Mineralogy of copper deposits and ancient slags at the vicinity of Jabal Samran arc metavolcanics, Western Central Saudi Arabia

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Abstract

Secondary copper mineralizations at Jabal Samran area are located essentially in the form of a NE-trending shear zone characterized by hydrothermally altered metadacite formed in Precambrian arc setting. The disseminated sulphides in the metavolcanics host might also played an important role in the genesis of secondary copper mineralization that are confined to the shear zone. Hence, it is suggested that seawater and/or magmatic water were circulating and then emanated into the sea floor along deep-seated fractures forming an oxidizing hydrothermal cell rich in CO_2. The movement of such hydrothermal fluids was responsible for dissolution of the Cu-bearing disseminated sulphides and the formation of contemporaneous extensive alteration zone in the underlying metadacites and to lesser extent in the metatuffs.

It is believed here the formation of paratacamite by Cl-rich seawater oxidation of primary sulphides on the seafloor. It is believed that albitization and silicification of the host metavolcanics at Jabal Samran, mostly metadacite, promoted a type of acid neutralizing hydrolysis reactions at low pH leading to the formation of hydrous Cu-phases, chrysocolla and paratacamite.

The mineralogical investigation of Samran copper slags revealed that the badly processed native copper prills still preserve relict chalcocite which is here considered as the main copper ore used by the ancients (the Abbasiyeen in particular) in addition to paratacamite, brochantite and other S-bearing phases (e.g. barite and jarosite). A mixture of copper ore minerals and two different types of fluxes (calcium carbonate and hematite) in order to lower the fluxing temperature of copper. Some of the collected slags still preserve relics of charcoal that acted as the source of energy. The copper slags of Jabal Samran area are air-cooled slags which are supported by the rope-like surface.

Introduction

Jabal Samran is a very prominent geological feature within the so-called "Rabigh Quadrangle" that is wholly covered by Precambrian basement rocks of the Arabian Shield. Jabal Samran is located about 90 km to the northeast of Jeddah harbour city in central western Saudi Arabia (Fig. 1). The area is known for its copper-gold-silver mineralizations that were worked out during the early Islamic Periods with intense activities during the rule of Abbasiyeen (Sahl et al., 1999). According to the code registration (known as MODS) by the Ministry of Petroleum and Mineral Resources of Saudi Arabia, the Jabal Samran prospect has the code number 001410 (Collenette and Grainger, 1994). The early works of Smith and Kahr (1966), Liddicoate (1966), Nebert (1969), and Rexworthy (1972) documented the presence of ancient copper mining and smelting at Jabal Samran area. From the historical point of view, both iron and copper slags are found as cultural heritage belonging to different times in several localities all over the world, especially those of the Mediterranean region. For example, copper slags in Italy display diversity in age from the Etruscan time close to the 8th century B.C. (Manasse et al., 2001) to the medieval time during the 13th and 14th centuries A.D. (Manasse and Mellini, 2002). Also, copper slags are known from the Eneolithic culture, the 5th to 4th millennia B.C. in the northeast Balkan, particularly in Bulgaria (Ryndina et al., 1999). Copper deposits and ancient smelters of different ages are known from

Egypt (both in the Eastern Desert & Sinai), Jordan and Palestine (Afia, 1985 & 1996).

As far as the author aware, nothing has been previously published about the mineralogy of copper slags at the vicinity of Jabal Samran arc metavolcanics despite of occurring as huge piles close to the mined copper-bearing trenches and shafts. For this reason, the present aims to give in detail the mineralogical characteristics of these slags in order to have an idea about the sintering of the copper ore, physico-chemical conditions of smelting and nature of catalysts or fluxes. The present paper also presents the first detailed mineralogical and geochemical studies for the mineralized zones (either the quartz veins or the altered metavolcanics) in order to envisage the nature of mineralizing fluids and ore paragenesis. For such task, many analytical techniques are here used in order to achieve such goals.

Methodology

About forty-five samples were collected in the field covering all the mineralized zones and most of them were carefully selected to avoid weathering effect and tarnishing. Out of these samples, about thirty-nine representative polished and polished-thin sections were prepared for the identification of gangue and opaque minerals, in addition to the study of the genetic relations between ores and the host rocks. The microscopic investigation was carried out using Leitz polarized microscope equipped with a full automatic microphotographic attachment housed at the Department of Mineral resources and Rocks, King Abdulaziz University, Jeddah.

Runs for X-ray diffraction analyses (XRD) were carried out at the Department of Mineral resources and Rocks, the Department of Mineral resources and Rocks, King Abdulaziz University, Jeddah, Saudi Arabia. The machine is Philips PW 1840/20 using Cu K_α-radiation and Ni-filter at working conditions of 40 kV.

Scanning electron microscope (SEM) analyses for some samples of the ores and slags were carried out. The samples were analyzed by a scanning electron microscope (SEM) housed at the Central Laboratories of the Egyptian General Authority of Mineral Resources in Dokki. The model of the SEM machine is Philips XL30 attached with energy dispersive X-ray (EDX) Unit working at accelerating voltage of 30 kV, magnification 10 x up to 400.000 x and resolution for W (3.5 nm). All investigated samples were coated with thin carbon films before the SEM examination.

In order to determine the content of some trace elements in the quartz veins and altered metavolcanics, some representative samples were subjected to atomic absorption analysis at the geochemical laboratories of the Saudi

Geological Survey (SGS) in Jeddah. Gold content of the same samples was determined by the fire-assay technique at the same laboratories.

Field observations

Jabal Samran area is almost covered by metavolcanics (Fig. 1). According to Ba-Battat (1982) and Ba-Battat and Hussein (1983), the area is made up of a sequence of volcanics and volcaniclastics that are intercalated with marble thick bands and cut by unmappable masses of gabbro-diorite (Fig. 2a), granites and intermediate dykes (mostly andesite). They are of calc-alkaline composition and were evolved at island-arc tectonic setting (Ba-Battat and Hussein, 1983). The mapped area of Jabal Samran shown in Figure 1 possesses four varieties of volcanic rocks in addition to the marble. They comprise from oldest to youngest: agglomeratic tuffs, marble, rhyolite porphyry, dacite-rhyodacite and andesite. Only the andesite dykes are fresh and no signs for any alterations were observed. On the other hands, the rest four varieties are obviously regionally metamorphosed in the regime of greenschist facies. Outside the mine area, other metavolcanic varieties are encountered, especially along the Samran-Abu Mushut stretch. They hence comprise varieties ranging in composition from basaltic andesite to rhyolite in a 3-cyclic order as identified by Ba-Battat (1982). He (op cit.) concluded that two cycles (I&II) are metamorphosed whereas cycle III is represented by nonmetamorphosed flows and epiclastic andesites equivalent to the andesite dykes revealed by the present study.

At Jabal Samran prospect (22 20’ N & 39 32’ E), the copper mineralization is essentially confined to numerous quartz veins that extend along the contact between hydrothermally altered metavolcanics and the metavolcaniclastics that comprise kaolinitization and hematitization (Fig. 2b). The quartz veins and the altered metavolcanics both bear common secondary copper minerals of bluish green and dark green colours.

The mineralized zone extends from the NE direction towards the west side and shows a noticeable thickness variation in the field through the contact. The exploited parts are represented either by stretched shafts with sheared walls or as wide localized pockets. In some few cases, the shafts are located within the highly altered metavolcanics, being very close to the quartz veins and stringers

The highly altered metavolcanics are characterized by the predominance of the silica, which reflects the acidic nature of these metavolcanics. The highly altered metavolcanics still preserve fresh relics of dacite. These fresh relics are concentrated in the central part of the highly altered metavolcanic belt. Confinement of oxidized pyrite along the fractures in the metadacite is a common feature. Well-developed coloured rings (liesegang rings) characterize the altered metavolcanics. The formation of these rings can be attributed to some sort of iron diffusion process that is controlled by the conjugate fracture system in the metavolcanics. This is ensured by the encrustation of some main fracture by dense iron oxides, which is supposed to be resulted from the circulation of heated fluids leading to the development of this self-organized ornamental texture. The “liesegang rings” occur in restricted area at the basal metatuffs whereas the effect of the hydrothermal alteration is very limited, weak and gradational. Generally, the studied occurrence represent extensively altered arc volcanics characterized by alteration zones dominated by oxidation reactions.

In some instances, the quartz veins contain many fragments along the contact between the metavolcaniclastics and the metavolcanics. These fragments show some sort of variation in their sizes, but the maximum dimension of the fragments is generally less than 15 centimeters. They are composed mainly carbonates and less dominant hydrothermally altered metavolcanics and quartz. Many patches of the secondary copper mineralization, characterized by different shades of green colour, are recorded close to the mined pockets as well as along the shaft walls. These secondary cupriferous minerals are associated in some localities with silica and ochreous iron minerals. In some spots, the basal parts of the metatuffs are characterized by the presence of pyritic siliceous metatuffs.

The present field observations document the prsence of huge amount of ancient copper slags at the footslope of Jabal Samran. These slags are characterized by knobby surface and rope-like appearance due to stearing (Fig. 2c). The present author had also the opportunity to record some old ruins of labor houses near the mined shafts (Fig. 2d).

XRD and microscopic investigations

The present work presents here the first detailed mineral composition of the mineralized zones of Jabal Samran copper prospect. Table 1 gives the summary of the mineralogical composition of copper-bearing rock varieties being distinguished into major, minor and trace phases according to the abundance of each mineral. Data of Table 1 clearly distinguishes the gangue minerals from the opaque ones taking in considerations that not all of the non-opaques are not ore minerals because secondary copper minerals of green and blue colours are somehow translucent and easily identified in thin-sections. Identified XRD peaks of the common minerals in some of the analyzed samples are shown in Fig. 3. The provided table and figure show that the slightly to moderately sheared quartz-malachite rock with traces of black ore (sample Nos. T40 & T41) are dominated by secondary copper minerals in the form of paratacamite and brochantite whereas the sole primary copper minerals are either an oxide one (cuprite) or sulphide (chalcocite). The latter mineral is responsible for the prominent black coloration of these sheared altered rock varieties. Possibility of chrysocolla is present but the lines of the mineral are interfered with those of both paratacamite and brochantite. Strong lines of Ag-bearing pyrite (argentopyrite) are also identified which is confirmed by some EDX investigation. It is believed that the common occurrence of barite in the carbonated quartz-malachite rock is attributed to the breakdown of feldspars in the host volcanics and leaching of Ba^{2+} into the mineralized zones that also contain jarosite and traces of chalcocite (sample No. T42). The highly sheared hematitized-kaolinitized rock variety (T43) bears both chalcocite and Ag-free pyrite. The hematitized varieties with traces of black ore (T44 & T45) are characterized by the presence of more than one primary Cu-minerals, namely cuprite, tenorite and chalcopyrite, in addition to sporadic occurrence of rhodocrosite and natrojarosite. In overall, the given mineralogies of all rock varieties represent the uppermost oxidation zone of a blind massive sulphide ore below the water table. In very rare cases, the hydrothermaly altered metavolcanics still preserve a common porphyritic texture. The petrographic investigation revealed that the mineralogy of altered dacite and rhyodacite can be summarized as follows:

1. Little plagioclases are present.
2. Amphiboles are represented by hornblende ± actinolite ± tremolite. Tremolite occurs as perfect rhombs (Fig. 4a).
3. Groundmass is rich in chlorite replacing amphiboles and plagioclase.
4. Abundant coarse zoisite replacing plagioclase is present.
5. Some samples show few biotite replacing amphiboles.
6. Great amount of opaques (up to 30 %)

Most of the investigated rock varieties are fine-grained but in some cases they become coarse-grained due to the hydrothermal growth of quartz and barite crystals. They show common shear fabrics like conjugate fracturing (Fig. 4b), CS-fabrics and many samples still retain the traces of foliation. In some other instances, the rock foliation is totally obliterated due to hydrothermal growth of both opaques and non-opaques. Rigidity of some opaque phases (e.g. pyrite) makes the mineral competent enough to defense shearing and in this case strain shadows of fringes are developed (Fig. 4c).

Ore characteristics of the altered dacite-rhyodacite are:

1. Titanomagnetite replaced by titanite. It is also altered to rutile-hematite (sub-graphic texture)
2. Coarse martitized magnetite enclosing silicates.

3. Sulphides (30-83 % of opaques) are mostly chalcocite and chalcopyrite that are altered to covellite and other secondary Cu-minerals in the form of random batches or veinlets (Fig. 4d).

The microscopic investigation of the copper slags of Jabal Samran revealed the formation of radiating Fe-Mn aluminosilicate phases rimming a glassy base (Fig. 4e). The native copper resulting from the smelting process is either pure or impure. This native copper always has perfect circular outlines known as “copper prills”. In case of bad smelting the copper prills are not typically of circular outlines and in this case, relics of sub-rounded chalcocite and abundant silicate droplets are encountered (Fig. 4f). The pure circular copper prills are sometimes suffer from rusting due to weathering leading to the formation of greenish rusty crust around concentric or excentric fresh native copper (Fig. 4g). In many cases, the copper prills display great variation in size (Fig. 4h) that may indicate abrupt change in the temperature of the smelting furnace. Spot chemical analyses of synthetic phases in the studied copper slags will be given later on in a separate section.

Mineralogical characteristics

A. Sheared metavolcanic rocks:

Mineralogically, the sheared metavolcanic rocks (particularly the metadacite) show some sort of variation in the carbonate to quartz ratio. It ranges from nearly pure carbonate to rocks formed entirely of quartz. The carbonates are present either in the form of colloform texture or sacchroidal texture with different sizes. The latter texture contains many crystals of rhombic shape with oxidized brown borders. These textures are commonly obliterated due to the recrystallization of the carbonate into larger form. Small-sized oxidized pyrite cubes are widely distributed in such rocks. Some of them are aggregated in pockets within the sucrosic carbonate crystals and the other colloform carbonate contains the pyrite along the bands. The pyrite in these rocks is associated with quartz, which resulted from the permeation of secondary silica solutions along the fracture planes and commonly along the colloform bands. The Quartz also fills the cavities left by the early-crystallized carbonate crystals that ensuring the later crystallization of quartz.

With increasing the quartz content the carbonate will be diminished. Such silicic rock is characterized by the presence of secondary iron minerals (lepidocrocite), barite and secondary copper minerals. Both of the metadacite-rhyodacite and the underlying tuffs are sheared. This shearing leads to the development of strain fringes of quartz and chlorite adjacent to the oxidized pyrite cubes. The resulted fractures were filled by mobilized secondary copper minerals and less commonly by quartz-pyrite.

B. Altered metavolcanic rocks:

The altered metavolcanics are characterized by the development of coloured liesegang rings. Mineralogically, these rocks are consist mainly of quartz, sericite, pyrite and albite in order of decreasing abundance. The later one is scarcely found and noticed in the rocks with poorly developed rings. The difference in colours within the rock is owing to the staining of each ring by different secondary iron materials (oxides and hydroxides) as alteration products of the pyrite. The weakly altered dacite is characterized by the development of large pyrite crystals enclosing parts of the groundmass. The growing of such large pyrite cubes is always related to the tiny quartz veinlets dissecting the rock as a preliminary stage in the silicification and the crystallization of pyrite defining the liesegang in the highly altered rocks.

Geochemistry and mineral chemistry

Whole-rock chemical analyses (trace elements) by the ICP technique in some rock varieties as given in Table 2. The barren quartz veins clearly indicate very poor content of Cu (4-8 ppm) as given in Table 2. From this table, some features can be noticed as follows: The mineralized quartz-sericite rock is enriched in B, Ba and V. Amount of V is 86 ppm which is attributed to the incorporation in the lattice of both magnetite and pyrite. The altered or bleached metavolcanic (metadacite) has the highest B, Ba and Cu contents amounting 120, 445 and 94 pm respectively due to the presence of barite and Cu-bearing minerals (secondary in most).

Gold was determined by the fire assay technique (Table 3), the studied quartz veins and altered metadacite are not enriched in the noble metal as it never exceeds 0.15 g/t and most of samples show content lower than 0.02 which is the detection limit.

Several representative semi-quantitative spot analyses for the different phases in the copper slags were carried out using the SEM-EDX technique. These analyses show that the copper prills are totally composed of native copper that is weathered at the outer peripheries into Fe-bearing copper rust containing 2.62 wt% Fe (Fig. 5). It was interesting to notice that abundant sulphur content (21.81 wt%) is sometimes encountered in the outer peripheries of the native copper indicating that the primary processed Cu-ore was sulphide in most.

Figure 5 illustrates that impure copper prills of irregular outlines contain dark droplets of different sizes. The native copper groundmass is Fe-bearing, containing 1.88 wt Fe, indicating either incorporation of magnetite and lepidocrocite with the copper ore or the use of hematite for fluxing purposes. The irregular native copper has coarse irregular Fe-Cl phase containing 12.93 wt% Cl that may be attributed to the use of Cl-bearing secondary copper ores

(Fig. 6). This figure also documents the petrographic identification of unprocessed chalcocite relics.

The groundmass of the copper prills are represented either by long rods or fine dendrites, both of silicate composition (Fig. 7). The long rods stand for Fe-Mn silicate with 12.34 wt MnO that is explained by the presence of $MnCO_3$ (rhodocrosite) in the altered mineralized metadacite which is documented by the XRD results of the present paper. On the other hand, the fine dendrites are Fe-silicates with about 40 wt% FeO and appreciable oxide contents of Na, Al, Si, Ba and Mn. Figure 8 shows that the long Fe-Mn silicate rods may contain appreciable CaO (7.27 wt) which can be attributed to either primary feldspars or the use of calcium carbonate for fluxing. There is an interstitial finely-ornamented phase to the Fe-Mn silicate rods which is Fe-Al silicate (spot B, Fig. 8) that contains 3.71 BaO.

EDX microanalysis of cuprite invading quartz is given (Fig. 9). The unprocessed secondary copper ore is represented by hydrated Cu-Al silicate phase in the form of veinlets rimmed by goethite and lepidocrocite (Fig. 10). The copper content of this phase amounts 9.59 wt%.

Conclusions

i. Copper mineralization

Secondary copper mineralization is located essentially in the form of disseminated sulphides in the metavolcanic hosts. Such disseminations are believed to play an important role in the genesis of secondary copper mineralization that are confined to the shear zone. Hence it is suggested that the seawater and/or magmatic water were circulating and then emanated into the sea floor along deep-seated fractures forming an oxidizing hydrothermal cell rich in CO_2. Incorporation of some penetrating meteoric water can not be excluded which needs isotopic evidence in the future studies. The movement of such hydrothermal fluids was responsible for dissolution of the Cu-bearing disseminated sulphides and the formation of contemporaneous extensive alteration zone in the underlying metadacites and to lesser extent in the metatuffs. The most pronounced feature of this alteration is the development of “liesegang” by the process of diffusion accompanying the alteration that is controlled by the geometry of fractures. It is believed that the quartz veins acted as an impermeable cap that prevented the escape of the mineralized hydrothermal fluids and so these fluids emanated their content on the sea floor in a focused manner.

The remained copper is present in its oxidized state in the form of secondary minerals, mainly amorphous Cu-hydrated silicate (chrysocolla) and crystalline Cu-hydrated halide (paratacamite). Arcuri and Brimhall (2003) documented the formation of paratacamite by Cl-rich seawater oxidation of primary sulphides on the seafloor. It is believed that albitization and silicification of the host metavolcanics at Jabal Samran, mostly metadacite, promoted a type of acid neutralizing hydrolysis reactions at low pH leading to the formation of hydrous Cu-phases, chrysocolla and paratacamite. Spencer and Chávez (1999) presented similar reactions and assemblages but in the scope of supergene oxidation of primary Cu-sulphides which is not the case of Jabal Samran.

ii. Copper slags

In order to have an idea about the archeometallurgical method for copper extraction by the Abbasiyeens, the mineralogy of the Samran copper ores and slags were studied in detail. Such detailed mineralogical investigation of Samran copper slags revealed that the badly processed native copper prills still preserve relict chalcocite which is here considered as the main copper ore used by the ancients. Presence of some Fe-Cl phase in some studied slags at Jabal Samran ancient sites supports also that the used copper ore also contained secondary copper minerals that bear chlorine in its structure such as paratacamite $Cu_2Cl\ (OH)_3$. Also, the presence of appreciable amounts of sulphur in some rusty peripheries of the produced copper prills suggest that the copper ore minerals also included brochantite that has the formula $Cu_4(SO_4)(OH_6)$. In this respect, probably both barite and jarosite were also responsible for sulphur content in the copper prills.

A mixture of copper ore minerals and two different types of fluxes (marble and hematite) in order to lower the fluxing temperature of copper. Some of the collected slags still preserve relics of charcoal that acted as the source of energy. The present author was also able to record some debris of charcoal and potteries inside the old ruins of Jabal Samran.

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Following the classification of Gorai et al. (2003), the copper slags of Jabal Samran area are air-cooled slags which are supported by the rope-like surface, that can not resulted from pouring the metal into water by the Abbasiyeen.

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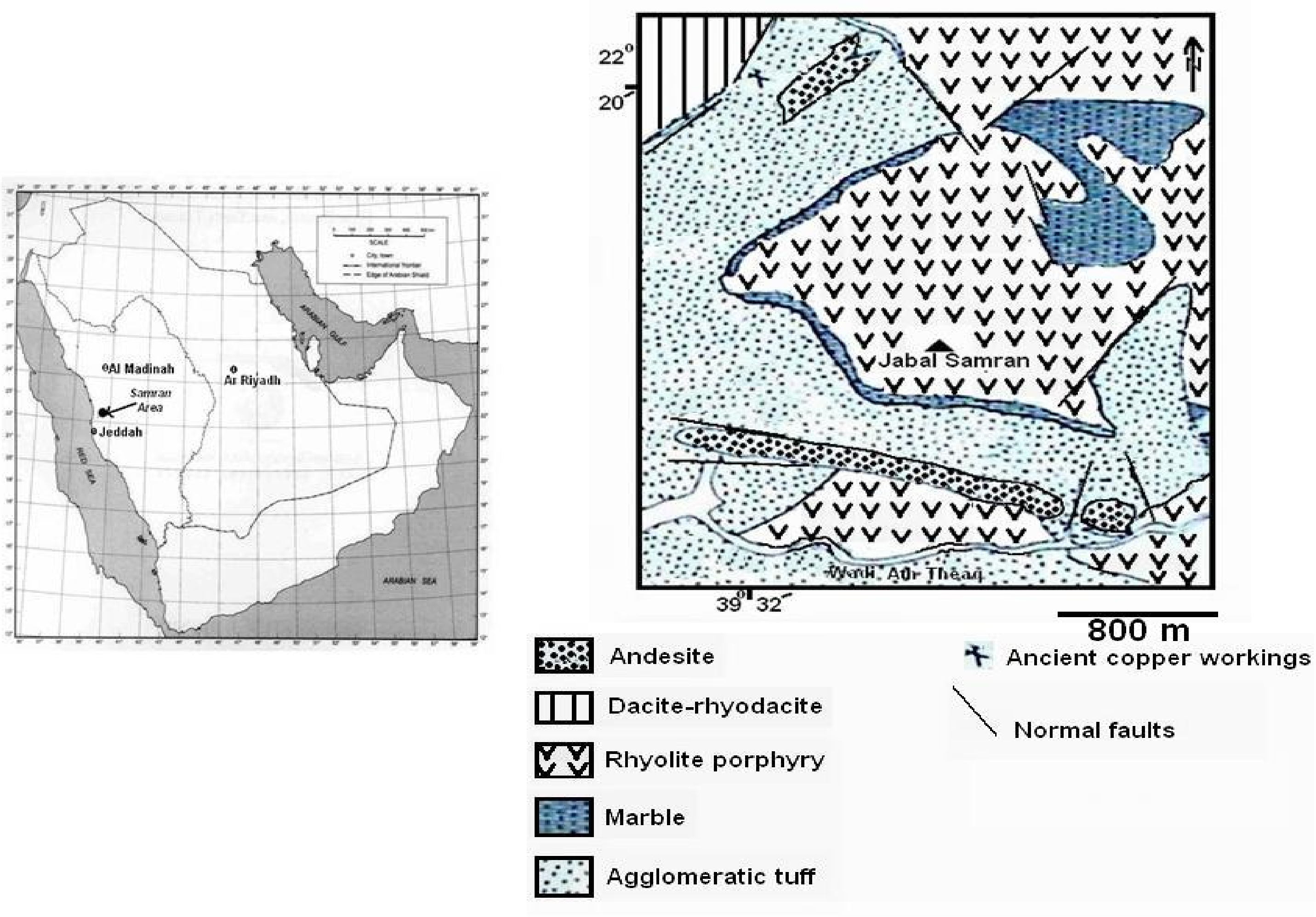


Fig. 1: Location map and geology of Jabal Samran area (modified after Ba-Battat, 1982)

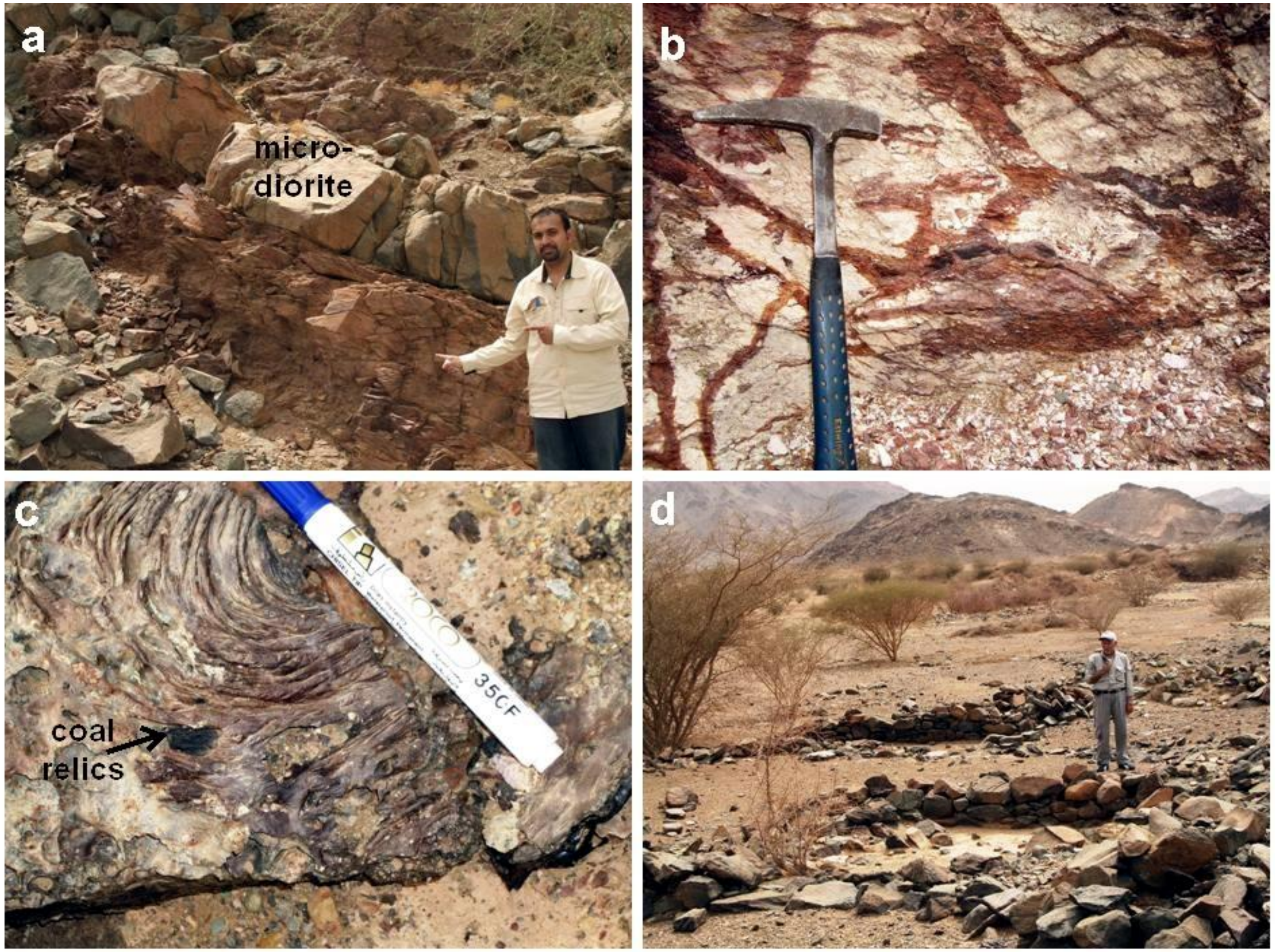


Fig. 2: a) Microdiorite intruding hydrothermally alterd metavolcanics. b) Hydrothermal alteration of metadacite viz. hematitization. c) Rope-like surface of ancient copper slag. Notice the presence of relict charcoal. d) Ruins of ancient labour houses probably dated back to the time of Abbasiyeen.

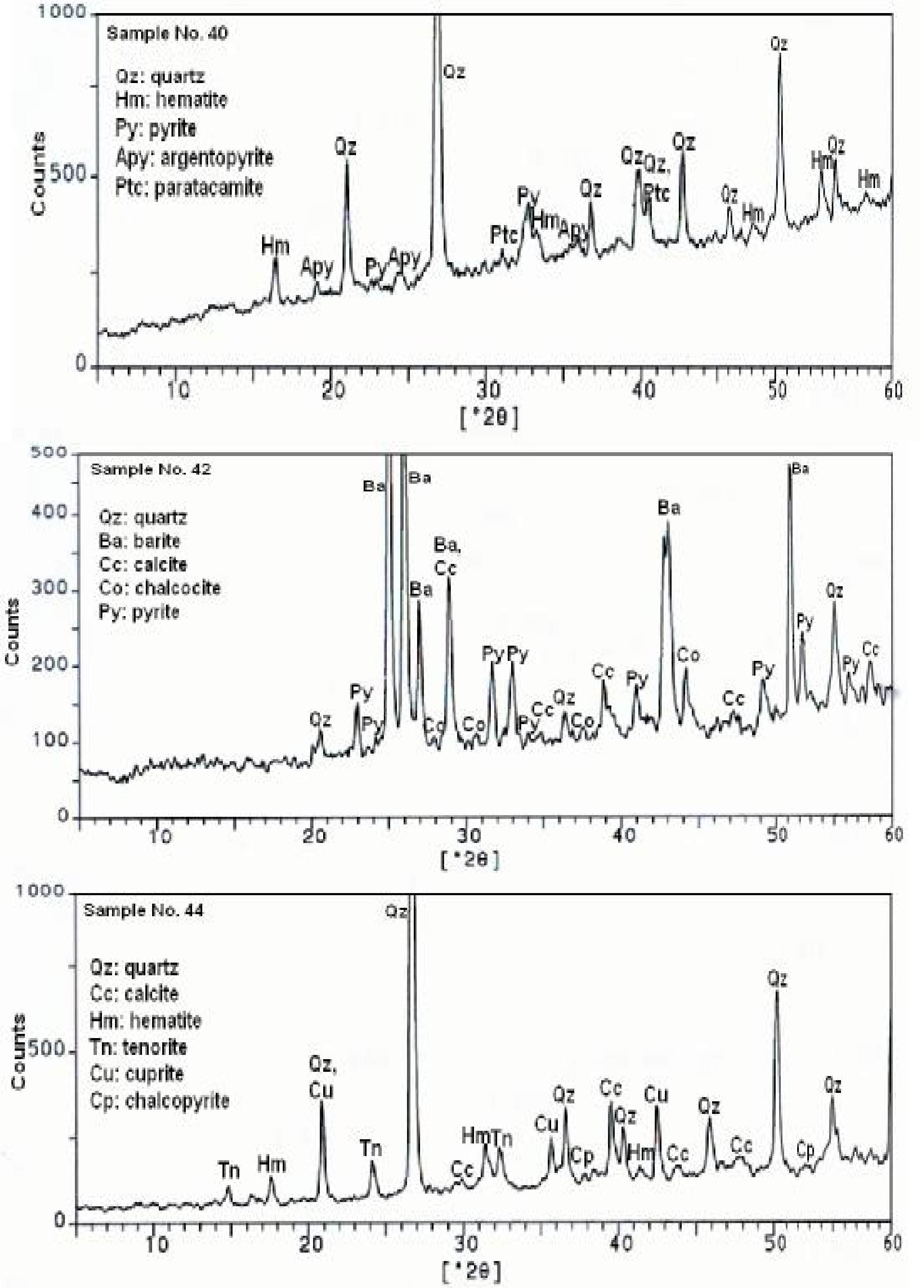


Fig. 3: XRD charts of some analyzed samples from the mineralized shear zone at Jabal Samran

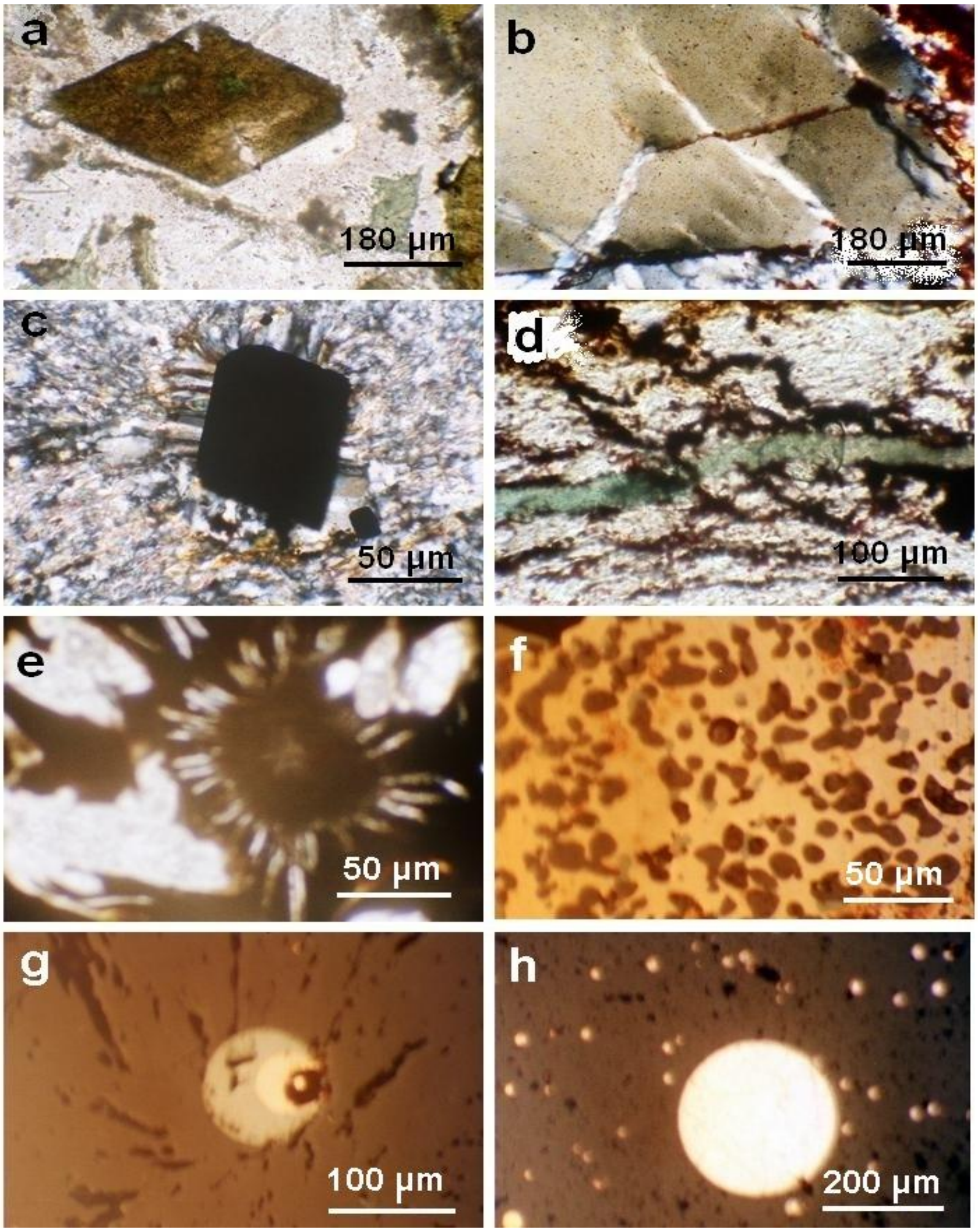
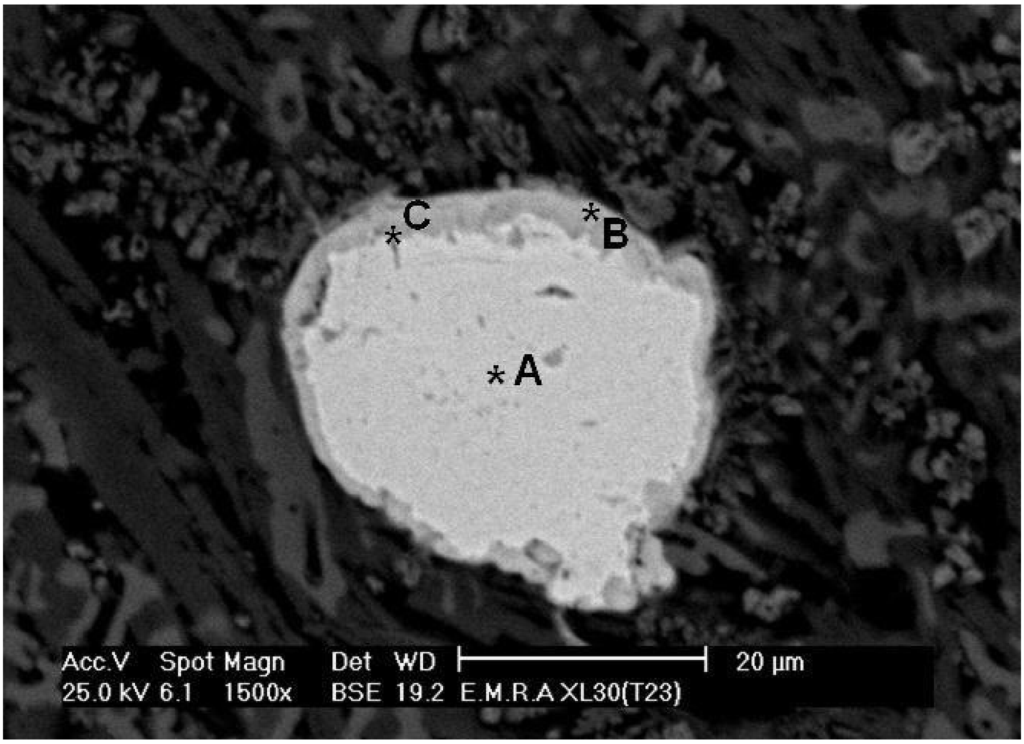
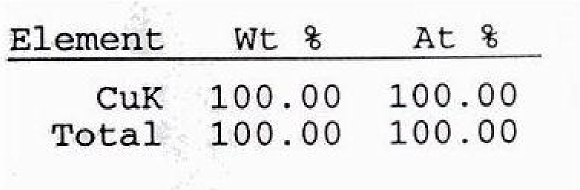


Fig. 4: a) Perfect actinolite rhomb in altered metadacite, P.P.L. b) Micro-conjugate fracturing of coarse quartz clast due to shearing, C.N. c) Resistant pyrite cube (black) showing strain shadow around as an indication of shearing, C.N. d) Paratacamite veinlet in highly hematitized metadacite, P.P.L. e) Radiating Fe-Mn silicate rods growing on a glass base in copper slag, P.P.L. f) Impure native copper showing numerous droplets of silicate and relict chalcocite, copper slag, reflected-light, P.P.L. g) Rusty copper prill showing fresh excentric native copper core, copper slag, reflected-light, P.P.L. h) Two different sizes of completely fresh copper prills in the copper slag, reflected-light, P.P.L.

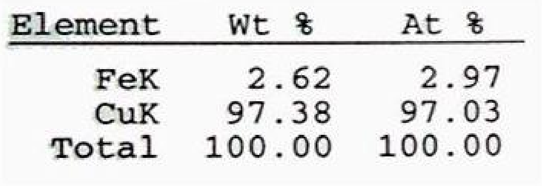


Spot "A"
Core of copper prill



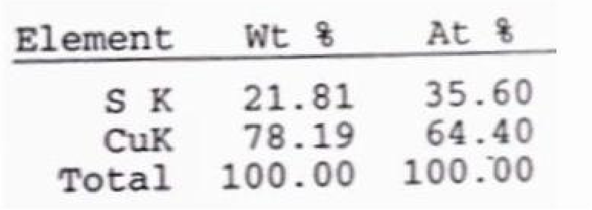
Element	Wt %	At %
CuK	100.00	100.00
Total	100.00	100.00

Spot "B"
Fe-bering copper rust
at rim



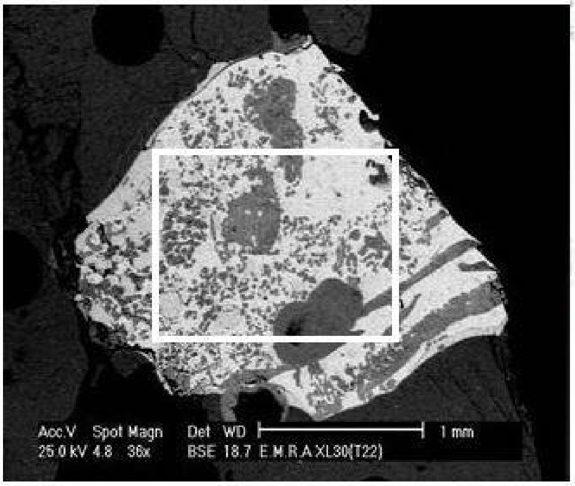
Element	Wt %	At %
FeK	2.62	2.97
CuK	97.38	97.03
Total	100.00	100.00

Spot "C"
S-rich copper rust
at rim



Element	Wt %	At %
S K	21.81	35.60
CuK	78.19	64.40
Total	100.00	100.00

Fig. 5: SEM image and EDX microanalyses of copper prill and its alteration products in a copper slag



Spot "A" Copper

Element	Wt %	At %
FeK	1.88	2.13
CuK	98.12	97.87
Total	100.00	100.00

Spot "B" Fe-Cl phase

Element	Wt %	At %
ClK	12.93	18.96
FeK	87.07	81.04
Total	100.00	100.00

Spot "C" Chalcocite relics

Element	Wt %	At %
S K	22.16	36.07
CuK	77.84	63.93
Total	100.00	100.00

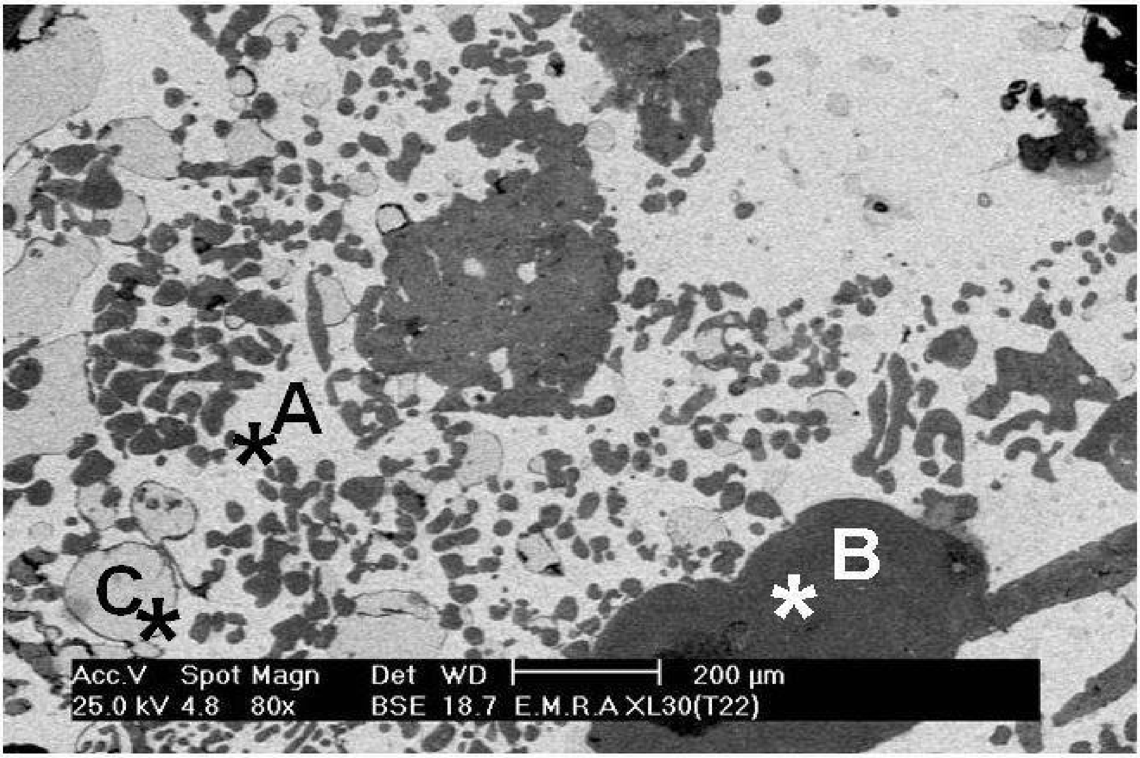
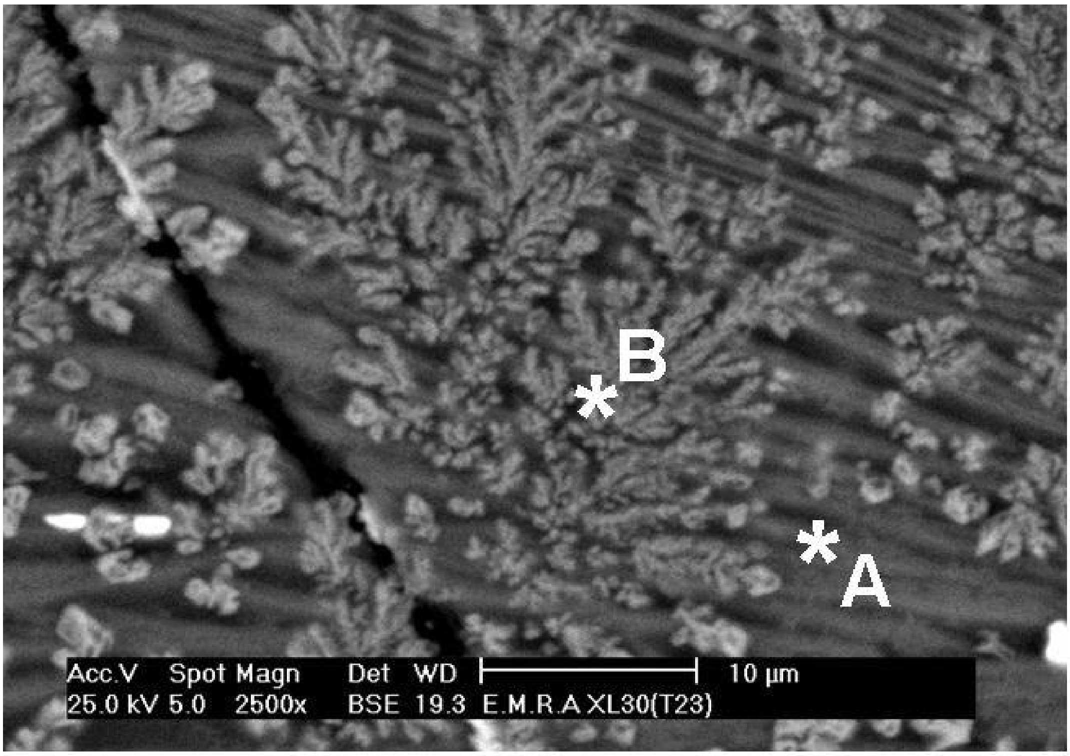
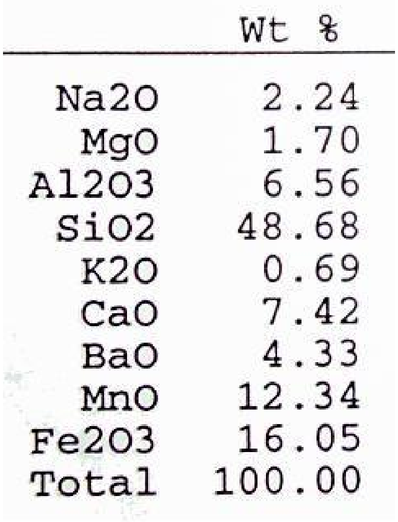


Fig. 6: SEM image and EDX microanalyses of impure copper prill and enclosed dark Fe-Cl droplets and relict chalcocite in a copper slag

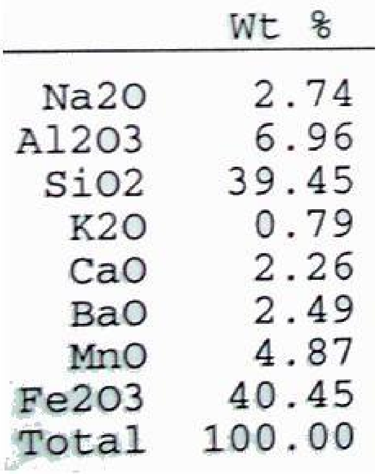


Spot "A"
Fe-Mn silicate long rods



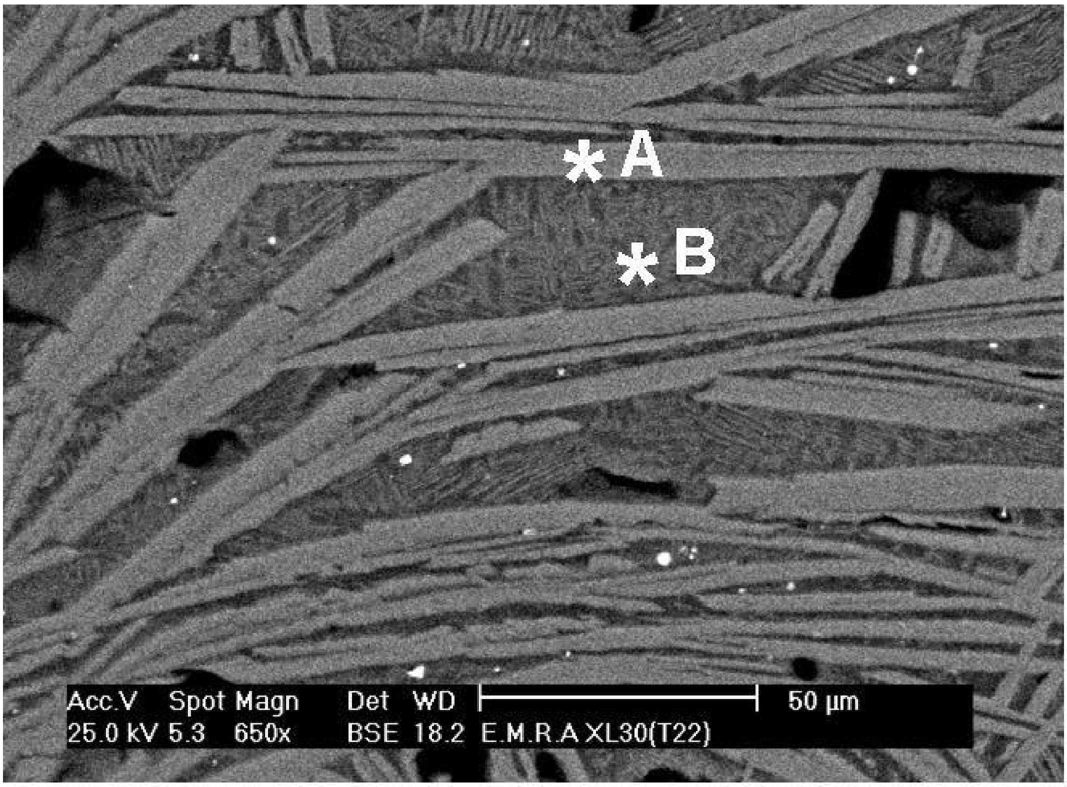
	Wt %
Na2O	2.24
MgO	1.70
Al2O3	6.56
SiO2	48.68
K2O	0.69
CaO	7.42
BaO	4.33
MnO	12.34
Fe2O3	16.05
Total	100.00

Spot "B"
Fe silicate dendrites



	Wt %
Na2O	2.74
Al2O3	6.96
SiO2	39.45
K2O	0.79
CaO	2.26
BaO	2.49
MnO	4.87
Fe2O3	40.45
Total	100.00

Fig. 7: SEM image of a copper slag and EDX microanalyses of rod-like and dendritic phases.



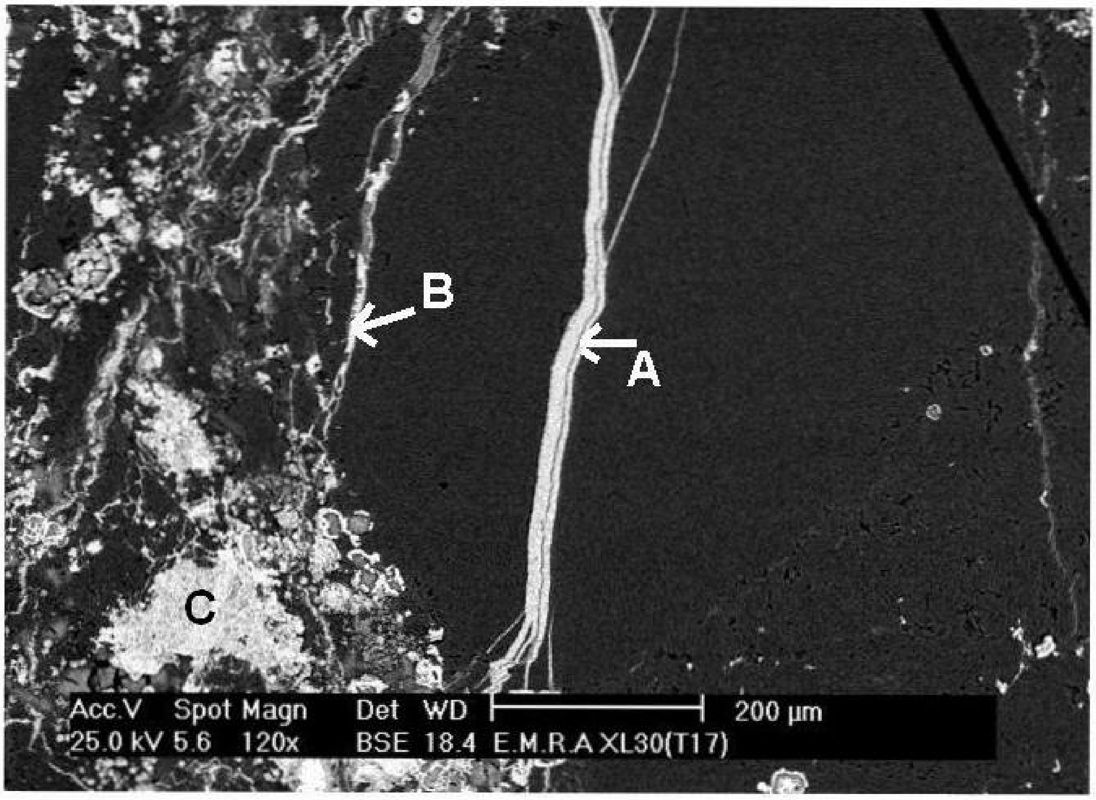
Spot "A"
Fe-Mn silicate long rods

	Wt %
SiO_2	47.86
CaO	7.27
MnO	23.71
Fe_2O_3	21.16
Total	100.00

Spot "B"
Fe-Al silicate groundmass

	Wt %
Al_2O_3	14.39
SiO_2	52.91
K_2O	1.92
CaO	3.96
BaO	3.71
MnO	4.92
Fe_2O_3	18.20
Total	100.00

Fig. 8: EDX microanalyses and SEM image of a copper slag showing an interstitial Fe-Al silicate phase to the Fe-Mn rods



Spot "A"
Pure cuprite veinlet

	Wt %
Cu	100.00
Total	100.00

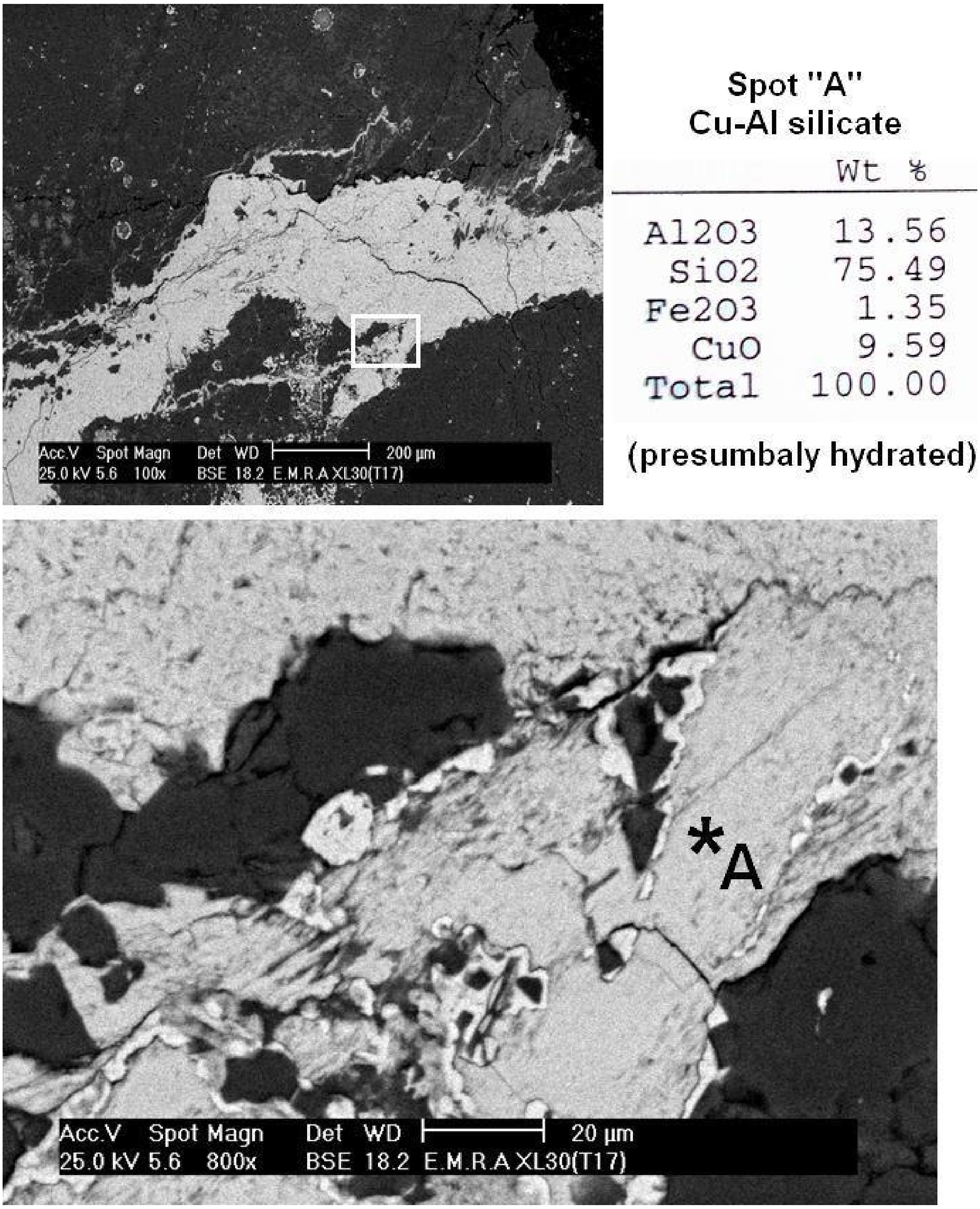
Spot "B"
Contaminated cuprite

	Wt %
Si	5.10
Cu	94.90
Total	100.00

Spot "C"
Goethite

	Wt %
Si	2.76
Fe	97.24
Total	100.00

Fig. 9: SEM image of a copper ore showing cuprite veinlet invading coarse quartz. The EDX microanalysis of goethite is also provided.



Spot "A"
Cu-Al silicate

	Wt %
Al_2O_3	13.56
SiO_2	75.49
Fe_2O_3	1.35
CuO	9.59
Total	100.00

(presumbaly hydrated)

Fig. 10: SEM image showing dense secondary copper veinlet in altered metadacite. The EDX microanalysis of this hydrated Cu-Al phase is also given.

Table 1: Mineralogy of some studied rock varieties determined from the XRD runs

Sample No.	**Rock Variety**	**Major**	**Minor**	**Trace**
T40	**Moderately sheared quartz-malachite rock with traces of black ore**	Quartz-paratacamite-brochantite	Pyrite-argentopyrite-hematite	Chrysocolla ?
T 41	**Slightly sheared quartz-malachite rock with traces of hematite**	Quartz-brochantite-calcite	Cuprite	Chalcocite
T 42	**Carbonated quartz-malachite rock**	Barite-quartz-calcite	Pyrite	Chalcocite-jarosite
T43	**Highly sheared hematitized kaolinite rock**	Quartz-kaolinite (sericite)-calcite-siderite	Chalcocite	Pyrite
T44	**Quartz-hematite rock with traces of black ore**	Quartz-calcite-rhodocrosite- hematite	Cuprite-tenorite	Chalcopyrite
T 45	**Carbonated Quartz-hematite rock with traces of black ore**	Quartz-calcite-natrojarosite-hematite-goethite	Cuprite-lepidocrocite	Chalcopyrite

Table 2: Composition of trace elements in some rock varieties measured by the ICP technique (in ppm)

Sample No.	Rock variety	B	Ba	Bi	Co	Cr	Cu	Mo	Sr	V	W	Zn	Zr
T1	**Barren quartz vein**	10	25	<10	1	23	8	<2	7	12	<5	60	<1
T2	**Barren quartz vein**	10	37	<10	1	5	4	<2	7	22	<5	16	<1
T3	**Barren quartz vein**	8	17	<10	3	43	5	<2	3	10	<5	26	<1
T4	**Barren quartz vein**	30	18	<10	3	32	5	<2	19	13	<5	23	<1
T5	**Quartz-sericite rock**	97	83	11	11	57	11	<2	72	86	6	65	1
T6	**Hematitized quartz vein**	24	20	<10	2	113	14	6	9	7	<5	36	1
T7	**Hematitized quartz vein**	20	18	<10	<1	31	9	<2	8	5	<5	13	1
T8	**Bleached metavolcanic***	120	445	<10	2	94	94	<2	26	134	<5	42	3

* The rock is highly sheared and contains abundant kaolinite and hematite

Table 3: Gold content in some rock varieties obtained by fire assay technique

Sample No.	Field name	Petrographic name	Au content (g/t)
T1	**Milky quartz vein (slightly smoky) with coarse "limonite"-goethite batches**	**Barren quartz vein**	<0.02 *
T2	**Milky quartz vein (slightly smoky) with coarse "limonite"-goethite batches**	**Barren quartz vein**	0.15
T3	**Milky quartz vein (slightly smoky) with coarse "limonite"-goethite batches**	**Barren quartz vein**	<0.02
T4	**Milky quartz vein (slightly smoky) with coarse "limonite"-goethite batches**	**Barren quartz vein**	<0.02
T5	**Quartz-sericite rock**	**Quartz-sericite rock**	0.15
T6	**Brecciated hematitized quartz vein**	**Hematitized quartz vein**	<0.02
T7	**Brecciated hematitized quartz vein**	**Hematitized quartz vein**	<0.02
T8	**"Bleached metavolcanic rock" consists of kaolinite and hematite**	**Bleached metavolcanic**	<0.02

* Limit of detection is <0.02

معدنية رواسب النحاس والخبث القديم الموجودة في نطاق البركانيات القوسية المتحولة بمنطقة جبل سمران، غرب وسط المملكة العربية السعودية

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الملخص العربي

تمعدن النحاس الثانوي بمنطقة جبل سمران موجود في الأساس علي هيئة منطقة قص (جز) تأخذ الأتجاه الشمال شرق والتي تتميز بصخر الداسيت المتحول المتكون في بيئة قوسية خلال زمن البريكامبري والداسيت متغير أيضا بفعل المحاليل الحرمائية. وتلعب الكبريتيدات المنثورة بالبركانيات المتحولة دورا مهما في نشأة تمعدنات النحاس الثانوية بمنطقة الدراسة والمحددة بمنطقة القص. ويعتقد هنا أن مياه البحر بمفردها أو مع المياه المحماوية التي يتم دورانها ومن ثم انبعاثها إلي قاع البحر بطول شقوق عميقة مكونة خلية حرمائية مؤكسجة غنية بثاني أكسيد الكربون. وحركة السوائل الحرمائية كانت مسئولة عن تحلل كبريتيدات النحاس المنثورة، مع التكوين المتزامن لمناطق تغير كثيفة في أسفل الداسيت المتحول، وفي الزفيريات المتحولة الأخرى ولكن بدرجة أقل.

ويعتقد هنا أيضا أن تكوين معدن الباراتكميت بفعل مياه البحر الغنية بالكلور والتي تؤكسد كبريتيدات النحاس الأولية علي قاع البحر. كما يعتقد أن عمليات الألبته والسليسه لصخور البركانيات المتحولة (داسيت في الغالب) الحاضنة للتمعدن بجبل سمران تم تسريعها ببعض تفاعلات التحلل المتعادلة الحموضة في ظروف أس هيدروجيني منخفضة، وأدي ذلك الي تكون معادن نحاس مائية مثل الكريزيكولا والباراتكميت.

أوضحت الدراسة المعدنية لخبث النحاس الموجود بسمران أنة لم يكن يستخلص بطريقة متطورة، حيث وجدت كريات النحاس العنصري محتويه علي بقايا كثيرة من معدن الكالكوسيت والذي يعتقد أنه كان يستخدم كخام نحاس أساسي أثناء عمليات التعدين القديمة خلال العصر العباسي علي وجه التحديد. وكريات النحاس بها أيضا بعض البقايا من معدني الباراتكميت والروشانتيت وبعض المعادن الحاويه لعنصر الكبريت (مثل معدني الباريت والجاروسيت). ويعتقد أن خام النحاس كان يخلط بنوعين من مخفضات درجة الانصهار (كربونات الكالسيوم والهيماتيت). وبعض عينات الخبث التي تم جمعها مازالت تحتوي علي بقايا الفحم الذي كان يستخدم كوقود. ويعتبر هنا أن خبث نحاس جبل سمران كان من النوع الذي كان يبرد بالماء وهو الذي يستدل عليه من سطح الخبث الشبيه بالحبال.