The roots of glazing techniques : copper metallurgy ?

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Cet article présente une étude de fragments glaçurés de four, verdâtres, parfois bleuâtres ou rouges provenant des sites de Feinan et de Timna, dans le Wadi Araba, où l'on fondait le cuivre au 3e millénaire av. J.-C. En raison de leur situation géographique, ces sites peuvent avoir eu leur importance pour la production des glaçurés en Egypte («faïence égyptienne »). Les glaçurés ternies sont du verre Ca-Al-Silicieux, à l'origine riche en alkalis mais lessivés au cours des millénaires. La couleur verte actuelle est due à de faibles concentrations de cuivre divalent. La teinte devait être bleue à l'origine, virant au vert avec le temps. La formation de glaçure est le résultat de l'utilisation de grès calcaire local dans la construction des fours. Pendant la fonte celui-ci a réagi avec le potassium et le calcium provenant des cendres de charbon de bois ainsi qu 'avec le minerai de cuivre. Des glaçurés semblables n 'ont pas encore été observées ailleurs sur des fonderies préhistoriques, probablement en raison de la composition défectueuse des minerais. Des expériences de replication de formation de glaçure pendant la réduction du cuivre ont été effectuées afin de tester les procédés techniques mis en œuvre dans le glaçurage. Les résultats expérimentaux ont confirmé l'évidence archéologique. Des points essentiels communs à la formation de glaçure dans les fours servant à la fonte du cuivre et à la «faience égyptienne » sont une matière première riche en quartz et sa réaction chimique avec le cuivre, et les sels alcalins à haute température. Des différences importantes consistent en de fortes concentrations de potassium dans nos échantillons, alors que le sodium est un constituant majeur de la «faïence égyptienne ». Il reste à résoudre certains problèmes de chronologie, étant donné que les premières perles glaçurées précèdent l'évidence archéométallurgique discutée dans cet article.

THE ROOTS OF GLAZING TECHNIQUES : COPPER METALLURGY ?

A. HAUPTMANN, R. BUSZ, S. KLEIN, A. VETTEL and R. WERTHMANN

Abstract : *This paper reports on finds of greenish, partially bluish and red glazed furnace fragments from 3rd millennium BC copper smelting sites at Feinan and at Timna, Wadi Arabah which, due to their geographic location, could have been of significance for the production of glazes in Egypt ("Egyptian faience"). The weathered glazes consist of Ca-Al-siliceous glass originally high in alkalis, the latter extracted by leaching over the millennia. The presently observed green color is due to minor concentrations of divalent copper; the color is considered to have been blue originally, with changes to green due to weathering processes. Glaze formation is the result of furnace-constructions using locally available calcareous sandstone, which during smelting reacted with potassium and additional calcium from charcoal ash and with copper from the ore. Comparable glazes have not yet been observed elsewhere at prehistoric smelting sites, probably due to inadequate composed raw materials. Experimental work was carried out to replicate the formation of glazes during copper smelting in order to prove technological relationships to glaze-manufacturing processes. The experimental results confirmed the archaeological evidence. Decisive points in common between glaze formation in copper smelting furnaces and "Egyptian faience" are a quartz-rich matrix and its chemical reaction with copper and alkali-salts at high temperatures. Major differences are high potassium concentrations in our samples while sodium was found to be a major constituent in "Egyptian faience". Chronological problems are not yet sufficiently solved, since the earliest glazed beads predate the archaeometallurgical evidence discussed in this paper.*

Résumé : *Cet article présente une étude de fragments glaçurés de four, verdâtres, parfois bleuâtres ou rouges provenant des sites de Feinan et de Timna, dans le Wadi Araba, où l'on fondait le cuivre au 3e millénaire av. J.-C. En raison de leur situation géographique, ces sites peuvent avoir eu leur importance pour la production des glaçures en Égypte (« faïence égyptienne »). Les glaçures ternies sont du verre Ca-Al-Silicieux, à l'origine riche en alkalis mais lessivés au cours des millénaires. La couleur verte actuelle est due à de faibles concentrations de cuivre divalent. La teinte devait être bleue à l'origine, virant au vert avec le temps. La formation de glaçure est le résultat de l'utilisation de grès calcaire local dans la construction des fours. Pendant la fonte celui-ci a réagi avec le potassium et le calcium provenant des cendres de charbon de bois ainsi qu'avec le minerai de cuivre. Des glaçures semblables n'ont pas encore été observées ailleurs sur des fonderies préhistoriques, probablement en raison de la composition défectueuse des minerais. Des expériences de réplication de formation de glaçure pendant la réduction du cuivre ont été effectuées afin de tester les procédés techniques mis en œuvre dans le glaçurage. Les résultats expérimentaux ont confirmé l'évidence archéologique. Des points essentiels communs à la formation de glaçure dans les fours servant à la fonte du cuivre et à la « faïence égyptienne » sont une matière première riche en quartz et sa réaction chimique avec le cuivre, et les sels alcalins à haute température. Des différences importantes consistent en de fortes concentrations de potassium dans nos échantillons, alors que le sodium est un constituant majeur de la « faïence égyptienne ». Il reste à résoudre certains problèmes de chronologie, étant donné que les premières perles glaçurées précèdent l'évidence archéo-métallurgique discutée dans cet article.*

Key-Words : *Early Bronze Age, Copper metallurgy, Glaze formation, Smelting experiments, Related craftsmanship.*
Mots Clefs : *Age du Bronze ancien, Métallurgie du cuivre, Formation de glaçure, Expérimentations de fonte, Artisanat.*

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INTRODUCTION

In various publications about "Egyptian faience" (*i.e.* bluish and greenish, and in some cases brown or even red glazed beads, figurines, vessels and other objects made of a siliceous body free of clay), it has been repeatedly stated that green and blue copper-containing glasses and glazes might have their origin in extractive copper metallurgy [1]. However, because of the age of the earliest faiences these thoughts came up against limiting factors very quickly. The small glazed beads in Egypt probably date to Predynastic times (Naqada I, approx. 4 000-3 500 BC), whereas in Mesopotamia they are possibly dating far back to the 5th millennium BC. Those who searched for possible relationships between techniques for the production of faience and copper metallurgy cited the copper-workshop at Tell Abu Matar, where glazes have been found on coarse tempered ceramic sherds. The sherds have been interpreted as fragments of copper crucibles, perhaps even as parts of some sort of a smelting furnace [2]. They were dated to the Chalcolithic period, *i.e.* the transition of the 5th/4th millennium BC. At first glance, the Abu Matar sherds do not seem to be much of a help in answering the question of faience origins, since their glazes are not green or blue but completely red colored. Moreover, it is hard to find further evidence of such glazes from the beginnings of extractive metallurgy during this period, for example from the crucibles found at Tepe Ghabristan and Tal-i Iblis in Iran, or from Merhgarh II in Baluchistan/Pakistan [3]. Crucible fragments found in Chalcolithic eastern Anatolia [4] or from the other localities of the southern Levant do reveal a coating of red glaze at their inner surface, but never the colors we are looking for.

There is, however, an important compositional aspect which may help to solve the problem addressed in this paper : the red glazing that is sometimes observed in the crucibles is caused by tiny inclusions of cuprite (Cu_2O) embedded in a highly vitrified clay-made pottery [5]. Hence, these red glazes like those investigated in this paper obtained their color from copper.

GLAZES IN EARLY BRONZE AGE COPPER SMELTING FURNACES

Whith regard to color, the earliest analogies for faience can be found in the fully developed Early Bronze Age (EBA), specifically in finds of glazed furnace fragments from smelting sites of the copper districts of Feinan and Timna, located in the Wadi Arabah between Dead and Red Sea (fig. 1). In the area of Feinan, at the eastern margin of the Arabah, more than 50 copper smelting furnaces have been found in a number of sites. Many of these furnaces were excavated in the 1980s, in several soundings by the Deutsche Bergbau-Museum Bochum (fig. 2; see also Craddock, this volume, fig. 3) [6]. Their ages were determined by a series of radiocarbon measurements which fall mainly between 3 000 and 2 300 BC, *i.e.* EBA II and III. At the moment, these are the earliest securely dated as well as the best preserved copper smelting furnaces known from the Old World. These smelting furnaces were operated with natural wind [7]. The use of this technique was obviously not limited to Feinan : smelting sites and furnace remains that are significantly exposed on hilltops and steep slopes (sometimes at some distance to the ancient mines) can be found in the whole Wadi Arabah, in the Sinai peninsula, in the Eastern Desert of Egypt and in the Aegean.

At the EBA smelting site of Ras en-Naqab in the Feinan area, many furnace fragments that have been collected are covered by glazes (pl. VIII : 1). The glazed fragments vary from colorless and transparent green, blue and they show sometimes a dull red color. The fragments consist of white sandstone slabs extremely low in iron-oxide. They were usually heavily slagged, but obviously not so densely packed that an irregular and unwanted air supply could be prevented during smelting. Similar finds have been made at Timna, at a smelting site near Givat Sasgon (Timna 149) [8]. This site might possibly be somewhat younger than those from Feinan; pottery found at the site dates to EBA IV, *i.e.* to the end of the third millennium BC. These are the only known indications of glaze formation in high temperature reaction vessels.

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[1] Cf. overviews in MOOREY, 1994; WARTKE, 1999.

[2] PERROT 1955; TYLECOTE, 1976; GOLDEN, 1998.

[3] MAJIDZADEH, 1979; DOUGHERTY and CALDWELL, 1966; JARRIGE, 1984; see also contribution CRADDOCK, this volume, page 151.

[4] MÜLLER-KARPE, 1994.

[5] HAUPTMANN *et al.*, 1993.

[6] HAUPTMANN and RODEN, 1988; HAUPTMANN, 2000.

[7] HAUPTMANN and RODEN, 1988; see also HAUPTMANN, 2000; KÖLSCHBACH *et al.*, 2000.

[8] ROTHENBERG and SHAW, 1990.

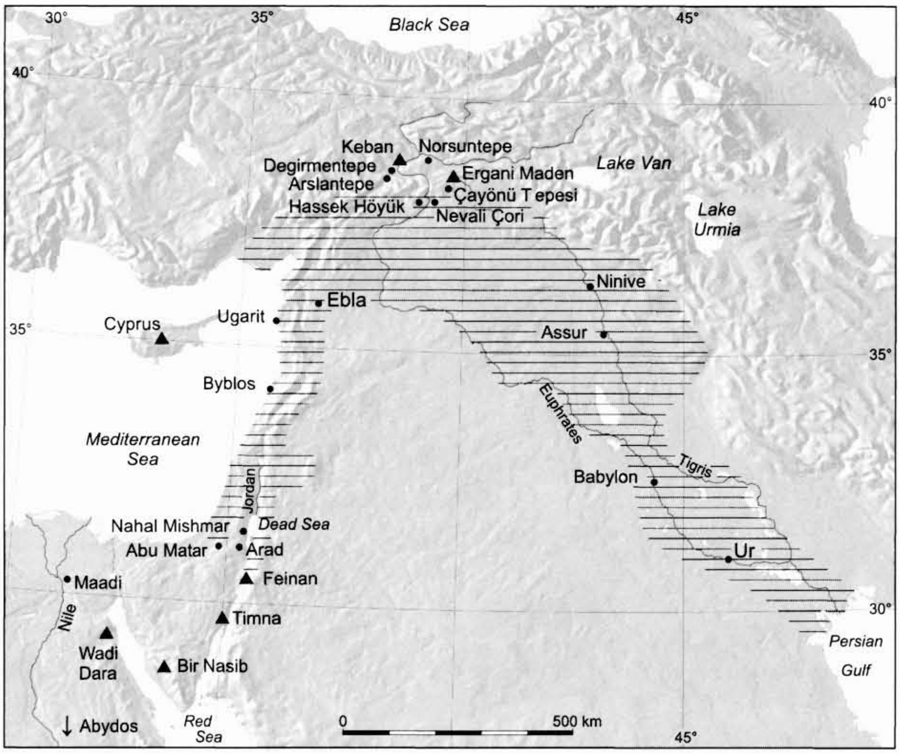

Fig. 1 : *Geographic overview of the Near East showing the fertile crescent and the localities of Feinan and Timna and other sites mentioned in the text.*

Such glazed fragments have not yet been described yet from any other smelting site in the Old World; they are not known from Cyprus, Oman or from Rio Tinto in the south-western part of Spain – just to name some of the locations which have played an important role in copper production during prehistoric times. In the Arabah, glazed furnace fragments are exclusively found in the EBA, when copper production reached its first "industrial" peak. Although hundreds of furnace fragments were found in the huge Late Bronze Age or Iron Age slag heaps from Timna and Feinan, the glazes are no longer observed. On the other hand, several bowl-shaped pits in a faience workshop at Abydos, which are thought to be the remains of kilns utilized for faience production, do not show any traces of glazed materials so that the connection to this craftsmanship remains dubious [9]. The Abydos pits date to the middle of the Old Kingdom or the early Middle Kingdom, corresponding to the middle of the third millennium BC, *i.e.* the EBA.

Which were the conditions that led to the formation of these green or blue glazes ? Of basic importance is a white body made up of siliceous ceramics or quartz powder to bring out the bright green or blue color. In the case of the Feinan and Timna materials, this is sandstone. The following processes for the production of Egyptian faience or Mesopotamian siliceous ceramic are described in the literature [10].

1. *Efflorescence method* : An object is shaped from a mixture of quartz powder, water, a water-soluble alkali salt (soda or potash carbonate) and a small amount of copper ore or copper filings. The object is then dried in air. The salt migrates to the surface, and during firing at approximately 900 °C, it reacts with quartz and forms a glaze. This is a so-called self-glazing process.

2. *Cementation method* : An object is shaped from quartz powder, water and some glue. The object is then embedded in a (pot of) glazing powder of quartz, calcium carbonate, ash from salt-containing plants, and a copper containing dye. This mixture is then heated up to 900-1 000 °C. Due to the evaporation of alkalis and copper, the surface of the object is partially liquefied, and a blue glaze is forming. The object, covered by the glaze, separates from the glazing powder by

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[9] NICHOLSON and PELTENBURG, 2000.

[10] NICHOLSON, 1993; BUSZ and SENGLE, 1999.

Fig. 2 : *Feinan 9 (Feinan, Jordan). Relics of an Early Bronze Age smelting furnace (approx. 2 500-2 300 BC). Clearly visible is the semicircular cross-section of the furnace bottom and the multiple renewed back wall made up of single ceramic layers. The front of the furnace was in part constructed with sandstone slabs, as found most frequently at the nearby smelting place of Ras en-Naqab. The furnace height was about 60 cm.*

volume contraction caused by sintering effects and decomposition of the lime. This method is applied as "Qom" technique in Iran up to now.

3. *Application of glaze* : A shaped object which can be made of various white materials high in silica, is dipped into water that is mixed with glazing powder that can be made of partly soluble ingredients or of crushed glass. The object is then fired approximately between 900 and 1 100 °C. The use of crushed glass is known from Egypt since the 8th century BC or so and has been applied during medieval times in all faience manufactures in Europe.

What all three processes have in common are a multistage processing of several (in all cases similar) raw materials, and a firing process under high temperatures. Of basic importance is a white body made up of siliceous ceramic or quartz powder to bring out the brilliant blue or green color; then, water-soluble sodium or potassium salt and copper fillings or copper ore were added. If the roots of faience production are in fact to be looked for in metallurgy, then a supply of the described raw materials must have been available in combination with each other in the first place. For a better understanding, a short overview of the most important copper ore deposits of the eastern Mediterranean is given in the following chapter.

GEOLOGICAL AND MINERALOGICAL FEATURES OF ORE DEPOSITS IN THE EASTERN MEDITERRANEAN

Copper ore deposits of the eastern Mediterranean can be divided regionally and genetically into two main units based on their geological developments.

The northern unit is located in the orogen belts of the Inner and Outer Taurids in southeastern Turkey; especially in the area of the upper Euphrates, numerous copper-based ore districts occur, such as the one in the Keban area. Further, a series of copper ore deposits can be found in ophiolitic rocks along the Zagros fold mountains, where the ore districts of Ergani Maden, Siirt/Madenköy, Kadere, Cüngüs-Midye are located[11]. The ophiolitic rocks extend in a southwestern direction. Finally, in the ophiolites of Hatay and Baer-Bassit, near the border of Turkey and Syria, the whole sequence of ophiolithic rocks are exposed from the ultrabasic basement to volcanic rocks on top. These, along with the ore district located in the ophiolitic complex of Troodos on Cyprus, form a geological unit. In this region, no ore deposits embedded in quartz-rich sediments are present; the copper ores are connected, as a rule, to dark-colored magmatic or metamorphic rocks or occur as karst deposits embedded in caves and hollows in limestone.

The second unit is to be found in the southern Levant and in the Sinai peninsula and is in part strongly interrelated with the formation of a rift system, which stretches from Eastern Africa to the recent Syria. In contrast to the ore districts located farther north, sedimentary and staratabound copper- and copper-manganese ore deposits occur here, embedded in sand- and claystones, which are parts of the huge series of the "Nubian Sandstone". Of special interest are the above mentioned ore deposits of Feinan and Timna, which are widely exposed to the surface at the eastern and western margins of the Wadi Arabah. Geologically and mineralogically comparable copper ore deposits are also located in the southwestern Sinai in the area of the Gebel Umm Rinna – Serabit el-Khadim – Wadi Maghara[12], where the precambrian basement is

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[11] WAGNER and ÖTZUNALI, 2000.

covered by the "Nubian Sandstone". The largest smelting site in this area is Bir Nasib. "Nubian Sandstone" also occurs in the Eastern Desert of Egypt, where copper mineralizations were exploited at Wadi Dara during the EBA II and later [13].

Typical ores in these deposits comprise, among others, malachite ($Cu_2[(OH)_2[CO_3])$, paratacamite ($Cu_2(OH)_3Cl$) and chrysocolla ($CuSiO_3 \cdot aq$). They occur as impregnations, nodules and lumps, in Timna often as cuprified plant relics. The white sandstone that is especially important for this discussion, was used for furnace constructions during the EBA at Timna and in the Feinan area. In general, it is a calcareous, solid rock, in parts even rich in rock salt (up to several percent of Na_2O). Other layers are only loosely consolidated [14].

COMPOSITION AND ORIGIN OF GLAZES FROM ARCHAEOLOGICAL CONTEXTS

The formation of light green and occasionally blue transparent glazes are exclusively to be observed on white and fine-grained sandstone slabs. The glazes never occur on ceramic material made of clay, except if it is high in silica.

In addition to some previously published analyses [15], analyses on glazed furnace fragments from Ras en-Naqab have been carried out at the Institute of Mineralogy, University of Frankfurt/M. as part of a larger investigation on the technical ceramic and refractory materials from the Feinan area that is currently performed by the authors (S.K. and A.H.). Surface-polished thin sections were investigated under light microscopy and glazes were analyzed by electron probe microanalysis (EPMA). The latter was carried out by quantitative spot analysis with high magnification.

The glazes usually consist of compact silica-rich glass. The borderline between glaze and sandstone shows protrusions and irregular resorption lines. Occasionally, glass formation was observed in the matrix between sandstone grains some millimeters below the surface (fig. 3). Under the microscope it has a light green, sometimes yellowish-brown tint. Inclusions that appear as red spots dissolve in the surrounding glaze. In parts, the glass shows beginning recrystallization. Inclusions of quartz grains show reaction rims by disintegration and transformation to high-temperature modifications such as tridymite and cristobalite [16]. As already observed earlier, the glazes are not homogeneously composed. We occasionally measured glazes from Ras en-Naqab with SiO_2, CaO, Al_2O_3, and MnO as the major constituents. Here, alkali-oxides and copper were found to be just in the 1/10 percentage range. In contrast, a sample from Timna 149 revealed the composition of an alkali-silicate-glaze with 16 wt. % copper. In this case we could not exclude the possibility that tiny prills of metal have been included in the sample, which led to such extremely high copper concentrations. Figure 4 displays a micrograph of the glassy matrix of a sample from Ras en-Naqab/Feinan : the variably colored streaks result from the changing contents of these elements, and areas of brighter occurrence are richer in copper and manganese. Tiny globules embedded in the glaze (∅ ca. 1 µm) could be identified as colloidal copper. Otherwise we found cuprite to be the colorant agent in red glazes. All these data confirm the macroscopic and microscopic evidence of a rather heterogeneous composition of the glaze. Wollastonite (ideal composition $CaSiO_3$) was identified too in recrystallized parts of the glass; it contains copper only in the 1/10 percentage range, and some Al_2O_3. With this composition, it differs significantly from the copper-containing cuprorivaite ($CaCuSi_4O_{10}$), which is the essential coloring component of Egyptian blue. The latter has been produced in a comparable way as faience already in the Old Kingdom of Egypt [17].

EPMA-analyses of three samples from Ras en-Naqab are compiled in Table 1. Quantitative wavelength dispersive line profiles were carried out by analyzing the glazes from their outer surface to the sandstone-glaze interface as shown for the distribution of potassium oxide in Figure 5. Again, SiO_2, CaO and Al_2O_3 constitute the predominant compounds but, as a rule, high concentrations of alkali oxides were measured with potassium oxide between 3 and 12 wt. % and sodium oxide at the 1 percentage-level. Chlorine was below detection limit (< 0.001 wt. %). The totals of the analyses are in part well below 100 % which is due to hydration of the glazes in the course of weathering. In addition, as often observed in natural rocks, weathering of glazes is usually connected with a leaching of alkali-oxides. We therefore assume that the original concentrations of potassium and sodium were higher in the EBA than determined today, especially in those samples that were analyzed earlier. Such a leaching can be seen by a decrease of K_2O from the sandstone – glaze interface to the glaze's surface.

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[12] ROTHENBERG, 1987.
[13] CRADDOCK, this volume, page 151.
[14] HAUPTMANN, 2000.
[15] HAUPTMANN and KLEIN, 1999.
[16] *Ibid.*
[17] SCHIEGL *et al.*, 1990.

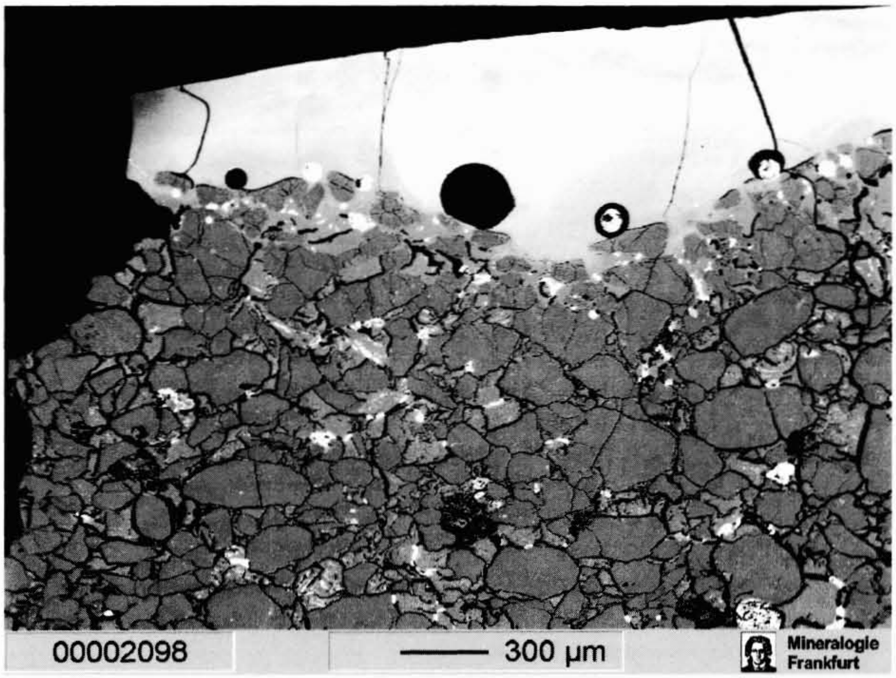

Fig. 3 : *Sample JD-5/12C, Ras en-Naqab (Feinan, Jordan). Greenish glazed sandstone slab used for furnace construction during the Early Bronze Age. The glaze shows a transition und protrusions into the sandstone, where quartz grains are absorbed and transformed to tridymite and cristobalite. Glass/glaze formation begins by reactions of finegrained components in the matrix between the quartz grains. SEM-image, backscattered electron mode.*

The formation of the green glazes observed at Feinan and Timna seems to be based on reactions between sandstone, copper ore (which was smelted in the furnace) and (alkali-rich) charcoal. These reactions took place in the range of 1 000 °C, well below the maximum temperatures reached during firing at the tuyeres. Potassium oxide from charcoal ash along with some sodium oxide and even calcium chloride evaporated and deposited on the sandstone surfaces, forming an alkali-silicate glass with CaO and Al_2O_3 from sandstone. Copper evaporated, *e.g.* as Cu_3Cl_3 which is stable under the temperatures mentioned. It reacted after oxidation by spots of oxygen surplus as Cu^{2+} with previously formed glazes on the furnace wall. This mechanism, admittedly, cannot be a watertight inference from our analyses. However, it had already been demonstrated[18] that concentrations of K_2O and Na_2O could be obtained in experimentally produced glazes that reached the same level as those from furnace fragments from Timna (see below). In addition, the lower level of alkali oxides in our samples might find its explanation in a leaching due to weathering processes, which probably also caused a shifting from an original blue color of the glaze to green[19].

EXPERIMENTAL ARCHAEOLOGY : THE ORIGIN OF GLAZES IN COPPER SMELTING FURNACES

In order to replicate the formation of blue and/or green glazes by experiments, simulations of prehistoric smelting processes have been carried out. The aim was to achieve a glaze formation on the furnace wall under nearly authentic conditions, according to the archaeological field evidences from Ras en-Naqab (Feinan) and Givat Sasgon (Timna 149) (figs 1 and 2). It should also be verified that a glaze-formation took place not only by chance but as a regular by-product during copper smelting in such a type of (non-ideal) furnace construction.

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[18] VETTEL, 1999.

[19] SCHIEGL *et al.*, 1990.

Table 1 (a, b) : *Representative microprobe analyses of glazes from Ras en-Naqab (Feinan, Jordan). Not all values plotted in figure 6 are listed here. All values in weight percent.*

	SiO_2	K_2O	Na_2O	CaO	MnO	MgO	TiO_2	Al_2O_3	P_2O_5	FeO	CuO	Total
Point 2 Line2	54.1	3.0	1.0	21.3	0.9	1.9	1.0	11.6	0.5	0.7	2.7	98.7
Point 3 Line2	55.3	3.1	1.0	20.6	0.9	1.9	0.9	11.9	0.5	0.8	2.3	99.2
Point 4 Line2	55.7	3.2	1.1	20.1	0.9	1.8	0.9	12.0	0.4	0.9	1.9	98.9
Point 5 Line2	55.7	2.8	1.1	20.5	0.9	1.9	0.9	11.8	0.4	1.1	1.8	98.9
Point 6 Line2	55.2	2.5	1.1	21.0	1.0	2.0	0.9	11.8	0.5	1.1	1.8	98.9
Point 7 Line2	56.8	2.7	1.2	19.6	0.9	1.7	0.7	12.3	0.4	1.1	1.6	99.0
Point 8 Line2	57.6	2.9	1.3	18.7	0.9	1.6	0.6	12.6	0.5	1.1	1.6	99.4
Point 9 Line2	59.3	3.5	1.5	16.2	0.7	1.3	0.5	14.0	0.4	0.9	1.4	99.7
Point 10 Line2	59.5	3.9	1.8	14.5	0.6	1.0	0.4	15.8	0.4	0.6	1.2	99.7
Point 2 Line6	56.3	4.2	1.4	18.7	0.4	1.8	0.7	12.0	0.4	0.6	2.6	99.1
Point 3 Line6	57.4	4.7	1.6	17.1	0.3	1.6	0.7	12.4	0.4	0.6	2.0	98.8
Point 4 Line6	57.8	4.8	1.6	16.9	0.3	1.6	0.8	12.4	0.4	0.7	1.8	99.1
Point 5 Line6	57.8	4.7	1.6	17.2	0.3	1.6	0.8	12.5	0.3	0.7	1.7	99.2
Point 6 Line6	57.7	4.6	1.6	17.6	0.3	1.7	0.8	12.5	0.4	0.7	1.5	99.4
Point 7 Line6	58.2	4.7	1.5	17.4	0.3	1.6	0.8	12.7	0.4	0.7	1.4	99.7
Point 8 Line6	58.0	4.6	1.5	17.5	0.3	1.7	0.9	12.6	0.4	0.6	1.4	99.5
Point 9 Line6	59.6	5.3	1.6	15.6	0.3	1.4	0.7	13.0	0.4	0.6	1.2	99.7
Point 10 Line6	61.7	6.7	1.8	11.2	0.2	0.9	0.5	14.7	0.3	0.4	0.9	99.3
Point 11 Line6	63.6	7.9	1.9	7.5	0.1	0.6	0.4	16.1	0.1	0.3	0.6	99.1
Point 2 Line8	56.7	3.4	1.0	19.5	0.3	1.9	0.7	12.3	0.4	0.8	2.3	99.3
Point 3 Line8	56.9	3.4	1.1	19.2	0.3	1.8	0.8	12.7	0.4	0.8	1.8	99.2
Point 4 Line8	56.8	3.1	1.1	19.6	0.3	1.9	0.8	12.6	0.4	0.8	1.6	99.0
Point 5 Line8	56.8	3.0	1.1	20.1	0.3	1.9	0.8	12.8	0.4	0.8	1.5	99.5
Point 6 Line8	57.0	2.9	1.1	19.7	0.3	1.9	0.8	12.8	0.4	0.8	1.4	99.1
Point 7 Line8	57.1	2.7	1.1	19.9	0.3	1.9	0.8	12.9	0.4	0.7	1.4	99.2
Point 8 Line8	57.9	2.9	1.2	19.4	0.3	1.8	0.8	13.0	0.4	0.7	1.4	99.8
Point 9 Line8	58.2	2.9	1.2	18.9	0.3	1.7	0.8	13.1	0.4	0.7	1.3	99.5
Point 10 Line8	58.2	2.8	1.2	18.8	0.3	1.7	0.8	13.0	0.4	0.7	1.3	99.2
Point 11 Line8	58.2	2.8	1.2	18.8	0.2	1.6	0.9	13.0	0.4	0.7	1.3	99.1
Point 12 Line8	58.6	2.8	1.2	18.4	0.2	1.6	0.9	13.3	0.4	0.6	1.2	99.2
Point 2 Line9	59.1	4.7	1.3	14.9	0.3	1.3	0.6	13.8	0.2	0.6	2.3	99.1
Point 3 Line9	59.6	4.9	1.4	14.6	0.3	1.3	0.6	14.0	0.2	0.6	1.8	99.3
Point 4 Line9	59.9	5.0	1.4	14.0	0.3	1.3	0.7	14.2	0.2	0.6	1.5	99.1
Point 5 Line9	60.2	5.2	1.4	13.6	0.3	1.2	0.6	14.4	0.2	0.6	1.3	99.0
Point 6 Line9	60.7	5.3	1.4	13.4	0.3	1.3	0.6	14.4	0.2	0.6	1.1	99.3
Point 7 Line9	61.0	5.2	1.4	13.3	0.3	1.3	0.7	14.3	0.3	0.6	1.1	99.5
Point 8 Line9	61.3	5.4	1.4	12.9	0.2	1.2	0.6	14.5	0.3	0.5	1.0	99.3
Point 9 Line9	62.0	5.9	1.6	11.4	0.2	1.0	0.5	15.4	0.2	0.4	0.9	99.5
Point 10 Line9	63.0	6.4	1.6	9.9	0.2	0.8	0.4	16.1	0.2	0.4	0.7	99.7
Point 11 Line9	64.3	7.1	1.8	8.1	0.1	0.6	0.3	16.9	0.2	0.3	0.6	100.3

Four different smelting furnaces have been constructed. These experiments were carried out at the University of Kassel within a research project on *siliceous ceramic* "Türkis und Azur"[20]. The results of the experiment in furnace no. IV are presented here. Various objects consisting of steatite (= talc, a magnesium hydroxy-silicate), of sandstone or of a mixture of quartz plus additives were placed into the furnace on protruding edges of the furnace wall.

The experimental furnace no. IV was constructed of light colored slabs of sandstone. They were consciously loose-packed to replicate a rounded shaft (fig. 6) leaving tiny cracks and leaks, in accord with the archaeological evidence. The height of the shaft was ca. 50 cm. Larger interstices in the wall were filled from the outside with quartz-rich clay. The bottom of the furnace was also shaped with clay. Because of inadequate wind conditions at Kassel, ceramic pipes with 1 cm diameter were used as tuyeres to provide artificial air supply.

The front of the furnace was formed slightly rounded to obtain a complete glowing of the charcoal loading. The furnace bottom was formed concave just as at Feinan 9 with a gentle slope towards the slag tap hole. Because the front walls of the furnaces from Feinan are not preserved, the air – or wind-supplies were reconstructed based on experimental works and ethnographic evidence from Africa[21]. Our furnace, contained four tuyeres in the front wall, located to the right and left of the slag tapping hole. Here we followed the operating principles of medieval wind-powered iron smelting furnaces from Sri Lanka, which, as a rule, were equipped with a number of tuyeres[22].

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[20] See also VETTEL, 1999.

[21] KÖLSCHBACH *et al.*, 2000.

[22] HIRSCHBERG und JANATA, 1980 ; CELIS, 1991 ; JULEFF, 1996 ; HAUPTMANN, 2000 ; KÖLSCHBACH *et al.*, 2000.

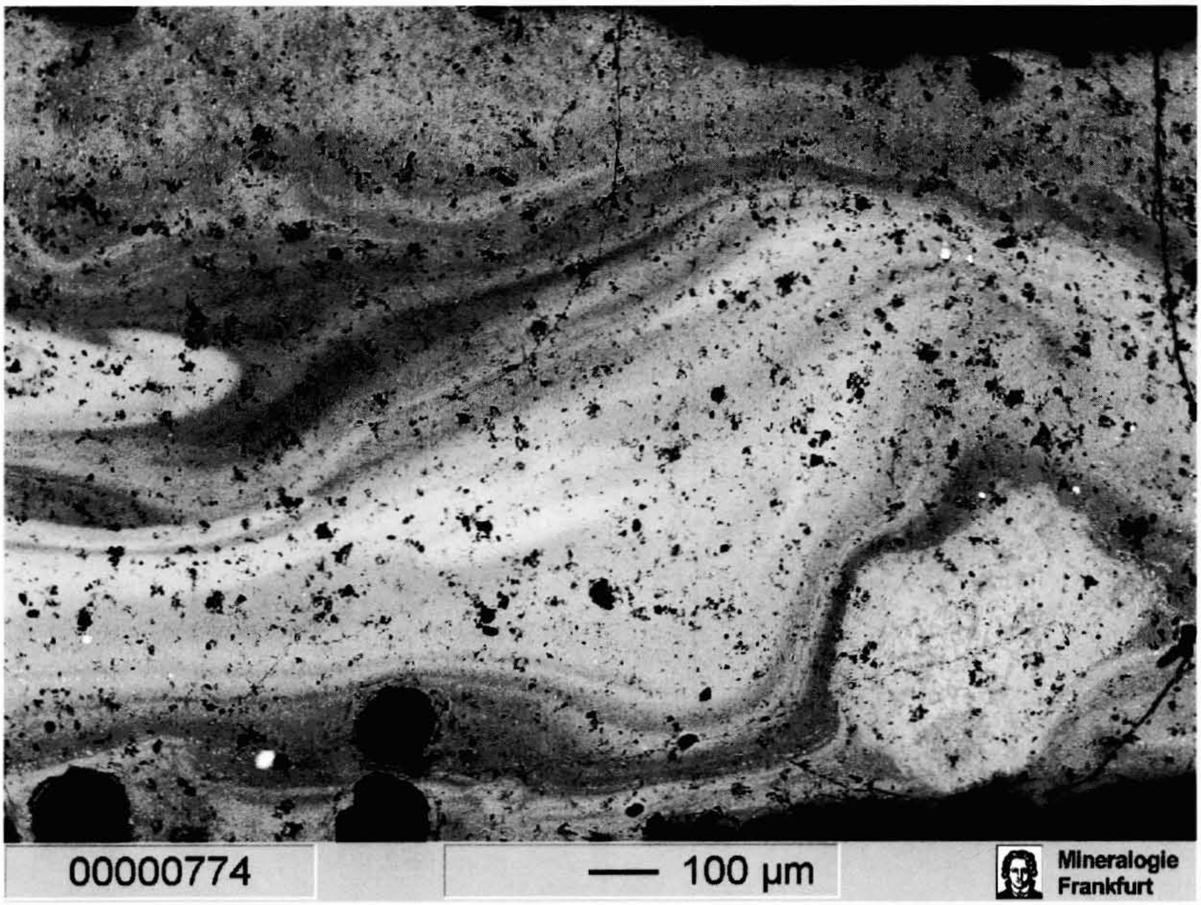

Fig. 4 : *Sample JD-5/12B, Ras en-Naqab (Feinan, Jordan). Greenish glazed sandstone slab used for furnace construction during the Early Bronze Age. The streaks are due to varying concentrations of different elements. Basically, the light streaks are enriched in copper. SEM-image, back-scattered electron mode.*

We wanted raw materials necessary for furnace construction, charcoal, and the ore charged to come close to the original raw materials composition [23]. The original salt contents of the ore, clay and sandstone from Feinan and Timna were simulated by the addition of 3 % of a mixture of the same amount of soda (Na_2CO_3) and sodium chloride ($NaCl$) or exclusive sodium chloride to the ore charge. The composition of the ore charge has been calculated for an eutectic slag formation, based on slag analyses from Timna and Feinan [24]. For the smelting process, copper ores and fluxes were crushed and mixed with carob grain flour, soda, sodium chloride, and were shaped to pellets of 3 cm in diameter. After this, the pellets were dried.

Furnace temperatures during smelting were measured at various spots at the inner part of the furnace wall (fig. 6) by platinum/platinum-rhodium thermocouples, which facilitated the recording up to 1 600 °C. Only one thermocouple was placed at the inner part of the furnace, in the race near the bottom. Oxygen was supplied by compressed air and measured by means of flowmeters for each of the tuyeres.

EXPERIMENTAL RESULTS

The furnace was preheated with charcoal and artificial air supply [25]. After preheating, it was charged alternately with ore

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[23] See chemical analyses in VETTEL, 1999.

[24] VETTEL, 1999 ; WERTHMANN, 1999.

[25] VETTEL, 1999.

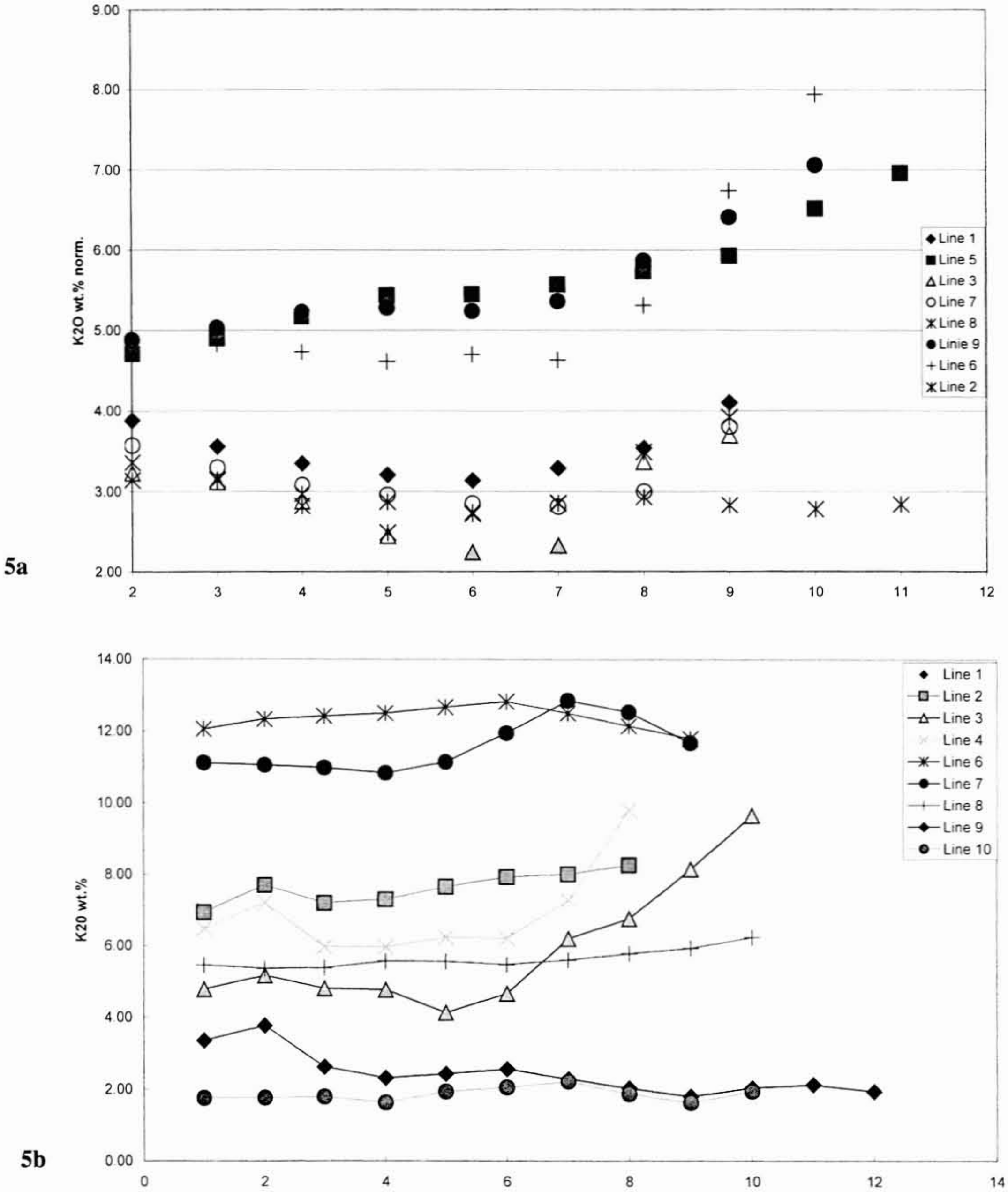

Fig. 5 : *Samples JD-5/12A (a) and JD-5/12B (b), Ras en-Naqab (Feinan, Jordan). Distribution of potassium oxide (K_2O) in glazes on furnace fragments made of sandstone. The microprobe analyses were taken stepwise from the glazes surface (point 1, 2) to the glaze – sandstone – interface (points 9-11). See also Table 1.*

and charcoal. The smelting process was successful and a satisfying separation of the liquid copper from slag took place. The experiments showed that the actual reaction zone of this furnace type was limited to the front part of the furnace and especially to the area where tuyeres were located; here, the inner part of the furnace was slagged. Next to the tuyeres, in the race, temperatures of up to 1 500 °C could be measured. The metal reduced from the ore was found in fist-sized lumps lying directly in front of the tuyeres. In contrast, charged material at the bottom and the back wall of the furnace

Table 2 : *Description in which parts of the furnaces and under which conditions glazes were formed during experimental copper smelting. Results from experiment no. 9 in furnace IV. Additional data : 4 tuyeres (furnace front) ; height of furnace : 48 cm, volume : 16 liters, air supply per tuyere : 1,6 m*^{3}*/h ; charging time (= "sputtering time") : 4 h. For position of thermocouples (T1, T2, T3) see figure 6.*

	Height inside furnace above bottom					
Experiment 9	**48 – 34 cm** **Inv. no. VI/2 0**	**34 – 28 cm** **Inv.no. VI/2 1a-d**	**28 – 23 cm** **Inv. no. VI/2 2a-c**	**23 – 14 cm** **Inv. no.. VI/2 3a-g**	**14 – 10 cm** **Inv. no.VI/2 4a-e**	**10 – 0 cm** **(Bottom)**
Temperature		800 - 1000°C (1)		1000 - 1200 °C (2)		1200 - 1500°C (3)
Glaze	No	Poor	Strong	Extraordinary strong	Extraordinary strong	Extraordinary strong
Position in furnace	–	Front above tuyeres + 20 cm to each sidewall	Entire front wall + 20 cm to each sidewall	Entire front wall + 20 cm to each sidewall	Entire front wall + 20 cm to each sidewall	Entire front wall + 20 cm to each sidewall
Position on sandstone slabs	–	In cracks underside	In cracks underside + on sidewalls above tuyere. Partly on side directed to furnace.	In cracks underside + on sidewalls. Partly on side directed to furnace.	In cracks on top and underside, on sidewalls. Partly on side directed to furnace.	On bottom near furnce front and in cracks on sidewalls. Partly on side directed to furnace.
Depth of glazing	–	Top:- Underside up to 6 cm	Top 3 cm Underside up to 6 cm	Top up to 5 cm Underside up to 12 cm	Top up to 5 cm Underside up to 12 cm	Top up to 8 cm
Color	–	Blue, red, also black	Blue and olive green	Blue and red	Blue and red	Blue, olive green and red
Test objects	-	-	Beads partially blue glazed.	Beads partially blue and red glazed.	Beads heavily blue glazed. Strong glazing on bead in niche 5 cm from furnace inside.	Beads partially blue glazed.
Remarks	Sandstone slabs show firing.	Sandstone slabs heavily slagged.	Inside furnace heavily slagged	Inside furnaces heavily slagged. Sandstone slabs covered by slag layer. Clay vitrified.	Thick slag layer. Beads stick to sandstone slabs.	Beads stick to vitrified clay.

had not significantly reacted. Such parts remained mainly intact. These results are in accordance with the archaeological evidence, and with results achieved by experimental smelts at Feinan [26].

Previous experiments at Kassel have shown that glaze formation on the surface of sandstone slabs of the furnace wall was a regular phenomenon, no matter if the smelting process itself was successful or not [27]. The character of the glazes produced, at least macroscopically, were identical to the archaeological evidence, but clearly blue colored glazes prevailed. These colors were formed in the interstices between the sandstone slabs of the furnace wall (pl. VIII : 2-5 and table 2), *i.e. not* in the actual reaction zone of the furnace where ore was transformed to metal. Glaze formation was limited to the lower 2/3 of the furnace, and especially to the front parts of the furnace, the tuyeres and the two lateral areas of the wall. Significant glaze formation was observed in a temperature range from 1 000 to 1 400 °C, approximately from 25 cm below the upper part of the furnace [28]. This corresponds to a range of temperatures which in general lies approx. 200 to 400 °C above the minimum temperature required for glaze formation. The different colors appeared one next to the other : red glazes were formed at the inner side of the wall and blue and green glazes further outside, between leaks and interstices. This association bears a striking similarity to the archaeological record.

As for the blanks of sandstone and quartz mixture, they were partly coated with a blue or green glaze too. The steatite objects took a bluish color, but were not glazed (pl. VIII : 2-5). It is of interest, that the quality of these glazes are obviously not negatively affected by tiny particles of charcoal, as suggested earlier [29].

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[26] HAUPTMANN, 2000 ; KÖLSCHBACH *et al.*, 2000.

[27] See also VETTEL, 1999.

[28] The classification of the intensity of the glaze was carried out by visible criteria. Further experiments with more exact, small dimensional temperature monitoring and analytical valuation of the intensity of the glazes are under study.

[29] NICHOLSON and PELTENBURG, 2000.

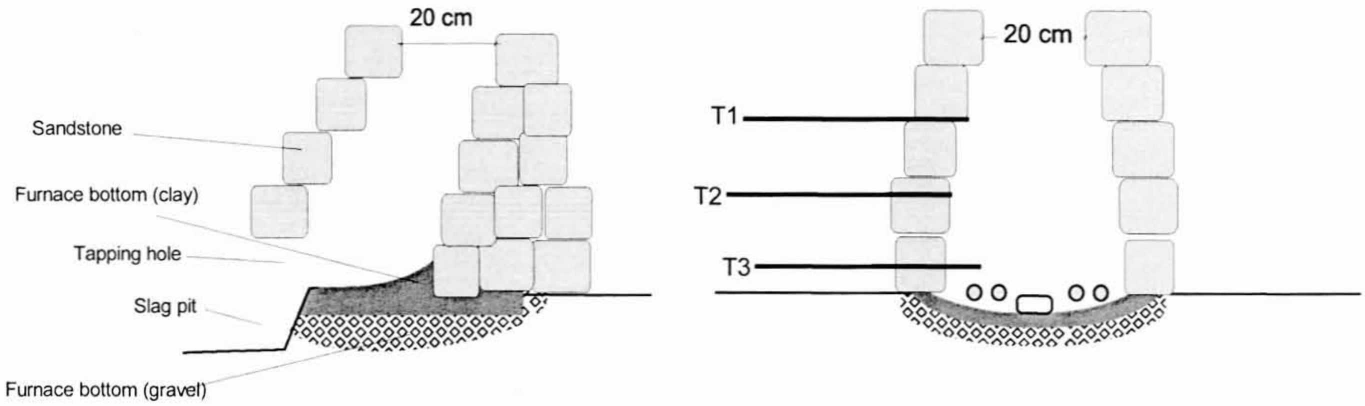

Fig. 6 (a, b) : *Sections of experimental furnace no. IV. The furnace wall was constructed with sandstone slabs. The furnace bottom was made of fire-clay and sandstone gravel. Four tuyeres were set into the front wall next to the tapping hole. Note the inclined furnace bottom which was made in accord to the archaeological evidence. Temperatures were measured by two thermocouples (T1 = 35 cm, T2 = 20 cm above furnace bottom) at the furnace wall; T3 was positioned in the reaction zone (5 cm above furnace bottom).*

COMPOSITION OF GLAZES FROM SMELTING EXPERIMENTS

Investigations to determine the chemical composition of the experimentally produced glazes were carried out at the Potash Research Institute, Heringen, by K + S Consulting GmbH at Kassel. Surface-polished sections of glazed fragments were analyzed using a scanning electron microscope (type LEO S 430) coupled with an electron beam microprobe (type RÖNTEC EDWIN). Micrographs were taken by a QRE detector in the backscattered electron mode, thus showing as clear as possible the distribution of lighter and heavier elements.

Figure 7 shows a section of a sandstone slab coated by a green glaze with a thickness of approximately 150 µm. The chemical composition of the glaze is basically similar to the archaeological material reported above. It is, however, considerably higher in potassium and copper. Significantly, potassium predominates over sodium (table 3)[30]. This is in contrast to archaeological glazes of ancient siliceous ceramics, which due to their production techniques consist of sodium silicates[31].

Detailed measurements were carried out on blue-, green- and red-colored glazes. In each sample, of 15 by 15 µm squares were analyzed stepwise from the surface to the glaze – sandstone interface as indicated in table 3 and figures 7 and 8. As a rule, SiO_2 – concentrations show little variation in the glaze's surface (62 to 66 wt. %). SiO_2 slightly increases in the inner part of the glaze and reaches its maximum in the sandstone. Potassium is nearly constant on the glaze's surfaces in all three samples, ranging from 11 % to slightly above 13 % (13 % to 16 % K_2O) on the surface and slightly decreasing towards the sandstone. The behavior of calcium is similar. As the sandstone itself is low in potassium (below 1 wt. %), and in calcium, these enrichments are due to the charcoal charged together with the ore itself.

More than two-thirds of the glaze is thus composed mainly of SiO_2, K_2O and CaO. Aluminum is unevenly distributed in the glaze, due to its spot-like occurrence in the matrix of the sandstone. The concentrations of the other elements show larger relative variations between green, blue and red glazes. The copper concentrations are of particular interest. They decrease from the surface of the glaze (2-8 wt. %) to the sandstone by about 50 %. This points to a later deposition of copper-rich glaze, whereas a glaze layer low in copper was built up right from the beginning by a reaction between the potassium oxide produced by burning charcoal and the sandstone itself. As copper ore was charged several hours later, when the furnace reached its operation temperature, it was successively enriched in the upper layer of the glaze. In contrast to green and blue glazed objects from archaeological contexts, where it is a major component, sodium oxide is just around 1 wt. % and distributed similarly to copper in the glaze because rock salt was added together with the copper ore. Unevenly distributed concentrations of iron in the glaze result from ore, forming spots of iron-silicates in the glaze.

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[30] Concerning the vaporization of Na_2O and $_2O$ and the resulting alkali contents in the glazes of the furnace fragments cf. WERTHMANN, 1999.

[31] VANDIVER, 1982a, b; BUSZ und SENGLE, 1999; BRANDT, 1999.

Table 3 : *Microprobe analyses of glazes from experimental copper smelting. All values in weight percent. See also Figures 7, 8. n.d. = not detected.*

	SiO_2	K_2O	CaO	Al_2O_3	CuO	FeO	MnO	Na_2O	MgO
Blue Glaze									
A	63.3	16.0	5.4	5.7	5.8	1.2	0.7	1.5	0.4
B	64.3	15.8	5.0	6.2	5.1	0.9	0.7	1.5	0.5
C	66.7	16.6	5.4	3.1	5.1	1.1	0.8	0.8	0.4
D	66.9	16.5	5.5	3.3	4.5	1.3	0.8	0.8	0.4
E	67.6	16.5	4.7	2.9	3.8	2.5	0.6	0.8	0.6
F	69.5	15.9	3.9	2.9	3.3	2.6	0.6	0.8	0.5
G	73.8	14.5	3.8	1.4	2.9	1.7	0.6	0.8	0.5
H	97.2	0.6	0.1	1.7	0.2	0.1	n.d.	n.d.	0.1
I	97.8	0.1	0.1	1.7	0.1	0.1	n.d.	n.d.	0.1
Green Glaze									
A	62.8	13.5	6.0	2.7	9.9	3.0	1.2	0.2	0.7
B	62.9	13.5	6.5	2.9	9.0	2.9	1.0	0.4	0.9
C	63.5	13.5	6.6	3.0	8.1	2.9	1.0	0.4	1.0
D	64.4	13.4	6.2	2.6	8.1	3.0	1.2	0.3	0.8
E	64.5	13.4	6.1	2.6	7.9	3.2	1.2	0.2	0.9
F	65.8	13.3	5.8	2.6	7.0	3.0	1.3	0.3	0.9
G	67.8	13.5	4.7	3.5	5.8	2.4	1.2	0.3	0.8
H	72.4	12.0	3.7	3.1	4.9	1.6	0,9	0.3	1.1
I	96.9	0.4	0.1	1.8	0.4	0.1	0,1	0.1	0.1
Red Glaze									
A	65.8	13.2	7.6	6.4	2.8	2.1	1.0	0.4	0.7
B	66.3	12.8	7.6	7.1	2.0	1.8	0.8	0.4	1.2
C	66.0	12.9	7.9	6.8	2.0	1.9	1.0	0.4	1.1
D	68.1	12.5	6.6	7.4	1.6	1.5	0.9	0.4	1.0
E	69.8	12.0	5.8	7.5	1.8	1.2	0.8	0.3	0.8
F	70.7	12.0	5.3	7.7	1.5	0.9	0.7	0.3	0.9
G	92.0	0.9	0.4	6.0	0.2	0.1	0.1	n.d.	0.3
H	100.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

GLAZE FORMATION IN THE EXPERIMENTAL SMELTING FURNACE

The conditions that lead to glaze-formation in the experimental smelting process were described previously[32], and they can be compared with observations we made. The furnace charge is liquefied, reacts with charcoal ash and eventually with the furnace lining in the lower part of the shaft and forms a liquid slag, while volatile elements such as chlorides and in part alkali oxides (K_2O, Na_2O) vaporize and escape with the fume. In addition, these elements in their gaseous state react with the sandstone of the furnace wall at temperatures of at least 900 °C and quickly form a colorless alkali melt, which will be colored blue or green by the vaporization of small amounts of copper chloride. In the glazes, no equivalent chloride content is detectable (table 3). It is known that copper chloride is absorbed by the melt in the gaseous state, but the chlorine itself escapes as alkali chloride or hydrochloride acid[33]. Variables controlling the formation of glaze are furnace temperature, alkali and chloride concentrations in the material charged (charcoal, ore) into the furnace, and the oxygen content of the gas atmosphere.

The formation of bluish (or greenish) colored glazes is based upon the take-up of divalent copper in the liquid glaze and, hence, depends on a surplus of oxygen. It is restricted, therefore, to the areas of the tuyeres, the tapping hole, or such parts of the shaft, where oxygen enters the furnace by cracks and leaks. Eventually, the colors might have been influenced by trivalent iron, giving a more greenish color by a mixture of blue (Cu^{2+}) and yellow (Fe^{3+})[34]. Red colored glazes were formed in those parts of the furnace where a slightly more reducing atmosphere prevailed. Occasionally observed purple, black and transparent glazes were not analyzed. These colors are due to the manganese contents of the ore charge, or can also originate from the charcoal. In these cases, the color depends on the composition of the gas atmosphere in the furnace : if oxygen is in surplus, bivalent colorless manganese will be oxidized to its trivalent form. This causes colors of rich purple to black[35]. Two furnace fragments were colored

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[32] BERGER und BRANDT, 1997.

[33] See also WERTHMANN, 1999.

[34] Compare also WEYL, 1951.

[35] WEYL 1951.

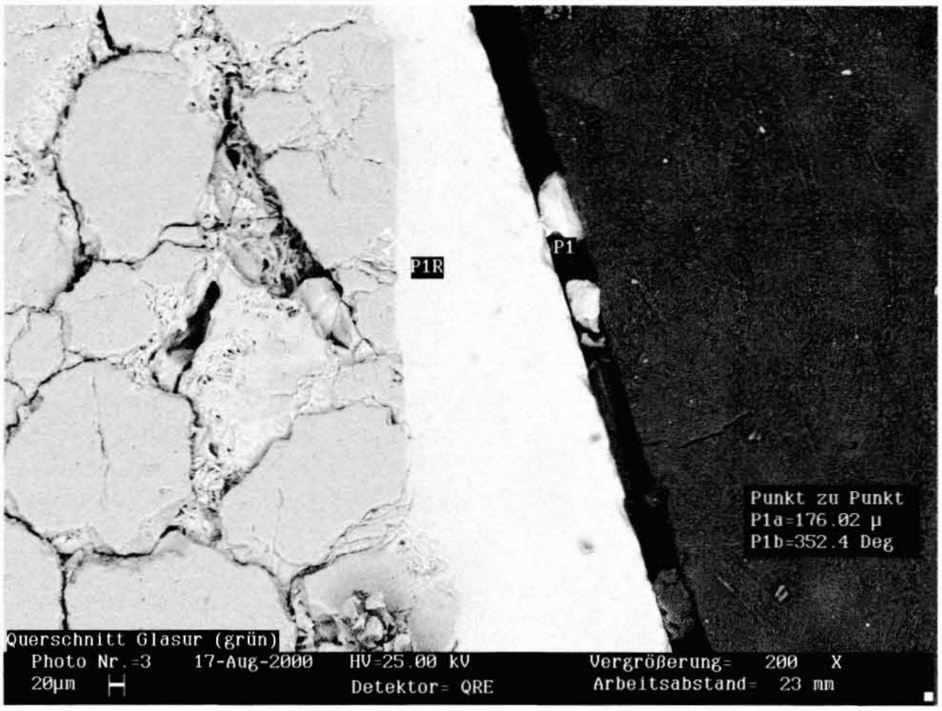

Fig. 7 : *Micrograph of green glaze on sandstone produced by experimental smelting. The rather homogeneous glaze shows a bright shade due to higher concentrations of heavy elements such as potassium, copper, calcium and aluminum. Indicated is as an example the line (P1 – P1R) from the rim to the transition glaze-sandstone where EDS-measurements were stepwise taken in several samples (see Table 3). SEM-picture, back-scattered electron mode.*

by a striking ink-blue glaze. This is due to minor cobalt concentrations in the sandstone used for furnace construction.

Like magnesium, calcium and aluminum, divalent copper improves the weather resistance of a glaze. This had already been proved by previous investigations of ancient objects made of siliceous ceramic [36]. In the course of time, pure alkali silicate would liquefy as water-glass in contact with moisture. Different elements have different tendencies to vaporize under the applied conditions. Elements irregularly distributed in the glaze such as aluminum, iron, or magnesium are likely to be less volatile, whereas the distributions of potassium, sodium, copper and calcium result from depositions from a vapor phase [37].

CONCLUSIONS

Looking into the chronological window of the full developed EBA in the third millennium BC in the southern Levant and Sinai we state that metallurgical processes of copper smelting and the production of "Egyptian faience" as described in this paper, represent two technologies of high-temperature craftsmanship at an advanced stage. The production of "Egyptian faience" is a multi-step technology with primary processing of raw materials such as crushing and grinding and shaping a SiO_2-rich body with calcium oxide, the preparation of the faience itself, and finally the firing process that leads to an alkali(Na_2O) – silicate-glaze colored by a dose of copper. The finds of thousands of wall-tiles used in the Third-Dynasty pyramid of Djoser at Saqqara represent the best example. Copper smelting was based upon mining and beneficiating ores; the smelting process itself led to the production of metal which was separated from slag for the most part in the liquid state. The metal was further processed by re-melting, casting, and hammering. Copper objects were at that time used for

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[36] VANDIVER, 1982a, b; TITE *et al.*, 1983; BERGER und BRANDT, 1997.

[37] BERGER und BRANDT, 1997.

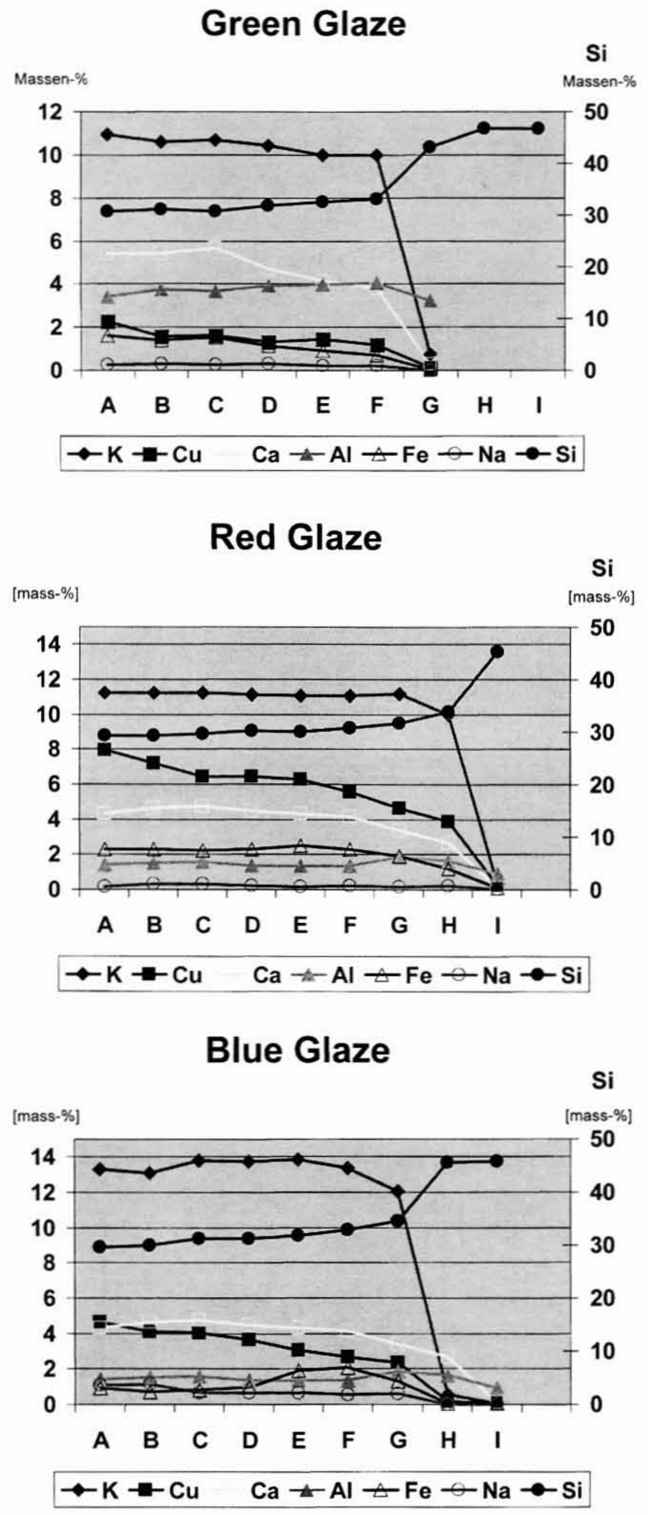

Fig. 8 : *Microprobe analyses of experimentally produced green, blue and red glazes on sandstone slabs. The analyses were taken stepwise between the rim (P1...) and the transition glaze-sandstone (see also figure 7). All values given in weight percent.*

daily life purposes of social communities. The goals of these processes were focussed in different directions. For glaze production, an oxidizing gas atmosphere had to be kept in the reaction vessel, in which divalent copper was incorporated in the alkali melt. This is in full contrast to the principle of copper smelting, which requires stronger reducing conditions to enable metal reduction from ores in the liquid state.

Taking this starting point we seem to be faced with technological and chronological problems. Blue glazed objects were discovered in Egypt (and in Mesopotamia as well) long before the EBA smelting furnaces in the Arabah were operated. This might be seen as hampering the hypothesis that copper metallurgy is the ancestor of glazing techniques. We believe, however, that this discrepancy is probably due to an absence of evidence in the archaeological record and may be balanced out by other observations.

In the history of early high-temperature processes, glazes do not appear before the rise of extractive metallurgy in the Old World, during the Chalcolithic in the 5th/4th millennium BC. The tradition of making pottery was old at that time, but glass itself was still unknown. Other than in archaeometallurgy, where early craftsmanship of copper-, silver-, lead- and gold-(s)melting can be traced back to its very beginning by numerous finds from workshops or factories, evidence on the roots of glaze-production are non-existent. This is true until the Middle and Late Bronze Age (in Egypt Middle and New Kingdom) when excavations has brought to light sufficient basic informations for reconstructing glaze making[38].

The earliest indication of glaze formation is, at the same time, actually a link to copper metallurgy. It is represented by red glazed crucible fragments from Chalcolithic sites in the Beer Sheva-Basin, namely from Abu Matar. Even if these glazes show another color from that of the earliest glazed objects, they are of comparable elemental composition and provide evidence that alkali-silicates with small amounts of copper are formed by crucible smelting[39]. This is worth mentioning because it underlines, as the arguments in this paper do, the necessity of high temperature firing for making glazes. If it was argued before that the earliest production of faience would share much in common with cold working technology[40], then it can only be true for the primary processing of raw materials and the shaping of the objects, and not for the firing itself.

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[38] NICHOLSON and PELTENBURG, 2000.

[39] VETTEL, pers. comm. The author presently works on a larger investigation on glazes and their possible origin in metallurgy. Parallels between these earliest glazes and metallurgy will be outlined in "Der Ursprung der Kieselkeramik. Ägyptische Fayence, Quarzkeramik, Ägyptisch Blau".

[40] See NICHOLSON and PELTENBURG, 2000.

At the transition from the Chalcolithic period to the beginning of the EBA, the archaeological evidence of safely dated high-temperature reaction vessels is, for the time being, nonexistent. We are not informed on technological developments in metallurgical furnace constructions, and, again, there is no evidence at all on any kilns or vessels used for glazing beads or other objects. The copper smelting furnaces at Feinan and the fragments found at Timna 149, more than 1 500 years later, are the next tangible proof for any reconstruction of our topic. They provide better informations on possible firing techniques than the kilns found at Abydos. At least, after this great leap, we have now information of a simple process whereby blue (and green) glazes have been formed unintentionally, by an accidental coincidence of suitable compositional and thermodynamic parameters. It is not by chance that these glazes are associated with red colored variations which we observed too in our experimental material. This is the compositional environment of the complex "furnace wall – charcoal/ash – fume". It might be described as a system consisting mainly of $K_2O(+Na_2O)$(= alkalis !) – $CaO(+Al_2O_3)$ – SiO_2, dotted with copper and chloride. Herewith it comes closest to the compositional system necessary for making blue (and green) glazes, which, in an advanced stage of development (cementation) is $Na_2O(+K_2O)$ – CaO – SiO_2, with sodium to be the major alkali-oxide. The "missing link" between copper metallurgy and faience production, hence, is the transition from potassium to sodium. The range of firing temperatures necessary for melting this composition is around 900–1 000 °C. This matches our observations : glazes found in cracks and leaks at the walls of copper smelting furnaces – in those from the archaeological context, and in those used for experimental work as well – were formed in a range of temperatures that, for copper smelting itself are too low.

It might be shown by future research whether the geographic proximity to Egypt and the availability of suitable raw materials for glazing at Feinan/Timna have been fortuitous or not. But these results show at best what is called a trial and error phase in the history of technology : self-going processes leading by chance to products of ideal or non-ideal composition. Our observations in the copper smelting furnaces at Feinan/Timna, and at Kassel, are basically time-independant models, and are probably also applicable to earlier furnaces of a shape and design unknown to us.

Within the history of metallurgy, it is generally accepted that man went through an experimental phase[41] which, in the 5th/4th millennium BC, is characterized by numerous "exotic" compositions of metal objects. During this period, deliberate selection and mixing of various raw materials (for instance the deliberate use of fluxes) to improve the quality and quantity of smelting processes, and to optimize the separation of metal in the liquid state, was hardly practised[42]. There is no basis for any claim for a more advanced technology in glaze production that was outlined above. On the contrary, it is significant to note that the earliest "glazed" objects provide a variety of different colors and compositions that support this model[43]. It could be demonstrated by laboratory investigations that glazes are formed in a large range of compositional variety within the system SiO_2 – CaO – Na_2O/K_2O – MgO – Al_2O_3 – CuO, even without adding alkali-salts[44]. An example of an "accidental" glaze formation might be exemplified by an experiment carried out in the laboratories at Kassel[45] where several specimens of copper containing sandstone were heated in a kiln at temperatures of approximately 1 000 °C. By adding some sodium-containing salts, the ore easily formed an alkali-silicate glaze which was colored by copper. Sodium for glaze formation is not basically necessary, and it can be replaced by potash from charcoal ash. Both are "fluxes", useful tools to enhance glaze formation at lower temperatures or within a shorter period of time.

Skilled craftsmanship to develop controlled glaze production in later periods is a logical consequence. A superb example of how several different crafts can evolve with a variety of final products by using a limited range of raw materials such as copper or copper ores comes from LBA Piramesse-Qantir, where an enormous bronze-working factory to cast items as heavy as 100 kg was excavated. Close by, mass production of faience and glass took place and along with the manufacture of Egyptian blue[46]. This industrial quarter was obviously specialized in high-temperature processes, and specialists reliably controlled the various states of oxidation of copper which are necessary to produce red and blue glass, and red, blue or green faience.

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[41] STRAHM, 1994 ; BACHMANN, 1980.

[42] *Contra* MERKEL and ROTHENBERG, 1999.

[43] WARTKE, 1999.

[44] BERGER und BRANDT, 1997 ; BRANDT, 1999.

[45] BUSZ und SENGLE, 1999.

[46] REHREN and PUSCH, 1997 ; REHREN, 1999.

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