ARCHAEOMETALLURGICAL AND MINING-ARCHAEOLOGICAL INVESTIGATIONS IN THE AREA OF FEINAN, WADI ‘ARABAH (JORDAN)

by
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Situated between the Dead Sea and the Red Sea,the Wadi ‘Arabah rift valley divides a geologically and genetically related copper ore district the eastern part of which is located in the foothills of the Jordanian highlands, and the western part at the border of the Negev desert (Fig. 1). Since prehistoric times ores have been exploited in both regions.

West of the ‘Arabah, the Timna‘ area has been investigated for over a decade.[1] With its innumerable and well-preserved pits and smelting sites, Timna‘ is a very well known copper producing area of the early period. For here the beginnings of the exploitation of copper is postulated as far back as the 4th millennium B.C. An intensification of the copper production has been documented during Dynasty XIX of the Egyptian New Kingdom (13th and 12th centuries) at a time when Egyptian mining expeditions together with those of the Midianites exploited the deposits there.[2] This activity was echoed during the Roman occupation of the second century A.D.

The part of the ore district east of Wadi ‘Arabah, which is situated in present-day southern Jordan especially in the neighbourhoods of Feinan and Petra, has been investigated, particularly for modern economic purposes, by the Jordanian Natural Resources Authority and the Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover (Germany). But the importance of the copper deposits in prehistoric and early historic times remained nearly undiscovered.

This presumably is also the reason why the history of copper metallurgy, not only of Palestine, but also of isolated parts of the Near East have repeatedly concentrated on the Timna‘ deposit, or on those in southern Sinai. However, the archaeological-historical and economic-historical picture of the copper production in this part of the world only comes into perspective in looking beyond the present political borders, and considering the eastern part of ‘Arabah in Jordan. For these reasons an archaeometallurgical research project devoted to the study of the eastern side of the ‘Arabah was initiated with the help of the Jordanian Department of Antiquities. In 1984 we began fieldwork in the areas of Feinan, Khirbet en-Naḥas and Wadi el-Jariye[3] (Fig. 2). The early mining and smelting area of Petra was excluded for the time being, owing to the large number of finds from Feinan. The areas just mentioned are not unknown, archaeologically speaking. As was the case with Timna‘, these archaeological areas have been visited over the years by several travellers.[4] However, they either failed to recognize their importance as a source of raw materials, or were unable to differentiate the finds chronologically. Twenty years ago the geologist Hans Dieter Kind studied early copper working on the eastern side of the ‘Arabah.[5].

The most recent surveys have shown that in the area investigated around Feinan, copper was produced in quantities unparalleled in the southeastern Mediterranean, with the possible exception of Cyprus. Anywhere from 150,000 to 200,000 tons of slag remain from the early smelting activities around Feinan.[6] That which follows summarizes the results of the

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[1] Conrad, H.G. & Rothenberg, B. (1980).
[2] Rothenberg, B., in: Conrad, H.G. & Rothenberg, B., (1980); Rothenberg, B., (1980).
[3] Bachmann, H.G. & Hauptmann, A., (1984).
[4] Musil, A., (1907/1908); Frank, F. (1934); Glueck, N., (1945).
[5] Kind, H.D., (1965).
[6] Bachmann, H.G. & Hauptmann, A. (1984).

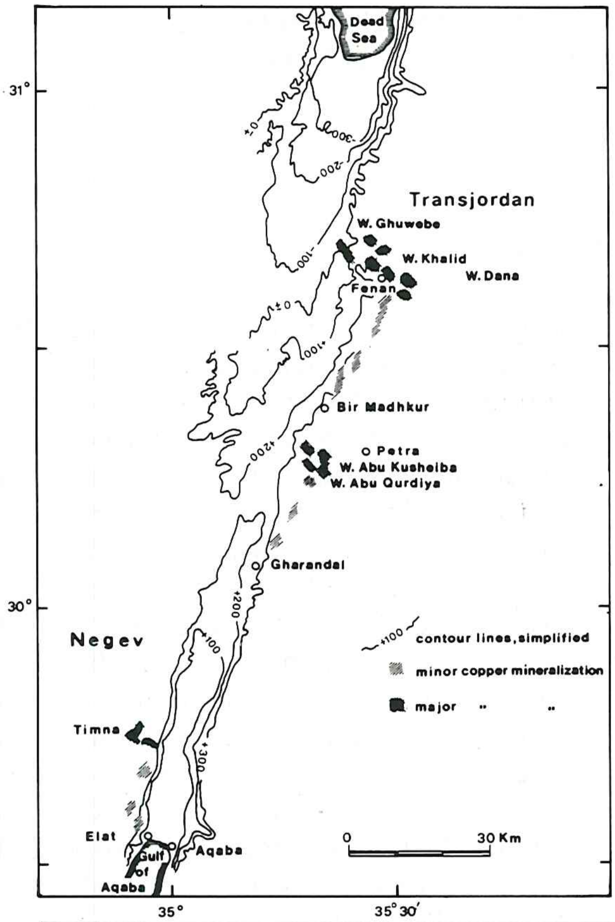

Fig. 1: Copper mineralizations in Wadi ‘Arabah (modified after Bender).

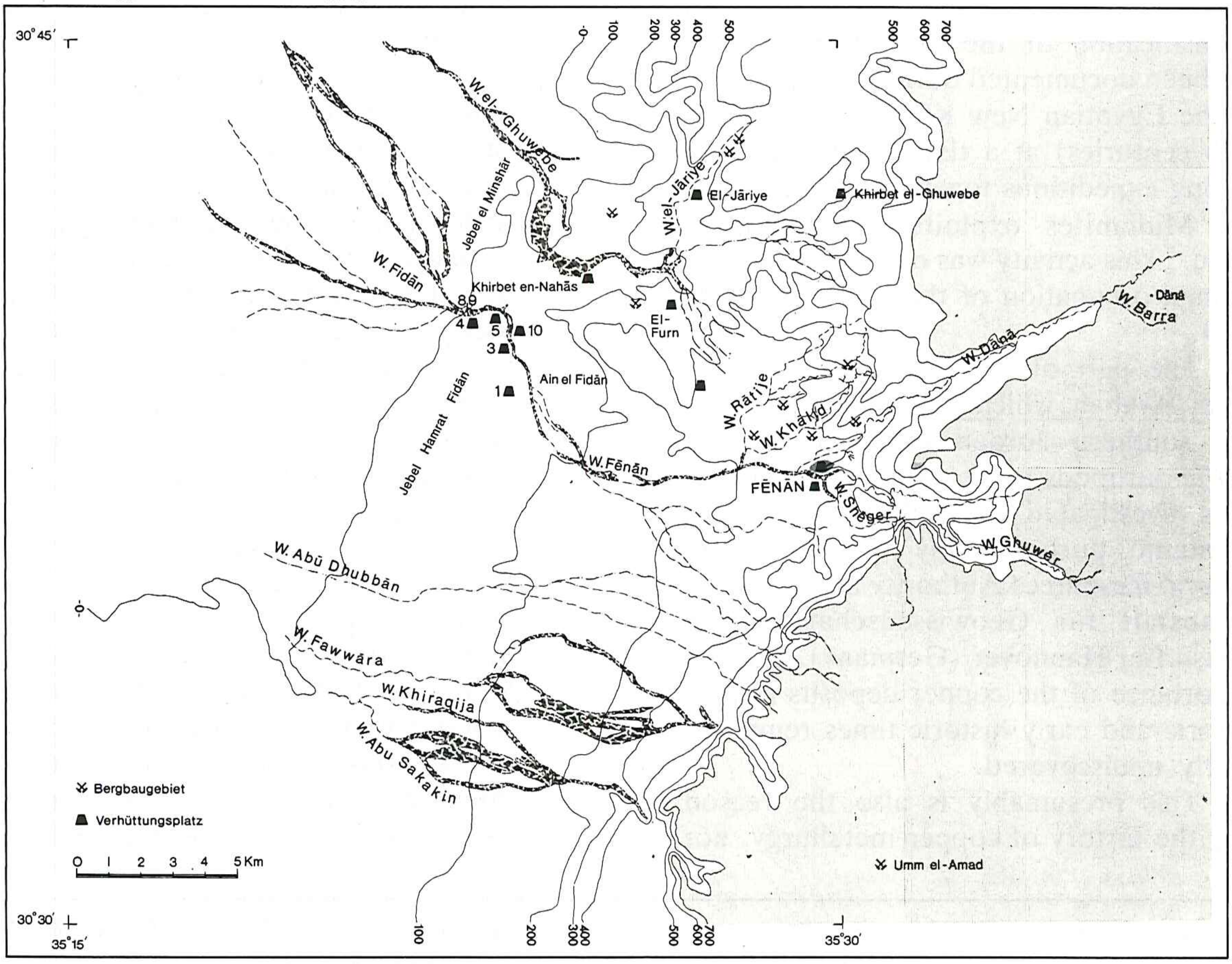

Fig. 2: Map of the project area: Feinan - Wadi Ghuwebe - Wadi el-Jariye and surroundings. The symbols show mining areas (⚒) and smelting sites (▲).

1984 season, and the first data of ongoing laboratory work. For the transliteration of Arabic names we have used the simplest forms.

Geology and Mineralogy of the Copper Ore Deposits

The copper deposites of Feinan, Khirbet en-Naḥas and Wadi el-Jariye embody the greatest ore concentrations on the belt which lies on the eastern side of the 'Arabah[7]. A further concentration of mineralization occurs some 20 km southwest of Petra.

Among the mineralizations which occur in different minerals in this area which were important for early mining belong the following geological strata (Fig. 3):

1. Copper mineralizations in the fine White Sandstones of the Lower to Middle Cambrian.
2. Copper-manganese mineralizations in a contemporary sequence from partly sandy dolomites, limestones and shales with the associated coarse-grained sandstones in the valley walls.[8]

The widely distributed and low-percentage secondary ores of the copper mineralizations of type 1 occur in the form of diffuse, irregular impregnations, as nodules, lentoids and carpet-like mineralizations or from up to fist-sized rinds. The copper ores consist principally of malachite ($Cu_2[(OH)]_3/CO_3$), with atacamite ($Cu_2(OH)_3Cl$); chalcocite (Cu_2S), and bornite (Cu_5FeS_4). These mineralizations are relatively poor. Copper-contents up to 15-25% or more are attainable only by the labourious collection of nut-sized pebbles.[9]

Mineralizations of this type were observed especially in Wadi Ratiye, some 2 km northwest of Feinan, and also near the mine of Umm el-'Amad to the south. These mineralizations were also sighted in the area of Wadi Abu Khusheiba southwest of Petra.[10]/

Typical for the mineralizations in the dolomite-limestone-shale-formation (type 2) is a crumbly, 1-3 m thick stratigraphic sequence, which at the bottom gradually merges into massive or bedded dolomite. Here, fissure mineralization and pockets of minerals such as chrysocolla ($CuSiO_3+aq.$) and malachite are evident, closely intergrown with lenses of pyrolusite (MnO_2) and other manganese minerals[11].

These intergrowths of copper and manganese minerals are particularly characteristic, for they were exploited from the Early Bronze Age up to the Late Iron Age. As opposed to the mineralizations in the White Sandstone, the ores occur here in a much more concentrated form, for which the copper content must have been far higher. Measurements carried out with a portable X-ray fluorescence spectrometer in the field have shown that here copper ore collected by hand can easily contain up to 35% copper (Table 1).

Copper-manganese mineralizations are concentrated especially in Wadi Khalid, Wadi Ḍana, near Khirbet en-Naḥas and in Wadi el-Jariye (Fig. 2).

With the exception of the iron and manganese contents, the copper ores are relatively pure. The trace elements (zinc, tin, nickel, cobalt, lead) are with a few exceptions (lead up to 2.818%) below 1%. The sulphur content also is less than 0.5% (Table 1).

The Periods of Copper Production

The copper production in the area of Feinan, Khirbet en-Naḥas and Wadi el-Jariye extends from the Chalcolithic Period up into the 13th century A.D. On the strength of the chronological evidence gathered during the 1984 campaign[12] including pottery finds, mining tools and

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[7] Bender, F. (1965).

[8] Bender, F. (1965); Boom, G.v.d. (1969).

[9] The chemical composition of the ores was determined photometrically and with Atomic Absorption Spectrometry. A part of the samples was measured earlier in the field using a portable X-ray fluorescence spectrometer, type X-Met from Outokumpu-Oy/Finland.

[10] Bender, F. (1965).

[11] Bender, F. (1965); Schürenberg, H. (1963) p. 1-16.

[12] A comprehensive overview on the dating of the sites with pottery is given in: Hauptmann, A., Weisgerber, G. & Knauf, E.A. (1985).

en-Naḥas.

Wt.-%	*Cu*	*Fe*	*Mn*	*Pb*	*Sn*	*Zn*	*Ni*	*Co*	*S*
JD-1/20	16.15	0.49	0.14	0.113	0.059	0.041	0.005	<0.001	0.37
JD-2/19	24.03	0.30	0.77	0.114	0.144	1.32	0.006	0.003	0.17
JD-12/1	40.68	8.99	0.02	0.037	0.115	0.021	n.d.	n.d	n.d.
JD-3/3a	35.71	0.33	10.59	0.570	0.167	0.110	0.014	0.016	0.08
JD-3/5	35.08	0.99	4.10	0.760	0.165	0.090	0.011	0.008	0.01
JD-3/13	3.69	2.40	8.43	2.818	0.008	0.045	n.d.	n.d.	n.d.
JD-6/1	2.65	31.90	9.78	0.280	0.048	0.381	0.022	0.019	0.02

JD-1/20 = pieces of ore from the Roman slag heap of Feinan (type 1)
JD-2/19 = pieces of ore from the Iron Age (?) slag heap of Khirbet en-Naḥas (Type 1)
JD-12/1 = copper-bearing sandstone from Wadi Ratiye; ore concentration by hand-picking
JD-3/3a = manganese-bearing dolomite with copper mineralization from Wadi Khalid (Type 2); concentrated by hand-picking
JD-3/5 = manganese-bearing shales with copper mineralization from Wadi Khalid; concentrated by hand-picking
JD-3/13 = limestone-containing manganese ore with copper mineralization, Wadi Khalid (Type 2); concentrated by hand
JD-6/1 = pieces of ore from the Mamluk-Turkish slag heap of el-Furn (Type 2).

coins, the following periods emerge, with reference to the cultural epochs of M. Galling[13]:

Chalcolithic (4500-3100 B.C.)
Early and Middle Bronze Age (EBI-III 3100-2900 B.C.; MBI 2100-1900 B.C.)
Iron I (1200-1000 B.C.)
Iron IIC (800-400 B.C.)
Roman Period (1st - 4th Century A.D.)

A new discovery in the archaeometallurgy of the Near East is the discovery of Chalcolithic and Early Bronze Age copper production, which on the basis of the find circumstances, is far greater than could have been absorbed by local needs. Chalcolithic sites in the Feinan area have already been described by Tom Raikes and were dated to these periods on the basis of ceramic and flint finds[14].

The most recent campaigns revealed in these places and at several new ones in Wadi Fidan (Wadi Fidan 1, 4, 5) near Ras en-Naqab and in Khirbet en-Naḥas the traces of copper smelting as well as of metal working. The copper production in and around Feinan, which started at a few sites in Chalcolithic times, developed to larger activities in the Early Bronze Age and seems to have continued, without any dramatic technology changes, into the Middle Bronze Age. This conclusion rests on the evidence of Chalcolithic and Bronze Age pottery which was found *in situ,* as well as together with archaeometallurgical finds which, phenomenologically speaking, are very homogenous. In the Iron Age radical technical changes took place, and the copper production assumes industrial proportions. The most obvious indications for this are the two immense smelting areas, Feinan and Khirbet en-Naḥas (Pl. LXVI,1 & 2). To judge from the amount of pottery observed, presumably the greater share of the *ca.* 100,000 tons of slag was produced in the Iron IIC Period. Also at several sites (Khirbet el-Jariye, Khirbet en-Naḥas, Khirbet Ghuwebe and Wadi Ḍana) pottery dating to Iron Age I and II occurs.

Interestingly enough, the chemistry

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[13] Galling, K. (1977), p. 386.

[14] Raikes, T. (1976) p. 1-48.

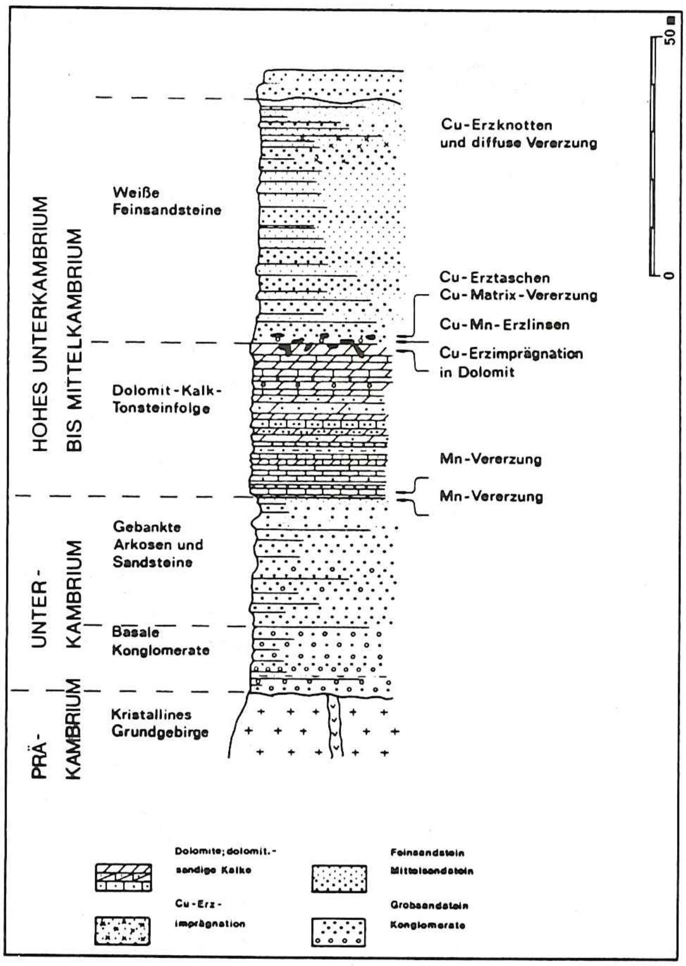

Fig. 3: Vertical distribution of copper mineralizations in the stratigraphic sequence of Wadi Khalid and Wadi Ḍana (after Bender).

and typology of slags, the tuyères, and the remains of ancient smelting furnaces in Iron Age slag heaps in Feinan and Khirbet en-Naḥas are strikingly similar to those which B. Rothenberg describes from stratum 1 at site 30 in Timna'[15]. The remarkably similar smelting processes following from these finds clearly indicate a transfer of technology between both sites at this time. Stratum 1 at Timna' site 30 is contemporary with the Egyptian Dynasty XXII (945-715 B.C.), and possibly with the political activities of Sheshonk in Palestine at around 920[16].

Copper mining and smelting during the Roman Period could only be determined in the immediate vicinity of Feinan (Wadi Ratiye, Wadi Khalid) and some 5 km to the south (Umm el-'Amad). They are assigned to the 1st to 4th centuries A.D. Directly to the south of the Feinan ruins lay some 40,000 tons of slag. Evidently the ores from all the Roman mines were smelted at this site. With the help of pottery and coins of the later 1st century A.D. the dating of the Roman slag heaps can be correlated with such contemporary activities in Beer Ora/Timna'[17]. However, the pottery from the slag heaps and that from the mines belongs to the 2nd - 3rd century AD[18]. The mining activities, not to mention the forced internment of criminals and Christian martyrs, as well as those who embraced unorthodox variants of Christianity (especially in the 4th century) are recounted in a most direct fashion by church fathers such as Eusebius.[19]

Following this flourishing period of copper production, the mining and smelting activities ceased. Only during the

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[15] Rothenberg, B. (1980); Bachmann, H.G. & Rothenberg, B. in: Conrad, H.G. & Rothenberg, B. (1980).

[16] Kitchen, K.A. (1973), p. 467.

[17] Rothenberg, B. (1973) p. 211ff.

[18] Hauptmann, A., Weisgerber, G. & Knauf, E.A. (1985) p. 190ff.

[19] Geerlings, W. (1985).

short renewal of activity occur. Thus a smelting site was discovered at el-Furn, about 1 km southeast of Khirbet en-Naḥas, dating to the 13th century, and associated with a settlement.

Mining

Chalcolithic and Bronze Age mining concentrated in the area of Feinan, in particular at Wadi Khalid (Fig. 2). A chronological differentiation is not possible by means of different mining techniques or with the help of differing mining picks. Pottery finds shed some light, however, mainly in the context of the following observations. Evidence for copper production came to light during our survey at the site Wadi Fidan 4. Slag and ore were located on the elevated part of a terrace in what Raikes has designated the "township"[20]. Its Chalcolithic dating is indicated by the rough pottery[21], a fragment of a basalt vessel, flint implements, and biconical, bored stone hammers (Fig. 4) as well as mace heads.

Directly at the foot of the "city hill" lies a slag heap which contains *ca.* 15 tons of a homogenous slag of the same kind as that which occurs in diverse areas in the area of the "township". In the slag heap, fragments of conical clay sticks were observed similar to those collected at other sites in Wadi Fidan (W. Fidan 1), Wadi Feinan, and from Feinan itself (sites 8-10, 13, 15) in large quantities together with slag which lay on the surface (Pl. LXVII,1). They seem to have served as tools in connection with the smelting of copper ore. This Chalcolithic mining is also observed by the occurrence of numerous biconical drilled stone hammers in and near the mines. Numerous as well are grooved hammers and "prism" hammers (Fig. 4:3,4) which were used during the Chalcolithic and Early Bronze Age. Since the age of the stone hammers in the mines is disputable, it may be noted that, in Feinan, they have not been found yet in the Middle Bronze Age or to the Iron Age. In this connection, some hitherto unknown mining picks can be described (Fig. 4:2,5). They are formed by quartz-porphyry pebbles which were worked to a prismatic form, pointed and then bored.

Between Wadi Khalid and Wadi Ratiye, several mines were not investigated in 1984 for reasons of time. However, preliminary observations suggest their dating to the Early Bronze Age on the evidence of pottery which occurred in the tailings inside the mines. The ceramic in question is a red polished ware with a typical comb motif. In one case a sherd of this ware was used as a lamp, as evidenced by the traces of soot on its edges (Fig. 5:1). It was located 22 m away from the surface in the tailings from pit no. 43 (Pl. LXVII,2). The ancient gallery itself was exposed by modern prospection work carried out by the Natural Resources Authority, and could be followed 55 m into the mountain. In these early periods predominantly rich copper minerals (copper silicates, malachite) were mined from the copper-manganese horizon in the dolomite-shale layers. In order to exploit the mineralized strata the pits were built in a chamber-pillar construction. The height is 1-1.5 m and they extent laterally at least 30 x 50 m! The chambers sometimes are supported with artificial pillars. They follow the slightly inclined ore horizon to a depth of some 15-20 m. Curiously, all of the pits of this period were carefully backfilled (Pl. LXVII,2), possibly for religious reasons. Thus, near the mouths of the mines, only small dumps are visible which gave no inkling of the true dimensions of the early mines.

The rich copper-manganese ores in Wadi Khalid and the area of Khirbet en-Naḥas seem to have predominated in the Iron Age as well. Owing to more readily accessible deposits, and for logistical reasons, the authors' fieldwork centred on the mines in Wadi Khalid, where almost 50 pits could be recorded. Here, owing to

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[20] *Cf.* site No. 6 in Raikes (1980).

[21] Hauptmann, A., Weisgerber, G. & Knauf, E.A. (1985) p. 185ff.

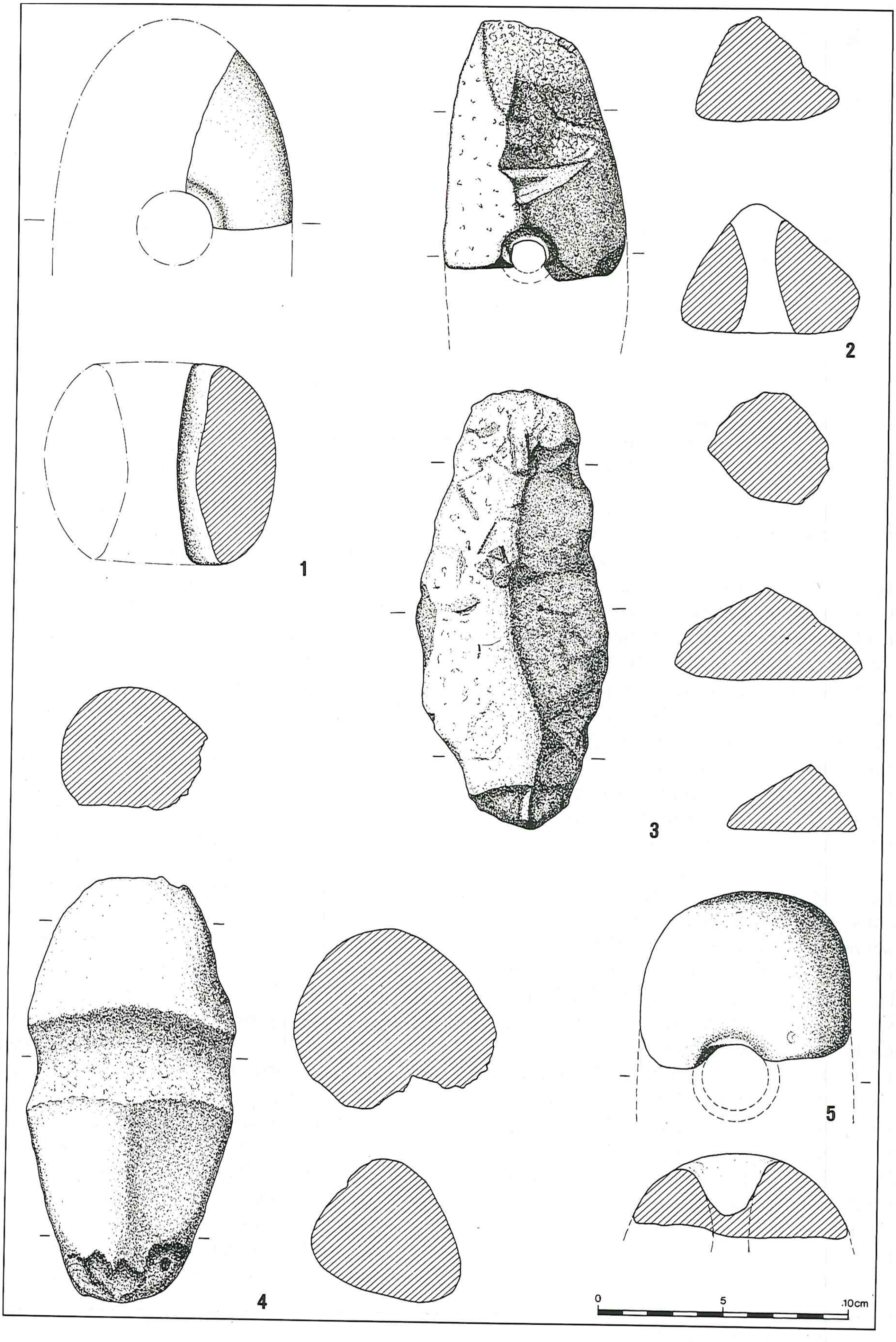

Fig. 4: Mining tools from the area of Feinan and Khirbet en-Naḥas, made of natural rock.

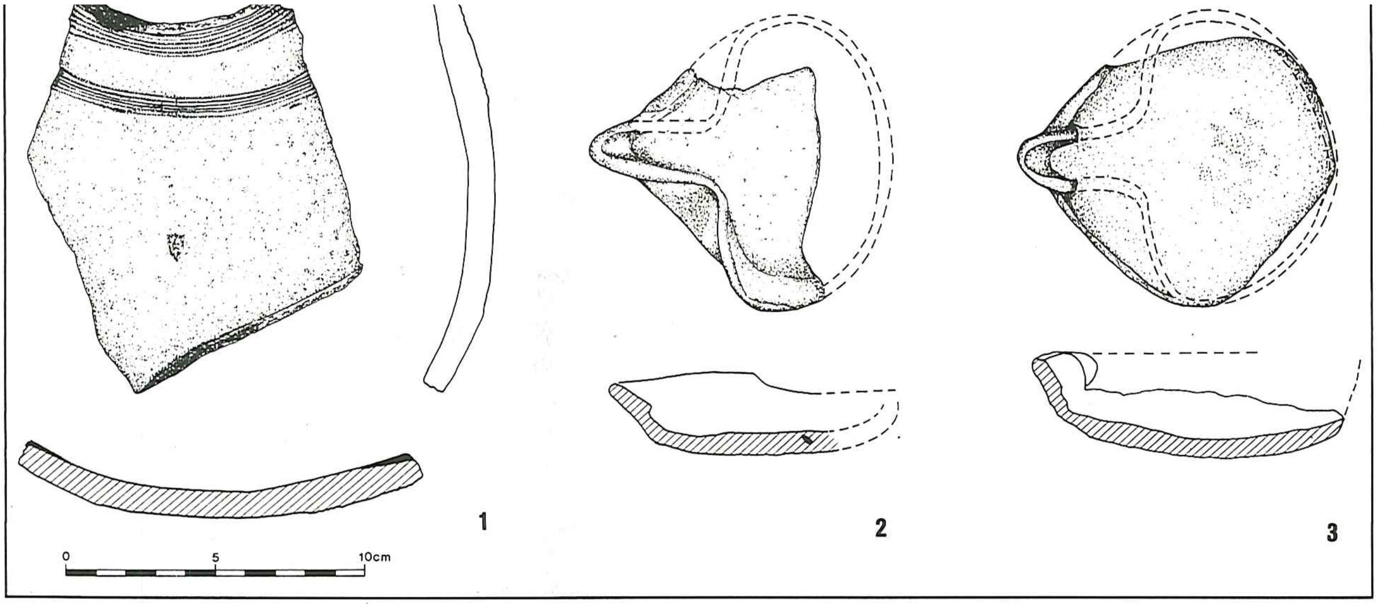

Fig. 5: Mining lamps from the Middle Bronze (No. 1) and Iron IIC Periods (Nos. 2, 3).

the mining activities of earlier periods, the miners in the Iron Age were forced to work the parts of the deposits by shafts which were not yet excavated. To the more interesting pottery finds of the Iron IIC Period belong two lamps which occurred on the dumps of pits 4 and 10 (Fig. 5:2 & 3). The mining equipment of this period includes hand-sized maul-stones of considerable weight which were formed of tough quartz-porphyries and fine-grained granites. These tools show use-wear, but were never worked with the purpose of giving them a particular form.

Of all the mining remains of this period, which generally appear simply as dumps, the construction of a mining shaft deserves special attention[22]. Three shafts which were sunk directly alongside each other ("triple shaft", Pls. LXVIII and LXIX,1) can still be seen. They were excavated by the mining engineer Mr. Kasim Omari of the Jordanian Natural Resources Authority[23]. On the evidence of pottery finds from the excavation dumps, two of the shafts were sunk in the Iron IIC Period. They are irregularly formed and severely weathered. Steps are visible at irregular intervals. At a few metres depth the shaft walls collapsed as a result of tectonic movements, and possibly for this reason they were abandoned a relatively short time after their construction. The third shaft distinguishes itself from the other two in its exact and regular form. It did not, however, reach the horizon of the ore. It was sunk with the help of an elaborate fixed scaffolding which itself was reachable by means of several neatly cut steps. Two iron chisels which were found in the dump were evidently used for the construction of the shaft, scaffolding and steps (Fig. 6). This shaft is datable by a Roman coin to the 1st century A.D. The shaft was apparently constructed for prospection purposes. It is unparalleled in the history of mining, and owing to the uniqueness of this monument of technology we devoted considerable effort to its photogrammetric measurement (Pl. LXVIII).

As opposed to the above-mentioned early periods of mining, in the Roman Period copper mineralizations in the sandstone (Type 1) without manganese were exploited since the rich copper-manganese ores were probably exhausted, and a continuation of the mining in these areas was unfavourable for technical reasons. This situation is inferable based on numerous pits in Wadi Ratiye, as well as on the mine, Umm el-'Amad, 5 km south of Feinan.

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22. Bachmann, H.G. & Hauptmann, A. (1984) p. 114.
23. Omari, K. (1983).

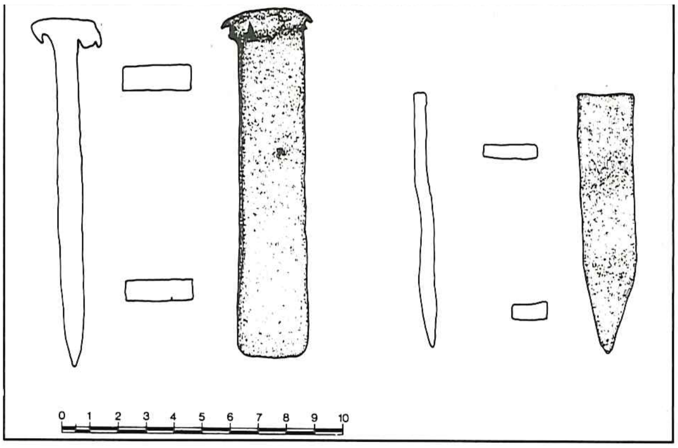

Fig. 6: Roman iron chisels, found in the waste dumps of the "triple-shaft".

The mines were all in operation until the 2nd/3rd century A.D.

In Wadi Ratiye, thus far nearly 30 mines have been located. They lie in a tectonically extraordinarily intensive stressed area. The ores mined had a rather low metallic content because of the extensive distribution of the copper minerals (Table 1). The ores had to be extracted from large quantities of host rock and were then concentrated by ore dressing. The mining techniques could not be studied in detail because all of the pits were destroyed. Again turning to the church fathers, we may recall their recounting that the convicts had only the slightest chances of survival.

One of the most impressive mining monuments is the mine Umm el-'Amad, 5 km to the south of Feinan. As opposed to the mines in Wadi Ratiye, this pit is still well preserved. Assumably, it was driven mostly in the 2nd/3rd century A.D. The mouth, which in terms of Roman mining is atypical (Pl. LXIX,2), may date back to a far earlier period, perhaps to the Bronze Age.

The mine was driven almost horizontally into the mountain with a chamber-pillar construction, into a horizon with secondary copper-minerals in the White Sandstone (Pl. LXIX,3). Slit samples cut from the copper-bearing layer near the mouth showed a Cu-content of only 1.12%[24] and indicate that these mineralizations contain a lower percentage than the copper-manganese mineralizations which were mined in the earlier periods in Wadi Khalid.

In contrast to earlier reports[25], this mine, extending as it does laterally, 55 x 120 m, and with a height up to 2.5 m, is six times as large as previously known. The pillars are cut in a perfect technique and are situated at regular intervals. Just as on the roof, they also show precise and still fresh chisel marks which surprisingly on the pillars are not oriented slanting and downward, but rather in a horizontal direction (Pl. LXIX,3).

In Umm el-'Amad, similarly to the triple shaft in Wadi Khalid, a mine exists, which to judge from its technical execution, state of preservation, and its completeness, must be considered as a monument of the technical achievement of the Roman Imperium.

The circumstances surrounding the mines in Feinan and their adaption to the geological deposits clearly reflect the development of mining and its effect on metallurgy.

While during the Chalcolithic period and the Bronze Age very rich mineralizations could be easily exploited in Wadi Khalid, over the course of time greater effort was required in order to reach these ores. The situation in Wadi Khalid shows that successively deeper shafts were necessary. By the beginning of the Roman

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[24] Kind (1965) found at the same place a copper content of 0.8%.

[25] Frank (1934); Glueck (1945) p. 71.

was no longer possible. The inhabitants had no other recourse than to mine a poorer ore, at the same time a much greater effort in terms of time and energy became necessary. In addition the composition of the ore changed. While in the earlier periods the copper ore already contained the manganese necessary for fluxing, to the Romans only a manganese-free ore was available. As a result, this had to be added during smelting. Thus the increasing mining of low-grade ores served as an impetus for the development of new mining and smelting techniques. This insight also pertains to the present period with its fewer and poorer raw materials.

All in all, fewer mines exist in the Feinan area than in Timna‘, but in their size they excel the latter[26]. This fact, and the (at least in earlier periods) availability of rich ores give witness to the more intensive exploitation of the resources on the east side of the ‘Arabah.

The Smelting of Copper Ores

Field Observations

In the Feinan area copper ores were smelted at more than 20 sites, some of which can be clearly attributed to the different cultural periods, but which, however, over the millennia up to the activities of the Romans, are witnessed by accumulations of slag.

The previous dating of these sites can be described in the following way. In the Chalcolithic Period smelting activities were just discovered at the site Wadi Fidan 4 (= Raikes site c). During the Early Bronze Age numerous and disparate sites were strewn across the landscape where smelting took place, sometimes kilometers away from the mines (*cf.* Wadi Feinan, Feinan, Ras en-Naqab and others). The formal typology of the slag, even by the end of the Bronze Age, changed little. Characteristic are small pieces of slag with a viscous structure and fair amounts of charcoal inclusions. This kind of weathering, and not only an intentional crushing in order to recover metallic inclusions. Sometimes slag fragments full of bubbles and charcoal inclusions can be found, which lend an idea of the original size. On the dumps from these periods, fragments of tuyères and furnaces can frequently be found, which evidence the existence of low, pot-sized smelting furnaces (Pl. LXX,1).

These smelting furnaces were always built in batteries composed of several exemplars, which sometimes stood close to each other. At Ras en-Naqab the remains of 12 furnaces made of thin, flat pieces of standstone were counted directly next to the steep gorge. In Feinan 8-11, more than 20 furnaces were found, the bottom and sides of which were made of clay layers with a thickness of several centimeters. The furnaces were built on a slope, and the slag pits which lay directly beneath them were recognizeable by their masonry (Pl. LXX,1).

For the first time, in the Iron IIC Period, the presence of large clumps of tapslag (40-60 kg!) evidence metallurgical advances. The ores from the surrounding mines were smelted in two central sites: Feinan and Khirbet en-Naḥas. Also for the first time in Iron IIC, the slag was smashed in large amounts in order to recover metallic inclusions, and to enable their recycling. The form and size of the smelting furnaces is not yet exactly known. The tuyères, however, had an outer diameter ranging from 15 to 18 cm, and were surprisingly made in two parts (Pl. LXX,2).[27]. The internal part of the tuyère was made of rough, slag-tempered clay, as was the lining of the furnaces. Around this a highly fire-resistent cap was placed which served to insulate the structures from high temperatures during the smelting process. They were made of SiO_2-tempered clay.

The slag dating to the Roman period disintegrated owing to weathering so that the original size of the cakes is unknown. Except for a few fragmentary building

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[26] Cornard, H.G. *et al.*, in: Conrad & Rothenberg (1980).

[27] Rothenberg, B. (1980) p. 198, Fig. 215; Bachmann, H.G. & Rothenberg, B. (1980) Fig. 238.

stones which are *in situ* as kiln floors, there is no evidence for the form and size of the smelters. According to R.F. Tylecote we can assume that Roman smelting furnaces sometimes reached a height exceeding 1.5-2 m[28].

The Scientific Investigation of the Slag

On the basis of mineralogical and chemical analysis of the ores from the Feinan area, it appears that they were smelted in a one-stage reduction process without roasting. Related to the different kinds of smelting furnaces, different smelting techniques can be reconstructed by using archaeological and metallurgical finds as well as with the help of chemo-physical investigations.

Of the abundant archaeometallurgical finds which were recovered (slag, tuyères, raw copper, furnace fragments), as yet only the slag was analyzed to determine its chemical and mineralogical composition. Now, this regularly produced waste material can be used in order to reconstruct the pyrotechnology and to gain an idea of the processes which took place in the early smelting furnaces.

Chemistry and Mineralogy of the Slag.

Corresponding with conditioning characteristics of the individual deposits in the area investigated, with few exceptions (Mamluk-Turkish Period) manganese silicate slags occur[29] which are rare in early metallurgy. Similar slag is known only from Cyprus[30] and Oman[31] and interestingly, has been observed in Timna‘ in the 10th century B.C.[32].

Chemical analysis carried out using an X-ray-fluorescence-spectrometer and wet-chemical processes[33] revealed that the manganese-rich Jordanian slags contain 25-42% weight MnO, 28-48% SiO_2, 1-13% CaO, 1-5% FeO, 0.5-4% MgO, and up to 6% Al_2O_3 (Table 2). With the use of X-ray diffraction and a microprobe (results not given here) the following mineral phases were identified in the slag. The main components are tephroite (Mn_2SiO_4) and a pyroxenoide ($((Mn, Ca)_3\ SiO_3O_9$, Pl. LXXI,1 & 2), and in the case of slag with a high degree of oxidation, also hausmannite (Mn_3O_4). The phases tend towards the formation of crystal skeletons, but the slag usually shows a distinct tendency towards glassy solidification. Resulting are swarms of µm to mm large gas bubbles, and these glassy slags sometimes are coloured red by copper silicates. The Mamluk-Turkish slag, on the other hand, contains 17-20% FeO and just as much MnO. Phases occuring here are knebelite ($(Mn, Fe)_2SiO_4$) as well as Mn- and Fe-pyroxenes. In contrast to the manganese slags, these are distinctly more completely crystallized.

From the projection of the chemical composition in the concentration triangle CaO(+BaO) - MnO(+FeO+MgO) - SiO_2 (Fig. 7) and in the diagrams MnO/CaO(+FeO) (Fig. 8) it is clear that the slag shows a relatively narrow range of variation. This is conditioned by the available raw material which was mixed in an attempted standard composition which can be determined owing to the chemo-physical characteristics of melted silicates. But with the study of the main components, local and chronological variations can already be distinguished and therefore traced to the areas of the copper deposits. Thus Fig. 8 shows clear distinctions between the slags from Feinan and Khirbet en-Naḥas whereby the first, with an increased CaO(+FeO) content, have less MnO than those from the second area. In this way, it is possible to identify the deposits from which the Bronze Age slag heaps arose.

Fig. 7 shows that slags from the earlier

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[28] Tylecote, R.F. (1976) p. 53ff.

[29] Bachmann & Hauptmann (1984) p. 116.

[30] Bachmann, H.G. (1982).

[31] Hauptmann, A. (1985) p. 42.

[32] Bachmann, H.G. & Rothenberg, B. (1980).

[33] The chemical analyses were carried out using an X-ray fluroescence spectrometer, type PW 1400, at the Institute of Mineralogy, University of Bochum. For this, a collection of selected slag samples was assorted after measuring the copper, manganese, iron, and calcium contents with a portable X-ray fluorescence spectrometer in the field.

	Chalc./Bronze Age			*Iron Age*				*Roman*			*Mamluk*	
Sample JD	*1/7B*	*1/7C*	*7/2B*	*1/4*	*2/2A*	*2/2B*	*2/5A*	*1/10*	*1/11*	*1/23A*	*1/2A*	*6/2A*
SiO_2	32.9	27.5	27.9	32.6	29.8	32.1	32.7	36.2	47.8	42.6	35.5	34.0
TiO_2	0.24	0.26	0.21	0.20	0.23	0.20	0.20	0.25	0.22	0.30	0.32	0.22
Al_2O_3	5.62	5.63	4.56	4.89	5.05	4.60	4.27	2.90	2.63	4.86	6.52	5.16
FeO*	3.47	3.07	0.05	3.52	3.32	3.61	3.90	2.51	2.35	5.26	20.0	38.4
MnO	26.4	28.2	42.4	36.7	41.0	37.5	40.7	40.4	29.8	32.90	17.3	14.3
MgO	3.94	3.60	0.57	1.33	1.38	1.28	1.60	0.83	1.22	0.49	1.44	0.47
CaO	13.0	13.3	7.35	7.92	7.55	9.18	7.63	1.14	6.03	2.29	10.6	2.48
BaO	6.85	2.71	1.02	0.65	0.56	0.48	0.36	0.60	0.53	0.65	2.79	0.61
K_2O	1.76	2.80	2.96	3.26	2.75	2.19	2.45	1.84	2.63	1.32	1.79	1.01
Na_2O	0.65	0.31	0.66	0.72	0.50	1.03	0.55	0.11	0.40	0.42	0.55	0.28
P_2O_5	1.80	5.35	3.43	2.25	2.71	2.10	2.45	0.13	0.04	0.13	2.54	0.47
S	0.07	0.10	0.54	0.82	0.76	1.80	0.56	0.36	1.63	0.16	0.31	0.19
Ni	0.07	0.07	0.06	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.08	0.07
Cu	2.47	2.90	0.52	0.61	0.36	0.40	0.37	1.97	0.51	0.56	0.33	1.33
Zn	0.12	0.11	0.05	0.06	0.04	0.02	0.03	0.02	—	0.02	0.04	0.07
Pb	0.69	0.69	0.27	0.27	0.02	0.02	0.03	—	—	0.01	0.03	0.06
Glv	—	1.47	2.41	1.69	2.35	1.63	1.97	3.22	0.38	1.94	—	—
Ž(wt%)	99.96	98.07	94.96	97.56	98.45	98.22	99.84	92.55	96.24	93.98	100.14	98.82
phase content	Teph Glass	Teph Glass	Teph Glass	Teph Glass	Teph Glass	Teph Glass	Teph Glass	Bust Teph Glass	Bust Teph Glass	Bust Teph Glass	Kneb Px Glass	Kneb Px Glass
viscocity log η at 1200°C	1.43	1.09		0.87	0.57	0.92	0.68	0.92	5.66		1.49	

*: Total amount of iron, calculated as FeO

Abbreivations:
Teph = tephroite, Bust = bustamite, Px = pyroxene, Kneb = knebelite

Localities:

JD-1/7B	Feinan 11
1/7C	Feinan 11
7/2B	Wadi Fidan 1
1/4	Feinan 5
2/2a	Khirbet en-Naḥas
2/2B	Khirbet en-Naḥas
2/5a	Khirbet en-Naḥas
1/10	Feinan 1
1/11	Feinan 1
1/23a	Feinan 1
1/2A	Feinan 2
6/2A	El-Furn

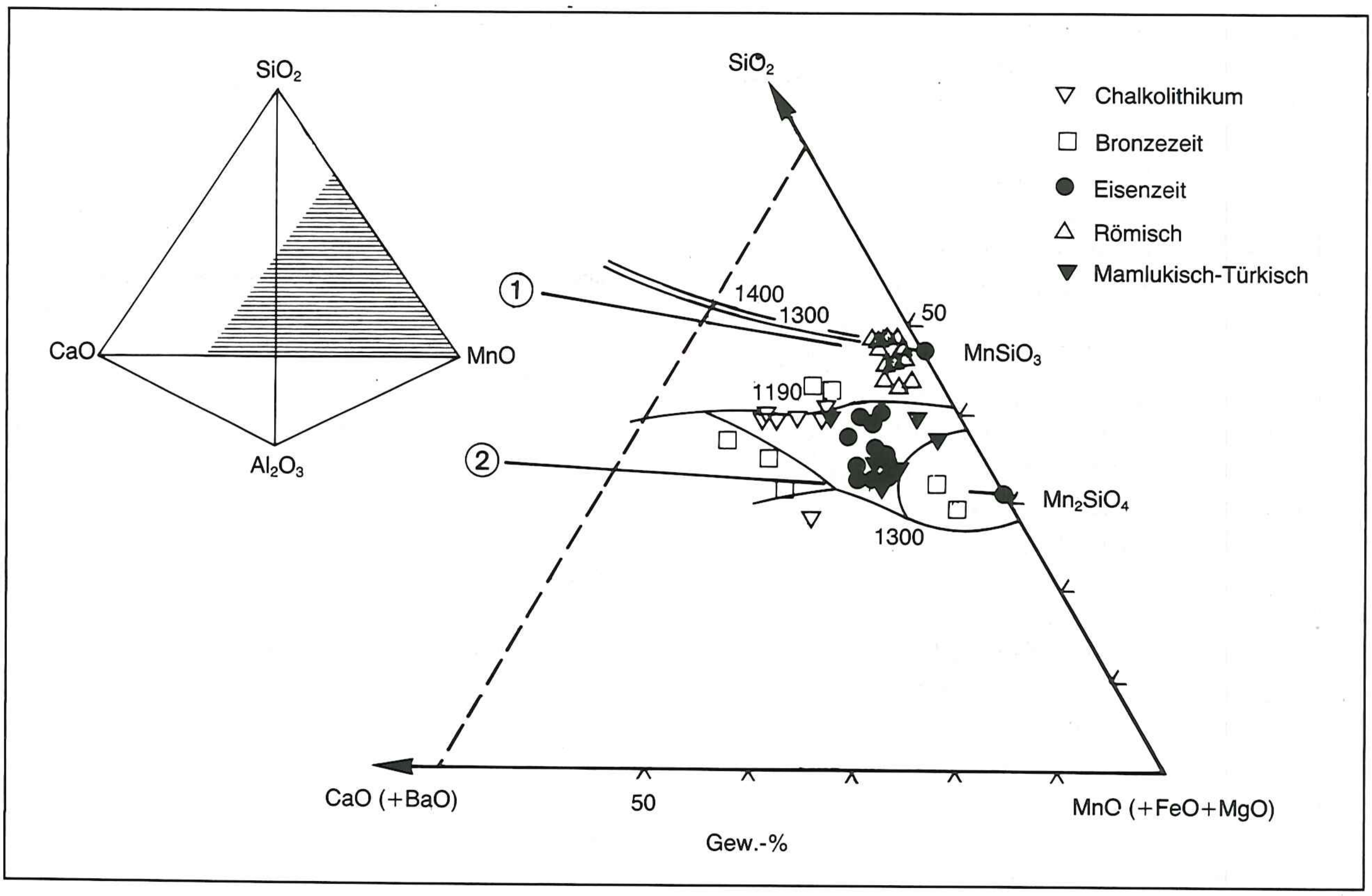

Fig. 7: Chemical composition and "melting" temperature of copper slags from Jordan, projected in the system CaO(+BaO) - SiO_2 - MnO(+FeO+MgO) (according to Glasser). 1 = metasilicates, 2 = orthosilicates.

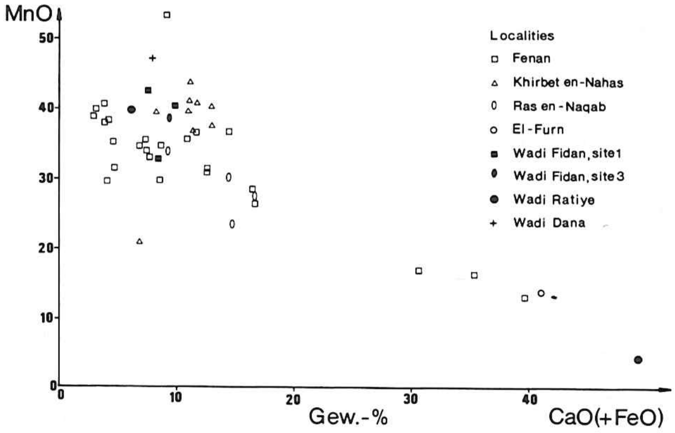

Fig. 8: MnO/CaO(+FeO) contents of copper slags from Jordan. The values show a clear difference between slags from Feinan and those from Khirbet en-Naḥas.

periods (Early and Middle Bronze Age) have a wider variation spectrum than Iron Age and Roman slags. Evidently, in these epochs large quantities of dolomite-limestone-shale layers (Fig. 3) were mined. A comparison of the composition of slag including pieces of unreacted ore show that manganese-rich ores imbedded in chalky lenses were preferred for mining and smelting. This is indicated by the high CaO and MnO content of the slag. Striking in comparison with the remaining slag is the extremely low CaO content of the Roman slag, which is well documented by samples collected in the surveys and which is linked to the ores in the CaO-poor sandstones.

The high MnO content of the slag suggests the addition of a fluxing agent (pyrolusite), the site of exploitation of which has not yet been localized.

As in mineralogy and petrology, which use the mineral chemistry and the experimentally determined stability ranges of natural minerals in order to gather evidence regarding the structure of the earth's crust and mantle, the phase content of a slag can be compared with known equilibria diagrams. In this way it is possible to get a look into the "black box" of a smelting furnace used in ancient times and we can measure the gas atmosphere, the temperature in the furnace as well as the viscosity of the slag in its liquid state.

The manganese-rich Jordanian slags have certain peculiarities in comparison to the otherwise widespread iron-silicate slags, which were usually produced in archaeometallurgy.

The "Melting" Temperature of the Slag

The determination of the "melting" temperature of slag is the basis for the estimation of the most important process parameter — the firing temperature of the furnace. What must be taken into consideration here is that it only yields an indication of the minimal furnace temperature, and not the actual temperature which was reached. The melting temperature of the slag was determined using a theoretical basis: the bulk analyses of the slags were reduced to the main components, then the reduced analyses were plotted on to a suitable phase diagram, in this case the system $CaO(BaO)$ - $MnO(+FeO+MgO)$ - SiO_2 (Fig. 7). As the "melting" temperatures for all points in this system are known, a rough estimation was also possible for the slags from the projection points.

It is obvious that a large part of the slag of the different cultural epochs belongs to different temperature ranges. Early Bronze Age slags cluster around a melting point of 1190°C, Iron Age slags fall in the range of 1250 - 1300°C, while Roman slags, owing to their generally higher SiO_2 content have melting points up to 1400°C. These slags show the narrowest variation between charges.

Recognizable from a juxtaposition of manganese-rich and iron-rich silicates is that manganese-silicate slags should not have a lower melting point than iron-silicate slags, as postulated by Bachmann and Rothenberg[34], but that they melt at *higher* temperatures. This result was shown by means of experimental measurements using Omani slags.[35].

Degree of Oxidation of the Slag

A decisive source of information for the construction and function of ancient smelting furnaces is an understanding of the gas atmosphere, i.e. the reduction effect which is caused by the oxygen content or the CO/CO_2 ratio during the firing.

Since in most cases ancient smelting furnaces are completely destroyed, important details of construction are lost; for example, the height of the furnace or the size and number of the tuyères used — two factors which together with the temperature control the state of oxidation and reduction in the furnace.

If texture and phase content of the slag are considered, the oxygen content (pO_2) can be estimated roughly from the systems MnO-Si-O, Fe-Si-O and Cu-O in dependence on the temperature (Fig. 9).

For the manganese-rich slags from Feinan and Khirbet en-Naḥas, important differences from iron-silicate slags which are a result of the intentional addition of manganese fluxes are noted. The slag-forming oxide MnO is stable over a far higher temperature and pO_2 range than "FeO" (wuestite)[36]. This prevents on the one hand the precipitation of unwanted metals (iron resp. manganese), as has happened very often in archaeometallurgy, owing to an over-reduction (formation of a furnace sow). This effect is the most

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[34] Bachmann & Rothenberg (1980) p. 227.

[35] Hauptmann (1985) p. 62ff.

[36] Huebner, J.S. (1969); Huebner, J.S. & Sato, M.

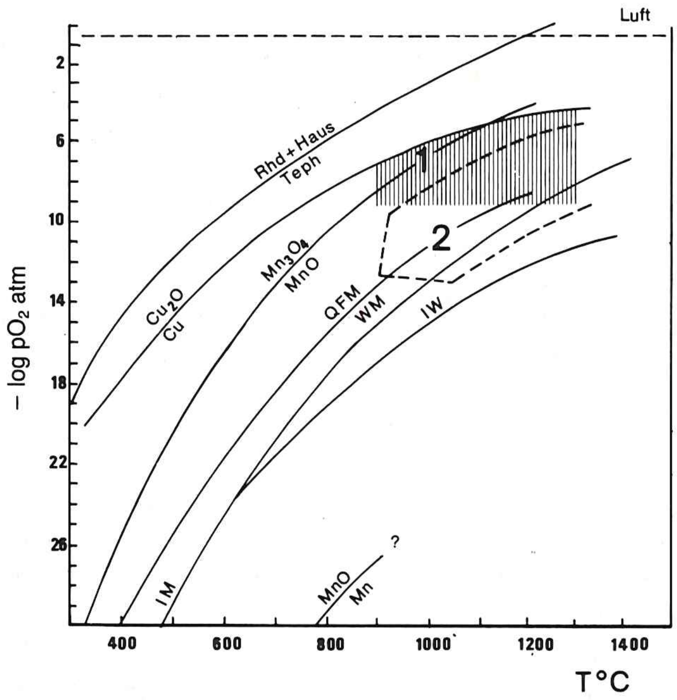

Fig. 9: Estimated oxygen/temperature ranges (pO_2/T) of copper slags from Jordan, shown in the pO_2/T diagrams of the systems Mn-Si-O and Cu-O (1).
Teph-Rhd = tephroite - rhodonite + hausmannite.
For comparison the stability range of iron-rich slags (2) together with appropriate buffer equilibria of the system Fe-Si-O is shown.
QFM = quartz + magnetite - fayalite
IW = iron - wuestite
Wm = wuestite - magnetite
(after data from Huebner, Huebner & Sato, Abs-Wurmbach *et. al.*, Eugster & Wones).

frequent reason for the use of manganese fluxes in archaeometallurgy.[37] Otherwise, at minimal temperatures of around 1200-1250°C (as determined for the Jordanian slags), the formation of manganese-silicate slag with the main component tephroite is possible — in contrast to iron-silicate melts — even when air enters the furnace[38]. The crystallization of manganese oxide is almost entirely suppressed, which has a decisive effect on the separation of the metal from the slag. The separation of iron oxides (magnetite) is feared in iron-rich slag[39] because at high temperatures the slag becomes very viscous and aggravates the separation of the metal.

Copper smelting in the area of Feinan, on the basis of the available finds, seems to have taken place in shallow furnaces during the Early Bronze Age, and the point just mentioned is of great importance because here the oxygen content would certainly be higher than in the early shaft furnances of the later periods. This hypothesis is highlighted by the results of pyrotechnical experiments which Tylecote and Boydell conducted, who deduced that a good, i.e. iron-free copper could only be produced in shallow smelting hearths on the pattern presumed to have been used in Timna‘[40]. The authors emphasize here the difficulties of copper smelting processes at high temperatures: thus, with the high CO_2 content in the furnace, the reduction to copper without problems is possible, but a separation from the slag can be difficult because of the crystallization of magnetite.

(1970); Eugster, H.P. & Wones, D.R. (1962).

[37] Bachmann (1982); Steinberg, A. & Koucky, F. (1974).

[38] Abs-Wurmbach, I. *et al.* (1983).

[39] Tafel, V. (1951) p. 319-325.

[40] Tylecote, R.F. & Boydell, P.J., in: Rothenberg, B. (1980).

Summary

The results of the surveys in the area of Feinan, Khirbet en-Naḥas and Wadi el-Jariye on the eastern part of Wadi ʻArabah showed that from the Chalcolithic Period through nearly all of the succeeding ages up to the Roman Period, presumably the largest volume of copper produced in the entire southeastern Mediterranean was produced in this area. This can amount to, according to the first cautious estimation, several thousand tons of metal. The main periods of activities were the Iron Age IIC and the 1st to 4th centuries A.D.

A new discovery is the Chalcolithic and the voluminous Early Bronze Age copper production which forms an extraordinarily new aspect with regard to the origin of all the copper and bronze findings in Transjordan and Palestine. The copper deposits in the Feinan area have a key position as a source for this metal. No provenance studies have been carried out as yet, but the correlation of the ores from Feinan with copper artefacts using trace element analysis and lead isotope analysis is under study.

At present, reconstruction of archaeometallurgical processes can be accomplished only gradually, based upon the chemo-physical study of the sites and their finds. Thus, further scientific investigations of slags and excavations of smelting sites are planned, and here the dating by archaeological and physical methods is of the greatest importance.

The investigation of copper ores and slags has shown that in the early periods of copper production up to the beginning of the Roman Period, copper ore was mined and smelted together with manganese ore. Manganese ore was naturally intergrown with the copper ore and not consciously added as a flux. On the basis of the location of the Roman mines in the manganese-free areas, we must assume, however, that the furnaces were then intentionally charged with manganese ore in order to attain the desired composition of the slag.

The chemo-physical characterization of the manganese silicate slags found in the project area shed light on the smelting conditions which show distinctions and advantages to smelting processes with the production of iron-rich slag. Manganese-rich slag may be formed under more oxidizing conditions. The formation of undesired oxides and metals is suppressed.

A further result is the observation that the chemical and mineralogical composition of slag (for example the copper content) and the macroscopic typology could only be used in a few cases to reconstruct the history of technical developments.

Numerous difficulties connected with copper smelting experiments carried out in recent times in which iron oxide was used for fluxing include the unintentional precipitation of iron in copper, and magnetite-rich slag[41]. Considering this, it seems likely that the old smelters in the Feinan area probably enjoyed a considerable technological advantage in comparison to other copper producing centres owing to the availability of manganese ore.

If one compares the rich areas of the copper deposit which was mined in the early periods with the low-grade ores available to the Romans, an exemplary situation of a progressive lack of raw materials is recognized. It is this predicament which fostered new technologies and fostered the further development of mining and smelting.

By means of the new findings regarding copper production in the area of Feinan, Khirbet en-Naḥas, and Wadi el-Jariye, the hitherto assumed importance of other mining and smelting districts in this region (e.g. Timnaʻ, or Bir Nasib) must be reconsidered and relativized in terms of the archaeometallurgy and economic history of Palestine.

Acknowledgements

The fieldwork in Feinan was carried

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[41] Tylecote, R.F. & Boydell, P.J. (1978); Merkel, J.F. (1983); Bamberger, M., Bachmann, H.G., Rothenberg, B. & Wincierz, P., in preparation; communication Prof. V. Rychner.

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