The local and global dimensions of metalliferous pollution derived from a reconstruction of an eight thousand year record of copper smelting and mining at a desert-mountain frontier in southern Jordan

Hunt, Chris; Grattan, John; Gilbertson, D.

Published in:
Journal of Archaeological Science

DOI:
10.1016/j.jas.2006.04.004

Publication date:
2007

Approximate age; with lithostratigraphic member; and radiocarbon dating in the Wadi Faynan	**Environment in the Wadi Faynan (after Hunt et al. 2004; in press; McLaren et al. 2004).**	**Nature and intensity of copper mining and smelting, largely after Hauptmann (2000)**	**Predicted and * actual anthropogenic sediment metal-pollution, and related geomorphic outcomes**
~9600 to ~7500 BP Pre- Pottery Neolithic. (8th-7th Millennium BC) Faynan Member, upper component. – including a palaeosol overlying a fluvial channel fill at 5015 dated to 7240 ± 90 BP; cal BP 8276-7868 (Beta 11121).	Trees and shrubs (*Quercus*, *Ostrya carpinifolia*, *Juniperus*, Pinus, *Tamarix*, with steppe and grasslands, perhaps affected by grazing) grow in wetter climate than prevails today which progressively desiccates, before wetter conditions in late Neolithic.	The first use of local copper ores in the Wadi Ghuweir. 'Greenstone' beads and green powder for cosmetic purposes from Faynan became popular throughout Jordan and Palestine.	Negligible anthropogenic pollution expected
~7500 – ~ 6000 BP Late Neolithic (6th- 5th Millennium BC). Faynan Member – upper component. Sample G in the fluvial-stream bank sequence of 5021 radiocarbon dates to 7240±40 BP; 2σ cal. BP 7240-6990 (Beta 205964) – the Faynan Member, upper component. Field relationships with Tell Wadi Faynan - TWF (Najjar et al. 1990) adjacent to 5021; both are overlain by the deposits of exposure 5022. At TWF archaeological materials dated to 6110 ± 75 BP: cal BP 7235-6761 (HD12338): 5740 ± 35 BP; cal BP 6654-6412 (HD 12337): and 5375 ± 30; cal BP 6278-5995 (HD12336).	A wetter climate with perhaps ≥ ~150 mm a^{-1}, rainfall which supports a perennial river in the wadi Faynan. This deposits epsilon cross-bedded sands and silts with anthropogenic wastes that form the upper part of the Faynan Member. Trees and shrubs (*Quercus*, *Ostrya carpinifolia*, *Juniperus*, *Pinus*, *Tamarix*, perhaps at stream sides, elsewhere with steppe including *Ephedra*, perhaps also grasslands), however, as a result of distinctive regional climatic aridification, the lowland landscape changes to steppe with some *Pinus* and *Pistacia*. Cultivation and pastoral farming present. During the latter stages of this period, aeolian processes become important depositing dunes of silt and sand with carbonate induration which form the basal part of the Tell Loam Member.	Copper ores and some 'greenstone' beads at Tell Wadi Faynan; reflecting the use of copper, but not deliberate smelting of ores. Ores from Umm 'Ishrin Sandstone (sometimes with significant lead) used from exposures in wadis and mountain front.	Negligible anthropogenic pollution that is relatively lead-rich expected with corresponding minimal pene-contemporaneous re-cycling. * Occasional pollution of stream bank environment with small pockets of significant pollution in copper, and particularly of lead and thallium, when associated with ash and charcoal (5021; #B, C,D,G, H,L) that were discarded onto the banks of a perennial stream. The precise character of the human activities that produced these packets of polluted sediment is unknown, at present.

~5500 BP Chalcolithic. Tell Loam Member. 5022 dated by reference to 5021 below. Khirbet Member associated with Chalcolithic and Bronze Age at 5051 and 5518 (Hunt and Gilbertson 1998; Barker et al. 1998).	Marked climatic aridification continues, with perennial water confined to spring-fed runoff water in the Wadis. Wind-blown water-washed silts, sands with carbonate induration and ped development at on low rise on the Tell Wadi Faynan produces Tell Loam Member (5022). A grass-dominated steppe with no evidence of trees may have occurred at this time or slightly later occurs. Essentially the modern pattern of climate, with its occasional winter storms and floods. Braid-plains incise, causing the older Holocene fluvial deposits to be buried, eroded, or abandoned in wadi-cliff edges.	As at other Chalcolithic settlement in Jordan and Palestine, evidence of pyro-metallurgical activities in the second half of the 4th millennium B.C. indicating "household metallurgy" – small-scale operations. Small pieces of Chalcolithic slag and copper prills at Tell Wadi Faynan, small scale mining and metal working took place in the region in the Faynan.	Small-scale, local pollution, with corresponding pene-contemporaneous re-cycling of liberated metals. ***** Estimated to be represented by 5022, geochemical zone 4, - sustained, distinctive, increase in copper and lead when compared to 5021; but with no proportional increase in lead to accompany copper (zone 4b); no peaks of thallium or other volatile elements associated with ash-charcoal. Minor re-cycling and/or dilution of metal pollutants in carbonate, as a result of wind and surface wash in an increasingly open arid environment.
~5550-~3950 BP Early Bronze Age; Tell Loam Member at 5022 age estimated by reference to 5021 below and reference to adjacent TWF (Najjar et al. 1990). Atlal Member at 1491/5741 – radiocarbon date of 4240 ± 40 BP; cal BP 6190-5940 (Beta 203414); which is overlain by 5690 ± 40 BP; cal. BP 6550 – 6400 (Beta 203413).	A grass-dominated steppe with no evidence of trees may have occurred at this time. Essentially the modern climate and geomorphic regime: represented by the Tell Loam Member of 5022. "Social collapse" or some form of move from urban settlements to rural settlement posited elsewhere in Early Bronze Age IV.	The first extensive mining and pyro-metallurgical activities, peak in Early Bronze Age II and III; high-grade, copper-manganese ores from widespread but thin, secondary enrichment - including malachite and chryscolla – in Numayr Dolomite Limestone and elsewhere in Burj Dolomite Limestone-Shale exploited. Mines in Wadis Khalid and Dana. Mining and pyrotechnology improve. Large scale copper "manufactory" at Khirbat Hamra Ifdan (~4150-~4650 calendar years BP).	Significant local pollution, relatively low in lead, with corresponding pene-contemporaneous re-cycling. *****Estimated be represented by 5022 (geochemical zone 4 b/a) with sustained increase in copper pollution, with no proportional increase in lead to accompany copper peak – i.e. relatively lead-poor ores; no peaks of thallium or other volatiles that could have been deposited onto ash and charcoal.
~3950 – ~3450 BP Middle Bronze Age, Tell Loam Member at 5022 age estimated by reference to 5021 below and reference to adjacent TWF (Najjar et al. 1990).	Essentially the modern climate and geomorphic regime: represented by the Tell Loam Member of 5022; but strong sustained drought evidenced to the west; perhaps with significant down-cutting by water in wadis? A grass-dominated steppe with no evidence of trees may have occurred at this time.	Relatively little ore extraction or processing. Minimal pollution, only minor re-cycling.	Minimal pene-contemporaneous anthropogenic pollution, minor re-cycling of existing metal pollution burden. ***** Sustained absence of pollution signatures (5022, zone 3)

~3650-~2850 BP. Late Bronze Age to Early Iron Age; Tell Loam Member - At 5022 age estimated by reference to 5021 below and reference to adjacent TWF (Najjar et al. 1990). Atlal Member at 5739 - radiocarbon dating: 2860 ± 40 BP; cal BP 2862-3140 (Beta 203411) and 3390 ± 40 BP; cal BP 3485-3816 (Beta 203402) at 5512.	Trapping and management using walls of winter floodwaters to sustain runoff farming take place; development of the major network of walls to manage water, and provide crops and animal products east of the Wadi Faynan. A grass-dominated steppe with no evidence of trees may have occurred at this time. Essentially the modern climate and geomorphic regime: represented by the Tell Loam Member of 5022.	Renaissance of metal production and smelting.	Significant local metal pollution, relatively low in lead, with corresponding pene-contemporaneous re-cycling. ***** Progressive increase in copper pollution, a proportionately larger increase in lead pollution (5022 zone 2d), followed by minor reduction in heavy metal pollution (5022 zone 2c); (uncertain - inferred decline in input by wind of carbonate minerals?). Substantial metal pollution of clastic sediments within slags at 5739. Substantive metal burdens in ore-processing deposits at 5512 (unit 6).
~2850 -~2550 BP Iron Age 1st Millennium BC Tell Loam Member at 5022 where age estimated by reference to At 5022 age estimated by reference to 5021 below and reference to adjacent TWF (Najjar et al. 1990) and overlying Roman-Byzantine sherds. Atlal Member at base of 5512 - radiocarbon date of 3390±40 BP; cal BP 3485-3816 BP (Beta 203402).	A grass-dominated steppe with no evidence of trees may have occurred at this time. Essentially the modern climate and geomorphic regime: represented by the Tell Loam Member of 5022, and wadi floor and barrage infill deposits at 5512 and 5017.	Second main period of copper production in region. Innovations in mining and smelting occur, together with further substantial expansions of copper mining and smelting. Original outcrops of high grade copper ores in Burj Dolomite Limestones Shale become exhausted. Mining reverts to the Umm 'Ishrin Sandstone, which contains less lead with re-processing of earlier prehistoric slag. Metallurgical activities on an new industrial scale. Mining and smelting, well-organised and sophisticated scale with improved geological understanding. Exploitation of deep mineralization by shafts 60 m deep. Faynan region has largest copper production of the entire Near East beside Cyprus. 100,000 tons of black, copper slag, still often unvegetated, left at the Khirbet Faynan and Khirbet en-Nahas.	Substantial metal pollution, relatively lead-rich anticipated, with corresponding extensive pene-contemporaneous re-cycling. ***** Sustained increase in sediment pollution in copper; with significant pollution in lead that fluctuates slightly in its intensity (5022 zones b and a). Notable pollution associated with ore-processing at 5512.

~2550 to ~1450 BP Roman-Byzantine Period Tell Loam Member through field relationships with Roman-Byzantine remains at (5022 zone1). Atlal Member at 5731, 5738, 5741; Khirbet Member at 5512-5017. Excavation, archaeological associations, pollen-biostratigraphy; basal radiocarbon date 1800 ± 40 BP; cal BP 1611-1858 (Beta 203401). Disaggregated charcoal fragments in borehole 5017 ~225 cm 2630 ± 50 BP; cal BP 2543-2859 (Beta 110840) suggest recycling of old charcoal.	Steppic and desertic vegetation and geomorphic regime, with a wetter climate; perhaps but not certainly local exhaustion of wood supplies. Extensive pressures on wooded vegetation for fuel and for cultivation and grazing may have caused the vegetation to remain open and steppic In Byzantine Period, Khirbet Faynan became an even more significant location: it became the Seat of a Bishopric, with three other churches. Lower parts of barrage infill deposits at Khirbet Faynan (5512, 5017, and ash-rich smelting waste (e.g. 5738, 5741).	Extensive use of shafts and deeper underground passages in Mn-rich ores in Umm 'Ishrin Sandstone - together with new methods of smelting countered the local exhaustion of the thin seams of DLS. Large scale mining and smelting from the first century BC to fifth century A.D, much exploitation in the third and fourth centuries A.D. At Umm el-Amad, mines first worked 2,500-3,000 years earlier during the Chalcolithic/ Early Bronze ages, are significantly re-used; old mines serve as entrances for the new larger underground mines driven through shafts with deep connected underground passages. 1.5m high galleries interpreted to indicate animals transport the ore inside the mines as well from the mines to the central smelting works at Faynan. Spring and stream water was supplied to the Khirbet by a series of aqueducts and stored in a large reservoir. 50-70,000 tons of copper slag at Faynan (e.g. 5052, 5053). Metal working with professional mine engineers. Reports that forced labourers on occasion receive brutal treatment.	Substantial metal pollution, relatively lead-rich anticipated, with corresponding extensive pene-contemporaneous re-cycling. ***** Substantial and dangerous concentrations of copper and lead, initially rich in lead, with change from relatively lead-poor to lead-rich pollution in wastes reaching >40k ppm Pb; 16k ppm Cu, and substantial 90 ppm Tl where there are ash-charcoal from smelting (5738, 5741); transition from relatively rich to lead-poor pollution at dangerous, poisonous and toxic with substantial pollution in crushed ores in colluvium, then in impounded water by smelting areas. Disposal of massively contaminated wastes from smelting as piles and onto braid plain where rapid geomorphic removal and/or dilution down-wadi (5731 – Unit 3), suggesting significant geomorphic re-recycling indicated by fluvial deposits producing heterogeneity and undated wind-induced distance-decay effects to south SP8-2; copper and lead appear to behave differently. Many smaller sites (SP1,6,18, 31, 32-35, intense local pollution with copper and lead with associated suites of dangerous volatile metals sporadically preserved with ash-charcoal (5022 zone1).
~1450 -~ 650 calendar years BP Early Arab period; Khirbet Member at 5512, 5017 through biostratigraphic correlation with radiocarbon dated deposits nearby; and underlying radiocarbon dates; ?Atlal Member at 430±40 BP; cal BP 350-330 BP (Beta 203412).	Steppic and desertic vegetation and geomorphic regime, in climate similar to that of the present day, but which became increasingly arid. Represented by barrage infill deposits at 5512 and 5017, and Upper and Lower Dana Wadi Members.	Mining and smelting activity around Faynan decline rapidly after the Roman-Byzantine period. After ~500 AD the Faynan ceases to be as a major copper supplier in the Levant. Small-scale smelting, during the early medieval Islamic periods at el-Furn, Faynan, Ain Fidan and probably in the Wadi Dana. Minor local pollution expected, with local re-working of exposed smelting wastes from preceding smelting. In late Ayyubid / early Mamluk period of the thirteenth century A.D, possibility that in addition to copper, lead was deliberately smelted.	Loss of anthropogenic metal pollution input, with progressive decrease metals at the aggrading sediment surface. ***** Initial rapid decline in concentrations of copper and lead, and associated metals after peak of Byzantine activity, followed by progressive reduction over ~1300 years to present, during periods in which the geomorphic environments altered with one sustained episode of aridity; input of strontium increases; lead reduces in concentration in surface deposits much less rapidly than copper. One episode detected of the deposition of copper slag?

~650 to present; Khirbet Member ? Atlal Member at 5450 dated to 430±40 BP; cal BP 350-330 BP (Beta 203412).	Steppic and desertic vegetation, become fully desertic with marked aridification that lasts from about ~550 - ~100 year ago, when fully modern conditions occur, with wind-blown silts entering the global atmosphere.	No metallurgical activity: re-cycling of surface deposits anticipated. Modern survey of ore resources by the Natural Resources Agency clears some entrances to mines and adits.	Progressive decrease in re-cycled metals – minor input of new anthropogenic metals in sediments about ~ 500 years ago. ***** One episode detected of the deposition of copper slag? Recycling of copper and lead continued at comparatively low rate through biological processes to a few hundred ppm; fluvial and aeolian processes on wadi floor produce great heterogeneity in heavy metal burdens; mix of aeolian and overland flow, recent ploughing and clearance, and the sporadic nature of many sites, the surface heavy metal loads beyond the land around the Khirbet Faynan and the wadi-floor are also heterogeneous.

Table 1. Summary of information on the chronology and dating; past environmental conditions, the scale of mining and metallurgy, anticipated pollution outcomes and those actually established at key sites in this paper. The lithostratigraphic terminology follows Hunt et al. 2004, in press; McLaren *et al*. 2004; other information from Barker et al. 1997, 1998, 1999, Frumkin et al. 1991, 1994, 1998; Hauptmann 2000; Hauptmann *et al*. 1992; Hunt *et al.* 2004; in press; Levy *et al*. 2002, 2004; Najjar *et al*. 1990; and authors therein. Calibrated radiocarbon dates are quoted at 2σ determined using the CALIB Rev. 5.0.1; and in addition with OXCAL where stratigraphic sequences exists.

Vegetation

Composition, form, cover; interception capability; soil drainage; soil biological, physical & chemical properties; bioaccumulation in food chains and decomposer chains; soil binding and protection; long-term changes & responses to climate, colonisation & recolonisation, fuel gathering, wood for construction, grazing and browsing, clearance and burning; selective uses, susceptibility to toxins especially riparian vegetation.

Regional & local climatology

Global & regional climate changes, wetter early Holocene, mid-Holocene aridification, arid later Holocene. Short term fluctuation & extreme events, droughts, floods, storms, local climatology. Katabatic winds, wildfire, bioclimatology, shelter & shade, updraughts.

Sources of ore metals in the environment.

Bedrocks: Lower Palaeozoic

Proterozoic

"Natural" Quaternary sediments

Polluted sediments and soils
Colluvium
Fluvial sediments

Bioaccumulation and human activity

Differential recycling by deep rooted trees, pasture & crops, grazing & geophagy by invertebrates and vertebrates; defecation by herbivores. Burning wood and manure as fuel that releases or absorbs metals in ash. Human inhalation, ingestion, consumption, contact, washing and cleaning; medicines; dyes and cosmetics, cooking; use of manure as fertiliser; night-soil as fertiliser; waste disposal; open water storage and transport; washing, handling and contact with tents, clothing, textiles, artefacts, animals, fuel, tents and materials. Metal slags as building materials.

Land surface changes

Inter-connected changes in surface geomorphology & soils, especially soil & slope stability from mass-movement, mining, quarrying of building stone, rock breaking and crushing, smelting; trampling by people, animals, wheeled and sledge vehicles; ploughing, tillage, sowing, harvesting, rain and floodwater collection, transport and use of plant wastes, animal manures and night-soil as fertiliser; changes in infiltration capacity, overland flow, in surface and stream runoff rates; differential erosion, transport and deposition by wind and water, deposition of dust, changes in the size, erodibility, floods and windstorms on the floodplain. Sub-surface differential leaching, translocation and accumulation, and biological concentration and transport by soil fauna and vegetation. Accumulation behind walls, within and from natural and constructed water courses & water storage facilities; upon and within tents, clothing, artefacts.

Deposits - sequence	Summary – location, lithology, properties
Modern land surface Palimpsest of deposits and materials of different ages.	Surface samples SP1-38 obtained along transects across and through the modern braid-plain and onto Holocene deposits of the Wadis Dana and Faynan. These include modern and late Holocene, wind blown and water-washed silts and sands, and deposits of copper smelting slag that range in age from the Bronze Age to Byzantine. The modern surface associated with in the ancient wall networks is visibly a palimpsest of *in situ* and re-worked materials reflecting its modern geomorphic situation and its episodic development from the Bronze Age to Byzantine, parts of the wall network continue to concentrate and re-direct overland flow in times of storm (see figures 4 & 5).
Ancient barrage - impounded sediments and earlier land surface deposits. ~3700 calibrated BP ; and ~1800 calbrated BP to the Present Day.	Khirbet Member overlying Atlal Member. The Khirbet Faynan Barrage – immediately north of Khirbet Faynan, sites 5017 and 5512). The Khirbet Member of aeolian, storm and pond deposits from the present to the base of lithological unit 5 at 260 cm near to a radiocarbon date 1800 ± 40 BP; cal BP 1611-1858 (Beta 203401). Disaggregated charcoal fragments in borehole 5017 ~225 cm 2630 ± 50 BP; cal BP 2543-2859 (Beta 110840) suggest recycling of old charcoal. The basal 70 cm of exposure is of the Atlal Member (unit 6) comprises colluvium and crushed ores – radiocarbon dated to 3390 ± 40 BP; cal BP 3485-3816 (Beta 203402) at 5512. The lower 70 cm of crushed ores and colluvium accumulated rapidly as a result of metallurgical and colluvial processes. The overlying sediments plus a mix of lacustrine, fluvial, aeolian and colluvial material accumulated behind the well-constructed barrage until about 1400 years ago; after which time, aeolian sands, colluvium and fluvial sediments have infilled the basin (see figure 6).
Chalcolithic to Mediaeval metal-working sediments ~5450 – 500 calibrated BP.	Atlal Member, – intrusive inter-bedded fluvial sand lenses. Three accumulations of metal slags with ash; radiocarbon dates exist at two sites located between the Khirbet Faynan barrage and the braid plain of the wadi Dana: In the basal 20-30 cm at 5738 and 1471/5741b, copper slag and ash were interbedded with fluvial braid-plain sands (see figure 7). Atlal Member at 1491/5741 – radiocarbon date of 4240 ± 40 BP; cal BP 6190-5940 (Beta 203414); which is overlain by 5690 ± 40 BP; cal. BP 6550 – 6400 (Beta 203413) which suggests re-working; and which is in turn overlain by 430 ± 40 BP; cal. BP 350 – 330 (Beta 204412). Atlal Member at base of 5512 - radiocarbon date of 3390 ± 40 BP; cal BP 3485-3816 BP (Beta 203402). Atlal Member at 5739 - radiocarbon dating: 2860 ± 40 BP; cal BP 2862-3140 (Beta 203411); and 3390 ± 40 BP; cal BP 3485-3816 (Beta 203402) at 5512.
Copper mine – Nabatean - Byzantine	Hamman Member. Wadi Khalid, 5740 (mine 2 in Grattan et al. 2004): 1.1 m of post mining colluvial and aeolian slumped back into mine entrance covering 1 m of slumped mining debris that is attributed to the Nabatean to Byzantine times (see figure 7).
Neolithic - Byzantine environmental sequence. ~6200 – 1400 calibrated BP.	Tell Loam Member. A quasi-continuous sequence of water-washed wind-blown silts/sands without pits or cuts exposed in a cliff at the southern edge of the braid-plain of the Wadi Faynan at a location that is 5-10 m higher than all the immediate surrounding area. This extends at site 5022 from surface copper smelting slag with ash and pottery attributed to the Roman-Byzantine (~2000-1600 years ago) down through similar water-washed aeolian deposits Iron Age, Bronze Age, Chalcolithic to the upper parts of the Late Neolithic site of Tell Wadi Faynan 6110 ± 75 BP; cal BP 7235-6761 (HD12338):. 5740 ± 35 BP; cal BP 6654-6412 (HD 12337): and 5375 ± 30; cal BP 6278-5995 (HD12336). The site overlies 5021 radiocarbon dates to 7240±40 BP; 2σ cal. BP 7240-6990 (Beta 205964). Detailed field examination of the excavation face that produced site 5022 is summarised in Figure 9.
Early-Mid Holocene perennial stream deposits ~7470 – ~ 6525 calibrated B.P.	Faynan Member – upper component. A quasi-continuous sequence of fluvial, stream bank and anthropogenic deposits of a perennial meandering stream in a wetter climate with evidence of channel fill, erosion and non-sequences at site 5021. Sample G of ash, as well as charcoal; the latter gave a radiocarbon date of 7240±40 BP; cal BP 2σ 7240-6990 cal. (Beta-205964). These deposits can be traced lithostratigraphically in the cliff exposure to the lower components of the Late Neolithic site at Tell Wadi Faynan at 5022 (Najjar et al. 1990; their plate II: 1-2) where the appropriate part of the sequence provided the following radiocarbon dates: 6110 ± 75 BP; cal BP 7235-6761 (HD12338): 5740 ± 35 BP; cal BP 6654-6412 (HD 12337): and 5375 ± 30 BP; cal BP 6278-5995 (HD12336 (see figures 10 and 11).
List of radiocarbon dates quoted	430 ± 40 BP; cal. BP 350- 330 (Beta 204412). 1610 ± 40 BP; cal. BP 1403–1601 (Beta 203399) 1800 ± 40 BP; cal BP 1611-1858 (Beta 203401). 1870 ± 40 BP; cal BP 1712–1890 (Beta 203400) 2630 ± 50 BP; cal BP 2543-2859 (Beta 110840) 2860 ± 40 BP; cal BP 2862-3140 (Beta 203411)

	3390 ± 40 BP; cal BP 3485-3816 (Beta 203402) 4240 ± 40 BP; cal BP 6190-5940 (Beta 203414); 5690 ± 40 BP; cal BP 6550- 6400 (Beta 203413) 5375 ± 30 BP; cal BP 6278-5995 (HD12336) 5740 ± 35 BP; cal BP 6654-6412 (HD 12337) 6110 ± 75 BP; cal BP 7235-6761 (HD12338) 7240 ± 40 BP; cal BP 7240-6990 (Beta 205964).

Table 3. Summary of the Holocene sequences and radiocarbon dates in calibrated years BP combined to provide evidence for about eight thousand years of copper working through Holocene in the vicinity of the Khirbet Faynan: the sites are located in Figures 2 to 5, and the analytical results shown graphically in Figures 7 to 12. (The table is based upon Barker et al. 1997-2000, Grattan et al. 2004; Hauptmann 2000; Hunt et al. 2004, Hunt et al. in press, McLaren et al. 2004; Mohammed 1999, Najjar et al. 1990, Raikes 1980, together with unpublished information; radiocarbon dates are calibrated to 2 σ using the CALIB Rev. 5.0.1 and with OXCAL where a stratigraphic sequences exists).

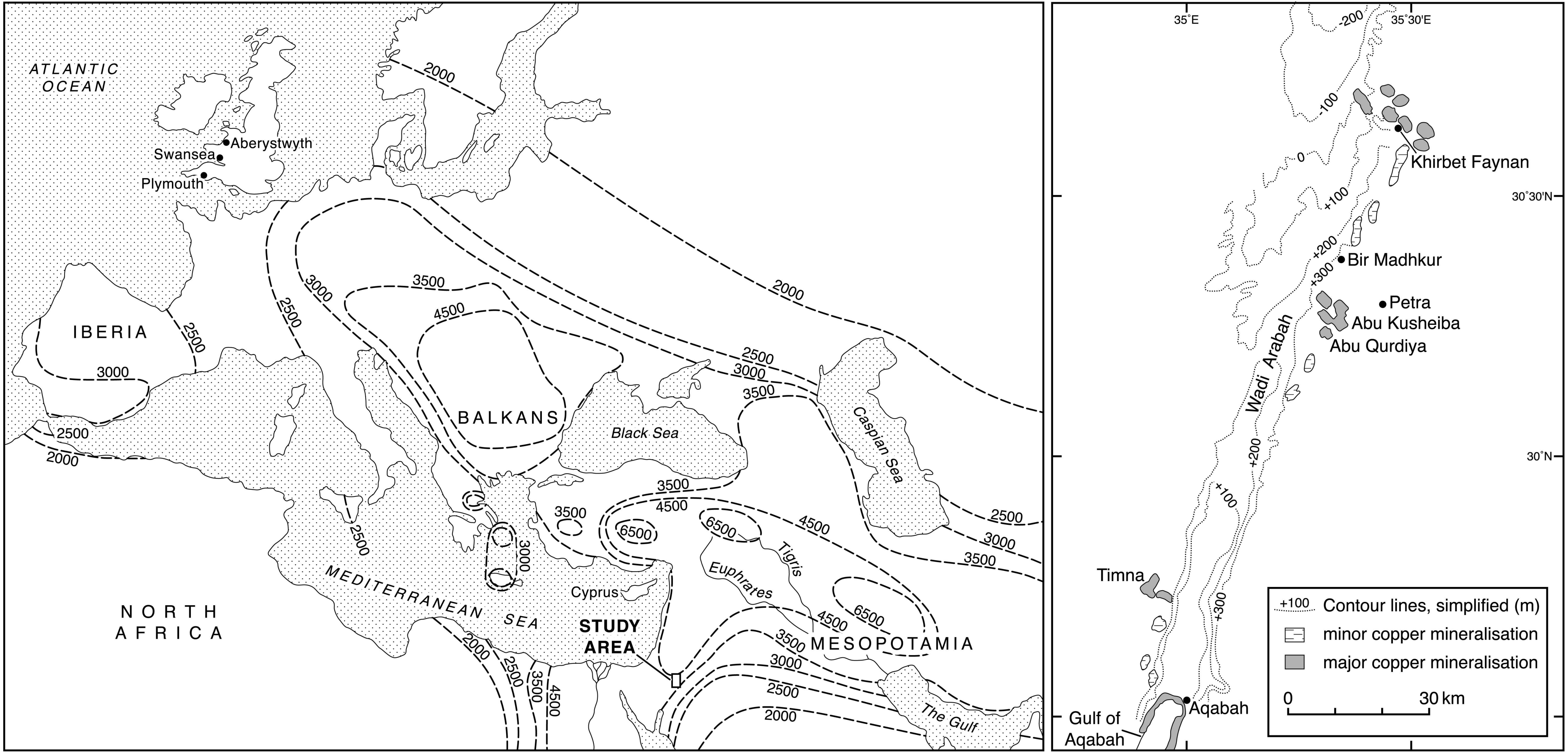
WF5512.

Lithofacies unit 5512	Depth cm	Sedimentological properties and dating
1	0 - 86	Alternating layers (1-2mm thick) of clay and silt; sometimes distinctly organic with leaf remains; interbedded with layers of fine and medium sand, often well sorted; individual layers bioturbated; pale brown; occasional roots; occasional large boulders; transitional lower boundary. *Interpretation - wind blown and water-washed and barrage-pool deposit of reworked sand with boulders from catchment, boulders introduced by or fallen from adjacent archaeological remains; clay-silt layers and organic debris are intermittent periods of pond-sedimentation*.
2	86 -	Clay, silt and sand; sands often well sorted often in couplets of coarse to fine sands ~3 mm thick, but ranging from 1-8 cm thickness; pale brown; slightly irregular surfaces. Biostratigraphic correlation with arid episode of the Little Ice Age (Hunt et al. in press). *Interpretation – aeolian deposits with episode of barrage-pool sedimentation at times of storm, some events with large sediment load.*
3	157 – 158	Fine sand with grit; forming irregular laminae, pale brown. *Interpretation - distinctive flood-lag deposit in the barrage-pool*.
4	156 - 205	Pale brown fine quartz and limestone sand; distinctive thin (1- 4 mm thick) laminations; typically well-sorted; marked fining-upward in laminae with granite-derived grit and fine pebbles of lag deposits at the base of each laminae. Greater % sand than Unit 5 below; brown hues. There was no evidence of any of the following were found: ash, charcoal, copper ores, copper slag, colluvial activity, local turbidity currents, mass-movement or sediment deformation, intra-sequence desiccation cracks, induration, or mineral deposition. Roman potsherds at 1.95 m. Dating: charcoal fragments between 174-176 cm, 1610 ± 40 BP; cal. BP 1403–1601 BP cal. (Beta 203399); between 204-206 cm 1870 ± 40 BP; cal BP 1712–1890 years (Beta 203400). *Interpretation - runoff and storm deposits into a perennial pool behind the barrage-pool; moving water re-working of surface materials in the immediate area.*
5	205 – 260	Fine sand, often with much clay, some silt; irregularly laminated with laminae between 1 and 3 mm thick; lenses of sorted sands, including lenses of sorted sand-sized, green copper ores; comminuted charcoal present throughout; some large clasts of charcoal but less comminuted charcoal than Unit 6 beneath; cobbles and boulders are common; the bases of several have deformed underlying laminae producing distinctive “bird’s eye” deformation-loading structures; comparatively high %LOI and very high magnetic susceptibility. Localised variant between 240-260 cm clay-rich deformed sediment; overall poor sorting; occasional lenses of well sorted, sand-sized grains of copper ore and ash, colour varies – sand matrix -pale brown; ore sands – green; ash – grey. No evidence found of intra-sequence desiccation cracks, induration, or mineral precipitation. Roman potsherd at 2.28 m. Dating: Nabatean potsherd at 2.35 m; charcoal fragments at 224-226cm 1800 ± 40 BP; cal BP 1611–1858 (Beta 203401). *Interpretation – a complex of individual mass flow deposits and local turbidity currents, and deposits of ponded-water and moving-water that accumulated rapidly in a perennial pool on a wadi-floor. Frequent local use of hot fires producing ash and charcoal hereabouts and some smelting nearby; at the site there was mass-movement and deformation of wet sediment and re-working, in perennial water; where crushed ores had been crushed, graded, and size-sorted (perhaps using moving sorted in a flume or sluice), but not yet smelted. High clay content reflects erosion of exposed surfaces and profiles. No evidence of dryland colluvial activity or dry wadi floor.*
6	260-285	Diamicton; matrix supported; abundant sand-sized of different materials; some silt and clay; with numerous angular clasts of angular of slag-clinker; angular cobbles of limestone, no evidence of abrasion; much comminuted charcoal but no charcoal clasts seen; overall very poorly sorted; stratification not clear; rests upon a very hard, impenetrable layer of clay-sand located on a bedrock surface; black to dark brown colours. No evidence of intra-sequence desiccation cracks, induration, mineral deposition, slip planes, ponded or moving water. Comparatively raised % LOI and magnetic susceptibility. Dating: charcoal between 267-276cm was 3390 ± 40 BP; cal. BP 3485 –3816 (Beta 203402). *Interpretation – product of ore-smelting involving fire, “anthropogenic colluvium” and mass movement, with minor impact of deposits of airfall ash and silts from catchment, and overland flow, in a wadi floor that was dry, suggesting a hot and arid climate. The abundant sand-sized materials related to disintegration of the bedrock and ore materials. No perennial water, no barrage.*

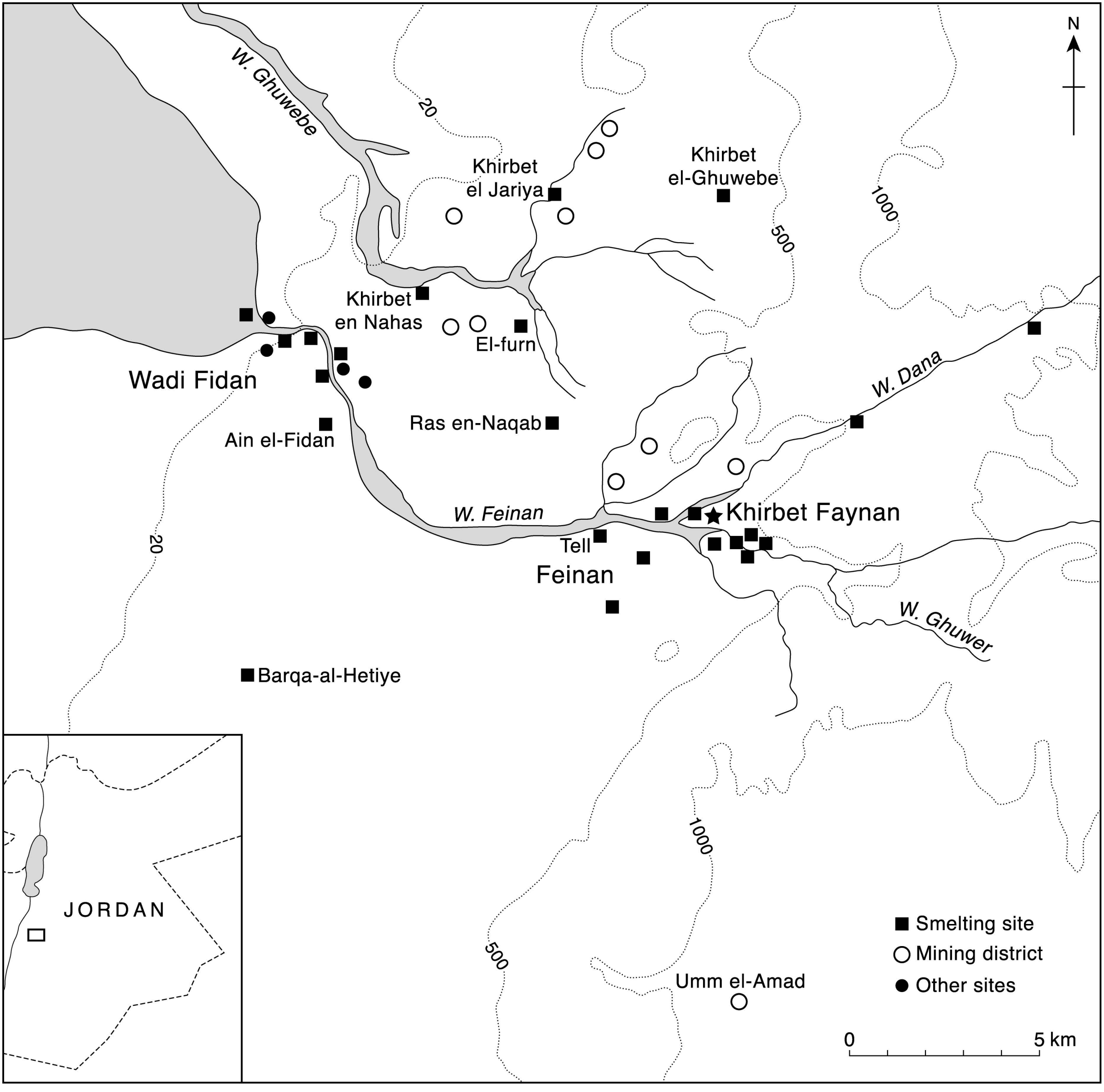
WF5512 - Geochemical properties

Geochemical zone 5512 – KFB	Depth cm	Geochemical properties and trends
1	0 - 160	Typically copper less than 1000 ppm, lead typically 300 – 500 ppm; minimal fluctuations after an overall decline in concentrations upwards from the initial copper concentrations of ~2100 ppm at 159 cm, strontium 320-450 ppm and thallium ~1.5 – 2.5 ppm. *Interpretation: recycling by wind and runoff of natural materials and exposed smelting products.*
2	160 - 230	Four or more fluctuations in concentrations of copper and lead; thallium concentrations low; overall a long-term decline in the input of heavy metals. Copper concentrations vary from ~1800 ppm to ~4500 ppm; lead concentrations are low, typically ≤ 200 ppm, with minimum ~75 ppm; strontium 200-450 ppm; thallium low ~1.5 – 2.5 ppm. Transitional change below to geochemical zone KFB3. *Interpretation. An uncertain combination of the following - incorporation and sorting of polluted earth surface materials from the area by wind and perhaps overland flow into a perennial water body with abundant moving water in an area of overall declining metal processing activities; from metallurgy nearby but not at this particular wadi-floor site; and-or the pattern of loss of residual pollutants on adjacent land surfaces by natural processes from a landscape from which metallurgy had already ceased.*
3	230-260	Up-profile from base; copper declines to minimal ~470 ppm at 250 cm, then increase to ~4500 ppm in concentrations of copper. Lead concentrations at ~500 ppm and essentially stable with minor trough at 250 cm; strontium ~50-300 ppm; thallium typically <3.5 ppm, but 26 ppm at 250 cm. *Interpretation: pollution from ore processing and smelting, fluctuates in intensity according to type and intensity of ore processing and smelting, and according to input by geomorphic processes of metal-poor clays from adjacent surficial deposits*.
4	260 – 282	Two peaks and a trough with lead concentrations in range from ~2400 – ~7825 ppm; and always significantly exceeding those of copper in range ~1000-~2230 ppm; high thallium, 9-13 ppm at base; maximum 25-33 ppm at top of zone; strontium ~320-450 ppm. *Interpretation: lead-rich copper ore accumulating on dry wadi floor during the processing and smelting of copper ores.*

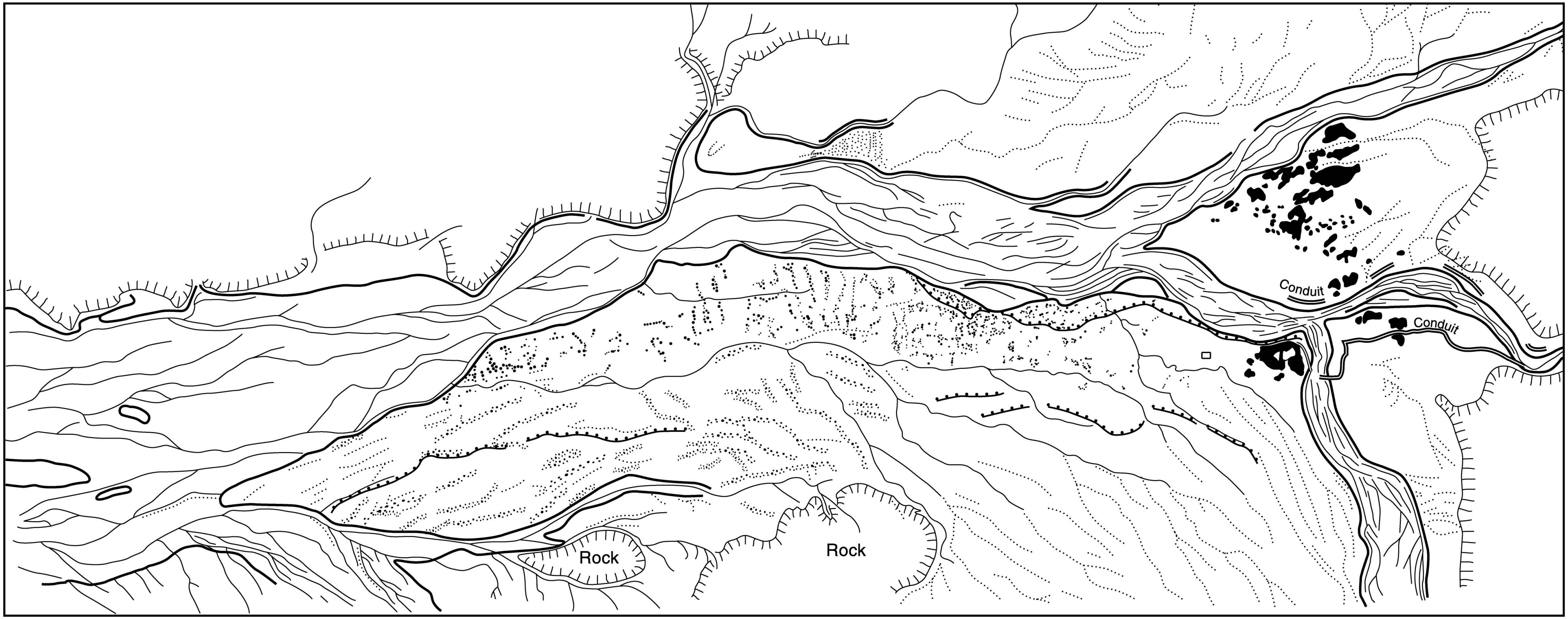
Table 4. Summary of sedimentological and lithological properties and radiocarbon dating evidence in calibrated years BP in wadi-floor sediments at pit WF5512; together with summary of the geochemical properties and a geochemically-based zonation of these sediments. The site is 30 m up-wadi of the Khirbet Faynan barrage; illustrated in Figure 7; immediately adjacent is borehole WF5017=5017.

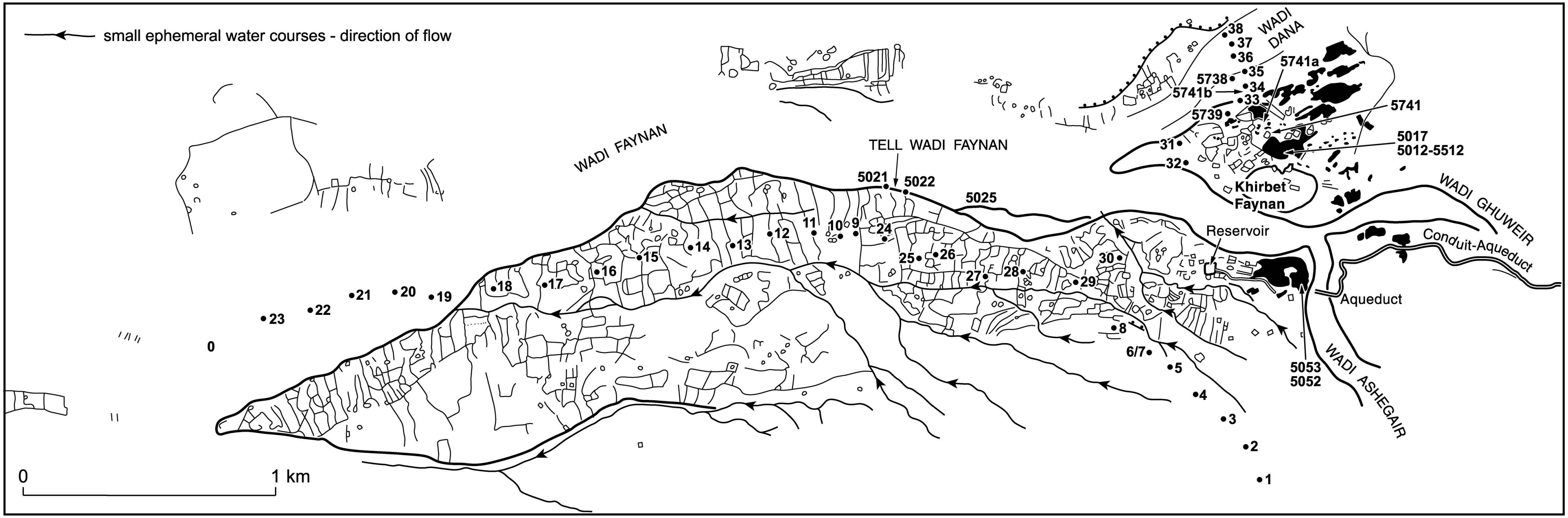


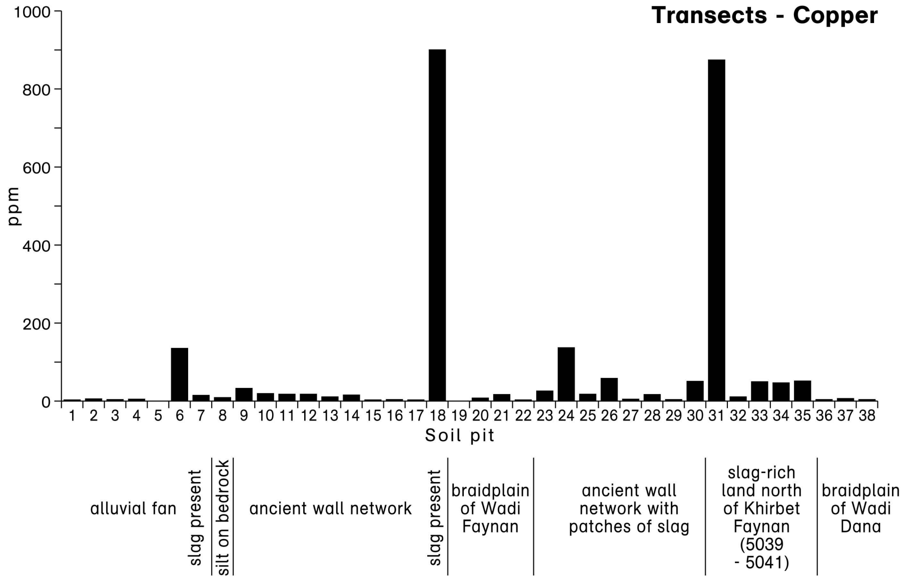
ATLANTIC OCEAN
Aberystwyth
Swansea
Plymouth
IBERIA
BALKANS
Black Sea
Caspian Sea
NORTH AFRICA
MEDITERRANEAN SEA
Cyprus
STUDY AREA
Euphrates
Tigris
MESOPOTAMIA
The Gulf
2000
2500
3000
3500
4500
6500
35°E
35°30'E
30°30'N
30°N
-200
-100
0
+100
+200
+300
Khirbet Faynan
Bir Madhkur
Petra
Abu Kusheiba
Abu Qurdiya
Wadi Arabah
Timna
Aqabah
Gulf of Aqabah
+100 Contour lines, simplified (m)
minor copper mineralisation
major copper mineralisation
0
30 km

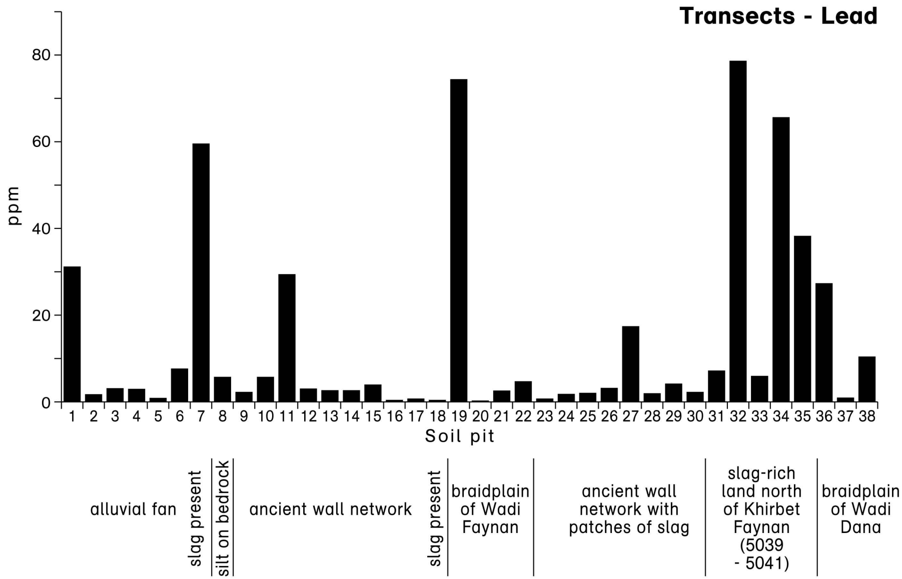


N
W. Ghuwebe
20
Khirbet el Jariya
Khirbet el-Ghuwebe
1000
500
Khirbet en Nahas
El-furn
Wadi Fidan
W. Dana
Ras en-Naqab
Ain el-Fidan
W. Feinan
Khirbet Faynan
Tell
Feinan
W. Ghuwer
20
Barqa-al-Hetiye
JORDAN
1000
500
Umm el-Amad
Smelting site
Mining district
Other sites
0
5 km

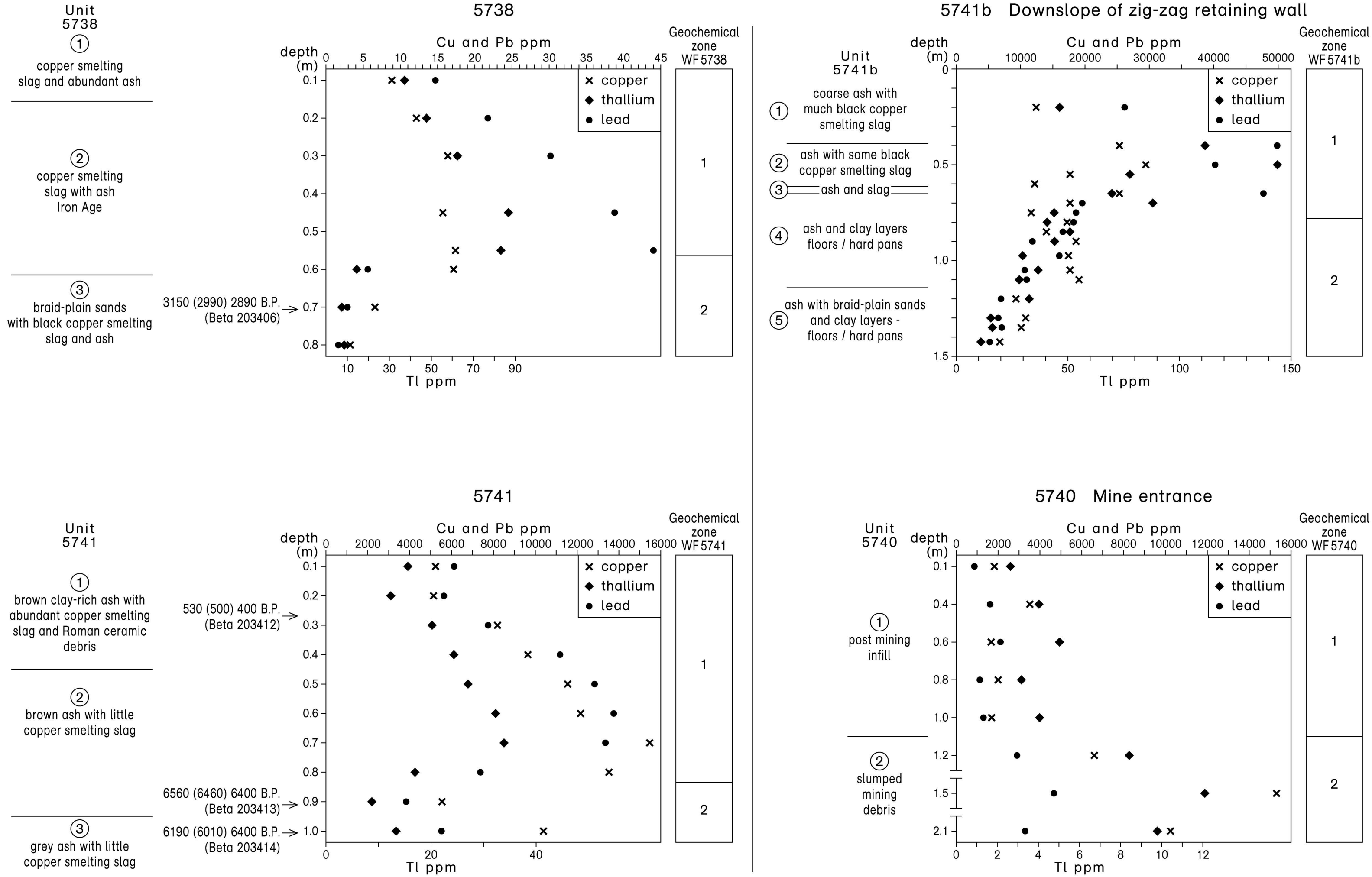

Conduit
Conduit
Rock
Rock

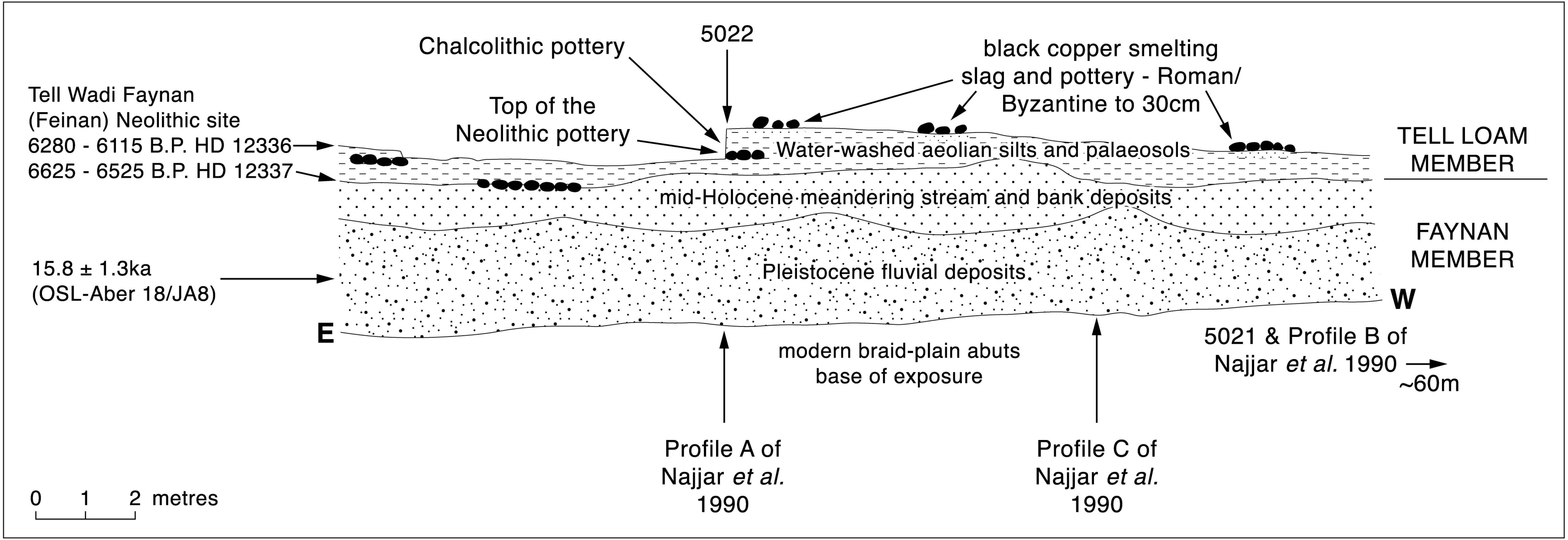

small ephemeral water courses - direction of flow
WADI FAYNAN
TELL WADI FAYNAN
WADI DANA
38
37
36
35
34
33
5738
5741a
5741b
5739
5741
5017
5012-5512
31
32
Khirbet Faynan
WADI GHUWEIR
5021
5022
5025
Reservoir
Conduit-Aqueduct
Aqueduct
WADI ASHEGAIR
5053
5052
0
1
2
3
4
5
6/7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
0
1 km


Transects - Copper
1000
800
600
400
200
0
ppm
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
Soil pit
alluvial fan
slag present
silt on bedrock
ancient wall network
slag present
braidplain of Wadi Faynan
ancient wall network with patches of slag
slag-rich land north of Khirbet Faynan (5039 - 5041)
braidplain of Wadi Dana

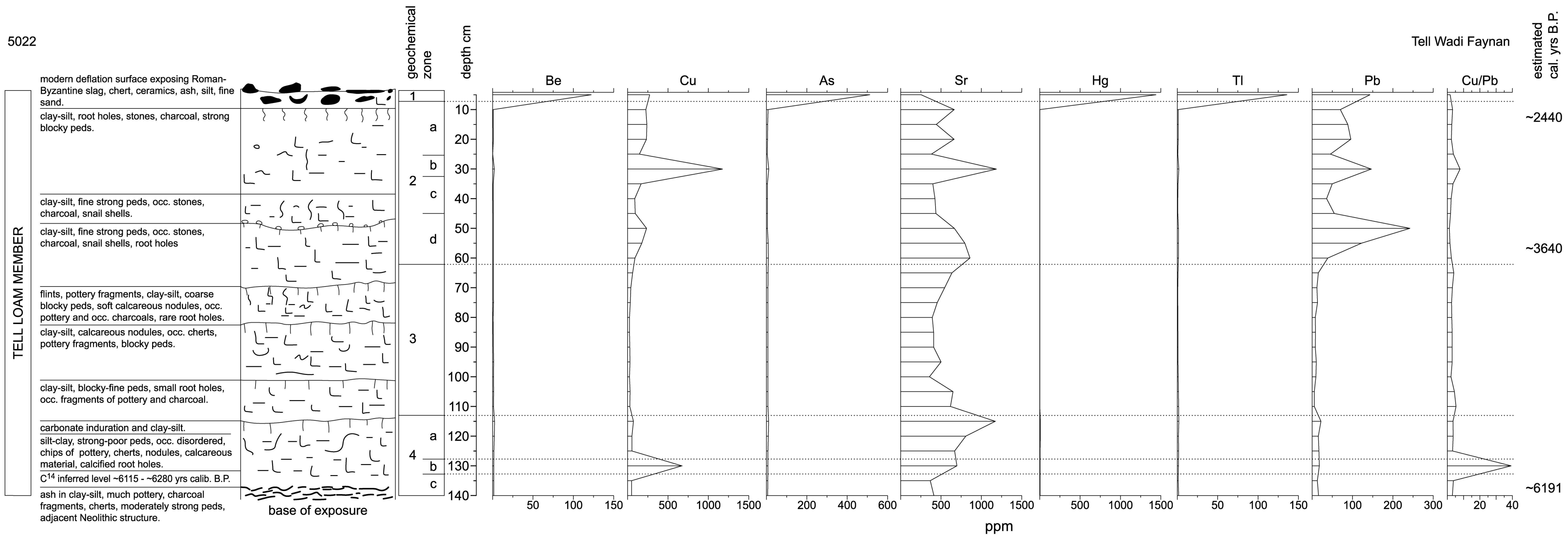

Transects - Lead
80
60
40
20
0
ppm
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
Soil pit
alluvial fan
slag present
silt on bedrock
ancient wall network
slag present
braidplain of Wadi Faynan
ancient wall network with patches of slag
slag-rich land north of Khirbet Faynan (5039 - 5041)
braidplain of Wadi Dana

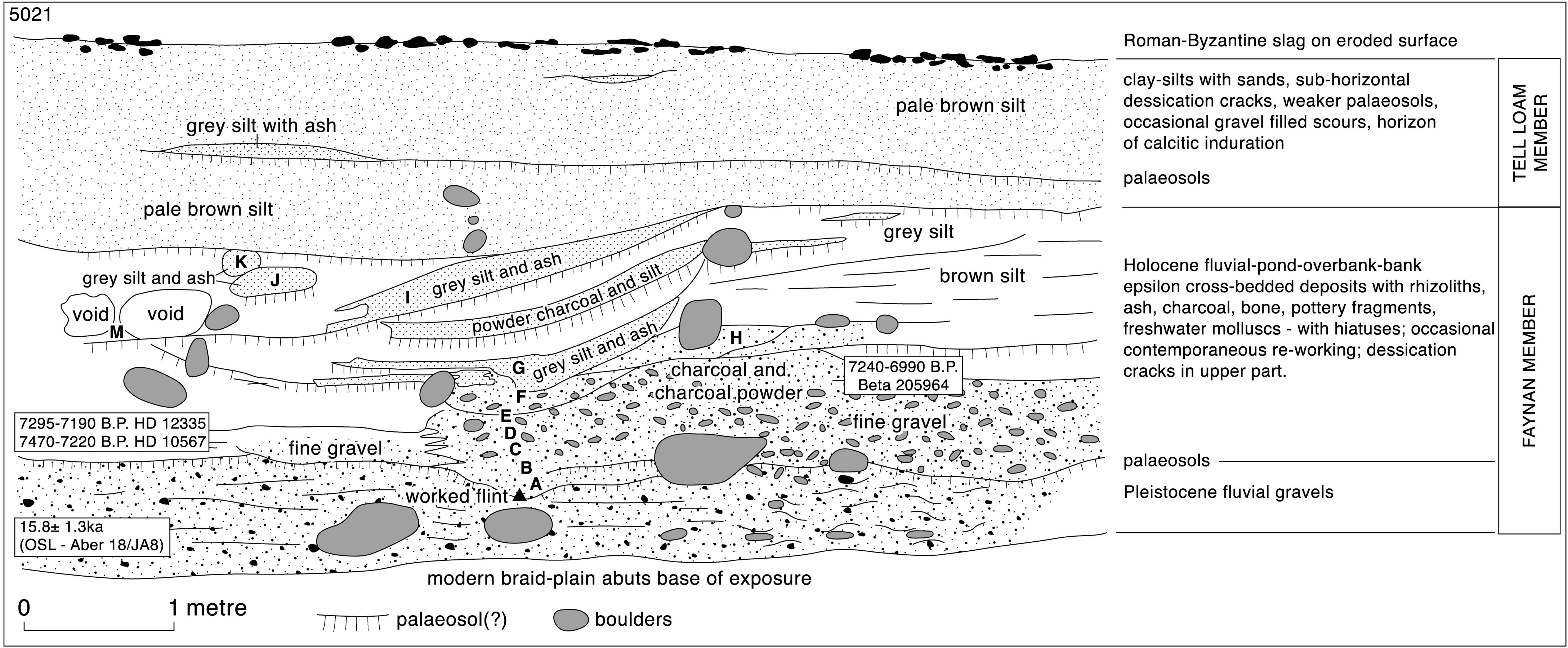

5512
Depth cm
interpolated and radiocarbon dates in calendar years B.P.
0
85
155
190
260
285
1
2
3
4
5
6
~100
~1350
1540 (1520) 1410 B.P. (Beta 203399)
1890 (1820) 1710 B.P. (Beta-203100)
1830 (1720) 1610 B.P. (Beta-203401)
~1850
3710 (3640) 3550 B.P. (Beta-203402)
Be
Cu
As
Sr
Hg
Tl
Pb
Cu/Pb
Geochemical zone 5512
0 1000 3000 5000
0 100 200 300 400 500
0 20 40
0 2000 4000 6000 8000
0 20 40
ppm

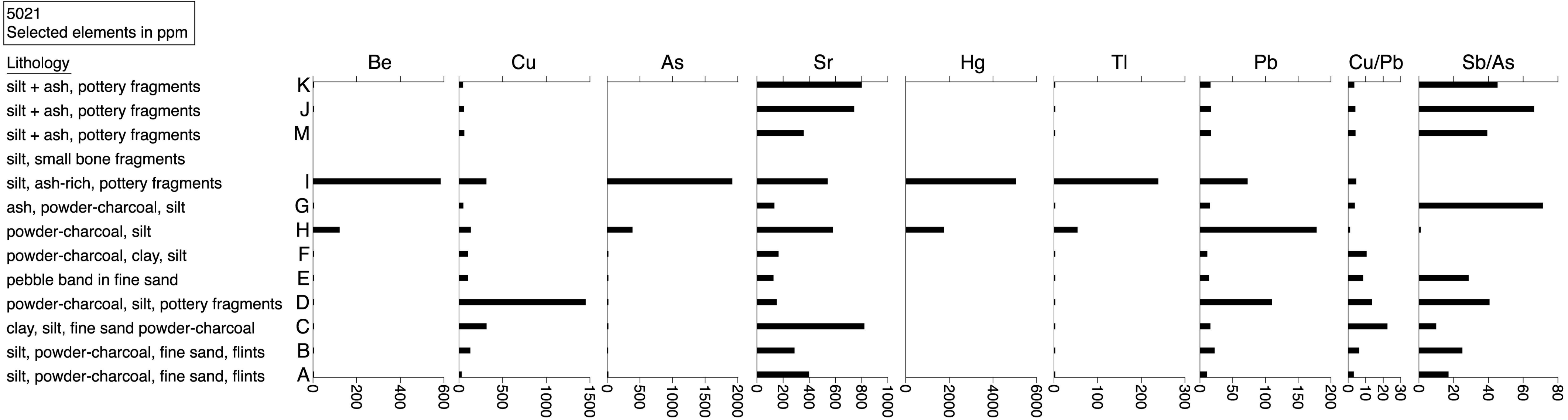

5738
Unit 5738
① copper smelting slag and abundant ash
② copper smelting slag with ash Iron Age
③ braid-plain sands with black copper smelting slag and ash
3150 (2990) 2890 B.P. (Beta 203406)
depth (m)
Cu and Pb ppm
Tl ppm
copper
thallium
lead
Geochemical zone WF 5738
1
2
5741b Downslope of zig-zag retaining wall
Unit 5741b
① coarse ash with much black copper smelting slag
② ash with some black copper smelting slag
③ ash and slag
④ ash and clay layers floors / hard pans
⑤ ash with braid-plain sands and clay layers - floors / hard pans
depth (m)
Cu and Pb ppm
Tl ppm
copper
thallium
lead
Geochemical zone WF 5741b
1
2
5741
Unit 5741
① brown clay-rich ash with abundant copper smelting slag and Roman ceramic debris
② brown ash with little copper smelting slag
③ grey ash with little copper smelting slag
530 (500) 400 B.P. (Beta 203412)
6560 (6460) 6400 B.P. (Beta 203413)
6190 (6010) 6400 B.P. (Beta 203414)
depth (m)
Cu and Pb ppm
Tl ppm
copper
thallium
lead
Geochemical zone WF 5741
1
2
5740 Mine entrance
Unit 5740
① post mining infill
② slumped mining debris
depth (m)
Cu and Pb ppm
Tl ppm
copper
thallium
lead
Geochemical zone WF 5740
1
2



5022
Chalcolithic pottery
black copper smelting
slag and pottery - Roman/
Byzantine to 30cm
Tell Wadi Faynan
(Feinan) Neolithic site
6280 - 6115 B.P. HD 12336
6625 - 6525 B.P. HD 12337
Top of the
Neolithic pottery
Water-washed aeolian silts and palaeosols
TELL LOAM
MEMBER
mid-Holocene meandering stream and bank deposits
FAYNAN
MEMBER
15.8 ± 1.3ka
(OSL-Aber 18/JA8)
Pleistocene fluvial deposits
W
E
5021 & Profile B of
Najjar et al. 1990
~60m
modern braid-plain abuts
base of exposure
Profile A of
Najjar et al.
1990
Profile C of
Najjar et al.
1990
0 1 2 metres


5022
Tell Wadi Faynan
TELL LOAM MEMBER
modern deflation surface exposing Roman-Byzantine slag, chert, ceramics, ash, silt, fine sand.
clay-silt, root holes, stones, charcoal, strong blocky peds.
clay-silt, fine strong peds, occ. stones, charcoal, snail shells.
clay-silt, fine strong peds, occ. stones, charcoal, snail shells, root holes
flints, pottery fragments, clay-silt, coarse blocky peds, soft calcareous nodules, occ. pottery and occ. charcoals, rare root holes.
clay-silt, calcareous nodules, occ. cherts, pottery fragments, blocky peds.
clay-silt, blocky-fine peds, small root holes, occ. fragments of pottery and charcoal.
carbonate induration and clay-silt.
silt-clay, strong-poor peds, occ. disordered, chips of pottery, cherts, nodules, calcareous material, calcified root holes.
C14 inferred level ~6115 - ~6280 yrs calib. B.P.
ash in clay-silt, much pottery, charcoal fragments, cherts, moderately strong peds, adjacent Neolithic structure.
base of exposure
geochemical zone
1
2
a
b
c
d
3
4
a
b
c
depth cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Be
Cu
As
Sr
Hg
Tl
Pb
Cu/Pb
50 100 150
500 1000 1500
200 400 600
500 1000 1500
500 1000 1500
50 100 150
100 200 300
20 40
ppm
estimated cal. yrs B.P.
~2440
~3640
~6191


5021
Roman-Byzantine slag on eroded surface
clay-silts with sands, sub-horizontal dessication cracks, weaker palaeosols, occasional gravel filled scours, horizon of calcitic induration
palaeosols
TELL LOAM MEMBER
pale brown silt
grey silt with ash
pale brown silt
grey silt
brown silt
grey silt and ash
K
J
I
grey silt and ash
powder charcoal and silt
void
void
M
grey silt and ash
H
G
charcoal and charcoal powder
7240-6990 B.P. Beta 205964
F
E
D
C
B
A
fine gravel
fine gravel
7295-7190 B.P. HD 12335
7470-7220 B.P. HD 10567
worked flint
15.8± 1.3ka (OSL - Aber 18/JA8)
Holocene fluvial-pond-overbank-bank epsilon cross-bedded deposits with rhizoliths, ash, charcoal, bone, pottery fragments, freshwater molluscs - with hiatuses; occasional contemporaneous re-working; dessication cracks in upper part.
palaeosols
Pleistocene fluvial gravels
FAYNAN MEMBER
modern braid-plain abuts base of exposure
0
1 metre
palaeosol(?)
boulders



5021
Selected elements in ppm
Lithology
Be
Cu
As
Sr
Hg
Tl
Pb
Cu/Pb
Sb/As
silt + ash, pottery fragments K
silt + ash, pottery fragments J
silt + ash, pottery fragments M
silt, small bone fragments
silt, ash-rich, pottery fragments I
ash, powder-charcoal, silt G
powder-charcoal, silt H
powder-charcoal, clay, silt F
pebble band in fine sand E
powder-charcoal, silt, pottery fragments D
clay, silt, fine sand powder-charcoal C
silt, powder-charcoal, fine sand, flints B
silt, powder-charcoal, fine sand, flints A
0 200 400 600
0 500 1000 1500
0 500 1000 1500 2000
0 200 400 600 800 1000
0 2000 4000 6000
0 100 200 300
0 50 100 150 200
0 10 20 30
0 20 40 60 80

5512
Cu
Pb
~100 BP
~1350 BP
~2600 BP
~2600 BP
5022
Cu
~5375 BP
~5740 BP
Pb
ppm
5021
Cu
Pb
6360 BP
6410 BP
Cu production(metric tons/year)
Industrial Revolution
Peak production in Swedish Falun mine
Decline of Roman metallurgy and mining
Roman Republic and Empire
Use of coinage
Rise and fall of Athens
Beginning of Bronze Age
Years ago
Pb concentration (pg/g)
Pb production (metric tons/year)
Industrial revolution
Spanish production of silver in New World
Silver production in Germany
Exhaustion of Roman Lead mines
Roman republic and empire
Rise & fall of Athens
Use of coinage
Discovery of cupellation
Years B.P.
1350 BP
2110 BP
3000 BP
5320 BP
Pb or Sc flux (mg/m2/yr)