ANCIENT MINING AND SMELTING ACTIVITIES IN THE WADI ABU GERIDA AREA, CENTRAL EASTERN DESERT, EGYPT: PRELIMINARY RESULTS*

Y. ABD EL-RAHMAN,† A. A. SUROUR, A. H. W. EL MANAWI, M. RIFAI, A. ABDEL MOTELIB, W. K. ALI and A. M. EL DOUGDOUG

1Geology Department, Faculty of Science, Cairo University, Giza 12613, Egypt
2Faculty of Earth Sciences, King Abdulaziz University, Jeddah 80200, Saudi Arabia
3Conservation Department, Faculty of Archaeology, Cairo University, Giza 12613, Egypt
4Saudi Geological Survey, Saudi Arabia
5Supreme Council of Antiquities, Cairo, Egypt

Old mining and smelting features in the Abu Gerida area have been studied using field observations, microscopy and SEM–EDS to detect the ores that were exploited in antiquity. There are two groups of shafts in the area. The first group encloses secondary copper minerals and is associated with glassy slags containing copper prills. The other group is associated with hematite that was extracted and transferred to a smelting station to the west of the mining site, where iron slags and charcoal fragments are found. These slags are composed mainly of wüstite, fayalite–kirschsteinite and traces of metallic iron. Pottery fragments from this area were dated to the Ptolemaic Period, which may be the age of iron exploitation. Copper might have been exploited earlier.

KEYWORDS: IRON, COPPER, MINING, SMELTING, EASTERN DESERT, EGYPT

INTRODUCTION

The Eastern Desert of Egypt (Fig. 1 (a)) was a principal gold-producing area in ancient times. Klemm et al. (2001) linked the legendary wealth in gold of ancient Egypt to the high number of gold mining sites in the Eastern Desert. The oldest mine map in the world was made during the reign of Ramses IV (1151–1145 BC) to depict the settlements of one of these gold mining sites at the Fawakhir area and to show the hills within which the gold veins occurred in the central Eastern Desert (Bromehead 1940; Harrell and Brown 1992; Habashi 2005). In addition to gold, the Eastern Desert was a source for other ores such as copper, iron and lead (Lucas 1962; Afia 1985; El Gayar and Jones 1989; Scheel 1989; Castel et al. 1995). Nevertheless, among geologists it is common to assign any ancient settlements and excavated shafts in the Eastern Desert to gold mining. Such a practice may have led to an underestimation of ancient mining and smelting activities for ores other than gold from the Eastern Desert.

Wadi Abu Gerida (Fig. 1 (a)) is an example of the uncertainty over the type of ore that was extracted from ancient shafts. Barron and Hume (1902, 257) and Forbes (1964, 181) pointed to the Abu Gerida area as a source of iron, due to the presence of specular hematite, while El-Mansi (1994) mentioned that the area was used to exploit gold during ancient times. Harrell (2005) cited the unpublished work of Barnard and Sidebotham, to show that both iron and gold were extracted

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†Corresponding author: email yasser@sci.cu.edu.eg
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Figure 1  (a) A location map of the Abu Gerida area in the Eastern Desert of Egypt. (b) A Google Landsat image of Wadi Abu Gerida, showing the ancient mining and ore smelting sites. (c) A geological map of the tributary of Wadi Abu Gerida, enclosing the ancient worked shafts (modified after Abdel Naby et al. 1977; Minex 1991).
during Ptolemaic times. In addition to gold and iron, Afia (1985, 229) mentioned that copper was also exploited from Wadi Abu Gerida during Roman times. Such controversy over the type of ore extracted comes from the inadequate geological observations on the shafts, and the absence of integration between such geological information and the archaeological finds in the area.

OBJECTIVES AND METHODS

The objectives of this study are to determine the type of ores that were extracted from the shafts in the Wadi Abu Gerida area, to understand ancient ore smelting activities in the area, and to consider the ore exploitation from an archaeological perspective. To achieve these objectives, field observations of the shafts and the smelting sites were conducted. This study is a preliminary investigation in which all of the samples were collected from the surface, with no excavation conducted, and a detailed survey still needs to be accomplished in the area.

For this pilot study, eight samples of the ores and four of the slag were examined using a polarized transmitted light and reflected light microscope along with a scanning electron microscope (SEM). The slag phases were analysed chemically using micro-energy dispersive X-ray fluorescence spectrometry (micro-EDX). The microscopic investigation was carried out using a Nikon Optiphot-Poll polarized microscope equipped with a fully automatic microphotographic unit (Nikon FX32) at the Geology Department, Cairo University. Two samples were examined by SEM, housed at the Central Laboratory of the Egyptian Geological Survey and Mining Authority (EGSMA). The SEM model was a Philips XL30, with an EDX unit attached, working at an acceleration of 25 kV. The samples examined by SEM were coated with thin carbon film.

GEOLOGICAL FRAMEWORK

The area under consideration is a part of the central Eastern Desert of Egypt (Fig. 1 (a)). The Eastern Desert constitutes the north-western extension of the Arabian–Nubian Shield. A general background on the Eastern Desert and the Arabian–Nubian Shield can be found in Klemm et al. (2001) and Antonelli et al. (2010). The area is located to the south of the Qena–Safaga road that connects the Nile Valley and the Red Sea Coast (Fig. 1 (a)). The area is traversed by Wadi Abu Gerida. All of the ancient mining sites are located in a small tributary of Wadi Abu Gerida (Fig. 1 (b)). Only a small ore smelting site is located in this tributary. Another smelting site is located close to the intersection of Wadi Abu Gerida with Wadi Maghrabiya, to the east of the mining sites at the mouth of Wadi Hamama (Fig. 1 (b)). The small tributary of Wadi Abu Gerida is called ‘Wadi Hamama’ by local Bedouins. This name will not be used here for such a tributary, to avoid confusion with the main Wadi Hamama. Because the ancient mining activities are concentrated in this tributary, its geology will be considered in detail.

Similar to most of the rocks in the central Eastern Desert, Wadi Abu Gerida is covered mainly by igneous and metamorphic rocks of the Neoproterozoic age (Fig. 1 (c)). These Neoproterozoic rocks are non-conformably overlain by Phanerozoic clastic sedimentary rocks, known as Nubian Sandstone, of either Palaeozoic or Mesozoic age. The Neoproterozoic volcanic rocks are the dominant rock unit in the area (Fig. 1 (c)). They comprise basalt, dacite and rhyodacite and their volcaniclastic equivalents. The volcaniclastic rocks are differentiated into banded tuffs, lapilli tuffs, and volcanogenic greywackes and conglomerates. All these rocks were metamorphosed under low-grade greenschist facies conditions, which changed most of their primary mineralogy, but their igneous and sedimentary fabrics are still preserved. The volcaniclastic layers alternate
with iron-rich bands. The iron bands are composed of variable proportions of minute hematite and magnetite crystals, forming laminae that alternate with jasper laminae. The contact between the volcanic rocks and the volcaniclastic rocks is marked by the presence of quartz–carbonate body as well as shearing (Fig. 1 (c)). The volcanic rocks close to the quartz–carbonate bodies are highly altered. The contact is also marked by the occurrence of secondary green copper minerals. The volcanic and volcaniclastic rocks are intruded by a variety of plutonic rocks, including tonalite–trondhjemite, quartz–diorite and quartz–feldspar porphyry dykes (Fig. 1 (c)). The tonalite–trondhjemite body hosts numerous quartz–specularite veins, especially close to its contact with the volcanic rocks. The quartz–feldspar porphyry dykes are the youngest Neoproterozoic rock unit and extend along the NE–SW direction (Abdel Nabi et al. 1977; Minex 1991).

OBSERVATIONS RELATED TO MINING ACTIVITIES

On the basis of the geology of the area, the shafts can be clustered into two groups. The first group is localized in or close to the quartz–carbonate body (Fig. 2 (a)). The second group is located within the tonalite–trondhjemite rocks (Fig. 3 (a)). The quartz–carbonate body, which encloses the first group of shafts, shows a noticeable variation in thickness (Fig. 1 (c)). The body separates the hydrothermally altered volcanic rocks on the northern and north-western side from the unaltered to slightly altered volcaniclastic rocks on the southern and south-eastern side. The exploited segments of the body are represented either by stretched shafts with sheared walls or by wide pits (Figs 2 (b) and (c)). Three shafts, out of six, are located within the highly altered and sheared volcanic rocks, but very close to the quartz–carbonate body. Copper mineralization is widespread in these shafts and pits, and is represented by secondary green minerals (Fig. 2 (d)). These minerals are recorded as patches along the walls of the shafts and pits and as veinlets dissecting the sheared altered volcanic rocks and carbonates. Microscopically, the ratio of carbonate to quartz varies in the quartz–carbonate body. Calcite and dolomite are the main carbonate minerals and are associated with malachite. On the contrary, chrysocolla is identified in the sheared volcanic rocks containing oxidized pyrite crystals. Red and yellow ochreous iron minerals are associated with the secondary copper minerals. Surour et al. (2006) recorded the presence of paratacamite along with malachite and chrysocolla.

The second group of shafts is enclosed within the tonalite–trondhjemite mass at the tributary of Wadi Abu Gerida. These shafts are steeply dipping and more or less parallel to each other and generally have a north–south to NNE–SSW tend (Fig. 3 (a)). The largest shaft is about 4 m wide and extends from the contact with the mafic volcanic rocks into the tonalite–trondhjemite mass. Three shafts out of 10 are bifurcated (Fig. 3 (b)), where the shafts revolve around standing ledges composed of brecciated quartz cemented by hematite. The hematite has a specular or micaceous form (specularite). The walls of the shafts contain small specularite offshoots (Fig. 3 (c)), and less commonly quartz–specularite veinlets. Generally, the tonalite–trondhjemite mass is heavily dissected by specularite, quartz–specularite and quartz veins. Their size is variable, ranging from microscopic to less than a metre wide. A few specularite–quartz veins are also recorded in the tonalite–trondhjemite mass of the main course of Wadi Abu Gerida. These veins have limited thickness, up to 40 cm wide, and are composed of massive specularite margins surrounding a vugy specularite-bearing quartz core (Fig. 3 (d)). The enrichment of specularite along the margins of veins was also recorded by Barron and Hume (1902, 51). The hematite along the margin is smaller in size and more massive than the specularite associated with the quartz core.
Figure 2  (a) A Google Landsat image showing the main ancient copper mining sites (arrows), the copper smelting site (rectangle) and the miners’ settlements (circles), enlarged from Figure 1 (b). (b) An ancient shaft enclosed in the quartz–carbonate body along the contact with altered sheared volcanic rocks. (c) A mined pocket within the quartz–carbonate body along the contact with the volcaniclastic rocks. (d) Secondary green copper minerals (arrow) on the wall of the shafts.
Figure 3  (a) A Google Landsat image of the mining area for iron ore, showing the largest mined shaft (arrow), enlarged from Figure 1 (b). (b) Bifurcated mined shafts. (c) A specularite offshoot dissecting the wall of one of the shafts. (d) An intact quartz–specularite vein with massive specular hematite margin (arrow) and a white quartz core.
Microscopically, hematite forms aggregates of flaky crystals that cross-cut each other, radiating into a rosette form (Fig. 4 (a)) or folding in an irregular manner. Some of the specular hematite laths are partially to completely engulfed by goethite, which is mostly pseudomorphic after pyrite cubes (Fig. 4 (b)).
A number of small ancient dwellings are located adjacent to the quartz–carbonate body (Fig. 5 (a)). They were built close to the mined shafts and pits. Scattered small dumps with secondary green copper minerals were found close to the ancient dwellings. The grinding stones are recorded in the area; they are rectangular in shape with a concave smooth surface and are made of quartz–diorite (Fig. 5 (b)). The hand-held stones were made from the hard, fine-grained massive tuff. Close to these small dwellings, there is a larger site established on a peneplained area, and midway between the mined shafts and pits (Figs 2 (a) and 5 (c)). The site contains a few copper ore pieces and slag remains (Fig. 5 (d)). The slag has a glassy scoriaceous surface on the top of a friable red to buff pottery base. The pottery fragments with a slag surface are either flat or have a convex shape (Fig. 6 (a)) and only one has a semi-circular structure (Figs 6 (b) and (c)). The slag also encloses remnants of oxidized copper prills, which are characterized by their green colour and rounded outlines (Fig. 7 (a)). Microscopic examination of the slag revealed the presence of copper prills in the glassy matrix. The prills are variable in size, whereas the finer ones are composed of pure copper (Fig. 7 (b)) and the coarser ones are composite prills (Fig. 7 (c)). The pure copper prills are characterized by a homogeneous yellow–orange colour. The composite copper prills consist mostly of copper, along with probable metallic iron globules and skeletal dendrites and silicate inclusions (Figs 7 (c) and (d)).

Figure 5  (a) Ancient settlements in the copper mining area. (b) A saddle quern from the copper mining area. (c) The copper smelting site in the area, marked as a rectangle in Figure 2 (a): the white lines in the upper part of the photograph are recent remains of the Minex Company Camp in the area. (d) Glassy slag remains from the copper smelting site.
Close to the second group of shafts, the massive specularite fragments are widespread at the site, along with few tables and grinders. The tables are semi-rounded and have a rough pitted surface with a large central depression. The grinders are large and dumbbell-shaped. Both the tables and the grinders are made of fine-grained massive and lapilli tuffs. No slags are recorded from this location.

About 5 km away from the mining sites, another small working site is located at the mouth of Wadi Hamama, close to the intersection of Wadi Abu Gerida and Wadi Maghrabiya (Figs 1 (a) and 8 (a)). For the purposes of this publication, this site will be called the ‘Hamama station’. At the site, the openings in the sediments, supported by blocks of different kinds of rocks, may represent ancient furnaces (Fig. 8 (b)). Pulverizing and crushing tools, iron slag and charcoal are also recorded. The milling tables are rounded and have a concave smooth surface (Fig. 8 (c)). They are mostly made of quartz–feldspar porphyry, but some are made of volcanic rocks. Charcoal fragments are present as bands, alternated with bands of recent alluvium deposits (Fig. 8 (d)), and as inclusions in the slag fragments. Slag fragments are frequent and have different shapes and sizes. Two types of slags were identified. The first one has vugs and displays a scoriaceous appearance. The second type has a flow texture with a ropy crumbled surface that is akin to lava flow (Fig. 9 (a)). Microscopic observation using the reflected light microscope for polished sections of the second type of the slags reveals the predominance of iron-rich phases that appear in varying shades of grey (Fig. 9 (b)). Although mineral names should be used for naturally formed compounds, the mineral names will be used here to describe the slag phases.
Bachmann (1982) adopted the same practice, due to the similarity between the artificial minerals in the slags and the naturally occurring equivalents. Metallic iron, characterized by a white colour and high reflectance, is present as skeletal and anhedral patches. Wüstite is the second most dominant phase in the slag, and occurs as dendrites and as sub-rounded globules (Fig. 9 (b)). Olivine is the most common phase in the slags. The idiomorphic olivine crystals demonstrate zoning. EDX analyses revealed that the core is iron-rich fayalitic, while the darker rim is more enriched in calcium and kirschsteinitic in composition (Fig. 9 (c)). The dark glassy matrix is squeezed between the fayalite–kirschsteinite phases and encloses minute undifferentiated phases. One of these minute phases is yellow in colour and could be either pyrite or pyrrhotite–troilite.

DISCUSSION

Types of ores exploited

It is difficult to identify what types of ores were mined at this location over time without understanding the geological setting of the shafts and the remains of the smelting processes. There are two groups of shafts detected in the mining area. The first is associated with the quartz–carbonate body extending along the contact between volcanic rocks and their volcanioclastic rocks (Fig. 1 (c)). The volcanic rocks are mainly basaltic to andesitic in composition, while the volcanioclastic rocks are andesitic to dacitic in composition. The volcanic rocks of the Wadi Abu Gerida area have an immature island-arc geochemical signature (Hassan 2005).
Volcanogenic massive sulphides are related to the island-arc tectonic settings (Hannington et al. 2005), in which the sulphides are associated with their volcanic and volcaniclastic units (Franklin et al. 2005; Piercey 2010, 2011), similar to the one recorded in the Abu Gerida area. These deposits are not present only in the Eastern Desert of Egypt, but they also occur in the rest of the Arabian–Nubian Shield (Barrie et al. 2007, fig. 2). The volcanogenic massive sulphide deposits are formed on or immediately below the seafloor, at which many of them overlie hydrothermally altered volcanic rocks and are overlain by less altered to unaltered volcaniclastic rocks (Lydon 1984; Doyle and Allen 2003). Some of these deposits are associated with exhalative silica and carbonate deposits (Franklin et al. 2005). The first group of shafts is underlain by mushroom-shaped hydrothermally altered volcanic rocks and is overlain by unaltered volcaniclastic rocks (Fig. 1 (c)), similar to the geological framework of typical volcanogenic sulphide deposits.

In terms of mineralization, disseminated pyrite is the most abundant phase in the hydrothermally altered volcanic rocks, and the volcanogenic massive sulphides are enriched in copper, and to a lesser extent in zinc, and some of them are enriched in lead (Franklin 1995). The first group of shafts contains relics of secondary copper minerals, present as patches on the walls of the shafts or as veinlets dissecting the surrounding host rocks (Fig. 2 (d)). Pyrite is widespread in the hydrothermally altered rocks surrounding the shafts. Minex (1991) recorded high Zn anomalies within the shafts area. All these features indicate that these shafts are akin to volcanogenic
Figure 9  Iron slag. (a) Tap slag with a quenched surface. (b) A reflected light micrograph of the iron slag, showing blocky olivine crystals (Ol), dendritic wüstite (W), metallic iron (Fe) and interstitial glass-rich portions (g). (c) An SEM micrograph (backscattered electrons) and an EDX analysis of an olivine crystal, showing zoning with an iron-rich (fayalitic) core and a calcium-rich (kirschsteinitic) rim.
sulphide deposits, which are hosted in a silica–carbonate body of probable exhalative origin. However, the presence of copper minerals in their oxidized secondary forms, such as malachite, chrysocolla and paratachmite, indicates that the sulphide minerals were affected by weathering processes. These processes led to the formation of the gossaneous quartz–carbonate body with secondary hematite/limonite and goethite (Minex 1991). The gossan, as a surface manifestation of weathered volcanogenic sulphide deposits, is a common feature in the Arabian–Nubian Shield (Schellekens 1986; Abdelsalam et al. 2000; Barrie et al. 2007). The widespread pseudomorphic transformation of pyrite cubes of the hydrothermally altered rocks surrounding the shafts into goethite supports the prevalence of oxidation and hydrolysis of the sulphides, which may indicate that the ores exploited in the past were secondary copper minerals. In addition to the geological evidence, the ancient exploitation of secondary copper minerals from these shafts is confirmed by the discovery of an ore smelting site with remnants of fragments bearing secondary copper minerals, along with slag fragments containing copper prills (Fig. 7).

The second group of shafts is clustered in the tonalite–trondhjemite body. The specularite fragments are the only recorded ore in this area. There are 10 worked shafts, which are associated with intact quartz veins, and three of these shafts bifurcate around quartz–specularite ledges (Fig. 3 (b)). The intact quartz–specularite veins with limited dimensions of Wadi Abu Gerida may be comparable with the shafts that have quartz–specularite central ledges. As the veins of Wadi Abu Gerida have massive specularite selvages surrounding quartz–specularite cores (Fig. 3 (d)), the exploited ore from these shafts was most probably specularite. Many of the walls of these shafts have massive specularite veinlets. These veinlets may represent small specularite offshoots from the main exploitable thick specularite veins (Fig. 3 (c)). Although no iron smelting sites were recorded close to the second group of shafts, there is a site at the mouth of Wadi Hamama (to the west), where both specularite and iron slag fragments are widespread.

Both the geological evidence and the ore smelting remains indicate that copper and iron ores were exploited; however, the area is known in the literature as an ‘ancient Hamama gold mine’ (Afia 1985, 103). This spurious name may derive from the high geochemical gold anomalies that were recorded in the area. The highest gold content (2 g ton⁻¹) was recorded in the quartz–carbonate body (Surour et al. 2006) close to the first group of shafts. Some volcanogenic massive sulphide deposits are gold-rich (Dubé et al. 2007) and the processes related to gossan formation may enhance gold concentration in such a setting (Mann 1984). Nevertheless, the gold is not visible in hand specimens and so could not be extracted by the ancient miners with their limited technology. Moreover, ancient miners generally exploited native gold hosted in quartz veins, which are distinguished by their white colour. Although quartz veins are present in the vicinity of the second group of shafts, no sign of working is recorded in these veins, except for limited digging on their margins, where workers were probably trying to find hematite, as in the quartz–specularite veins.

**Copper ore processing and smelting**

From the geological setting of the shafts, mining appears to have been connected with copper ores and specularite. Two types of slags are recorded at different sites in the area. The first type of slag has copper prills and is found in association with fragments containing secondary copper minerals (Fig. 5 (d)). These copper slags are present in a site close—in fact, almost central—to the shafts along the quartz–carbonate body (Fig. 2 (a)), which indicates that this site was used for copper smelting. The small size and confined location of the copper smelting site may indicate the limited scale of mining undertaken at these sites. After the copper ore had been mined, it was
crushed and ground into fine particles. Ore grinding can be inferred from the presence of saddle querns close to the shafts along the quartz–carbonate body (Fig. 5 (b)). Ore crushing and hand picking of copper ore minerals are important processes to maximize the yield (Doonan 1994).

There are two modes of copper production, crucible smelting, which is considered the earliest mode of copper production, and furnace smelting, which depends on complex technical knowledge (Amzallag 2009). On the other hand, melting/refining of raw copper was done in crucibles (Hauptmann 2007, 218). The remnants of the copper smelting process in the Abu Gerida area include pottery fragments with black to brown glassy surfaces, which are porous to some extent and contain copper prills. Due to the absence of any furnace structure at the smelting site, these pottery fragments may represent broken remains of smelting crucibles. Contrary to the external heating assumption of Amzallag (2009, 2010), the occurrence of only one vitrified side of the slag fragments and the absence of any thermal effects on the other side indicate that the crucibles were heated from inside. It is hard to define the shape of the crucibles, because the fragments are relatively small. However, the curved shape of some pieces with a glassy surface on the convex side may indicate kidney-shaped crucibles, similar to the one preserved in the Middle East Department of the British Museum (AN166605001) (Fig. 6 (a)). The semi-circular structure in one of the fragments may represent a hole through which the forced air was applied through a blowpipe. Blowing human breath through pipes, rather than supplying ambient air through bellows, was a technique used to induce fuel combustion for copper smelting in Egypt before the invasion of the Hyksos in about 1670 BC (Rehder 2000, 78).

As the present study is a preliminary one, the non-appearance of furnace structure in the Abu Gerida area is not a conclusive support for crucible smelting. An alternative hypothesis is to use a furnace, yet to be found, for smelting copper ore and then to use crucibles to refine the produced raw copper. In this case, the slag with a glassy convex side may represent a piece of a fragmented tuyère with an internal diameter of about 8 cm (Fig. 6 (a)). The highly reducing condition during smelting is probably achieved in furnaces rather than crucibles, which is reflected in the formation of wüstite (Craddock 2000) and/or metallic iron (Craddock and Meeks 1987). Thus, the iron phase, either wüstite or metallic iron, which is associated with the metallic copper prills, may suggest furnace smelting rather than crucible smelting.

Iron oxide was used as a flux for copper smelting, which results in the recording of iron traces in many copper-based artefacts (Craddock and Meeks 1987). The iron flux might be added to the copper ore during smelting or the copper ore could be self-fluxed by the iron oxide present in the ore (Bourgarit 2007; Hauptmann 2007, 207). Smelting secondary copper oxide ores with iron oxide induces the formation of a mass of iron minerals, or even metallic iron in addition to metallic copper prills (Cooke and Aschenbrenner 1975; Ogden 2000). The limited amount of iron associated with the copper prills and the presence of secondary iron minerals in the quartz–carbonate body may indicate that there was no flux added and that the smelted copper ore in Wadi Abu Gerida area was a self-fluxed one. Bulk-element chemical analyses are required to confirm this conclusion.

The scarcity of the copper slag remains may be attributed to use of the high-grade copper ore, and in this case no flux is needed to smelt the ore (Craddock 1995, 135; Hauptmann, 2007, 228). Unlike most sulphides, secondary copper minerals, such as malachite and atacamite, contain only volatile components. Thus, their smelting will lead to virtually slagless copper production (Rehren, 2009). Thus, the low amount of copper slag in Wadi Abu Geirda may indicate the exploitation of high-grade copper ore, rather than being ascribed to the small scale of copper exploitation in the area. Similarly, no sizable amount of slag has been found in many other settlements of the Eastern Mediterranean during early periods of the Bronze Age, because of the
smelting of the almost pure pieces of copper ore in crucibles (Hauptmann 2007 and reference therein, 14).

Iron ore processing and smelting

The second type of slag is enriched in iron phases (Fig. 9). The slag heaps of this type are found at the mouth of Wadi Hamama, which is far to the west of the shafts associated with quartz–specularite veins (Fig. 1 (b)). The mineralogy of these slags and the presence of specularite pieces support the idea that this site (the Hamama station) was used for iron smelting. The iron smelting activities at this site were proposed previously by Harrell (2005), following the unpublished study of Sidebotham and Barnard. The iron smelting site is larger than the copper smelting one, has more slag and is located in a more peneplained area, away from the specularite mining sites (Fig. 1 (b)). It is presumed that iron mining and smelting were performed on a larger scale than copper mining and smelting. This is why Harrell (2005) considered the iron processing and smelting site as a station.

The iron ore was also subjected to pre-treatment. Close to the specularite mine, a large grinding table with a pitted surface and a dumbbell-shaped grinder were used to break down the sizable specularite chunks prior to their transfer to the smelting site. Another possible use for the table and the grinder is to separate large specularite fragments from the adhering quartz (Fig. 4 (a)). At the Hamama station, specularite ore was subjected to more crushing and grinding into small particles to be picked for smelting, leaving other gangue minerals—especially quartz. Large rounded mills, which are made of quartz–feldspar porphyry, are present at the site (Fig. 8 (c)). According to Rehder (2000, 193), pulverizing iron ore to particles with a diameter of 1 mm is suitable for efficient smelting and the particles would not be able to blow out. However, hematite powder resulting from milling could be used for purposes other than smelting, such as making pigments and red glaze.

Slags from the Hamama station contain mainly fayalite and dendritic iron oxides (Fig. 9 (b)). Both minerals were recorded in the slag fragments derived from the Predynastic and Old Kingdom copper smelting sites in Sinai (El Gayar and Rothenberg 1995). The occurrence of fayalite in slags during copper smelting processes is a common feature (Steinberg and Koucky 1974; Cooke and Aschenbrenner 1975; Tumiati et al. 2005; Georgakopoulou et al. 2011), which can be attributed to the addition of iron oxide as a flux during the copper smelting processes (Hauptmann 2007, 21). Lyle (2001) classified the Roman fayalite-bearing slag from Carthage in Tunisia into copper slag and iron slag depending on the high content of copper droplets in the former and of fayalite and wüstite in the latter. Thus, the high fayalite and wüstite contents in the second type of slag along with the absence of copper droplets and the presence of metallic iron support the iron smelting source of this type of slag. Bachmann (1982, 17) stated that the amount of metallic iron is higher in bloomery slag than in copper slags. Moreover, the abundance of iron ore at the Hamama station suggests iron smelting rather than copper smelting activities, which were conducted at a small site in the tributary of Wadi Abu Gerida.

The iron smelting was carried out in furnaces dug horizontally in the stream sediments (Fig. 8 (b)). Reducing iron ore to produce metallic iron requires both heat and a reducing atmosphere; that is why charcoal fragments are present at the Hamama station. Charcoal fragments are present as inclusions within the iron slags and were preserved as a layer in the sediment profile recently cut by the wadi (Fig. 8 (d)). This charcoal layer may represent the hearth of one of the furnaces that was eroded after being filled with younger sediments rather than being an older occupation level at the site. Two types of iron slags were recorded in the station. The first
type is dense with a varying degree of porosity, while the second type has little porosity and has a well-defined flow texture on its surface, and both types enclose charcoal fragments. Chirikure and Rehren (2004) identified iron slag with similar characteristics from the primitive Nyanga Agricultural Society, which dates back to AD 1300. According to their classification, the first type of Hamama iron slag is furnace slags, which formed and solidified at the base of the furnace and were removed on completion of the smelting process, while the second type of slag is similar to tap slags.

The iron-rich olivine, fayalite, is a pyrometallurgic phase in slags resulting from the iron smelting process (Muhly et al. 1985; Ackerman et al. 1999; Veldhuijzen and van der Steen 1999; Rehren et al. 2007; Veldhuijzen and Rehren 2007; Severin et al. 2011). The olivine crystals of the iron slag from the Wadi Hamama area exhibit a zonal texture in which the core is fayalite while the rim has a more kirschsteinitic (Ca-rich) composition (Fig. 9 (c)). Manasse et al. (2001) ascribed the presence of kirschsteinitic olivine in archaeological slags to the high temperature of the furnaces. The kirscheinitic olivine occurs at temperatures higher than approximately 1100°C (Manasse and Mellini 2002), which may reflect the minimal temperature estimate of the furnace used for iron smelting at the Hamama station. Surour et al. (2006) attributed the occurrence of kirschsteinitic olivine in the slags to the usage of limestone brought from the Nile Valley as a flux during the smelting processes. Veldhuijzen and Rehren (2007) criticized the interpretation of the high CaO content in some slags as a sign of limestone fluxing during the Iron Age, which is an advanced smelting technique adopted much later in the blast furnace technology. Fuel ash is likely to account for the lime content in the slag (Crew 2000; Chirikure and Rehren 2004; Rehren et al. 2012), which may result in the formation of kirscheinitic olivine (Iles and Martinón-Torres 2009). Also, the absorption of calcareous sandstone used in constructing the furnace at the Hamama station is another possibility for explaining the formation of the kirschsteinitic olivine in the slag.

The archaeological context of the ore exploitation

Although charcoal deposits are widespread at the smelting site of the Hamama station, no absolute age has been determined. However, most of the surface pottery of the Hamama station has been dated to the Ptolemaic Period (c. 330–30 BC) by Steve Sidebotham (University of Delaware, USA) and Hans Barnard (University of California at Los Anglos, USA) in an unpublished study (http://www.barnard.nl/desert/gerida.html). Harrell (2005) supported the Ptolemaic Period for mining activities because of the presence of saddle querns. Klemm et al. (2001) proposed that saddle querns were employed in Egypt only during the Ptolemaic Period.

In addition to Ptolemaic pottery remains, Harrell (2005) recorded the presence of early Imperial Roman pottery at the Hamama station. He attributed the Roman pottery remains to the quarrying activities for the quartz–feldspar porphyry (‘porfido roso laterizio’) during the Roman Period (first and second centuries AD). There are more Roman quarrying activities for the different varieties of gabbro (‘gabbro eufotido’ and ‘granito verde plasmato’) from the nearby Wadi El Maghrabiya, where the only way to transport the blocks is through the Hamama station (Harrell et al. 1999).

The age of the iron ore mining and smelting activities at the Wadi Abu Gerida area is compatible with the history of the iron industry in ancient Egypt. Iron smelting increased during the 26th Dynasty of the Late Period (664–525 BC) at Naucratis and Defenneh, two of the Greek settlements in Delta, where iron objects and slags along with specularite iron ore were identified by Petrie (1886, 39; 1888, 77–8). However, the age of iron ore mining and smelting in the Wadi Abu Gerida area is comparable with the widespread use of iron tools that were supplied to
quarrymen during the Ptolemaic Period (Lucas 1962, 239). Furthermore, Forbes (1964, 231) has suggested that the Iron Age did not start properly in Egypt until the Hellenistic Period.

Unlike iron, copper exploitation in the Wadi Abu Gerida area is not recorded in the early historical resources. Only Afia (1985, 229) mentioned small-scale mining activities for copper during the Roman Period too, but he did not mention any archaeological evidence from the area except that iron exploitation was generally blooming during the Greco-Roman Period in the Eastern Desert. It is probable that iron and copper exploitation from the Abu Gerida area are not contemporaneous. Copper became known to man much earlier than iron. In Egypt, copper was employed as far back as early Predynastic times, either in its metallic form or as copper ore (Ogden 2000). By the end of the Predynastic period and during the early Dynastic periods, copper tools were in use in considerable numbers (Lucas 1962, 200).

There are many indications that the Wadi Abu Gerida area had been known since Predynastic times and not just since Hellenistic times. Many of the Predynastic sites are located along the low-lying desert edge bordering the floodplain of the River Nile close to Qena, such as Naqada, Armant and Laqelita (Butzer 1960). Afia (1985, 42–3) argued that the contact between the Nile Valley and the Red Sea coast through the desert has been influenced by two major factors since Predynastic times. First, the source rock of lithic vessels used during Predynastic times is the Eastern Desert, which yielded materials such as marble, porphyry, greywacke, serpentinite and talc. The second factor is the presence of shells derived from the Red Sea coast in the tombs of the Predynastic Period. The Abu Gerida area is located along the route connecting the Nile Valley and the Red Sea, about 75 km from Qena, which makes the copper ore of the area accessible for exploration before the Ptolemaic Period.

Petrie and Quibell (1896, 54) recorded copper from a Predynastic cemetery at Naqada containing 1.55% of zinc. Lucas (1962, 223) attributed the proportion of 2% zinc in copper to the natural association of copper ore with zinc. Afia (1985, 51) proposed that the source of this copper could be the Um Samuiki deposit in the southern portion of the Eastern Desert. This deposit is similar to, but larger than, the copper deposit of Abu Gerida. The Um Samuiki deposit is a volcanogenic massive sulphide type located close to Ras Banas and its copper ore is enriched in both zinc and lead (Botros 2003). Assuming that the Predynastic people of Naqada used Zn-bearing copper ore, the Abu Gerida deposit will be a more likely source to be exploited than the Um Samuiki deposit, which occurs a very long distance from the Predynastic sites along the Nile Valley. As copper ore was probably exploited in the Predynastic Period from Wadi Abu Gerida, specular hematite might have been picked up from the area on a smaller scale, but not as iron ore. Hematite and red jasper derived from the area might have been used by the ancient Egyptians for beads and amulets as early as the Predynastic times (Barron and Hume 1902, 52, 266; Petrie 1920, 43; Lucas 1962, 395, 397).

The above-mentioned points raise the possibility of having earlier copper ore exploitation activities than the Ptolemaic period, when iron ore was exploited. Moreover, the scarcity of slag due to the smelting of high-grade copper ore in crucibles is known for the Early Bronze Age (Cradock 1990; Hauptmann et al. 1996; Adams 2002). Also, internal heating of the crucibles is characteristic of pre-Roman age, as Roman crucibles show complete firing and vitrification throughout the crucible body (Rehren 2003; Bayley and Rehren 2007; Thornton et al. 2010). Thus, the copper mining may date back to times older than the Ptolemaic times; however, the archaeological remains might have been buried and overprinted by the younger Ptolemaic activities. From their observations on the profiles cut by the Wadi, Sidebotham and Barnard in their unpublished study, suggested a prolonged period of occupation for the area.
CONCLUSION

The Wadi Abu Gerida area is characterized by the presence of ancient shafts, ore smelting remains and settlements for miners. The mining activities and ore smelting remains relate to ancient mining of both copper and iron. The exploited copper ore consists of secondary copper minerals, chrysocolla and malachite, which were formed due to the oxidation of the volcanogenic sulphide lenses located along the boundary between the altered volcanic rocks and the volcanioclastic rocks. The smelting of the copper ore took place close to the ore extraction sites, where pounding tools and glassy slag with copper prills were found. Although smelting remains, such as slags and crucible fragments, can provide valuable information on the technological processes, the inadequate sampling of these remains leads to only tentative conclusions on the ancient smelting technology.

Specular hematite is the principal iron mineral that was exploited from the area in antiquity. Hematite is present as veins associated with quartz that were enclosed in the tonalite body in the tributary of Wadi Abu Gerida. The ore was crushed and transported to the smelting site at the Hamama station, to the west of the mining sites. The ore was subjected to further pulverization for beneficiation in preparation for smelting in a furnace dug horizontally in the stream sediments. Charcoal fragments are widespread at the site. These conditions resulted in the formation of iron slag containing wüstite and fayalite–kirschsteinite, along with traces of metallic iron. The presence of kirschsteinitic olivine might demonstrate the derivation of lime from fuel ash and/or absorption of calcareous sandstone from the furnace, which was working at a temperature of not less than 1100°C.

The pottery finds in the area indicate that the main mining event was undertaken in the Ptolemaic Period. This corresponds to the start of Iron Age in Egypt, during the Hellenistic Period. This was the era when much of the iron mining and smelting in this area was carried out. However, copper exploitation might have started in the area before iron exploitation and earlier than the Ptolemaic Period. The familiarity of the Predynastic people with copper smelting technology, along with the closeness of the Abu Gerida area to the Predynastic sites along the Nile Valley, such as Naqada, supports the idea of earlier copper mining in this area. However, thorough investigation through excavation is needed to detect an accurate age of copper exploitation from the area.

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