Toxicology and Industrial Health 2002; **18:** 297–307
www.tihjournal.com

'Death . . . more desirable than life'? The human skeletal record and toxicological implications of ancient copper mining and smelting in Wadi Faynan, southwestern Jordan

John Grattan[a], Steven Huxley[a], Lotus Abu Karaki[b], Harry Toland[a], David Gilbertson[c], Brian Pyatt[d] and Ziad al Saad[b]

[a]*The Institute of Geography and Earth Science, The University of Wales, Aberystwyth, UK*
[b]*The Institute of Archaeology and Anthropology, Yarmouk University, Irbid, Jordan*
[c]*School of Geography, The University of Plymouth, Drake Circus, Plymouth, UK*
[d]*Interdisciplinary Biomedical Research Centre, School of Science, The Nottingham Trent University, Clifton Lane, Nottingham, UK*

Skeletal material from 36 people, dating from the early Christian era, who lived by or worked in the notorious Roman copper mines of Phaeno, were analysed to determine their exposure to copper and lead. We demonstrate that many of the bones analysed had a substantially higher concentration of these cations than modern individuals exposed to metals through industrial processes. Health, toxicological and environmental implications of these data are reviewed. *Toxicology and Industrial Health* 2002; **18:** 297–307.

Key words: *ancient industry; ancient pollution; copper; human bone; lead; smelting*

Introduction

Studies of the pollution burden contained in retrieved ice cores have indicated that industrial pollution is not a modern phenomenon; the industries of the ancient world have also left their mark in the form of enhanced lead and copper concentrations in the Greenland ice core record (Hong *et al.*, 1994, 1996) This paper presents the results of a study of the skeletal chemistry of some of the people responsible for this ancient pollution, details of the environment in which they lived and a analysis of the toxicological implications. The analyses presented in this paper form part of an extensive integrated research project, which addresses the current and ancient environmental impact of large scale ancient metal mining and smelting in the desert of southern Jordan. Our aims are to determine the extent to which the ancient inhabitants were exposed to toxins released by the mining, ore processing and smelting activities in which they were engaged. This study is also of relevance to modern contexts, in particular for modern populations similarly exposed to heavy metal pollution, either in their workplace or in their environment.

Address all correspondence to: John Grattan, The Institute of Geography and Earth Science, The University of Wales, Aberystwyth, SY 23 3 DB, UK
E-mail: John.Grattan@aber.ac.uk

The study area

The remnants of one of the major centres of copper mining and smelting in the ancient world may be

10.1191/0748233702th153oa

found today in Wadi Faynan (Figure 1), a remote wadi found in southwestern Jordan (Hauptmann *et al.*, 1992; Hauptmann, 2000), at the foot of the mountain front that forms the eastern flank of the Wadi Arabah. On the banks of the wadi lies Khirbet Faynan (Arabic: The Ruins of Faynan), the ruins of the Roman city of Phaeno, which is recorded in history as an industrial centre of the Roman world (Knauf and Lentzen, 1987; Klein and Hauptmann, 1999). Khirbet Faynan itself was clearly the hub of an extensive metal processing industry. For ~10 km to the north and south, industrial archaeology in the form of numerous buildings, adits and shaft mines, ore spoil, furnaces and slag heaps may be found (Hauptmann *et al.*, 1992; Hauptmann, 2000).

Whilst the copper ores were the main objectives of the ancient industry, numerous other metals are present in significant quantities in copper bearing strata. The Faynan mines and adits penetrate complex ore bodies formed by several distinct phases of mineralization – variously involving copper and lead, which inevitably would have been liberated during quarrying and ore processing

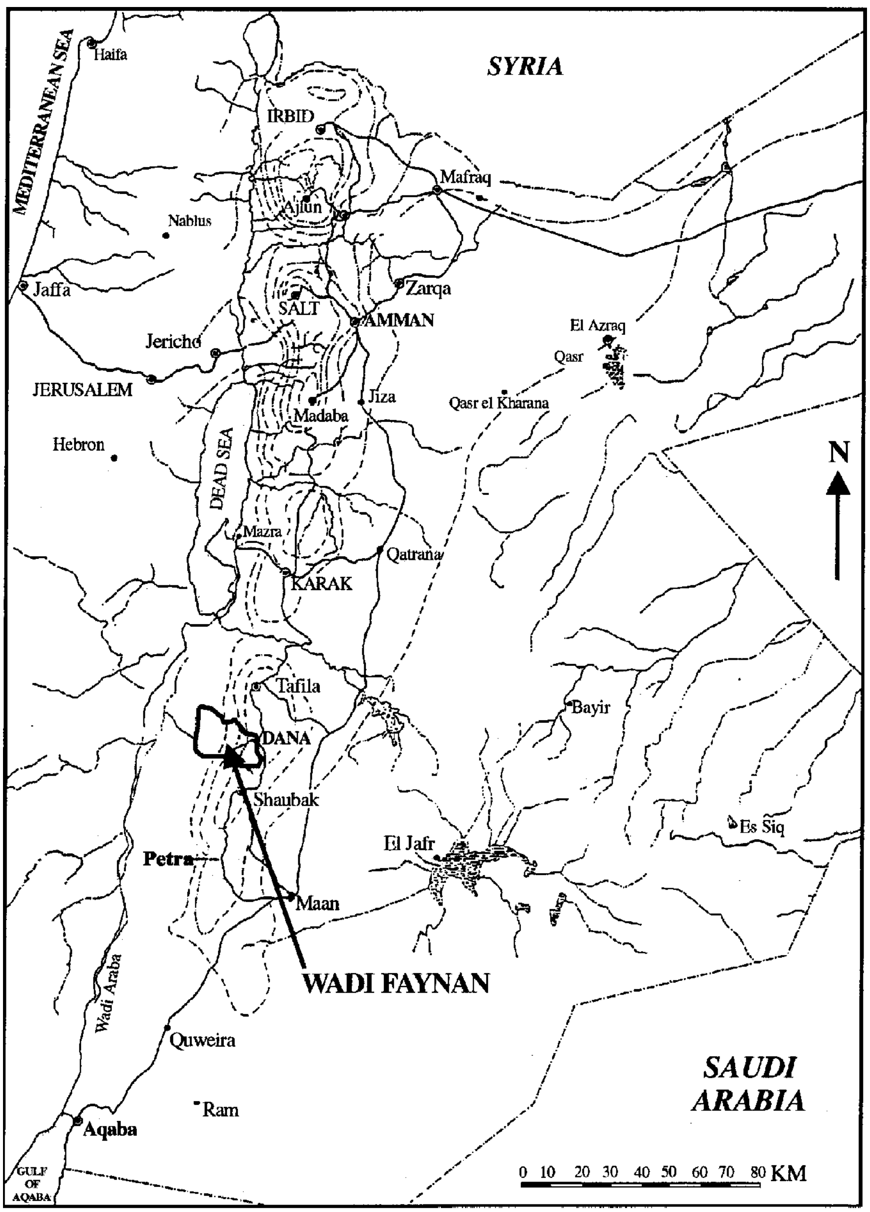

Figure 1. Location of the study area

(Alloway and Ayres, 1993). Several major sedimentary rock formations are involved. These include the Numayr Dolomite limestone of the Burj Dolomite Siltstone Formation and the 'Umm Ishrin Sandstone. These sedimentary rocks include various shale horizons. They overlay a complex of metal-rich, fractured and water-yielding Proterozoic granitic and volcanogenic bedrocks (Bender, 1974; Barjous, 1992; Rabb'a, 1994; Hauptmann, 2000).

The logistical support required to maintain such a complex industrial network in this remote location must have been complex and it is no surprise that the industrial archaeology is closely associated with a complex and extensive irrigated field system of fields, designed and maintained to support the workforce, both slave and volunteer, in this remote arid area (Barker *et al.*, 1998, 1999, 2000).

Pollution studies and environmental toxicology in Wadi Faynan

The modern environment

Although today, lying within the Dana Nature Reserve, an area considered an example of profound natural beauty, the pollution legacy of ancient metal extraction activities remains considerable (Gee *et al.*, 1997; Maskall and Thornton, 1998). Pyatt and Grattan (2002) noted that traditional foods prepared by the Bedouin of the area may be contaminated with high concentrations of lead and copper; while Grattan *et al.* (2003a) have reported significant enhancements of heavy metals within the floor sediments of Bedouin tents pitched within a kilometre of Khirbet Faynan; copper concentrations reached 2849 mg/kg soil, with the highest values measured around the hearths where food is prepared. The exceptional enhancement around the cooking hearths probably resulted from the combustion of plants as fuel, which contain high levels of absorbed metals; copper in the stem of *Ephedra alte*, frequently burned in these fires, was measured at 603 mg/kg dried plant (Pyatt *et al.*, 2000). Ingestion of plants containing enhanced metal burdens also appears to be contaminating the modern invertebrate food chain (Pyatt *et al.*, 2002); the accumulation of metals by modern vertebrates is discussed in Pyatt *et al.* (1999), where modern goat skeletons were shown to contain lead and copper in excess of 100 μg/g bone. These studies suggest that in the present day several pathways operate by which organisms may accumulate body burdens of heavy metals emitted by ancient industrial activities (Pyatt and Grattan, 2001). These include the direct ingestion/inhalation of airborne metalliferrous dusts; the ingestion of food contaminated during preparation by metal-rich dusts in the air, on the ground and via the release of adsorbed metals during the combustion of plant material during cooking; the ingestion of food, both animal and plant derived, containing metals absorbed during growth (Leita *et al.*, 1991; Ylaranta, 1996; Moustakas *et al.*, 1997).

It is clear that modern exposure to metals derived from ancient industrial activities is considerable, which begs the question of the degree of exposure endured by the inhabitants of the area in ancient times, when the ore extraction and metal production was at its peak and what were/are the toxicological implications of inhabiting such a polluted area. These questions are considered below.

The ancient environment

Studies by Pyatt *et al.* (1999, 2000) indicate that cereals grown in the irrigated field system and animals grazed on their products would have accumulated a significant burden of heavy metals. With urban and agricultural land use in close proximity to industrial processes in ancient times, not only miners and metal workers, but agricultural workers, administrators, indeed any occupant of the district (voluntary or involuntary), may have been exposed to potentially toxic concentrations of copper and other metals. In this respect, the Faynan region is identical to many modern industrially polluted areas (Kachur *et al.*, 2003). Additional pathways by which metals could have accumulated in the ancient occupants of Wadi Faynan include the inhalation of metalliferrous dusts and flue gases generated by industrial processes, such as mining, quarrying, ore preparation and smelting. Analysis of buried palaeosols, sediments which have accumulated in archaeological features and mine and smelting waste suggest that during ancient times the region was highly polluted; copper and lead concentrations ranged as high as 11 961 μg/g soil and

15 205 μg/g soil, respectively (Pyatt *et al.*, 2000). In the developed world, contaminant values at these levels would invoke legislation and require intervention (Canadian Council of Ministers of the Environment, 1991), yet these are the remnants of pollution emitted between 4000 and 1500 years ago. These values suggest that we should consider the Faynan landscape, beautiful as it is today, to be a relict industrial zone and that Khirbet Faynan could be described as a huge abandoned smelting plant, which continues to generate toxicological problems in the modern environment.

The environmental and toxicological story is enhanced by the historical record. The intensive metallurgical activities at this site in the third and fourth centuries AD are popularly known from the writings of Bishop Eusebius of Caesarea. He described the notorious copper mines and furnaces to which slaves, criminals and Christians from Palestine and Egypt were transported and were 'damnatio ad metal'; a place 'where even a condemned murderer may live only a few days' (Eusebius, 1969; Schick, 1995).

Ancient population

A preliminary analysis of the metal content of the skeletons of two individuals excavated from the Christian cemetery in Wadi Faynan (Findlater *et al.*, 1998) indicated that the fifth century AD inhabitants had absorbed lead and copper in concentrations which indicated industrial exposure (Grattan *et al.*, 2003b). This current work develops that study by an analysis of the metal content of the excavated skeletons of 36 individuals, established by ICP-MS analysis.

Analytical methodology

The skeletons of 36 individuals dating from the Byzantine era, fourth–seventh century AD, were excavated in 1996 (Findlater *et al.*, 1998; Karaki, 1999) and stored in the University of Yarmouk, Irbid, Jordan. The cemetery was located on an alluvial fan formed from the erosion of rocks of the Ghuweir volcanic series (Finlayson *et al.*, 2000; Rabb'a, 1994). Soil samples were also collected in order to establish the pre-copper smelting soil content and the residual industrial pollution in the modern landscape.

Samples of bone from each of the 36 individuals arrived at the laboratory in Aberystwyth pre-sectioned and labelled. Labels indicated the grave from which the sample was collected and the specific bone from which the sample was carefully removed. The bones selected for analysis were pre-cleaned with a soft brush to remove any remaining soil or detritus. Subsamples of the sectioned bones were removed and placed in an ultrasonic bath for five minutes. The cleaned bone samples were then placed under protective covers in a dust-free atmosphere and allowed to air-dry for 48 hours. The samples were weighed, bagged and relabelled, ready for analysis. Before analysis, the samples were placed in 100-mL conical flasks and 10 mL of Milli-Q water was added. To this 2 mL of H_2O_2 was added, followed by 10 mL of conc HNO_3. The flasks were covered with watch glasses and transferred to the fume cupboard where they were placed on a hotplate set at the lowest level and allowed to digest for 48 hours. Several blank solutions were made up simultaneously and in the same manner and these were transferred to the fume cupboard. When completely digested the samples were allowed to cool and to each 2 mL of Ru (5 μg/mL) was added. The Ru acts as an internal standard for the ICP-MS. A fresh batch of standard, known as 'All Elems.' was prepared. This is typically made up into 1-L batches and is a solution of Milli-Q water with 5% HNO_3 (v/v) and all the common elements at 100 ppb (with the exception of Ca and Fe at 1000 ppb). The cooled samples were transferred to 100-mL volumetric flasks and made up to the mark with Milli-Q water before being transferred to the ICP-MS facility. Prior to analyses the ICP-MS was run for an hour to 'warm up' and subsequently optimize using an in-house 'tune solution'; this ensured maximum output for any given analyte of interest.

Before sample analysis the blank sample was analysed (× 3) followed by the All Elems.' solution (× 3). Each of the digested bone samples was then analysed (× 1), every five to 10 analyses were made in duplicate. At the end of each run, (typically about two hours) a repeat analysis of the initial blank and 'All Elems.' was performed to check for instrument drift. Raw data (in counts per second) were manipulated online, using the internal standard (Ru) within the samples, calibrated against Ru within the 'All Elems.' standard. Data were available in μg/g. Calibrated data were downloaded and the recorded blank was subtracted from each of the samples to give actual trace metal content from each bone sample in μg/g.

The soil samples were transported to the laboratory in clean, relatively large plastic zip bags; each of the bags were subsampled and the resulting sample was weighed and recorded, bagged and relabelled. The new samples were placed in 100-mL conical flasks into which 10 mL of conc HNO_3 was added. These were placed in the fume cupboard, covered with watch glasses and allowed to digest for 72 hours. After digestion, the samples were filtered through a #1 Whatmann filter, into 100-mL volumetric flasks. Subsequently, 2 mL of Ru (5 μg/mL) was added to each flask and then made up to 100 mL with Milli-Q water. Blank samples were also prepared at this time. The samples were transferred to the ICP-MS laboratory and analysed following the same procedure as that previously described.

Results

The results of the chemical analyses of the bones are presented in Table 1; these indicate that while all the analysed samples contained some metal, 16 of the individuals analysed contained high concentrations of copper and lead. These data suggest either direct exposure to metals in the workplace, or as the result of living in a contaminated environment, or perhaps a combination of both. A comparison of the metal concentration in the bones examined with reference data compiled from a geographically remote and uncontaminated ancient human population (González-Reimers *et al.*, 2001; González-Reimers *et al.*, in press) suggest that 11 of the individuals examined had absorbed over four times the copper concentrations reported in the reference population; and that 19 individuals had absorbed over four times the lead concentrations reported in the reference population (Table 2). Fourteen individuals contained over 25 μg/g copper, and eight contained over 70 μg/g copper. Copper content in the bones analysed was up to 70 times in excess of the typical figure for modern vertebrate bone, 4.2 μg/g (Scheinberg, 1979), and up to 28 times the average value reported by Gonzalez-Reimers *et al.* (2001; in press) for the ancient inhabitants of Fuerta Ventura (Tables 2 and 3). The average lead content in the Faynan skeletons was approximately 15 times higher than that recorded for the ancient populations of the Canary Islands, with 14 individuals containing lead burdens greater than 40 μg/g. Four individuals have lead concentrations above 100 μg/g bone, five between 50 and 99 μg/g bone

Table 1. Metal content of bone μg/g.

Grave	Copper	Lead
5	278.5	47.6
10	17.0	20.7
11	9.8	1.8
12	88.6	12.3
22	13.2	1.6
25	109.1	170.0
27	30.7	47.5
66	24.0	55.3
67	181	289.2
69	17.1	27.6
70	5.0	1.0
72	3.0	13.0
73	296.2	19.1
75	7.0	42.0
76	20.0	21.6
78	20.0	12.8
80	6.3	37.7
81	7.0	27.9
83	11.0	28.9
85	43.7	1.0
86	2.4	15.0
87	2.4	4.7
88	135.6	75.6
89	2.5	16.0
91	30.0	26.6
94	2.1	9.2
96	90.7	44.2
97	5.7	13.7
101	29.2	24.3
102	27.5	204.6
104	43.1	17.01
105	17.9	37.1
110	2.8	8.4
112	5.9	14.4
113	73.9	46.7
117	22.4	93.7
Mean	52.57	42.49
Maximum	296.2	289.2
Minimum	2.1	1.0

Table 2. Comparison of Faynan bone metal content with ancient humans from the Canary Islands.

μg/g	Copper	Lead
Faynan mean value	52.57	42.49
Reference values	10.5[a]	4.06[b]

[a] González-Reimers *et al.* (2001).[b] González-Reimers *et al.* (in press).

Table 3. Enhancement of Faynan skeletal metal content in comparison with metal content of ancient human bone in the Canary Islands (Feinan bone metal/Canary Island reference value).

Grave	Copper	Lead
5	26.52	11.72
10	1.62	5.10
11	0.93	0.44
12	8.44	3.03
22	1.26	0.39
25	25.44	41.87
27	2.92	11.70
66	2.29	13.62
67	17.32	71.23
69	1.63	6.80
70	0.48	0.25
72	0.29	3.20
73	28.21	4.70
75	0.67	10.34
76	1.90	5.32
78	1.90	3.15
80	0.60	9.29
81	0.67	6.87
83	1.05	7.12
85	4.16	0.25
86	0.23	3.69
87	0.23	1.16
88	12.91	18.62
89	0.24	3.94
91	2.86	6.55
94	0.20	2.27
96	8.64	10.89
97	0.54	3.37
101	2.78	5.99
102	7.54	50.39
104	4.10	4.19
105	1.70	9.14
110	0.27	2.07
112	0.56	3.55
113	7.04	11.50
117	2.13	23.08

and nine between 25 and 49 μg/g bone. Seven individuals have skeletal copper concentrations above 100 μg/g bone, and a further seven between 50 and 99 μg/g bone. In comparison with the Canary Island data, used here as reference values, the Faynan material may be considered to be markedly enhanced (Table 3).

In summary, many of the skeletons excavated from the South Cemetery in Faynan may be seen to contain copper and lead at concentrations far in excess of uncontaminated reference populations and which bear comparison with modern bone from areas considered to be contaminated today (Baranowska *et al.*, 1995). In particular, material retrieved from graves 5, 12, 25, 27, 67, 70, 73, 85, 88, 91, 101, 102, 104, 105, 113 and 117 contained notably high concentrations of both copper and lead (Figure 2). These values are higher than those presented in Baranowska *et al.* (1995), which reported the skeletal metal content of the inhabitants of Silesia, a report which emphasized that the individuals examined were living in an ecological/toxicological disaster zone.

Soil samples were not recovered for each grave, but subsequent sampling of the fan sediments have yielded copper values ranging between 0.29 and 3.4 μg/g soil, lead values ranging between 0.28 and 3.56 μg/g soil.

Discussion

It is clear from the values reported above that most of the excavated skeletons from the Faynan cemetery contained copper and lead in concentrations higher than those reported for ancient populations that can be reliably assumed not to have been directly exposed to these metals. The possibility that post-mortem diagenesis is the source of these data should be considered. Oakberg *et al.* (2000) proposed that the metal content of ancient human bones could be used to infer exposure to metal processing activities, a view challenged by Pike and Richards (2002), who suggested that the concentrations measured could be best explained by post-mortem diagenesis; the exchange of ions between the bone and the soil. The average bone/soil ratio reported by Oakberg *et al.* (2000) for arsenic, which was the sole metal studied, was 9.5:1. Taking the average metal concentrations for the cemetery sediments as copper 1.7 μg/g soil and lead 1.4 μg/g soil, it is possible to broadly indicate the average bone/soil metal ratio for Faynan; these are copper 30.9:1 and lead 30.4:1. We therefore propose that the concentration data reported here are unlikely to be the result of post-mortem diagenesis and are best explained by direct exposure to these metals, in the workplace and/or environment, during the latter part of their lifetime.

Another potential source of contamination is via exposure to lead in domestic use throughout the lifetimes of the individuals examined. Lead was used widely in the Roman world, both to line aqueducts and as drinking and eating utensils (Gilfillan, 1965; Waldron, 1988) and it is reasonable to suggest that some of the body burden of lead reported above comes from 'domestic' rather than industrial exposure. Nriagu *et al.* (in press) inves-

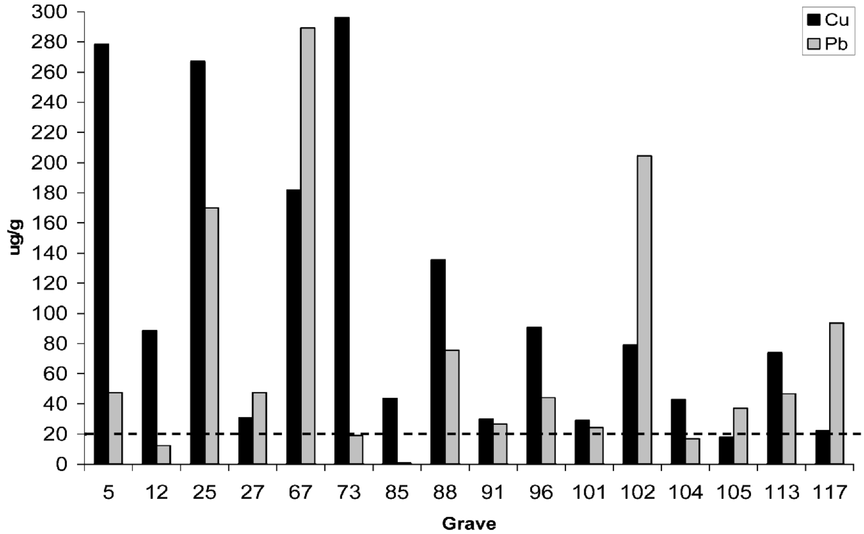

Figure 2. Metal content, µg/g bone, of individuals assessed as exposed to industrial processes. Dashed line indicates the mean lead value in a Roman population.

tigated the exposure of the 98 Roman skeletons to lead in their environment and noted that the concentrations of this metal in their samples ranged between 0.87 and 86 µg/g bone, with an average of 21 µg/g. In comparison, the Faynan bone lead concentrations range from 1 to 289.2 µg/g bone, with a mean of 42.49 µg/g bone. Nriagu *et al.* are careful to note that the samples studied represent a 'middle-class' population, enjoying their share of domestic conveniences, comforts and the 'finer things' in life. The individuals examined here cannot be described as middle-class. There was a paucity of grave goods and ample evidence in the skeletal pathology for lives spent in toil rather than comfort (Karaki, 1999).

The samples analysed in the present study were obtained from deep, not superficial, burials in an elevated part of this desert region; the cemetery is located well above the nearest dry wadi. In temperate parts of the world, cations can exhibit an enhanced affinity for the phosphate-rich apatite to be found in bones. However, in our research area, with its long-term arid climate, processes involving the mobilization of heavy metals by means of soil water are likely to have had extremely limited effects. Indeed, it may further be noted that in such arid areas decomposition of organic material, post-mortem, is also severely retarded. It should also be noted that the absorption processes we infer have been operating in the past are active in the present day and high levels of metal accumulation have been noted in the mammal, insect and plant species of the wadi (Pyatt *et al.*, 1999; 2000; 2002).

Sixteen graves contained individuals whose bones contained lead and copper concentrations (Figure 2) as high as any that have been reported from industrially contaminated modern sites (Baranowska *et al.*, 1995) and this part of the Faynan population best bears comparison with modern industrially exposed workers (Table 4). In Sweden, the lead content of the bones of metallurgical workers were 40–100 µg/g bone (Ahlgren *et al.*, 1976; Ahlgren and Mattsson, 1979); 11 of the Faynan samples had a lead content higher than 40 µg/g bone and three graves, 25, 67 and 102, had a lead content in excess of 100 µg/g bone; the highest value being a lead content of 289.3 µg/g bone (Figure 2, grave 67). The highest copper value reported for Silesia was 5.17 µg/g bone; in stark contrast, the average value determined from the

Table 4. Comparison of the metal content of the Faynan population and a sample drawn from the population of a modern industrial region, Silesia in Eastern Europe (Baranowska *et al.*, 1995).

	µg/g	Minimum	Mean	Maximum
Lead	Silesia	2.9	57.55	204.53
	Faynan	1	42.49	289.2
Copper	Silesia	0.18	0.59	5.17
	Faynan	2.18	52.57	296.2

Faynan material was 52.57 μg/g bone and the highest is 296.2 μg/g bone (Figure 2, grave 73). The copper concentrations determined also point to industrial processing and wider environmental contamination as being the most probable pathways by which this accumulation took place. Not all individuals excavated from Faynan have a bone metal content that indicates active involvement in the industrial process or long-term exposure to industrial byproducts. Nineteen individuals (56%) have bone metal content typical of the wider population at the time. Eusebius (1969) suggests that people condemned to work in Faynan were expected to die quickly in the harsh conditions there, and these individuals may bear silent testimony to that expectation, dying of exhaustion, sickness or disease before their bodies were able to accumulate an abnormal body burden of copper and lead. In summary, therefore, while 44% of the Faynan material (Figure 2) has the appearance of a population that has been exposed to heavy metals via multiple environmental pathways, probably the result of direct involvement in the extraction and processing of the metals, 56% appear to have died soon after they arrived in the area.

Health/toxicological implications

The metal burdens indicated in the bone analysed suggest that the metal workers of Faynan may have been vulnerable to a range of illnesses related to exposure to metals. Moderate symptoms of copper toxicity noted in the literature include: salivation, epigastric pain, nausea, ulceration of the nasal septum, vomiting and diarrhoea (Cohen, 1979; Mason, 1979). Copper has also been shown to induce pulmonary inflammation (Rice *et al.*, 2001) Additional serious health problems include intravascular haemolysis, hepatic necrosis and failure, haemoglobinuria, proteinuria, hypertension, tachycardia, acute renal tubular failure, coma and death (Williams, 1982). Recently, Theophanides and Anastassopoulou (2002) have associated exposure to copper with damage to DNA and the subsequent development of cancers. Lead has a wide range of notorious impacts on human health, which will only be reviewed in outline here. Mobilization of this metal from the adult female skeleton may pose a threat to both the foetus and the nursing infant. In adults it poses a risk for osteoporosis and it may disrupt the normal formation of calcium hydroxyapatite, critically weakening the bone (Wittmers *et al.*, 1988; Skinner, 2000). A recent example of lead poisoning has been described by Tandon *et al.* (2001); in this study refiners were exposed to lead as the result of the smelting of silver, a not dissimilar situation to that in Faynan, where lead was released through the smelting of copper ore. Symptoms included anaemia, abdominal colic, blue lining of the gum and muscular wasting. All of these would have been problematic for people forced to hard physical labour in Faynan

Conclusions

Industrial pollution and contamination are not solely legacies that the modern world leaves to the future. Ancient cultures needed metal and they too have left a legacy that persists into the present day. The lessons we may draw from Wadi Faynan are that careless exploitation of the landscape may impact upon the environment for thousands of years. This analysis of the bone metal content of people associated with Phaeno, one of the industrial centres of the ancient world, has painted a stark picture. Many of the people excavated had a bone metal content that suggests they were living in a contaminated environment, absorbing metals through pathways that continue to operate in the present day; in addition, a small group of individuals contained very high bone metal values, which indicate direct exposure to metals liberated during mining, ore preparation, perhaps a combination of all of these. The concentrations measured suggest that some of these individuals may have developed debilitating illness as a consequence of this.

We have been left a stark account of life in the metal mines of Arabia in the second century BCE, which bears repeating,

> For though they are sick, maimed or lame, no rest nor intermission in the least is allowed them; neither the weakness of old age, nor women's infirmities are any plea to excuse them, but all are driven to their work with blows and cudgelling, till at last overborne with the intolerable weight of their misery, they drop down dead in the midst of their insufferable labours, so that these miserable creatures always expect the future to be more terrible, even than the present and

therefore long for death as far more desirable than life (Agricola, 1950, p. 279).

Even moderate symptoms of copper toxicity must have made life unbearable for the unfortunate souls condemned to mines, mills and smelters, and small wonder, therefore, that Roman chroniclers stated that life expectancy was short in the mines and furnaces of Phaeno (Eusebius, 1969). These analyses demonstrate that industrial regions in ancient times were as polluted and dangerous as their equivalents during the industrial revolution and that industrial workers in the Roman world accumulated significant body burdens of copper and lead.

Acknowledgements

The authors gratefully acknowledge the financial and material support of The Council for British Research in the Levant, The British Academy, The University of Wales and The Nottingham Trent University. This research has benefited from the companionship in the field of David Mattingly, Chris Hunt, Graeme Barker and Sue Mclaren and could not have taken place without the excavations directed by George Findlater.

References

Agricola, G. 1950 (1556): *De Re Metallica*. Translated by Hoover, H. and Hoover, L.H. New York: Dover Publications.

Ahlgren, L. and Mattsson, S. 1979: An X-ray fluorescence technique for in vivo determination of lead concentration in a bone matrix. *Physics in Medicine and Biology* 24, 136–45.

Ahlgren, L., Liden, K., Mattsson, S. and Tejning, S. 1976: X-ray fluorescence analysis of lead in human skeleton in vivo. *Scandinavian Journal of Work and Environmental Health* 2, 82–86.

Alloway, B.J. and Ayres, D.C. 1993: *Chemical principles of environmental pollution*. London: Blackie Academic and Professional.

Baranowska, I., Czernicki, K. and Aleksandrowicz, R. 1995: The analysis of lead, cadmium, zinc, copper and nickel content in human bones from the Upper Silesian industrial district. *The Science of the Total Environment* 159, 155–62.

Barjous, M. 1992: *Geology of the Ash-Shawbak area*. *Map Sheet 3151 III*. Hashemite Kingdom of Jordan: NRA, National Mapping Division.

Barker, G.W., Adams, R., Creighton, O.H., Gilbertson, D.D., Grattan, J.P., Mattingly, D.J., McLaren, S., Newson, P., Reynolds, T.E.G. and Thomas, D.C. 1998: Environment and land use in the Wadi Faynan: geoarchaeology and landscape archaeology. *Levant* 30, 5–25.

Barker, G.W., Adams, R. Creighton, O.H., Crook, D., Gilbertson, D.D., Grattan, J.P., Hunt, C.O., Mattingly, D.J., McLaren, S., Mohammed, H.A., Newson, P., Palmer, C., Pyatt, F.B., Reynolds, T.E.G. and Tomber, R. 1999: Environment and land use in the Wadi Faynan Southern Jordan: the third season of geoarchaeology and landscape archaeology. *Levant* 31, 255–98.

Barker, G.W., Adams, R., Creighton, O.H., Daly, P., Gilbertson, D.D., Grattan, J.P., Hunt, C.O., Mattingly, D.J., McLaren, S., Newson, P., Palmer, C., Pyatt, F.B., Reynolds, T.E.G., Smith, H., Tomber, R. and Truscott, A.J. 2000: Archaeology and desertification in Wadi Faynan: the fourth (1999) season of the Wadi Faynan Landscape Survey. *Levant* 32, 27–52.

Bender, F. 1974: *Geology of Jordan*. Berlin: Gebrüder Borntraeger.

Canadian Council of Ministers of the Environment. 1991: *Interim Canadian environmental quality criteria for contaminated sites*. Report CCME EPC-CS34. Winnipeg, Manitoba.

Cohen, S.R. 1979: Environmental and occupational exposure to copper. In Nriagu, J., editor, *Copper in the environment Pt II, human health*. London: John Wiley, 1–16.

Eusebius. 1969: *The history of the church from Christ to Constantine*. Harmondsworth: Penguin Books.

Findlater, G., El-Najjar, M., Al-Shiyab, A., O'Shea, M. and Easthaugh, E. 1998: The Wadi Faynan project: the south cemetery excavation, Jordan 1996. *Levant* 30, 69–83.

Finlayson, W., Mithen, S., Carruthers, D., Kennedy, A., Pirie, A. and Tipping, R. 2000: The Dana-Faynan-Ghuwayr early history project. *Levant* 32, 1–26.

Gee, C., Ramsey, M.H., Maskall, J. and Thornton, I. 1997: Mineralogy and weathering processes in historical smelting slags and their effect on the mobilisation of lead. *Journal of Geochemistry Experiments* 58, 249–57.

Gilfillan, SC. 1965: Lead poisoning and the fall of Rome. *Journal of Occupational Medicine* 7, 53–60.

González-Reimers, E., Velasco-Vásquez, J., Arnay-de-la-Rosa, M., Santolaria-Fernández, F. and Galindo-Martin, L. 2001: Palaeonutritional analysis of the pre-Hispanic population of Fuerte Ventura (Canary Islands). *The Science of the Total Environment* 264, 215–20.

González-Reimers, E., Velasco-Vásquez, J., Arnay-de-la-Rosa, M., Alberto-Barroso, V., Galindo-Martin, L. and Santolaria-Fernández, F. 2003: Bone cadmium and lead in prehistoric inhabitants and domestic animals from Gran Canaria. *The Science of the Total Environment* 301, 97–103.

Grattan, J.P., Huxley, S. and Pyatt, F.B. 2003a: Modern Bedouin exposures to copper contamination: an imperial legacy? *Ecotoxicology and Environmental Safety* 55, 108–15.

Grattan, J.P., Condron, A., Gilbertson, D.D., Karali, L.O., Pyatt, F.B., Taylor, S. and al Saad, Z. 2003b: A legacy of Empires? An exploration of the environmental and medical consequences of metal production in Wadi Faynan, Jordan. In Catherine, H., Skinner, W. and Berger, A., editors, *Geology and health: closing the gap*. Oxford University Press, 99–105.

Hauptmann, A. 2000: *Zur Fruhen matallurgie des kupfers in Fenan/Jordanien*. Bochum: Deutch Bergbau Museum.

Hauptmann, A., Begemann, F., Heitkemper, E., Pernicka, E. and Schmitt-Strecker, S. 1992: Early copper produced at Faynan, Wadi Araba, Jordan: the composition of ores and copper. *Archaeomaterials* 6, 1–33.

Hong, S., Candelone, J.-P., Patterson, C.C. and Boutron, C.F. 1994: Greenland ice evidence of hemispheric lead pollution two millennia ago by Greek and Roman civilisations. *Science* 265, 1841–43.

Hong, S., Candelone, J.-P., Patterson, C. and Boutron, C.F., 1996: History of ancient copper smelting pollution during Roman and Mediaeval times recorded in the Greenland ice. *Science* 272, 246–49.

Kachur, A.N., Arzhanova, V.S., Yelpatyevsky, P.V., Von Braun, M. and Von Lindern, I.H. 2003: Environmental conditions in the Rudnaya River watershed – a compilation of Soviet and post-Soviet era sampling around a lead smelter in the Russian Far East. *The Science of the Total Environment.* 303, 97–103

Karaki, L.O.A. 1999: Skeletal biology of the people of Wadi Faynan: a bioarchaeological study. Unpublished MA Thesis. Jordan: Yarmouk University.

Klein, S. and Hauptmann, A. 1999: Iron Age leaded tin bronzes from Khirbet edh-Dharih, Jordan. *Journal of Archaeological Science* 26, 1075–82.

Knauf, E.A. and Lentzen, C.J. 1987: Edomite copper industry. *Studies in the History and Archaeology of Jordan* 3, 83–88.

Leita, L., Enne, G., De Nobile, M., Baldini, M. and Segui, P. 1991: Heavy metal bioaccumulation in lamb and sheep bred in smelting and mining areas of SW Sardinia, Italy. *Bulletin of Environmental Contamination and Toxicology* 48, 887–93.

Maskall, J.E. and Thornton, I. 1998: Chemical partitioning of heavy metals in soils, clays and rocks at Historical lead smelting sites. *Water, Air and Soil Pollution* 108, 391–409.

Mason, J. 1979: A conspectus of research on copper metabolism and requirements. *Journal of Nutrition* 109, 1979–2006.

Moustakas, M., Ouzounidou, G., Symeonidis, L. and Karataglis, S. 1997: Field study of the effects of excess copper on wheat photosynthesis and productivity. *Soil Science and Plant Nutrition* 43, 531–39.

Nriagu, J., Sakamoto, M., Blum, J., Klaue, B., Schwarcz, H., Prowse, T., Machiarelli, R. and Bondioli, L. In press: Exposure of a Roman Middle Class population to lead. *The Science of the Total Environment*.

Oakberg, K., Levy, T. and Smith, P. 2000: A method of skeletal arsenic analysis, applied to the chalcolithic copper smelting site of Shiqmim, Israel. *Journal of Archaeological Science* 27, 895–901.

Pike, A.W.G. and Richards, M.P. 2002: Diagenetic arsenic uptake in archaeological bone. Can we really identify copper smelters? *Journal of Archaeological Science* 29, 607–11.

Pyatt, F.B. and Grattan, J.P. 2001: Consequences of ancient mining activities on the health of ancient and modern human populations. *Journal of Public Health Medicine* 23, 235–36.

Pyatt, F.B. and Grattan, J.P. 2002: A public health problem? Aspects and implications of the ingestion of copper and lead contaminated food by Bedouin. *Environmental Management and Health* 13, 467–70.

Pyatt, F.B., Barker, G.W., Birch, P., Gilbertson, D.D., Grattan, J.P. and Mattingly, D.J. 1999: King Solomon's miners – starvation and bioaccumulation? An environmental archaeological investigation in southern Jordan. *Ecotoxicology and Environmental Safety* 43, 305–308.

Pyatt, F.B., Gilmore, G., Grattan, J.P., Hunt, C.O. and McLaren, S. 2000: An imperial legacy? An exploration of ancient metal mining and smelting in Southern Jordan. *Journal of Archaeological Science* 27, 771–78.

Pyatt, F.B., Amos, D., Grattan, J.P., Pyatt, A.J. and Terrell-Nield, C.E. 2002: Invertebrates of Ancient heavy metal spoil and smelting tip sites in Southern Jordan: their distribution and use as bio indicators of metalliferrous pollution derived from ancient sources. *Journal of Arid Environment* 52, 53–62.

Rabb'a, I. 1994: *The geology of the Al Quraryqira* (Jabal Hamra Fadda). Map Sheet 305 II. Amman: Geology Directorate, Geological Mapping Division, Bulletin 28.

Rice, T.M., Clarke, R.W., Godleski, J.J., Al-Mutairi, E., Jiang, N., Hauser, R. and Paulauskis, J.D. 2001: Differential ability of transition metals to induce pulmonary inflammation. *Toxicology and Applied Pharmacology* 177, 46–53.

Scheinberg, I.H. 1979: Human health effects of copper. In Nriagu, J., editor, *Copper in the environment Pt II, human health*. London: John Wiley, 17–39.

Schick, R. 1995: *The Christian communities of Palestine from Byzantine to Islamic rule: a historical and archaeological study*. London: Darwin Press.

Skinner, H.C.W. 2000: In praise of phosphates, or why vertebrates chose apatite to mineralise their skeletal elements. *Geology International* 42, 232–40.

Tandon, S.K., Chatterjee, M., Bhargava, A., Shukla, V. and Bihari, V. 2001: Lead poisoning in Indian silver refiners. *The Science of the Total Environment* 281, 177–82.

Theophanides, T. and Anastassopoulou, J. 2002: Copper and carcinogenesis. *Critical Reviews in Oncology/Hematology* 42, 57–64.

Waldron, T. 1988: The heavy metal burden in ancient societies. In Grupe, G. and Herrann, B., editors, *Trace elements in environmental history*. Berlin: Springer-Verlag, 125–33.

Wittmers, L.E., Wallgren, J., Allich, A., Aufderheide A.C. and Rapp, G. 1988: Lead in bone IV. Distribution of lead in the human skeleton. *Archives of Environmental Health* 43, 381–91.

Williams, D.M. 1982: Clinical significance of copper deficiency and toxicity in the world population. In Prasad, A.S., editor, *Clinical, biochemical and nutritional aspects of trace elements*. New York: A.R. Liss, 277–99.

Ylaranta, T. 1996: Uptake of heavy metals by plants from airborne deposition and polluted soils. *Agriculture and Food Science in Finland* 5, 431–77.