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# Environmental impacts of ancient copper mining and metallurgy: Multi-proxy investigation of human-landscape dynamics in the Faynan valley, southern Jordan



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## ABSTRACT

The environmental impact of mining and metallurgy is an issue that has affected societies in the ancient Near East over the past 8000 years. We present the results of a multidisciplinary project using agricultural sediments from ancient terraces as a cultural archive of environmental pollution and land use in the copper ore-rich Faynan valley of southern Jordan. Due to the simultaneous production of agricultural goods and copper metallurgy throughout the last 6000 years in the valley, environmental pollution and its consequences for human health have been considered as a factor in settlement abatement. Sediments from two farming terrace systems adjacent to the major mining and smelting locales were analyzed. The sediment analyses included metal concentrations, lead-isotopes and phytolith analysis, and OSL dating. Although measurable concentrations of lead and other heavy metals persist in ancient metallurgical waste piles, our investigations found minimal evidence for contamination in the adjacent terrace systems. Based on these results, we argue that the occurrence of environmental pollution in the Faynan valley is highly variable, and that the distribution of heavy metals resulted from a combination of natural and cultural factors, including persistent landscape features that helped contain the most polluted metallurgical deposits. These findings are significant for understanding the processes of landscape change and human impacts on desert environments, including the ways in which past human actions have negatively affected the environment, as well as preserved and protected the environment from further degradation.

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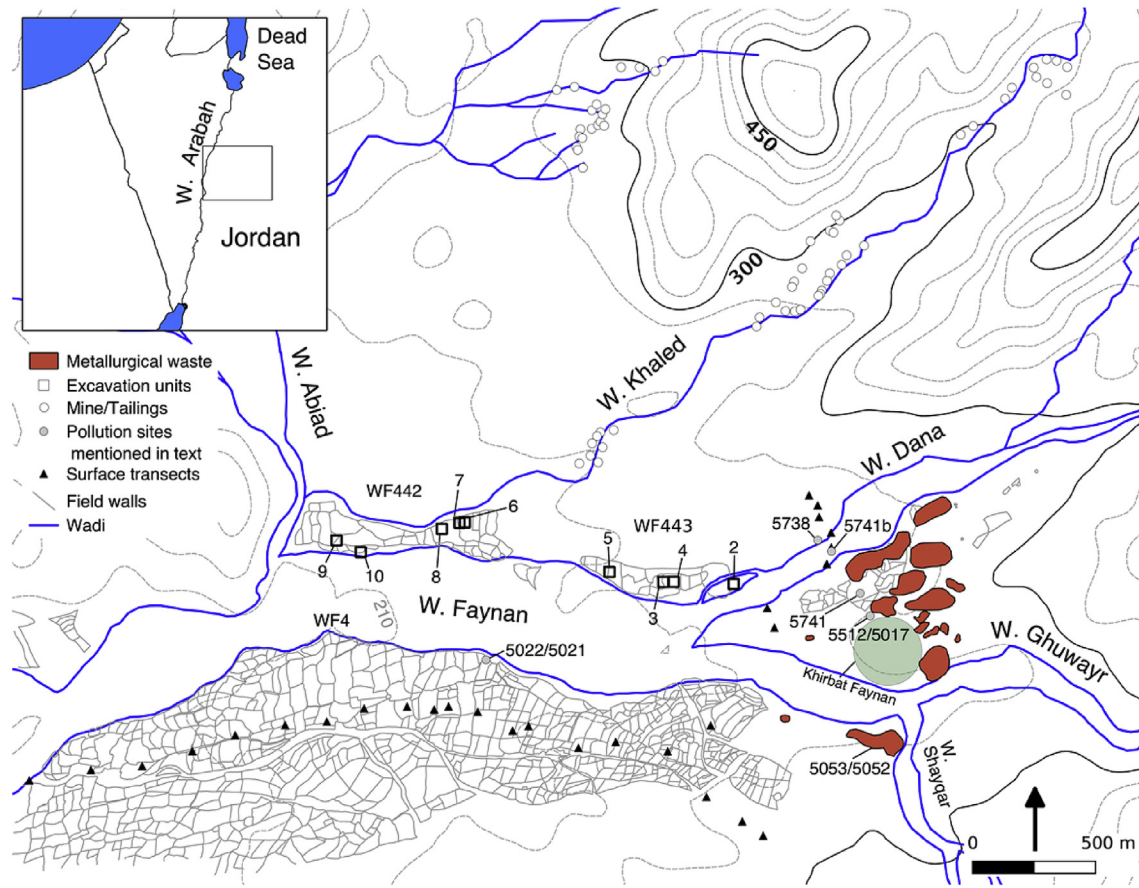
## 1. Introduction

The mining and smelting of copper metals was an essential component of the ancient political economy of complex societies. The remnants of these activities often leave a lasting imprint on the landscape visible even in modern times (Pyatt et al., 2002b). One such locale is the Faynan Valley of southern Jordan, where settlement organization in the valley changed significantly in response to

the economic interests of the region's copper producers (Fig. 1). As Wadi Faynan was a locus of agricultural production and copper exploitation for the last 10,000 years, the region is an excellent case study for the evolution of socio-political complexity and environmental degradation. Through time, communities in Jordan's marginal desert zones responded to changing political, economic, and environmental shifts in a number of ways. Their strategies ranged from participation in the 'boom and bust' economics of copper mining (Barker et al., 2007; Knauf, 1992; Levy et al., 2014b), to creating small-scale subsistence economies that were based on risk-management, flexibility, and commensalism (Hill, 2006; Laparidou and Rosen, 2015; Lev-Tov et al., 2011; Porter, 2011). In

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**Fig. 1.** Map of Wadi Faynan research area, showing the main tributary valleys and their relationship to archaeological features and excavation units. Topographic lines indicate 150 m intervals (solid) and 30 m intervals (dashed). Unit 1 was not included in the study and is not shown on the map. The agricultural terraces are ca. 2–7 m above the modern Wadi Faynan channel. Mining activities are concentrated in the valleys north of Wadi Faynan. The densest concentration of smelting debris can be found in the areas around Khirbat Faynan, the largest settlement in the valley. The locations of major pollution study sites summarized in [Table 1](#) are also shown. Inset shows location of Faynan valley within the eastern Mediterranean area.

all these cases, human actions, decisions, and choices in the realms of politics, economy, and social life had both intentional and unintentional consequences for the surrounding landscape they inhabited. The Faynan Valley has been the primary focus of the University of California, San Diego's Edom Lowlands Regional Archaeological Project (ELRAP) for nearly two decades.

### 1.1. Ancient environments: human adaptations and impacts

The study of human impacts on the environment has become one of the most important areas of study in archaeology, driven by one of the fundamental questions of human nature – is the evolution of complex society maladaptive? This question has been taken on recently by those in the field of socio-natural studies (Butzer and Endfield, 2012; Fisher et al., 2009; Hill, 2004; Kohler and Leeuw, 2007; Scarborough, 2003; van der Leeuw and Redman, 2002), whose research has centered on topics of deforestation, erosion, climate change, mass extinction, salinization, and pollution. Within this line of inquiry, archaeologists seek to understand the relationship between increasing political economic complexity and human impacts on the environment (Adams, 1965; Butzer, 1982; Redman, 1999; Sanders et al., 1979; Steward, 1968; van der Leeuw, 1998). Because human societies require physical resources to develop, subsidize, and expand, the local ecology is an important variable in understanding how societies changed, and how they changed their environment (Balée, 1998; Butzer, 2015;

Crumley, 1994). In this article we present a long-term, multi-proxy record of land use and environmental pollution from ancient agricultural terraces in the Faynan Valley, southern Jordan, focusing primarily on the presence of lead and copper. Based on the results of optically stimulated luminescence (OSL) dating, geochemical, and phytolith analysis, we propose that – unlike nearby loci of copper smelting and waste disposal – the agricultural terraces were much less affected by heavy metal pollution despite their close proximity to the sources of contamination.

One framework for understanding the dynamic relationships between society and the environment is a form of landscape modification known as “landesque capital”, a term originally coined by Brookfield (1984) and later taken up by ecologists and archaeologists (Blaikie and Brookfield, 1987; Brookfield, 2001; Fisher, 2009; Håkansson and Widgren, 2014; Kirch, 1994). Landesque capital is a concept used to identify the manipulation of a landscape for long-term gains in productivity, and can include terraces, irrigation, and other infrastructures that involve labor-saving inputs for future production. It allows for further infrastructural improvements from continued occupation of the land, and innovations that lead to further improvements in production (Brookfield, 1984). It is similar to the concept of biocultural structures in resiliency theory (Gunderson and Holling, 2002; Redman, 2005). In the archaeological literature, landesque capital has mostly been applied to agricultural intensification, but it could easily be applied to any production system that requires the

construction of and maintenance of landscape infrastructure.

For the current study, a key component of landesque capital is that landscape stability requires a relatively small amount of maintenance compared to the initial investment in the original construction. Periods of prolonged neglect or abandonment, however, can have profound and negative consequences for the landscape. The factors behind the withdrawal of labor are culturally contingent and variable through time and place, as are the strategies and techniques for the development of capital infrastructure (Fisher, 2009). Archaeological studies have shown that when degradation occurs it often does so under conditions of political, economic, and demographic duress (Butzer, 1996; Denevan, 2001; Dunning et al., 2002; Fisher et al., 2003; van der Leeuw, 1998; Whitmore and Turner, 2001). Consequently, an explanation of the causes of environmental degradation must include the consideration of both political and economic processes as well as purely environmental ones. The following study does so by considering both the preserving capabilities of landesque capital in the Faynan valley, as well as the potential for degradation resulting from metallurgical practices and infrastructure neglect.

### 1.2. Study rationale

Previous environmental studies of pollution from ancient metallurgy have noted the relationship between an increased regional and global output of toxic chemicals and the intensification of production that coincides with the growing political and economic complexity of ancient states and empires (Cooke et al., 2008; Grattan et al., 2007; Hong et al., 1994; Jouffroy-Bapicot et al., 2007; Karlsson et al., 2015; McFarlane et al., 2014; Mighall et al., 2014; Nriagu, 1996). While this is certainly the case in a broad sense, increasingly sophisticated archaeological and environmental methods for geochemical analysis and chronological determinations have opened the doors for more nuanced explanations of landscape degradation that account for coupled human and natural impacts (Romey et al., 2015), site abandonment processes (Iavazzo et al., 2011), and economic and land-use practices (López-Merino et al., 2014). This socio-natural perspective on ancient human environmental impacts motivates the research of Wadi Faynan's complex archaeological and environmental history presented here.

A prominent theme in the previous research on Wadi Faynan has been the issue of paleo-pollution. Previous research in the study area has suggested that copper mining and metallurgy have resulted in the spread of heavy metals that have polluted the environment, which has led to negative health and environmental consequences for agricultural yields, local fauna and flora, and ancient humans (see background review section below). Beyond their contribution to the study of environmental degradation, these propositions have far reaching consequences for understanding ancient and modern populations living in Wadi Faynan. Building on these previous studies, our research presents a new perspective on the extent and nature of heavy metal pollution in Wadi Faynan, focusing on Pb and Cu concentrations. Our results show that outside of the loci of metallurgical waste disposal, the concentrations of these heavy metals are far lower, suggesting that we must rethink how we understand this phenomenon of environmental degradation and its consequences in southern Jordan.

### 1.3. Research background in Wadi Faynan

Previous studies on the issue of anthropogenic pollution in Faynan have demonstrated elevated levels of heavy metal concentrations in tested samples. The samples for measuring the heavy metal content of ancient and modern contexts were collected from

sedimentary deposits, from plant and animal tissues, and from osteological remains found throughout the Faynan valley are summarized below, and for Pb are presented in Table 1. Overall, the previous research demonstrates the capacity of various sediments and biological remains to retain contaminants over long time-scales.

Sedimentary deposits from metallurgical, anthropogenic, and natural contexts have revealed Pb concentrations ranging from expected background levels to upwards of 50,000 ppm. Grattan et al. (2007, 2013) present the most comprehensive study of sedimentary deposits in the Faynan valley. Sampling from a number of locations in the valley, they demonstrate that there are elevated heavy metal concentrations at sites of metallurgical debris accumulation. These include: the ancient barrage wall (WF5512) – a semi-continuous accumulation of metallurgical debris beginning 1866–1535 BCE (Grattan et al., 2007: 96–100); metallurgical debris piles and associated field walls (WF 5738, and WF5741/b) located adjacent to Khirbat Faynan (Grattan et al., 2007: 100–101); an ancient mine (WF 5740) located in Wadi Khaled (Grattan et al., 2007: 101); a stratigraphic sequence from sites in the area of Tell Wadi Faynan (WF 5022 and WF 5021), dating back to 5290–5040 BCE and as recent as the Roman/Byzantine period (Grattan et al., 2007: 101–103); and a transect of surface samples along Wadi Faynan, sampling from the Wadi bed, from agricultural fields, and from metallurgical debris piles (Grattan et al., 2007: 92). Pb and Cu concentrations were highest from the metallurgical debris contexts, and lowest from contexts without any trace of smelting or mining. Additional data on heavy metal concentrations in sedimentary deposits were presented by Pyatt et al. (1999, 2000) from metallurgical debris deposits adjacent to Khirbat Faynan, and by Hunt and El-Rishi (2010) from the WF4 field system, also near Khirbat Faynan. Overall, measurements from sedimentary deposits reported in previous studies reflect elevated Pb and Cu concentrations of the metallurgical debris piles near Khirbat Faynan.

Plant and animal remains were also tested for their heavy metal concentrations. Pb concentrations for these samples reach as high as 1000 ppm. These samples were collected from a number of locations throughout the valley, and included invertebrates, modern sheep and goat tissue and excrement, and vegetation. Invertebrate samples were collected from sites throughout the Faynan valley, in metallurgical debris contexts, agricultural fields, and control sites away from mining and smelting. The results reported by Pyatt et al. (2002a: 60, 2000: 774) indicate that modern-day invertebrates collected from the agricultural fields had similar concentrations of Pb as the control samples collected from a site 2 km away from Khirbat Faynan, while invertebrates collected from the waste piles had up to twice the Pb concentration (Pyatt et al., 2002a: 60). Vegetation was likewise collected from both metallurgical waste and control contexts, with only those samples collected from metallurgical waste contexts showing signs of Pb contamination (Pyatt et al., 2000: 774). Samples from sheep and goat were collected from animals that were known to have grazed in the vicinity of Khirbat Faynan, including vegetation growing on slag piles (Pyatt et al., 1999, Pyatt et al., 2000, Pyatt et al., 2005). Consistent with the sediments dataset above, measurements from plants and animals reported in previous studies also reflect elevated Pb and Cu concentrations in close proximity to metallurgical debris piles.

In addition to the above samples, osteological remains recovered from a cemetery in Wadi Faynan are reported to contain evidence for Pb and Cu contamination (Grattan et al., 2002; Pyatt and Grattan, 2001; Pyatt et al., 2005). Measurements of bone were compared with sediments collected from the surrounding burial matrix to control for diagenetic uptake. The Pb and Cu concentrations measured in selected samples are reported to reach nearly 300 ppm (Grattan et al., 2002: 301). In a recent analysis by Beherec

**Table 1**  
Summary of previous reports of Pb concentration in the environment of Wadi Faynan mentioned in the text. The majority of samples were sourced from metallurgical debris piles (slag heaps and mining tailings). Outside of these contexts Pb concentrations are significantly lower.

Sampling location	Sample type	Approx. Pb conc. (ppm)	C14 date range (cal BP)	Locale description	Method
Surface transects	Sedimentary	0–80	Modern	Land surface – slag present	ICP-MS HNO <sub>3</sub> extraction
Surface transects	Sedimentary	0–75	Modern	Land surface – slag not present	ICP-MS
WF512/5017	Sedimentary	200–8000	3816–1403	Metallurgical debris behind ancient barrage	ICP-MS
WF1491/5741	Sedimentary	3500–14,000	6550–330	Metallurgical debris field north of KF	ICP-MS
WF1491/ 5741b	Sedimentary	5000–50,000	6550–330	Metallurgical debris field north of KF	ICP-MS
WF5738	Sedimentary	10,000–45,000	6550–330	Metallurgical debris field north of KF	ICP-MS
WF5740	Sedimentary	3000–5000	Likely Roman	Mine debris from W. Khaled	ICP-MS
WF5740	Sedimentary	800–2000	Likely Roman	Post-abandonment infill	ICP-MS
WF5022	Sedimentary	10–250	7235–5995	Metalworking and anthropogenic debris	ICP-MS
WF5021	Sedimentary	10–200	7240–6990	Pre-metalworking anthropogenic debris	ICP-MS
Khirbat Faynan	Sedimentary	200 (Cu)	Iron Age-Roman	Metallurgical debris piles at KF	Merck Mercko-quant strips
Khirbat Faynan	Animal	3–10 (Cu)	Modern	Faynan area – goat urine, feces, milk	Merck Mercko-quant strips
Control site	Invertebrate	2–17	Modern	Non-metallurgical site 2km SSE of KF	FAAS following acid digestion
Khirbat Faynan	Invertebrate	3–38	Modern	Metallurgical debris adjacent to KF	FAAS
Field systems	Invertebrate	2–17	Modern	Agricultural field system	FAAS
Site 5037	Sedimentary	18	Likely Neolithic	Pre-metalworking anthropogenic debris	FAAS
Control site	Sedimentary	1564	Unknown	2.5km south of KF	FAAS
Khirbat Faynan	Vegetation	30–120	Modern	Metallurgical debris adjacent to KF	FAAS
Khirbat Faynan	Sedimentary	15,204	Likely Roman	Metallurgical debris adjacent to KF	FAAS
Khirbat Faynan	Vegetation	200–1000	Modern	Metallurgical debris adjacent to KF	FAAS
Faynan region	Animal	200–600	Modern	Faynan region	FAAS
WF S. cemetery	Human	1–290	Byzantine	Cemetery ~100 m south of KF	ICP-MS
WF N. cemetery	Animal	200–520	Byzantine	Cemetery ~100 m north of KF	FAAS
WF N. cemetery	Human	70–100	Bronze age	Cemetery ~100 m north of KF	FAAS
WF N. cemetery	Human	20–200	Byzantine	Cemetery ~100 m north of KF	FAAS
Faynan region	Animal	10–360	Modern	Cemetery ~100 m north of KF	FAAS

et al. (2016)) comparing measurements of ancient human teeth collected from the Wadi Fidan 40 cemetery (ca. 13 km downstream of Khirbat Faynan), they suggest that comparison to the surrounding soil matrix is an inadequate method to control for diagenetic uptake (cf. Pike and Richards, 2002). Instead, by separately analyzing tooth enamel and tooth dentin to control for the diagenetic uptake of heavy metals, they report only a small fraction of bioaccumulated Pb and Cu in the sample population. While the metal content of osteological remains is beyond the scope of the research presented here, these studies demonstrate the need for further research into the question of the relationship between metallurgy and human health.

In the context of this previous research, we collected new data to address the following questions regarding resource production and landscape change in the Wadi Faynan research area: 1) Has ancient copper metallurgy resulted in the spread of significant quantities of Pb and Cu throughout Wadi Faynan? 2) What are the extent and distribution of anthropogenic Pb and Cu in the agricultural fields? and 3) What are the socio-natural processes that contributed to anthropogenic Pb and Cu in Wadi Faynan?

The results of this research are not just significant for the study of human-environmental impacts in antiquity, but for the contemporary management of natural resources and human populations in southern Jordan as well. The implications of whether or not copper metallurgy negatively impacted the local environment contribute to a better understanding of the social processes behind environmental pollution, its long-term effects on human health and ecosystem stability, as well as the role it has played in settlement collapse and abandonment in the Faynan valley through time.

#### 1.4. Description of the research area

Wadi Faynan is located in the Arabah valley, approximately 50 km southeast of the Dead Sea (Fig. 1). To the east of the research area, the foothills rise to the Jordan Plateau, which reaches elevations of up to 1600 masl. The Faynan region is dominated by the large Wadi Faynan alluvial drainage system that is fed by a number

of tributaries, including Wadi Dana, Wadi Ghuwayr, Wadi Shayqar, Wadi Abiad, and Wadi Khaled. These drainages combine after descending from the mountains to the east and then flow westward through a wide expanse of alluvial and colluvial floodplains that comprise Wadi Faynan. After turning north the drainage becomes Wadi Fidan, which then empties into the Wadi Arabah.

In ancient times, seasonal rainfall in the eastern mountains eventually drained into the Wadi Faynan catchment to the west. These floodwaters were harvested by ancient farmers who constructed the agricultural terraces that are standing to this day (Crook, 2009; Newson et al., 2007). Investigation of the agricultural terraces, which are grouped into eight field systems, suggests their use began by the Early Bronze Age, if not earlier, although the most intensive use of the terraces dates to the Iron Age and the late Roman period (Mattingly et al., 2007a, Mattingly, et al., 2007b). Paleoclimate reconstructions suggest that rain-fed agriculture (i.e. minimum 200 mm/y annual precipitation for barley) has not been possible in Wadi Faynan and surrounding lowland desert regions since the Early Holocene (Hunt et al., 2004). Thus, the construction of irrigation works in seasonally flooding valleys, natural springs, and aquifers found throughout the Arabah Valley has been an important source of water for millennia.

The Faynan area is also a natural resource zone rich in copper ore (Rabb'a, 1994), and for this reason hundreds of copper mines were exploited in the tributaries leading to Wadi Faynan (Ben-Yosef et al., 2010; Hauptmann, 2007; Knabb et al., 2014; Levy et al., 2014a). Copper ores from the Wadi Arabah have been subject to comprehensive analysis by Hauptmann (2007: 63–73, plus references therein). The richest and most frequently exploited copper ore mineralizations are found in two geological units: dolomite limestone shales (DLS) and massive brown sandstone (MBS). The ores found in these units are primarily oxidic and silicate copper minerals, and include paratacamite-Cu<sub>2</sub>(OH)<sub>3</sub>Cl, chrisocolla-CuSiO<sub>3</sub>•2H<sub>2</sub>O, malachite-Cu<sub>2</sub>[(OH)<sub>2</sub>/CO<sub>3</sub>], diopside-Cu<sub>6</sub>[Si<sub>6</sub>O<sub>18</sub>]•6H<sub>2</sub>O, planchéite-Cu<sub>8</sub>[(OH)<sub>2</sub>/Si<sub>4</sub>O<sub>11</sub>]<sub>2</sub>, chalcocite-Cu<sub>2</sub>S, and cuprite-Cu<sub>2</sub>O. Geochemical analysis (Hauptmann, 2007: 73–79) demonstrated that the percentage of trace elements is low with the

exception of lead, which reaches up to 6% in the DLS (median 2%). The smelting of metal from these ores involves a one-step smelting process, unlike the multistage process of roasting and smelting required to smelt sulphide ores.

The most prominent settlement feature in this arid region is Khirbat Faynan, one of only a few tell sites (i.e. ancient occupation mound) in southern Jordan, with archaeological evidence for metallurgy dating between the Early Bronze Age II/III (ca. 2800–2400 BCE) and the Middle Islamic period (ca. 1000–1300 CE). Settlement density at Khirbat Faynan peaked during the Iron Age and Roman period (Levy et al., 2012; Mattingly et al., 2007b), coinciding with the major episodes of metallurgy. This geography – the combination of floodplains suitable for agriculture and copper ores – provides a unique case study in which to diachronically study the relationship between social complexity and environmental degradation.

Sedimentary deposits in the Faynan valley were formed through alluvial, colluvial, and aeolian processes, mostly originating from within the Faynan escarpment (Hunt et al., 2007; McLaren, 2004). Many of the archaeological sites, as well as the agricultural fields, were constructed on geological deposits formed between the late Pleistocene and late Holocene (el-Rishi et al., 2007; McLaren et al., 2004), and whose composition and depositional history varies with relationship to local and regional paleoclimate regimes (Bar-Matthews and Ayalon, 2004; Cordova, 2008; Frumkin et al., 1999; Hazan et al., 2005; Rosen, 2007). More recent Holocene deposits, including those comprising the agricultural terraces are composed of low-energy alluvial and aeolian sediments, including epsilon cross-bedded silts and sandy gravels, well-sorted fine sands, and braided fluvial or wind-blown deposits (Hunt et al., 2007). The literature on the geoarchaeological and paleoclimatological context of ancient agriculture and metallurgy in Faynan is extensive (cf. Barker et al., 2007; Ben-Yosef et al., 2010; Hauptmann, 2007; Hunt and El-Rishi, 2010; Hunt et al., 2007; Levy et al., 2014a; Mithen and Black, 2011), and further review is beyond the scope of this paper.

Of the eight field systems recorded in previous archaeological surveys, WF442 and WF443 were selected for the current study due to their proximity to the mining and smelting areas, and the absence of modern agricultural production we observed in other field systems during our fieldwork. WF442 and WF443 are neither the largest nor the densest field systems in Wadi Faynan. The primary source of irrigation for these terrace systems was from the tributaries Wadi Dana and Wadi Khaled. Their modern tributary channels have not been significantly incised as in the case of Wadi Faynan. Terrace construction is more irregular and open than the field walls of the largest field system (WF4), which is believed to have been most intensively used during Roman period and later.

## 2. Methods and materials

### 2.1. Archaeological field methods

During the ELRAP's 2011 field season collected 38 samples from 10 excavation units in the WF442 and WF443 fields systems on the north bank of Wadi Faynan (Fig. 1). Excavations revealed that the mixed aeolian/alluvial sediments mostly rest on late Pleistocene-early Holocene alluvial deposits. This project represents the first systematic excavation of ancient agricultural fields in the Faynan region. Two of the excavation units (1 & 2) are excluded from this study due to the shallowness of the archaeological horizons (<20 cm).

Each of the excavation units was  $2 \times 1$  m with the exception of Unit 7, which was extended to  $3.5 \times 1$  m to accommodate the depth of the excavation (Fig. 2). Units were spread across the two field systems under investigation, and placed either bisecting or adjacent to a field wall visible on the surface, or in the center of a field.

The purpose of this research sample design was to determine the depth of walls visible on the surface, and whether there were observable differences between sediment deposition upstream or downstream of the terrace walls. All units were excavated until sterile soil was reached – indicated by sandy, reddish brown Pleistocene alluvium and colluvium that predates farming in the region.

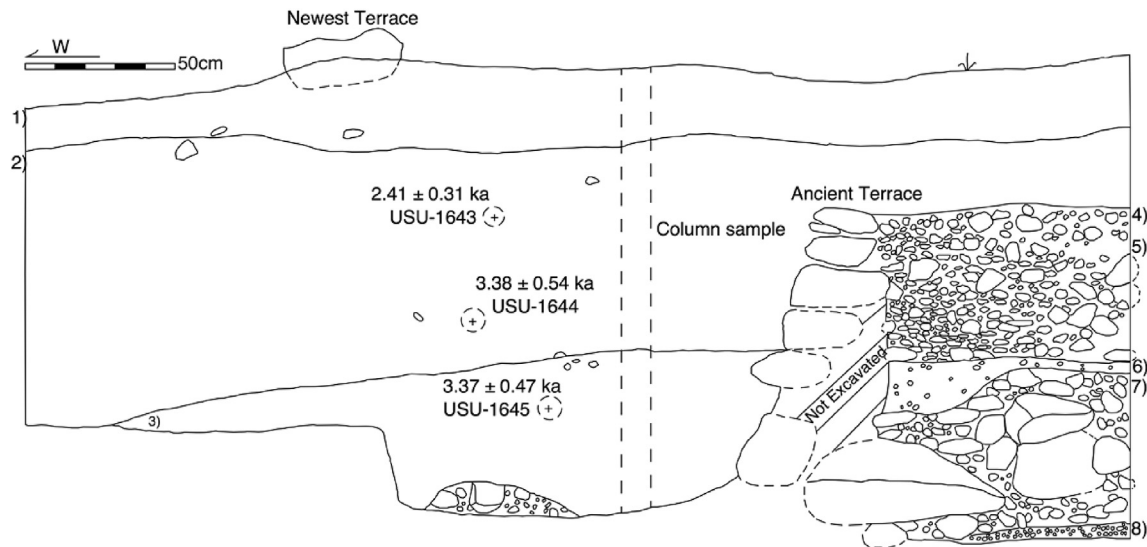
In general, the deposits above the sterile, pre-farming layers were fairly homogenous – light yellowish brown sandy silts and clay with moderate to high compaction. Excavation was carried out in 20 cm levels. Photographs and measurements were taken at the surface before excavating each unit and for each new locus. Additional photographs were taken of archaeological features as they were uncovered. All sediments excavated from these units were screened using a 1/4 in. sieve, and all artifacts were recorded and collected. A total of 38 samples were collected for geochemical analysis and 8 samples for phytolith analysis. These were collected in 20 cm levels from a  $10 \times 10$  cm column excavated in the sidewall of each unit. The dry samples were stored in acid-free plastic bags until the analysis was completed. One of the biggest challenges was to date the ancient agricultural terrace systems, as there was a paucity of material culture – especially datable artifacts – found during the excavations.

### 2.2. Optically stimulated luminescence dating of ancient agricultural fields

The lack of carbonized samples in the agricultural terrace systems made OSL the best option for objective dating (Liritzis et al., 2013). Samples for OSL dating were collected in the field under pre-light morning conditions. Approximately 1 cm of sediment was scraped from the sidewall of each excavation unit prior to collecting the samples in PVC pipe covered at the ends with newspaper, foil, and duct tape. All samples were opened and processed under dim amber safelight conditions within the lab. Sample processing for quartz OSL dating followed standard procedures involving sieving, gravity separation and acid treatments with HCl and HF to isolate the quartz component of a narrow grain-size range, usually 90–150  $\mu\text{m}$ . The purity of the quartz samples was checked by measurement with infrared stimulation to detect the presence of feldspar.

Samples were analyzed by the Utah State University Luminescence Lab following the latest single-aliquot regenerative-dose (SAR) procedure for dating quartz sand (Murray and Wintle, 2000; 2003; Wintle and Murray, 2006). The SAR protocol includes tests for sensitivity correction and brackets the equivalent dose (DE) the sample received during burial by irradiating the sample at five different doses. The resultant data are fit with a saturating exponential curve from which the DE is calculated on the Minimum Age Model (MAM) of Galbraith and Roberts (2012). In cases where the samples have significant positive skew, ages are calculated based on a MAM. OSL age is reported at  $1\sigma$  standard error and is calculated by dividing the DE (in grays, gy) by the environmental dose rate (gy/ka) that the sample has been exposed to during burial (Table 2a).

Dose-rate calculations were determined by chemical analysis of the U, Th, K and Rb content using ICP-MS and ICP-AES techniques and conversion factors from Guerin et al. (2011). The contribution of cosmic radiation to the dose rate was calculated using sample depth, elevation, and latitude/longitude following Prescott and Hutton (Prescott and Hutton, 1994). Dose rates are calculated based on water content, sediment chemistry, and cosmic contribution (Aitken, 1998) (Table 2b). The results will be discussed later on in the paper.



**Fig. 2.** Profile illustration of Unit 7. Excavations revealed that the surface wall is only one course high, as was the case in all units. However, another terrace wall was discovered approximately 40 cm below the surface, signaling the long-term use and reconstruction of landesque capital in the valley. Soil colors are munsell-code based. Sediment types are based on field observations, which combine silt and clay into one category. OSL dates suggest the deposition of these sediments during the Middle-Late Holocene (Table 2). Sediment characterization is as follows: (1) Light Brown Sandy Silt (Windblown/Plowzone); (2) Compact Light Brown Sandy Silt; (3) Light Reddish Brown Sandy Silt; (4) Light Reddish Brown Sandy Silt w/25% gravel inclusions; (5) Light Reddish Brown Sandy Silt w/75% cobble inclusions; (6) Light Brown Sandy Silt w/10% gravel inclusions; (7) Light Brown Silty Sand w/75% cobble inclusions; (8) Light Brown Silty Sand w/75% gravel.

### 2.3. Geochemical investigations

Samples for geochemical analysis were analyzed at the Hebrew University's Earth Science Institute. The chemical composition of the sediments were measured using ICP-MS for trace and major metal analysis (Erel and Torrent, 2010). Soil samples were prepared for ICP-MS following standard protocol. Samples were sieved through a 125  $\mu\text{m}$  screen following the wet-screen method with double distilled water (DDW), then lightly crushed and homogenized. A 0.1 g aliquot of each soil sample was completely dissolved (total digestion) in Teflon beakers in a mixture of ultra pure concentrated HF, HNO<sub>3</sub>, and HClO<sub>4</sub> followed by complete evaporation. One ml HNO<sub>3</sub> was added to the sample and diluted 1:50 in DDW and stored in 50 ml plastic tubes. Sample aliquots were prepared for ICP analysis at a dilution of 1:1000.

After sample dissolution, trace metals were analyzed with an Agilent 7500cx ICP-MS (Table 3, Fig. 3). Prior to the analysis the ICP-MS was calibrated with a series of multi-element standard solutions (Merck ME VI). Internal standards (50 ng/ml Sc, 5 ng/ml Re

and Rh) were added to every standard and sample for drift correction. The contribution of metals by the acid used in procedures was determined by measuring procedural blank samples. The blank and four selected standards were re-examined every 30 samples and at the end of the analysis for precision and detection limit estimation. In addition, standard reference samples (USGS SRS T-183, T-175) were examined at the end of the calibration and at the end of the analysis for accuracy estimation. The precision and accuracy of the ICP-MS were less than  $\pm 10\%$  for most samples.

A selected number of samples were prepared for Pb isotopic analysis (Table 3, Fig. 4). These samples included both sediments that were enriched and not enriched with Pb and Cu, as well as samples from various depths. Pb was separated for isotopic measurements using ion exchange columns according to the protocols outlined in Erel et al. (2006). Then, the samples were analyzed by a MC-ICP-MS (Neptune, Thermo). Replicate measurements of <sup>208</sup>Pb/<sup>206</sup>Pb and <sup>207</sup>Pb/<sup>206</sup>Pb ratios of SRM-981 standard over the course of this study yielded <sup>208</sup>Pb/<sup>206</sup>Pb = 2.1658  $\pm$  2 and <sup>207</sup>Pb/<sup>206</sup>Pb = 0.9144  $\pm$  1 (2 $\sigma$ ), n = 5. The isotopic composition of Pb

**Table 2a**

Optically Stimulated Luminescence age estimates for 9 samples collected from the WF442 and WF443 agricultural terraces. The dating confirms the deposition of sediments during the periods of peak metal production in Wadi Faynan.

Sample num.	USU num.	Depth (m)	Num. Of aliquots <sup>a</sup>	Dose rate (Gy/ka)	D <sub>E</sub> <sup>b</sup> $\pm$ 2 $\sigma$ (Gy)	OD <sup>c</sup> (%)	OSL age $\pm$ 1 $\sigma$ (ka)	Calendric age $\pm$ 1 $\sigma$ (BCE)
WF05 unit 3	USU-1639	0.25	13 (32)	1.69 $\pm$ 0.10	3.63 $\pm$ 0.55	12.9 $\pm$ 4.8	2.15 $\pm$ 0.23	200 $\pm$ 230
WF06 unit 3	USU-1640	0.62	17 (28)	1.57 $\pm$ 0.09	4.89 $\pm$ 1.01	18.8 $\pm$ 5.1	3.11 $\pm$ 0.41	1160 $\pm$ 410
WF21 unit 6	USU-1641	0.45	26 (32)	2.22 $\pm$ 0.13	7.14 $\pm$ 0.89	18.4 $\pm$ 3.6	3.22 $\pm$ 0.33	1270 $\pm$ 330
WF22 unit 6	USU-1642	0.7	16 (32)	2.35 $\pm$ 0.13	8.22 $\pm$ 1.64	33.7 $\pm$ 6.8	3.49 $\pm$ 0.45	1540 $\pm$ 450
WF29 unit 7	USU-1643	0.5	19 (33)	1.97 $\pm$ 0.12	4.20 $\pm$ 1.02	32.2 $\pm$ 7.5	2.14 $\pm$ 0.31	460 $\pm$ 310
WF31 unit 7	USU-1644	0.7	19 (37)	2.28 $\pm$ 0.13	7.71 $\pm$ 1.82	23.6 $\pm$ 6.5	3.38 $\pm$ 0.54	1430 $\pm$ 540
WF32 unit 7	USU-1645	1.14	22 (40)	1.51 $\pm$ 0.09	5.09 $\pm$ 1.13	22.9 $\pm$ 5.5	3.37 $\pm$ 0.47	1420 $\pm$ 470
WF54 unit 10	USU-1646	0.58	22 (27)	2.08 $\pm$ 0.12	6.09 $\pm$ 0.91	24.2 $\pm$ 4.4	2.94 $\pm$ 0.32	990 $\pm$ 320
WF57 unit 10	USU-1647	1.37	24 (35)	1.85 $\pm$ 0.11	6.17 $\pm$ 0.79	21.8 $\pm$ 4.3	3.33 $\pm$ 0.35	1380 $\pm$ 350

<sup>a</sup> Age analysis using the single-aliquot regenerative-dose (SAR) procedure of Murray and Wintle (2000) on 2 mm small-aliquots of quartz sand. Number of aliquots used in age calculation and number of aliquots analyzed in parentheses.

<sup>b</sup> Equivalent dose (D<sub>E</sub>) calculated using the Minimum Age Model of Galbraith and Roberts (2012).

<sup>c</sup> Overdispersion (OD) represents variance in D<sub>E</sub> data beyond measurement uncertainties, OD > 20% may indicate significant scatter due to depositional or post-depositional processes.

**Table 2b**

Dose Rate Information for 9 samples collected from the WF442 and WF443 agricultural terraces.

Sample num.	USU num.	Grain size ( $\mu\text{m}$ )	H <sub>2</sub> O <sup>a</sup> (%)	K <sup>b</sup> (%)	Rb <sup>b</sup> (ppm)	Th <sup>b</sup> (ppm)	U <sup>b</sup> (ppm)	Cosmic (Gy/ka)
WF05 Unit 3	USU-1639	125–250	0.3	0.58 $\pm$ 0.01	21.1 $\pm$ 0.8	7.6 $\pm$ 0.7	1.9 $\pm$ 0.1	0.19 $\pm$ 0.02
WF06 Unit 3	USU-1640	125–250	0.6	0.79 $\pm$ 0.02	27.8 $\pm$ 1.1	4.0 $\pm$ 0.4	1.6 $\pm$ 0.1	0.18 $\pm$ 0.02
WF21 Unit 6	USU-1641	75–150	0.8	0.78 $\pm$ 0.02	30.7 $\pm$ 1.2	5.9 $\pm$ 0.5	3.7 $\pm$ 0.3	0.18 $\pm$ 0.02
WF22 Unit 6	USU-1642	125–212	0.3	1.23 $\pm$ 0.03	45.0 $\pm$ 1.8	6.5 $\pm$ 0.6	2.4 $\pm$ 0.2	0.18 $\pm$ 0.02
WF29 Unit 7	USU-1643	125–250	0.8	0.63 $\pm$ 0.02	26.7 $\pm$ 1.1	5.7 $\pm$ 0.5	3.5 $\pm$ 0.3	0.18 $\pm$ 0.02
WF31 Unit 7	USU-1644	90–180	1.1	0.94 $\pm$ 0.02	37.4 $\pm$ 1.5	6.8 $\pm$ 0.6	3.1 $\pm$ 0.2	0.18 $\pm$ 0.02
WF32 Unit 7	USU-1645	125–250	0.2	0.63 $\pm$ 0.02	23.5 $\pm$ 0.9	5.6 $\pm$ 0.5	1.6 $\pm$ 0.1	0.17 $\pm$ 0.02
WF54 Unit 10	USU-1646	63–250	0.8	0.62 $\pm$ 0.02	27.0 $\pm$ 1.1	6.2 $\pm$ 0.6	3.8 $\pm$ 0.3	0.18 $\pm$ 0.02
WF57 Unit 10	USU-1647	125–250	1.0	0.53 $\pm$ 0.01	23.4 $\pm$ 0.9	4.4 $\pm$ 0.4	3.9 $\pm$ 0.3	0.16 $\pm$ 0.02

<sup>a</sup> In-situ gravimetric water content, assumed 3  $\pm$  3% for moisture content to represent burial history for all values.<sup>b</sup> Radioelemental concentrations determined by ALS Chemex using ICP-MS and ICP-AES techniques, dose rate is derived from concentrations by conversion factors from Guerin et al. (2011).**Table 3**

EF values calculated for Cu and Pb. Isotope data for selected samples described in text as well as Faynan unpolluted soils and DLS ores.

Unit # & depth (cm)	EF of metals to Al		Sample concentration		Isotopic values	
	Cu	Pb	Pb (ppm)	Cu (ppm)	<sup>208</sup> Pb/ <sup>206</sup> Pb	<sup>207</sup> Pb/ <sup>206</sup> Pb
T3 0-20	55	7	52	360	2.103	0.859
T3 20-40	41	6	42	253		
T3 40-60	11	4	33	70		
T3 60-80	12	4	33	80		
T4 0-20	13	3	34	108		
T4 20-40	6	3	29	55		
T4 40-60	6	3	29	47	2.085	0.848
T4 60-80	10	4	34	79		
T5 0-20	13	9	77	88		
T5 20-40	58	8	81	470		
T6 0-20	40	9	69	246		
T6 20-40	44	7	59	318		
T6 40-60	50	6	55	352		
T6 60-80	137	14	118	922	2.114	0.866
T6 80-96	85	11	89	555		
T7 0-20	40	6	52	270	2.100	0.858
T7 20-40	38	6	50	257		
T7 40-60	44	6	54	298		
T7 60-80	42	6	52	297	2.102	0.859
T7 80-100	58	8	71	408		
T7 100-120	102	15	91	526		
T7 120-140	98	16	120	616	2.115	0.865
T7 140-150	83	12	95	536		
T8 0-20	23	4	31	136		
T8 20-30	52	6	54	377		
T9 0-20	11	3	21	66		
T9 20-40	11	3	11	36	2.080	0.844
T9 40–60*	10	3	17	42		
T9 60-80	10	6	34	46		
T10 0-20	14	4	30	95	2.080	0.846
T10 20-40	8	4	28	50		
T10 60-80	6	3	20	40		
T10 80-100	6	2	17	38		
T10 100-120	6	2	19	41		
T10 120-140	6	2	16	37	2.062	0.837
T10 140-160	6	3	18	36		
T10 160-180	8	5	27	35		
Faynan un-polluted soils <sup>a</sup>					2.058	0.834
DLS ores <sup>b</sup>					2.117	0.869

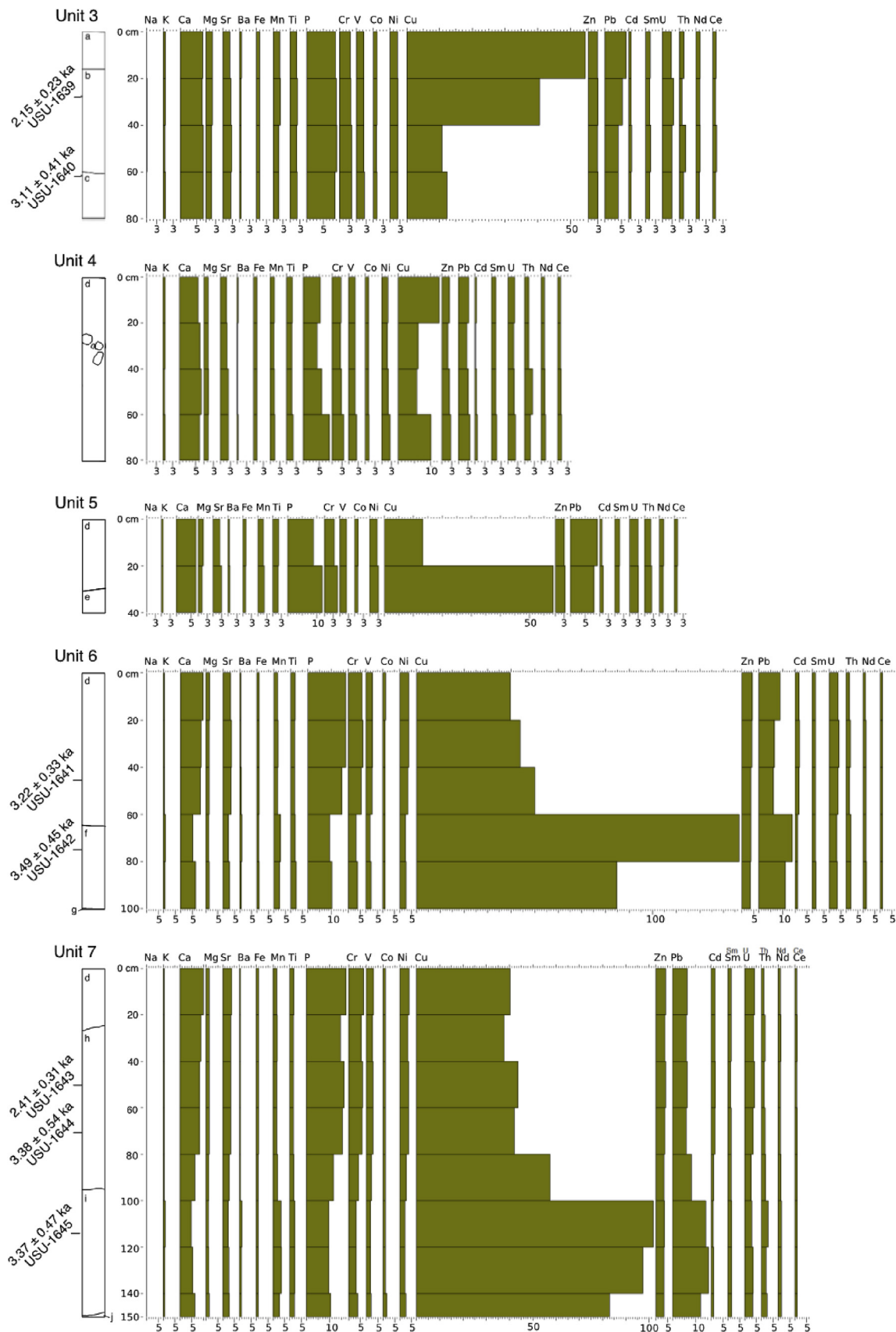
<sup>a</sup> Beherec et al. (2016).<sup>b</sup> Hauptmann (2007).

in the sediment was compared with the isotopic composition of Pb in production slags at Khirbet en-Nahas, Faynan and with soils and sediments from the Faynan area (Beherec et al., 2016; Hauptmann, 2007). The results of elemental concentrations and Pb isotope analysis are discussed later on in the paper.

#### 2.4. Phytolith analysis

Sediment samples for phytolith analysis were processed at the Environmental Archaeology Lab in the Anthropology Department

at the University of Texas at Austin, using a protocol adapted from Rosen (2005) as follows. A well-established plant phytolith reference collection regionally specific to the Near East was available for the purposes of plant and crop identification. 800 mg of archaeological sediment was sieved using a 0.5 mm sieve. A 10% HCl solution was used to remove pedogenic carbonates while any remains of HCl were removed using a centrifuge at 2000 rpm for 5 min. The 0.5 mm sieve was used in order to retrieve large multi-cell silica skeletons that are useful for the identification of the primary economic crops of the periods studied, including wheat and barley



**Fig. 3.** Enrichment factor (EF) values of sediments collected from soil column. When normalizing to Al, most concentrations converge to unity. The EF of Al is not shown because in all cases this value is 1. Soil colors are munsell-code based. Sediment types are based on field observations, which combine silt and clay into one category. Soil profiles are as follows: a) pink silty sand with gravel; b) Light yellowish brown silty sand and gravel; c) Reddish brown sand and gravel; d) Light brown silty sand; e) Light reddish brown silty sand; f) Light reddish brown medium sand; g) Light reddish brown silty sand and gravel; h) Light brown sandy silt; i) Light reddish brown sandy silt; j) Light brown silty sand and cobbles; k) Light brown sandy silt and cobbles; l) Light reddish brown silty sand and large cobbles; m) Brown top soil; n) Sand with cobbles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

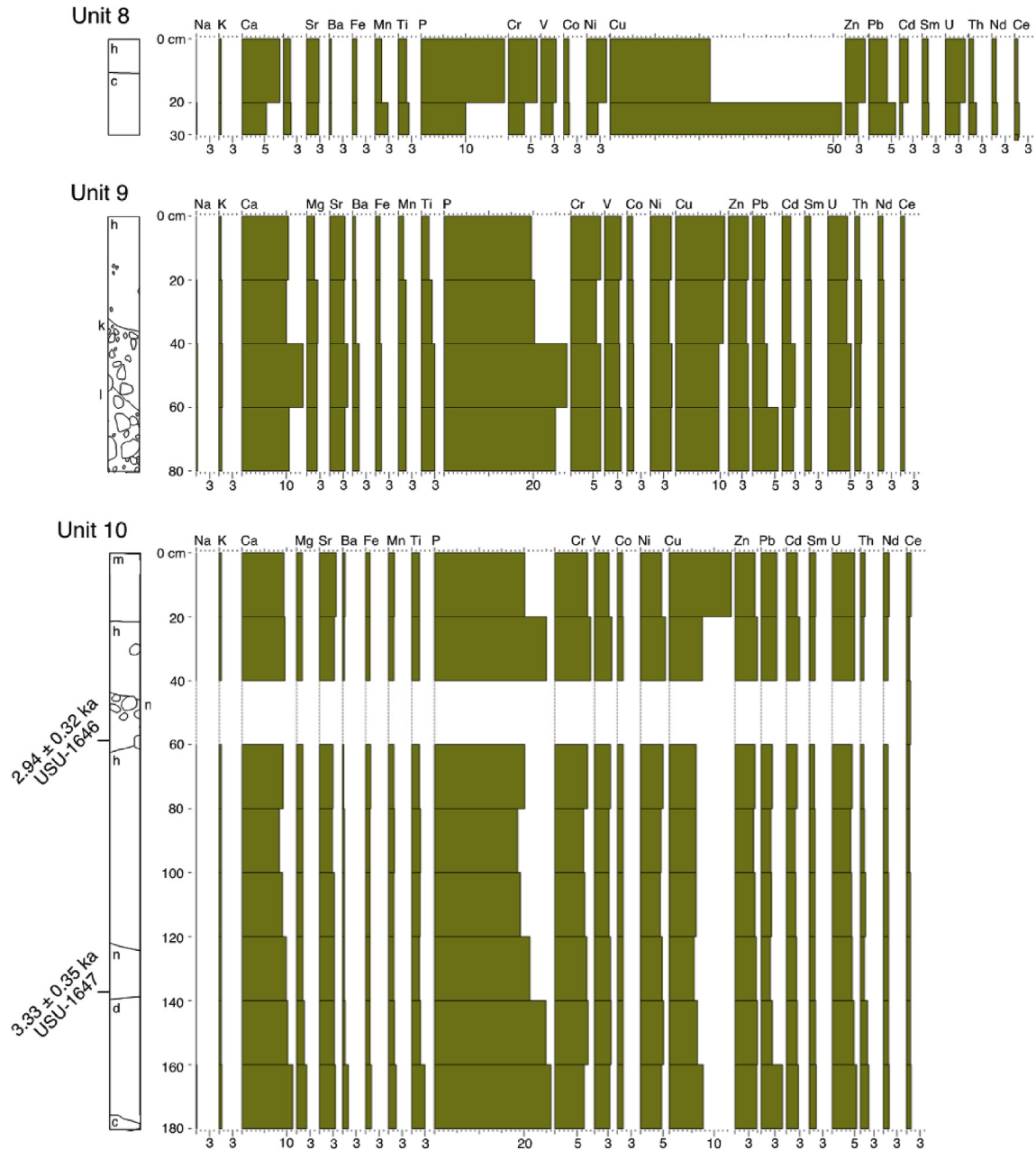


Fig. 3. (continued).

husk phytoliths. Clays were removed by settling using a Calgon solution (sodium hexametaphosphate). Air dried samples were burned in a 500 °C furnace for 2 h in order to remove organic matter. Finally, phytoliths were separated by adding 3 ml sodium polytungstate solution to the samples and then centrifuged to extract the phytolith content. Distilled water was used during the phytolith separation processing stage. Phytolith remains were left to dry and 2 mg of phytoliths per sample were mounted on microscope slides using Entellen (Merk) solution. Microscope slides were left under the fume cupboard for two weeks before counting.

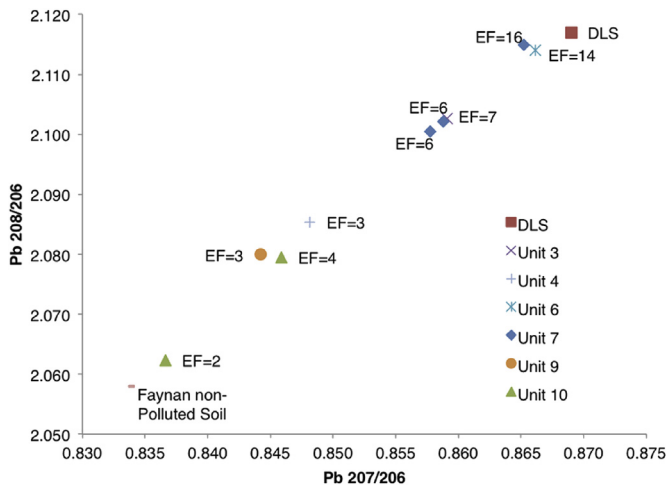
A minimum of 200 single cell phytolith morphotypes was identified for every sample presented here (Fig. 5). While it is standard procedure to count 100 multi-cell phytoliths for statistically significant data, only 73 multi-cell forms were recovered and identified in all 8 samples. Slides were scanned and phytoliths were

counted using a light transmitting microscope at  $\times 400$  magnification. Absolute counts of phytoliths per gram of sediment were used in order to allow comparisons between stratigraphic layers. Samples were selected to be representative of all contexts and periods of agricultural terrace use in Wadi Faynan. As an assemblage, the phytolith results provide a reflection of the plant content of the different strata as well as the state of preservation of phytoliths, and indicate what was cultivated on the terraces. These data are presented below.

### 3. Results

#### 3.1. OSL results

OSL ages (Table 2a) and dose rate information (Table 2b) were



**Fig. 4.**  $^{208}\text{Pb}/^{206}\text{Pb}$  versus  $^{207}\text{Pb}/^{206}\text{Pb}$  of sediments excavated from agricultural terraces and dolomite limestone shale (DLS) ore bodies. EF values indicate Pb enrichment. Note the correspondence between the extent of Pb enrichment and its isotopic composition, where the more polluted soils have Pb with isotopic composition closer to the DLS isotopic value. See also Table 3.

obtained for nine samples. All of the dates are in stratigraphic order and within the expected range for the formation of the field systems given our understanding of the development and use of the fields.

The OSL age estimates range from  $1540 \pm 450$  BCE to  $200 \pm 230$  BCE. In terms of cultural chronology, these dates span the Middle Bronze Age (beginning ca. 2000 BCE) through the Early Roman Period (ca. 100 BCE–100 CE). However, there is little evidence for human occupation of Wadi Faynan during the Middle and Late Bronze Age (ca. 2000–1200 BCE), so it is unlikely that dates within this range reflect systematic use of the terraces, but rather deposition during times of disuse. When interpreting luminescence dates from a context such as this, it is important to keep in mind that there are a variety of cultural and natural processes that can complicate the results, including plowing, soil addition and removal, sudden and high-energy erosion, and deflation. That said, the OSL ages, combined with the archaeological data from the terraces and the surrounding areas, suggest that sediment deposition and the use of the agricultural terraces occurred within the historical framework outlined in the ‘Site Description’ section above.

### 3.2. Excavation and geochemical results

Few subsurface artifacts were found during the excavation of the ancient agricultural fields, and most came from the upper 20 cm or were collected from the surface. Soil samples were also extremely poor in macro-botanical remains, and no materials for radiocarbon dating were recovered. The depth of agricultural deposits varied significantly, ranging from 30 cm to as much as 180 cm. The excavations also revealed that many of the surface field walls are no more than 1–2 courses high. Subsurface architecture was present in Unit 7 (Fig. 2), which contained a terrace wall approximately 40 cm below the surface and 7 courses high, and extending just below the basal layer of sterile, pre-agricultural soil approximately 150 cm below the surface. We also observed plow marks on surface rocks near shallow units, which suggest surface deflation and/or erosion has occurred in some areas of the fields.

The ICP-MS geochemical results (Fig. 3) are consistent with the interpretation of an agricultural function for the terraces, and show that the anthropogenic addition of heavy metals from copper

smelting varies considerably with location and depth. The data are presented as enrichment factor (EF) values:

$$EF = \left( \frac{M}{Al} \right)_{\text{sample}} / \left( \frac{M}{Al} \right)_{\text{UCC}}$$

where M is the concentration of the element; upper continental crust (UCC) values are from Taylor and McLennan (1985). This method has proven effective in similar studies elsewhere (Beherec et al., 2016; Delile et al., 2016). Alternative methods for calculating the EF yielded similar results. Comparison to crustal values from Turekian and Wedepohl’s sedimentary rocks lowered EF values by approximately 12%, while normalization to Ti as suggested by Shoty (1996) lowered EF values by as much as 40% for Pb. Thus, we are confident that the chosen calculation for EF is the most appropriate.

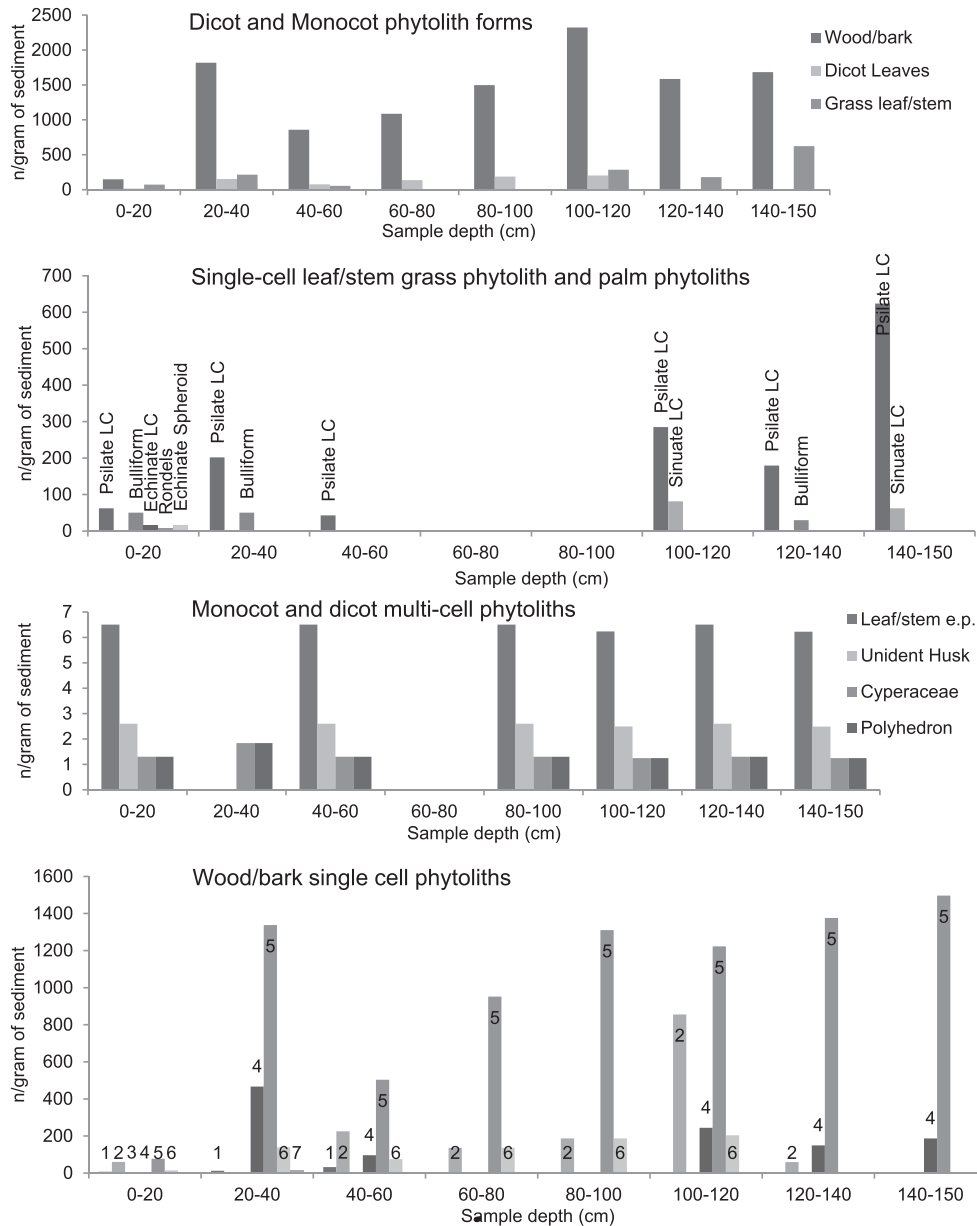
We use EF values due to the fact that elevated concentrations (in ppm, ppb, etc.) are not a stand-alone indication of an anthropogenic origin. As natural variations in the abundance of minerals have an important effect on the concentrations of elements in the deposit, we must normalize the elemental concentration to an element without an anthropogenic contribution, and then compare this to the ratio in crustal rocks. Generally an enrichment factor greater than five is an indication of an anthropogenic origin and considered contaminated, while any value below five may be of natural origin or uncontaminated (Erel et al., 2006; Rahn, 1999; Winchester, 2002). When normalized to Al, many EF values converge to unity – further evidence of the appropriateness of the EF calculation used. Notable exceptions are Ca, P, Pb, and Cu. The anthropogenic addition of Ca and P relate to the agricultural use of the fields. These elements are common additions to soils as a result of human activities, including agriculture (Holliday and Gartner, 2007). Anthropogenic addition of Pb and Cu, in most cases, derives from activities related to mining and smelting of local copper ores.

### 3.3. Pb enrichment

Evidence for anthropogenic addition of Pb is represented in most of the 37 sediment samples. EF values equal to or larger than three might contain some contamination (as suggested by their isotopic values – Table 3), but we consider EF values higher than five as undisputable anthropogenic addition. EF values higher than five appear in 19 samples. Spatially, this occurs in Unit 3 and Units 5–9. Only the upper two levels (0–40 cm) of Unit 3 revealed an EF indicating the anthropogenic addition of Pb (Table 3, Fig. 3). However, given the elevated values of Cu enrichment described below, it seems likely that Pb and Cu concentrations throughout the unit are at least somewhat related to mining and smelting activities. For the upper two levels of Unit 3, the processes behind this enrichment may have a different origin, as excavations uncovered a small quantity of pottery sherds, slag, and lithics in the first 20 cm of excavation. The presence of slag and pottery (which can also carry heavy metals) in these upper deposits may have played a role in the increased Pb observed in this unit.

Unit 5 is unusual in that the Pb enrichment appears to decrease slightly with depth, although this change is not within the tolerance of our measurements. Cu, however, increases significantly (Table 3, Fig. 3). This non-correlation between the two metals is unusual in our sample population.

Units 6 and 7 reveal the highest levels of Pb enrichment. These value increases parallel those of Cu (Table 3, Fig. 3). Peak Pb enrichment factor values are found well below the surface, at 80–100 cm for Unit 6, and from 100–140 cm for Unit 7. This increase is noticeable for the sudden jump to higher values, rather



**Fig. 5.** Phytolith results from Unit 7. Horizontal axis labels reflect lab numbers for each strata i.e. 0–20 cm, 20–40 cm, etc. a) Dicot and Monocot phytolith forms; b) Single-cell leaf/stem grass phytolith and palm phytoliths; c) Monocot and dicot multi-cell phytoliths; d) Wood/bark single cell phytoliths, 1 = Globular Spheroid, 2 = Silica aggregate, 3 = Tracheids, 4 = Compound platelet, 5 = Platelet (sheet), 6 = Single polyhedron, 7 = Single jigsaw puzzle. Note the predominance of wood/bark phytoliths, suggesting tree/shrub cultivation.

than a gradual increase with depth. For both units, the basal layers below these peaks decrease slightly in Pb enrichment. Excavation of these units revealed no artifacts below the surface. Thus, the Pb values are interpreted as having an anthropogenic origin unrelated to dispersal via lead bearing artifacts such as pottery and slag.

Units 8 and 9 show evidence of anthropogenic Pb in their basal layers only (Table 3, Fig. 3). In the case of Unit 8, interpretation of the value measured at 20–30 cm is difficult to interpret, as there are only two data points from this shallow unit. Additionally, excavation to 30 cm exceeded the depth of agricultural soils, and included some of the Pleistocene alluvium and colluvium described above. These deposits certainly comprised a variety of source materials, which could have affected the heavy metal concentration in that level. Further evidence to this interpretation comes from the low values of Ca and P that one would expect to find in pre-farming

and non-anthropogenic sediments. Interestingly, the jump in Pb at the basal layer of Unit 9 does not correspond to an increase in Cu as observed in nearly every sample reported here. In fact, the Cu/Pb ratio from this sample is closer to the ratio in crustal rocks (Taylor and McLennan, 1985).

### 3.4. Cu enrichment

Cu enrichment is observed in all samples reported here, i.e., EF values higher than five. However, the most Cu enriched samples coincide with high values of Pb enrichment (i.e. Units 6 and 7, where the EF of Pb reaches 15.6 and the EF of Cu reaches 136. Correspondingly, those samples without evidence of Pb enrichment are also less enriched in Cu (e.g. Unit 10, where Pb enrichment is below 3, and Cu enrichment is below 7 in all but the basal layers).

Cu enrichment in Unit 3 is highest at the upper two levels, consistent with the pattern for Pb described above. These values decrease significantly from 40–80 cm, where no artifacts were recovered. As argued above, it is possible that the elevated metal concentrations near the surface are related to the redeposition of copper smelting artifacts.

Unit 4 contains some of the lowest values of Cu enrichment throughout the entire profile, though the values are still enough to indicate an anthropogenic addition. Unit 5 exhibits a large increase in Cu at the 20–40 cm layer – a trend not matched in the Pb values.

The peaks of Pb and Cu enrichment from Units 6 and 7 greatly surpass those measured in other samples. Enrichment factor values decline significantly toward the surface of the units, with a two-fold decrease in Cu enrichment observed in Unit 7, and a four-fold decrease in Cu enrichment observed in Unit 6. Lacking artifacts or other evidence of waste disposal, the source of metal enrichment in these units seems to be related to anthropogenically induced environmental changes, perhaps resulting from the erosion of mines and mining debris upstream, rather than direct contamination (as in the case of Unit 3). We will revisit this in the discussion section below.

Units 9 and 10, both of which are the farthest downstream from the metallurgical production areas, contained relatively low Cu enrichment values. Excavations in both of these units were completely absent of artifacts. Unit 10 was the deepest unit excavated, extending 180 cm before reaching sterile soil. This unit abutted a terrace wall that was at least 5–6 courses high, and was located at the southwest boundary of the WF442 field system, above a relict Wadi terrace.

### 3.5. Pb isotopes

The results of Pb isotope analysis indicate that the samples from Unit 6 and 7 share the closest affinity to the dolomite limestone shale (DLS) copper ores from Faynan (Fig. 4). These ores are located throughout the Faynan valley and surrounding area, but were especially exploited in the tributaries feeding the agricultural terraces. Thus, it is likely that the DLS ores were a significant source of the Pb contributed to these sediments. The rest of the samples appear to plot on a mixing line between uncontaminated soils and the DLS ores (Fig. 4). Furthermore, there is a good correspondence between the extent of Pb enrichment and its isotopic composition, wherein increasingly enriched soils have isotopic compositions closer to the DLS isotopic value (Fig. 4).

### 3.6. Phytolith results

The results from Unit 7 show that densities of single-cell and multi-cell phytolith forms were very low, which is to be expected for off-site locations such as agricultural terraces. Single-cell forms were more common than multi-cell forms and large multi-cell forms consisting of more than ten conjoint cells were absent from all samples. Thus, taxonomic identification of single-cell and multi-cell phytoliths was only possible at the family and subfamily level. Identification down to genus was possible for the single-cell echinate spheroid phytoliths that form in date palm (*Phoenix dactylifera*) (Rosen, 1992). While grasses produce twenty times more phytoliths than dicots (Albert et al., 2003), the results suggest that dicot plants were more abundant than grasses in all samples (Fig. 5a). Multi-cell grass phytoliths were totally absent in the sample from 60–80 cm, while single-cell grass phytoliths were totally absent in the samples from 60–80 and 80–100 cm (Fig. 5b and c).

Single-cell phytolith morphotypes were integrated into three major categories (Fig. 5a): wood/bark phytoliths, dicot leaf

phytoliths and grass phytoliths. Multi-cell phytolith morphotypes were grouped into four major categories: leaf/stem elongate psilate, unidentified cereal husk, Cyperaceae, and polyhedral phytoliths that form in dicot leaves (Fig. 5c). Fig. 5b shows the phytoliths that form in monocotyledons.

Grass leaf/stem phytoliths represent any monocot plant leaf/stem as well as cereal culms. Multi-cell forms of dendritic long-cells are present in some of the samples (Fig. 5c). Those phytolith morphotypes form in cereal husks and their presence suggests that cereal cultivation took place on those terraces at times. Cyperaceae plant phytoliths, which are forage plants, are also present in some samples and could reflect the use of animal dung as fertilizer. Echininate long-cell phytoliths that form in wild grass husks are present in the 0–20 cm level (Fig. 5b), and likely represent the growth of wild flora following the abandonment of the terraces.

Figs. 5a and 5d show the average numbers per gram of sediment of certain phytoliths derived from wood and bark as well as dicot leaves (polyhedral single-cell and multi-cell forms, 'jigsaw puzzle' phytolith forms). Phytolith forms that are formed in the wood and/or bark of trees or shrubs are present in higher densities than grass phytoliths in all samples; their presence in samples derived from all stratigraphic layers is understood to indicate the cultivation of trees and shrubs or co-cultivation of trees and cereals at times on these terraces. Given the relative lack of cereal phytoliths from an area known through previous archaeological research to have been used for farming, the practice of horticulture/cultivation is supported.

Single-cell phytolith morphotypes, which form in most grasses (including hairs, unidentified leaf/stem long cells, and trichomes), are present in six samples. They are absent from level 60–80 and 80–100 cm. Also, date palm (*Phoenix dactylifera*) phytoliths are present in level 0–20 cm (Fig. 5b).

The Graminae family includes the Pooid, Panicoid and Chloridoideae subfamilies that produce rondel-, bilobe- and saddle-shaped single-cell phytoliths. The absolute counts of those single-cell morphotypes were very low, and thus these data cannot be used as strong environmental and ecological indicators. In general, C<sub>3</sub> plants, which are indicative of moderate climatic conditions, produce rondel-shaped short-cells. Rondels are only found in very low counts in level 0–20 cm and could have derived from temperate plants like wheat and barley (Fig. 5b). However, rondel-shaped short cells could be produced by Panicoid grasses too. Panicoid grasses grow in warm and wet, humid environments and produce bilobes and cross-shaped phytoliths. Chloridoideae grasses, which indicate dry land grasses and a warm and dry habitat, produce saddle-shaped short-cells, which are not found in any of the samples (Piperno, 2006; Twiss, 1992; Twiss et al., 1969).

The 'jigsaw puzzle' phytolith forms are produced by deciduous and non-deciduous trees, legumes and shrubs and are likely to be formed in regions of humid climate, high precipitation and/or heavy irrigation (Tsartsidou et al., 2007), and are present in the 20–40 cm level. The results indicate that the agricultural terraces were primarily used for horticulture and/or arboriculture rather than the cultivation of cereals. Single-cell and multi-cell grass phytoliths are present in small quantities in all samples except level 60–80, and imply limited cereal cultivation albeit on a rather small scale and perhaps only infrequently. Furthermore, large multi-cell forms of cereal-husks that indicate intensive farming of cereals via irrigation are completely absent from the assemblage (cf. Rosen and Weiner, 1994). At the same time, the presence of Cyperaceae plant phytoliths is ubiquitous in all samples suggesting that the environment never became extremely arid (Fig. 5c). Cyperaceae could indicate small-scale wheat and barley cultivation or the presence of animal dung used as manuring.

#### 4. Discussion

Based on the results above, we can make a number of observations regarding the spread of heavy metals from their origins in mining and smelting activity areas. First and foremost, within the agricultural terraces there is little evidence for the degree of environmental pollution previously measured within the metallurgical waste piles. For Pb, this is the most significant difference; the anthropogenic contribution of Pb was determined in our measurements to be highly variable with respect to sample location and depth. Measurements of Cu have a much stronger representation in the samples, in which we have a clear anthropogenic contribution, although the extent of the enrichment is also quite variable. Overall, these figures contrast with the quantities of Pb and Cu observed in the metallurgical waste deposits (e.g. up to 50,000 ppm for Pb, see Table 1).

Second, the spatiotemporal pattern of metal enrichment indicates multiple instances and sources of contamination. This is reflected in the conflicting patterns of stratigraphic metal distribution, with some units showing accumulations of Cu and Pb, and others showing the opposite. As our results show that the chemical and isotopic composition of contaminated sediments varies across the site, different processes must have been responsible for these effects at different times and locations. One of these processes may be suggested by the results of Pb isotopes analysis, namely, that the most contaminated strata resemble the isotopic composition of DLS ores rather than the metallurgical debris piles. Rather than contamination decreasing with distance from Khirbat Faynan, the pattern reflects a mosaic of multiple contamination sources resulting from complex socio-natural processes described in more detail below.

As we had anticipated, the OSL results did not provide narrow enough resolution to attempt to identify specific episodes of deposition, whether contaminated or not. However, the chronological constraints they provide – combined with archaeological and phytolith indicators of ancient land-use – permit us to make some preliminary observations regarding the spread of contaminated sediments through time. Specifically, the OSL results confirm that *sediment deposition* occurred throughout the periods in which copper metallurgy was practiced. The archaeological data – from prior analysis of surface ceramics, from the excavations carried out for this study, and from the phytolith data presented in this article – confirm our claim that the agricultural terraces were in use when Iron Age and Roman period metallurgical production was occurring.

Turning to the three units for which we have OSL age estimates, the results suggest sediment deposition over a ca. 2500 period. For Unit 3, the upper measurement, taken from 25 cm below surface ( $2.15 \pm 0.23$  ka, 200 BCE) suggests the most recent accumulation of sediment postdates the Iron Age smelting activities from ca. 1000–800 BCE, instead occurring during or before the Early Roman period. The lower measurement, taken from 62 cm below surface ( $3.11 \pm 0.41$  ka, 1160 BCE), falls within the Late Bronze - early Iron Age. The high levels of Pb and Cu enrichment from 0–40 cm thus appears to be a later historical phenomenon, occurring long after Iron Age copper production in Faynan. For the lower levels with less Cu enrichment, the dates indicate that these were likely deposited prior to Roman metallurgical activities. Spatially, Unit 3 is one of the closest to the sources of metal contamination (see Fig. 1), just 700 m from debris piles dated by C14 to 6550–330 cal. BP. Despite this fact, the anthropogenic contribution of Pb and Cu is relatively small compared to the most enriched samples measured in this study. Furthermore, metal enrichment decreases significantly with depth, which may be due to contamination from smelting-related artifacts near the surface (see below).

An upper OSL age from Unit 6, taken 45 cm below surface ( $3.22 \pm 0.33$  ka, 1270 BCE) unfortunately does little to constrain the date of sediment deposition with the lower age estimate, at 70 cm, although it may indicate that a significant volume of agricultural sediments had accumulated by the end of the Iron Age. It is interesting to note that the lower OSL age ( $3.49 \pm 0.45$  ka, 1540 BCE) corresponds to the peak in Cu enrichment ( $EF = 137$ ) and Pb enrichment ( $EF = 14$ ), and occurs well before Roman period metallurgy commences in Wadi Faynan. This contrasts with the data from Unit 3 above, in which Cu enrichment is measured in post-Iron Age levels. Furthermore, Cu enrichment is much higher in Unit 6, despite the fact that Unit 6 is 1.5 km away from sources of heavy metal contamination – nearly 1 km farther than Unit 3.

The upper OSL age from Unit 7, taken 50 cm below surface ( $2.41 \pm 0.31$  ka, 460 BCE) encompasses a chronological range from the late Iron Age to the early Roman period. Pb and Cu enrichment near the surface are less than half the measured values from deeper strata. The age estimate from the lowest level, taken from 114 cm below surface ( $3.37 \pm 0.47$  ka, 1420 BCE) corresponds to peak levels of Cu enrichment ( $EF = 102$ ) and near peak levels of Pb enrichment ( $EF = 15$ ). Peak Pb enrichment was measured in the level below (120–140 cm,  $EF = 16$ ). The OSL age of the sample taken from 70 cm below surface ( $3.38 \pm 0.54$  ka, 1430 BCE) closely resembles the lower date, but corresponds to very different EF values in the sediments. Thus, it within this time frame we see a significant change in the enrichment of Pb and Cu, accompanied by only a slight change in soil color (light reddish brown to brown) at 90 cm (Fig. 2). In any case, the most contaminated levels of Unit 7 predate Roman period copper smelting in Wadi Faynan, and the unit is located approximately 1.5 km from metallurgical deposits.

OSL age estimates from Unit 10 also predate the Roman period by hundreds of years. The upper date, from 58 cm below surface ( $2.94 \pm 0.32$  ka, 990 BCE) spans the Late Bronze Age and Late Iron Age. Sediments above 58 cm were likely deposited during later historical periods, but were not measured. As previous archaeological work has shown, the terraces were actively used during the Iron Age and Roman periods, as well as intermittently in the years that followed until the modern day. The lower date probability range, at a single standard deviation, from 137 cm below surface ( $3.33 \pm 0.35$  ka, 1380 BCE) spans the Middle Bronze Age and Iron Age. Sediments from each level of this excavation unit exhibited no evidence for the anthropogenic contribution of Pb, and only minor evidence of an anthropogenic contribution of Cu.

##### 4.1. Spatial distribution of anthropogenic Pb and Cu

As indicated above, the spatial distribution of anthropogenic Pb and Cu in the WF442 and WF443 agricultural terraces is quite variable and does not match a pattern of pollution as a direct result of metallurgical production. Rather, sediments that are most enriched with heavy metals are located near tributaries that would have provided some of the irrigation water feeding the terraces, leading us to argue that the DLS ores in these tributaries are one of the primary sources of the anthropogenic Pb and Cu. Given the degree of landesque capital constructed in Wadi Faynan (especially the agricultural terraces and to some extent, the metallurgical infrastructure) it seems that labor invested in local infrastructure contributed greatly to the preservation and protection of agricultural terraces and metallurgical debris alike. A comparison of Pb and Cu concentrations from the debris piles and from the terraces suggests that contamination was relatively contained within the former. Similarly, the same social processes that led to the preservation of terraces WF442 and WF443 may have additionally protected them from contamination by the debris piles, in that the terraces were literally walled off from these potential sources.

Naturally, this was not a perfect system, and to some extent both cultural processes and natural erosion and weathering of the metallurgical deposits must have contributed in some part to the heavy metal content of the terraces.

An example of these preservation processes can be seen in Unit 3, which is the closest unit to the large metallurgical debris deposits. The EF values are relatively low here (max values for Cu = 360 ppm, Pb = 52 ppm), and stand in stark contrast to previous measurements taken from debris piles just 500 m upstream, which reach 50,000 ppm for Pb. Thus, it appears that the existing infrastructure built for mining and smelting activities, including the barrage wall (constructed ca. 1900–1800 cal. BP) adjacent to Khirbat Faynan and other structures built to contain smelting waste, prevented the highly contaminated sediments from entering the environment on a large-scale. Further to this point, the terrace walls may have indirectly provided some protection for the agricultural soils in cases where contaminated sediments did manage to spread beyond their original context. This example illustrates the utility of *landesque capital* as a concept for understanding the dynamic relationship between political economy (production systems and the built environment in the above example) and environmental changes, and the potential for future applications of the concept to Faynan in light of our interpretations below.

The elevated levels of Pb and Cu in Unit 3 can perhaps be explained by the presence of copper slag and pottery sherds collected from the surface and the first 20 cm of the excavations. Metallurgical debris (including slag) and ceramics have been implicated as a vector for the redistribution of heavy metals into Wadi Faynan (Grattan et al., 2007). This can be further confirmed by the sample measurements from Unit 4, located approximately 15 m from Unit 3, and where Cu enrichment is lower and Pb enrichment is not significant. Adding further complexity to the varied distribution of Pb and Cu is Unit 5, where Cu enrichment was highest in subsurface sediments, while Pb enrichment did not change significantly. It should be noted that this unit was not located near a tributary Wadi, so contamination by water erosion is not an explanation easily invoked here. The case may be that other natural or cultural processes contributed to the deposition of contaminated sediments, and that our small excavation did not detect these processes. Regardless, these results testify to the varied and mosaic spatial patterning of metal enrichment throughout the valley.

The elevated concentrations of Pb and Cu from Units 6, 7, and 8 are perhaps the strongest evidence for deposition of these metals from erosion, as the units are clustered around the outlet of Wadi Khaled, one of the major tributaries feeding the terraces. These units are located more than 1.5 km from the metallurgical debris piles of Khirbat Faynan, but contained the highest values for Pb and Cu enrichment. The tributary Wadi from which irrigation water was harvested contains a high density of copper mines originally dating to the Early Bronze Age (ca. 3600–2000 BCE), but which were reused during the Iron Age and (especially) Roman periods. Evidence of preliminary smelting was also found at a few places near the mines, but it is during these later periods that the mines were opened to their fullest extent and mining intensity peaked (Hauptmann, 2007: 116–121). Therefore, it is interesting that the strata with the highest enrichment factors for Pb and Cu predate the Roman exploitation of Faynan's natural resources. Under Roman rule, land-use patterns changed significantly, and in ways that altered the agricultural landscape. A cistern and aqueduct were constructed near the southern bank of Wadi Faynan. Agricultural intensification was most significant in the WF4 field system, also along the south bank of Wadi Faynan, and was likely extended to WF442 and WF443 on the north bank as well. Under this new agricultural regime, the distribution and quantity of metals entering the agricultural terraces by water may have actually

decreased.

Lower Pb and Cu concentrations are present in Units 9 and 10, which are located approximately 500 m west of Unit 8 and adjacent to a tributary without significant mining activities. The mining areas of Qalb Ratiye and Wadi Abiad (Hauptmann, 2007), both of which are small tertiary valleys connected to the main tributary west of Units 9 and 10, would not likely have been a source of irrigation water. This is primarily due to the fact that the valleys terminate just above the mining areas, and do not extend up to higher elevations like other valleys that provided irrigation water. Even if small amounts of water passed from Qalb Ratiye and Wadi Abiad to the terraces downstream, these mining areas were not exploited as extensively as Wadi Khaled or Wadi Dana. Qalb Ratiye is also unique for the Faynan region in that there is no indication of smelting near the mines (Hauptmann, 2007: 114), a practice that surely contributed to the potential effects of Pb and Cu contamination elsewhere.

#### 4.2. Agricultural uses of the terraces

The results from Unit 7 suggest there was not intensive cereal cultivation. While leaf/stem and husk phytoliths are present in low densities in all samples across the section except one, level 60–80 cm, the data rather show that the terraces were dominated by woods and shrubs and very few Pooid grasses. The single-cell phytoliths of Pooid grasses (rondels) in the top stratum might reflect the cultivation of wheat and barley, perhaps in more recent times. The presence of modern furrows on the surface of the terrace plot from which the samples derived further attests to the temporary reinstitution of agriculture. Currently, the terraces north of Wadi Faynan (WF442 and WF443) are not in use, whereas local residents have begun farming tomatoes and other horticultural crops on some of the terraces from the large WF4 terrace system. Woody plants are also common following abandonment of agricultural terraces, when species such as *Retama* recolonize the surface. As there is evidence for the abandonment of the site at various periods of time, including between the Iron Age and Roman period, then these plants may have also contributed to the quantity of phytoliths measured.

The presence of the water-loving Cyperaceae plants in the phytolith record indicates an environment that was never extremely arid. Wet conditions existed for the cultivation of trees and shrubby plants (either due to natural conditions or as a result of irrigation), from which animals could graze. Based on the proportions of wood vs. grasses it is possible to suggest that small plots of cereals were grown potentially in the same terraces, as co-cultivation of trees and cereals is a common farming practice in the region for restoring soils. Cyperaceae are forage plants and their presence in the samples could indicate the use of dung for manuring (Ollendorf, 1992). This not only provides further confirmation for the long-term use of the terraces, but the practice of manuring may have been one of the pathways through which Pb and Cu entered the environment, particularly if livestock were grazing near contaminated areas. This practice has, in fact, been observed in recent times in Wadi Faynan.

The phytolith results are not just important for understanding the agricultural history, but also for determining the possibility of bioaccumulation processes leading to the depletion of metals via crop harvesting. As cereals were not a major crop grown on the sampled terraces it is unlikely this had an effect. Furthermore, previous research from the WF4 terrace – where cereals were likely harvested – shows that metal contamination persists (Hunt and El-Rishi, 2010). While trees also bioaccumulate metals (Pyatt, 2001), less of the plant is harvested suggesting that this would not have major impacts on contamination levels. Although beyond the scope

of this study, the biodynamics of these processes are worth investigating further to gain a better understanding of how metals enter and exit the environment as well as the relationship to human health.

## 5. Conclusion

As previous research has demonstrated, the legacies of 6000 years of intensive copper mining and smelting include the prominent black slag mounds composed of metallurgical debris, and the environmental risks they pose should the various constraints restricting the heavy metals to the immediate vicinity of the heaps be disturbed. Another, though less visible and subject to less study, is the system of agricultural terraces blanketing a large swath of Wadi Faynan's alluvial basin that provided an important source of agricultural provisioning for the historical mining operations in the region. A novel contribution of the analysis presented here is the focus on the long-term relationship and history of interaction between these two features of the built environment.

Reconstructing the environmental impacts of large-scale copper smelting requires careful examination of the various socio-natural factors involved in environmental change. The multi-proxy record we have presented, based on geochemical analysis, luminescence dating, and archaeological and phytolith analysis, indicates that environmental pollution of the agricultural terraces WF442 and WF443 was not as widespread or as severe as previous research has suggested. While Pb and Cu have certainly been released into the environment in large quantities, these contaminants are mostly contained within the metallurgical debris piles. Beyond these specific loci, contamination is variable but relatively low, and the chronology of paleo-pollution suggested by the OSL data indicates that the deposition is not tied to major periods of metal production. The processes through which anthropogenic pollution entered the environment cannot be explained with simple, unidirectional cause-and-effect model of environmental degradation. Our data show that runoff from the mines had the largest impact on terraces WF442 and WF443, but the contamination was limited to certain sites. Additional sources of contamination included the redeposition of metal contaminated objects (e.g., pottery and slag in Unit 3), and wind or water erosion of debris piles as indicated in previous studies. Still, the environmental impact we observed in the terraces is lower than expected given their proximity to highly contaminated deposits. Thus, a view of complex society as the inevitable destroyer of natural harmony that has characterized the previous environmental research must be reconsidered in light of these new data.

We argue that the ecological concept of *landesque capital* is important for understanding how and why the metallurgical impact on the agricultural terraces was so small compared to measurements taken from metallurgical activity areas. As a type of *landesque capital*, the agricultural terraces represent the long-term investment in the land for labor-saving and productive gains. The result of this construction was a local landscape of increased resilience and decreased need for labor input. Maintaining these systems was necessary to their preservation, and periods of neglect greatly increased the potential for degradation. These structures, in turn, minimized pollution diffusion from the debris piles. Moving between different scales of analysis, one can imagine how local processes (e.g., smelting, erosional events, etc.) and macro-regional processes (e.g., changing subsistence and economic regimes, land-use patterns, etc.) interacted to transform the landscape in different ways.

Specific episodes of pollution have the potential to occur over a few days or over hundreds of years. While our data do not permit us to diagnose when these episodes occurred precisely, they do

demonstrate that multiple such episodes occurred during the long-term history of Wadi Faynan, and that they did not necessarily corresponded to mining activities. This effect not only varied chronologically, but spatially as well, with indications of pollution fluctuating significantly across the terraces and even from plot-to-plot. The evidence from phytolith analysis supports the long-term utilization of the agricultural terraces for the cultivation of trees and shrubs combined with periods of abandonment. Again, while it is difficult to state precisely what was grown and when, the results do permit us to make some general statements about the history of land-use, and point to a number of possible uses, including tree cultivation, perhaps mixed with intermittent and small-scale cereal agriculture, and the practice of manuring with animal dung. Of course, these uses may have been employed in changing combinations in response to the regional political economy and as the needs of copper producing communities changed through time.

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