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Mineralogy and Geochemistry Studies of the Sorkheh Sediment-hosted Stratiform Copper (SSC) Deposit, NW Iran

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Abstract

The Sorkheh deposit in northwestern Iran exhibits several readily visible general characteristics of sediment-hosted stratiform copper (SSC) mineralization. It consists of fine-grained disseminated base-metal sulfides within gray sandstones (gray beds, the basal whitish Miocene sandstone and shallow-water) that overlie a thick sequence of red beds (Miocene Upper Red Formation). The host gray beds are the basal sandstone and are intercalated with red bed sandstones, which are shown from textural studies to be carbonaceous and to have initially contained very fine-grained, disseminated, syndiagenetic pyrite. The sediment-hosted stratiform copper deposit of the Sorkheh area formed in a location where basinal fluids passed through a series of highly oxidized rocks and could obtained copper, which was then precipitated as the fluids encountered a reductant that destabilized the complexing ability of the fluid. According to the proposed model, the Sorkheh deposit appeared to have begun formation during diagenesis when mineralizing fluids became focused into constrained areas by stratigraphic and/or structural architecture. To form the Sorkheh sediment-hosted stratiform copper deposit, a number of major features must be present: abundant, highly oxidized metal source rocks, highly reduced strata in a position favoring interaction with significant amounts of fluid that previously passed through the oxidized strata package, and significant thicknesses of evaporates capping the reduced strata to serve as a hydrologic seal and a source of high-salinity (and possibly sulfur-rich) brines.

Ore-stage sulfides are zoned vertically and obliquely through the mineralized zones, from cupriferous sulfides at low stratigraphic levels to copper-rich mineralization above, with unreplaced pyrite remaining within the upper Miocene. The zoned sulfides and their replacement textures, configuration of the mineralized zones, and the position of ore stage mineralization adjacent to a stratigraphically defined redox transition from red beds upward into graybeds indicate an overprint of copper (and accompanying ore-stage metals) on originally pyritic gray beds. The influx of ore-stage metals, presumably in an oxidized low-temperature brine, terminated with a silicification event that effectively sealed the host sandstones. Consequently, these observations and the overall genetic interpretation are consistent with the general deposit-scale genetic model for early diagenetic SSC mineralization. The regional geologic context is also consistent with its classification as a SSC deposit and is hosted by sediments that were formed in association with evaporates at a low latitude in a Sabkha environment. Source of Sorkheh deposition has been indicated as a sedimentary arid type. Sandstones of the Sorkheh area tectonic settings are obtained in a passive continental margin.

Keywords: *Sediment-hosted stratiform copper, Sorkheh, Azerbaijan, NW Iran*

1. Introduction

The research presented in this paper was undertaken (1) to provide a basic description of the relatively unknown Sorkheh copper deposit situated in upper Miocene sediments in the Tabriz basin, northwestern Iran (Fig. 1), (2) to explain the genesis of this mineralization, and (3) to determine whether this deposit qualifies as sediment-hosted stratiform copper (SSC) mineralization such as that found in the Central African Copper Belt or in the Kupferschiefer of Europe. The first formal proposal that the mineralization was of the SSC type led to mapping and chemistry examination by a private company. Most of the drilling and trenches that were taken in the area were limited to near-surface zones of oxide and mixed Oxide–sulfide mineralization characterized by malachite–azurite and mostly chalcocite staining. However, many fundamental characteristics of SSC mineralization (e.g., fine-grained disseminated cupriferous sulfides in sandstone units overlying red beds) were confirmed. A report by Rajabpour et al. (2013) also studied the Cheshmehkonan area very near to this district as a SSC model during their field mapping, and geology and geochemistry researches.

Thus far, the Cheshmehkonan copper deposit is the most economically promising of numerous occurrences of SSC mineralization in the Upper Red Formation (Qom Formation) sedimentary rocks in the north and northwestern part of Tabriz, NW Iran. By 2013, these widespread occurrences of sediment-hosted copper were correlated with an extensive shallow deep sea, Sabka environment (Rajabpour et al. 2013), as are most

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other SSC deposits in the world (Jowett 1989; Kirkham 1989; Brown 1992). The widespread sediment-hosted mineralization was labeled the “Tabriz basin NW Iran SSC Copper Belt” (Geological Survey of Iran; GSI), coincident with its extensive shallow deep-sea Upper Red Formation sediment. To test the validity of this exploration model, we have done the current research in field and laboratory studies. The present report describes (1) the tectonic and sedimentary contexts of the mineralization; (2) the mineralogy, textures, paragenesis, and zoning of the primary sulfides; and (3) the timing of mineralization relative to the deposition of the host sediments, to their subsequent diagenesis. Much of this information is found in geological reports prepared by government and university services and in publications of scientific researches. An important portion of our understanding of the regional geology of the area also derives from GSI that have focused on the same Upper Red Formation (Qom formation) sediments as those hosting the deposit and Cheshmehkonan, Nazkhatun and Nahand stratiform copper deposits (Sadati et al. 2014).

Fig. 1: Location of the Study area on Iran geological map

2. Regional geologic setting

The Neogene Tabriz Basin in NW Iran is a basin that is bounded to the north and northeast by the terrestrial clastic sediments of the Upper Red Formation currently considered as Middle to Late Miocene in age (Gansser 1955; Fisher 1968; Moine Vaziri and Amine Sobhani 1977; Moein Vaziri 1999). The Tabriz Basin is part of a strike-slip fault system that developed during the Late Miocene between the colliding Arabian and Eurasian plates (McKenzie 1972; Axen et al. 2001; Allen et al. 2004). To the west, the Tabriz Basin opens to the lowlands of Lake Urmia, a hypersaline lake sourced by saline solutions from Miocene evaporates (Schweizer 1975). Marine limestones and marls of the largely Lower Miocene Qom Formation are present north-west and east of Tabriz city; and on the islands of Lake Urmia they indicate that the region of the Tabriz Basin was part of the Tethys up to the Early Miocene (Rieben 1935; Stöcklin 1977; Davoudzadeh et al. 1997; Mollai et al. 2014). The regression of the Qom Sea was followed by a period of continental sedimentation in NW and central Iran and Azerbaijan; these deposits have been termed formation gypso-salifère by Rieben (1935) and Upper Red Formation by subsequent authors. In NW Iran, the Upper Red Formation is more than 2000 m thick and considered Middle Miocene or Middle to Late Miocene in age (Davoudzadeh et al. 1997; Allen et al. 2004; Sen and Purabrishemi 2010; Ataabadi et al. 2011).

The Tabriz fault led to the formation of the Tabriz Basin in the Late Miocene (Kelts and Shahrabi 1986). The Neogene basin fill is composed from the bottom to the top of the Lignite Beds; the latter are overlain by Quaternary alluvial conglomerates (Rieben 1935). In a research, Reichenbacher et al. (2011) re-evaluated the stratigraphic age and palaeo environment of the Lignite Beds in order to provide insight into the past environments and processes during the subsidence of the Tabriz Basin and during the Late Miocene. Then they presented fission-track data for the northern hinterland of the Tabriz Basin (Upper Red Formation).

The apatite FT results by Reichenbacher et al. (2011) indicated an age of 11.2 (±1.1) Ma for the Upper Red Formation. They concluded that the Upper Red Formation of today, which forms the hinterland to the north and northeast of the Tabriz Basin, was uplifted when the Tabriz Basin developed and was deposited as a result of the tectonic subsidence of the Tabriz Basin.

At the regional scale, the Sorkheh deposit is located within the Tabriz basin, NW Iran, which comprises of the northwestern portion of the belt (Fig. 2).

In the Sorkheh area, Tertiary rocks and quaternary sediments occurred as igneous and alluvial units. The roots of the Miocene sediments were formed during the early Miocene-Paleozoic basement. Major structural lineaments that developed at this time are considered to have played repeated roles in controlling regional-scale compressional and extensional displacements throughout the following Alpian (Late Tertiary) orogenic cycles (see, for example, (Rajabpour et al. 2013)). The Tabriz area has been and continues to be closely related to the shallow deep sea environment of the Upper Red beds (Qom Formation). A widespread marine sedimentation that developed in central Iran includes the northwestern portion during the Miocene time (Alpine orogeny). Central and northwestern Iran were filled largely by red beds, and then by intercalation of green bed sandstones and carbonates. Later, the Alpine (Early to Late Tertiary) disturbances folded and faulted the late Tertiary sediments of the area.

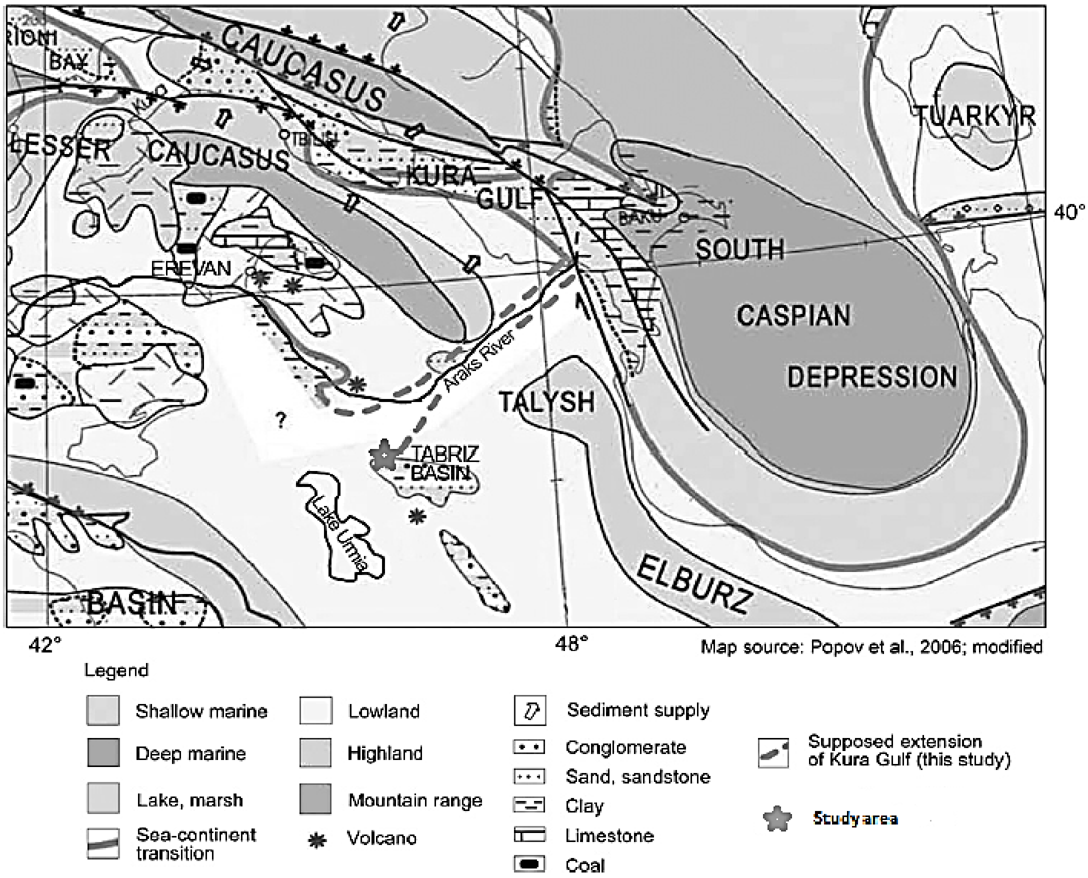


Fig. 2. Palaeogeographic map of the Southern Caspian Sea and the Tabriz basin (Eastern Paratethys) for the terminal Tortonian and early Messinian (after Popov et al. (2006); Reichenbacher et al. (2011))

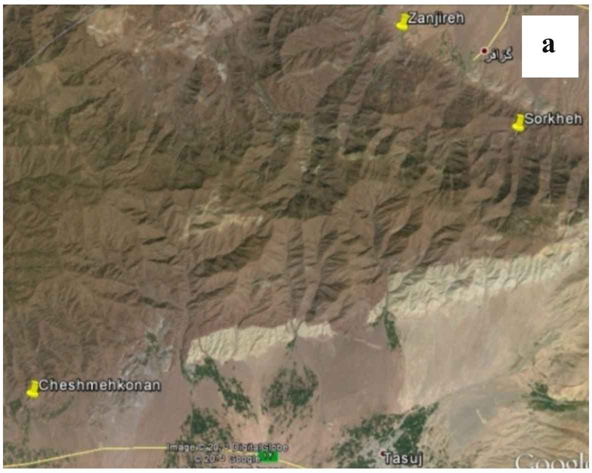
2.1. Stratigraphy of the Tasuj area, northwestern Iran sedimentary basin

Upper Red Formation sedimentation began in the Miocene with the deposition of shallow deep red-green bed dykes in Middle to upper-Miocene time (Qom formation, Fig. 3; (Khodabandeh and Amini Fazl 1991; Rajabpour et al. 2013). The Upper Red Formation sedimentary section is composed of Late Miocene shallow-water shore-clastic sediments composed of a basal sandstone (Redbed Formation) that grades rapidly upward into shallow marine or lacustrine limestone and sandstones (Rajabpour et al. 2013). Sedimentation continued with intruding volcanic dacitic dikes, and culminated in the Quaternary with the deposition of alluvium and fluvial sediments and evaporates (Fig. 3).

The northwestern and southeastern margins of the Tasuj area are delineated by the Tasuj and Soufian lineaments, respectively (Rajabpour et al. 2013), along which dacitic volcanic dikes were intruded into the accumulation of Tasuj-Sorkheh redbeds.

3. Geography and geology

The Sorkheh deposit is located in northwestern Iran (45°26′ E, 38°28′ N), about 25 km northwest of the city of Tabriz, and is easily accessible via national highways (Fig. 1). The topography is hilly, varying in elevation from about 1000 to 2,400 m. The principal exposures of stratiform mineralization are found on three ridges (Sorkheh and Zanjireh in the eastern, and the Cheshmehkonan in western portions of the district (Fig. 3), all of which may be reached by all-terrain vehicles. The geology of the Sorkheh property is dominated by slices of Miocene sedimentary rocks thrust up and folded onto an early Miocene–Paleozoic basement, which was deformed intensely during the Tertiary, Alpine Orogeny. The area is occupied by Sorkheh redbeds, whereas the domes are generally represented by the more resistant volcanic dacitic rocks. The geology map and lithologic compositions of the stratigraphic units and subunits on the property are shown schematically in Fig. 4. The occurrence of copper mineralization on the property is evident from abundant malachite-azurite staining on weathered rock surfaces. Highly mineralized outcrops may also have visible disseminated cupriferous sulfides as well as their oxides.



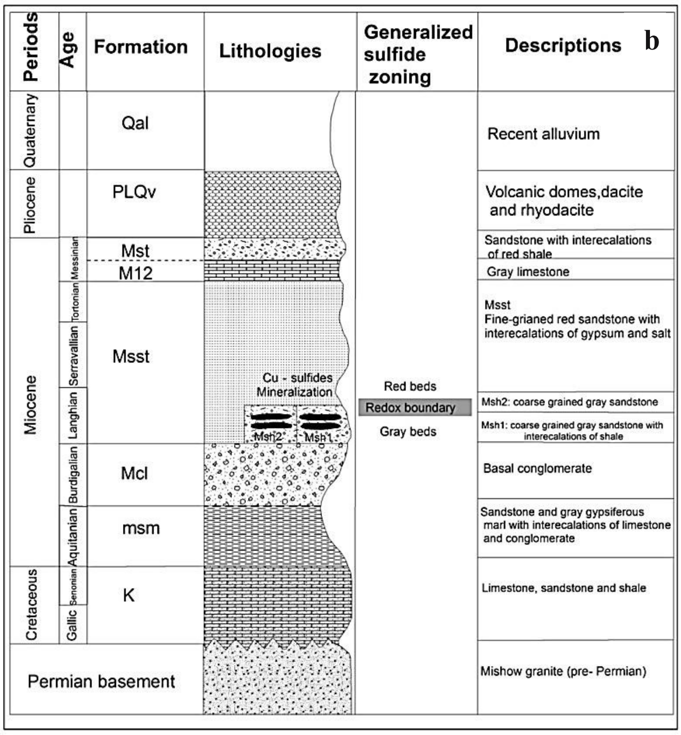


Fig. 3. a) Distribution of sedimentary copper deposits in Tasuj area, NW of Tabriz basin (Sorkheh, Zanjireh and Cheshmehkonan, google earth, 2015); b) Stratigraphy and inter basin correlation of the Qom formation sedimentary, Upper Red Formation in Tasuj area, Cheshmehkonan sedimentary deposit (from (Rajabpour et al. 2013)

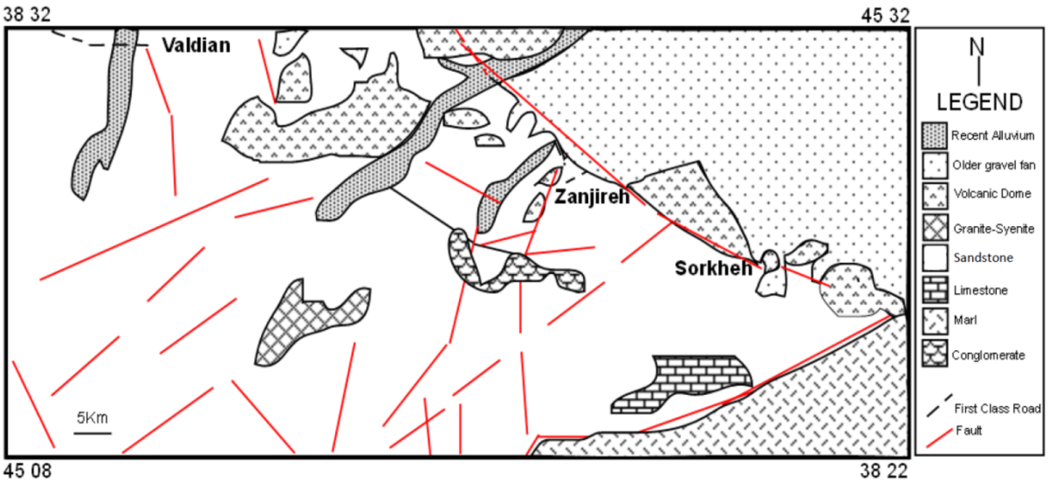


Fig. 4. Simplified geological map of the Sorkheh property, as determined from detailed surface mapping and exploration drilling (simplified after Khodabandeh and Amini Fazl (1991)). Sediment-hosted copper mineralization occurs in the Upper Red Formation.

3.1. Host-rock petrology and petrography

An understanding of the genesis of SSC mineralization generally requires a close examination of both the host greenbeds and the underlying footwall redbeds (see for example descriptions and interpretations in (Kirkham 1989; Brown 1997; Brown 2003; Brown 2005; Hitzman et al. 2005; Hitzman et al. 2010). At Sorkheh, the footwall redbeds are composed of the coarse-grained reddish clastic sediments of the Upper Red (Qom) Formation, and the greenbeds are represented by the overlying greenish Sorkheh sandstone.

3.2. Sorkheh sandstone

The Sorkheh sandstone unit is the principal host of copper mineralization in the district. It is grayish in color on exposures or greenish (malachite and azurite stained) due to the oxidation of cupriferous sulfides. Fractures containing organic matters are common. Shallow-water facies of the Upper Red Formation include grainstone, mudstone, siltstone, marl, and intraformational conglomerate. In some cases, the layers are formed from microfossils or terrigenous clasts; other allochems include intraclasts, macro- and microfossils, pelloids, and lumps.

The permeability of grainstones was probably high due to fabric-selective intra particle and mouldic porosities.

Grainstones of the Qom Formation resemble grainstones in hand specimens, but in thin sections they are found to have micritic matrixes. Some limestone clasts have intergranular sparitic, microsparitic, and/or dolomicritic cements; the cements may be vadose, having formed during subaerial exposure.

Both fine-grained and coarse-grained pyrites are commonly included. Clastic layers may contain fossil oolites, pellets, and other allochems. Siltstones and marls form the finest-grained facies of the Upper Red Formation. Siltstones, composed mainly of thinly laminated silt with an argillic matrix and calcareous cement, are abundant toward the top of the Upper Red Formation. The principal mineral components are quartz and feldspar in the coarse silt fraction and phyllosilicates in the argillaceous matrix. Marls, on the other hand, are more abundant in the Upper Red Formation. They have a grayish color compared to the siltstones and are composed of clays with calcareous cement.

The cement is dolomitic and/or calcitic. Although commonly referred to as a simple carbonate unit, the Qom Formation varies from high-energy facies (grainstones and packstones) to low-energy facies (siltstones, and mudstones), with an overall gradation from predominantly calcareous sediments in the basal portions of the Qom Formation and more siliciclastic sediments in upper sections. Examined more closely, the grainstones and packstones are characterized by oolitic and oncolitic grains and by graded beds typical of wave-dominated high-energy environments (Greensmith 2012). The fine parallel-laminated nature of the mudstone suggests deposition in calm and/or restricted environments.

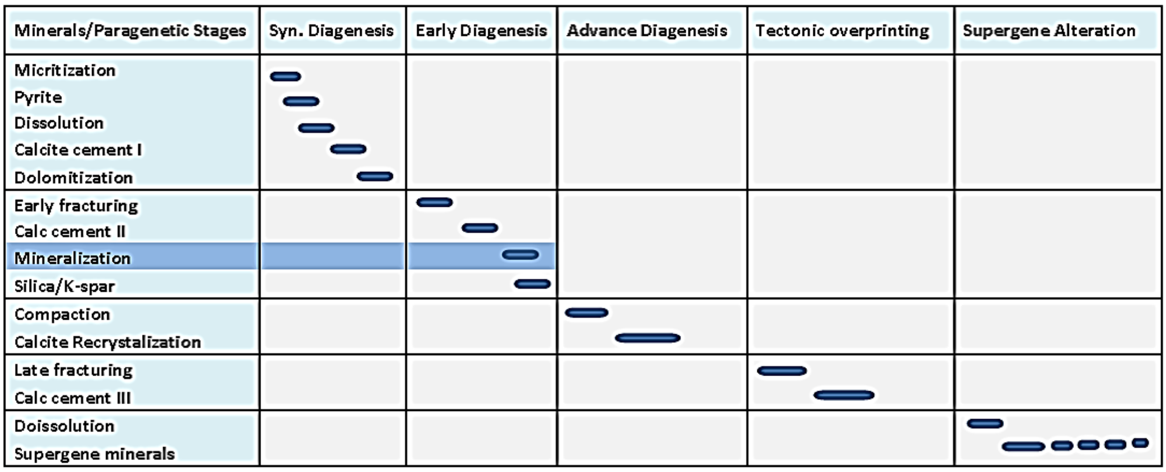
The mudstones are commonly burrowed, a feature also typical of calm or restricted environments of sedimentation such as those found in shallow lagoons.

The many transitions from low to high-energy sediments form repeated shallowing-upward sequences characteristic of stable carbonate platforms where the rate of sedimentation would have exceeded the rate of subsidence and where successive sediments would have been deposited in progressively shallower waters (Friedman et al. 1973; James 1984; Friedman et al. 1992; Tucker and Wright 2009). Such shallowing upward sequences are found especially in lacustrine low gradient ramp margins (Tucker and Wright 2009), as in the lacustrine Eocene Green River Formation of the western USA (Williamson and Picard 1974) and in the modern lake sediments of the East African Rift (Kendall 1969; Reading 1982; Platt and Wright 2009).

4. Pre-ore, ore-stage, and post-ore petrographies

Petrographic studies were undertaken on the various facies of the Sorkheh Formation and their fabrics in an attempt to bracket the timing of emplacement of ore-stage sulfides relative to four successive events in the history of the Sorkheh host rocks: sedimentation, diagenesis, tectonic deformation, and supergene oxidation. Table 1 summarizes the relative timing of particular features, events, and emplacements, as recognized in this petrographic study.

Table 1: Sequence of minerals formed and associated events identified in the petrography of the Sorkheh Formation hosting copper mineralization. The horizontal axis is divided from left to right into progressive stages: syndiagenesis, for very early diagenetic effects, that take place in a sediment soon after deposition and at very shallow burial; early diagenesis, for effects at moderate burial; advanced diagenesis, for effects at deep burial, followed by tectonic effects (e.g., deformation, fracturing) resulting principally from Alpine orogenesis; and recent supergene alteration of the host rock and mineralization.



4.1. Pyrite: a pre-ore sulfide

Coarse-grained pyrite is difficult to see, and it is not the dominant textural type; abundant very fine-grained pyrite provides a more pervasive amount of iron sulfide, most of which cannot be observed except in polished sections. Two textural types are recognized: (1) very fine-grained (typically up to 10 µm in size) disseminations of pyrite, in part framboidal (Fig. 5a and b) and (2) coarse-grained euhedral pyrite and aggregates of pyrite grains (commonly 20 µm to 0.5 mm or more in size; Fig. 6a, b).

At the microscopic scale, very fine-grained pyrite is seen to be principally associated with laminations of apparent organic matters (Fig. 7). Fine disseminations of pyrite may outline recrystallized and have been recognized in thin moulds of micrite, including sediments that were micritized before the deposition of sparry cements. High concentrations of very fine-grained pyrite are also found in sources of organic matter that, in turn, supported anoxic bacterial activity and bacterial reduction of sulfates (Fig. 7). Besides framboidal aggregates, very fine-grained pyrite may also form nodular aggregates (up to 0.9 cm in size) in interparticulate spaces (Fig. 5a, b). Very fine-grained pyrite is considered to be syndiagenetic in origin (Fig. 5a), having formed in the earliest unconsolidated sediment from sulfide produced by bacterial sulfate reduction; the sulfide reacted, in turn, with iron normally available in impure sediments to form iron sulfides that matured into syndiagenetic pyrite. Coarse-grained euhedral pyrite typically occupies intergranular spaces.

Aggregates of very fine-grained pyrite may be partially or wholly annealed to form coarse-grained euhedral pyrite, suggesting that coarse-grained pyrite was formed during advanced diagenetic recrystallization of very fine-grained pyrite that may have accompanied sediment compaction and/or tectonic pressures.

4.2. Ore-stage copper-iron, and copper sulfides

The dominant primary ore-stage mineralization at Sorkheh consists of disseminated sulfides, mainly in the coarser grained host facies (grain stone) of the Upper Red Formation. A minor amount occurs in compact siltstone and mudstone; local concentrations also occur in the porous burrowed portions of sandstone. Primary cupriferous sulfides also occur as cement (principally chalcocitic) in the uppermost whitish-green Sorkheh sandstone. Ore sulfides are visible to the naked eye, and are best seen with the aid of a hand lens. Details are most readily seen in polished sections.

As described below, the cupriferous sulfides (chalcocite, bornite, chalcopyrite, and tetrahedrite as mineralization) formed at a distinctly later stage of diagenesis than the syndiagenetic pyrite described above. These ore-stage sulfides are discussed in the order of their appearance in a generalized paragenetic sequence:

(tetrahedrite)→chalcopyrite→ bornite→chalcocite.

Tetrahedrite that was not obvious in hand specimens because of its minor occurrence and its intergrowths with other sulfides, is readily found in polished sections containing chalcopyrite and other copper sulfides (Fig. 8a, b). It occurs mainly as small grains associated with chalcopyrite and is considered contemporaneous with a chalcopyrite deposition.

Chalcopyrite generally becomes the dominant sulfide at surface levels. Remnants of pyrite may still occur in the upper levels of chalcopyrite mineralization. Chalcopyrite occurs as isolated disseminated anhedral grains and aggregates. Individual grains range up to 200 µm in size. Chalcopyrite has been observed as auhedral grains and veinlets. Tetrahedrite and chalcopyrite replaced earlier sulfides and commonly inverted to other secondary ores in the next stages. The close association of tetrahedrite and chalcopyrite, and the occurrence of chalcopyrite inclusions in tetrahedrite, suggest that the two sulfides were deposited closely together in time. Chalcopyrite is replaced in turn by the more copper-rich sulfides, bornite, covelite and chalcocite (Fig. 8a, b).

Bornite is typically found in the Sorkheh district sediment Formation. It is generally observed as irregular disseminated grains and converted to other copper sulfides respectively. Irregular grains of bornite commonly occupy primary intergranular and secondary diagenetic porosities. As with other sulfides, bornite may be concentrated along a fossil remanent. Aggregates of irregular grains of bornite vary in size up to 600 µm in diameter. Two distinct varieties of bornite are noted: a "purple" bornite that is typically sulfur-poor and copper-rich, and a "pink" (or anomalous) bornite that is typically sulfur-rich (Yund and Kullerud 1966; Ramdohr 2013). The two bornites are vertically zoned, with the pink variety more abundant in the upper portions of the overall bornite zone. Pink bornite may exhibit a basket-weave intergrowth with chalcopyrite lamellae, generally interpreted as an exsolution of chalcopyrite resulting from an excess of sulfur and iron in the host bornite. Such compositionally anomalous bornite could be a metastable "redbed copper" bornite formed initially during rapid crystallization at low temperatures. During subsequent mild annealing, as could occur during burial to modest depths, oriented chalcopyrite lamellae may have formed along the crystallographic planes of bornite (Brown 1971) showed that annealing at a temperature of 75°C over 24 h was sufficient to incite an exsolution of chalcopyrite from the pink bornite of the White Pine deposit. The existence of a natural chalcopyrite exsolution at Sorkheh suggests then that the mineralization formed at low temperatures (Fig. 8, 9).

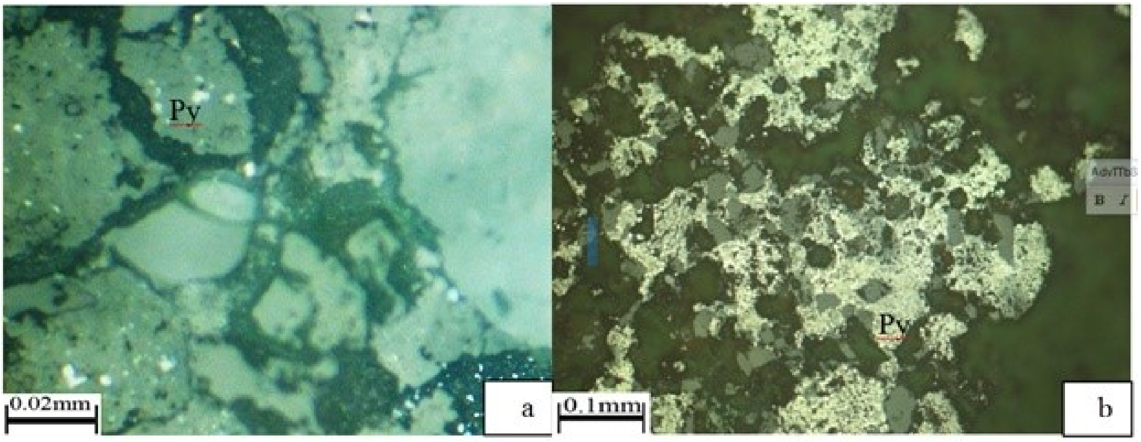


Fig. 5: Fine-grained pyrite: a) Disseminated, b) Framboidal groupings (Reflected, plane polarized light). Py: pyrite.

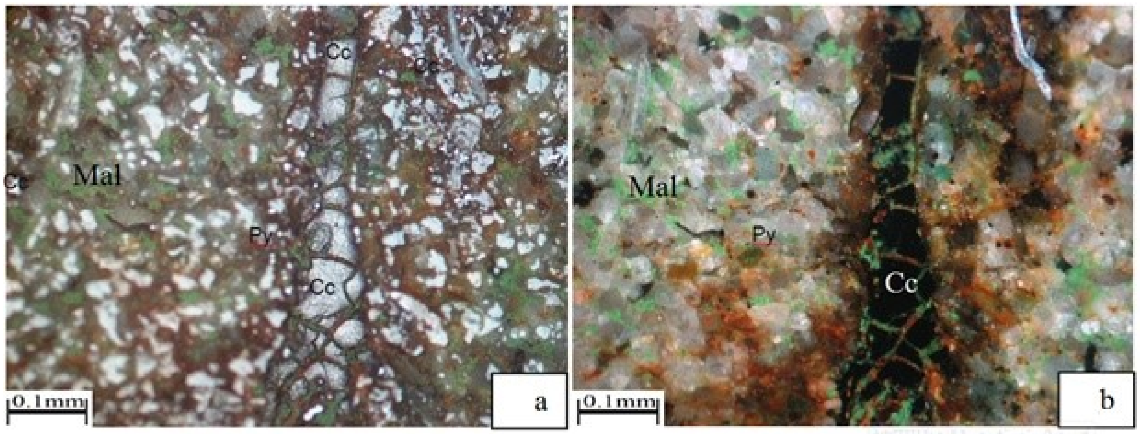


Fig. 6: a, b) Remnant pyrite and chalcocite in addition to malachite and organic matters (Transmitted, planepolarized Light), Py: Pyrite; Cc: Chalcosite; Mal: Malachite.

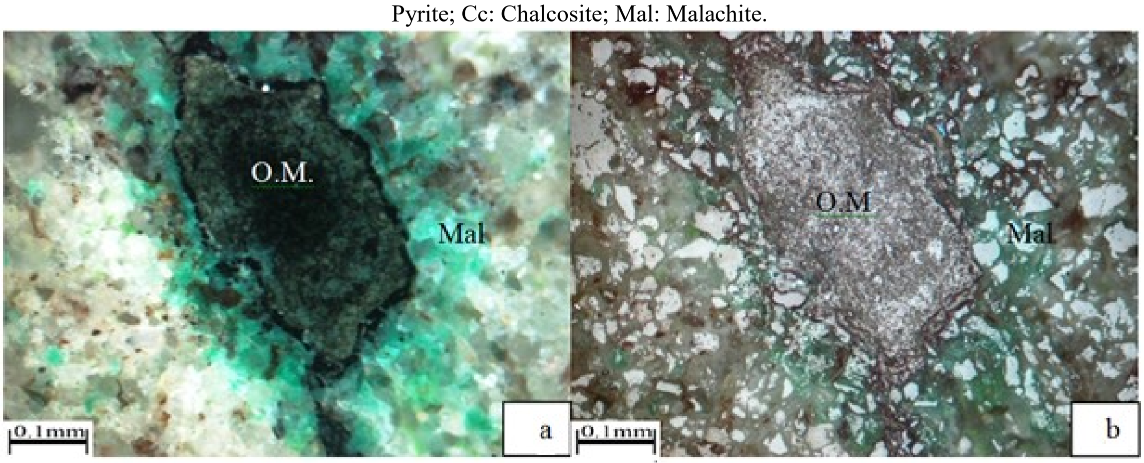


Fig. 7: a, b) Organic matters with malachite surrounded with in the intergranular porosity of the more permeable sandstone rock type. In both plane-polarized, transmitted light. O.M: Organic matters; Mal: Malachite.

The most common sulfides associated with bornite are chalcocite and digenite. Where chalcocite or digenite rims bornite, the bornite is typically the purple (i.e., copper-rich) variety (Fig. 8a). Bornite (especially the pink variety) also forms boundary contacts with paragenetically earlier sulfides. Inclusions of remnant pyrite are rare but not uncommon.

Chalcocite is a common disseminated copper-rich sulfide, filling primary intergranular porosities in the lower Sorkheh Formation, where it is generally subordinate in abundance to bornite; it may be the dominant or sole cupriferous sulfide in the Upper Red Formation. Examined in detail, some apparent chalcocite is, in fact, bluish in reflected light and should be identified as digenite, especially where associated with bornite. Aside from cases where digenite is seen clearly to rim or replace bornite, most digenite has been described and discussed in this paper under the term "chalcocite." Typically, individual chalcocite grains are irregular in shape and of variable size. It is observed as rims around all paragenetically earlier sulfides (pyrite, tetrahedrite, chalcopyrite, and bornite) and is not seen as inclusions in those sulfides. The sulfides most commonly associated with chalcocite are bornite (Fig. 9a,b)) and less commonly chalcopyrite.

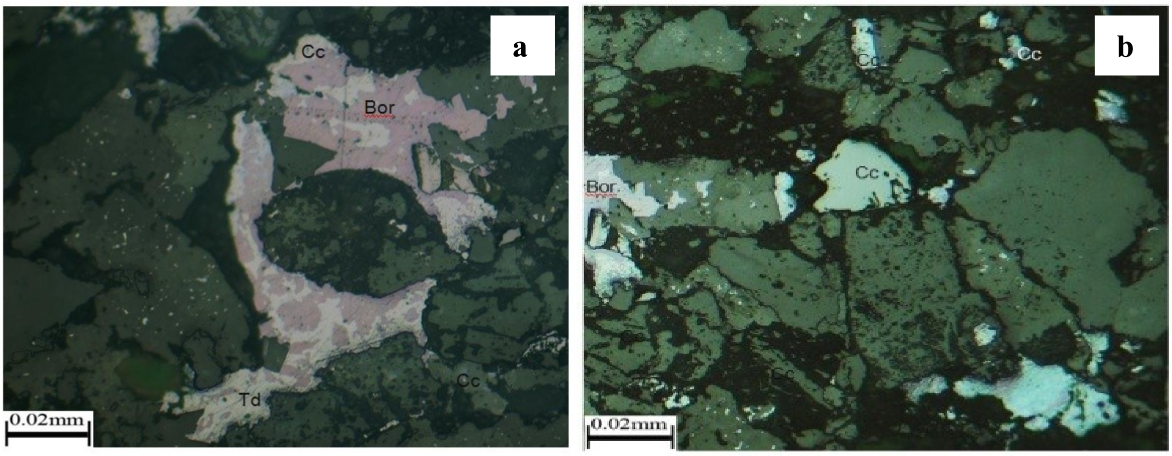


Fig. 8: a) Tetrahedrite (Td) replaced by an assemblage of copper sulfides (Bor; Bornite), and chalcocite (Cc; Chalcosite: Reflected, plane-polarized light). b) Purple bornite (Bor) partially replaced by chalcocite (Cc, Large anhedral chalcocite grains, enclosing remnants of purple bornite. Reflected, plane-polarized light.

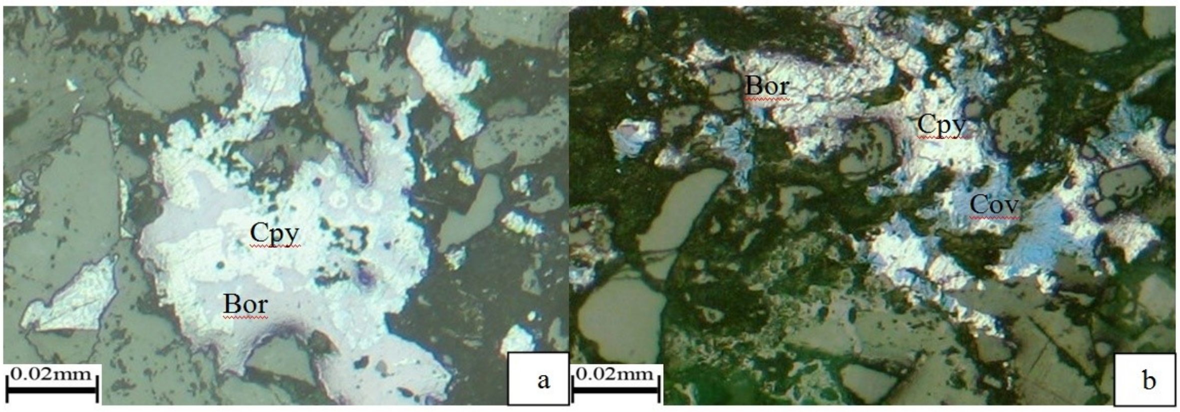


Fig. 9. a). Chalcopyrite, and bornite. Chalcopyrite shows either intergrowths with or replaces bornite, b) Bornite is converted into Covellite.

4.3. Primary sulfide zoning

Under surficial oxidation, the spatial distributions of pre-ore pyrite and ore-stage cupriferous sulfides outline a general trend from more chalcophile minerals in the basal portions of the Upper Red Formation to less chalcophile minerals at higher stratigraphic levels: from a copper sulfide (or Cu)-dominant zone in basal strata of the formation to an pyrite (Fe)-dominant zone. A similar broad zoning is evident among the principal cupriferous sulfides. Chalcocite is generally positioned beneath bornite that is, in turn, located beneath chalcopyrite. Tetrahedrite is most commonly found with chalcopyrite and at the upper limit of the cupriferous zone.

4.4. Post-ore features

The emplacement of ore-stage minerals in the lower to middle Sorkheh strata apparently terminated with a silicification event that effectively eliminated the porosity and permeability of the shallow-water carbonate-siltstone host rocks. Subsequent post-ore events are related to advanced burial diagenesis, tectonic overprinting (including late fracturing of the host rocks), and continuing supergene alteration (Fig. 10).

Post-ore silicification consists mainly of quartz and, to a lesser extent, K-feldspar that partially preserved these structures from subsequent deformation during deep burial compaction. At the same time, authigenic quartz filled inters granular pores and formed overgrowths on them.

Organic matters are observed in the intergranular porosity of the more permeable sandstone rock type. Still more commonly, these matters are associated with fractures cross-cutting all lithologies and along structures including cements, and matrix material (Fig. 11). They are interpreted to post-date the formation of fractures generated during late tectonic deformation.

Post-ore Alpine tectonic deformation has been important at Sorkheh. The Sorkheh and Cheshmehkonan strata and their sediment-hosted mineralization are folded, tilted, and faulted, and consequently, the usually attractive lateral continuity of SSC-type mineralization has been disrupted severely (Fig. 10). Alpine tectonism has also been responsible for the location of the Sorkheh mineralization.

Supergene alteration is generally modest in the vertical extent at Sorkheh, probably due in large part to rapid rates of erosion; boulders with primary chalcocite cementing Sorkheh and Cheshmehkonan sandstones are exposed on steep slopes at high elevations. Oxidation is most obvious and pervasive as malachite staining on mineralized outcrops and as goethite staining where overlying sandstone strata were originally pyritic. Seen from a distance, the mineralized Sorkheh strata are typically greenish, in contrast to underlying Sorkheh redbeds and overlying buff-colored unmineralized Sorkheh beds. Supergene mineralization consists mainly of copper carbonates especially malachite, azurite, iron, and manganese oxides (e.g., limonite, hematite, and pyrolusite). Malachite prominently replaces copper sulfides, as evident in the upper parts of Cheshmehkonan and Sorkheh, which are stained with a characteristic greenish color. Both malachite and, to a lesser extent, azurite form rims over chalcocite, bornite, and chalcopyrite exposed on outcrops, and fill dissolution cavities in sandstones.

Secondary copper sulfides are most evident in polished sections in the form of digenite and covellite rimming and penetrating primary chalcocite, bornite, and chalcopyrite. Supergene digenite is observed in samples only from the deepest levels of oxidation, where it occurs as rims on primary bornite and chalcopyrite. In thin sections, goethite is a byproduct of the supergene replacement of ferruginous copper sulfides such as bornite and chalcopyrite. Manganese oxides (e.g., pyrolusite) occur on bedding planes, especially forming black dendritic patterns on outcrops. Iron oxides and hydroxides fractures and are as exposures.

Volcanic dacitic dikes

In the Sorkheh area, domes are often intruded into Cu bearing stratas (Fig. 12). They have shown a very high content of mineralization in analyzed samples and studied sections.

Typically, the Cu mineralized zones at Sorkheh and Cheshmehkonan are comprised of dasitic domes that show high contents of Cu, Co, Cr. The higher-grade ore portions typically are comprised of bornite and chalcopyrite and commonly show copper sulphides: chalcopyrite, and bornite. Chalcopyrite shows either intergrowths with or replaces bornite (Fig. 9a). Sulphide phases are observed at the Sorkheh area only and include pyrrhotite. Secondary minerals include digenite after bornite and chalcopyrite, which in turn altered into covellite (Fig. 9b). Digenite is also located as individual grains, which are in many places crosscut by a lattice of haematite. The sulphides are coarse-grained, commonly elongated within a planar fabric and readily observed as inclusions (Fig. 9a, b).

5. Geochemistry methods, ICP, XRF

Seven whole rock multi-element ICP and XRF analyses were completed on taken samples from the Sorkheh at the Amdel, Australia, Geoscience Laboratory (Table 2). These data show detection limits for major elements of 0.01 % and trace elements typically to 0.1 ppm. Accuracy is well within acceptable limits, typically replicating major values to between 3% and 5% and trace element concentrations to better than 10 %.

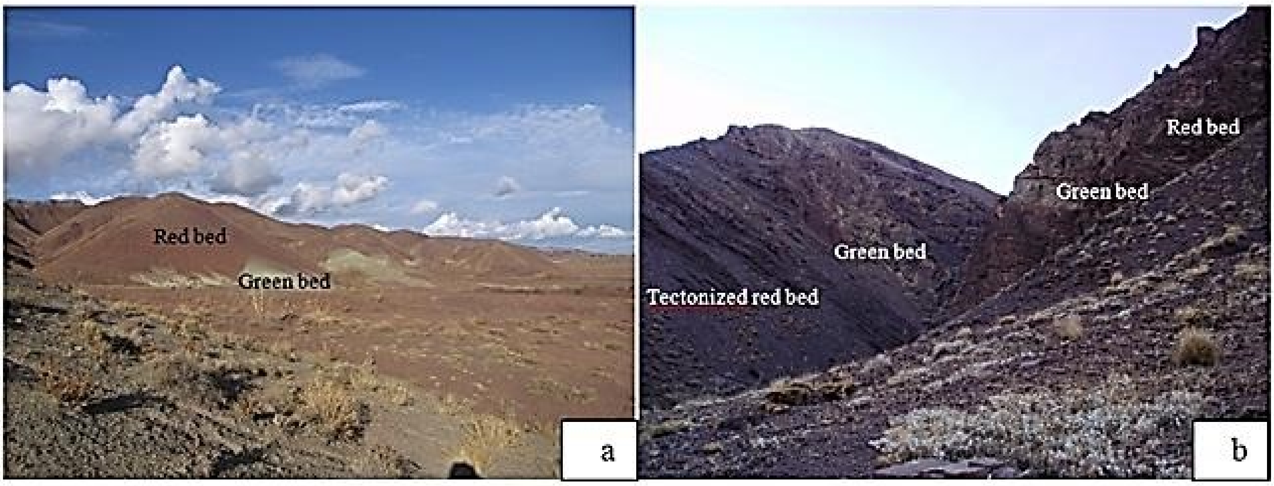


Fig. 10: a) Folded tectonized system in Cheshmehkonan stratiform copper deposit, b) the same in the Sorkheh SSC deposit but stronger tectonized strata

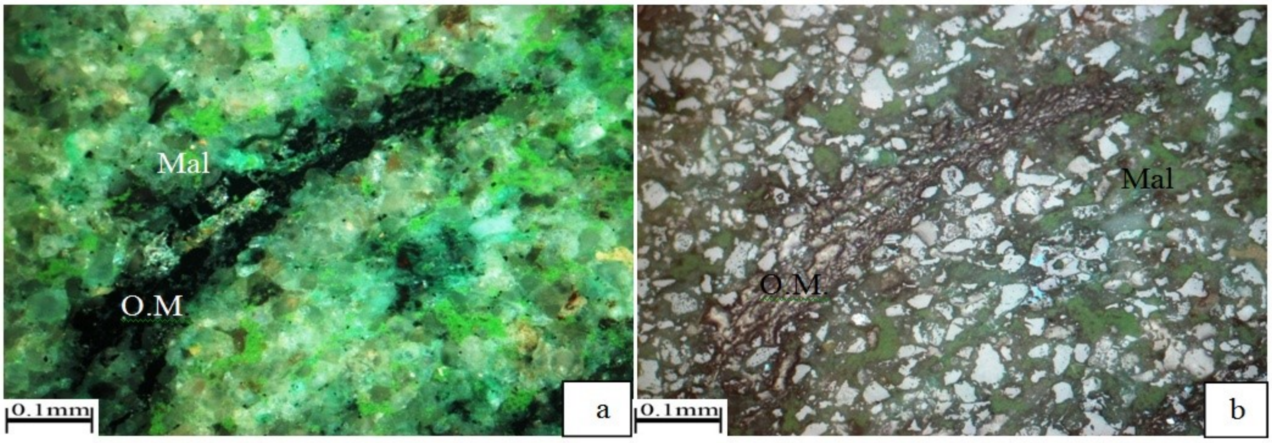


Fig. 11: Organic matters in fractures (malachite is rich in the sections). Transmitted (a), plane-polarized light (b), O.M. organic matter; Mal: malachite.

Fig. 12: Dacitic dike in the Sorkheh area, red beds and green beds are seen in the picture

5.1. Whole rock analyses

Copper assay values show the highest concentrations in the Sorkheh sandstones. Plots of Zr versus Nb, Cr, and TiO_2 for rocks from Sorkheh suggest a relationship between the sandstones and ore elements (Fig. 13, 14, 15). The rocks tend to show lower Nb contents and higher Cr and TiO_2 values. Included on these diagrams is a whole rock data set for all samples observed at the Sorkheh Mine, enabling a comparison with host rocks in the Sorkheh Copper deposit (Fig. 13).

In Figure 14 negative regression between Cu with Mg_2O, TiO_2, Co, and Rb and positive regression relative of Cu with Th and Fe_2O_3 are observed. There is a negative correlation between the copper and cobalt mineralization. Frequencies of Th, Cu, Zn, V, and Ni elements in the Sorkheh area has been shown in figure 15a. Figure 15b shows a spider diagram of La, Ce, Y, and Yb. Figure 15c shows a spider diagram of some elements with high contents of Ba, Rb, Sr, Cr, Ni, La, Ce, Y and Zr. Figure 15d shows spider scattering diagrams of REE, MREE, and HREE in the Sorkheh deposit. According to Bajwah et al. (1987); Brill (1989); Xu (1998) in Fig. 16a, a sedimentary source of sandstones in the Sorkheh area has been indicated. In Fig. 16b, an arid-type of deposition of sandstones and in Fig. 16c, based on the discriminal diagram (Bhatia 1983) sandstones of the Sorkheh area tectonic settings are estimated in passive continental margines [A: Oceanic island arc setting, B: Continental island arc setting, C: Continental active margines, D: Continental passive margines].

Table 2. ICP geochemical data from the study area

Element	SORK1	SORK2	SORK3	SORK4	SORK6	SORK7	SORK8
SiO_2	67.5	67.78	69.42	66.84	61	66.73	62.08
Al_2O_3	10.11	10.22	8.97	9.71	13.11	9.47	14.56
Cao	10.66	10.57	10.58	13.43	7.55	11.85	8.53
Fe_3O_4	3.75	3.34	2.66	2.23	5.77	4.22	3.95
Fe_2O_3	3.88	3.46	2.75	2.3	5.96	4.37	4.09
K_2O	1.03	1.08	1.09	1.06	4	0.25	1.88
MgO	3.71	3.9	4.26	3.66	3.64	3.38	2.68
Na_2O	2.42	2.3	2.39	2.26	3.13	3.33	5.16
MnO	0.08	0.08	0.11	0.09	0.12	0.11	0.08
TiO_2	0.56	0.54	0.36	0.54	1.01	0.49	0.67
P_2O_5	0.13	0.14	0.12	0.13	0.63	0.13	0.35
Th	6.9	7.5	6.8	7.9	13.7	7.8	7.9
Ba	115	232	169	109	1392	566	579
Pb	18	17	11	5	6	5	5
Cu	7290	10629	40841	9438	215	16642	13593
Co	24	25	14	18	26	17	19
Cr	460	388	390	306	152	528	136
Zn	83	101	243	89	141	149	99
Nb	18	19	19	17	27	15	15
Rb	6	11	9	7	30	1	3
V	112	95	72	81	155	84	121
Y	17	18	16	19	18	14	13
Ni	219	224	146	199	144	136	142
Sr	153	162	158	149	318	224	173
La	14	17	14	15	45	16	22
Ce	22	26	22	24	83	24	36
Y	17	18	16	19	18	14	13
Yb	2.3	2.3	2	2.4	2.1	2	1.7
Zr	99	100	72	98	313	65	196

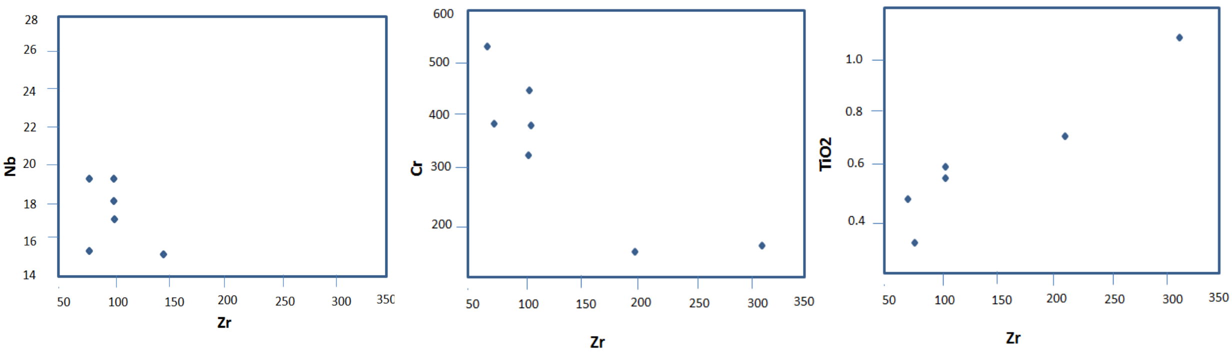


Fig. 13. Whole rock analyses of Sorkheh rocks. Analysis shows lower Nb with increased concentrations of Cr and TiO_2.

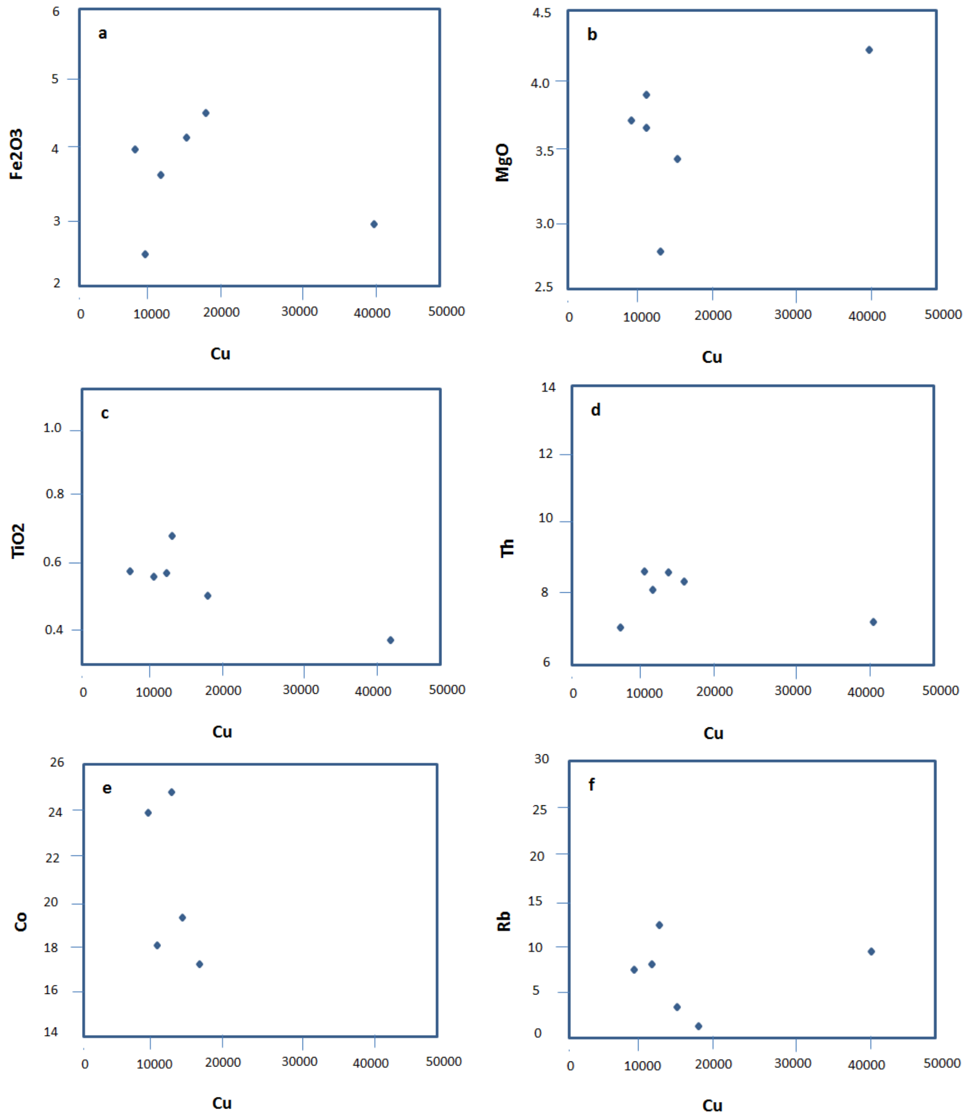


Fig. 14. Negative regression between Cu with Mg_2O, TiO_2, Co, and Rb and positive regression relative of Cu with Th and Fe_2O_3

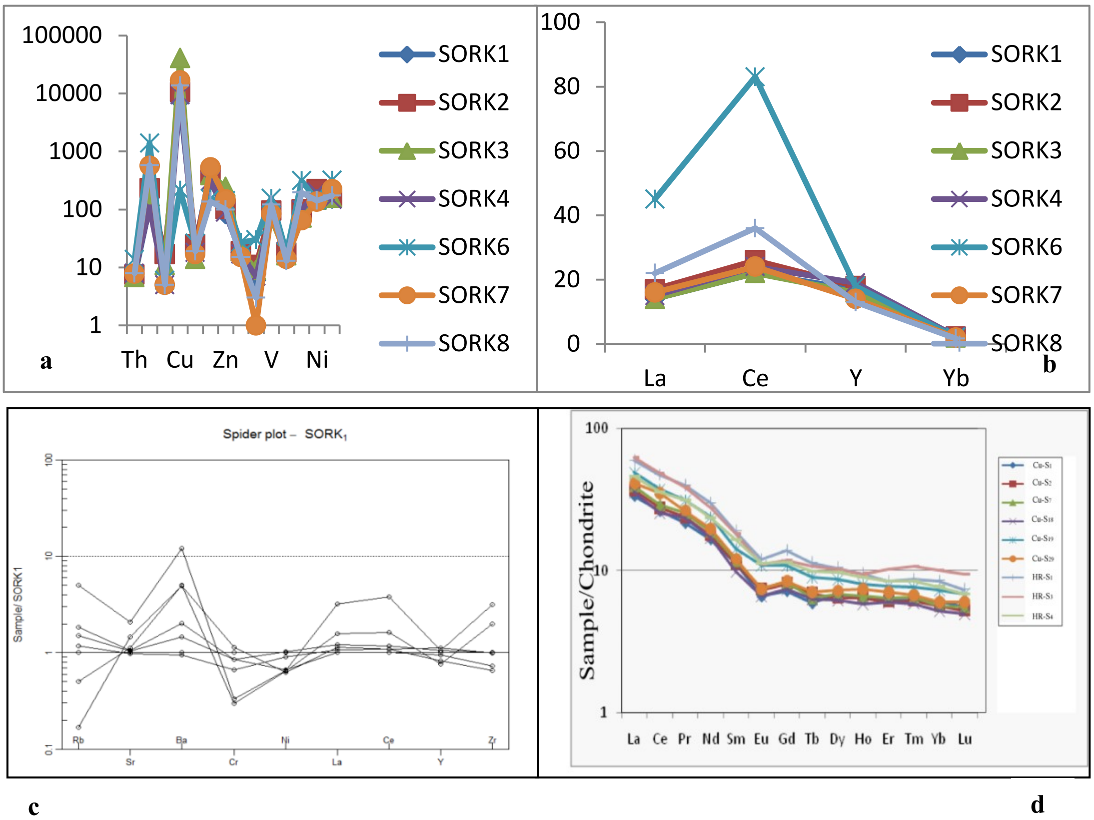


Fig. 15. a) Frequencies of Th, Cu, Zn, V, and Ni; b) Spider diagram of REE; c) Spider diagrams; d) REE, MREE, and HREE scattering in the Sorkheh deposit.

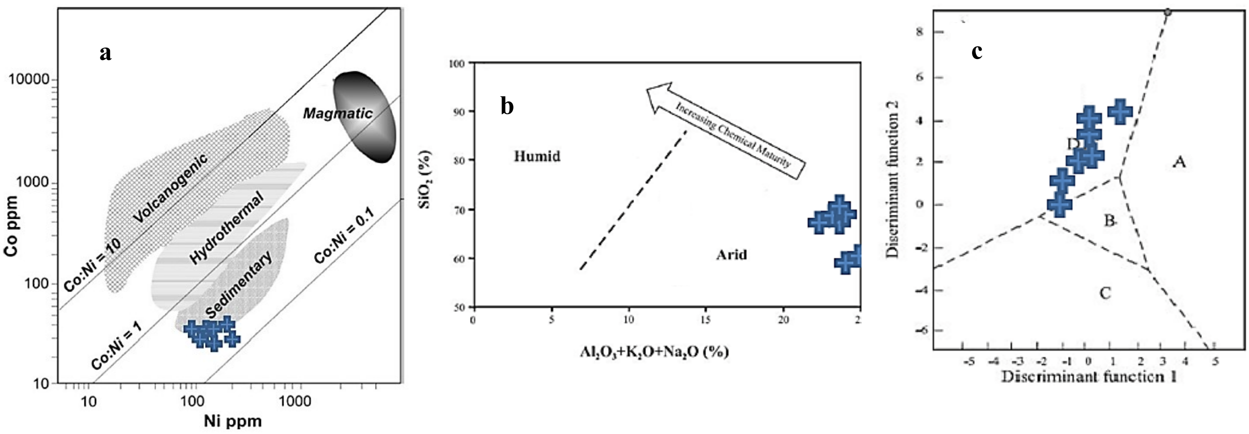


Fig. 16. a) Sedimentary source of sandstones (Bajwah et al. 1987; Brill 1989; Xu 1998) b) Arid-type of deposition of sandstones and c) Discriminal diagram Bhatia (1983) for indicating Sorkheh sandstones tectonic settings [A: Oceanic island arc setting, B: Continental island arc setting, C: Continental active margines, D: Continental passive margines].

6. Disscusion and Results

The sedimentation of the host rock to the mineralization, strong fabric development, and transitional nature of contacts between greenish sandstones as ore bearing basement strongly suggest the Tasuj area deposits are hosted in basement to Upper Red Formation stratigraphy. However, other features of the Tasuj area mineralization are common to the stratiform copper belt, for example: the observed suite of ore minerals; typical metal enrichment (Cu, V, and Ni). The presence of transitional contacts between the host rock and sandstones appears to be the result of a sedimentation and deformation for ore deposition. First, using data from Sorkheh as an example of typically mineralized Upper Red Formation it is evident of the mineralization or elevated values of Cu, Ni and V.

The Sorkheh deposit exhibits several readily visible general characteristics of sediment-hosted stratiform copper (SSC) mineralization. It consists of fine-grained disseminated base-metal sulfides within gray sandstones (graybeds, the basal Miocene sandstone, and shallow-water) that overlie a thick sequence of red beds (Miocene Upper Red Formation). The host gray beds are the basal sandstone and are intercalation with redbed sandstones, which are shown from textural studies to be carbonaceous and to have initially contained very fine-grained, disseminated, syndiagenetic pyrite. These sediments would have been sufficiently porous and permeable in early diagenetic time to allow an infiltration of metalliferous fluids from the underlying redbeds, resulting in the observed progressive replacement of in situ pyrite by common base-metal sulfides (copper-rich sulfides: first chalcopyrite, then bornite, and finally chalcocite). Ore-stage sulfides are zoned vertically and obliquely through the mineralized zones, from cupriferous sulfides at low stratigraphic levels to copper-rich mineralization above, with unreplaced pyrite remaining within the upper Miocene. The zoned sulfides and their replacement textures, configuration of the mineralized zones, and the position of ore stage mineralization adjacent to a stratigraphically defined redox transition from redbeds upward into graybeds indicate an overprint of copper (and accompanying ore-stage metals) on originally pyritic graybeds. The influx of ore-stage metals, presumably in an oxidized low-temperature brine, terminated with a silicification event that effectively sealed the host sandstones. These observations and the overall genetic interpretation are consistent with the general deposit-scale genetic model for early diagenetic SSC mineralization. The regional geologic context is also consistent with its classification as a SSC deposit: It is hosted by sediments that were formed in association with evaporites at a low latitude in a Sabkha environment.

Detailed studies of SSC deposits have repeatedly led to the conclusion that the ore-stage metals were introduced after sedimentation, and in many cases, this mineralization is found to have pre-dated significant deformation, other than early deformations that may have accompanied synsedimentary faulting in the host rocks. The genesis of such mineralization is commonly said to have taken place during diagenesis of the host sediments.

Sulfide minerals and their textures may be interpreted to be primary and contemporaneous with oro genesis, and their emplacements are commonly said to be related to deep structural pathways for ore fluid flow (e.g., (Bechtel et al. 2001; Blundell et al. 2003; Muchez et al. 2005; McGowan et al. 2006). The regional geological setting of the Sorkheh deposit is also consistent with its assignment to the SSC deposit type. The Miocene age of the Tasuj host rocks assures that the Sorkheh mineralization qualifies on this basis. Second, the Sorkheh mineralization is hosted by a major continental shallow deep system, as are all significant SSCs (Brown 1984; Jowett 1989; Kirkham 1989; Brown 1992; Brown 1997; Hitzman et al. 2005). This feature assures that large amounts of copper may have been leached by oxygenated brine from the trace amounts available throughout the footwall red beds. Although probably not essential to the formation of SSC mineralization, the presence of bimodal dacites within the basins may also have been a favorable feature, perhaps adding to the copper that could have been leached from mafic minerals in the footwall units, or perhaps signaling anomalous amounts of magmatic heat in an otherwise cold basin fill. Consequently, sediment-hosted stratiform copper deposits of the Sorkheh area formed in a location where basinal fluids had passed through a series of highly oxidized rocks and could obtain copper, which was then precipitated as the fluids encounter a reductant that destabilized the complexing ability of the fluid (Fig. 17).

According to the model that has been shown by Hitzman et al. (2010) (Fig. 17), all deposits in the area appeared to have begun formation during diagenesis when mineralizing fluids became focused into constrained areas by stratigraphic and/or structural architecture. However, to form sediment-hosted stratiform copper deposits, a number of major features must be present: abundant, highly oxidized metal source rocks, highly reduced strata in a position favoring interaction with significant amounts of fluid that previously passed through the oxidized stratal package, and significant thicknesses of evaporites capping the reduced strata to serve as a hydrologic seal and a source of high-salinity (and possibly sulfur-rich) brines. It is critical that the basin is relatively quiescent for long periods of geologic time, but sufficient energy must be input to promote convection of fluids within the basal section of oxidized clastic rocks. Evidence suggests that in addition to these factors, seawater chemistry may be important for the genesis of these deposits. Nonetheless, reconnaissance geologic studies to confirm the existence of sedimentary basins with significant basal oxidized clastic sedimentary sequences (typically red beds), with overlying strata that include discrete in situ reduced layers, and an upper thick evaporite cap (that may often have disappeared from the geologic record) are needed to evaluate the potential for this deposit type (Hitzman et al. 2010). Holland (2005) speculated that the amount of organic matter entering the oceans may have resulted in much less common reduced sedimentary rock facies that are critical for formation of sediment-hosted stratiform copper deposits.

Finally, Kirkham (1989) has shown that SSCs are closely associated on a global basis with evaporitic sediments formed in hot arid climates at low paleo latitudes; evaporates could be responsible for the high salinity of the footwall pore fluid. Again, the Sorkheh deposit qualifies because the Tasuj sandstones contain gypsum blades typical of shallow-water carbonates formed under hot arid conditions (Kendall 1969; Kinsman 1969), while the region was located at a latitude of about 38°N in Miocene time (Kirkham 1989). Based on the results of geochemical studies, the sedimentary source and arid-type of deposition of sandstones in the Sorkheh area with passive continental margines tectonic setting are indicated. Consequently, the exact timing of the mineralization at Sorkheh area is an open question. Although petrographic evidence supports a sedimentary origin, whether the initial mineralization is related to Upper Red Formation.

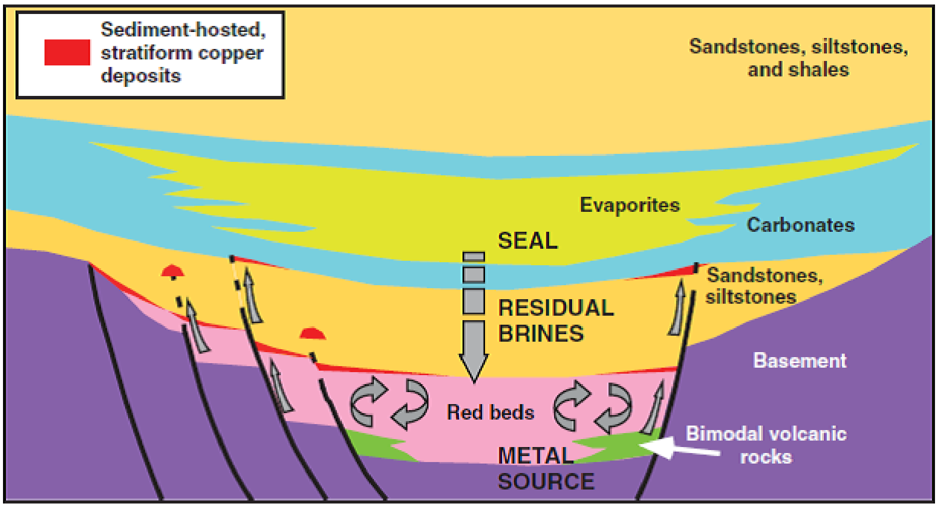


Fig. 17. Modelling of copper stratiform deposits forming sets and their mineralization (Hitzman et al. 2010)

7. Conclusion

The Neogene Tabriz Basin is part of a strike-slip fault system that developed during the Late Miocene between the colliding Arabian and Eurasian plates. To the west and northwest, the Tabriz Basin opens to the lowlands of Lake Urmia, a hypersaline lake sourced by saline solutions from Miocene evaporates. Marine limestones and marls of the largely Lower Miocene Qom Formation are present north-west and east of Tabriz city and on the islands of Lake Urmia; indicating that the region of the present day Tabriz Basin was part of the Tethys up to the Early Miocene. The regression of the Qom Sea was followed by a period of continental sedimentation in NW and central Iran and Azerbaijan; these deposits have been termed Upper Red Formation. In NW Iran, the Upper Red Formation is more than 2000 m thick and considered Middle Miocene or Middle to Late Miocene in age and indicated an age of 11.2 (±1.1) Ma for the Upper Red Formation. The Tabriz fault led to the formation of the Tabriz Basin in the Late Miocene. The Neogene basin fill is composed from bottom to top of the Lignite Beds; Quaternary alluvial conglomerates overlie the latter. The host gray beds are the basal sandstone and are intercalation with red bed sandstones, which are shown from textural studies to be carbonaceous and to have initially contained very fine-grained, disseminated, syndiagenetic pyrite.

Petrographic studies were undertaken on the various facies of the Sorkheh Formation and their fabrics in an attempt to bracket the timing of emplacement of ore-stage sulfides relative to four successive events in the history of the Sorkheh host rocks: sedimentation, diagenesis, tectonic deformation, and supergene oxidation. The dominant primary ore-stage mineralization at Sorkheh consists of disseminated sulfides, mainly in the coarser grained host facies (grain stone) of the Upper Red Formation. A minor amount occurs in compact siltstone and mudstone; local concentrations also occur in the porous burrowed portions of sandstone. Primary cupriferous sulfides also occur as a cement (principally chalcocitic) in the uppermost whitish-green Sorkheh sandstone.

The cupriferous sulfides (chalcocite, bornite, chalcopyrite, and tetrahedrite as mineralization) formed at a distinctly later stage of diagenesis than the syndiagenetic pyrite. These ore-stage sulfides are discussed in the order of their appearance in a generalized paragenetic sequence:

(tetrahedrite)→chalcopyrite→ bornite→chalcocite.

Sediment-hosted stratiform copper deposit of the Sorkheh area formed in a location where basinal fluids had passed through a series of highly oxidized rocks and could obtained copper, which was then precipitated as the fluids encountered a reductant that destabilized the complexing ability of the fluid. According to the proposed model, the Sorkheh deposit appeared to have begun formation during diagenesis when mineralizing fluids became focused into constrained areas by stratigraphic and/or structural architecture. To form the Sorkheh sediment-hosted stratiform copper deposit, a number of major features must be present: abundant, highly oxidized metal source rocks, highly reduced strata in a position favoring interaction with significant amounts of fluid that previously passed through the oxidized strata package, and significant thicknesses of evaporates capping the reduced strata to serve as a hydrologic seal and a source of high-salinity (and possible sulfur-rich) brines.

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