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Hafit period fuelwood preferences associated with early copper production at Building V, al-Khashbah, Oman

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Summary
Analyses of archaeological fuel remains can provide insight into pyrotechnologies, resource management, and the local environment. In this paper, we examine archaeological charcoals from Hafit period (3300–2700 BC) levels in Building V at al-Khashbah (al-Khashaba), Oman, to understand fuel harvesting and burning preferences associated with early copper production. Building V is currently thought to be the earliest identified copper-production site in Oman based on the presence of abundant pyrotechnological remains, copper slag, and stratified radiocarbon results. Here, we build on previous anthracological work reconstructing woodland composition from the site. Anthracologists are increasingly recognising that fuelwood collection is often based on social or functional grounds rather than species availability. To that end, we have combined traditional taxonomic analysis with the application of dendro-anthracological methods to examine how intensive wood harvesting was for copper production and whether it had effects on the local vegetation. Dendrological reconstruction of wood calibre and condition at burning combined with spatial patterning of remains provides a more nuanced view of these preferences than can be achieved through taxonomic analysis alone.

Keywords: wood, environment, metalworking, Early Bronze Age, anthracology

Introduction

Understanding the development of early metallurgy is a major topic within the archaeology of Bronze Age Oman. Studies about Omani copper production in the Hafit and Umm an-Nar periods have focused on site prospection (e.g. Dumitru & Harrower 2018; Weisgerber 1980a; 1980b), artefact analysis (e.g. Döpper 2020; Giardino 2017), and archaeometallurgical analysis of pyrotechnic debris, ore, and metal objects (e.g. Begemann et al. 2010; Hauptmann & Weisgerber 1981). These approaches can provide important information on the location of ore sources and processing localities as well as details on pyrotechnological innovation.

Largely absent from such studies, however, is the consideration of the quantity and types of fuels required for copper production. Metallurgy and other forms of pyrotechnology require significant fuel inputs — in the past, this would have largely been derived from available woody biomass. In addition to providing further information on the pyrotechnological processes of metal production, fuel studies can document changes in the overall availability of wood and other fuel sources in dryland environments, the intensity/sustainability of wood harvesting, and the potential short- and long-term impacts of that harvesting on vegetation composition (Asouti & Austin 2005; Smith et al. 2015).

We present the results of an analysis of wood charcoal from Building V, a large so-called 'tower' structure dating to the Hafit period (3300–2700 BC) at the site of al-Khashbah, Oman (Fig. 1). Building V has yielded the earliest well-stratified evidence of a copper-production workshop in central Oman (Schmidt & Döpper 2019a). The present study was conducted within the broader framework of the UmWeltWandel Project (Hahn 2022), which explores human-environment relationships and climate change during the Early Bronze Age. Our goals for this analysis are to examine how early copper production sites in Oman were provisioned with fuel resources using Building V as a case study, and to consider the relationship more broadly between incipient Early Bronze Age copper production in Oman and local vegetation and resource availability. Specifically, we consider what fuel resources were available to Hafit-

Figure 1. *The location of al-Khashbah.*

period metalworkers at the site, and whether we can see any evidence for fuelwood preferences, intensity of fuelwood harvesting, or potential overexploitation.

Anthracological analysis of fuelwood

Fuel remnants can be used to assess the overall composition of local woodland fuel stocks. Analyses of wood charcoal provide insights into woodland composition, harvesting and management strategies, and long-term changes in both over time (Asouti & Kabukcu 2021). Anthracologists have long debated the role of fuel choice in producing charcoal assemblages, including whether fuelwood is harvested in proportion to its abundance in the landscape or whether people express preferences regarding species, functional characteristics, or some other culturally determined characteristics (Asouti & Austin 2005; Marston 2009; Smart & Hoffman 1988). Anthracological vegetation reconstruction has generally relied on the application of the 'principle of least effort' (Shackleton & Prins 1992), which hypothesizes that, all other factors being equal, people will tend to collect firewood taxa in proportion to their availability and proximity on the landscape. Critiques of this approach point out that eliminating preferences in this way hinders our understanding of both culturally conditioned and functional aspects of fuel management (e.g. Delhon 2021). Furthermore,

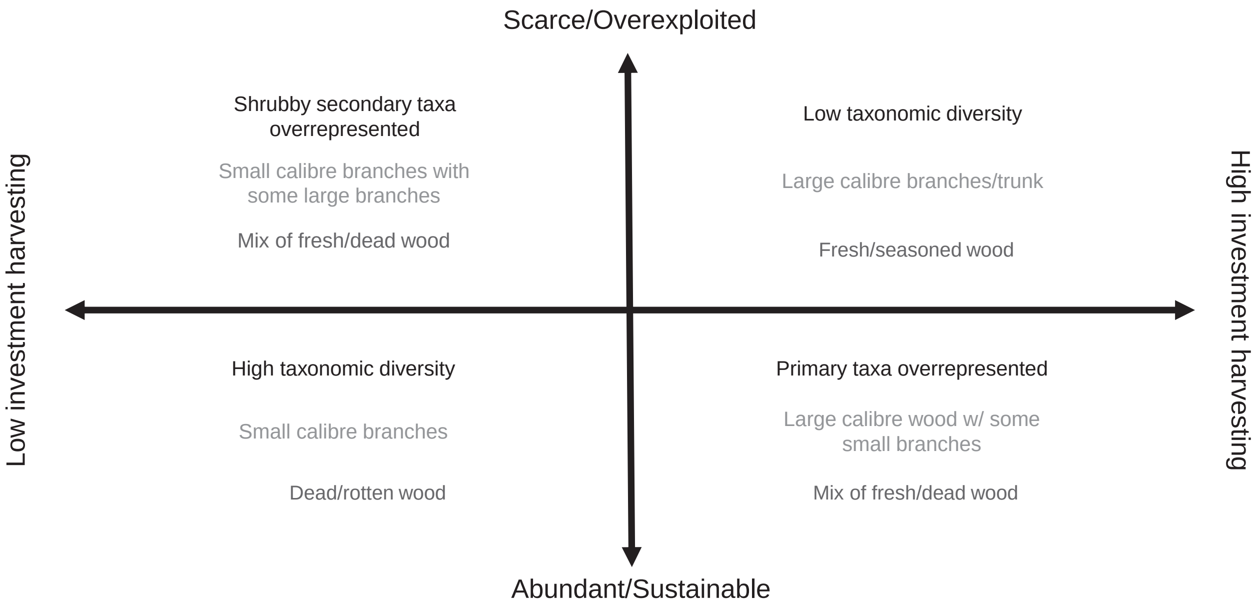

Figure 2. *Schema for interpreting dendro-anthracological data from fuel remains.*

ethno-archaeological studies of fuel use increasingly suggest that wood species itself may not be a particularly important factor for decision making during fuel harvesting choices compared to other characteristics of wood such as condition, size, ease of cutting, etc. (e.g. Henry et al. 2018; Picornell-Gelabert 2020), with the consequence that anthracological datasets could speak to both palaeo-vegetation and fuel managements provided those characteristics can be identified.

New methodological applications in anthracology utilizing qualitative and quantitative dendrological approaches provide tools for assessing non-taxonomic preferences and harvesting intensity (e.g. Marguerie & Hunot 2007; Kabukcu 2018; Wright 2018; Dufraisse et al. 2018; 2022). These types of data provide important information on wood condition, branch size, environmental stressors, and even evidence of coppicing/pollarding. However, these measures were developed for, and in the context of, analyses of deciduous temperate and alpine forests found throughout Europe. Abundant charcoal remains, clear seasonal growth patterns, and a large body of archaeological and experimental work on forest management in these regions aids in the detailed reconstructions of past woodlands. To date, few studies have employed these methods to dry-land regions in south-west Asia (but see Proctor 2021; Wright 2018) and none has yet been conducted on charcoal from Arabia.

To evaluate the results of taxonomic and dendrological analysis of wood charcoal from Building V and place them within the context of both wood-harvesting strategies and woodland composition, we adopted a simplified heuristic model based on two interpretative axes (Fig. 2). This schema assumes pre-industrial fuel harvesting without the aid of iron tools. The first axis represents the abundance of trees and overall health of woodlands, ranging from few/overexploited trees at one end to abundant/sustainably harvested trees at the other. The second axis represents the overall investment of time and energy devoted to wood harvesting. In each quadrant of the schema, we have listed the dendro-anthracological results we might expect in each situation. For example, in a dataset generated by low-investment fuel harvesting in a relatively abundant fuelwood environment, we might expect to find a relatively higher diversity of taxa represented, including dominant taxa, as well as higher proportions of small-calibre branches and deadwood expediently collected for fires.

Al-Khashbah

The oasis village of al-Khashbah is in the Ash Sharqiyah North (Shamāl al-Sharqiyya) governorate of Oman to the north-east of the city of Sinaw. The local area immediately surrounding the village preserves a rich archaeological landscape, with evidence of repeated occupations spanning the past 7000 years. The most visible and well-known archaeological features in the vicinity of al-Khashbah are a series of nine monumental mud-brick and stone-built structures dating to the Early Bronze Age, often referred to as 'towers'. These towers are located across an area of almost 10 km^2 adjacent to Wādī Samad, which runs just north of the modern oasis and village.

Archaeological research at al-Khashbah

Archaeological investigations at al-Khashbah were first reported by Weisgerber (1980a), who described the presence of several Early Bronze Age 'tower' structures. Al-Khashbah was also included in Al-Jahwari's 2004–2006 Wādī Andam survey (2008) as one of its six key sites in the region. Since 2015 a German research project from the University of Tübingen has conducted archaeological survey of the area (Döpper 2022; Herrmann et al. 2018; Schmidt & Döpper 2017) and targeted mapping and excavations of several of the towers (Schmidt et al. 2021; Schmidt & Döpper 2019b) This work has resulted in the identification of over 300 structures, largely dating to the Hafit and Umm an-Nar periods, in the vicinity of al-Khashbah. Importantly, excavation of two of the so-called towers, Buildings I and V between 2015 and 2019, has provided unprecedented information on the nature of Hafit period occupational sites and early copper production in Oman (Schmidt & Döpper 2019a).

Excavations and magnetometry at Building I revealed the presence of three roughly rectangular structures constructed out of mud brick, surrounded by 3 m-deep ditches. Due to erosional processes, only one of the structures was completely preserved and consists of small compartments. Radiocarbon dates from *in situ* charcoal recovered from stratified deposits provide consistent dates clustering around *c.*2800 cal. BC, with a few dates stretching back to *c.*3100 BC. Finds from Building I consisted largely of lithic debris and tools (Ochs et al. 2020), fireplaces, and some copper slag and crucible fragments. The function of the large ditches surrounding these structures remains unresolved, but current working hypotheses suggest they were used for water management or flood control.

Building V

Building V, located 1.5 km to the east of Building I where a rocky limestone ridge meets the southern bank of Wādī Samad, provides the earliest evidence to date of a copper-production workshop (see Schmidt & Döpper 2019a for a detailed description of the excavations). This structure consists of a large, circular limestone structure overlying bedrock that has a diameter of *c.*24 m (Fig. 3). Excavation of Building V began in 2015 with a small test trench and was subsequently expanded to include the entire south-eastern quadrant of the structure and several extensions into exterior areas to its south. Excavators were able to define two distinct occupational phases at the site, based on stratigraphy and radiocarbon dating — dates for these two occupational phases cluster around *c.*3300–3000 BC for the earlier phase and 2900–2700 BC for the later phase (Schmidt & Döpper 2019b: 273). The earlier phase consisted of a layer of several rooms (see Fig. 3 for the location of specific rooms) constructed out of mud brick, with a subsequent rebuilding of the original structure using stone masonry and foundation trenches cutting through parts of the original mud-brick structure. Outside the structure, three non-parallel stone walls were discovered. Accumulations of stone debris and waste from copper processing, including slags and prills as well as crucible fragments, were present between the tower and these smaller stone walls. The later phase consists of a layer of yellowish sediment overlying and sealing the earlier architectural remains, which also contained copper production debris. Charcoal remains from both phases were encountered in the interior and exterior of the structure.

Building V presented copious evidence for copper production, including slag and crucible fragments, copper ore, prills, and copper objects in both phases of occupation (Fig. 4). However, no *in situ* pyrotechnic features were identified inside the building and the evidence for copper production largely comes from

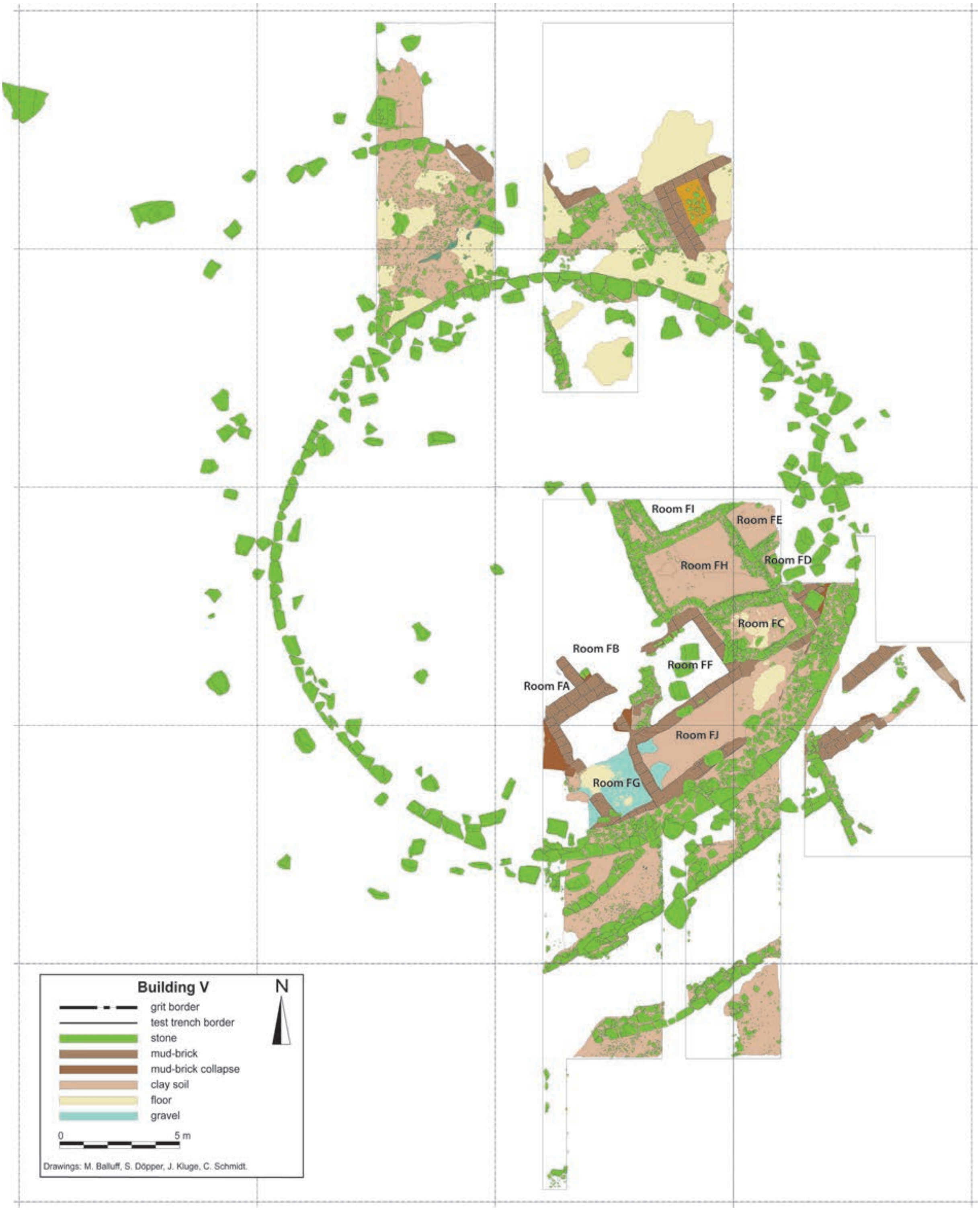

Figure 3. *Overall plan of Building V excavations with rooms labelled.*

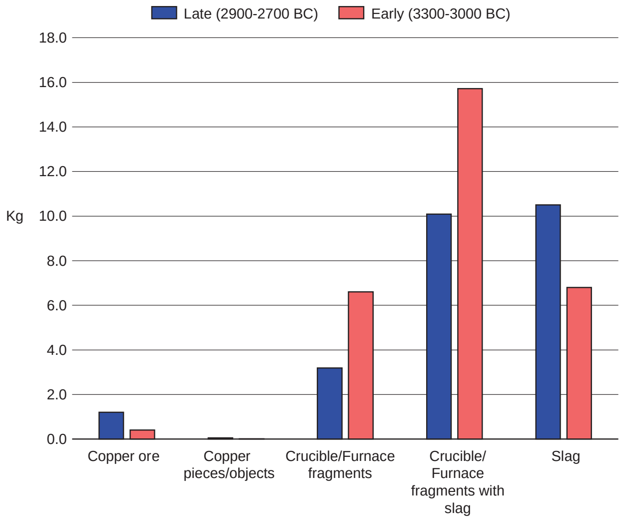

FIGURE 4. *A bar chart showing the relative weight in kilograms of copper-production materials by occupational phase.*

secondary and tertiary fill deposits. Surface finds were mapped and collected during a pedestrian survey of the building in 2015 prior to excavation. In general, there was a greater concentration of finds outside the building than inside, with concentrations of slag immediately to the south of the exterior wall and crucible fragments strewn across the limestone ridge to the west of the building (Döpper 2020). Excavations to the south of the building and in its interior revealed further quantities of slag, crucible fragments, and copper debris below the surface, confirming that copper-production activities occurred during the use-life of the building.

Palaeo-ecology and woodland resources at al-Khashbah

Palaeoclimate evidence from south-eastern Arabia has documented a period of markedly increased humidity (often referred to as the Holocene Humid Period) during the Early and Middle Holocene related to a northward shift in the ITCZ due to orbital precession (Lüning & Vahrenholt 2019). However, this shift began to reverse between 5000 and 3000 BC, resulting in the progressive aridification of the region as summer monsoon precipitation retreated southwards (Lézine et al. 2017; Preston & Parker 2013). This aridification appears to have had significant impacts on wadi discharge and potentially resulted in the reorganization of settlement patterns during the Early Bronze Age (Beuzen-Waller et al. 2022).

Unfortunately, there is little available information on palaeo-vegetation for the southern Hajar piedmont, its responses to the end of the Holocene Humid Period, or how it may have differed from the modern vegetation community. In order to establish a modern baseline from which to compare with the archaeological data, we conducted an informal qualitative survey of woody vegetation in the vicinity of al-Khashbah in 2021–2022, as part of an overall study of the local environment for the UmWeltWandel Project. The local vegetation in the region today is heavily impacted by human activity, including animal husbandry, oasis agroforestry, fuel consumption, and significant lowering of the water table due to pumping and irrigation. The dominant tree cover in the area consists of two species of acacia (*Acacia sensu lato*: *Vachellia tortilis* [Forssk.] Galasso & Banfi and *Vachellia flava* [Forssk.] Kyal. & Boatwr.) and ghaf (*Prosopis cineraria* (L.) Druce), which form the main components of an open 'pseudo-savanna' woodland (Fig. 5) found throughout relatively moister wadi-drainage areas of the southern Hajar piedmont zone (Ghazanfar 2003). There are at least ten different species of acacia found throughout Oman today (Ghazanfar 2007). Heavily overgrazed *Maerua crassifolia* Forssk. forms a secondary component of these woodlands. *Ziziphus spina-christi* (L.) Desf. was rather under-represented in the survey area outside cultivated areas but is more common to the north and west of the site, particularly near seasonally moist watercourses and depressions. At least two other species of *Ziziphus* can be found in northern Oman today — *Z. nummularia* (Burm.f.) Wight & Arn. and *Z. hajarensis* Duling, Ghaz. & Prendergast — but these have yet to be observed in the modern survey of the area.

Besides these trees, shrubs and low-lying woody taxa are common in the area, including various chenopodiaceous shrubs, *Lycium shawii* Roem. & Schult., *Salvadora persica* L., as well as *Leptadenia pyrotechnica* (Forssk.) Decne. Finally, in areas of Wādī Andam, where standing water can be found, stands of tamarisk (*Tamarix* spp.) grow in active wadi channels and along wadi banks. Date palms today are restricted to cultivated oases in the area, although modern wild stands have

Figure 5. *Representative photograph of vegetation showing mixed* Acacia *and* Prosopis *woodland near Lizq.*

previously been identified in Oman (Gros-Balthazard et al. 2017) and may have been present locally in the past if conditions were somewhat moister.

The present study builds upon previous work at al-Khashbah by Deckers, Döpper and Schmidt (2019) comparing wood charcoal from the 2015–2017 excavations at Buildings I, II, and V with analysed remains from the Umm an-Nar site of Bat. Deckers, Döpper and Schmidt identified the presence of *Acacia*, *Ziziphus*, tamarisk, palm, and *Moringa* sp. at al-Khashbah during the EBA but found no sign of significant vegetation change compared with today. In this study we analyse further samples from Building V and consider not just vegetation composition during the Early Bronze Age, but whether there is evidence of fuel selection preferences for copper-production activities.

Methods

Wood charcoal examined in this analysis was systematically recovered from Building V by dry sieving hand-picked remains visible during excavation. In total, 297 previously unexamined hand-picked samples collected between 2016 and 2018 were included in this study. Multiple samples were collected from each context, as encountered by the excavators, for a total of sixty-five unique contexts from two separate archaeological phases. All examined samples were processed following standard anthracological procedures. Samples were sieved to remove contaminates and small fragments. Charcoal pieces > 4 mm in size were selected for further analysis, counted, and weighed. The analysis was limited to this size class due to the necessity of having a sufficiently large view of the transverse section to accurately assess wood curvature degree for the dendrological analysis. While the examination of charcoal > 2 mm is relatively common, previous studies have argued that > 4 mm mesh sizes provide 'excellent results relative to sampling effort, and large enough fragments to facilitate accurate microscopic identification' (Kabukcu & Chabal 2021: 11; see also Chabal 1992). Each fragment was sectioned manually along its transverse, radial, and tangential section in order to clearly view its internal morphology and examine it individually using both low-magnification stereomicroscopy (Leica S6E) and high-magnification reflected light microscopy (Leitz Laborlux S, Leica DM4000M for photography). Visible morphology was then compared to various published wood identification guides (e.g. Akkemik & Yaman 2012; Jagiella & Kürschner 1987; Neumann et al. 2001), the African Wood Reference Collection at Goethe University Frankfurt, and local reference wood collected by UmWeltWandel. Due to differential preservation conditions and overlap in internal wood morphology between different tree species, identifications can rarely be made to the species level and are typically restricted to genera. Identifications, therefore, follow the 'type' concept, where identification distinctions are made based on the observation of diagnostically relevant anatomical differences, but may not always be able to reflect taxonomic differences at the species level.

This study represents a first attempt to explore whether the dendrological metrics frequently used by anthracologists in temperate Europe, such as wood calibre and wood condition, have potential in the study of desert fuel use in dry-land environments. Such methods have not previously been applied to wood charcoal studies of desert vegetation in Arabia. During examination, various morphological features and qualitative observations were made following published methodologies (e.g. Kabukcu 2018; Marguerie & Hunot 2007), including qualitative estimates of branch size based on ring curvature and ray orientation, evidence for the presence of dead or rotting wood in the form of internal fungal hyphae, as well as insect damage, vitrification, and other metrics. Ring curvature was estimated following the qualitative method used by Marguerie and Hunot (2007), and categorized as weak (CD1), intermediate (CD2), or strong (CD3). Because growth ring boundaries are frequently absent in wood species from the tropics, we also qualitatively compared the relative angle of divergence between rays in transverse section to wood examples of known size to roughly estimate distance from pith as an alternative method when necessary. The ratio of weak ring curvature/low ray divergence CD1 to strong ring curvature/high ray divergence CD3 provides a rough estimate of the proportion of large branches to small branches or twigs. Importantly, however, CD2 and CD3 fragments are also found within the interior of large branches rather than exclusively in small branches and twigs. Finally, the presence of bark and pith was also recorded, and fragments of both, less than 10 mm in size, were categorized as twigs. Twigs were not commonly encountered in either the > 4 mm fragments examined here or in < 4 mm sieved fractions.

Results

Taxonomic identifications

In total, 647 fragments of wood from sixty-five different contexts related to two phases of occupation in Building V were analysed in this study. In general, the diversity of taxa identified was somewhat low, with only ten unique genera identified. However, this is in line with previous studies of Early Bronze Age charcoals from the region, including Deckers, Döpper and Schmidt (2019) and Eckstein, Liese and Stieber (1987). In particular, the taxa identified in this study and their relative proportions closely match the previous Hafit period results from al-Khashbah produced by Deckers, Döpper and Schmidt (2019: 12), despite that study having examined a far larger dataset, suggesting that this low diversity is representative of the site as a whole.

Ziziphus was the single most abundant individual taxa in the dataset, accounting for 46% of the entire assemblage (Fig. 6). It was not possible to differentiate the various species of *Ziziphus* in this assemblage based on wood anatomy, although we may hypothesize that *Z. spina-christi* is the most likely candidate based on modern distribution and diameter estimations. Fabaceous taxa, meanwhile, accounted for 47% of the dataset, but can be divided into two types: *Acacia* and *Prosopis cineraria. Prosopis* (3%) was distinguished from other fabaceous charcoals on the basis of low, narrow

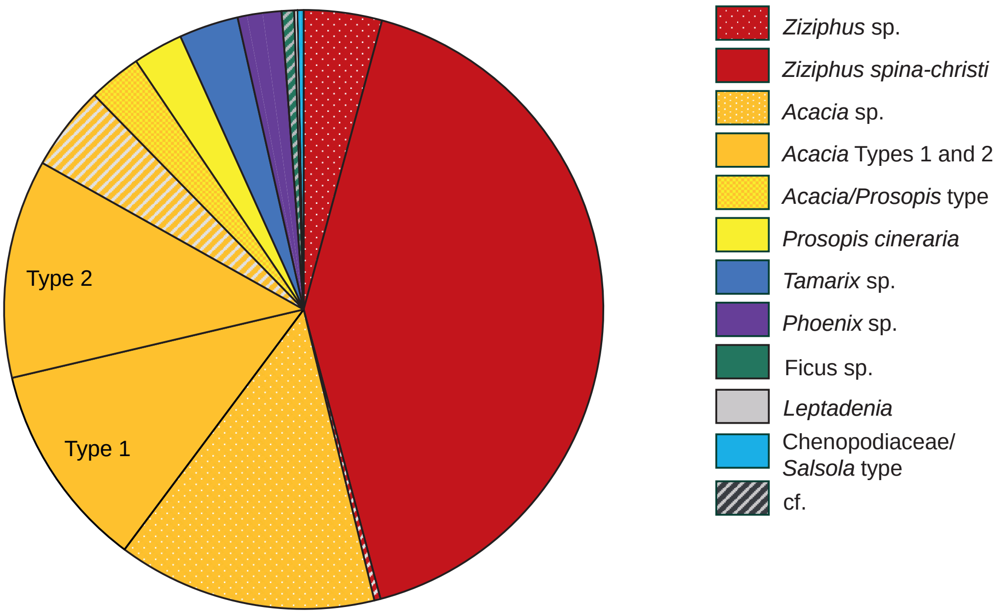

FIGURE 6. *A pie chart showing the overall taxonomic composition of charcoal from Building V.*

(generally bi- or tri-seriate) rays, relatively smaller vessel diameters, and a slight tendency towards vasiocentric parenchyma over aliform-confluent parenchyma (however, this feature is highly variable between the two genera). Additionally, the features allowed the distinction of two relatively consistent types of *Acacia* (37%). *Acacia* Type 1 represents fragments with high and low rays that are generally 3–6 cells wide, while Type 2 consists of consistently medium-height rays with widths up to ten or more cells wide. In both cases, parenchyma was aliform-confluent type, but Type 2 had larger, more often solitary vessels compared to Type 1 (Fig. 7).

The remaining taxa represent only 7% of the assemblage. Of these, tamarisk (*Tamarix*) and date palm (*Phoenix*) were the most abundant of the minor taxa, each representing only 3% of the assemblage. Date palm contributed slightly less than 3% of the entire assemblage and was able to be further differentiated into stem and petiole wood based on the organization of vascular bundles in the transverse section following Thomas (2013). A single date stone (Fig. 8) was also identified among hand-collected wood in sample KSB19H-q0244. Probable fig (cf. *Ficus*) accounted for less than 1% of the assemblage, while cf. *Calotropis* was identified in a single sample that probably post-dates the rest of the Building V occupation. Two fragments of Chenopodiaceae were identified. While Chenopodiaceae generally cannot be distinguished, one fragment was consistent in anatomical morphology with *Salsola*-type wood based on the organization of its included phloem, the presence of pseudo-rays, and vessels organized in radial multiples rather than clusters. Notably, *Maerua crassifolia* was not observed at all in this dataset, despite being relatively common in the area today.

Taxonomic results by phase and context

The results of this analysis were considered by occupational phase to track potential changes in fuel management over time. The overall composition of remains from the earlier phase (3300–3000 BC) of Building V is largely consistent with the later phase,

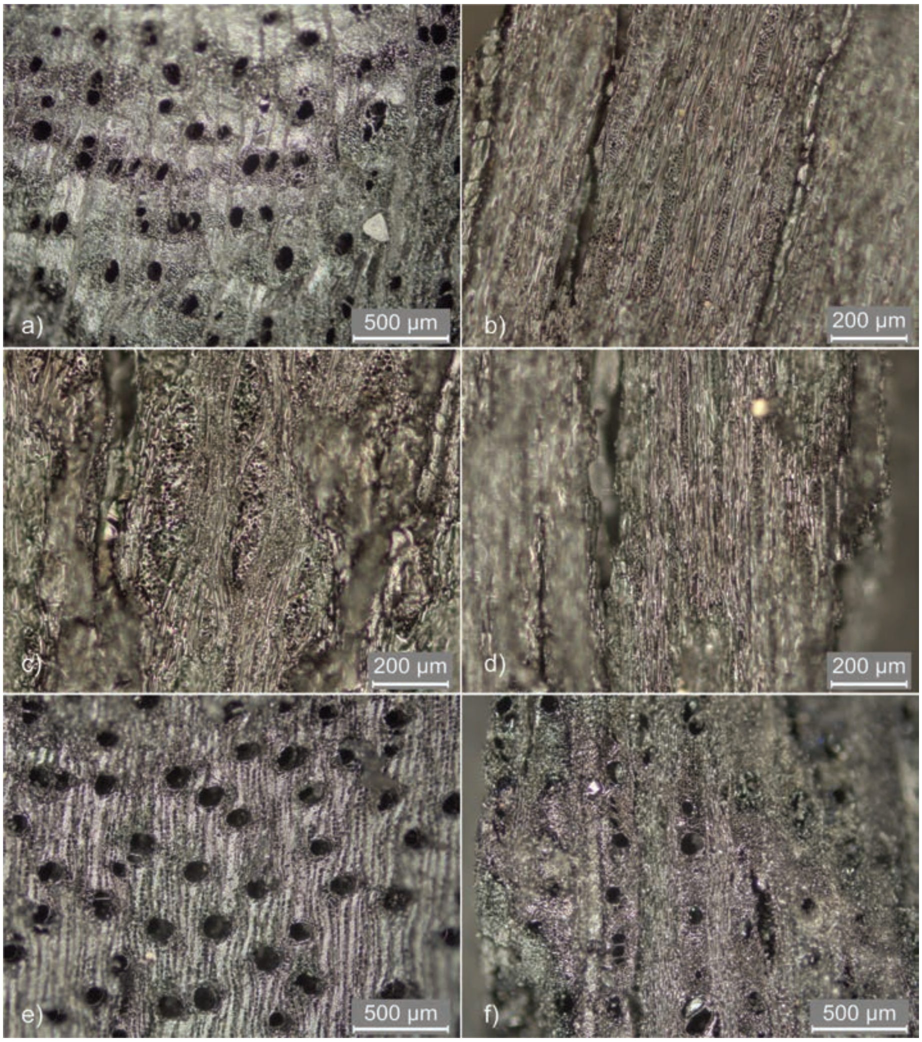

Figure 7. *Images of select identified wood taxa:* ***a.*** Acacia, *transverse section;* **b.** Acacia *Type 1, tangential section;* **c.** Acacia *Type 2, tangential section;* **d.** Prosopis cineraria, *tangential section;* **e.** Ziziphus, *transverse section;* **f.** Tamarix, *transverse section.*

Figure 8. *Date stone (*Phoenix dactylifera*) found in KSB19H-q0244.*

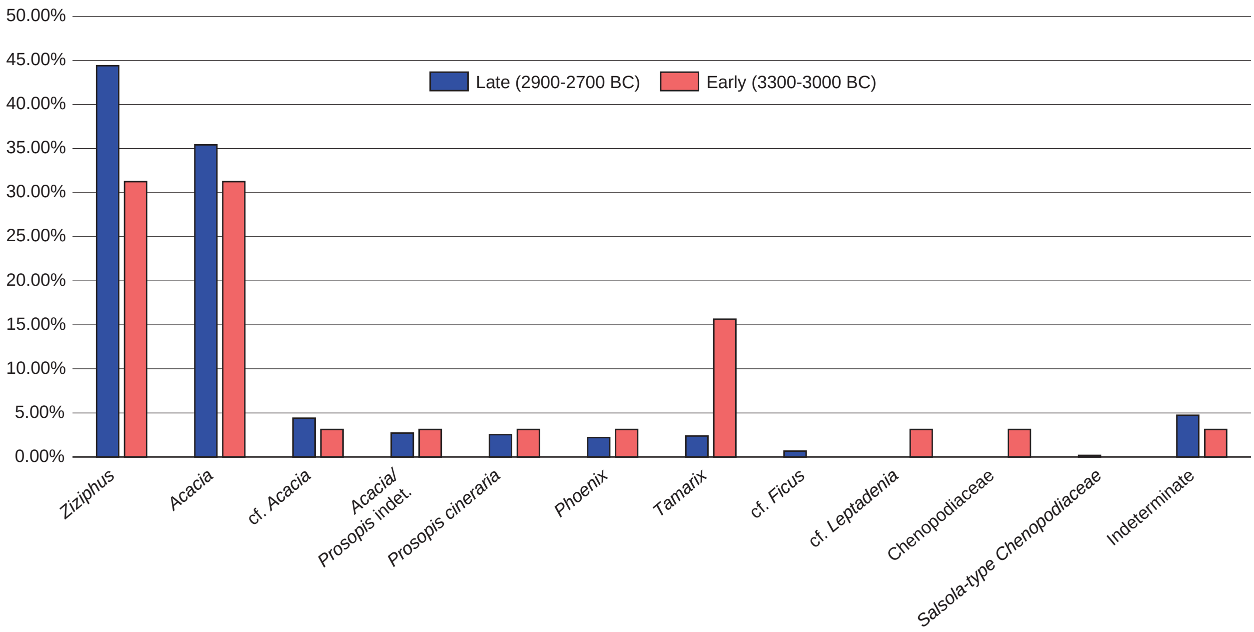

Figure 9. *A bar chart comparing taxonomic results for early and late phases at Building V.*

with a few minor differences (Fig. 9). *Ziziphus* is somewhat under-represented in the early samples compared to the later period (31.2%), while *Tamarix* makes up over 15%. The remaining taxa are mostly solitary fragments. The increased proportion of *Tamarix* might signal somewhat moister conditions in the wadi beds surrounding the site. However, it should be noted that specimen counts for this phase are low, owing to fewer available samples to analyse. Because of this, caution should be taken when interpreting the results from this phase. Minor taxa with low overall representation are susceptible to exaggerated shifts in relative proportion when the overall count is low, therefore the inferences that can be derived from the earlier Hafit occupation are limited. Owing to uneven sample coverage between the interior and exterior during this phase, few spatial inferences can be made for the early phase. Most of the identified fragments from the earlier phase come from refuse contexts outside the building and consisted of *Acacia* (62.0%) and *Tamarix* (23.0%). This area also contained greater concentrations of crucible fragments and a relatively high proportion of small pieces of copper compared to the interior of the building. Notably, *Ziziphus* from this phase was totally restricted to two interior contexts, Rooms FM and FE (see Fig. 3), with single fragments of Chenopodiaceae, *Acacia*, and *Tamarix.*

The vast majority of the identified charcoal from Building V belongs to the later phase (2900–2700 BC) deposit. *Ziziphus* (44.4%) and fabaceous taxa (45.0%, mostly *Acacia*-type = 35.4%) dominate the later Hafit assemblage. Tamarisk and date palm follow at much lower relative abundances (2.4% and 2.2% respectively). Samples for the later phase were distributed throughout the fill of several rooms in the interior of the building. The greatest concentration of charcoal was found in the centre of the structure, overlying Room FB (see Fig. 3), and was associated with slag, slag-bearing crucible fragments, and copper objects, as well as a grinding stone and several hammer stones. The charcoal samples here have higher proportions of *Acacia* (55.4%) compared to other areas. Meanwhile, *Ziziphus* was most abundant in the later phase near Rooms FE (62.1%), and FH (59.5%), where there was a concentration of animal bones found in the same layers (Schmidt & Döpper 2019a: 18–19). The data for

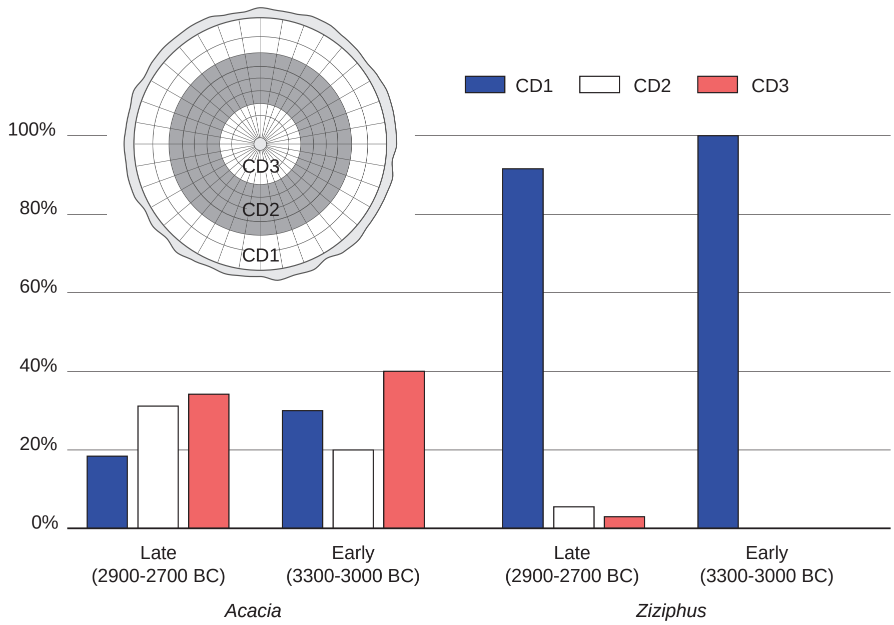

FIGURE 10. *Qualitative curvature analysis results for* Acacia *and* Ziziphus *specimens. CD1 = weakly curving wood; CD2 = intermediate curving wood; CD3 = strongly curving wood.*

the exterior of the building from this phase is limited, but a single sample consisting of nine fragments of wood yielded equal proportions of *Ziziphus* and *Acacia* wood. The clear spatial differentiation of *Ziziphus* in both phases might suggest a taxonomic preference for different activities.

Dendro-anthracological results

Wood specimens from Building V exhibited very low rates of insect damage (1.82% for *Ziziphus*, 4.66% for *Acacia/Prosopis*, a scant amount for the remaining taxa) and fungal infestation (1.45% for *Ziziphus*, 1.01% for *Acacia/Prosopis*), indicating that dead and rotting wood was not commonly used. Radial cracking was observed in 11.2% of the assemblage (n = 73), of which all but eleven fragments belonged to fabaceous (*Acacia* and *Prosopis*) wood. Similarly, 11.1% of the assemblage (n = 72) showed evidence of vitrification. Among fabaceous wood, 20.5% was vitrified while it was recorded for only 1.8% of *Ziziphus*. Ring curvature was successfully estimated for 482 fragments of identified wood in the assemblage. The vast majority of these data come from *Ziziphus* (n = 276) and *Acacia* (n = 173). The results indicate that larger *Ziziphus* branches were common, with over 90% of fragments categorized as having CD1, while there was a more mixed signal in *Acacia* (Fig. 10). *Acacia* also shows a slight increase in the proportion of CD1 fragments from the early to late phases of Building V (change from 40% to 34.2%), suggesting there may have been somewhat of a shift through time towards the harvesting of larger branches on average. However, low fragment counts for the early phase limit the strength of this comparison. Only two twigs, defined as strongly curved wood fragments with both pith and cambium visible, were observed, one Chenopodiaceae and one cf. *Acacia.* A visual scan of fragments < 4 mm from the assemblage not examined in this study did not find frequent twigs, therefore the low proportion of these in the assemblage does not reflect the size of the analysed specimens. Given the low specimen counts for the earlier phase of occupation, spatial differences in dendrological data, which must be considered on a taxon by taxon basis, will not be considered here.

Discussion

The taxonomic composition of charcoal from Building V is dominated by two major taxa, *Acacia* and *Ziziphus*, with only minor contributions of other trees, including ghaf, tamarisk, and palm. The relative frequencies observed in this dataset agree strongly with the assemblage from Buildings I, II, and V previously examined by Deckers, Döpper and Schmidt (2019) for the Hafit and Umm an-Nar periods. In this study, however, we were able to further delineate *Acacia*-type wood into *Prosopis cineraria*, two consistent types of *Acacia* sp., and indeterminate/intermediate forms based on anatomical markers.

Broadly, the charcoal data correspond to modern vegetation in the region. However, *Ziziphus* is somewhat over-represented in the Hafit dataset (L. Proctor, pers. obs.), while *Maerua crassifolia*, which today forms a secondary component of overgrazed acacia woodland in and around the wadi channels of the area, was completely absent from the assemblage. It is unclear why *Maerua* is absent from this dataset, but there are two possible explanations: 1) *Maerua* was absent in the Hafit period but became more common in recent times; 2) it was specifically excluded as a fuel source. The first option seems unlikely, as *Maerua crassifolia* is commonly found in association with *Vachellia tortilis*, *Ziziphus spina-christi*, *Salvadora persica*, and other common elements of Sahelian vegetation throughout southern Arabia (Ghazanfar 2003: 2–3) and North Africa (White 1983: 206–207). The author has also been able to identify small proportions of an ongoing reanalysis of charcoal from Building I, which will be presented in a future publication. The second option — that it was deliberately excluded as a fuel at Building V — seems to be the most likely explanation. Why that is the case, however, remains unclear. *Maerua* is a soft and moist wood when fresh, therefore may not have been considered to be a good fuel candidate without drying and aging. It is also heavily browsed by herd animals and bees, so perhaps it was excluded as a fuel in favour of its use as fodder for goat herds and wild animals.

Meanwhile, the presence of tamarisk, which is not found in the immediate vicinity of the site today, may suggests greater moisture availability in Wādī Samad than is present today. Tamarisk grows in brackish, water-receiving soils near wadis. The nearest modern sources of tamarisk are nearly 20 km to the north in Wādī Andam and to the north-east beyond Lizq. The presence of tamarisk at Building V may therefore provide evidence for greater water inputs in Wādī Samad during the Hafit period, although localized modern deforestation of the wadi beds cannot be entirely ruled out.

This analysis also yielded some evidence of potential non-fuel related activities. Deckers, Döpper and Schmidt (2019) reported a small percentage of date-palm (*Pheonix dactylifera*) wood in their initial study of Building V material, including both stem and petiole wood. In this analysis, we were also able to identify a small proportion of date palm, again including both stem and petiole wood, as well as a date stone. It is not possible to say conclusively whether these remains represent cultivated or wild date, but the combination of both date wood and stones points towards the intentional use of date at Building V during the Hafit period. Dates appear in the archaeobotanical record of south-eastern Arabia on the coasts by the beginning of the fifth millennium BC, but current debates on the beginnings of date-palm cultivation, gardening, and the development of oases are ongoing (Charbonnier 2017).

Wood harvesting at al-Khashbah

Returning now to the interpretative model introduced above, there does not appear to be evidence for overexploitation of woodlands. While the overall diversity of the assemblage was rather low, the assemblage is primarily represented by large, dominant trees with good quality fuelwood, including *Ziziphus*, *Acacia*, and *Prosopis*. Relatively few small, shrubby taxa were present, and only in small quantities. If available trees were scarce, we would expect to find a greater proportion of small shrubby taxa. These results fit with what one should expect for the Hafit period. While the late fourth and early third millennium BC represent periods of increasing aridity in the region, the recent introduction of metalworking, relatively small-scale production, and the low density of occupation suggest that even intensified fuel harvesting for copper production is still unlikely to have had much of an impact on woodland resources.

The results of this study also suggest an intensive harvesting strategy was employed, as evident from the higher proportion of large-diameter wood fragments in the assemblage and the overall lack of evidence for the use of dead and rotting wood. Low rates of fungal hyphae and insect damage suggest that fuelwood used at Building V was sourced from freshly cut or seasoned wood rather than deadwood. While dry conditions may offer an alternative explanation for the lack of fungal hyphae in the dataset, our observations of modern wood resources suggest that insect damage occurs rapidly and abundantly in dead and fallen branches in the region today, and therefore should be present if deadwood was collected. Fallen branches and rotting wood can be collected from the ground by hand or easily broken from trees as it decays. Meanwhile, an emphasis on fresh-cut wood would represent a considerable investment of time and energy, as acacia and ghaf wood in particular are dense and challenging to cut by hand, even with modern steel tools. Experimental studies have shown that tree species, diameter, and tool type (stone or metal) affect the amount of effort required to fell trees by hand (e.g. Mathieu & Meyer 1997).

Our results suggest that large-calibre branches of both *Acacia* and *Ziziphus* were used at Building V based on the relative proportion of CD1 to CD3 wood fragments (see Fig. 10). Studies employing this methodology have tracked increasingly intensive fuelwood harvesting practices in other areas of south-west Asia (Marston, Kováčik & Schoop 2021; Proctor 2021). However, caution is required when interpreting these results. The *Ziziphus* data had a far lower proportion of CD2 and CD3 fragments than expected, even for large branches. It is unclear why this was the case, but we cannot eliminate the possibility that this represents a limitation in the utility of the ray divergence estimation method for taxa with abundant uniseriate rays. Quantitative methods using trigonometric calculations may therefore be more appropriate for estimating *Ziziphus* branch size in the future, as they provide greater precision in estimating pith distance and cambial age (Deckers et al. 2021). However, such techniques suffer from lengthy analysis and the need for quantitative image analysis software.

Copper production and fuel requirements

Owing to the high transport costs of both metal ores and fuel, roasting and smelting are often thought to occur relatively close to ore sources. Copper outcrops can be found within 10–20 km of the site in the vicinity of al-Wāshiḥī, al-Shuwāʿī, and al-Muyassir, but not located in the immediate area of al-Khashbah. That said, a concentration of copper ore was recovered from Building V, suggesting at least some smelting was occurring in the vicinity of the building. One possibility is that Building V was used for metalworking due to its location near wadis with more abundant tree cover. However, proving this hypothesis is challenging. The data presented in this study cannot give indications of the overall availability of woody biomass in the area, and it is generally only possible to estimate broadly the number of trees on a past landscape.

In a comparative analysis of pyrotechnology from across the ancient world, Rehder (2000) estimated the fuel inputs for each stage of early copper processing. Nearly 200 kg of total biomass are typically needed throughout the production process to produce a single kilogram of refined copper product. However, this can vary considerably depending on the composition of ore, the smelting techniques and crucible used, and the degree of refining. Each stage of copper processing requires different fuel inputs. The most fuel-intensive steps of this process are the initial roasting and smelting of ore following its extraction. Furthermore, fire-set mining, if employed, also requires significant fuel inputs (e.g. Audra & Kindi 2023; Weisgerber & Willies 2000). Refining and casting, while requiring high temperatures, take far less time to complete than smelting, and therefore less fuel overall.

Previous studies have largely relied on estimates based on modern tree stands. Eckstein, Liese and Stieber (1987) provided local estimates for reconstructing Umm an-Nar period (2700–2000 BC) copper production at al-Muyassir. According to their calculations *c.*1000 tonnes of wood per year are required in order to produce enough charcoal for copper production and domestic heating fires. They further estimated the amount of wood available from contemporary acacia open pseudo-savanna in the area of al-Muyassir to be *c.*215 kg of wood per hectare on average, while dense relict stands of ghaf found near Lizq had up to 18 t/ha of wood (Eckstein, Liese & Stieber 1987: 427–428). If woodlands during the Umm an-Nar were similar in density to this ghaf woodland, Eckstein, Liese and Steiber estimated that local copper workers could have sustainably produced copper. If instead, woodland densities dropped towards levels similar to modern acacia stands in the region, there would be a significant risk of overexploitation.

One final factor to consider is whether charcoal was produced for copper smelting and refining activities at Building V. While it is possible to produce copper without the aid of pre-prepared charcoal owing to its relatively lower melting point (*c*.1000°C), charcoal provides both higher temperatures and a more efficient transition to the reducing environment essential for the smelting process (Horne 1982; Rehder 2000). However, distinguishing intentionally produced charcoal from the charcoal by-products of normal fires is challenging as there are no reliable morphological characteristics to distinguish the two processes. McParland et al. (2009) have suggested that reflectance analysis of charcoal, which produces an estimation of burning temperature, is an effective means of predicting the reburning of pre-prepared charcoal. However, such a technique may not be useful in metal production contexts, as temperatures are regularly reached regardless of the fuel source due to the use of tuyères and/or draft crucibles.

Conclusions

In conclusion, a combination of taxonomic and qualitative dendrological analysis suggests that fuel harvesting for copper production at al-Khashbah Building V during the Hafit period focused on relatively high-effort, high-quality wood harvesting strategies to support the local copper industry at the site with prime fuelwood, rather than using small, easily collected shrubs and deadwood. Large fresh or seasoned branches of *Ziziphus* and *Acacia* were preferred overall. Despite the harvesting of large-calibre wood, our results do not provide any evidence for overexploitation of fuelwood resources during the Hafit period, as might be expected for the earliest copper production in the region. That said, there remains little information on long-term vegetation development in the region during the Middle and Late Holocene and future anthracological analysis covering a wider span of time is essential for reconstructing the vegetation history of central Oman. To that end, future work will integrate this dataset into a longer-term diachronic study of vegetation from the vicinity of al-Khashbah as part of the ongoing UmWeltWandel Project.

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References

Akkemik Ü. & Yaman B. 2012. *Wood anatomy of eastern Mediterranean species*. Remagen/Oberwinter: Kessel Publishing House.

Asouti E. & Austin P. 2005. Reconstructing woodland vegetation and its exploitation by past societies, based on the analysis and interpretation of archaeological wood charcoal macro-remains. *Environmental Archaeology* 10: 1–18.

Asouti E. & Kabukcu C. 2021. Anthracology: Charcoal science in archaeology and palaeoecology. *Quaternary International* 593–594: 1–5.

Audra P. & Kindi M. 2023. Fire-set mining in an ancient lead mine: Khaf Al Laasif, Al ʿĀmrāt, Oman. *Arabian Journal of Geosciences* 16: 454.

Begemann F., Hauptmann A., Schmitt-Strecker S. & Weisgerber G. 2010. Lead isotope and chemical signature of copper from Oman and its occurrence in Mesopotamia and sites on the Arabian Gulf coast. *Arabian Archaeology and Epigraphy* 21: 135–169.

Beuzen-Waller T., Desruelles S., Marrast A., Giraud J., Gernez G., Bonilauri S. ... Fouache E. 2022. Late Pleistocene-Holocene fluvial records of the Wadi Dishshah: Hydro-climatic and archaeological implications (southern piedmont of the Hajar Mountains, Oman). *Géomorphologie: Relief, Processus, Environnement* 28/4: 223–239.

Chabal L. 1992. La représentativité paléo-écologique des charbons de bois archéologiques issus du bois de feu. *Bulletin de la Société Botanique de France* 139: 213–236.

Charbonnier J. 2017. The genesis of oases in southeast Arabia: Rethinking current theories and models. Pages 53–72 in E. Lavie & A. Marshall (eds), *Oases and globalisation*. Cham: Springer Geography.

Deckers K., Döpper S. & Schmidt C. 2019. Vegetation, land, and wood use at the sites of Bat and Al-Khashbah in Oman (fourth–third millennium BC). *Arabian Archaeology and Epigraphy* 30: 1–14.

Deckers K., Polisca F., Riehl S., de Gruchy M. & Lawrence D. 2021. Impact of anthropogenic activities on woodland in northern Syria (4th–2nd mill. BC): Evidence from charcoal assemblages and oak measurements. *Environmental Archaeology* 29/2: 129–164.

Delhon C. 2021. Is choice acceptable? How the anthracological paradigm may hinder the consideration of fuel gathering as a cultural behaviour. *Environmental Archaeology* 26: 159–167.

Döpper S. 2020. Ground stone tools from the copper production site Al-Khashbah, Sultanate of Oman. *Journal of Lithic Studies* 7: 1–24.

Döpper S. 2022. Survey methods and biases in the Al-Mudhaybi Regional Survey, Sultanate of Oman. *Arabian Archaeology and Epigraphy* 34/S1: 1–12.

Dufraisse A., Coubray S., Girardclos O., Nocus N., Lemoine M., Dupouey J-L. & Marguerie D. 2018. Anthraco-typology as a key approach to past firewood exploitation and woodland management reconstructions. Dendrological reference dataset modelling with dendro-anthracological tools. *Quaternary International* 463: 232–249.

Dufraisse A., Coubray S., Picornell-Gelabert L., Alcolea M., Girardclos O., Delarue F. & Nguyen Tu T-T. 2022. Taming trees, shaping forests, and managing woodlands as resources for understanding past societies. Contributions and current limits of dendro-anthracology and anthraco-isotopy. *Frontiers in Ecology and Evolution* 10/March: 1–10.

Dumitru I.A. & Harrower M.J. 2018. From rural collectables to global commodities: Copper from Oman and obsidian from Ethiopia. Pages 232–262 in N. Boivin & M.D. Frachetti (eds), *Globalization in prehistory*. Cambridge: Cambridge University Press.

Eckstein D., Liese W. & Stieber J. 1987. Holzversorgung im prähistorischen Kupferbergbau in Oman. *Naturwissenschaftliche Rundschau* 40: 426–430.

Ghazanfar S.A. 2003. *Flora of the Sultanate of Oman*. i. *Piperaceae – Primulaceae*. (Scripta Botanica Belgica, 25). Meise: Botanic Garden Meise.

Ghazanfar S.A. 2007. *Flora of the Sultanate of Oman*. ii. *Crassulaceae – Apiaceae*. (Scripta Botanica Belgica, 36). Meise: Botanic Garden Meise.

Giardino C. 2017. *Magan – The land of copper. Prehistoric metallurgy of Oman*. (The Archaeological Heritage of Oman, 2). Oxford: Archaeopress.

Gros-Balthazard M., Galimberti M., Kousathanas A., Newton C., Ivorra S., Paradis L. ... Wegmann D. 2017. The discovery of wild date palms in Oman reveals a complex domestication history involving centers in the Middle East and Africa. *Current Biology* 27: 2211–2218.e8.

Hahn R. 2022. UmWeltWandel: Reconstructing Bronze Age landscapes and the paleoenvironment in Central Oman through a new interdisciplinary project. *The IASA Bulletin* 28: 14–16.

Hauptmann A. & Weisgerber G. 1981. Third millenium BC copper production in Oman. *Revue d'Archéométrie* 1: 131–138.

Henry A., Zavadskaya E., Alix C., Kurovskaya E. & Beyries S. 2018. Ethnoarchaeology of fuel use in northern forests: Towards a better characterization of prehistoric fire-related activities. *Ethnoarchaeology* 10: 99–120.

Herrmann J.T., Fassbinder J.W.E., Scheiblecker M., Kluge P., Döpper S. & Schmidt C. 2018. Magnetometer survey of a Hafit monumental complex, al-Khashbah, Sultanate of Oman (poster). *Proceedings of the Seminar for Arabian Studies* 48: 119–124.

Horne L. 1982. Fuel for the metal worker: The role of charcoal and charcoal production in ancient metallurgy. *Expedition* 25: 6–13.

Jagiella C. & Kürschner H. 1987. *Atlas der Hölzer Saudi Arabiens. Die Holyanatomie der wichtigsten Bäume und Sträucher Arabiens mit einem holzanatomischen Bestimmungsschlüssel*. (Beihefte Zum Tübinger Atlas des Vorderen Orients, 20). Wiesbaden: Reichert.

Al-Jahwari N.S. 2008. Settlement patterns, development and cultural change in northern Oman Peninsula: A multi-tiered approach to the analysis of long-term settlement trends. PhD thesis, Durham University. [Unpublished.]

Kabukcu C. 2018. Wood charcoal analysis in archaeology. Pages 133–154 in E. Pişkin, A. Marciniak & M. Bartkowiak (eds), *Environmental archaeology. Current theoretical and methodological approaches*. Cham: Springer.

Kabukcu C. & Chabal L. 2021. Sampling and quantitative analysis methods in anthracology from archaeological contexts: Achievements and prospects. *Quaternary International* 593–594: 6–18.

Lézine A-M., Ivory S.J., Braconnot P. & Marti O. 2017. Timing of the southward retreat of the ITCZ at the end of the Holocene Humid Period in southern Arabia: Data-model comparison. *Quaternary Science Reviews* 164: 68–76.

Lüning S. & Vahrenholt F. 2019. Holocene climate development of North Africa and the Arabian Peninsula. Pages 507–546 in A. Bendaoud, Z. Hamimi, M. Hamoudi, S. Djemai & B. Zoheir (eds), *The geology of the Arab world – An overview*. (Springer Geology). Cham: Springer International Publishing.

McParland L.C., Collinson M.E., Scott A.C. & Campbell G. 2009. The use of reflectance values for the interpretation of natural and anthropogenic charcoal assemblages. *Archaeological and Anthropological Sciences* 1: 249–261.

Marguerie D. & Hunot J.Y. 2007. Charcoal analysis and dendrology: Data from archaeological sites in north-western France. *Journal of Archaeological Science* 34: 1417–1433.

Marston J.M. 2009. Modeling wood acquisition strategies from archaeological charcoal remains. *Journal of Archaeological Science* 36: 2192–2200.

Marston J.M., Kováčik P. & Schoop U-D. 2021. Environmental reconstruction and wood use at Late Chalcolithic Çamlıbel Tarlası, Turkey. *Quaternary International* 593–594: 178–194.

Mathieu J.R. & Meyer D.A. 1997. Comparing axe heads of stone, bronze, and steel: Studies in experimental archaeology. *Journal of Field Archaeology* 24: 333–351.

Neumann K., Schoch W., Détienne P. & Schweingruber F.H. 2001. *Woods of the Sahara and the Sahel: An anatomical atlas*. Bern: Paul Haupt.

Ochs U., Bretzke K., Crassard R. & Hilbert Y.H. 2020. A Hafit-period stone tool assemblage from Al-Khashbah, Sultanate of Oman. Pages 167–176 in K. Bretzke, R. Crassard & Y.H. Hilbert (eds), *Stone tools of prehistoric Arabia: Papers from the Special Session of the Seminar for Arabian Studies held on 21 July 2019*. (Supplement to Proceedings of the Seminar for Arabian Studies 50). Oxford: Archaeopress.

Picornell-Gelabert L., 2020. An archaeological approach to people-tree interactions: The ethnoarchaeology of firewood procurement and consumption among the Benga people of the island of Mandji (Corisco, Equatorial Guinea, Central Africa). *Journal of Archaeological Science, Reports* 34: 102591.

Preston G.W. & Parker A.G. 2013. Understanding the evolution of the Holocene Pluvial Phase and its impact on Neolithic populations in south-east Arabia. *Arabian Archaeology and Epigraphy* 24: 87–94.

Proctor L. 2021. Fueling socio-political complexity: Examining fuel use and fuel economies during the Chalcolithic and Iron Ages of northern Mesopotamia. PhD thesis, University of Connecticut. [Unpublished.]

Rehder J.E. 2000. *The mastery and uses of fire in antiquity*. Montreal/Kingston: McGill-Queen's University Press.

Schmidt C. & Döpper S. 2017. The development of complexity at third-millennium BC al-Khashbah, Sultanate of Oman: Results of the first two seasons, 2015 and 2016. *Proceedings of the Seminar for Arabian Studies* 47: 215–226.

Schmidt C. & Döpper S. 2019a. A Hafit period copper workshop at Al Khashbah, Sultanate of Oman. *Journal of Oman Studies* 20: 1–24.

Schmidt C. & Döpper S. 2019b. The Hafit period at Al-Khashbah, Sultanate of Oman: Results of four years of excavations and material studies. *Proceedings of the Seminar for Arabian Studies* 49: 256–274.

Schmidt C., Döpper S., Kluge J., Petrella S., Ochs U., Kirchhoff N. ... Walter M. 2021. *Die Entstehung komplexer Siedlungen im Zentraloman: Archäologische Untersuchungen zur Siedlungsgeschichte von Al-Khashbah*. (Arabia Orientalis, 5). Oxford: Archaeopress.

Shackleton C.M. & Prins F. 1992. Charcoal analysis and the 'principle of least effort' – A conceptual model. *Journal of Archaeological Science* 19: 631–637.

Smart T.L. & Hoffman E.S. 1988. Environmental interpretation of archaeological charcoal. Pages 167–205 in C.A. Hastorf & V. Popper (eds), *Current paleoethnobotany: Analytical methods and cultural interpretations of archaeological plant remains*. Chicago: The University of Chicago Press.

Smith A., Dotzel K., Fountain J., Proctor L. & Von Baeyer M. 2015. Examining fuel use in antiquity: Archaeobotanical and anthracological approaches in Southwest Asia. *Ethnobiology Letters* 6: 192–195.

Thomas R. 2013. Anatomy of the endemic palms of the Near and Middle East: Archaeobotanical perspectives. *Revue d'ethnoécologie* 4: 0–15.

Weisgerber G. 1980a. und Kupfer in Oman. *Der Anschnitt* 32: 61–110.

Weisgerber G. 1980b. Patterns of early Islamic metallurgy in Oman. *Proceedings of the Seminar for Arabian Studies* 10: 115–126.

Weisgerber G. & Willies L. 2000. The use of fire in prehistoric and ancient mining: Firesetting. *Paléorient* 26: 131–149.

White F. 1983. *The vegetation of Africa. A descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa*. (Natural Resources Research, UNESCO). Paris: UNESCO.

Wright N.J. 2018. Examining dendrological features of oak as possible signals of systematic woodland management in the central Anatolian Bronze and Iron Ages. *Quaternary International* 463: 298–311.

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