Late Neolithic and Chalcolithic copper smelting at the Yotvata oasis (south-west Arabah)

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Site 44 at Yotvata, its discovery and excavation

Yotvata is the modern name of an oasis located in the Arabah rift valley (G.R.155.923), about 40 km north of the Gulf of Eilat/Aqabah (*Fig. 1*). At the time of the first visit at the site

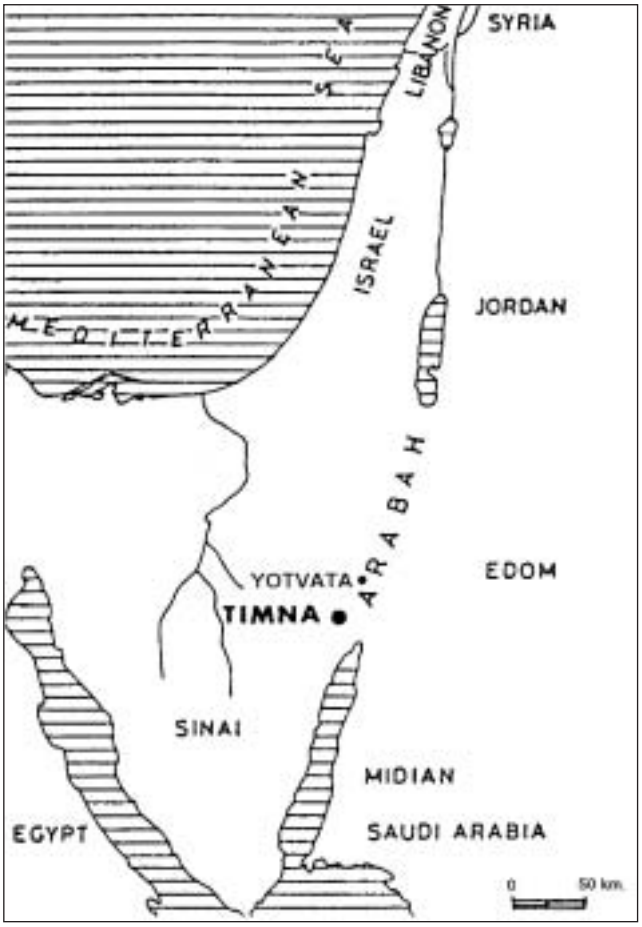


Fig. 1. Map of the Arabah and adjacent regions

by Beno Rothenberg in the early 1950s, the oasis was still called 'Ein Ghadyan[1], a name presumably derived from the nearby Roman station ad-Dianam (Tabula Iteneraria Peutingeriana, Segm.IX, Miller 1962). The oasis consisted of several shallow wells, a grove of date palms and an extensive area of tamarisks. The newly founded Kibbutz settlement was called 'Yotvata', due to the proposed identification of this oasis with "Jotbath, a region with running brooks", Deuteronomy 10:7, (JPS 1999), which finally became the official name of the oasis. Already during this first visit, numerous ancient sites were observed in and around Yotvata, some of which had already been reported by previous explorers (for references cf. Meshel 1993: 1517 and Rothenberg 1967: 139-140). The large number of ancient sites was obviously due to 'Ein Ghadyan being the most important source of water in the southern Arabah as well as an ancient major crossroads. However, its particular importance for us was due to the fact that it was, since early prehistoric times, the only major source of water and fuel for the often large-scale mining and smelting activities in the region, especially in the Timna Valley, the Wadi Amram and on numerous hillsites along the mineralized mountain range of the south-western Arabah, one of which, Site 44, was located at Yotvata itself (Rothenberg 1999).

Site 44 (G.R.15529234), located on top of a hill next to the Kibbutz settlement, was first recorded by Rothenberg in 1956 (*Fig. 2*) and again investigated by Rothenberg's 'Arabah Expedition' in 1960[2] and in 2001[3]. The architecture of this site (*Fig. 3*), and its location on a steep, high cliff overlooking the oasis, indicated that it was a stronghold to guard this rich source of water and wood. Related to the architec-

Fig. 2. Hill site 44 at Yotvata

Fig. 3. Architectural features (1960) on the hilltop

tural features of the site (see below, on Meshel's excavation), there was pottery very similar to the pottery found at the copper production sites at Timna, which is dated to Egyptian New Kingdom. There were also some Roman and Nabatean sherds, presumably related to tombs of this period on the hill[4].

On the flat hilltop, mainly on its east side, many small lumps of slag were found dispersed - estimated 30 kg[5] - evidently indicating copper smelting at the site. Flint tools and pottery, found among the slag, were at the time dated to the Chalcolithic period (Rothenberg 1967: 141; Rothenberg & Glass 1992: 152; Meshel 1993: 1517). Recent re-investigation of the finds also identified Late Pottery Neolithic sherds and flints[6] (see below). However, since the slag, flints and the finds were mostly found within the fortified area of the hilltop, dated to the 19th and 20th Dynasties of the Egyptian New Kingdom, it remained difficult to be sure about the date of the metallurgical activities, and whether there was one or several different periods of copper smelting at the site. This problem remained essentially unsolved even after the stratigraphic excavation by Meshel (Meshel 1993), who assumed that some of the metallurgical remains found inside the casemate fortress may indicate local smelting by the Egyptian New Kingdom inhabitants of the fortress (Meshel 1993: 1518). The solution of this problem was one of the main objectives of our visit at the site in 2001 and, foremost, the recent metallurgical investigations reported in the following.

Site 44 was excavated in 1976 by Zeev Meshel, Tel Aviv University (Meshel 1993: 1518-1519; 1990: 37-39). This excavation produced important stratigraphic information and a clear picture of the architectural remains (*Fig. 4*). The summit of the hill, isolated on three sides by steep cliffs, was only fortified on its western side, protecting the easy approach from the adjacent hills by a casemate wall, with rooms of irregular size (1.9-2.4 m) and varying length. The casemate wall's foundation, about one meter high, was built of undressed stones, topped by sun-dried mud bricks. It was built onto the flat surface of the site, without any foundation trenches. Bedrock or a leveled earthen fill comprised the floor inside the rooms.

About 75 m west of the casemate fortress, an earth-build fence enclosed more of the hill's summit, which the excavator suggested to be possibly of Chalcolithic date (Meshel 1993: 1517). A number of burials of the Classical periods were identified at the site, including a double tomb containing a skeleton and an empty cedar coffin, dated by pottery to the 1st century AD. Some metal jewellery was found with the skeleton[7].

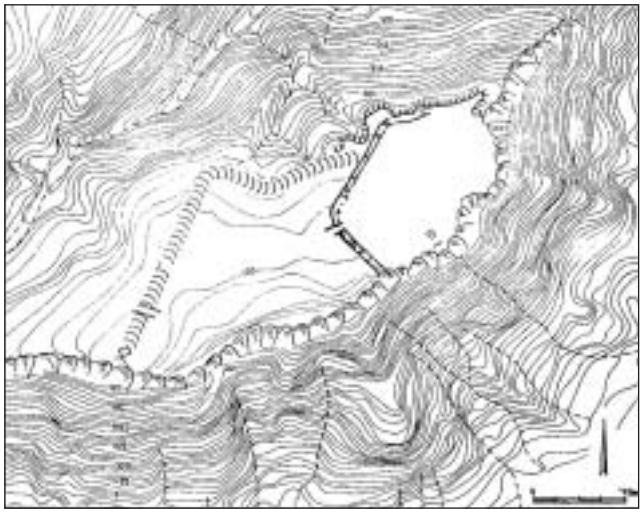


Fig. 4. Plan of the Yotvata hill site after excavation (Meshel 1990)

The excavation of the casemate wall produced a considerable quantity of pottery, including wheel-made storage jars, crude, handmade cooking pots (Negev Ware) and several Midianite sherds. Since the whole pottery assemblage, especially the Midianite ware, was most similar to the pottery found in the Egyptian New Kingdom copper industry of Timna (Rothenberg & Glass 1983: 65-124), the excavator related the "Yotvata fortress ... to the zenith of copper production at Timna" (Meshel 1993: 1518), *i.e.* from the late 14th century to the middle of the 12th century BC.

However, the dating problem of the metallurgical activities at Site 44 became more acute after Meshel's excavation, because the metallurgical remains[8] were found whilst clearing the "floors" inside the casemate rooms and because "in sections cut in the fortress's courtyard a layer of ashes and slag was found against the casemate wall". Meshel accepted these stratigraphic details as evidence for copper smelting by the New Kingdom inhabitants of the casemate fortress (Meshel 1993: 1518). This stratigraphic problem was re-investigated at the site by our team in 2001 and we now suggest another interpretation of this surface against the outside of the casemate wall: the casemate wall was built partly on bedrock and partly on the sandy surface of the hill top. This sandy surface is only a shallow layer of loose sand, covered by very soft wind-blown loess. The heavy wall would obviously settle into the soft surface, and the surface outside the casemate wall appeared to touch the wall at a higher level, *i.e.* appeared, wrongly, to be a floor of stratigraphic significance. We have met a similar situation in excavations in the loess-covered desert region of the Arabah and the Southern Negev.

Already during our earlier surveys at the site, we noticed that the rough slag of Site 44 was totally different from the tapped slag of the New Kingdom smelters at Timna (cf. Rothenberg 1990: 69) and that the stone tools dispersed on the surface of Site 44 were also not of the type common at New Kingdom Timna (cf. Rothenberg 1972: figs. 23-25). Obviously, there was need for closer study of the archaeological situation and, foremost, of the metallurgical remains. From the archaeological point of view it seemed to us that the casemate rooms had been built on top of earlier metallurgical activities, without any previous clearing of the surface. According to Meshel's report, the NK builders took earth from the near vicinity in order to level the floors of their rooms, and we assume that this fill contained earlier remains. In fact, Meshel's excavation report provided the archaeological evidence for this conclusion: "a thin layer of ash[9] that was found in several places in pockets in the bedrock beneath the walls and floors of the later fortress's casemate rooms. An unusual find was a deposit of about twenty grinding stones of different sizes, mostly made of granite, that were hidden in a sealed pit under the later fortress wall". Evidently, these finds are evidence for pre-New Kingdom activities at the site - also assumed by Meshel - but they do not exclude the possibility that also during the New Kingdom

copper was produced or worked at the site. We, therefore, undertook the investigation of the metallurgical remains found at the site and their comparison with other sites of well-dated copper metallurgy in the Arabah.

Besides the dating of the metallurgical activities, the main objective of our investigations was to establish the metallurgical technologies used at Yotvata, whatever the date. During our inspections of the site[10] and also during Meshel's excavation, no smelting installation of any kind was found. In fact, in the excavated casemate rooms no remains or traces of any metallurgical activities *in situ* were identified. We assume that somewhere on the hilltop smelting took place in a simple hole in the ground, as we know from other prehistoric smelting sites in the Arabah, as f.i. Late Neolithic Site F2 (Rothenberg & Merkel 1995; Segal *et al.* 1998) and Chalcolithic Site 39 of Timna (Rothenberg & Merkel 1998; Merkel & Rothenberg 1999). The Chalcolithic 'smelting furnace' at Site 39b, excavated by Rothenberg in 1965 (Rothenberg *et al.* 1978: 13, fig. 15), and lately ^{14}C-dated to the 5th millennium BC (Rothenberg & Merkel 1998), was such a simple hole in the ground, and produced the same type of porous, viscous furnace slag, as found at Yotvata.

Pottery and flint assemblage of Site 44, the archaeological dating evidence

During the survey of Site 44 in the early sixties, pottery and flint were collected on the surface of the site. The flint assemblage comprises 35 artefacts. The knapper used homogenous, fine-grained raw material that varied in colour from light grey to dark brown. However, the majority sustain patina which covers most of the debitage surfaces.

Waste
Within the waste material, flakes and blades appeared in equal numbers (8 each). There are also two chips. The blades are mostly large blanks, probably produced from large cores, while the flakes vary in size and include large as well as small flakes. Three cores were identified: A flake core, a broken blade core and one amorphous core (*Fig. 5:1*).

Tools
Tools (15) make up 43% of the entire assemblage:
The three borers identified are on thick flakes (*Fig. 5:4*).

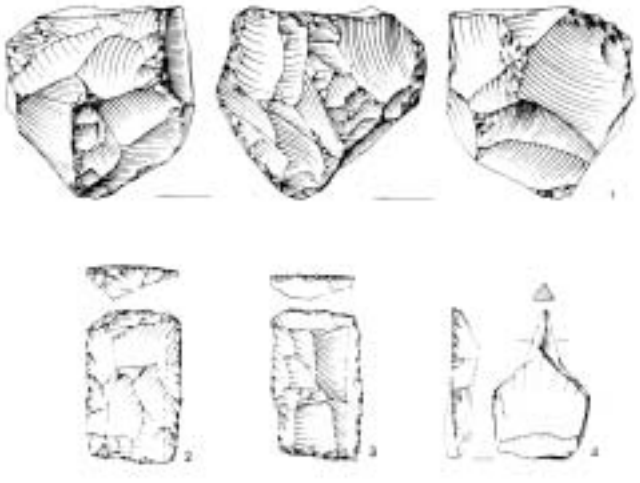


Fig. 5. Flints from Site 44

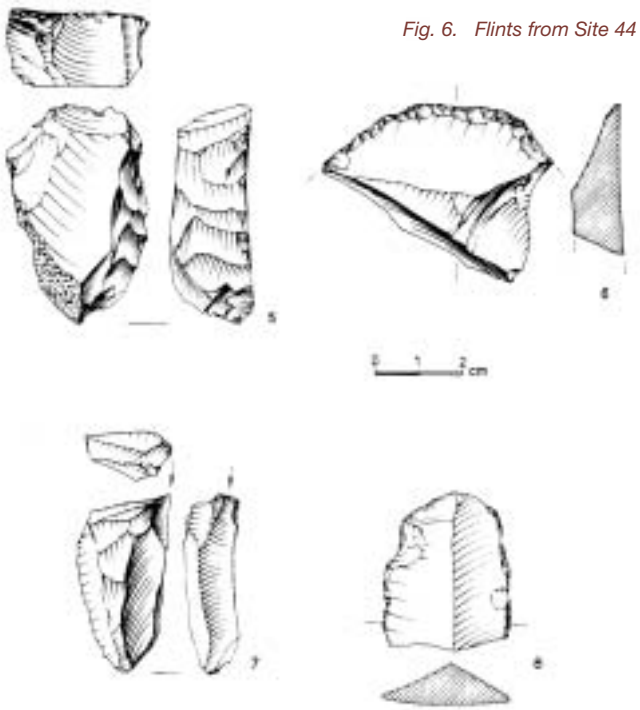


Fig. 6. Flints from Site 44

Their working edges were formed by a large notch on one side and a simple retouch on the other.

The five retouched blades were subdivided into two types, three of them are simple retouched blades, the other two are backed blades (*Fig. 6:8*). The two backed blades are made on wide blanks, over 22 mm, their cross sections triangular in shape.

Two sickle segments were identified, both were shaped on wide blanks (average 1.8 cm). One has a trapezoid cross-section and was backed by semi abrupt retouch. Its distal end is truncated while the proximal is natural (*Fig. 5:3*). Sickle gloss is visible on the working edge. The second sickle (*Fig. 5:2*) is rectangular in shape and relatively thick. Semi abrupt retouch shaped its back and the truncation. The working edge shows irregular retouch.

One of the two scrapers was made of a thick flake, the scraping retouch covers the distal end as well as one of the laterals (*Fig. 6:5*). The second scraper is a broken piece of what could be a fan scraper (*Fig. 6:6*). This identification is based not only on the morphological shape, but also on the light-brown raw material which is not common in this region and was probably brought from the western Negev area.

Pottery
The pottery collected comprises mainly body sherds. However, several rims and one base were among the collection. The pottery was manufactured of local clay tempered by small to medium black and white grits, part of them probably of magmatic origin.

The three sherds that could be defined consist of one bowl, one holemouth jar and one thick base, probably of a storage jar. The bowl (*Fig. 7:1*) is of a V-shaped type. This type of bowls was frequent in the Late Pottery Neolithic as well as in the Chalcolithic assemblage of the region. They occurred in a variety of shapes and sizes, but all have straight walls and a rim diameter almost twice their base diameter.

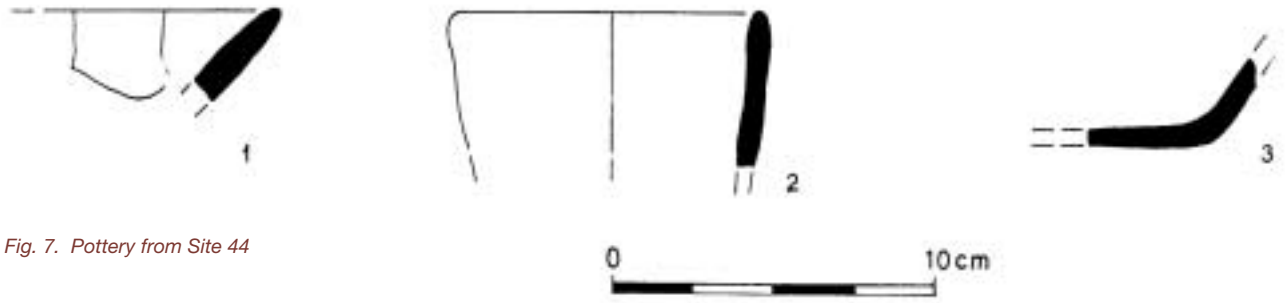


Fig. 7. Pottery from Site 44

The Holemouth jar (*Fig. 7:2*) is of a wide opening variant, which is very common in the Late Pottery Neolithic assemblages, and is characterized by cut rims and a wide opening, even broader than the base diameter. Most of these vessels have washed surfaces and no traces of decoration. Larger Holemouth jars are usually hand made and have a thick base (*Fig. 7.1.3:3*). This type of Holemouth jar is characteristic for the Wadi Rabah assemblages of the southern Levant (Garfinkle 1992: 1999).

Based on the nature of the pottery and the composition of the inclusions, it is possible to identified two ceramic cultures: Several sherds are Chalcolithic, but the majority are pre-Chalcolithic, *i.e.* Late Pottery Neolithic.

The early chronology of Site 44
The flint assemblage from Site 44 is rather small and lacks diagnostic types, but the presence of wide sickle blades among the tools indicates their chrono-cultural assignment. This type of sickle blades has been identified in Late Pottery Neolithic assemblages (Gopher & Gophna 1993), probably close to the transition to the Chalcolithic.

The Neolithic pottery from Yotvata consists of a limited repertoire of types. Notable is the presence of several diagnostic forms that are among the hallmarks of the pre-Chalcolithic cultures and are frequent in such assemblages. Among the types represented at Yotvata are the jars with a wide opening and the deep bowls. The majority of the vessels were manufactured of light clay, ranging in colour from beige to light grey. The surface was treated before firing, and the temper includes small to medium, dark, magmatic and chalky grits. Notably, the chalky grits mostly disappeared due to weathering. A similar material culture was found also in the Uvda valley, in the nearby mountain range west of Timna (Site 124.17, Avner 1990), dated by the excavator to the Neolithic period (Avner *et al.* 1994).

Metallurgical samples and analytical methods

By visual inspection, at Site 44 there was no tapped slag or related 'furnace slag' of the type common at New Kingdom Timna (Rothenberg 1990: 43-45), but only rough, viscous, crushed slag lumps as found previously at the prehistoric smelting sites of the Arabah, like Sites F2, N2, 39a, 39b, 189A and others (Rothenberg 1990: 5-6. table 1; Segal *et al.* 1998; Merkel & Rothenberg 1999).

Visually, the Yotvata slag samples could be divided into three groups (Table 1). Group 1: very small (0.5 - 2 cm), black, with metallic luster, very dense, without holes or pores; Group 2: small (1.5 - 3 cm), internally black, green on the surface and porous. Group 3: larger slag lumps (5 - 8 cm), black and porous (*Fig. 8*). Slag of Group 3 contained copper prills, visible with the naked eye on freshly broken surfaces. Three samples of Group 1 [samples 1-112S, 29-169 and 44-3], four of Group 2 [samples 15-159, 3-111, 44-1 and 44-2] and six of Group 3 [samples 15-155, 10-113S, 118 G.S., 18-139, 118(1) G.S. and 18-139,140] were selected for analytical characterization.

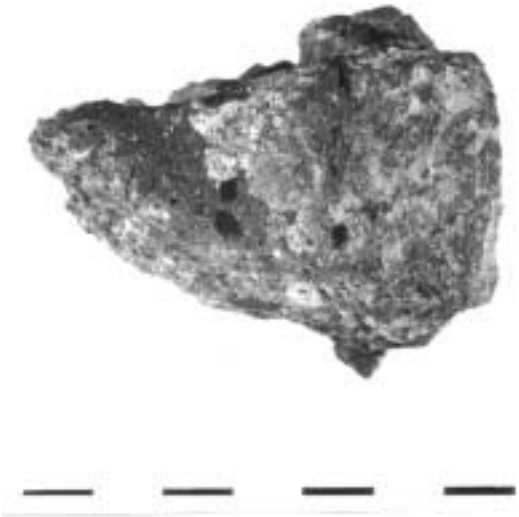


Fig. 8. Slag 118 and 18-139,140 found at Yotvata.

Besides slag, four pieces of nodular copper ore and two copper ingots (*Fig. 9*), found in the excavation by Meshel (*cf. Table 1*), were examined. First the samples were cut, then the sections were mounted in resin, ground and polished. Additional pieces were drilled or crushed and powdered for chemical and mineralogical investigations.

Chemical analyses of slag and copper ingots were made by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES with a Jobine Yvon JY-48 polychromator). Some of the trace elements (cadmium, arsenic, silver, tin, antimony, cerium, thorium and uranium) in slag were analyzed using a Perkin Elmer Sciex Elan 6000 Inductively Coupled Plasma Mass Spectrometer (ICP-MS), equipped with

Fig. 9. Copper ingot 12-148 found at Yotvata.

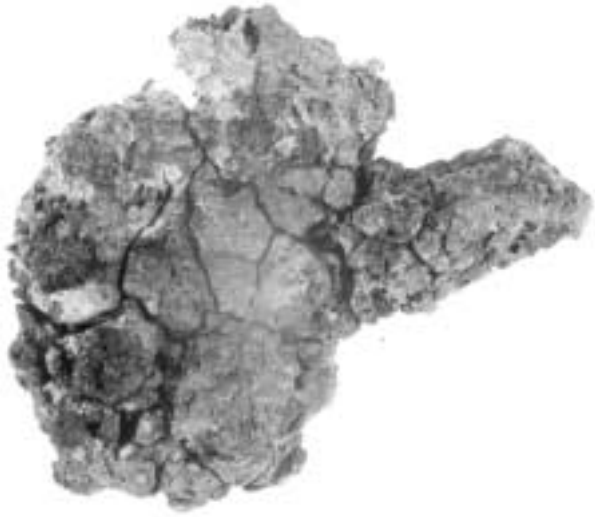


Table 1. Description of finds from Yotvata.

Identity	Size, cm	Description
Ores		
9-116	3	black, green surface
10-113 O	2	green
1-112 O		
9-116a		
Slag		
1-112 S	0.5	black, sub-metallic luster
29-169	2	black, sub-metallic luster
44-3	1.5	black, sub-metallic luster
15-159	2	black, green surface
3-111	1.5	black, green surface
44-1	2-3	black, green surface
44-2	3	black, green surface, white inclusions
15-155	5	black, white inclusions
10-113 S	5	black, attached to crucible?
118 G.S.	7	black, Cu inclusions
18-139	8	black
118(1) G.S.	6	black
18-139,140	6	black
Metal		
12-148	9x7x1.5	Ingot
16-201	5x4	Ingot

flow injection system for sample introduction. Operating procedures for slag analysis are described by Beyth *et al.* (1988) and of metal analysis by Segal *et al.* (1994). The precision or relative standard deviation (RSD) of the analyses is as follows: 1% for major elements, 3% for minor constituents and about 10% for traces.

The mineralogical composition of the slag was examined using a Philips X-ray powder diffraction spectrometer (XRD). Detailed micro-petrographic and mineral chemistry studies were carried out with a Scanning Electron Microscope (JEOL 840), equipped with an Oxford Energy Dispersive Spectrometer (SEM-EDS) and Back Scattered Electron Detector (BEI).

Results

Ores

Only the four ore samples found in Meshel's excavation were analyzed, and these, according to Amit Segev[11] (verbal information), are a type of ore not common in the Timna Valley, but common in the Wadi Amram (south of Timna) and, especially, in Jordan.

Chemical analyses and phase compositions of the ore samples are summarized in *Table 2*. The high-grade ores with copper contents in the range of 14 to 48% are ideally suited for a direct reduction process. The dominant copper mineral in the ore is atacamite, $Cu_2(OH)_3Cl$, followed by cuprite, Cu_2O, and malachite, $Cu_2(OH)_2(CO_3)$. Haematite, alpha-Fe_2O_3, and quartz, SiO_2, were identified as gangue minerals. The ores are low in silica (2 to 4 %), with variable Fe_2O_3 contents (2 to 53%) and very low MnO (< 0.06%). Ore sample 10-113O could have been reduced to copper metal without additional flux (due to its high copper content and low percentage of impurities); the other samples represent a type of ore which would have required the addition of silica to the smelting charge, in order to remove the admixed gangue components by slagging. As will be discussed below, there is, however, no need to conclude, based on the analytical data alone, that silica, *i.e.* quartz, was deliberately added to the charge as a flux.

Ores 10-113O and 1-112O contain sulphur. Petrographic examination showed remnants of chalcocite, Cu_2S. Oxidic ores with minor additions of sulphides are fairly widespread both at Timna (Shlomovich *et al.* 1994; Segev *et al.* 1992: 26) and Feinan (Hauptmann *et al.* 1992). These minor contents of sulphide did not affect the smelting process specific for oxidic ores. There was definitely no need for any preliminary roasting of the ore.

Slag

In the following interpretation of the analytical study of the slag, the ore samples in *Table 2* are seen as representing at least some of the ore used by the Yotvata smelters. With sand of the 'furnace wall'[12], and available oxides (MeO = FeO, MnO, MgO, CaO), slag silicates of pyroxene and/or olivine types could have been formed (ratio MeO/SiO_2 for pyroxenes is 1 and for olivines 2). However, non-equilibrium conditions (reaction time, temperature changes, CO/CO_2-ratio inside the 'furnace' etc.) during the smelting process resulted in the formation of heterogeneous slag. Several of the slag samples on *Table 3* are clearly indicative for the use of ore from the local Timna ore deposits and these are equally heterogeneous[13].

As shown in *Table 3*, the crystalline phases in the slag nearly always include oxides (spinels) in addition to silicates. Apart from the slag minerals that can be determined by X-ray diffraction, non-crystalline glass ("matrix") is most likely also present. Slag with a high content of spinels tends to be viscous, typical for prehistoric smelting. Therefore, since segregation is inhibited, much copper remains "trapped" in the slag and has to be manually separated. The slag sample 118(1) G.S. with the lowest Cu-content analyzed (1.3%), and magnetite as the only crystalline phase identified, has to be interpreted as rapidly cooled slag in which all the silicates apparently solidified as amorphous glass.

Table 2. Chemical composition of ores found at Yotvata.

	Wt %																ppm									
Identity	**SiO_2**	**Al_2O_3**	**CaO**	**MgO**	**Fe_2O_3**	**TiO_2**	**P_2O_5**	**SO_3**	**Cu**	**Mn**	**Pb**	**Co**	**Ni**	**Ba**	**Cr**	**V**	**Sr**	**Cd**	**Be**	**As**	**Ag**	**Sn**	**Sb**	**Ce**	**Mo**	**Th**	**U**	**Phase composition**
9-116	2.0	0.3	0.7	0.2	27.8	0.03	1.8	0.6	38.0	0.002	0.03	0.01	0.01	0.004	<0.001	<0.01	0.01	<1	<1	70	<1	<1	1	2	10	3	1	Atacamite, cuprite, haematite
10-113O	1.6	0.1	0.9	0.1	1.5	0.01	3.0	2.5	46.3	0.059	2.00	0.03	0.03	0.001	<0.001	<0.01	0.07	<1	<1	90	<1	2	<1	3	20	2	1	Atacamite, malachite, quartz
1-112O	3.6	0.4	0.3	0.2	53.4	0.02	0.8	3.1	13.7	0.044	0.04	0.02	0.04	0.011	0.001	<0.01	0.02	<1	2	340	15	220	12	7	60	3	5	Atacamite, cuprite, haematite
9-116a	2.8	0.3	1.0	0.2	13.2	0.03	2.1	0.4	48.4	0.010	0.03	0.01	0.02	0.004	0.001	<0.01	0.01	<1	<1	60	10	6	2	4	9	2	1	Atacamite, cuprite, haematite, quartz

Table 3. Chemical (ICP-AES and MS) and phase composition (XRD and SEM-EDS) of slag from Yotvata.*

	Wt %																ppm									
Identity	**SiO_2**	**Al_2O_3**	**CaO**	**MgO**	**Fe_2O_3**	**TiO_2**	**P_2O_5**	**SO_3**	**Cu**	**Mn**	**Pb**	**Co**	**Ni**	**Ba**	**Cr**	**V**	**Sr**	**Cd**	**Be**	**As**	**Ag**	**Sn**	**Sb**	**Ce**	**Mo**	**Th**	**U**	**Phase composition**
1-112S	28.2	1.6	10.5	1.1	49.7	0.08	0.4	0.7	4.4	0.03	0.25	0.02	0.02	0.05	0.02	0.05	0.16	1	13	47	3	<1	4	12	140	3	32	Magnetite, fayalite.
29-169	39.2	1.6	7.8	0.1	36.9	0.11	0.7	0.6	2.0	3.04	0.15	0.04	0.03	0.07	0.04	0.18	0.07	<1	11	24	<1	2	3	21	92	7	34	Knebelite, (Cu, Mn)-spinels
44-3	42.1	2.6	4.1	<0.1	28.2	0.14	0.6	0.4	2.8	7.55	0.33	0.02	0.03	0.96	0.05	0.03	0.08	<1	18	20	<1	2	4	33	127	8	36	Knebelite, spinels.
15-159	39.4	1.1	11.5	1.0	32.7	0.09	0.4	0.5	8.9	0.04	0.26	0.02	0.02	0.06	0.01	0.05	0.08	1	10	65	6	1	9	14	70	5	36	Magnetite, cuprite.
3-111	28.1	0.9	4.5	0.6	57.1	0.06	0.3	0.5	3.7	0.02	0.93	0.03	0.03	0.02	0.01	0.04	0.06	2	20	95	2	1	6	11	160	4	55	Magnetite, fayalite.
44-1	37.9	1.0	8.1	0.2	42.1	0.09	0.3	1.1	3.3	0.09	0.39	0.03	0.03	0.02	0.03	0.06	0.07	1	13	38	<1	2	5	19	110	7	51	Fayalite, magnetite
44-2	36.4	1.1	18.0	1.1	24.2	0.10	0.8	4.6	10.5	0.09	0.04	0.01	0.01	0.03	0.02	0.02	0.12	<1	7	34	30	1	7	15	60	5	40	Fayalite, Cu2S, Cu, wollastonite.
15-155	33.9	1.7	9.7	1.1	31.8	0.10	0.5	1.1	2.3	10	0.13	0.03	0.01	0.66	0.01	0.07	0.16	<1	12	14	3	<1	1	18	70	5	47	Spinel, knebelite.
10-113S	34.3	2.1	9.4	0.8	47.5	0.11	1.2	0.8	2.5	0.46	0.22	0.01	0.01	0.04	0.01	0.02	0.11	<1	30	11	5	2	2	16	50	3	44	Si min**, fayalite, traces of knebelite.
118 G.S.	37.8	1.4	9.8	1.3	24.4	0.10	0.8	0.6	16.7	0.01	0.33	0.02	0.01	0.05	0.01	0.07	0.10	1	10	76	2	2	8	13	50	5	30	Si min, delafossite, many cuprite.
18-139 118(1)	39.0	1.2	10.1	0.9	20.0	0.09	0.7	1.0	17.5	0.03	0.20	0.01	0.02	0.01	0.01	0.04	0.12	ns*	ns	ns	ns	ns	ns	ns	ns	ns	ns	Delafossite, cuprite.
G.S. 18-139, 140	42.5	1.0	7.9	0.3	42.5	0.13	0.4	0.9	1.3	0.08	0.04	0.01	0.01	0.03	0.02	0.07	0.07	0	15	10	<1	2	2	25	120	8	63	Magnetite.
	44.2	1.7	11.5	0.2	25.3	0.18	0.6	0.9	8.1	0.08	0.27	0.03	0.03	0.03	0.03	0.06	0.06	<1	11	72	<1	3	12	26	77	11	66	Magnetite, cuprite.

* ns - not sought. ** Si-rich mineral.

Group 1[14]: The knebelite-spinel slag (Table 3: 29-169, 44-3, 15-155) may be understood as indicating the use of a copper-manganese type of ore, to be found in the Shehoret Formation (Segev *et al.* 1992: 9-11) in the area of Har Michrot and Wadi Mangan, south of Yotvata. Elongated knebelite crystals (*Fig. 10*) and tiny spinels between them (*Fig. 11*) can be seen in sample 15-155. In this particular slag, copper occurs as rare sulphide prills. The copper content in this type of slag is relatively low.

Although manganese was intentionally used in Timna as the main flux for an advanced smelting practice at New Kingdom Site 2 and at late New Kingdom Site 30, Stratum I, (Rothenberg 1990: Table 3-4), producing high quality tapped slag, it appears that Cu-Mn ore of the Shehoret Formation (with relatively low Mn) was used in the hole-in-the-ground-furnace of the smelters of Yotvata. If this interpretation of samples 29-169, 44-3 is correct, it would also imply iron oxide flux being used at Yotvata for the smelting of this Timna copper ore. Intentional fluxing with iron oxide was already known in the Arabah since the early Chalcolithic (Site 39a and others, Rothenberg & Merkel 1998: 2).

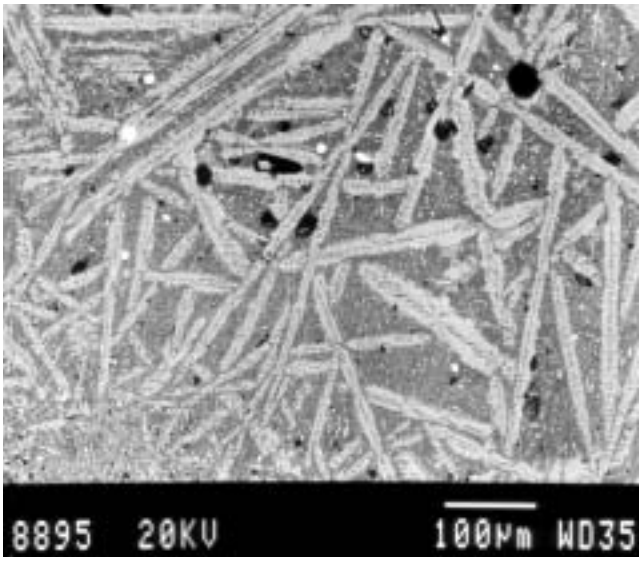


Fig. 10. Knebelite slag 15-155. Elongated, partly dissolved knebelites are seen in the matrix. White round inclusions consist of copper sulphide.

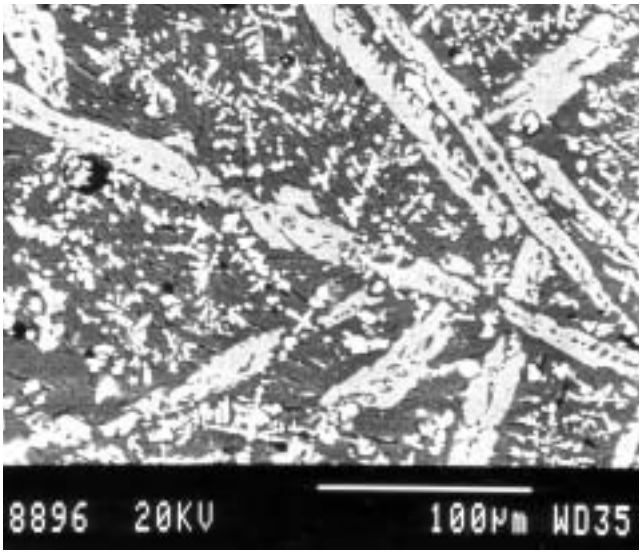


Fig. 11. Same as in Fig. 10 with large magnification. Dendrites of magnetite are dispersed between the knebelite crystals.

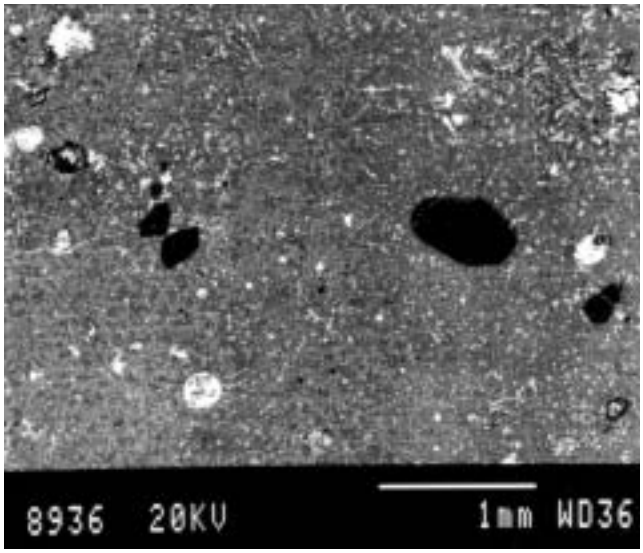
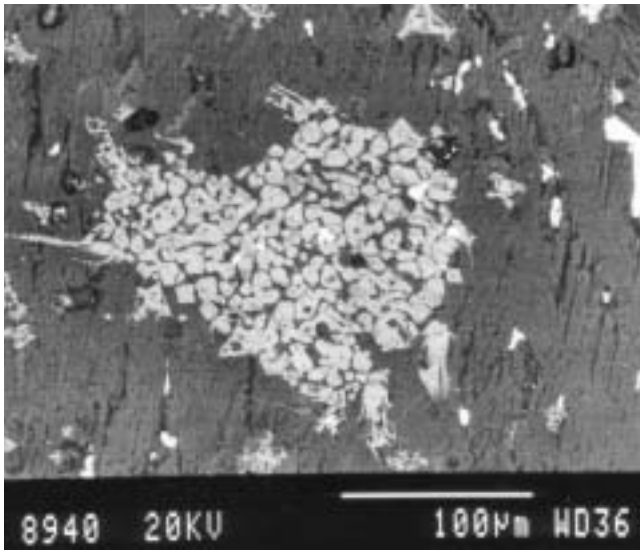


Fig. 13. Structure of magnetite slag 15-159. Tiny magnetites and large copper oxides (white) are dispersed through the slag. Note presence of cracked quartz inclusions.

Group 2: The typical structure of a magnetite-fayalite slag is shown in *Fig. 12,* with polygonal crystals and dendrites of magnetite and elongated fayalite. Here, copper occurs as small metallic prills and veinlets. Despite the formation of fayalite, metal-slag separation was inefficient and copper content in the slag is relatively high. In magnetite-rich slags 15-159 and 18-139, 140, tiny magnetite and cracked quartz crystals can be seen (*Fig. 13*). Quartz was not melted and undecomposed ore (haematite together with cuprite) remained almost unaltered in the slag (*Fig. 14*). Large (0.25 mm) copper oxide prills were also observed in these samples (*Fig. 15*). It would appear that this slag was produced from the ore of Table 2, reaching only a low temperature (below c. 1100 C) inside the hole-in-the-ground-furnace, combined with an insufficient, short period of smelting and was a product of the earliest smelting attempts at Yotvata.

Fig. 14. Remnants of non-decomposed ore within the slag 15-159. Grey polygonal minerals are haematites and white - cuprite. ▼



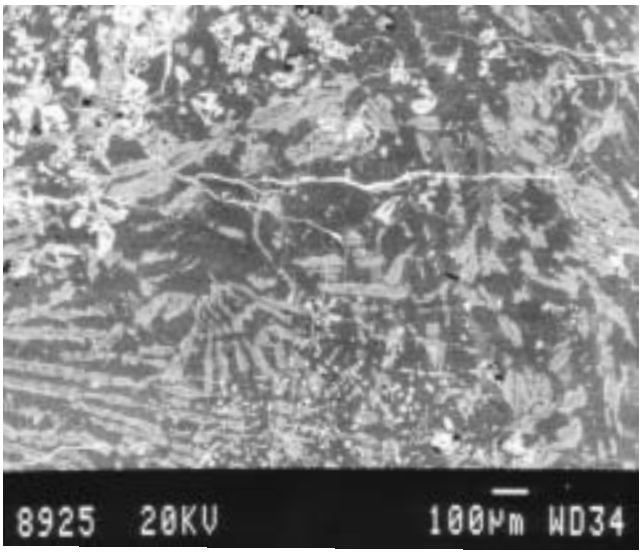


Fig. 12. Magnetite-fayalite slag 1-112S. Numerous polygonal magnetite crystals and darker elongated fayalites are distributed randomly in the matrix. Copper veins intersect the slag (all the photos are SEM-BSE images).

Group 3: Two samples of larger slag lumps (118 G.S. and 18-139) exhibit delafossite crystals with many large (0.3 mm) cuprite inclusions (*Fig. 16*). Under large magnification also numerous dendrites of copper oxide are visible (*Fig. 17*). Delafossite, $CuFeO_2$, an oxygen-rich mineral formation, is presumably the result of primitive smelting with insufficient reduction.

Some of the slag show copper prills of various sizes (up to 0.3 mm), containing about 2-5% iron. It appears that smelting took place in two stages: 1) decomposition of ore and other oxides from gangue etc. and 2) oxide reduction to metallic copper. In other slag, only copper sulphide inclusions, containing 2-10 % Fe, were observed. Slag 44-2, for example, contains Cu_2S prills up to 2 mm (SO_3-content in bulk analysis is about 5 %). This suggests the use of oxidic ores with some admixture of copper sulphides, typical for the oxidic ore of the Arabah.

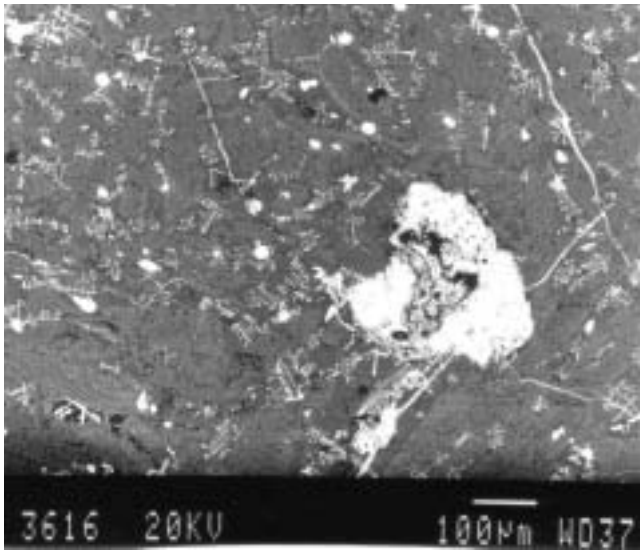


Fig. 15. Structure of magnetite slag 18-139,140. Dendrites of magnetite and large copper oxide inclusions and veins are distributed in the matrix.

Fig.16. Slag 18-139. Needle-like delafossites and white copper oxide inclusions present in this slag.▼

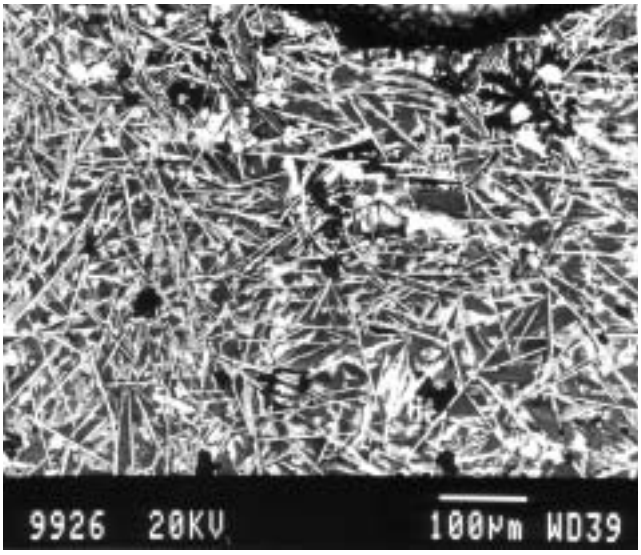
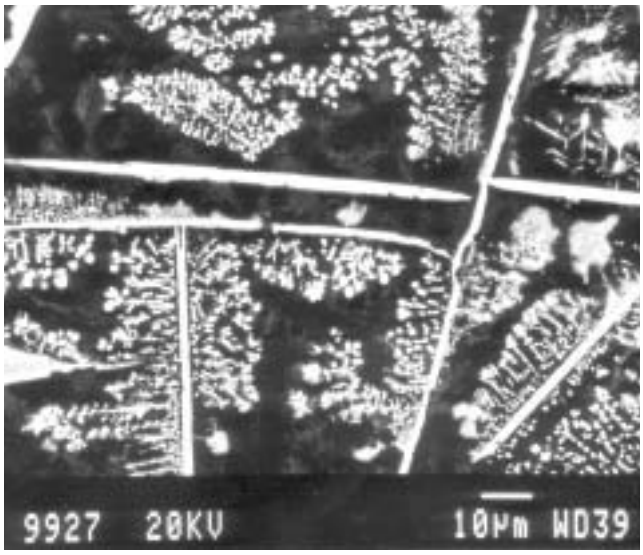


Fig. 17. Same as in Fig. 16 with large magnification. Dendrites of cuprite between delafossite crystals. ▼



Ingots

As chemical analyses show (*Table 4*), the copper ingots[15] contain up to 6.4 % Fe. SEM-EDS examination of polished sections revealed that the ingots are very inhomogeneous (*Fig. 18*). They contain iron and copper-iron oxides (*Fig. 19*), similar to those found in the smelting slag of Yotvata. Furthermore, several copper sulphide inclusions are randomly distributed. The sulfur content in the bulk analysis of different parts of the ingots varies between 0.4 - 3 %. The chemical composition of the ingots is similar to those of the prills

Table 4. Chemical composition of ingots from Yotvata, wt %.*

Identity	Cu	Zn	Fe	Pb	Ag	As	Sb	Ni	Co	Mn	Sn	S
12-148	78.4	0.18	3.8	0.4	0.003	0.01	0.03	0.031	0.013	0.001	nd	0.5
16-201	78.7	0.07	6.4	0.6	0.040	nd	nd	0.025	0.019	0.001	nd	0.2

* nd - not determined

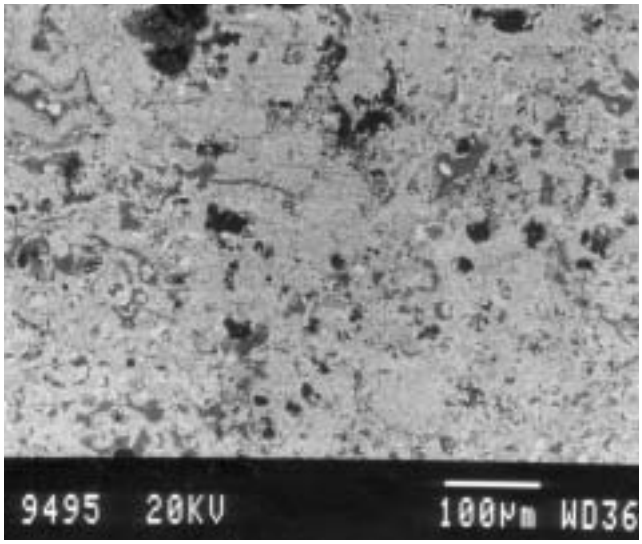


Fig. 18. Structure of the ingot 12-148 showing its inhomogeneity. Dark grey inclusions are magnetite remnants, round light grey - copper sulphide.

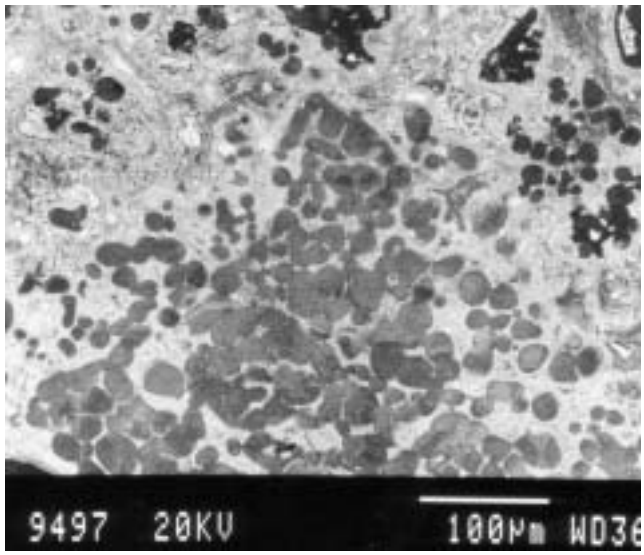


Fig. 19. Iron (dark grey) and iron-copper oxide inclusions near the planar surface of the ingot No.12-148.

in the Yotvata slag, including high iron content (*Table 5*). This indicates that the ingots are indeed a major part of the smelting product which formed below the slag at the bottom of the

Table 5. Fe in Cu prills in Yotvata slags

Slag	Cu-prills	Fe, %	Quantity + size of prills
10-113	Cu	3-4	rare
29-169	Cu_2S	10	rare, small
15-159	Cu	1	many, large
18-139, 140	Cu	2-3	many, large
44-1	Cu	5	rare, small
44-2	Cu_2S	2-6	many, large
44-3	Cu	1-2	rare, large
1-112	Cu	6	rare, small
15-155	Cu_2S	3	rare, medium

In ingots there is 4-6% Fe and sulfur content is 0.4-4%

Chalcolithic 'furnace', the other part being the entrapped prills in the slag, which had to be manually extracted. This also explains the somewhat 'plano-convex' shape of the ingots. Comparing the Yotvata ingots with (later) ingots from Timna (Roman 1990), it seems most likely that the Yotvata ingots were produced from the local oxidic ore of nearby Timna.

Discussion and Conclusions

Meshel's excavation established the stratigraphy of the hill-site of Yotvata. Based on the pottery finds and their similarity to Timna pottery, the casemate stronghold could be dated to the 19th-20th dynasties of the Egyptian New Kingdom. There was no trace of any New Kingdom metallurgy or any sign of metal working inside the casemate structure. However, all over the hilltop, and also underneath the casemate walls, a variety of metallurgical remains were found. These could be dated to the Late Pottery Neolithic (6th-5th millennium BC) as well as the Chalcolithic period (5th-4th millennium BC)[16] by Rothenberg's archaeological finds (of the 1950s and 60s, and again recently): flint objects, prehistoric pottery, its typology and comparative petrography, and by the type of metallurgy as established by the present investigation. There was no architecture or installation of any kind related to the prehistoric activities at the site, besides, perhaps, the earthen fence mentioned above.

Archaeological typology of the finds at Site 44 established a Late Pottery Neolithic as well as a Chalcolithic date for the smelting activities at the site. The technological characteristics of the slag indicated that Group 1 of the slag is of Chalcolithic date, whilst Groups 2 and 3 are Late Pottery Neolithic. Although this dating of the slag groups is somewhat tentative, based on the available evidence and comparisons with other sites in the region, these dates seem the most appropriate.

The establishment of the Late Pottery Neolithic as well as Chalcolithic date of the metallurgical activities on this hilltop site is of considerable significance for archaeo-metallurgy as well as for the history of the Arabah. Similar metallurgical activities, indicated by concentrations of slag of a primitive type, took place on top of many of the foothills along the mountain range of the South-western Arabah, which were difficult to identify and date because of lack of diagnostic archaeological remains. The results of the Yotvata investigations will now help to form a comprehensive picture of prehistoric copper in the Arabah and adjacent areas. The Late Pottery Neolithic and Chalcolithic copper producers of the Southern Arabah obviously belonged to the clusters of settlements of these periods, located in the Southern Arabah as well as in the nearby Uvdat Valley, in the Eilat Mountains. It is important to mention here that the Chalcolithic settlement/culture of this region does not show any traces of the Chalcolithic Beersheba-Ghassulian culture of Israel, which is also substantially different in its metallurgy[17].

Smelting the ore found at Yotvata needed additional silica for the slagging of its gangue. We assume that the source of the silica was the sand from the sides of the hole-in-the-ground smelting 'furnace' and not intentionally added silica. Although intentional addition of iron oxide ore, seemingly a vaguely understood, irregular kind of fluxing, was already practiced by early Chalcolithic smelters of the region, there is no evidence anywhere for intentional fluxing with silica in prehistoric times.

According to the analyses of the slag samples, the nodular oxidic copper ore of Timna, as well as copper-manganese ore from the region of the manganese deposits north of Timna, were used by the prehistoric smelters of Yotvata, besides the imported ore. Iron oxide flux, as used at Site 39 and, perhaps, also at other Chalcolithic sites, was widely available in close proximity to the copper ore of the region.

It is quite difficult to distinguish between Late Pottery Neolithic and Chalcolithic slag, because inefficient or unsuccessful smelting of any period may appear to belong to a more primitive, earlier phase of smelting technology. Nevertheless, since it is clearly possible to distinguish between compositions, phase mineralogy and quantities of Late Pottery Neolithic / Chalcolithic slag and slag of the Late Bronze Age / Egyptian New Kingdom, technological characteristics can obviously be used for tentative dating. However, it is not possible to date slag by its chemistry alone, which is also reflecting heterogeneous furnace operations. Furthermore, in many cases, not all representative samples of the smelting products are preserved and such 'missing links' also make it often difficult to identify technological developments and characteristics. Problems are also caused by the fact that we are dealing with small-scale activities, which took place for relatively very short periods between the 6th and the 4th millennium BC. Nevertheless, comparisons with the slag/technology of previously investigated prehistoric sites in the Arabah, and their distinct types of extractive metallurgical remains, dated by archaeological evidence, provided very useful chronological indications.

The analyses of the slag showed great heterogeneity, typical for prehistoric smelting. The differences of the slag phases: magnetite, fayalite, knebelite, delafossite and spinels, can be explained by the use of different ores and varying efficiency of the smelting process. High contents of spinels means very viscous slag, apparently typical for early prehistoric smelting, with much of the metallic copper entrapped in the slag as prills of different sizes, which have to be manually separated. Although fayalite was formed, metal-from-slag separation was still very inefficient, probably also because of the primitive hole-in-the-ground smelting installation. Tapping of the slag was unknown; at the end of the smelting process, after cooling down, the contents of the 'furnace' had to be removed, the ingot(s)[18] at the bottom (when present)

collected and the copper prills manually separated from the slag.

The small copper ingots found at Yotvata, which, according to their shape, were formed at the bottom of a furnace, are probably of Chalcolithic date, although no comparable finds are known from elsewhere. Their chemical composition is similar to that of the copper prills in the slag, including also some copper sulphide prills, which clearly indicates that the ingots were produced from local oxidic ore nodules with a chalcocitic core. Thus Yotvata is providing the evidence that already in Chalcolithic smelting enough metal segregation took place to form a lump of copper, a rough 'ingot', below the slag at the bottom of the 'furnace'[19]. The ingots as well as the copper prills in the Yotvata slag contain a high percentage of iron, again an indication that both are the result of primary copper smelting at the site.

The fact that no copper ingots were ever found at a smelting site of the Chalcolithic period before the excavation at Yotvata, should be followed by reconsideration of earlier research of prehistoric copper metallurgy. Is it possible that such ingots of rather rough, irregular shape, were actually produced in many Chalcolithic and other prehistoric smelters, but not identified or reported by the excavators. There is often prehistoric slag with very low copper content, smelted from very high-grade copper ore - we have to ask: where remained the copper? It seems most likely that ingots were indeed produced and removed, leaving only the slag behind.

The high iron contents of the ingots and of the copper prills in the slag of Site 44 seems to need some consideration, since high iron in copper has lately been taken to indicate a much later smelting process, using in effect the iron contents in copper as a chronological criterion (Craddock and Meeks 1987: 190)[20]. Based on "thousands of analyses of bronzes" and some copper objects of the British Museum's collection, Craddock uses the iron contents as indicator for the date of the original smelting process - low iron early, high iron much later "probably coincident with the improved smelting technology". These conclusions regarding copper smelting conditions and chronology, drawn from analyses of finished metal objects, do not seem acceptable to us for the interpretation of smelting remains, taking in consideration the many metallurgical changing parameters from the smelters to the finished tools, including of course the ever occurring recycling and related refining.

The copper prills with high iron content in smelting slag of Site 44 (cf. Table 5) are well dated by flint, pottery and comparative technology to the Chalcolithic period. In this connection there is important chronological evidence in the fact that the copper prills in furnace slag of Chalcolithic Abu Matar contained iron up to 4.12% (average 0.97%, Shugar 2000: 207). In their seminal paper on iron in ancient copper, Cooke and Aschenbrenner (1975: 253) list Chalcolithic copper objects from India with 2.57 % and 6.48 % iron, as well as a 12th dynasty (ca. 2000 BC) copper ingot from Sinai with 5.9 % iron. These authors do not use iron in copper as a chronological criterion but as an indicator for different smelting technologies in different regions of the ancient world. There is no doubt that iron in copper as such can not serve as a criterion for the date of the smelting of copper.

We propose to distinguish between some typical technological characteristics of Late Pottery Neolithic and Chalcolithic smelting processes at Site 44:

Late Pottery Neolithic: the LP Neolithic slag is extremely heterogeneous. Delafossite is probably a typical phase of LP Neolithic slag. Due to the high viscosity of the slag, there was no segregation and, therefore, all the copper produced in the hole-in-the-ground smelter remained in the slag, only part of which could be manually recovered. Consequently, the slag analysis show a very high copper content, mainly as small copper prills, veinlets and dendrites, as well as copper oxide prills.

Chalcolithic: Chalcolithic slag, though still heterogeneous, shows some common characteristics, which also assist in dating the slag. Due to intentional, though not well controlled, fluxing and improved process technology, like higher temperature and better reducing atmosphere, the slag was less viscous and segregation considerably improved. Comparing the Chalcolithic slag with the LP Neolithic slag of Yotvata, but also with the 5th millennium BC Chalcolithic slag of Site 39[21], the quantity of copper prills entrapped in the Chalcolithic Yotvata slag is quite low. Improved segregation caused the merging of the small copper prills in the slag into larger prills, manually easier to recover, but apparently much of the copper formed ingots below the slag, at the bottom of the furnace.

So far we have no close absolute date for the start of the production of ingots at the furnace bottom, but this significant development in the prehistory of extractive metallurgy was probably related to the introduction of improved fluxing, *i.e.* a better balanced smelting charge, at some time in the later Chalcolithic period.

Acknowledgements

The authors are very grateful to Zeev Meshel, head of the Yotvata research project (Meshel 1993) and the excavator of the Egyptian stronghold at Site 44, for his permission to investigate his metallurgical finds. Many thanks are due to our colleagues John Merkel, UCL/IAMS London and Hans-Gert Bachmann, Hanau, for their important advice concerning the interpretation of the analytical investigation of the finds from Yotvata.

Notes

1 Ein el-Ghidyan is the previous Arabaic name of the oasis, cf. Palestine Survey map 1939/44.

2 Cf. Rothenberg 1967a, attached map; *idem*, 1972: 11. The first plan of Site 44 was published in Rothenberg 1967: 286.

3 We visited Site 44 again in 2001 in order to clear up some stratigraphic/chronological problems which arose at the excavation of the site (see below).

4 At the time of the early Arabah Survey, before the discovery of the Hathor Temple in Timna, *i.e.* before the recognition that Timna was mainly an Egyptian New Kingdom copper industry of the late 14th to mid-12th centuries BC (Rothenberg 1972; 1988), the main activities in the mines and smelters of Timna were dated to Iron Age I. This date should now be corrected to 'Egyptian (Ramesside) New Kingdom', or Late Bronze Age IIA to Iron Age IA. The Classical pottery of the hill site was dated by M. Gichon (in preparation).

5 It is difficult to estimate the total quantity of slag dispersed on Site 44 since these slag fragments have been exposed on the surface for thou-

sands of years and much of the slag was probably washed down the slopes by the occasionally very heavy rain of the region. Our team found a quantity of slag at the bottom of the slopes of the site. Our estimation of 30 kg is meant to indicate the scale of production, compared with later smelting sites in the region, where many hundreds of kilograms to many thousands of tons of slag were found.

6 Hamoudi Khalaily, Israel Antiquities Authority, in July 2001 identified Late Pottery Neolithic as well as Chalcolithic pottery amongst the finds of our 1956 and 1960 surveys at Site 44.

7 We shall not deal in this paper with the metal objects of the NK and the Roman period found in the excavation of Meshel. These will be published in his final excavation report.

8 We chose the samples from the excavation for our investigation, rather than those collected during our surveys, since the metallurgical debris on the surface of the site were exposed for thousands of years and may now be quite different from the debris at the time of production. This is a common problem of archaeo-metallurgy and should be more taken into consideration.

9 There was no ash at all at the site - as typical for smelting sites - and we assume that Meshel noticed charcoal dust.

10 We inspected the site again in June 2001. Many hours of meticulous search on the hill as well as on the slopes below, produced only very few finds. As we were told by members of the nearby Kibbutz, Site 44 has been for very long a common "hunting ground" for nice stones, sherds, stone tools and other antiquities by the children of the Kibbutz.

11 Amit Segev, Israel Geological Survey, is a specialist of the geology of the Timna valley (Segev *et al.* 1992). H.G. Bachmann (verbal com.) found samples of this type of ore in the region of the Timna mines.

12 The whole process of slag formation is, to a degree, self-regulating. If, for instance, there is too much iron in the ore or charge, the slag simply forms with silica from the 'furnace wall' and (additional) CaO from the fuel (charcoal) ash (cf. Merkel 1990: 113)

13 The very low Mn in the four ore samples found at Site 44 (Table 2), compared with some of the slag analyses (knebelite-spinel slag, Table 3), is evidently an indication for the use of different types of ore at Yotvata.

14 The groups of slag reported in the following are not fully identical with the visually established "groups" of slag, described above, though the typology of these groups are certainly related to the different smelting characteristics.

15 We are using here the term 'ingot' to indicate that we are not dealing with metal objects or parts thereof. The two metal samples ('ingots') on Table 4 are in fact quite irregular copper lumps, of rather vaguely plano-convex shape.

16 So far it was not possible to establish closer, absolute dates within these period of about 3000 years. Efforts are now being made to establish absolute dates for our site.

17 Cf A. Shugar 2000. Based on new excavations at Abu Matar (Beersheva) by I. Gilead, Shugar could reconstruct the Chalcolithic Beersheva-Ghassul metallurgy, including copper smelting in clay-lined furnaces and melting/casting in crucibles. Some of the ore probably originated from Feinan (Jordan), but there was also a different ore imported probably from Anatolia.

18 Ingots, *i.e.* rough, irregular lumps of copper, form on the bottom below the tuyere. When several tuyeres are used, there may be a separate ingot below each tuyere, sometimes, depending on the quantity of copper produced and on its temperature, merging into one ingot. This interpretation is based on results of smelting experiments (Merkel 1990) and on the fact that these flat lumps of copper (our 'ingots') are totally different from the typical plano-convex, 1-2 kg Late Bronze Age ingots (Roman 1990).

19 For the formation of 'ingots' inside the furnace see Merkel (1990).

20 Craddock's conclusions, relating to the iron contents in copper, are based on his assumption (Craddock & Meeks 1987: 187-193) "that the low iron content regularly found in metalwork of the European Bronze Age implies a simple non-slagging process and explains why so few remains of smelting, as compared with mining, have been identified in Europe. The evidence is not lost but probably never existed".... "the low iron content in copper indicates a smelting process without slag formation can perhaps explain the apparent absence of smelting sites in most of Western Europe in prehistory..... Slag heaps are not found associated with the prehistoric mine workings quite simply because they never existed." Craddock's theory of prehistoric 'slag-less copper smelting', based on the fact that no slag heaps of this period have been reported, is totally unacceptable. First, what happened to the gangue, ash from the fuel etc. of the smelting charge? Even if the quantity is minute, the term 'slag-less smelting' is obviously a *contradictio in adjecto.* Second, the main reason why almost no prehistoric slag was found until rather recently next to the prehistoric mines identified in Western Europe, is simply because nobody looked for the slag. In the 1970s, my team undertook the first ever archaeo-metallurgical survey in the 'copper belt' of the Huelva province, SW Spain, where the local geologists had noticed ancient workings and numerous prehistoric mining tools, next to 19th century mines - but nothing else. We found and recorded numerous prehistoric mines all over the province (Rothenberg and Blanco-Freijeiro 1981) - later on also in the province of Almeria (Rothenberg 1988, 1989) - and near each of them, looking at the suitable spot in the rugged landscape, we found a concentration (flat heap) of primitive slag, often with crushing tools and diagnostic flint and pottery. We did not locate a single mine without a smelting site nearby - often near a group of megalithic structures of the same date ('dolmen'). These slag 'concentrations' indicated very small scale working, but quite comparable with the scale of prehistoric smelting sites in the Levant, including the sites reported in this publication.

21 We would propose to date Chalcolithic Yotvata to the first half of the 4th millennium BC.

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