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Late Neolithic Copper Smelting in the Arabah

'Tubal-Cain, instructor of every artificer in copper and iron' (Genesis 4:22)

The very beginning of extractive metallurgy, when man realized for the first time that he could turn rock into metal, was one of the most revolutionary events in the intellectual and material history of mankind. However, the location, date and circumstances of this 'creative moment' will probably remain forever unfathomable to science. It is highly interesting that we find the very beginnings of metallurgy deeply engraved in the early Biblical genealogy of Genesis 4 (19–22). The material background of the Cain and Abel story with its emphasis on the 'tiller of the ground' and the 'keeper of sheep' clearly reflects the socio-cultural Neolithic environment. The continuation of the list of descendants of Cain, as the 'fathers' of crafts and arts, leads to the figure of 'Tubal the smith', that eponymous ancestor of metal-workers. The association of iron with Tubal in Genesis 4:22 is certainly not part of the Neolithic environment, but small numbers of metallic objects made from native copper and lead have been excavated and dated to the Late Neolithic (Heskel, 1983). There are even a few small pieces of metallurgical slag from some sites, but to what extent should copper smelting be viewed as one of numerous 'crafts' of the Late Neolithic?

For a great many years, archaeometallurgists have tried to identify workshops of the earliest extractive metallurgy, but nothing representing such an incipient technological phase of copper smelting could hitherto be identified with certainty. For this reason, Chalcolithic copper smelting (see Rothenberg, 1990; Rothenberg, Tylecote and Boydell, 1978; Hauptmann, 1989, 1992) dated to the 4th millennium BC, was so far understood to be the earliest identifiable and datable beginnings of the metal making story in the Southern Levant.

Recent investigations by the present authors are taking the metal story a significant step further, showing that finds in the copper mining region of Timna (South Arabah, Israel) and Sinai, and in the Feinan mining region (North Arabah, Jordan), apparently represent copper smelting already at a late phase of the Neolithic Period. Based on recent excavations along the Nahal (Wadi) Besor, near Qatif (southern Gaza strip) by Gilead and Alon (1988), these finds can now be related to the 6th–5th millennium BC 'Qatifian' Pottery Neolithic culture (Gilead, 1990; Goren, 1990) and represent the first, incipient, step to the extractive metallurgy of copper. Based on our current scientific investigation of the metallurgical remains, we now propose a model of this earliest phase of smelting copper ore to metallic copper. Our identification of a Late Neolithic phase of extractive metallurgy in the region of the Arabah, closes a gap which seemed to have existed in the Levant, compared with developments in the Northern Fertile Crescent. Furthermore, Site F2 – and perhaps also the find spot of the early slag at Site Fidan 4 – is the earliest proper extractive metallurgical workshop identified anywhere.

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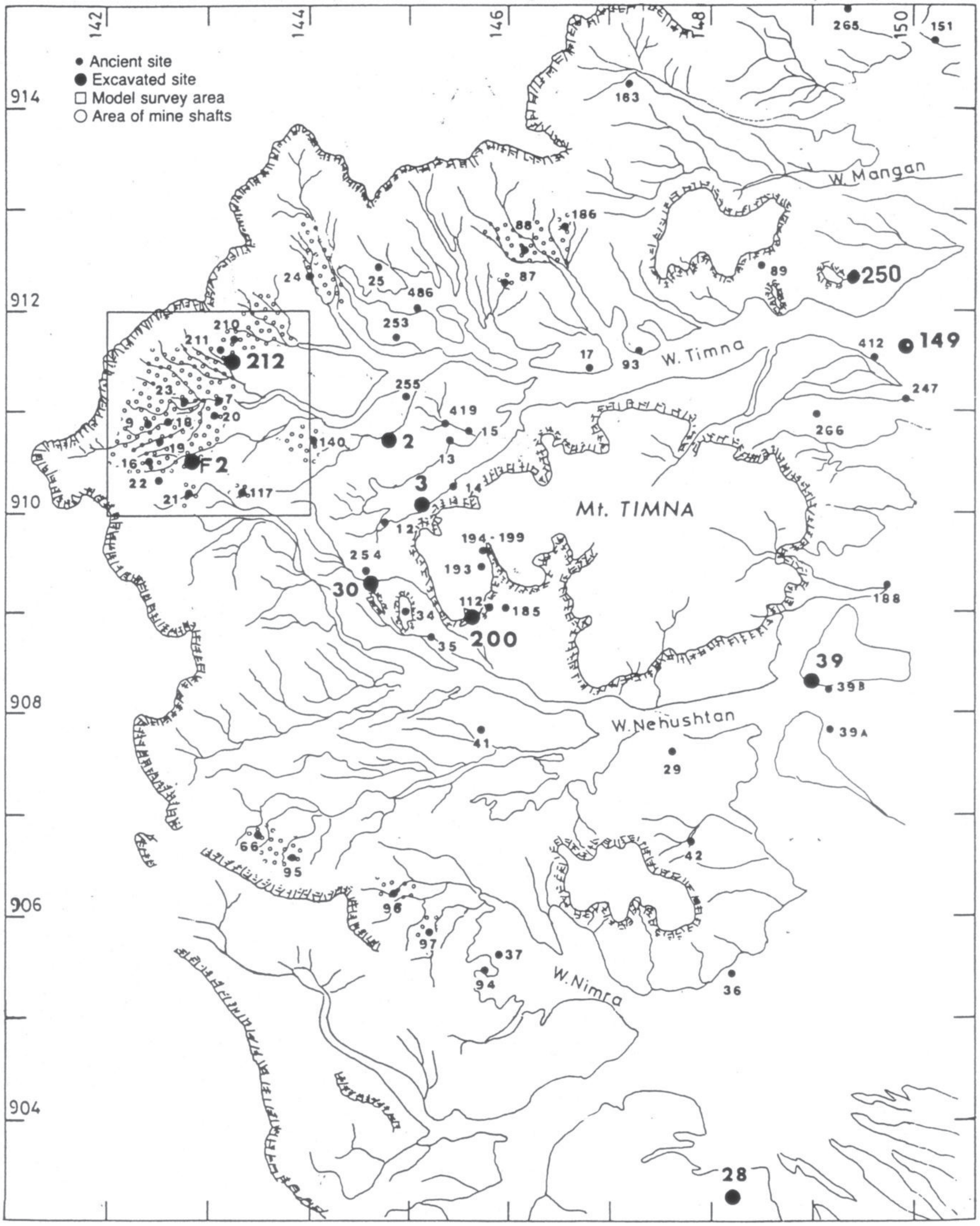


Fig. 1. Map of the Timna Valley with mining and smelting sites. The outlined square indicates the 'Model Survey' area.

The identification of Qatifian copper smelting adds about one millennium to the history of metal in the Levant.

1. A 'Qatifian' Neolithic smelter in the Timna mining area

The Timna Valley (Fig. 1) lies alongside the Arabah, some 30 km north of the Gulf of Eilat-Aqaba. Its ancient copper mines were mainly located in the Late Cretaceous sandstone formation along the foot of the Timna Cliffs, whilst the copper smelting took place well outside the mining area, in the centre of the Timna Valley, at its eastern fringes and in the adjacent region of the Arabah.

The location of the smelters in relation to the mines, reflects mainly logistical problems in the different periods of metallurgical activities in Timna (Fig. 1). Most of the Chalcolithic to Early Bronze Age IV (4th to 3rd millennium BC) smelting sites were located at or near settlements, as near as possible to the sources of water and firewood, i.e. in the nearby Arabah Valley and at the fringes of the Timna Valley. Some smelting also took place at a prehistoric camping site and shrine along the foot of 'King Solomon's Pillars' (around Site 112 and underneath the Egyptian Temple at Site 200).

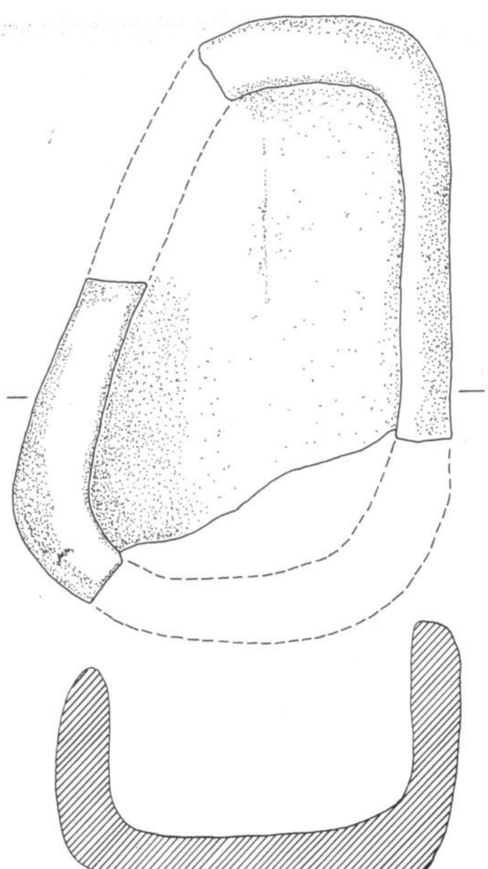
Reflecting a very efficient and quite different logistic system of supplies, and perhaps also aspects of security, the Egyptian New Kingdom smelting camps were set up in a close group west of Mt Timna, also well outside the mining region.

Fig. 2. Site F2 with, in the background, the Timna mines.

1.1 Site F2

No smelting of any kind or time had been found in the actual mining area of Timna until 1976, during our survey of a 'Model area' (Fig. 1), we discovered a small smelting site, which was named 'Site F2', deep in the mining area at the far west of the Timna Valley.[1] Site F2 consisted of a concentration of small slag lumps (estimated at about 5 kg) and copper ore nodules, around a group of stone tools for crushing (Fig. 2). In its centre was a deep mortar (Fig. 3) of a type we had not seen before at Timna, but the type was well-known from other prehistoric sites in Sinai. There was no architecture of any kind.

Fig. 3. Large coarse grain granite stone mortar used for crushing ores and slag.



The slag of Site F2 (Fig. 4) was extremely inhomogeneous in appearance, suggesting a very primitive smelting technology and most of it was in very irregular, rough, porous lumps. However, some surfaces were observed to be very smooth and sinuous whilst some fragments seemed very solid and dense and contained copper prills. From the collection of samples at Site F2, the general impression is that the slag was very diverse.

Fig. 4. Typical 'nodular' slag from Site F2.

Among the finds of slag were also slagged lumps of sandy soil, suggesting that smelting took place in a very shallow hole in the ground, without the use of stones or furnace lining: the earliest type of furnace discussed by Tylecote (1962: Fig. 3b). There were also a few fragments of small tuyeres (Fig. 5), apparently made by simply attaching a handful of sandy clay mortar to the nozzle of the bellows for protection against the fire and heat of the 'furnace'. These tuyeres (outer diameter 5–6 cm, length c. 4 cm, air hole diameter c. 1.5 cm) were the smallest ever seen in the Arabah.

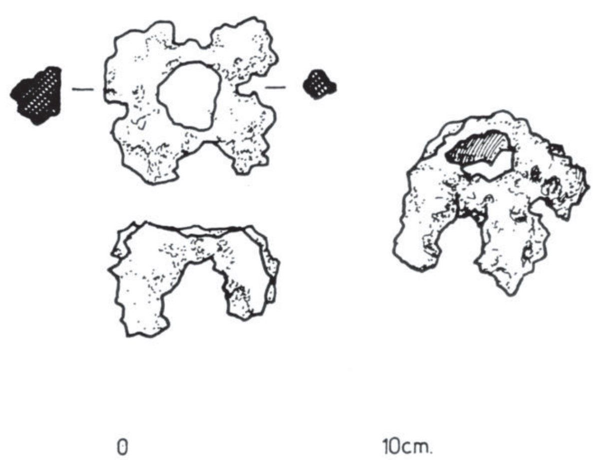


Fig. 5. Restored tuyere from Timna site F2.

In our survey of 1976, we found at Site F2, about 20 fragile, poorly fired ceramic sherds of a type not previously seen in the Arabah. These were mainly body sherds, but there were also fragments of simple rims of a crude bowl or holemouth jar, and the thick flat base of a large vessel, probably from the same holemouth jar. Petrographic studies of the sherds by J. Glass showed a coarse arkosic ware with abundant vegetal temper, indicative of the earliest pottery of the region (Glass and Ordentlich, in press).

Considering the pottery as well as the character of the few flint objects found at Site F2, and especially the small quantity of heterogeneous slag at the site, we began to interpret these remains as representing some of the very earliest encountered in our many years of archaeometallurgical surveying.[2] The fact that Site F2 was located next to a quite extensive area of primitive pit-mining (Model Survey Areas A and G in Conrad and Rothenberg, 1980: Abb. 44–6), completed the so far unique picture of a coherent prehistoric mining and smelting enterprise, as yet found nowhere else. However, the unusual location of Site F2, the character of its pottery, flints and primitive metallurgy, left the chronological and cultural context and the extractive technology of Site F2 as an enigma in the overall picture of the copper industries of the Arabah and Sinai – and indeed the Levant – and as a challenge for further research.[3]

We started this new line of inquiry by rechecking the archaeological records and find boxes of our Arabah and Sinai surveys of the 1960's and 1970's for any other pottery, flints and slag lumps similar to the specimens from Site F2. The result was the realisation that there seems to be a thin spread of similar assemblages of material from sites in the Southern Arabah and South Sinai, to be understood as evidence that the 'F2 Phenomena' – now proposed to belong to the 'Qatifian Neolithic' Period (see below) – was indeed a fairly widespread development of considerable culture-historical significance.

1.2 The 'Qatifian' Late Neolithic culture and the beginnings of metallurgy in the Arabah

Excavations by Gilead and Alon (1988) in the Nahal (Wadi) Besor area, in the southern Gaza strip near Qatif, identified a distinct 'Qatifian' Late Pottery Neolithic culture (Gilead, 1990). Calibrated C14 determinations date the Qatifian culture from the middle of the 6th millennium to most of the 5th millennium BC.

One uncalibrated C14 date for a Qatifian site (Qatif Y-3) 4090 ± 89 b.c. (Gilead and Alon 1988: 129), and several uncalibrated dates from pre-Ghassulian, apparently Qatifian, layers of Teleilat Ghassul, excavated by Hennesy (1989) from 4600 to 4400 b.c. (Goren, 1900: 104–6), when calibrated cover part of the 6th and much of the 5th millennium BC, which seems to us the right chronological range for the Qatifian Neolithic phase. The calibrated C14 date of 5500–5270 BC for a 'Pottery Neolithic' site in Wadi Feinan (Northern Arabah, Jordan) recently published by Hauptmann (1989: 119) is well in line with the Qatifian dates quoted above.

In recent papers, Gilead (1990) and Goren (1990) outlined the characteristics of the Qatifian artifacts[4] and the place of the Qatifian Neolithic culture in the culture-historical developments of the Negev and Sinai and its transition to the Chalcolithic period. The most conspicuous element of the Qatifian, of decisive relevance for the smelters of the Arabah and Sinai, is the typology and petrography of its pottery. Gilead and Goren listed a rather limited range of pottery types, mainly bowls, jars and holemouth vessels with thick bases and flaring loop handles, as criteria of the Qatifian pottery. Goren (1990: 101, 103) states, 'The pottery is of low quality and very crumbly. All vessels were made by hand using coils, the traces of which can still be seen. The clay used for producing these vessels was mixed with large amounts of straw and coarse grits, which causes the surface of the vessel to be porous and rough . . . All the pottery . . . is characterized by a dark core, due to poor firing and a high content of vegetal components in the raw materials'. The pottery of the Qatifian Late Neolithic culture is quite distinct from any other early pottery of the region and its characteristics are evidently of chronological significance.

The typology and petrography of the pottery of Site F2 established its great similarity to the Qatifian ware, though the matrix of the latter was of course different from the local Arabah ware. Considering the incipient copper metallurgy of Site F2, together with the distinct Qatifian pottery characteristics and stone tools, Site F2 evidently belongs to the Qatifian Pottery Neolithic culture of the 6th–5th millennium BC, representing the Neolithic beginnings of extractive metallurgy in the Levant.

2. Qatifian Neolithic copper smelting in the Feinan mining region (Northern Arabah, Jordan)

The earliest metallurgy from the ancient mining region of Feinan, represented by finds from Site Fidan 4 (Hauptmann, 1991: 411), was dated by pottery to the Chalcolithic Period (Raikes, 1980: 55; Weisgerber in Hauptmann et al. 1985: 185–8; Hauptmann 1989: 132). Hauptmann closely correlated Fidan 4 to the Late Chalcolithic Ghassul-Beersheba copper working sites and considered this correlation as a supporting dating evidence for Fedan 4 (Hauptmann, 1989: 122, 126).

Based on this dating and his detailed studies of the metallurgical finds, Hauptmann proposed a new model of Chalcolithic copper smelting involving 'solid state' smelting of copper ore and perhaps even a 'slagless metallurgy' (Hauptmann, 1991: 403; 1989: 123–6).[5]

2.1 Qatifian at Fidan 4 and Site F2

Site Fidan 4 was discovered in 1976 by T. D. Raikes (1980: 55, marked 'Fidan E') who also reported some slag at an unspecified location at the site. By comparison with pottery collected at Tell Magass-Aqaba, Raikes dated the site to the Chalcolithic period. This date was recently confirmed by Hauptmann (1991: 401) based on pottery collected at Fidan 4 (Hauptmann et al. 1985; Khalil, 1988).

Unfortunately, neither Raikes nor Hauptmann provided complete archaeological information about the correlation between the pottery, flint and slag finds and the actual (unexcavated) settlement at Fidan 4. This site was reported by Raikes as 'a small town . . . possibly about 4 acres', with numerous flints and much pottery, but the find circumstances of the metallurgical remains are not mentioned. Hauptmann (1989: 122) wrote: '. . . relics of Chalcolithic copper production such as ores, slags and copper prills were discovered in a settlement on top of a plateau'. Since Raikes and Hauptmann refer only to surface finds among the ruins of an unexcavated settlement, we must keep in mind that surface finds of slag are not necessarily dated by the ruins and the finds of the Fidan 4 settlement. We therefore refer here only to the pottery published by Hauptmann (1986) in relation to the slag finds at Fidan, assuming both were found in the same archaeological context.

I. Gilead of Ben Gurion University, Beer Sheva, was offered the opportunity to inspect the finds from Fidan and other pottery finds from the Feinan region at the Deutsches Bergbau Museum at Bochum. His recent assessment of the pottery from Fidan 4, which has now been published (Gilead, 1990: 60) is that the Wadi Fidan 4 pottery is '. . . undoubtedly a local version of the Qatif-P14 tradition . . . the archaeological entity that prevailed in the northern Negev at the turn of the fifth millennium B.C.'

We did not at first relate the change of identification and dating of the Fidan 4 pottery – from Late Chalcolithic to Qatifian Pottery Neolithic – to our finds at Site F2. It was only after the recent completion of the petrographic investigation of the Arabah and Sinai pottery by J. Glass, discussed above, the comprehensive publications by Gilead (1988; 1990), and especially the petrographic study by Goren (1990: 102–5) of pottery from Wadi Fidan, Khirbet e-Nakhas and Feinan, that it became clear that, together with Fidan 4, Site F2 has to be identified as a Qatifian Pottery Neolithic site. The new identification of Wadi Fidan 4 with copper smelting as a Qatifian Pottery Neolithic site, apparently one of several in the Feinan region (Hauptmann, 1991: 401; Goren 1990: 102) and the rather unusual characteristics of their metallurgical slag, also apparent at Site F2, now strongly support our identification of Site F2 as a Qatifian Late Neolithic copper smelter.

3. The Qatifian Neolithic extractive metallurgy at Site F2

Slag samples from Site F2 were investigated using the new JEOL Superprobe (Electron Probe Microanalysis) facility at the Wolfson Archaeological Science Laboratory at the Institute of Archaeology, University College London. Microanalysis has been used to investigate a random selection of twelve samples of the distinctive slag from the earliest archaeological context at Site F2. Each sample has had up to 10 separate, microscopic points analyzed. The following elements are measured quantitatively at each point: Cu, Fe, Mn, Mg, Al, Si, As, S, Ca, Ni, Pb, Zn, P, Ti and Ba. In contrast to bulk chemical analysis and phase analyses of metallurgical slag, this microanalytical approach is quite different in that microscopic mixtures of individual phases in the slag can be identified. This is very important for the early, heterogeneous slag samples because fragments of ore entrapped in the slag can be analyzed. Thus, it is possible to determine what ores were actually charged into the smelting furnace. Photographs of the microstructures, along with the point analyses, document the relationships between ore reduction, slag formation and metal product compositions. From these randomly selected samples of slag it is possible to infer a rather primitive or unsophisticated technology which appears to be at a stage near the threshold of iron ore flux utilization in copper smelting.

From the microanalytical investigation, two types of slag from Site F2 have been identified and simply classified as either glassy or crystalline. This distinction in microstructure, however, is not readily apparent in the outward appearance of the small, irregular lumps of slag from the site. Although the glassy slag compositions with about 10–15% calcium, 20–25% iron, 20–25% silica would approximate pyroxene in composition, there are no actual crystals of pyroxene (for example, hedenbergite, $CaFeSi_2O_6$). Nevertheless, all of the slag samples do have variable concentrations of iron. Through microanalysis (Fig. 6) it is possible to document numerous entrapped grains of copper ore as well as copper prills in the glassy slag. There are also numerous grains of unreacted quartz clustered in the copper ore fragments. Point analyses of the copper ore fragments indicate about 20% copper and 40% silica. Several of the glassy slag samples are attached to ceramic which is interpreted as furnace remains. In laboratory remelting experiments under carbon, the glassy slag melts at about 1250° C.

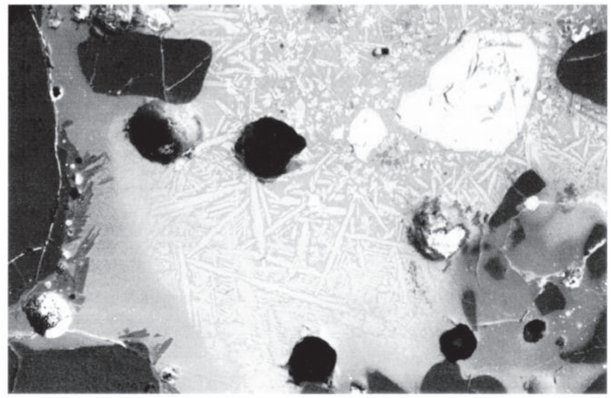


Fig. 6. The composition of the slag varies from area to area as shown in this backscatter image. These variations are documented by microanalysis.

Alternatively, the second type of slag is crystalline with crystals of fayalite (Fe_2SiO_4) in approximately the same matrix of pyroxene-glass. In a laboratory furnace, the crystalline slag is observed to melt at 1100–1150° C. Bulk analysis of one slag sample was done with Inductively Coupled Plasma Emission Spectroscopy (ICP). The major constituents were 36.7% Fe, 3.17% CaO and 22.0% SiO_2. The copper was low at 0.72% reflecting the inferred low viscosity due to the high iron composition of this slag specimen. Appropriate additions of iron ore flux, along with the copper ore characteristically found at Timna, represents the fundamental step toward increasing the small quantities of metal recoverable as prills from the slag by crushing.

Microanalysis of the crystalline slag revealed distinct fragments of iron oxides which are interpreted as reacting flux. Away from these iron oxide inclusions, the fayalite crystals diminish in quantity as the composition in a single lump of slag can grade into areas of glassy composition with higher melting temperatures. Figure 6 illustrates a good example of heterogeneous slag of variable compositions which can be directly related to the reaction of iron oxides in specific areas. The whole furnace charge was not molten, due to the variable slag compositions. For a meaningful increase in copper production, the slag should be of a composition which would allow the microscopic, disseminated copper prills to merge into larger sizes for recovery by hand from the crushed slag.

Whether iron ore had actually been added deliberately or not is still in question. While there are distinct fragments of iron oxides in the crystalline slag samples, there are also fragments of mixtures of copper and iron phases in other entrapped ore inclusions. At Timna, most ore nodules are distinctively green in colour, but some examples have quite recognizable combinations of the green malachite ($CuCO_3.Cu(OH)_2$) with the red-coloured hematite (Fe_2O_3). The 'ores' charged into the smelting furnace at Site F2 do not seem to have been adequately sorted. This mixture of copper ore, iron ore and mixed copper/iron ore is interpreted as somewhat 'accidental', more representative of the available 'ores' at Timna. Due to the presence of significant concentrations of iron in all twelve of the analyzed slag samples, the documentation of entrapped iron oxides, as well as numerous fayalite crystals in four of the twelve slag samples, iron ore was definitely added with copper ore. This could represent an early attempt to produce an appropriate copper ore-to-flux ratio. Nevertheless, iron ore was not added sufficiently or consistently along with the copper ore. Our overall impression is that the mixtures of 'ores' are accidental and not controlled.

Visible copper prills with diameters greater than about 1mm in the crystalline slag represent the only recoverable product from smelting at Site F2. Numerous prills of various sizes entrapped in the slag have been analyzed. The iron concentrations in the copper prills range up to about 3%. Lead is also present in minor concentrations. One piece of copper metal weighing several grammes collected from the site was analyzed. The results from microanalysis for this spill of metal were 95% copper, 3.5% iron, 0.3% lead and 0.1% arsenic. These concentrations would be appropriate for local metal. Previous analytical work by Craddock (1988) on a pin found at the site reported higher levels of arsenic and antimony. This pin is interpreted as an imported, finished object.

This stage of Late Neolithic or Qatifian extractive metallurgy seems far less advanced than that represented at Timna Site 39 dated to the Late Chalcolithic. Bachmann (1978: 21) reported that the slag from Timna 39 always had fayalite associated with oxides of the spinel type, such as magnetite. Although some 'trial-and-error' nature of the Chalcolithic smelting process is apparent, there seems much more consistent use of iron ore flux. This is not so at Site F2 where the concentrations of iron and calcium are more variable and the slag melting temperatures higher with the pyroxene-type compositions. Often the contributions of calcium in slag have been attributed to calcium in the ore or deliberate fluxing but, based on the low calcium concentrations of the entrapped ore compositions from the slag, this is unlikely. Smelting experiments by Merkel (1990) suggest fuel ash alone is sufficient to account for most of the calcium in the slag. As with quartz gangue in the copper ore, excess calcium from fuel ash also required additional flux to achieve appropriate lower melting temperature slag compositions. Excess calcium from fuel ash suggests very inexperienced workers using too much fuel trying to smelt copper.

Our current research into the process metallurgy of the prehistoric periods, even back into the Late Neolithic, indicates that there were specific technological achievements in copper smelting which occurred in a step-wise manner. The exact point of departure for each advance will be difficult to establish, but the effects of the developing use of flux and other process-related parameters in copper smelting are discernible in various sites. There will be chronological as well as geographic differences. The essential point is that as more prehistoric copper smelting sites are investigated, we continue to find more diversity which thus allows more technological detail to be placed into perspective. Metallurgical developments must be understood in terms of their archaeological context. Thus, the Late Neolithic context should now be discussed with the inclusion of the very beginnings of copper smelting along with the other more recognized arts and crafts.

Beno Rothenberg and John Merkel

Notes

1. After total removal of all surface finds during the initial survey, we returned to Site F2 in the autumn of 1976 and excavated most of the c. 20m-long ridge down to bedrock. This excavation was supervised by Paul Craddock and produced additional slag, pottery and flints, but no architectural remains. At the far end of the ridge at F2, a small circular stone setting of a fireplace, containing mainly wood ash, was uncovered. Stratigraphically, this stone setting was clearly intrusive, and in fact was dated by C14 to the Egyptian New Kingdom. A preliminary review of F2 was included in Rothenberg (1990: 6–9). Site F2 will be published in full by B. Rothenberg and J. Merkel, *The Prehistory of Copper in the Arabah: The earliest steps to copper metallurgy, from its prehistoric beginnings to incipient industrial copper production,* IAMS Monograph 2 (forthcoming).
2. Because of the indigenous character of the local population in the semi-arid region of the Arabah and Sinai, we propose to use a more suitable chronological terminology put forward by Rothenberg and Glass (1992) for the regional technological and cultural developments: The Sinai-Arabah Copper Age – Early Phase (late Neolithic to Early Bronze I), Middle Phase (Early Bronze II to Early Bronze III), Late Phase (Early Bronze IV and later). The petrographic investigations showed Site F2 to be the key site for the beginning of the Early Phase. See also Rothenberg (1990) for F2 as the earliest site of extractive metallurgy in Timna.
3. Our IAMS Prehistoric Metallurgy Project had been established early in 1994, when we recognized the significance of the Qatifian Neolithic remains for the prehistory of metallurgy. We expect to conclude this research project and its publication in 1995. We would like to express here our gratitude to Mr Felix Posen, London, for his encouragement and generous support of this project and its forthcoming publication (IAMS Monograph 2).
4. Since the totally different environments of Nahal Besor and the arid region of the Arabah and Sinai must have required a different assemblage or 'tool kit' of flints, we shall not deal in the present paper with the Qatifian flint assemblage in relation to our finds in the Arabah and Sinai. One diagnostic element in the Nahal Besor coastal area was a typical sickle blade – which would, of course, be out of place in Timna or South Sinai.
5. It seems rather difficult by definition to consider simultaneously a 'solid state' smelting process as well as 'slagless copper smelting' as has been recently proposed. Solid state reduction is, of course, possible for copper ores. However, experiments have shown that the metallic product would be very finely dispersed, and thus very difficult to recover by crushing and hand-sorting. Furthermore, there are many examples of heterogeneous slag where at least part of the mass has been molten. Appropriate slag compositions enable the recovery by hand of copper prills (>0.5mm). Based upon published evidence, we do not accept models for 'solid state' smelting of copper ores. 'Slagless smelting' of copper ore, as proposed by Craddock and Meeks (1987: 202) seems to us a misconception deriving from a lack of slag finds where such finds would have been expected. Even the smelting of the highest grade copper oxide ores leaves slag residue due to the fuel ash, high temperatures and poor quality refractory materials used as crucibles or furnaces. The residue from small-scale copper smelting does occur. Site F2 is exemplary.

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Sophisticated Roman Recovery Techniques for Gold

In his *Naturalis Historia*, Pliny the Elder has told us much about the state of science and technology at his time, i.e. the first century AD. The industrious author was well aware of the writings of his contemporaries, though he very rarely acknowledged them. For the wealth of material he wanted to communicate, he not only had access to what can only be termed a data base in the form of elaborately filed notes and quotations, but also to scores of scribes to whom he could dictate his books. Translations of Pliny's *Naturalis Historia* are numerous. However, some sentences are difficult to understand, others are even unintelligible. Therefore, a study group in Germany, consisting of linguists, scientists, technicians and historians has been engaged for more than 15 years in retranslating and reinterpreting Pliny's texts on metals.

When Pliny wrote about gold mining and beneficiation, he wrote with some authority. After all, he was procurator in Hispania Tarraconensis from AD 72 to 74. Iberia was once one of the main sources of gold for the Roman Empire, though not the only one. Bird (1984) discusses references which Pliny made to several gold mining and extraction techniques. These techniques include hushing, sluicing and the unique 'arrugia'-practice which is the systematic preparation of whole mountains by tunnelling for subsequent erosion by man-made floods from gigantic water reservoirs. Not mentioned by Bird (ibid) are Pliny's remarks that, for purification purposes, gold has to be 'cooked' (i.e. smelted) with lead. According to H. Rackham, this passage (*Nat. Hist.* XXXV, 60) is translated in English as '. . . for the purpose of purifying it is roasted with lead'. Furthermore, some gold ores have to be crushed and washed, as well as roasted and the smelting of the ore with lead produces a silver-colour alloy. This alloy would be considered a lead bullion in modern terminology. According to Pliny, the slag has to be crushed and returned (recycled) to the furnace. Using the Rackham translation again, this passage (*Nat. Hist.* XXXV, 69) is extremely interesting:

'The substance dug out is crushed, washed, fired and ground to a soft powder. The powder from the mortar is called the "scudes" and the silver that comes out from the furnace is the "sweat"; the dirt thrown out of the smelting furnace in the case of every metal is called "scoria", slag. In the case of gold the scoria is pounded and fired a second time; the crucibles for this are made of "tasconium", which is a white earth resembling clay. No other earth can stand the blast of air, the fire, or the intensely hot material.

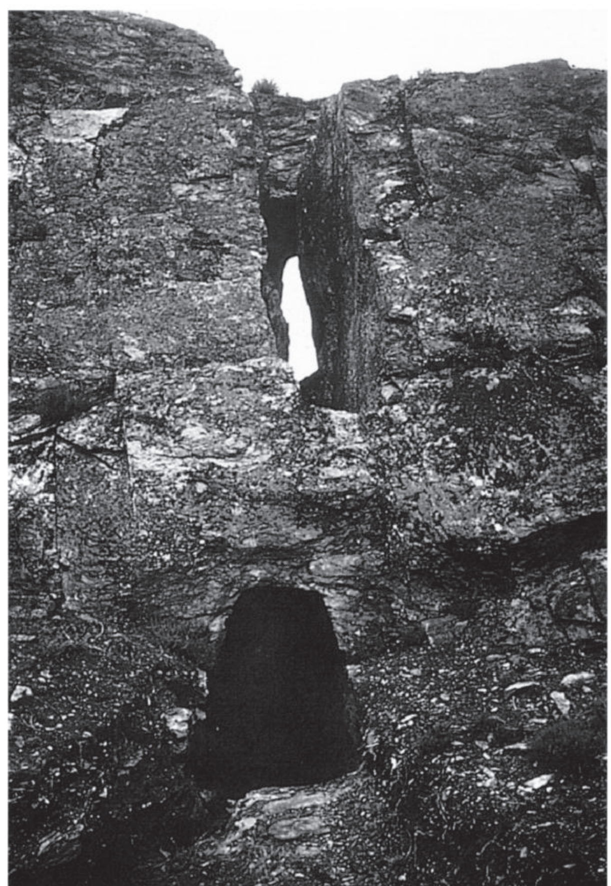

Fig. 1. Adits to Roman open cast gold mine: Três Minas, Portugal.