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A quantitative approach to the study of Neolithic projectile points from southeastern Arabia

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Conflict of interest statement

The authors declare that there is no conflict of interest.

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Abstract

Lithic projectile points always had an important diagnostic value for documenting the development and expansion of Arabian Neolithic material culture (ca. 8th – 4th millennium BC) and subsistence strategies due to the remarkable abundance of surface assemblages. Given the limitations of traditional arrowhead typology for analysing the increasing variability emerging from archaeological research in the region, we propose here a new systematic description of Neolithic projectile points, based on the consistent observation of technological and morphological change over time and space in a number of diagnostic parameters. A quantitative exploration of variation is carried out on both published and unpublished data through a number of pattern-recognition techniques and exploratory analyses such as Principal Component and Cluster Analysis. By presenting the first application of this approach to Arabian Neolithic projectile points, the research offers a valid tool for investigating temporal and cultural trends through different phases of the Neolithic in the region of interest.

Keywords
Neolithic, projectile points, attribute analysis, southeastern Arabia, quantitative methods.

Introduction

Lithic projectile points always represented a popular item of lithic industries analysis as they reflect aspects of social identity, technical creativity, and adaptation. Their abundance in the Early and Middle Holocene assemblages of the Arabian Peninsula, together with the paucity of stratified datable sites, always conferred to these lithic implements an important diagnostic value. This research is part of a broader PhD project that aims to analyse projectile points belonging to the Neolithic of southeastern Arabia (Oman and United Arab Emirates, UAE; Figure 1) in relation to potential surrounding influences: the Neolithic of the Levant and Zagros Mountains, hunter-herder groups moving across the Rub' al-Khali central desert, northeastern African Fayum cultures, and Yemeni Neolithic populations. At the present stage of research, however, the study region is limited to the territories corresponding to present-day Sultanate of Oman and United Arab Emirates.

Over the past decades, the archaeological and theoretical concept of "Arabian Neolithic" has endured several revisions. The abundance of seasonal or temporary hunter-gatherer campsites (characterised by large scatters of lithic materials, including projectile points, and linked to hunting activities), the increasing exploitation of marine and lagunar resources, and the absence of any typical features related to the Neolithic of the Fertile Crescent such as domesticates, agriculture and sedentary settlements, contributed to define this period as the Arabian "Late Stone Age" (Tosi, 1986; Uerpmann, 1992; Zarins, 2001; Cleuziou & Tosi, 2018). The scarcity if not the absence of faunal and botanical remains, together with poorly preserved stratigraphic sequences, led scholars to build hypotheses just based on lithic assemblages. Later research, however, made it clear that the neolithisation of Arabia consisted of a more complex process, with clear specificities and different from what emerged in the neighbouring regions (Cleuziou, 2004; Crassard, 2009; Crassard & Drechsler, 2013; Magee, 2014; Crassard & Khalidi, 2017).

During the Early Holocene (10th to 8th millennium BC), projectile weaponry in southeastern Arabia is characterised by the development of points made on flakes or blade-like blanks retouched to obtain a tang at the base (Cremaschi & Negrino, 2002; Charpentier & Crassard, 2013; Uerpmann et al., 2013; Crassard & Petraglia, 2014; Hilbert, 2014; Charpentier et al., 2016). These arrowheads form three well defined groups named Fasad, al-Haddah, Natif and Faya points (described in detail by Charpentier & Crassard, 2013; Charpentier et al., 2016). They vary in manufacturing technique and chronological determination. Their shape ranges from thinner and shorter points, as in Natif-2 (Charpentier et al., 2016), to large, irregular points as the ones found at al-Haddah (BJD-1: Charpentier et al., 1997; although the dating of this type might be later). Since this early phase, a number of specific and localised technological features emerged in the lithic industries of the Arabian Peninsula.

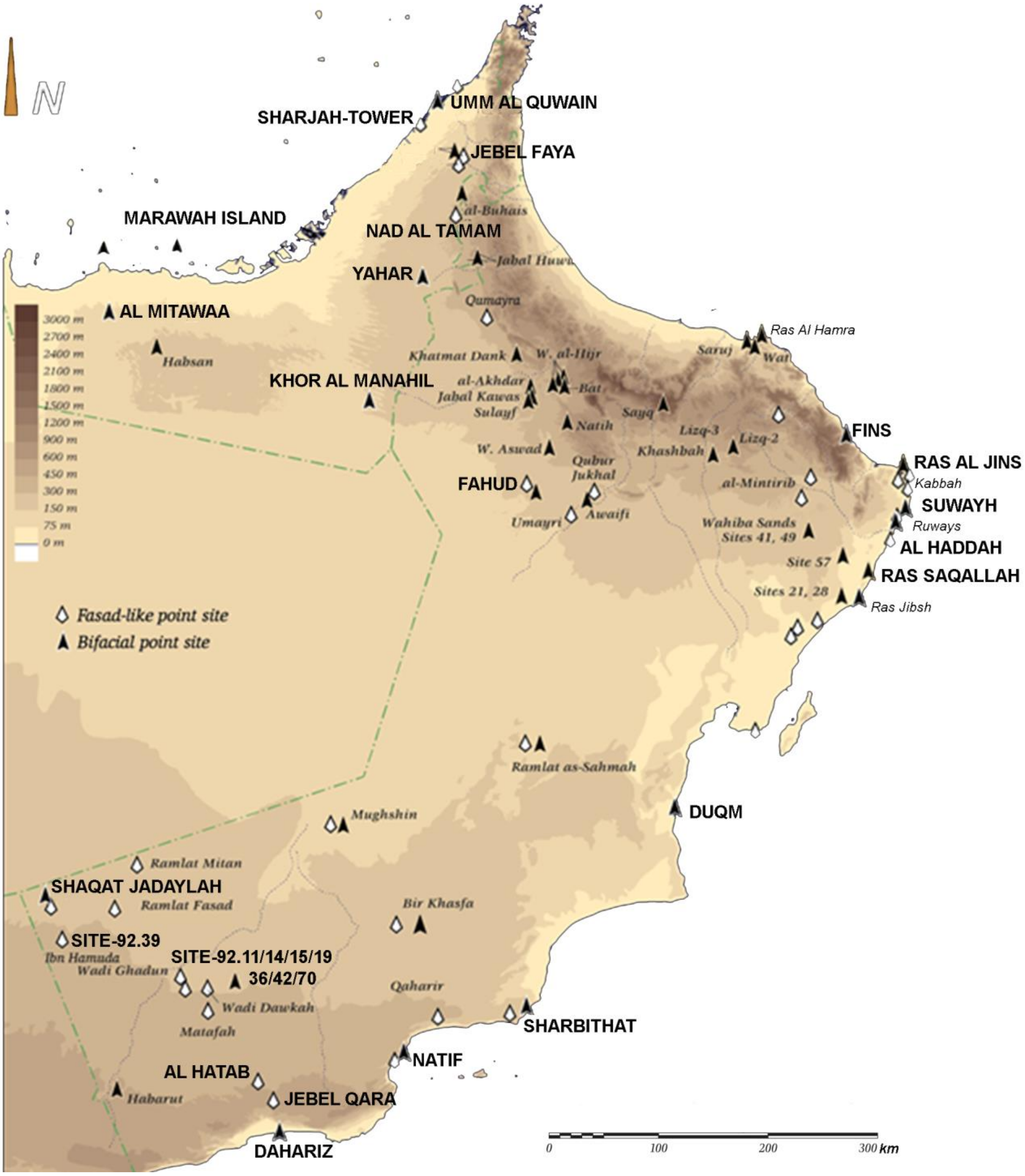

FIGURE 1 Map of the Late Palaeolithic and Neolithic sites of Oman and UAE. The name of the sites involved in the study are reported in capitals (modified after H. David-Cuny, from Cleuziou & Tosi, 2018, fig. 27).

Throughout the Middle Neolithic (7th to 5th millennium BC), more complex techniques such as parallel covering retouch and fluting are introduced to produce fine, elongated projectile points with triangular, biconvex or plano-convex sections. The appearance and spreading of such a sophisticated type of arrowheads, encompassing also ‘trihedral points’, marks the beginning of a flourishing period in lithic production of Southern Arabia (Charpentier, 2008). The sub-type of the so-called ‘Concorde points’ can be seen as the highest point in fine-retouched arrowhead production in the region (Crassard, 2008; Maiorano et al., 2018; see Figure 4: T18), as much as fluted points in Oman and Yemen hint at the diffusion of unprecedented skills in flintknapping (Charpentier & Inizan, 2002; Crassard et al., 2006). In the Late Neolithic Period 1 (4500-3800 BC; Charpentier, 2008), temporary campsites located along the mangroves growing on sea and lagoon coastlines turn into more structured settlements. The intensive exploitation of marine and lagunar resources is integrated by the consumption of wild and domesticated mammals. During this phase, the production of trihedral points declined, and elongated fusiform or tanged, shouldered points with biconvex or plano-convex section reached their maximum diffusion (Charpentier, 2008).

The recent discovery of a localised form of tanged points at Sharbithat (Dhofar region, Oman) suggests that during the Late Neolithic Period 2 (3700-3100 BC) arrowhead production persisted in the region (contrary to what was previously thought for Oman and the UAE), although technical investment in manufacturing decreased (Maiorano et al., 2018). These points consist of a rough thick flake-blank characterised by abrupt retouch made via direct percussion on anvil, and – given this irregular and aerodynamically unsound shape – possibly represent a shift in the use of weaponry (from projectile to thrusting). They were found in association with abundant backed bladelets and lunates, and with a particular kind of net sinker engraved with a continuous line along their longest axis, normally found in 4th – 3rd millennium BC assemblages.

The above mentioned narrative, however, presents many missing links, and questions on the main processes that led to the emergence and diffusion of the very specific traits identified in southern Arabian contexts have yet to be answered.

This paper aims to answer four main research questions through the application of quantitative methods for studying morphological and technological variability documented in southern Arabian arrowheads: 1) Are there specific morphological or technological attributes that drive variation across traditional classes and types? In other words, can we better understand change in point morphology over time and space if we consistently observe specific traits? 2) Is it possible to obtain a consistent classification that can help overcome limitations embedded in traditional typology (such as a weak scale of ordering, co-occurrence problems, non-metric and essentialist ordering; Burdukiewicz, 2006), and allow researchers to effectively compare projectile points uncovered in southern Arabia with those produced in the neighbouring regions? 3) Are the obtained classes (or taxa) in some way related, i.e. can we infer processes of cultural transmission (diffusion, cultural admixture, shared ancestry; or the absence of, e.g. convergence) that may explain at least part of the morphological variability emerging in the study; 4) Is it possible to use variability and diversity in point design to obtain temporal and spatial patterns that can be more easily interpreted? The study largely draws on theory and methods developed by the cultural evolutionary framework, which over the past thirty years developed the idea that cultural change can be effectively analysed and interpreted as an evolutionary process (Cavalli-Sforza & Feldman, 1981; Boyd & Richerson, 1985; Shennan, 2008). The systematic description of projectile points and character construction are based on paradigmatic classification as developed by the same theoretical framework (Dunnell, 1971; O'Brien et al., 2002; O'Brien & Lyman, 2003; Tehrani & Collard, 2009). Nevertheless, the possible relationship between shared derived characters and their ancestral states will not be directly analysed in the present work, where we rather focus on the quantitative study of morphological change (Gob, 1987; Sackett, 1966; Scerri et al., 2016; Shipton et al., 2016).

Quantitative methods and attribute-based analysis of lithic tools have been widely and increasingly used to generate testable hypotheses on the development and distribution of lithic industries found in a variety of geographical and temporal contexts (Gob, 1987; O'Brien & Lyman, 2003; Tehrani & Collard, 2009; O'Brien et al., 2010; Sackett, 1966; Scerri et al., 2016; Shipton et al., 2016; Shennan, 2018). This approach allows researchers to formally assess the relationship between patterns of change, to make probabilistic inference in the case of incomplete assemblages, and to generate syntheses of large-scale variability documented in the archaeological record.

Projectile points are complex structures resulting from the match between technological skills and functional needs within a traditional/cultural context. Change in projectile-point manufacturing and design takes place over generations and is the result of cumulative events of addition, loss, and transformations. Such addition or loss of variants is stored in material culture, and can be traced by looking at similarities and differences between existing structures, as well as the modification of existing ones (O'Brien & Lyman, 2003). In the present paper, we first identify and select the most relevant variables to explain projectile point variation and use them to develop a new systematic classification. The obtained classes are analysed with reference to traditional types described in the literature, and a number of exploratory analyses are carried out to examine change in point morphology and technology.

Materials and methods

Evidence of technological and morphological variability was based on the observation of 375 projectile points from 40 sites. Absolute dates were attributed to each point based on published data (Table 1).

TABLE 1 List of sites which were selected for the presented experiments, associated with the number of projectile points for each and the respective one ‐ millennium chronological range. The sites attended for a longer period were divided in two or more records.

Site	Region	Chronological range (cal. BC)	Points	Bibliographic reference
Al-Hatab	Interior Dhofar	10500-9500	2	Hilbert 2014*; Hilbert et al. 2015
ALH-1 (al Haddah)	Central Oman	5500-4500	10	Unpublished (Courtesy of Ministry of Heritage and Culture – Sultanate of Oman; Joint Hadd Project)
Al-Mitawaa	Abu Dhabi Region	5500-4500	5	Crombè 2000
BJD-1 (al Haddah)	Central coastal Oman	7500-6500	30	Charpentier et al 1997*
DHZ-2 (ad Dahariz)	Coastal Dhofar	6500-5500	4	Unpublished* (Courtesy of "Arabian Sea Shores – French mission to Oman", unpublished date)
DUQ (Duqm)	Central coastal Oman	4500-3500	3	Genchi et al 2017 and Unpublished (Courtesy of Ministry of Heritage and Culture – Sultanate of Oman)
Fahud	Central-Northern Oman	7500-6500	3	Pullar 1984 and Unpublished (Courtesy of Ministry of Heritage and Culture – Sultanate of Oman)
FASAD (Ramlat al Hashman)	Interior Dhofar	7500-6500	13	Charpentier 1996; Charpentier & Crassard 2013
FASADb (site with bifacial points)	Interior Dhofar	5500-4500	6	Unpublished (Courtesy of Ministry of Heritage and Culture – Sultanate of Oman)
FAY-NE-1 (Jebel Faya)	Sharjah region	8500-7500	14	Uerpmann et al. 2009*; Uerpmann et al. 2013
FAY-NE-10 (Jebel Faya)	Sharjah region	5500-4500	1	Uerpmann et al. 2009*; Uerpmann et al. 2013
FNS-7 (Fins)	Central-Northern Oman	4500-3500	5	Maiorano 2016
GQ-13/23 (Jebel Qara)	Interior Dhofar	8500-7500	3	Cremaschi et al. 2015*
KAM (Khor al Manahil)	Abu Dhabi Region	5500-4500	4	Kallweit et al. 2005
Mleiha	Sharjah region	4500-3500	6	Jasim 2001
MR-11 (Marawah Island)	Marawah Island	6500-5500	3	Beech et al. 2005*
SQJ-2 (Shaqat Jadailah)	Interior Dhofar	5500-4500	4	Unpublished (Courtesy of Ministry of Heritage and Culture – Sultanate of Oman)
SQJ-2 (b) (Shaqat Jadailah)	Interior Dhofar	6500-5500	15	Unpublished (Courtesy of Ministry of Heritage and Culture – Sultanate of Oman)
NTH (Nad al Tamam)	Sharjah region	7500-6500	6	Uerpmann et al. 2009*
NATIF-2	Coastal Dhofar	8500-7500	19	Charpentier et al. 2016*
RJ-37 (Ras al Jins)	Northeastern Oman	6500-5500	6	Charpentier 1991*

SAQ-1 (Ras’ Saqallah)	Northeastern Oman	4500-3500	7	Biagi 1988*
SHA-10A (Sharbithat)	Coastal Dhofar	3500-2500	26	Maiorano et al. 2018
SHA-10B (Sharbithat)	Coastal Dhofar	3500-2500	18	Maiorano et al. 2018
SHA-2 (Sharbithat)	Coastal Dhofar	3500-2500	6	Maiorano et al. 2018
SHA-2(b) (Sharbithat)	Coastal Dhofar	6500-5500	1	Maiorano et al. 2018
SHA-4 (Sharbithat)	Coastal Dhofar	6500-5500	9	Maiorano et al. 2018
SHJ-TOWER (Sharjah Tower)	Sharjah region	5500-4500	6	Millet 1988
SHU-3 (Shuwaiymiah)	Coastal Dhofar	5500-4500	4	Unpublished (Courtesy of Arabian Sea Shores – French mission to Oman)
SHU-3(b) (Shuwaiymiah)	Coastal Dhofar	6500-5500	2	Unpublished (Courtesy of Arabian Sea Shores – French mission to Oman)
Al-Madar (SITE-69)	Sharjah region	5500-4500	2	Boucharlat et al. 1991*
Al-Madar(b) (SITE-69)	Sharjah region	4500-3500	2	Boucharlat et al. 1991*
SITE-92.11	Interior Dhofar	3500-2500	4	Zarins 2001
SITE-92.11(b)	Interior Dhofar	4500-3500	1	Zarins 2001
SITE-92.14	Interior Dhofar	3500-2500	13	Zarins 2001
SITE-92.14(b)	Interior Dhofar	4500-3500	2	Zarins 2001
SITE-92.14(c)	Interior Dhofar	6500-5500	3	Zarins 2001
SITE-92.15	Interior Dhofar	3500-2500	5	Zarins 2001
SITE-92.19	Interior Dhofar	3500-2500	14	Zarins 2001
SITE-92.36	Interior Dhofar	3500-2500	4	Zarins 2001
SITE-92.39 (Ibn Hamuda)	Interior Dhofar	5500-4500	5	Zarins 2001
SITE-92.39(b) (Ibn Hamuda)	Interior Dhofar	6500-5500	3	Zarins 2001
SITE-92.42	Interior Dhofar	5500-4500	1	Zarins 2001
SITE-92.42(b)	Interior Dhofar	6500-5500	4	Zarins 2001
SITE-92.70	Interior Dhofar	5500-4500	4	Zarins 2001
SWY-1 (Suwayh)	Northeastern Oman	5500-4500	7	Charpentier 2004*
SWY-1 (b) (Suwayh)	Northeastern Oman	4500-3500	2	Charpentier 2004*
SWY-20 (Suwayh)	Northeastern Oman	4500-3500	4	Charpentier 2012
UAQ-2 (Umm al-Quwain)	Sharjah region	5500-4500	16	Unpublished* (Courtesy of Sophie Méry)
Yahar	Abu Dhabi Region	4500-3500	24	Rothfels Collection – Unpublished (Courtesy of Al Ain Archaeological Museum)
Yahar (b)	Abu Dhabi Region	7500-6500	14	Rothfels Collection – Unpublished (Courtesy of Al Ain Archaeological Museum)

A systematic description of the analysed projectile points was developed, based on the observation of technological and morphological variability. Such observation led to the definition of a number of diagnostic attributes such as elongation index, outer angle spread sum, apical, medial and basal section (listed in Table 2). A detailed description of retouch was obtained by virtually dividing each point in eight quadrants (i.e. sub-squares) along the morphological axis, and by separately recording retouch for each quadrant (following e.g. Clarkson, 2002). The final descriptive system is comprised of 64 diagnostic traits or attributes, all of which are categorical multimodal ones (i.e. each character can have multiple states; following e.g. Dunnell, 1989; O’Brien & Lyman, 2003). Their sequence univocally describes each point and makes it possible – if needed – to group empirical points into monothetic classes. In this way, the scale of observation and the scale of analysis shift from an entire arrowhead to a single trait. Continuous variables (such as elongation index, maximum length/basal length ratio, etc.) were also transformed into discrete variables (see Table 2) to facilitate data management and distance computation. Multimodal variables were then turned into binary ones to make them suitable to be analysed through the chosen exploratory data analyses.

TABLE 2 Character measurements involved in the analyses and related character states. Characters underlined were found to be the most useful for obtaining a consistent classification of projectile points.

Code	Character	Character states
LW	Elongation Index (Max. Length / Max. Width)	1- 1.1< x <2.16 2- 2.17< x <2.8 3- 2.9< x <3.68 4- x > 3.68
WtipW	max width / tip width (calc. at ¾ from the max.width)	1- 1< x <1.77 2- 1.78< x <2.06 3- 2.07< x <2.46 4- x > 2.47
LBL	max. length / basal length	1- 1.22< x <2.45 2- 2.46< x <3.33 3- 3.34< x <4.63 4- x > 4.64
MTH	medial thickness	1- 1.5< x <3.7 2- 3.8< x <4.5 3- 4.6< x <5.5 4- x > 5.6
ATH	apical thickness	1- 0.8< x <2.8 2- 2.9< x <3.3 3- 3.4< x <4.2 4- x > 4.3
BTH	basal thickness	1- 1.3< x <3.4 2- 3.5< x <4 3- 4.1< x <5.2 4- x > 5.3
OutAng	outer angles spread sum	1- 140< x <240 2- 241< x <276 3- 277< x <307 4- x > 308
MSec	medial section	1 trihedral 2 plano-convex 3 biconvex 4 romboidal 5 blank 6 irregular 7 approximation of trihedral
BSec	basal section	Same Character states as for Medial section
ASec	apical Section	Same Character states as for Medial section
APX	presence of wings or different appendixes	1 wings 2 “ears” (<4 mm) 3 denticulation 4 tang tips (hollow based point) 5 long wings (L≥tang length) 6 “ergot” (squared/sub-sq) 0 absence
RSD	dorsal retouch symmetry	1 symmetric 2 asymmetric 3 from one side 4 mixed 5 fluted 0 not retouched
RSV	ventral retouch symmetry	Same character states as for dorsal retouch symmetry
RTECH	retouch technique	1 pressure 2 direct

		3 direct on anvil 4 mixed
BLK	blank	1 flake: LW < 1.79 2 laminar flake:1.80<LW< 2.8 3 blade: LW > 2.80 4 unknown
Ipos	retouch position on the first sub-square	1 direct 2 inverse 3 alternate 4 alternating 5 crossed 6 bifacial 0 absent
Idelin	retouch delineation on the first sub-square	1 rectilinear 2 convex 3 concave 4 notched 5 denticulated 6 serrated 7 convex shoulders 8 concave shoulders 9 notched concave shoulders 10 winged shoulders 11 crossed shoulders 12 notched convex shoulders 13 “ergot” shoulders 0 absent
Iang	retouch angle on the first sub-square	1 abrupt (> 75°) 2 semi-abrupt(45°< x <75°) 3 low (< 45°) 0 absent
Imor	retouch morphology of the 1st sub-square	1 scaled 2 stepped 4 sub-parallel 5 horizontal parallel 6 oblique parallel 7 marginal 0 absent
Iext	retouch extension of the 1st sub-square	1 short 2 long 3 covering 0 absence
Idist	retouch distribution of the 1st sub-square	1 continue 2 discontinue 3 partial 0 absent
IIpos, IIdelin, IIang, IImor, IIext, IIdist; IIIpos, IIIdelin, IIIang, IIImor, IIIext, IIIdist; IVpos, IVdelin, IVang, IVmor, IVext, IVdist; Vpos, Vdelin, Vang, Vmor, Vext, Vdist; VIpos, VIdelin, VIang, VImor, VIext, VIdist; VIIpos, VIIdelin, VIIang, VIImor, VIIext, VIIdist; VIIIpos, VIIIdelin, VIIIang, VIIImor, VIIIext, VIIIdist;		Same character states used to describe the retouch of the other seven sub-squares
Total: 64 characters		Total: 336 character states
Selected by PCA: 23 characters		Selected by PCA: 124 character states

As a preliminary step to reduce the number of potentially redundant traits and character states, we tested for symmetry in the observed points by measuring Pearson's product-moment correlation coefficient (Pearson, 1948) among all pairs of variables measured in both left and right sub-squares. Since all correlations yielded strong and positive results (Table 3) we discarded variability observed in the right side and focused on the left side alone.

TABLE 3 List of Pearson correlation indexes calculated among all pairs of variables measured in left and right quadrants. Pearson's correlation coefficient was chosen as, when pairs of binary (1/0) variables are compared, it has the same value as Cramer's V obtained after computing a Pearson's chi - squared test of independence on the same pair of variables, and is therefore a reliable measure of association.

Left quadrants characters	**Right quadrants characters**	**Pearson correlation coefficient**
I_pos	II_pos	0.984
I_delin	II_delin	0.889
I_ang	II_ang	0.963
I_mor	II_mor	0.973
I_ext	II_ext	0.964
I_dist	II_dist	0.786
III_pos	IV_pos	0.964
III_delin	IV_delin	0.818
III_ang	IV_ang	0.892
III_mor	IV_mor	0.966
III_ext	IV_ext	0.969
III_dist	IV_dist	0.583
V_pos	VI_pos	0.947
V_delin	VI_delin	0.924
V_ang	VI_ang	0.94
V_mor	VI_mor	0.962
V_ext	VI_ext	0.974
V_dist	VI_dist	0.853
VII_pos	VIII_pos	0.917
VII_delin	VIII_delin	0.964
VII_ang	VIII_ang	0.975
VII_mor	VIII_mor	0.972
VII_ext	VIII_ext	0.978
VII_dist	VIII_dist	1

A Principal Component Analysis (PCA) was run on the presence/absence[1] of each character state

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[1] In this case quantitative variables reported in Table 2 were not taken into account. The analysis was performed only on binary variables (presence/absence) created from the multimodal dataset. The PCA results are reported as online supporting information (Table: Dataset_PCA).

across all points using the function prcomp in R (R Core Team, 2019), and was aimed at identifying traits that could explain most of the variability emerging in the present dataset (Figure 2). Based on the resulting variable loadings, 23 character states were selected (underlined codes in Table 2). PCA plots on PC1 and2 were then used to explore the possible presence of population structure based on traditional typology (Fasad, bifacial, trihedral, Sharbithat; Figure 2) as well as geography (Figure 3b; regions are listed in Table 1).

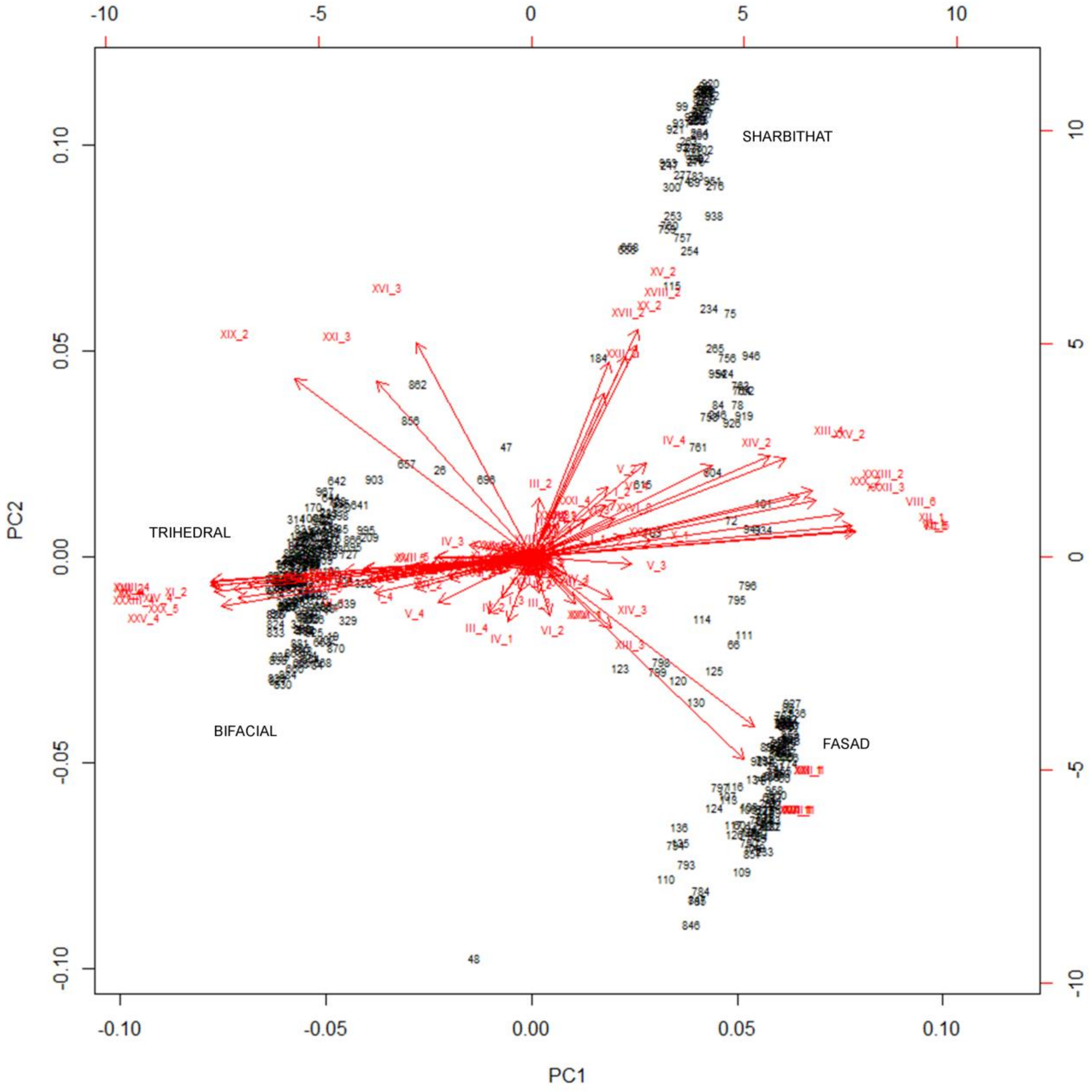

FIGURE 2 Biplot showing all obtained components of the PCA aimed at identifying traits that explain most of the variability emerging in the full sample of points. The black labels represent the points while the reds are the traits reported as Roman numerals.

In order to better quantify the relationship between points and groups of points, a pairwise dissimilarity matrix was generated based on Jaccard distance (i.e. a measure equal to the number of differences divided by the sum of differences and similarities between individual points; calculated using the function distance in the ecodist package in R; Goslee & Urban, 2007). Points were grouped through hierarchical clustering using the complete linkage agglomeration method, and the obtained clusters were exploited to identify new, unbiased taxa accounting for both morphological and technological aspects of point design (Figure 3a, Figure 4).

The Jaccard dissimilarity matrix was also used to formally test for the amount of population structure in the data through Analysis of Molecular Variance (AMOVA; Excoffier et al., 1992) following other applications of the method on cultural datasets (Ross et al., 2013; Shennan et al., 2015; Bortolini et al., 2017).

Correspondence Analysis (CA; function ca in the package ca in R; Nenadic & Greenacre, 2007) was employed to further examine the distribution of points over time based on the frequency of the newly identified descriptors measured in each taxon (Gob, 1987; Figure 5).

Subsequently, intra- and inter-site diversity measures were computed to introduce the role of human interaction/isolation and demographic fluctuations in the emerging picture on the occupation of the analysed area during the Neolithic, based on results reported in previous research on cultural evolution of non-selective traits (Neiman, 1995; Shennan & Wilkinson, 2001, Shennan & Bentley, 2008; Premo, 2012; Premo, 2014). When in absence of selective pressures or spatial barriers, if we look at an individual site, higher diversity indicates higher interaction and exchange (or an increase in size of the population interested by the exchange of cultural information). Lower diversity, on the other hand, suggests increasing isolation and a lower amount of exchange. At a regional level we would instead expect an opposite scenario. More specifically, such models of cultural change predict that when intra-site diversity increases, inter-site diversity is expected to decrease (i.e. if sites present with a more diverse composition, regional homogeneity often increases). Vice versa, when intra-site diversity decreases (i.e. a single variant likely dominates assemblage composition) sites are likely to become more different from one another, and regional homogeneity decreases. Archaeological sites were grouped into five subsets, each encompassing a temporal interval of 1000 years (6500-5500 BC, 5500-4500 BC, 4500-3500 BC; 3500-2500 BC) except for the first set that, given the low number of specimens, was extended to include all Fasad points (9500-6500 BC). Intra- and inter-site diversity were estimated using a generalised form of Wright's Fst (Wrigth, 1965) developed by Nei (Fst= 1- Hs/Ht where Hs is the average intra-site diversity and Ht is the total diveristy index; Nei, 1973) and used by Premo (2012) to demonstrate that intergroup diversity is heavily affected by network structure and episodes of local extinction. Empirical measures of overlap between sites (Morisita-Horn index using the function sim.table in the package vegetarian in R; Horn, 1966; Jost, 2007; Charney & Record, 2012) were also calculated to estimate similarity between sites and then graphically represented as links connecting sampling sites (Figure 6).

Results

PCA effectively separates points into three main sub-sets, all of which closely match previously acknowledged technological and morphological types (Figure 2): 1) laminar-unifacial-tanged points (grouped under the name "Fasad"); 2) bifacially retouched points (bifacial with biconvex and plano-convex medial section and trihedral points); and 3) a recently discovered – and probably chronologically later – class of unifacial tanged points made on thick blades and laminar flakes found in the area of Sharbithat (Dhofar region, Oman). When the same data set is characterised according to regional provenance (Figure 3b) no apparent or consistent geographic pattern emerges, with the only exception of Umm al-Quwain (UAQ-2) and a few other isolated cases, which might act as outliers because of a higher level of localism and specialisation in the production of denticulate bifacial points. On the other end, points uncovered in Oman and the UAE clusters together and seem to act as a unique region (Figure 3b).

When the reduced character set was analysed through cluster analysis, pairwise dissimilarity between points generates a wide and dense dendrogram where, at the second taxonomic level, four major clusters emerge, distributing the large groups of Fasad, Sharbithat, unifacial (probably incomplete), and bifacial points. From each of these, at different levels, lower-level clusters branch out and form 20 groups. Due to the great morphological and technological variability registered across all points, not all groups can be identified at the same taxonomic level. These 20 groups represent an unbiased taxonomic system in which both morphological and technological concepts are embedded. If these novel units are compared against the pre-existing types derived from published sources (Spoor, 1997; Zarins, 2001; Charpentier, 2008; Crassard, 2008; Uerpmann & Uerpmann, 2009; Uerpmann et al., 2013; Crassard & Petraglia, 2014), the grouping determined by known traditional types is maintained. New sub-groups, however, tend to emerge across the dendrogram. These subdivisions stress morphological and technological differences among assemblages such as Fasad *sensu stricto*, Al-Haddah points (as already reported by Charpentier & Crassard, 2013), and Sharbithat points (Maiorano et al., 2018; and other sites in Dhofar, see Zarins, 2001: sites 92:36 and 92:19).

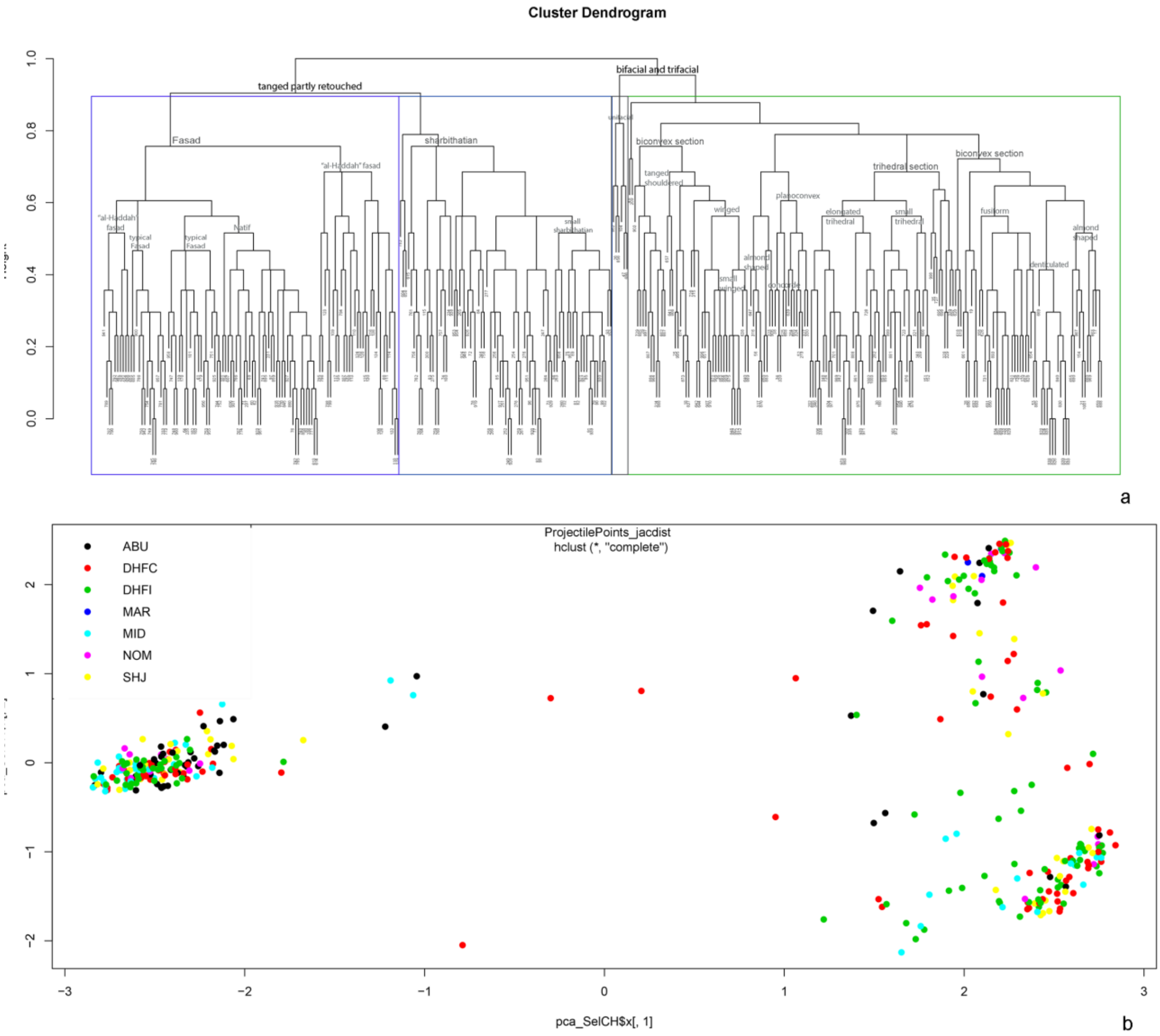

FIGURE 3 (a) Agglomerative hierarchical cluster explored to obtain new classes of projectile points. (b) Dissimilarity matrices for points distributed by provenance region (full sample). The results show no clustering by geographical sets.

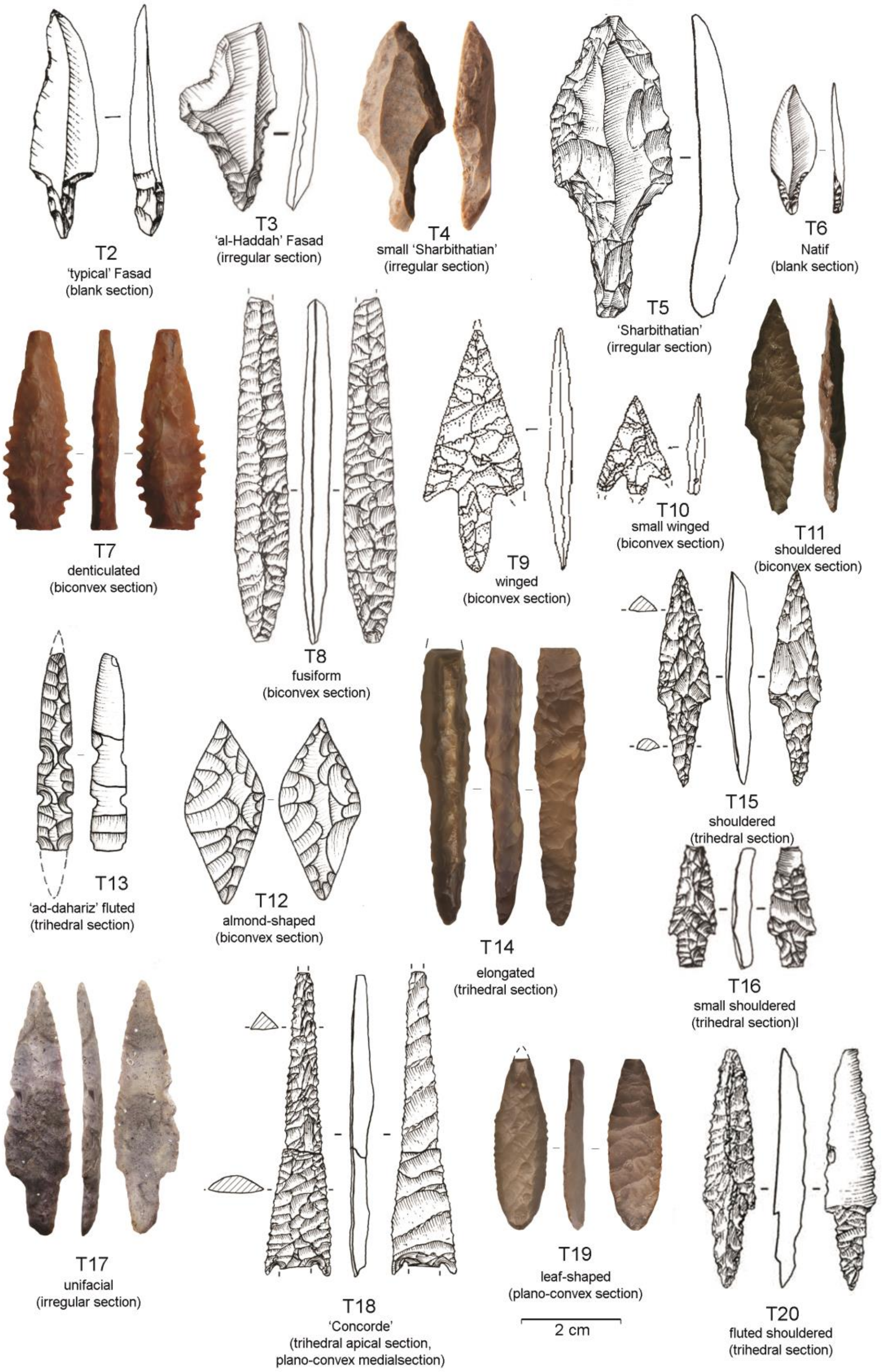

FIGURE 4 Illustration of 20 new major classes of points (taxa).

Turning to Correspondence Analysis, the first two axes (Figure 5) seem to order taxa according to chronology. In particular, Axis 1 (23.7% of total variation) places the oldest groups to the left (although the order is not completely correct), Middle Neolithic arrowheads at the centre, and Late Neolithic taxa to the right. As explained by several authors (e.g. Smith & Neiman, 2007), in ordination plots the presence of an arch (Gauch, 1982) occurs when the taxonomic composition of the sites progressively changes along a gradient that in our case might be a temporal one. The arch effect occurs when the first axis seems enough to order properly sites and taxa (Legendre & Legendre, 1998). If the relationship between column and row markers is inspected it can be seen that the later end (on the right side of the graph) is dominated by the Sharbithat points and the earlier end by Fasad points, although the separation is not perfect. CA therefore returns a good proxy of temporal seriation and suggests that: a) time might be the main driver of variation in the observed dataset; b) since the temporal dimension is relevant for all the observed points, this might indicate that the study region can be considered as one single spatial unit as the result of intense exchange between different locations (Neiman, 1995; Smith & Neiman, 2007) (Figure 5). This hypothesis is further supported by results of the PCA, in which no clear spatial pattern emerges, and geography seems to play quite a marginal role in the overall distribution of different morphological and technological traits (Figure 3b).

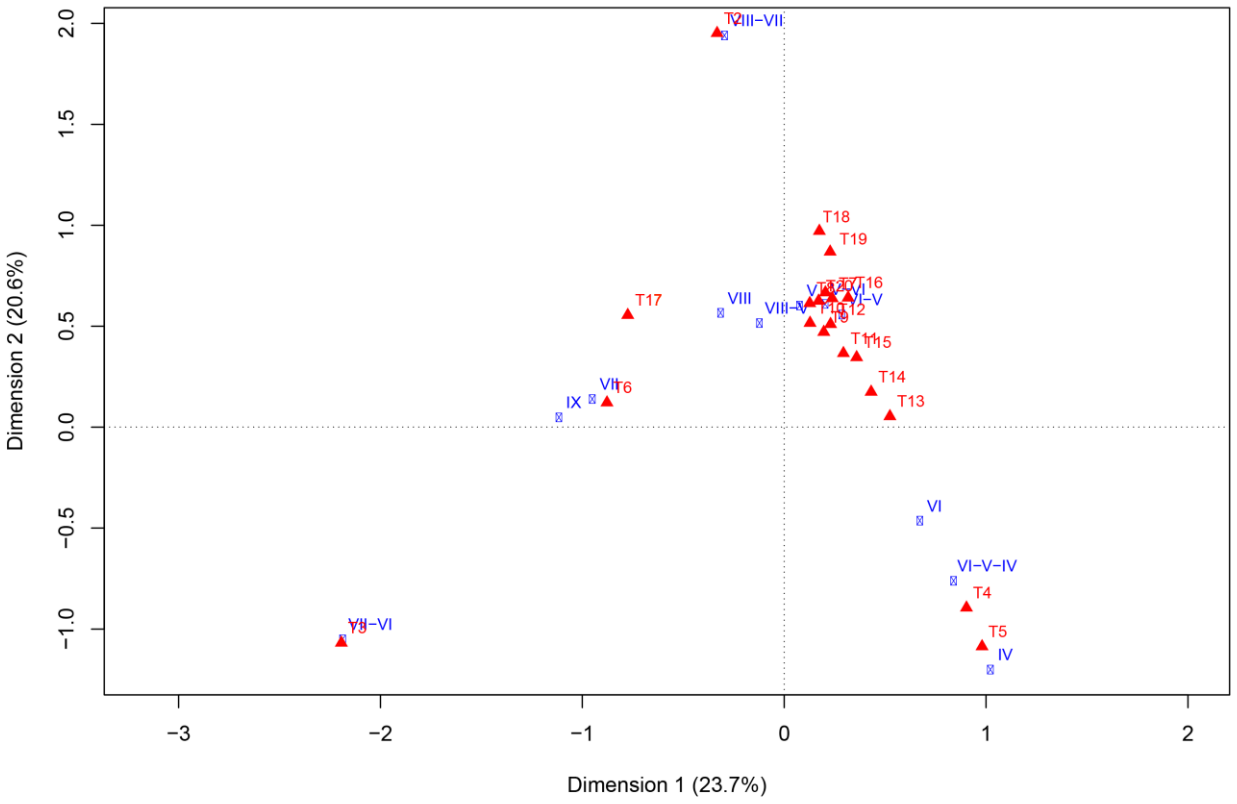

FIGURE 5 Ordination of points taxa (in red) according to chronological range (in blue) through correspondence analysis. Axes 1 and 2 describe 44.3% of the total variation.

The impact of both time and geography on the variability of trihedral and Fasad points (Table 4) was further tested through AMOVA. Results suggest that the influence of geography alone on trihedral points could be very limited, and variation may be ascribed to more complex processes of movement and interaction, influenced by climatic change (as suggested by the graph in Figure 7) as well as shifts in subsistence and settlement strategy. The same analysis yielded quite different results on Fasad points. While geographic segregation is still not able to explain the distribution of pairwise distances (Table 4), time seems once again to be critical in order to infer some generative processes of variation and confirm the results obtained with clusters and CA.

Values of inter-site overlap (Morisita-Horn index) tend to decrease over time in the entire study area, particularly during the last phase of the Neolithic and the advent of the Early Bronze Age. On the other hand, intra-site diversity is low at the beginning of the Holocene (when assemblages are dominated by different types of Fasad, *sensu* Charpentier & Crassard, 2013) showing a first period of isolation. However, such a diversity tends to increase (while inter-site diversity decreases, as predicted by cultural evolutionary models of change in non-selective traits) between the 6th and the 5th millennium BC, indicating high levels of interaction. Inner Dhofar and UAE exhibit generally higher intra-site diversity, suggesting higher population density and a higher volume of exchanged information, not only along the coast but also between coastal settlements and desert encampments. Aside from a general tendency to regional diversity, in the period between the 7th and the 5th millennium BC pairs of geographically close sites exhibit higher overlap (Figure 6, 7) than sites which are located farther apart.

From the second half of the 4th millennium onwards, we have a few dominant classes determining an increase in intra-site homogeneity mirrored by an unpredicted lower inter-site diversity (Figure 6, 7) that could correspond to the diffusion of the similar types across Dhofar, despite a tendency to local isolation due to climatic regression (Uerpmann & Uerpmann, 2009; Preston & Parker, 2013; Preston et al., 2015).

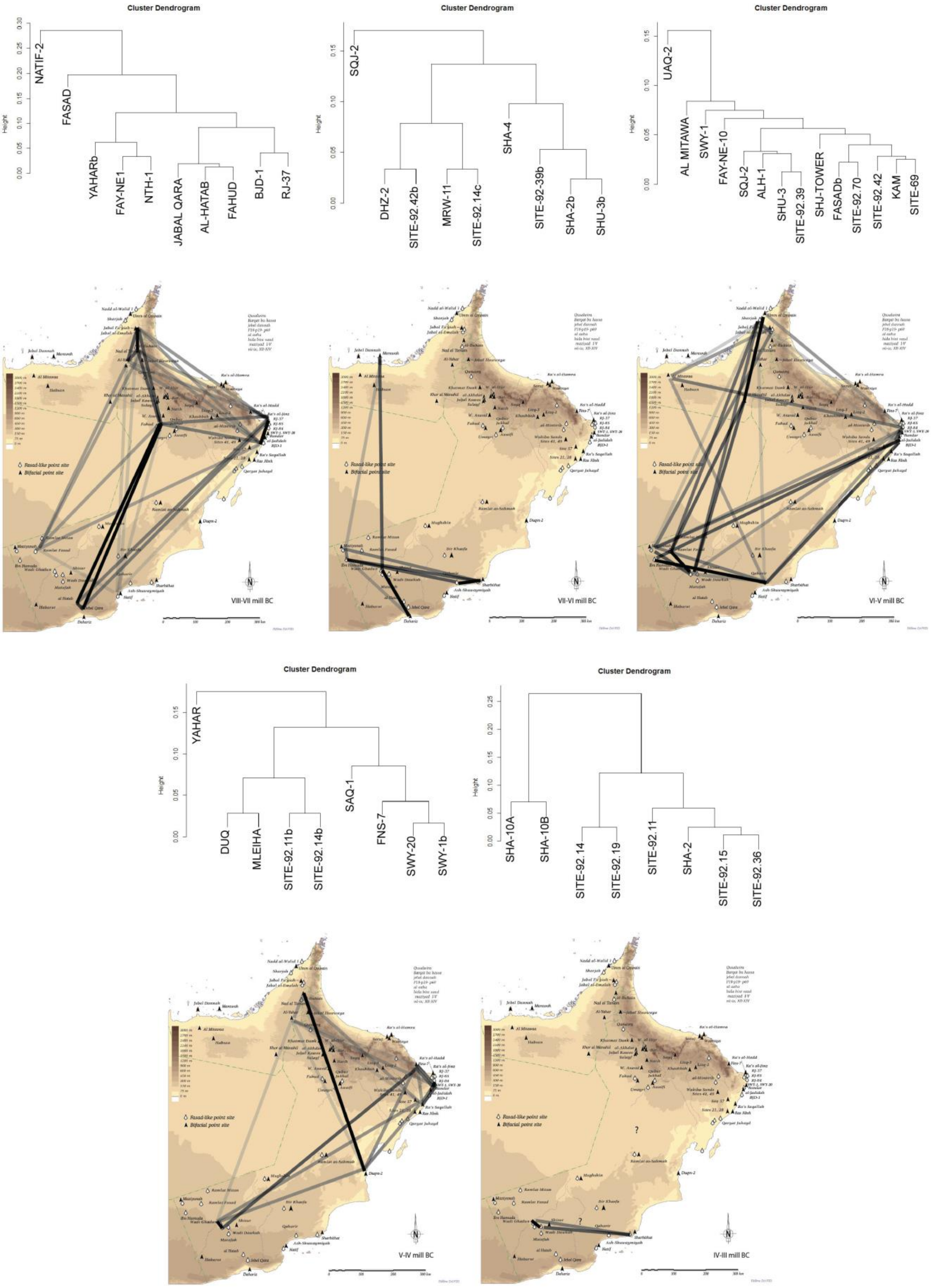

FIGURE 6 Maps of the study region showing pairwise inter‐site similarity as a measure of interaction. High similarity corresponds to full colour and 0 (absolute diversity) corresponds to a highly transparent line (maps modified after H. David‐Cuny, from Cleuziou & Tosi, 2018, fig. 27).

TABLE 4 List of ΦST values yielded by AMOVA analysis for chronological and geographic distances based on trihedral and Fasad distribution in Oman and UAE. AMOVA was performed using the function amova in package pegas in R (Paradis, 2010).

AMOVA - Fasad Points	AMOVA - Trihedral Points
Φ_{st}(region)= 0.1811092 p=0.01	Φ_{st}(region)= -0.03942239 p= 0.7263
Φ_{st}(date)= 0.3579412 p<0.001	Φ_{st}(date)= 0.05571486 p= 0.1409

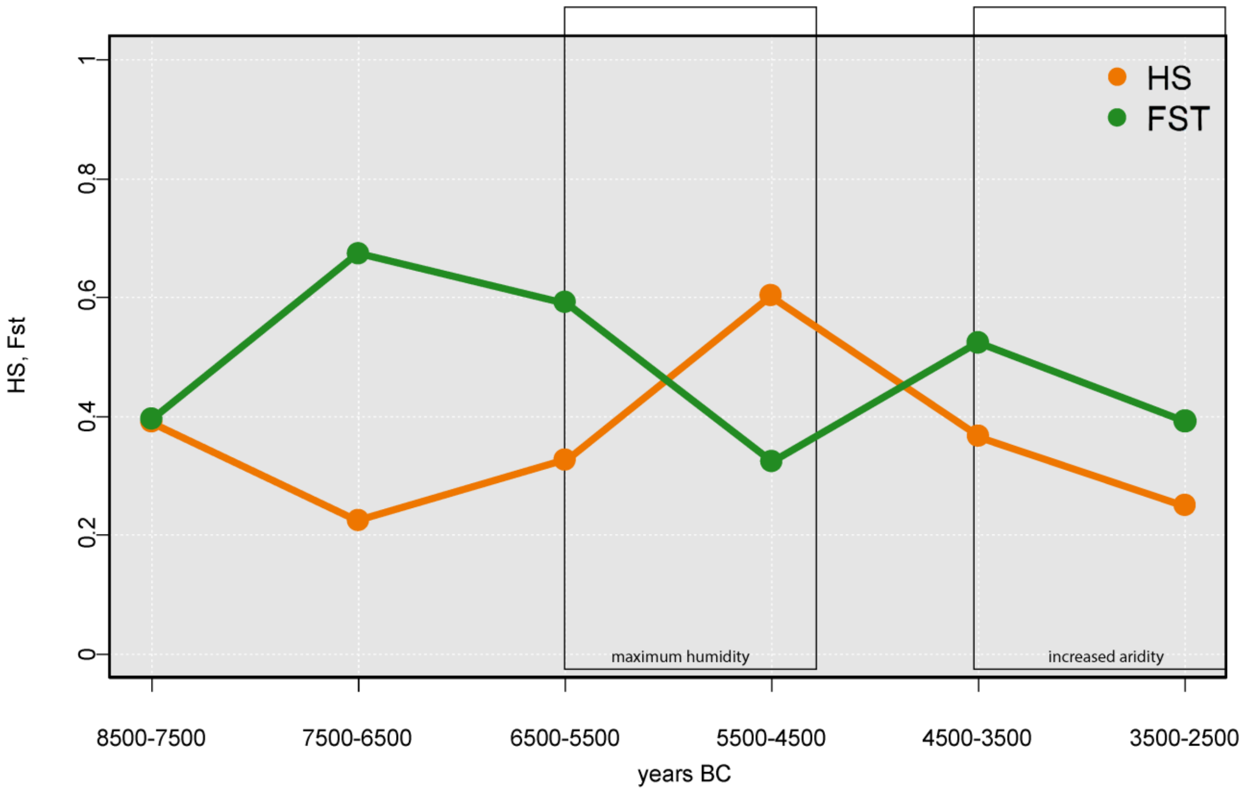

FIGURE 7 Comparison between the inter-site (FST) and intra-site (HS) diversity trends over cumulative chronological distance. Product-moment correlation coefficients are calculated at each chronological bin (size = 1000 years).

Conclusions and future implications

Results of exploratory analyses (PCA) point to the relevant role played by specific traits in driving morphological variation, such as retouch technique, basal medial and apical sections, blank, ventral and dorsal retouch symmetry, and some aspects of the retouch such as position and morphology. Critical change over time in the above mentioned traits is tightly related to the principal manufacturing techniques employed in point production.

The introduction of pressure techniques marks the most explicit passage from a primitive way of producing points denoted by shaping tang alone through direct percussion, to a new process entailing modelling of the entire shape following precise rules concerning symmetry and balance.

Once techniques based on pressure were ubiquitously adopted, variability was fuelled by the introduction of other sophisticated techniques such as parallel covering retouch and fluting. Their adoption affects shapes of sections (apical, medial, basal), and symmetry and morphology of retouch. In the last phase of the study period, as suggested by the points discovered at Sharbithat, there is a documented return to to the basic shaping with rough retouch and scarce preparation of very thick laminar blanks that were most frequent at the beginning of the sequence.

The null model based on the amount of interaction as the main driver of change in the frequency of non selective cultural variants (Neiman, 1995; Mesoudi & Lycett, 2009; Lipo et al., 1997; Newberry, 2018) would imply an expected pattern of decreasing diversification at a regional level due to higher intra-site diversity. Model expectations are met between 6500 and 4500 BC, when maximum humidity is reached and there is a much higher intra-site diversity than inter-site diversity. On the other hand, from the 4th millennium BC both intra- and inter-site diversity decrease against expectations. This might indicate either that projectile points do not conform to such a null model (i.e. the transmission of morphological traits does entail some level of selective pressure in this later phase), or that the complex, multi-scalar specificity of diversity results in a mild tendency towards the spread of specific forms that can be appreciated only at a regional level, while lower-scale differences emerge at a local level.

Through the suggested quantitative approach, this study demonstrated that a consistent classification of the projectile points is obtainable by describing the sample as a set of observable diagnostic technological and morphological traits.

Through the observation of diversity, it was possible to get some temporal and spatial distribution patterns which revealed a strong relationship between inter and intra-site diversity, time, and – possibly – climate. During periods of climatic regression, the vast desert as the plain between Ash Sharqiyah and al Wusta, but also that comprised between al Wusta and Dhofar, could have represented a natural barrier inhibiting regional exchange and isolating southern Oman where different technological solutions were developed (as suggested by the total absence of copper alloy items at Sharbithat, the oldest sites of Duqm and the Late Neolithic sites in the Rub al Khali). Comparisons between archaeological and palaeo-climatic contexts carried out by Preston and colleagues (2015), who merged data collected at Hoti cave (Fleitmann et al., 2007), Awafi (Preston et al., 2012) and Walahah (Preston et al., 2015), and generated probability density function plots of re-calibrated marine and non-marine dates collected from archaeological sites (Preston et al., 2015), demonstrated that at the end of the 5th millennium BC climatic instability following reduced precipitations did not favour human activities and generated the so-called Dark Millennium (Uerpmann, 2003). The increasing aridity recorded at the end of the Neolithic (which ends around 3700 BC) likely forced a reduction of inland settlement in central and northern Oman, while a few coastal settlements increased in size (Biagi, 1994), probably benefitting from greater ecological diversity.

To conclude, this regional and preliminary test demonstrates that arrowheads of southeastern Arabia exhibit quantifiable variation, and that a quantitative approach makes it possible to generate new, testable hypotheses through a series of reproducible descriptions, exploratory analyses, and results.

The shift in observational-analytical scale from point type to individual trait is therefore critical to apply this method to a wider, macro-regional context, and to reach a deeper understanding of the main mechanisms driving projectile point change in the Arabian Peninsula during the Early and Middle Holocene, which will be the focus of a future broader project.

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