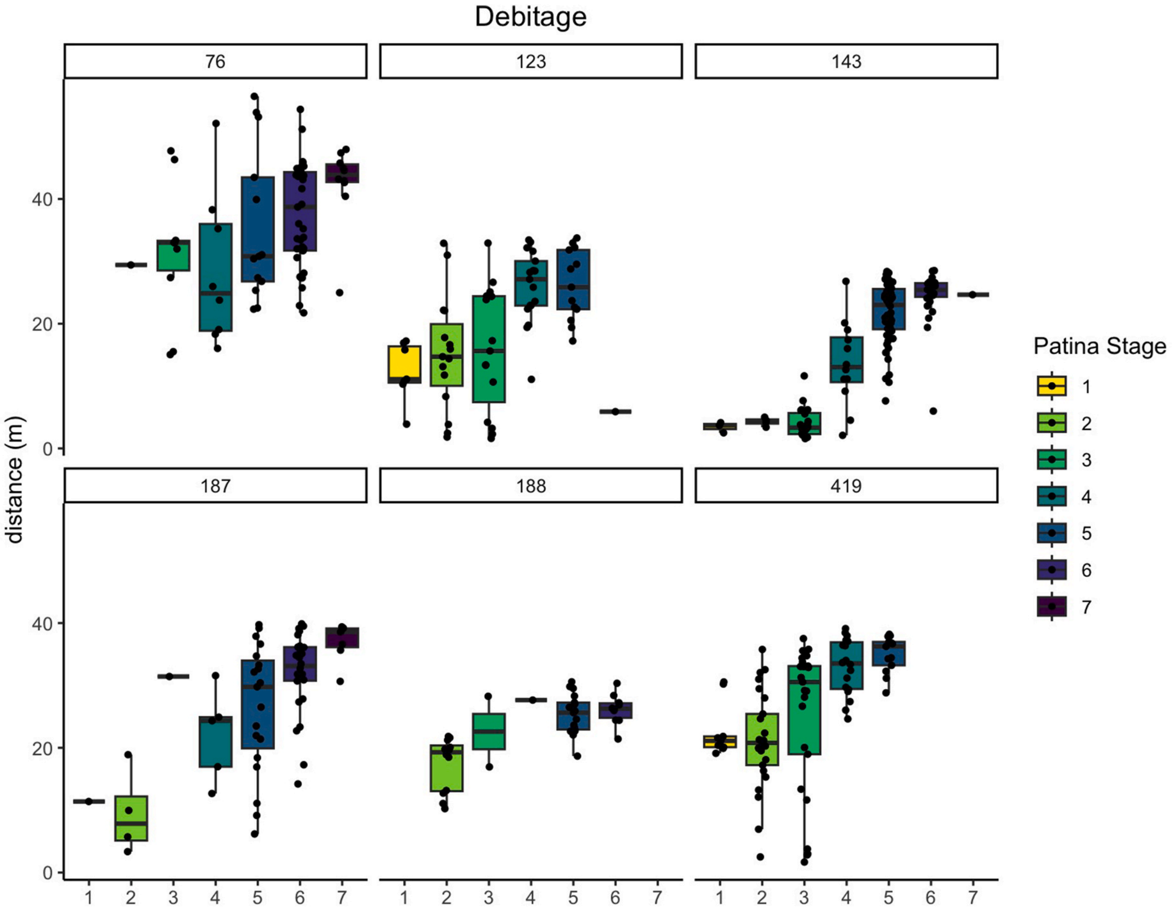

Fig. 7. Boxplots showing Euclidean distances between debitage and present chert exposure, sorted by patina stage.

warranted to evaluate lithic taphonomy as a relative chronological marker across all sites.

In order to quantify surface weathering, we employed a scoring rubric for each taphonomic category; the more heavily weathered the artifact, the higher the score (Fig. 6; Table 2). The scales are not uniform, as there are more clearly discernible stages of weathering in patination, edge damage, and dissolution versus abrasion. Some specimens exhibited different weathering patterns depending upon which side was facing down; to maintain consistency we recorded the more heavily weathered face. In cases of recycled artifacts, we considered the final stage of production (e.g., a MP prepared core recycled into a UP blade core was classified as the latter).

2.3. Statistical analysis

Spatial distribution analyses examined the distance between artifacts and the present chert exposure to test whether more distant artifacts have been lying on the surface for a longer amount of time.[1] Artifacts were separated into debitage, cores, and tools to account for different discard behaviors. We presume that debitage was left in situ after knapping, cores and pre-forms were carried across the landscape proportionate to their degree of exploitation, while completed tools remained in active usage across the site. Hence, this study predicts that the taphonomic states of debitage will exhibit a strong pattern of increasing patination stages with increasing distance to the outcrop.

We used non-parametric Kruskal-Wallis tests, which do not assume a normal distribution of data, to examine differences in the distance from artifacts to the present chert exposure across various groups based on individual taphonomic variables (scar abrasion, edge damage, dissolution, and patination). When a significant difference was detected, we performed post-hoc analysis using the Wilcoxon rank-sum test to determine which specific groups differed from one another. To control for false positives (Type I errors), we applied the Benjamini-Hochberg procedure to adjust *p*-values. Kernel density estimation heatmaps of the transect vertical profiles were produced to assess spatial distribution of artifacts along the slopes and to explore the role of topography in artifact accumulation. All statistical tests and plots were generated in R.

3. Results

The workshop sites included in this study cover a range of archaeological periods, indicated by the breadth of techno-typological variability (Table S1). TH.76, TH.143, and TH.187 are the oldest time-averaged landscape surfaces, with heavily weathered handaxes, large blade and flake cores, followed by somewhat less weathered Nubian Levallois cores and products. The array of patination stages at TH.123 and TH.188 is varied, with largely mixed assemblages composed of Nubian Levallois and more recent blade core reduction strategies. TH.419 is unique among the workshop sites, in that the overall assemblage lacks examples of heavy weathering and skews toward more lightly modified material.

Examining the spatial distribution of artifacts relative to the present chert exposure, debitage demonstrates the clearest signal of increasing patination with distance; the more heavily weathered the debitage, the more likely it was to be located further from the outcrop (Fig. 7;

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[1] Rose, J.I., Li, L., & Cascalheira, J., 2024. Research compendium for the paper “Mapping lateral stratigraphy at Palaeolithic surface sites: a case study from Dhofar, Oman.” Retrieved from osf.io/rnyfb

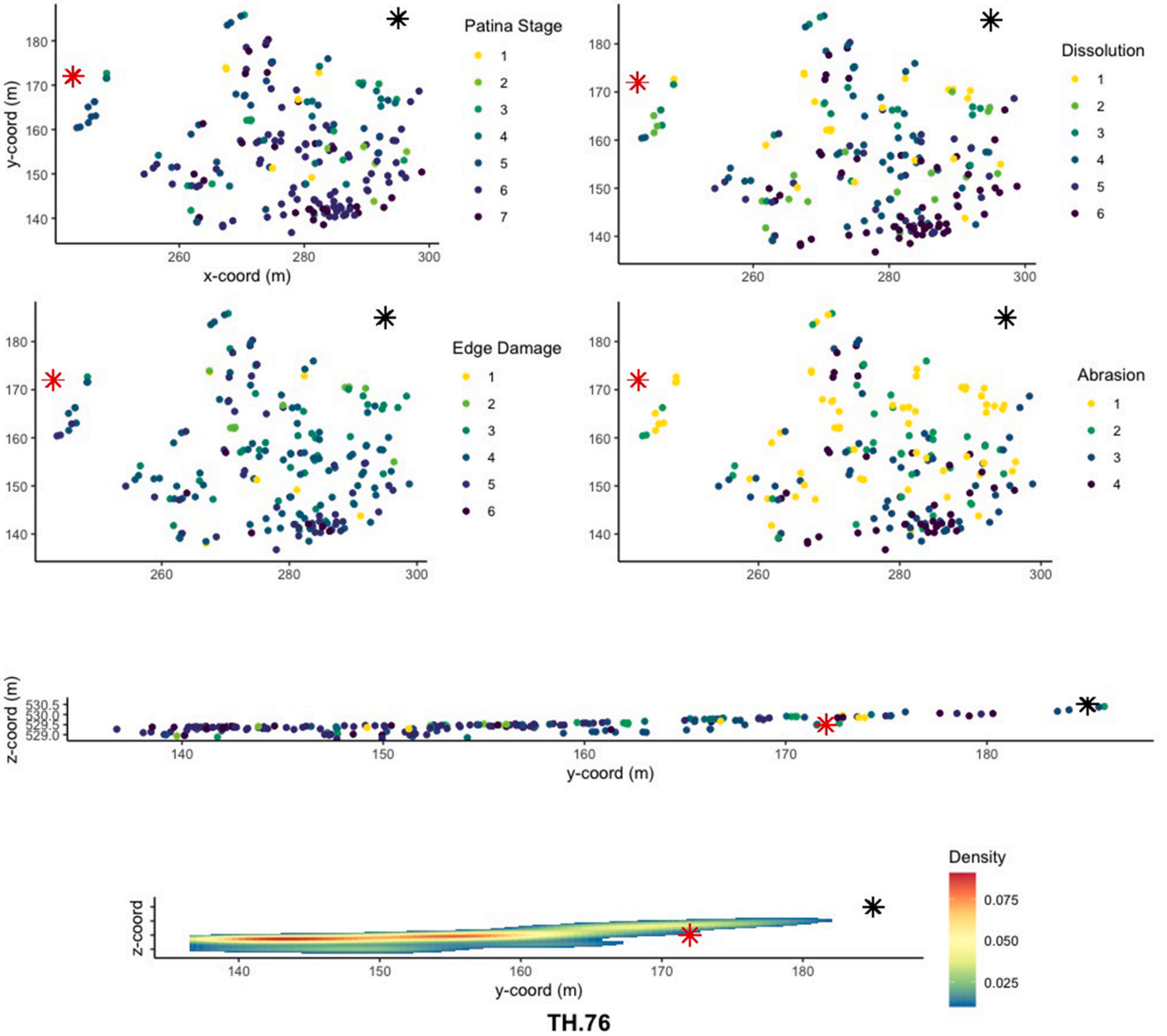

Fig. 8. (top) XY scatterplots of mapped artifacts at TH.76 by lithic taphonomy scores; (middle) YZ scatterplot by patina stage; (bottom) kernel density estimation of transect profile with 2x vertical exaggeration. Black star indicates position of TotalStation and primary outcrop, red star indicates position of secondary outcrop. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table S2). Tools and cores exhibit a more complicated relationship between patination and distance (Figs. S1–S11; Table S2). Results and spatial analyses from each study site are summarized below.

3.1. TH.76 (Aybut Hills 3)

TH.76 is located on a high plateau characterized by gently undulating hills overlooking Wadi Aybut. It is roughly 1 km from the dated Dhofar Nubian site of Aybut Auwal (Rose et al., 2011) and 3 km from the Dhofar Nubian site of TH.69, Aybut Hills 2 (Usik et al., 2013; Groucutt and Rose, 2023). Unlike the other workshop sites presented here that have a single constrained source of raw material, at least two patches of chert were outcropping within the 51 × 55 m study area (Fig. 8). A total of 197 artifacts belonging primarily to the LP and MP were mapped, including Acheulean handaxes, a radial core, and Nubian Levallois cores (Fig. 9; Table S1).

Spatial analysis shows significance in the distance between debitage and the outcrop for abrasion, dissolution, and edge damage (Table S2). Neither cores nor tools, however, demonstrate any spatial patterning. Pairwise tests reveal that most significant taphonomic differences are at the heavily weathered end of the spectrum (Table S3). Compared to less weathered specimens, these have an overall smaller range of variation in their distance to the outcrop, showing that more heavily weathered artifacts are less dispersed at the distal portion of the transect (Fig. 7, S3). The kernel density estimation heat map shows an accumulation of artifacts downslope, indicating some degree of lateral transport.

3.2. TH.123 (Aybut Hills 4)

TH.123 is located just under a kilometer from TH.76, on the same high terrace above Wadi Aybut. There are MP artifacts closer to the edge of the terrace and less weathered UP concentrations observed at the base of a low rise, associated with presently outcropping chert slabs. The terrain is relatively flat; it has a continuous slope angling about 2°

Fig. 9. Sample of artifacts from TH.76: (a–c) handaxes; (d) radial core, (e–f) bifacial tools; (g-i, p-r) Nubian Levallois cores; (j–k) bidirectional cores; (l–o) Levallois products (Photos A. Beshkani & Y. Hilbert).

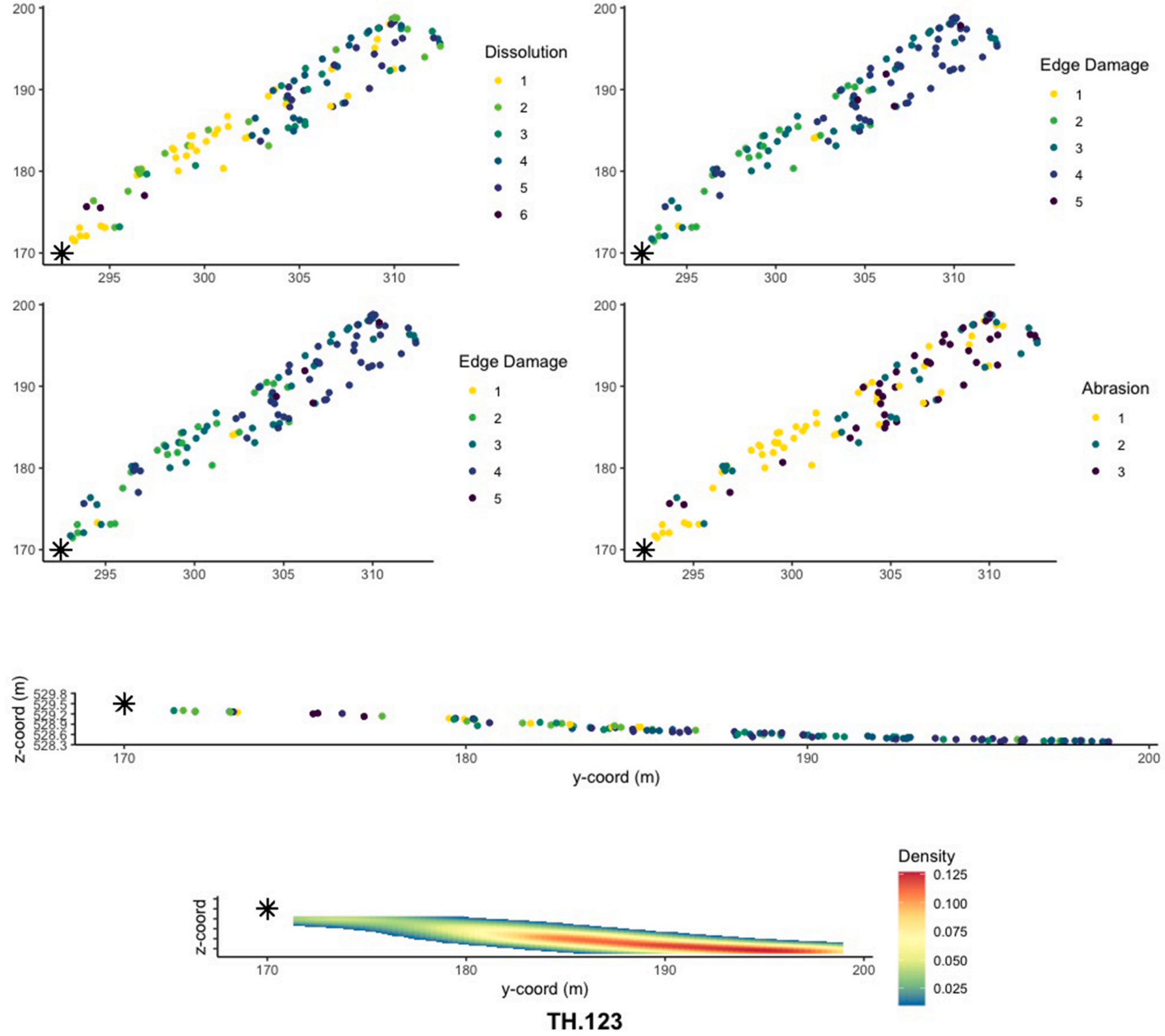

Fig. 10. (top) XY scatterplots of mapped artifacts at TH.123 by lithic taphonomy scores; (middle) YZ scatterplot by patina stage; (bottom) kernel density estimation of transect profile with 2x vertical exaggeration. Black star indicates position of TotalStation and outcrop.

downward from the modern outcrop. The site was initially discovered during the 2011 field season, at which time we collected a Dhofar Nubian assemblage from an 8 × 8 m grid (Rose et al., 2011). For this study, we set a transect measuring 32 × 5 m to include different assemblage types (Fig. 10). A total of 118 artifacts were plotted, consisting of heavily weathered bifaces, moderately weathered Nubian Levallois cores, and lightly weathered blades and foliates (Fig. 11; Table S1).

Examination of the distance between debitage and the outcrop demonstrates statistical significance in every taphonomic category, while cores and tools show few significant distribution clusters (Table S2). As was the case at TH.76, artifacts appear to have accumulated downslope and weathered specimens were more consistently distributed farther from the outcrop compared to less weathered artifacts (Figs. 7 and 11, S3). Pairwise tests of patination and dissolution distinguish moderately weathered artifacts in the 4–5 range from less weathe red material, but do not detect significant variations between less weathered artifacts (Table S4).

3.3. *TH.143 (Jebel Sanoora 1)*

The Jebel Sanoora area is located about 6 km south of the Aybut plateau, 2 km from an extant artesian spring. In contrast to the gently undulating hills above Wadi Aybut, Jebel Sanoora is a rugged landscape characterized by high inselbergs that are deeply cut by a network of steep channels. Workshop site TH.143 was found on the first terrace about 15 m above a wadi bed. Artifacts were manufactured on tabular chert slabs eroding from the scarp at the back of the terrace. The site was initially discovered during the 2011 field season, at which time an assemblage of Nubian Levallois material was systematically collected from an area of 20 m^2 (Rose et al., 2011). For the present study, we set a transect measuring 28 × 4 m across the terrace (Fig. 12). Near the terrace edge, the transect slopes downward at a relatively steep inclination of 8.5°, while the area closer to the outcrop has a moderate inclination of 3.5°. The kernel density estimation heat map again shows lithics accumulating downslope. A total of 218 artifacts were mapped, including both large and small blades and blade cores, bifacial foliates,

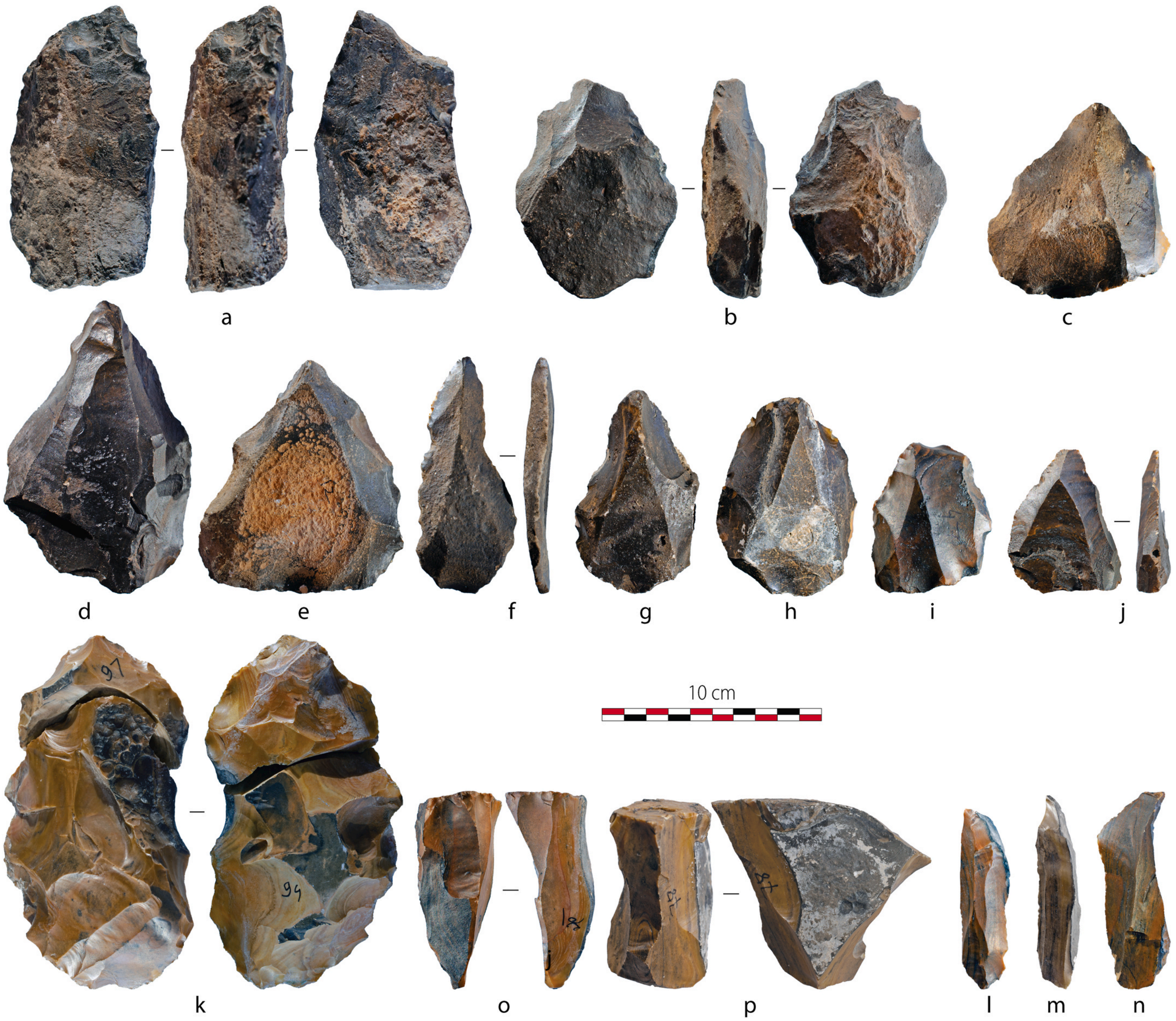

Fig. 11. Sample of artifacts from TH.123: (a, k) bifacial pre-forms; (b) handaxe; (c-e, g-i) Nubian Levallois cores; (f, j) Levallois products, (o–p) unidirectional blade cores, (l–n) blades (Photos A. Beshkani & Y. Hilbert).

and Nubian Levallois cores (Fig. 13; Table S1).

The spatial patterns observed at TH.143 were the clearest and most pronounced of all sites included in this study, with at least three distinct debitage weathering groups located at different distances from the outcrop (Fig. 7). This is confirmed by pairwise tests, showing significant differences in the distribution of each patination stage from 3 to 6 (Table S5). Closer examination of the patination and surface dissolution scores of debitage shows more heavily weathered artifacts located further away from the outcrop, and in a smaller range of variation compared to the less weathered artifacts (Fig. 7, S3). The distribution of cores and tools based on taphonomy, conversely, performed poorly and did not adhere to any spatial patterns (Table S2).

3.4. TH.187 (Jebel Sanoora 2)

Workshop site TH.187 is located roughly 1 km southwest of TH.143 in the area of Jebel Sanoora. Similar to TH.143, the scatter is situated on an erosional terrace and associated with a chert seam outcropping at the back of the terrace. We plotted 134 artifacts within a 31 × 7 m transect, extending from the upper ridge to the lower edge of the terrace. The transect drops 2 m and levels out on a virtually flat surface, with the highest density of artifacts mapped downslope (Fig. 14). The assemblage includes heavily weathered handaxes and large blades, Nubian Levallois cores, and lightly weathered small blades (Fig. 15; Table S1).

Within all taphonomic categories, there are significant differences in the distance between debitage and the modern outcrop, while tools and cores did not adhere to any spatial pattern (Table S2). Artifacts that were more heavily weathered were concentrated at the farther end of the transect (Figs. 7 and 14, S3). Inspecting individual categories with pairwise tests (Table S6), most of the significant spatial differences in weathering groups are seen at the heavier end of the spectrum. Three distinct patination groups are recognized, associated with different technologies: 6–7 (handaxe and large blades), 4–5 (Nubian Levallois), and 1–2 (small blades).

3.4. TH.188 (Jebel Sanoora 3)

Site TH.188 is located about 250 m west of TH.187 on the opposite

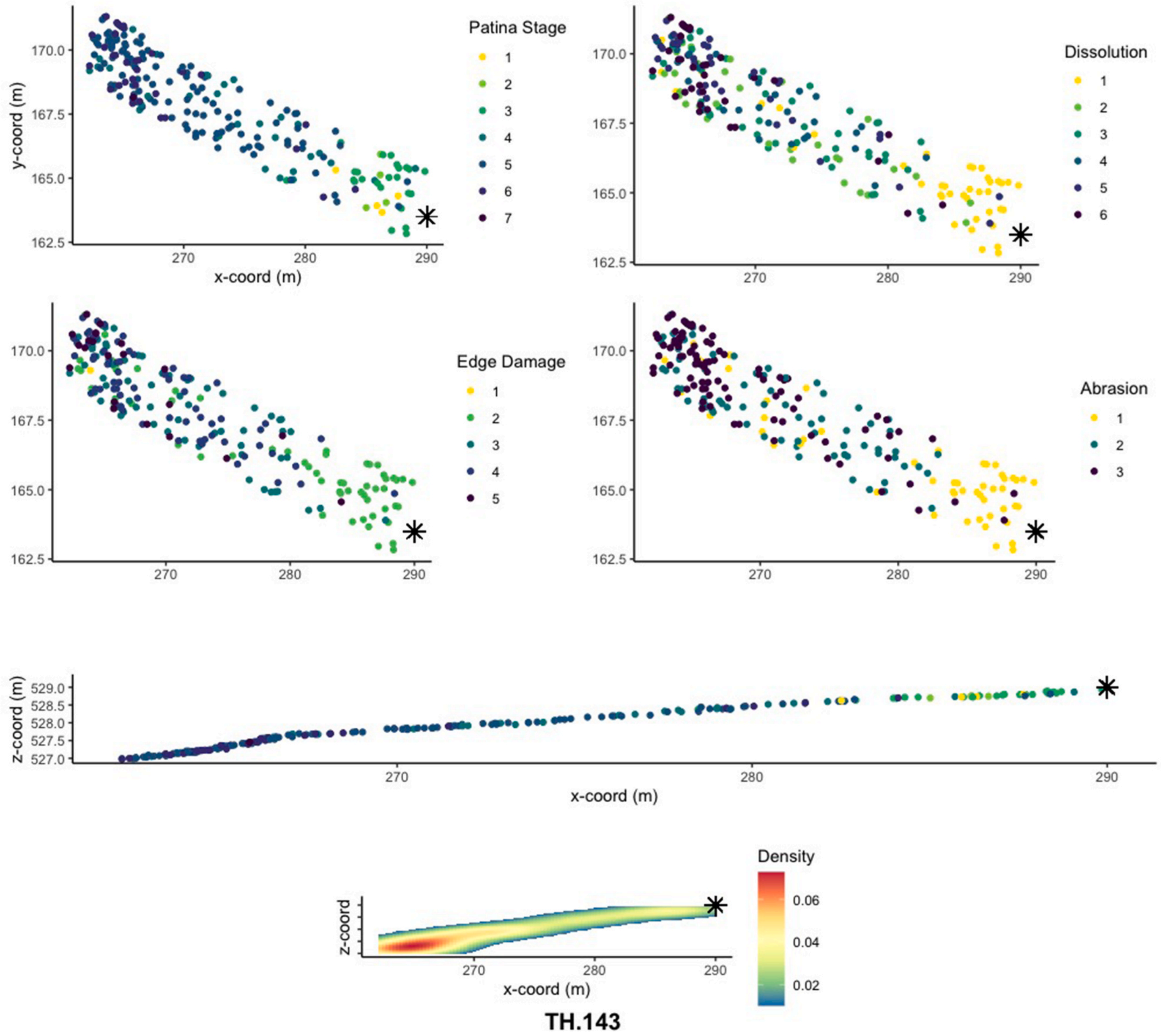

Fig. 12. (top) XY scatterplots of mapped artifacts at TH.143 by lithic taphonomy scores; (middle) XZ scatterplot by patina stage; (bottom) kernel density estimation of transect profile with 2x vertical exaggeration. Black star indicates position of TotalStation and outcrop.

side of the drainage channel. The scatter is situated on a high plateau away from the edge of the wadi, near a low hill with chert nodules outcropping from its base. The transect measures 37 × 5 m, encompassing a sloping surface that drops abruptly 2 m from the base of the hill, then dips gently downward at an angle of 1.7° degrees, where the highest density of artifacts has accumulated (Fig. 16). A total of 93 artifacts were mapped, including large heavily weathered blades, a radial core, Nubian Levallois cores and products, lightly weathered blade cores, and foliates (Fig. 17; Table S1).

Spatial analysis shows statistical significance in the distribution of debitage based on all taphonomic weathering categories except abrasion, while cores and tools, again, are not distributed in any significant patterns (Table S2). Pairwise tests reveal two different patination groups: 5–6 (old blades, radial core, and Nubian Levallois cores) and 2–4 (Nubian Levallois cores, blades, and foliates). While it is clear from a technological perspective that the lightly weathered Nubian Levallois cores and blade cores belong to markedly different reduction systems,[2] spatial distribution and lithic taphonomy suggest that not much time had elapsed between the two components.

3.5. TH.419 (Umm Mudayy 2)

The site of TH.419 is located between Aybut Hills and Jebel Sanoora, on a plateau overlooking the main channel of Wadi Aybut. The site consists of a widespread scatter radiating outward from a low scarp. The upper stratum of the scarp consists of hard bioclastic limestone, overlying soft dolomitic chalk with chert inclusions. A total of 282 artifacts were mapped within a transect measuring 30 m long and fanning out to

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[2] The former are flat, preferential, and prepared versus the latter that are volumetric, recurrent, and unidirectional.

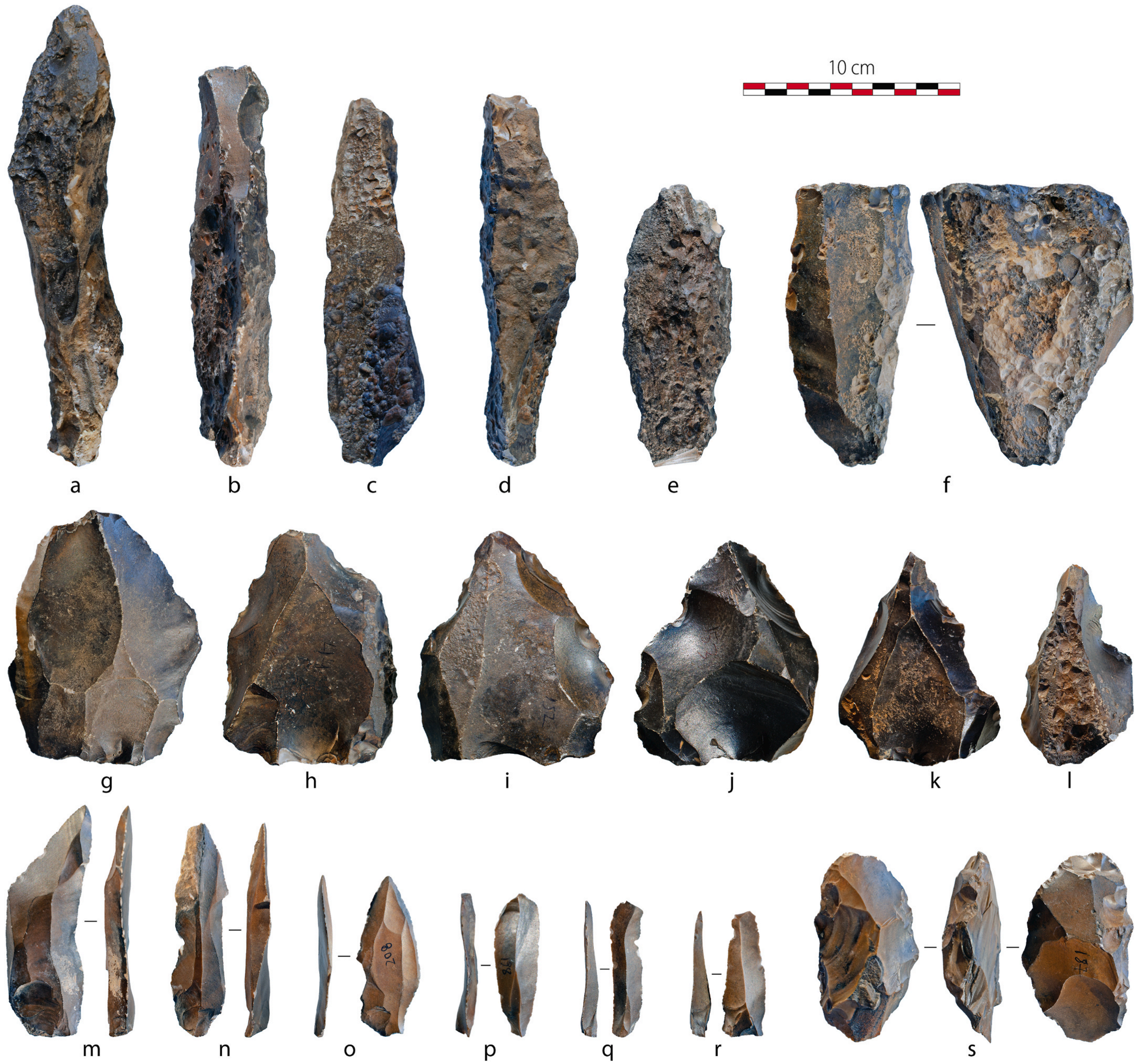

Fig. 13. Sample of artifacts from TH.143: (a-e, m-r) blades; (f) blade core; (g–l) Nubian Levallois cores; (s) bifacial preform (Photos A. Beshkani & Y. Hilbert).

a width of 15 m. The artifacts were found scattered on a nearly horizontal surface that rises slightly toward the low scarp, forming a shallow depression. The density heatmap shows the highest concentration of artifacts distributed at the lowest elevations in the transect (Fig. 18). There is a combination of MP and UP reduction systems present, including Nubian Levallois cores and products, small blades cores, and foliates (Fig. 19; Table S1). Nubian Levallois cores are substantially smaller than at sites with more heavily weathered variants. Also prevalent are rectangular bidirectional cores with opposed faceted platforms (Table S1; Fig. S6: s-aa), a specific core type that is absent at the other sites considered in this study. The co-occurrence of small Nubian Levallois and rectangular bidirectional cores is a local phenomenon of the western Nejd plateau, designated the Mudayyan industry (Usik et al., 2013; Rose and Marks, 2014; Rose et al., 2023).

Among all taphonomic categories, there are statistically significant differences in the distribution of both debitage and cores (Table S2). Tool samples, however, were insufficient to examine spatial patterns. In pairwise tests of debitage patina stages (Table S8), two groups are apparent: 1–3 (blades, foliates, bidirectional cores, smaller Nubian Levallois cores), and 4–5 (larger Nubian cores). Debitage with patination scores of 4–5 also had a smaller range of variation compared to those with scores of 1–3 (Figs. 7 and 18, S3). C omparison in the lengths of Nubian Levallois cores between these two groups demonstrates a trend for more heavily weathered cores to be larger than more lightly weathered specimens (Fig. S12).

4. Discussion

Our results are broadly consistent with the posited model of site formation: debitage shows post-depositional surface modifications increasing with distance from the outcrop. At every site, density heatmaps demonstrate artifacts accumulating at lower elevations, likely

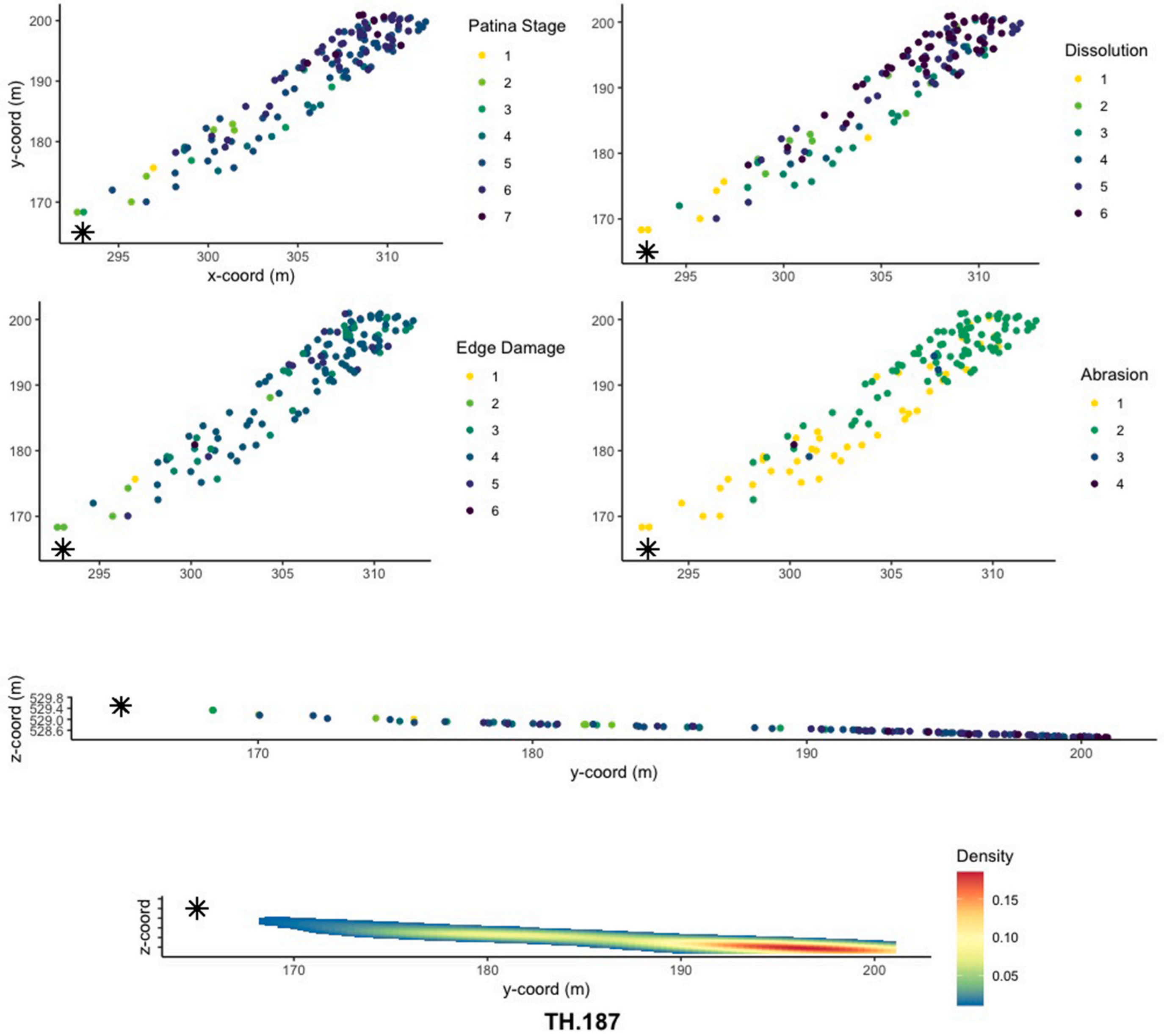

Fig. 14. (top) XY scatterplots of mapped artifacts at TH.187 by lithic taphonomy scores; (middle) YZ scatterplot by patina stage; (bottom) kernel density estimation of transect profile with 2x vertical exaggeration. Black star indicates position of TotalStation and outcrop.

resulting from lateral transport downslope. Of the four taphonomic variables considered in this analysis, patination was found to be the most robust predictor of spatial distribution; hence, provides the most effective signal of time elapsed that an artifact has been lying on the surface. Given these results, we currently reject the null hypothesis that the overall distribution of artifacts in relation to their taphonomic state is arbitrary. We discount the possibility that variable soil humidity has had a significant impact on patination rates, as the distance patterns we observe only apply to debitage, which were discarded and plausibly left where they fell. The taphonomy of cores and tools, for the most part, did not adhere to any discernible spatial patterns along the slope.[3]

4.1. *Techno-chronology*

We have shown that patination stages, in particular, are potentially effective spatial markers of site formation and time elapsed on the surface. This is corroborated by techno-typological variability across different weathering states. A histogram of patination stages on all bifacial tools, for example, demonstrates a bimodal distribution dividing heavily weathered tools (Lower Palaeolithic handaxes) and lightly

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[3] Cores and tools may be more relatively ‘mobile’ on a site compared to debitage, depending on the location of specific activities. Alternately, it is possible that temporally later people reused cores and tools produced by earlier peoples (Boulanger et al., 2022), moving them across a site from their original discard location. A number of cores at TH.419 exhibited older sheared surfaces indicative of recycling.

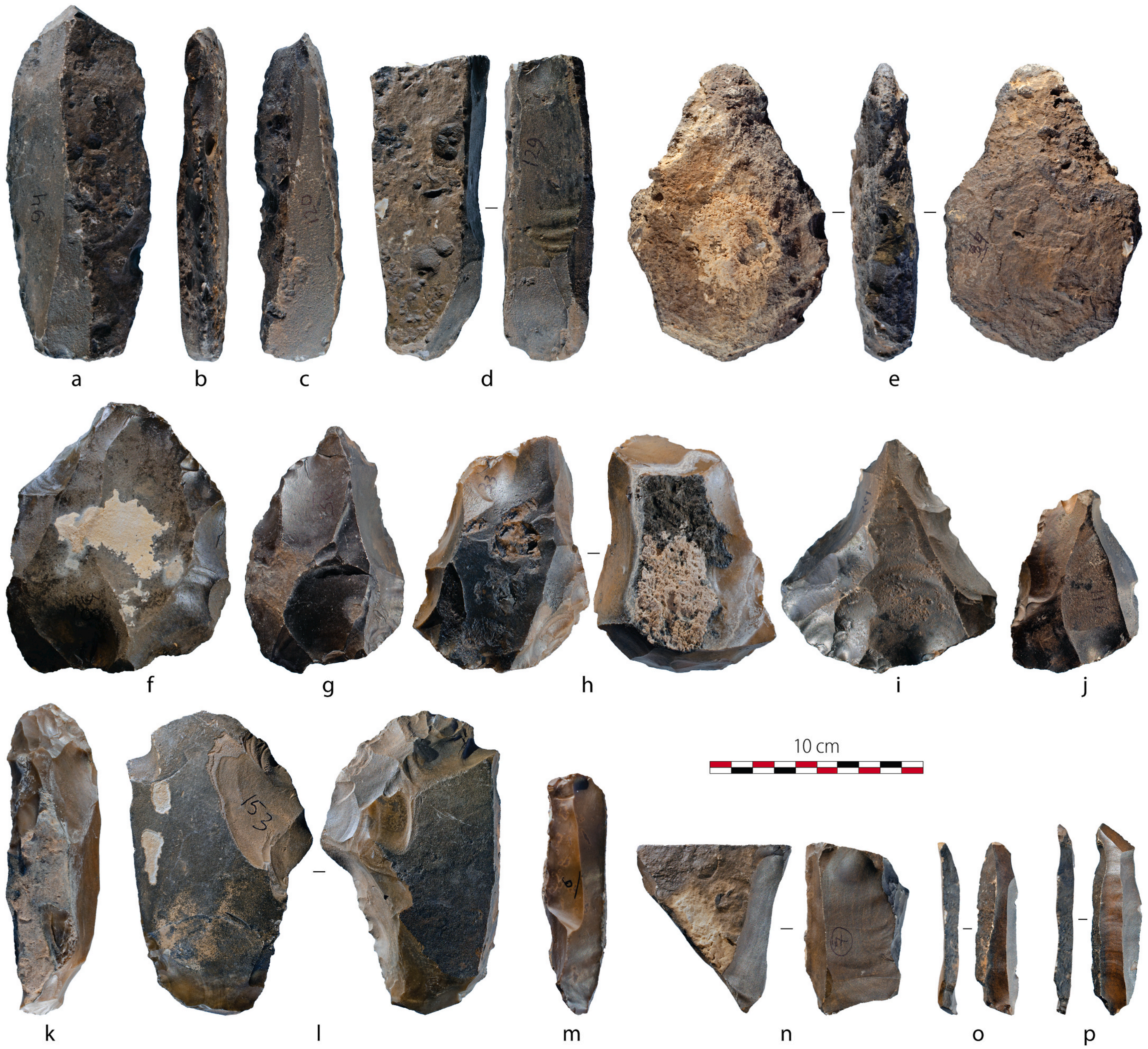

Fig. 15. Sample of artifacts from TH.187: (a-c, o-p) blades; (d) blade core; (e) handaxe; (f-g, i-j) Nubian Levallois cores; (h) bidirectional core; (k) end scraper; (l) bifacial tool; (m–n) blade cores (Photos A. Beshkani & Y. Hilbert).

weathered variants (Upper/Late Palaeolithic foliates). There are radical differences in patination between these technologically comparable groups, with no overlap (Fig. 20). So, in this obvious instance of bifacial tools at opposite ends of the Palaeolithic timeline, the degree of patina likely serves as an effective relative chronological indicator.

Blade technologies, as well, have a bimodal distribution suggesting chronologically distinct components. A metric comparison of blade and blade core lengths between different patination groups exhibits a consistent trend toward the manufacture of smaller products (Fig. 21) and pairwise tests identify four distinct metric groups (Table S11). Here, the application of lithic taphonomy permits us to evaluate technological trends and to record diachronic changes in technology.

While these observations support our hypothesis that there is a direct relationship between patination and the time elapsed that artifacts have been lying on the surface, the use of lithic taphonomy becomes more complex when dealing with artifact classes that occur closer together in time, or when an artifact class is time-transgressive. Simple flake cores and products demonstrate this latter issue, where the category itself is so broad that it shows a normal distribution across all weathering states (Fig. 20). In contrast to the other reduction strategies in this analysis, Nubian Levallois technology has the narrowest taphonomic range, occurring predominantly after the production of handaxes and large blades (patina = 7) and before the manufacture of small blades and foliates (patina = 1–2).[4]

As was the case with blade production, we can recognize changes in Nubian Levallois technology across different patination stages. Diminutive Nubian Levallois cores and products have already been recorded at

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[4] The inverse correlation between Levallois technology and bifacial tools calls into question whether there was functional overlap between the products of these radically different reduction systems.

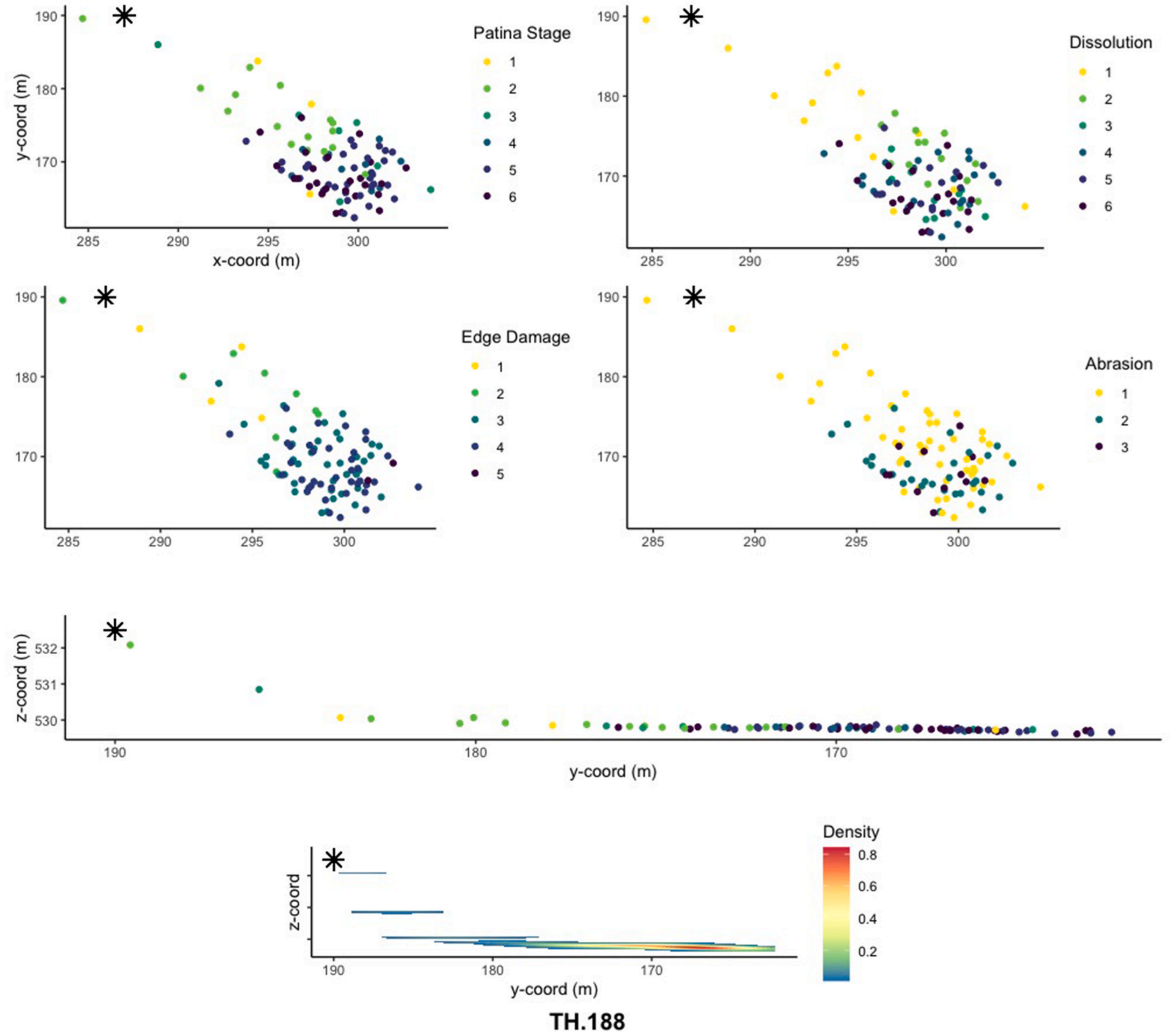

Fig. 16. (top) XY scatterplots of mapped artifacts at TH.188 by lithic taphonomy scores; (middle) YZ scatterplot by patina stage; (bottom) kernel density estimation of transect profile with 2x vertical exaggeration. Black star indicates position of TotalStation and outcrop.

workshop site TH.268, where they were found to occur in a significantly smaller metric range than “Classic Dhofar Nubian” assemblages found elsewhere on the Nejd plateau (Usik et al., 2013). The chronological relationship between large and small Nubian assemblages, however, could not be evaluated at the time. Comparing the length of all Nubian Levallois cores in this study by their patination stages, this phenomenon is now quantified (Fig. 22; Tables S9–S10). Rather than a simple bimodal distribution of large and small cores, there appears to have been a gradual process of miniaturization throughout the duration of their manufacture in Dhofar.

4.2. *Timescales & assessment*

This study has demonstrated a correlation between the length of time artifacts have been exposed on the surface and their degrees of weathering. The relationship between time and taphonomy, however, is not linear and is most effective within a limited range (Fig. 23). As we saw at TH.188 and TH.419, blades and foliates diagnostic of the Upper/Late Palaeolithic were conflated with bidirectional and small Nubian cores in the 1–3 patination range. In addition to the two reduction strategies being close in time, it seems that the rate of patination was too slow to record observable changes within this timeframe. Thus, artifacts younger than the Middle Palaeolithic may be conflated, both taphonomically and spatially. At the other end of the spectrum, patination reaches its maximum with Lower Palaeolithic handaxes, radial cores, and large blades, regardless of how long artifacts have been lying on the surface. Hence, we conclude that the optimal window in Dhofar for assessing relative changes in patination falls roughly between the late LP and early UP. Younger objects have not had enough time to develop a patina and older objects have reached equilibrium.

Evaluating the performance of lithic taphonomy, we seek to improve our methodology for wider applicability at surface sites in different arid regions. The success of this technique in Dhofar is predicated on certain

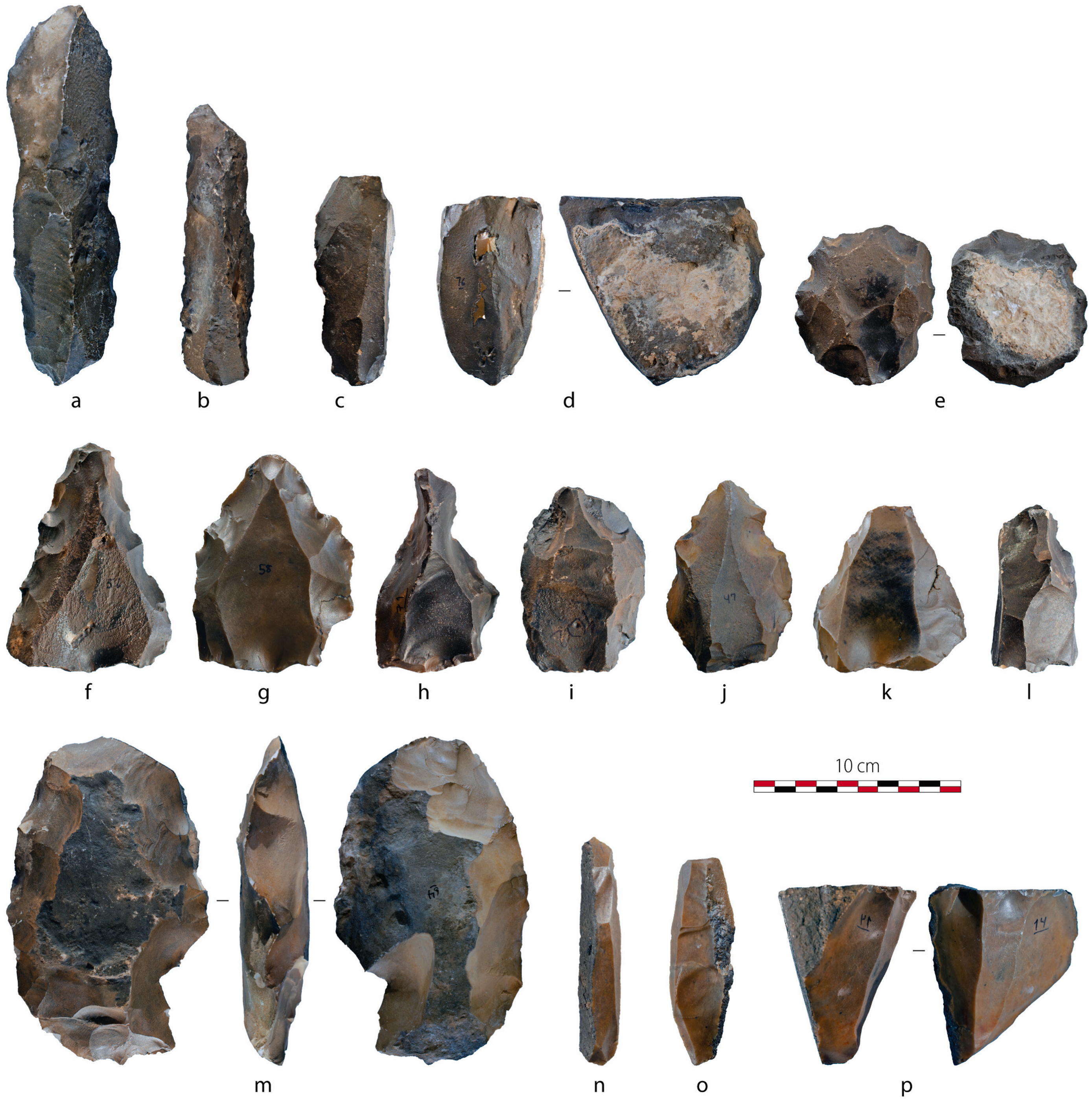

Fig. 17. Sample of artifacts from TH.188: (a-c, n-o) blades; (d, p) blade cores; (e) radial core; (f–k) Nubian Levallois cores; (l) bidirectional core; (m) bifacial pre-form (Photos A. Beshkani & Y. Hilbert).

conditions: 1) geochemically homogenous chert outcrops across a wide area, 2) analogous landscapes and climate at each site, 3) artifacts that have been consistently exposed and were not reburied,[5] 4) favorable topography with clearly defined outcrops, and 5) rapid landscape erosion of the soft bioclastic matrix, providing sufficient resolution to articulate spatial distribution. The only instance in which debitage patina score did not always correspond to distance was TH.76, where chert nodules were eroding from a crescent-shaped outcrop across at least two areas of the site. From this experience at TH.76, we determined the necessity of orienting the survey transect perpendicular to a single, linear outcrop. Our results were most effective at sites with a steeper scarp, where erosion was not as advanced and the outcrop was better defined.

The different weathering mechanism records were not consistently effective at each site and within the timeframe under consideration. Dissolution scores tended to skew low and pairwise tests did not detect as much variability within those groups. Given the observed

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[5] Where artifacts have been reburied, we observed separate surface modifications including bleaching (gypsum and other minerals replacing silica) and root-staining. None of the material included in this study exhibited such modifications, although we did note some partially bleached artifacts at TH.419 that were removed from the database.

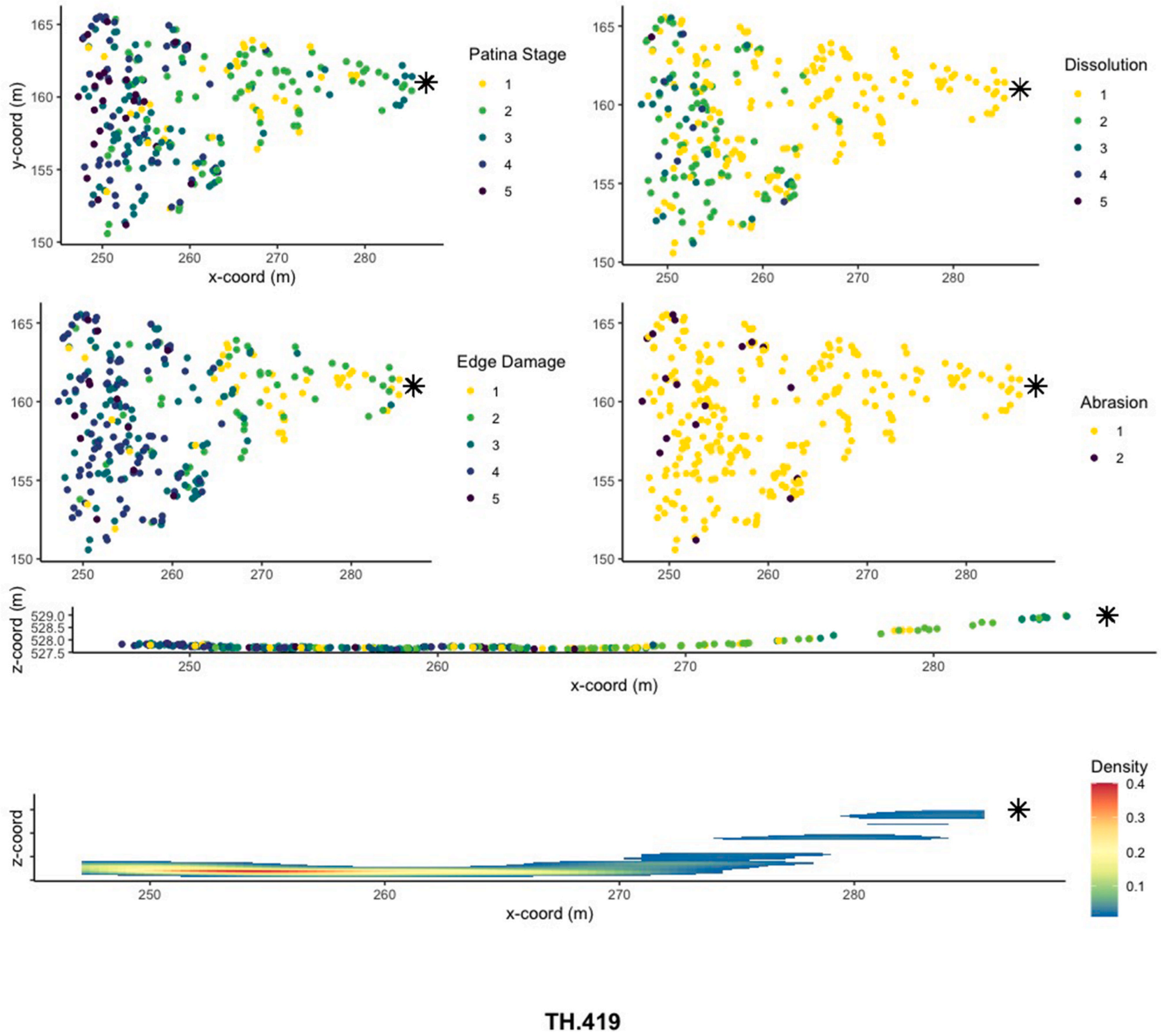

Fig. 18. (top) XY scatterplots of mapped artifacts at TH.419 by lithic taphonomy scores; (middle) YZ scatterplot by patina stage; (bottom) kernel density estimation of transect profile with 2x vertical exaggeration. Black star indicates position of TotalStation and outcrop.

accumulation of artifacts downslope, the rate of dissolution is likely to be a function of local topography, where moisture accumulates in local depressions (Thiry et al., 2014). Edge damage was not comparable across sites and is likely tied to local factors such as lateral transport, trampling, slope gradient, and artifact density. The magnitude of edge damage is also a function of edge angle (McPherron et al., 2014): thick cores with obtuse angles had less damage than thin debitage with acute angles. In terms or replicability between researchers on our team, edge damage and abrasion were found to be highly subjective, therefore, not effective taphonomic categories. While patina was most successful in our results, the rubric for classifying stages of discoloration is not necessarily replicable. Future attempts at recording lithic taphonomy should seek to quantify stages of patination for finer resolution and replicability (e.g., Gauthier and Burke, 2011; Parish, 2011, 2016; Caux et al., 2018; Parish and Werra, 2018; Lewis et al., 2022). Complete, systematically collected assemblages would allow for a more comprehensive analysis of technological trends and diachronic changes. The narrower the range of patination stages within such assemblages, the shorter the duration of human activity represented on the surface from which they were collected.

4.3. Summary

The study of lithic taphonomy in Dhofar has proven to be a potentially effective tool for mapping surface site formation and assessing long-term technological trends. Where the same reduction strategies were employed over extended periods, we can identify technological variability within those systems. While this approach shows promise, we recognize that this research represents only a first step, and much work remains to be done. Although surface sites cannot yet be reliably dated or used to define specific assemblage types or industries, under the right conditions, this method may allow us to distinguish artifacts from different time periods within palimpsest lithic scatters, document site formation processes, and track diachronic changes in lithic technology on time-averaged surfaces.

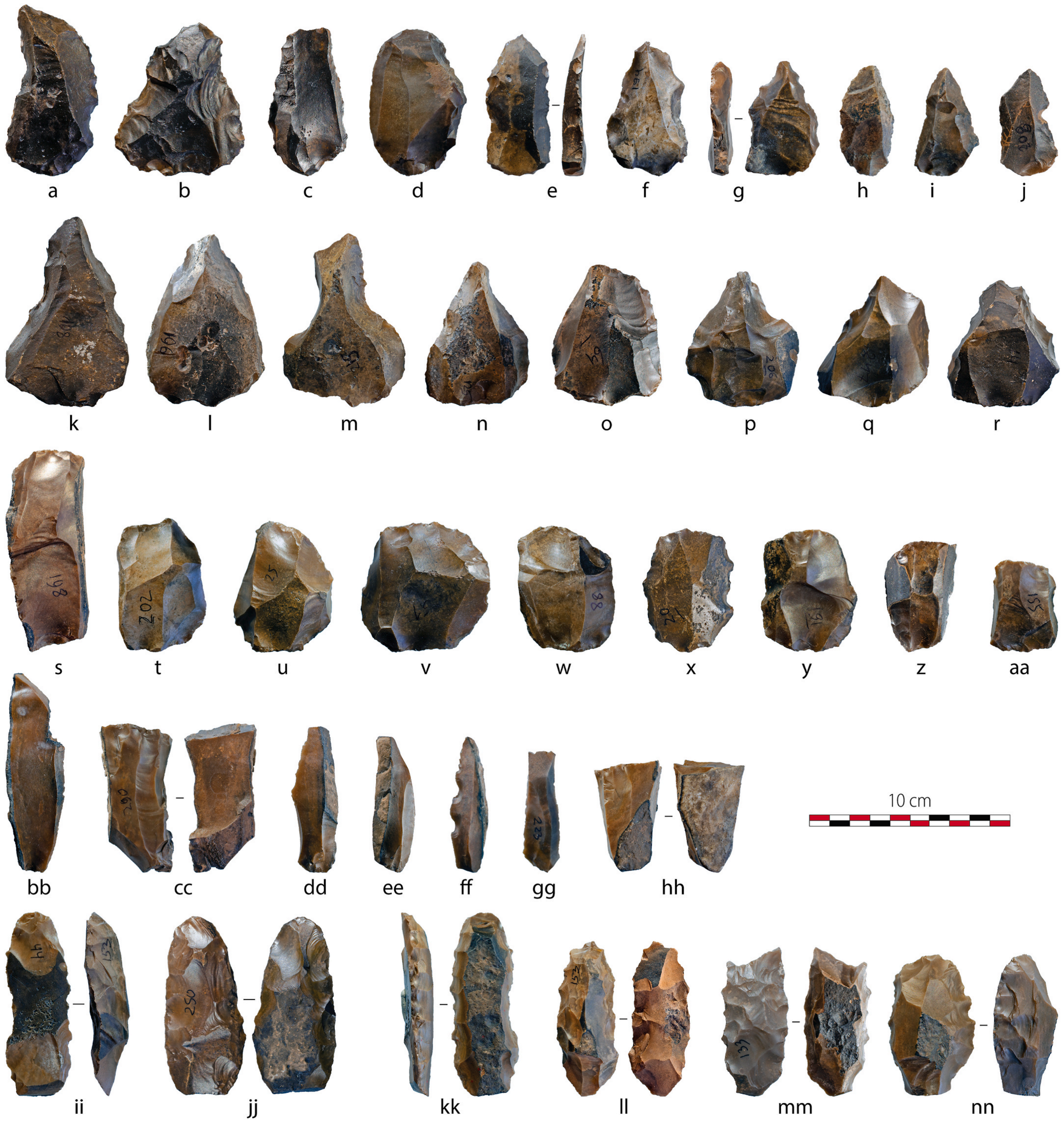

Fig. 19. Sample of artifacts from TH.419: (a–j) Levallois products; (k–r) Nubian Levallois cores; (s-aa) bidirectional cores; (bb, dd-gg) blades; (cc, hh) blade cores; (ii-nn) bifacial foliates in various stages of manufacture (Photos A. Beshkani & Y. Hilbert).

CRediT authorship contribution statement

Jeffrey I. Rose: Writing – original draft, Visualization, Software, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yamandú H. Hilbert:** Visualization, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Vitaly I. Usyk:** Methodology, Investigation. **Michelle R. Bebber:** Writing – review & editing, Conceptualization. **Amir Beshkani:** Visualization, Investigation, Data curation. **Briggs Buchanan:** Writing – review & editing, Validation, Formal analysis. **João Cascalheira:** Validation, Data curation, Conceptualization. **Dominik Chlachula:** Writing – review & editing. **Rudolf Dellmour:** Writing – review & editing, Visualization. **Metin I. Eren:** Writing – review & editing, Conceptualization. **Roman Garba:** Writing – review & editing, Visualization. **Emily Hallinan:** Writing – original draft, Formal analysis. **Li Li:** Writing – review & editing, Software, Methodology, Formal analysis. **Robert S. Walker:** Validation, Formal analysis. **Anthony E. Marks:** Writing – original draft, Methodology,

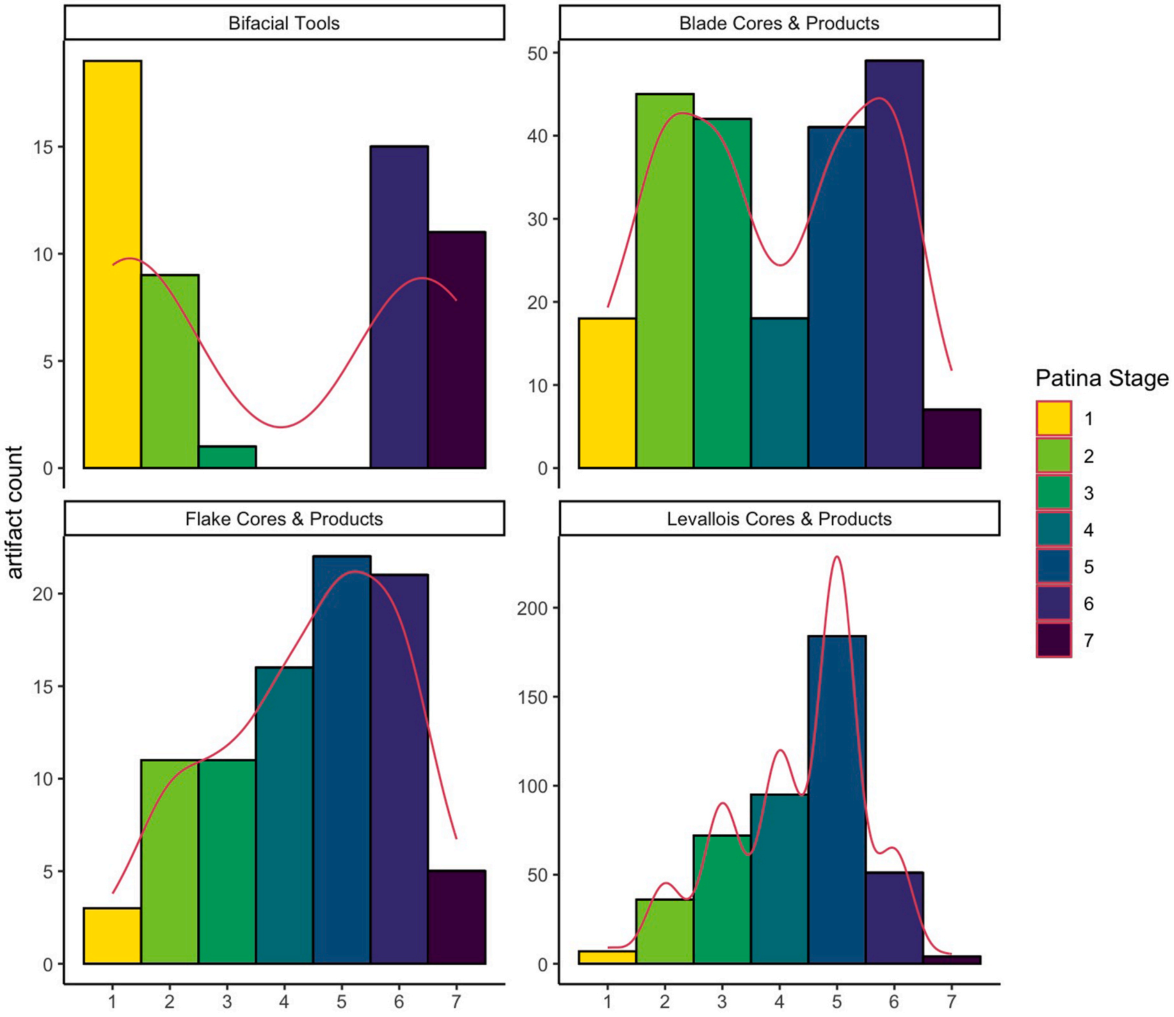

Fig. 20. Histograms showing separate reduction strategies by patina stage.

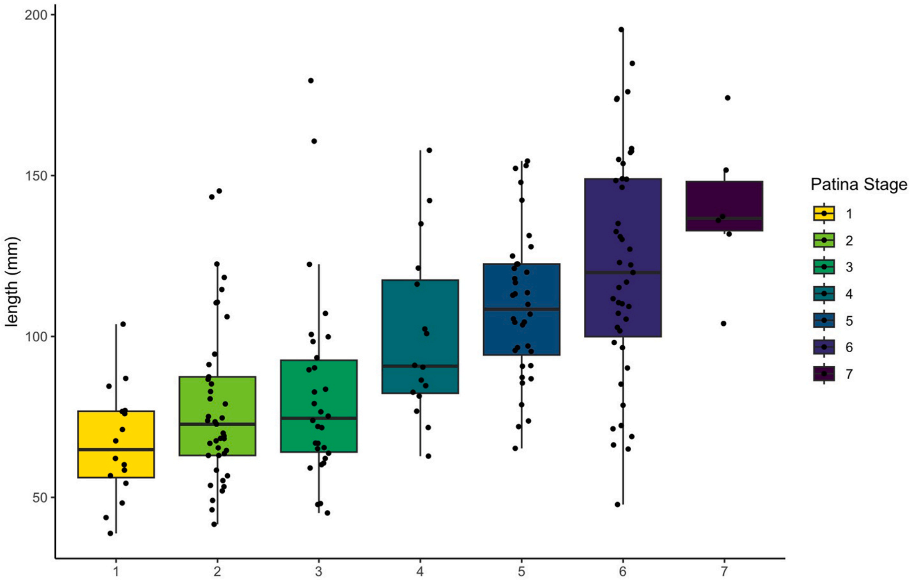

Fig. 21. Box plots of blade core and product lengths by patina stage.

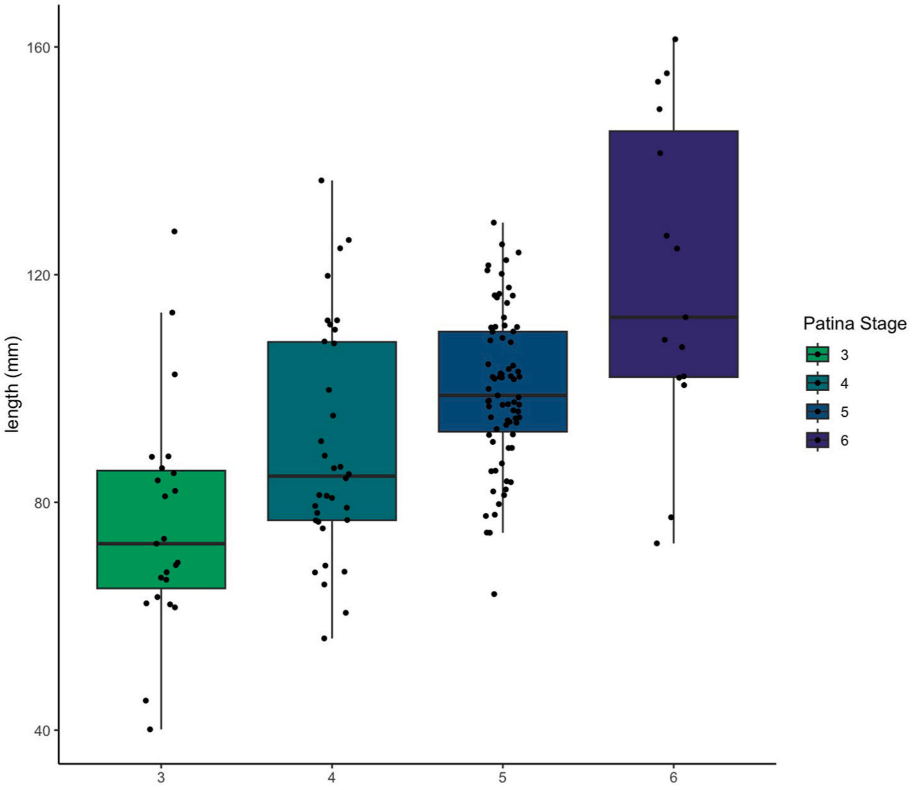

Fig. 22. Box plots of Nubian Levallois core lengths by patina stage.

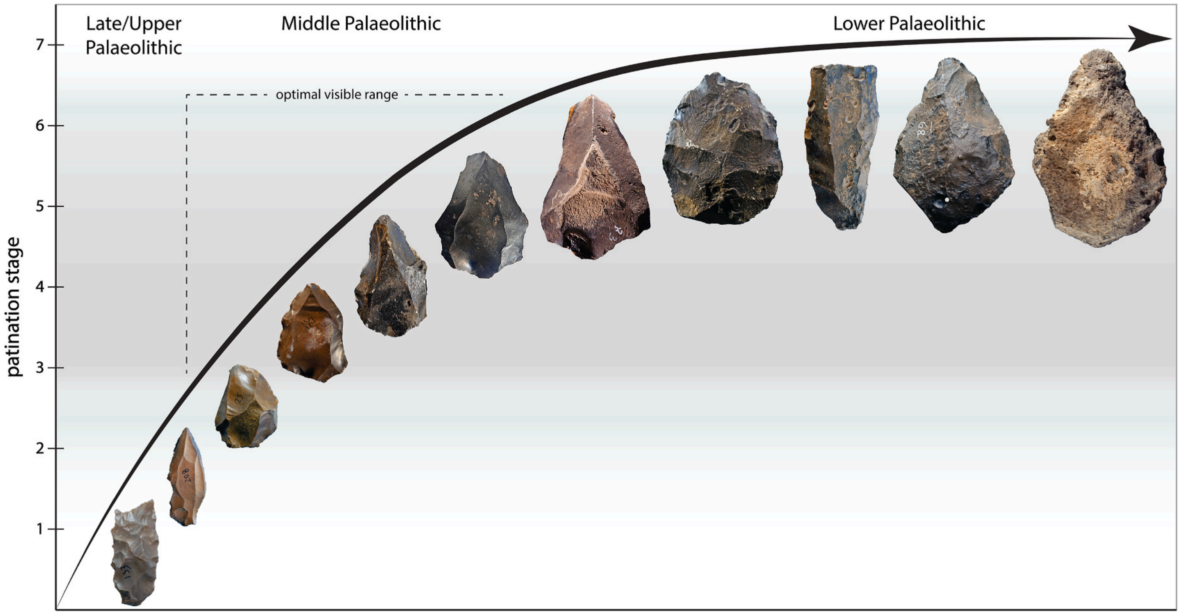

Fig. 23. Schematic showing optimal visible range for differentiating stages of patination.

Investigation, Conceptualization.

Data availability statement

Raw data and R code have been deposited in OSF under Rose, J.I., Li, L., & Cascalheira, J., 2024. Research compendium for the paper "Mapping lateral stratigraphy at Palaeolithic surface sites: a case study from Dhofar, Oman." It can be accessed via https://osf.io/rnyfb/.

Declaration of competing interest

We, the co-authors, declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere. We know of no conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. As Corresponding Author, I confirm that the manuscript has been read and approved for submission by all the named authors.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2024.106117.

Reproducibility Results

The Associate Editor for Reproducibility downloaded all materials and could reproduce the results presented by the authors.

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