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Sediment Hosted Stratiform Copper (SSC) Mineralization in Bhudoli-Basari Area, North Delhi Fold Belt, Mesoproterozoic Delhi Supergroup, Rajasthan

Shubhabrata Mukhopadhyay*, Vineet Kumar and Monika Sangwan
Geological Survey of India, Jaipur – 302 004, India
E-mail: *shubhashubho@gmail.com*

ABSTRACT

The rocks of the Kushalgarh Formation of the Delhi Supergroup in northeast Rajasthan, host low-temperature prospect generally known as sediment hosted stratiform copper (SSC) mineralization in Bhudoli-Basari area, district Sikar, Rajasthan. Mineralization is about 3km in length with variable width of up to 600m and sulphides occur mainly as fine dissemination as well as veinlets within the steeply dipping carbonate rocks, which were remobilized along the quartz-calcite veins during compaction and subsequent deformation. The prospect is product of low-temperature aqueous brines. The brines leached, transported, and deposited copper (and associated metals) as per physical and chemical stabilities. The mineralization in the Bhudoli-Basari SSC consists mainly of bedding-parallel disseminations of fine-grained sulphides, typically zoned. Copper is leached from poorly sorted first-cycle clastic sediments of footwall redbeds, associated meta/volcanics of the Raialo Group and basement rocks during their progressive diagenetic alteration by moderate-temperature oxygen rich brines. Ore mineral zoning from chalcocite to pyrite in the Bhudoli-Basari area is archetypal to other SSC deposits viz. the Kupferschiefer of Poland-Germany and the Central African Copper belt of Zambia.

INTRODUCTION

Rajasthan is known for its copper mineralization for long time. In the North Delhi Fold Belt, copper mineralization within the Kushalgarh Formation has been discovered in recent times in Bhudoli-Basari area (figure 5) in Sikar district, Rajasthan. The area is located in the western part of the Alwar sub-basin, which is one of the three sub-basins present in the North Delhi Fold Belt (NDFB) that exposes rocks of the Alwar and the Ajabgarh groups of the Mesoproterozoic Delhi Supergroup. Geographically, the area is located about 8km south of Nim Ka Thana town and about 10km west of Nim Ka Thana copper belt. Surface manifestations of copper mineralization includes malachite, chalcocite and bornite present within the carbonate rocks. Mineralization of this area is unique because of the chalcocite-bornite dominance over other sulphides, in contrast to other areas of the Khetri and eastern part of Alwar basin, where chalcopyrite is the dominant copper mineral. The present work is aimed to work out the nature and control of this chalcocite-bornite dominated copper mineralization within the Bhudoli-Basari area and its ascription to SSC, as the mineralization is very analogous to sediment hosted stratiform copper mineralization (SSC).

REGIONAL GEOLOGICAL SETUP

The Bhudoli- Basari area is a part of the North Delhi Fold Belt that exposes rocks of the Alwar and Ajabgarh groups of the Delhi Supergroup. The North Delhi Fold Belt is broadly divided into three sub-basins, namely the Lalsot-Bayana, Alwar and the Khetri sub-basins from east to west (Fig. 1). The NE-SW trending Alwar sub-basin starts from Jaipur in the south and extends beyond the Rajasthan-Haryana border in the north.

Regionally, the area is located about 30 km south of the Khetri copper belt. In the Alwar sub-basin, volcano-sedimentary rocks were deposited in fluvial and marginal marine environments and the volcanics show continental affinity (Singh, 1984a, b). The stratigraphy of the Delhi Supergroup in the Alwar sub-basin is given below (Chakrabarti et. al, 2004).

Delhi Supergroup	Ajabgarh Group	Arauli Formation
		Bharkol Formation
		Thana-Ghazi Formation
		Seriska Formation
		Kushalgarh Formation
	Alwar Group	Pratapgarh Formation
		Kankwarhi Formation
		Rajgarh Formation
	Raialo Group	Tehla Formation
		Serrate Quartzite Formation
		Dogeta Formation

Sedimentation in the Alwar basin started with the Raialo Group which is a combination of conglomerate, quartzite, sandstone, siltstone, limestone and metabasic. The Raialo Group has been divided into Dogeta, Serrate Quartzite and Tehla formations. The Dogeta Formation comprises of conglomerate, sandstone, siltstone, siliceous and dolomitic limestone. The Serrate Quartzite Formation comprises sandstone with interlayered oligomictic conglomerate, whereas the Tehla Formation comprises of basic volcanics, conglomerate, sandstone, siltstone and limestone.

The Alwar Group starts with the Rajgarh Formation, which contains a basal conglomerate followed upward by feldspathic quartzite and grit. The overlying Kankwarhi Formation comprises of micaceous quartzite, mica schist and calcareous biotite quartzite. The Pratapgarh Formation occupies the top of the Alwar Group with ortho-quartzite and sericite quartzite as the main rock types. The overlying Ajabgarh Group is a combination of calcareous, argillaceous and arenaceous components along with intercalations of volcanic rocks.

METHODOLOGY AND SAMPLING

The representative samples for chemical analyses, petrography, EPMA and XRD were collected to substantiate the mineralization.

In order to evaluate the potential for mineralization random grab bedrock and grid bedrock methods of sampling were adopted. During

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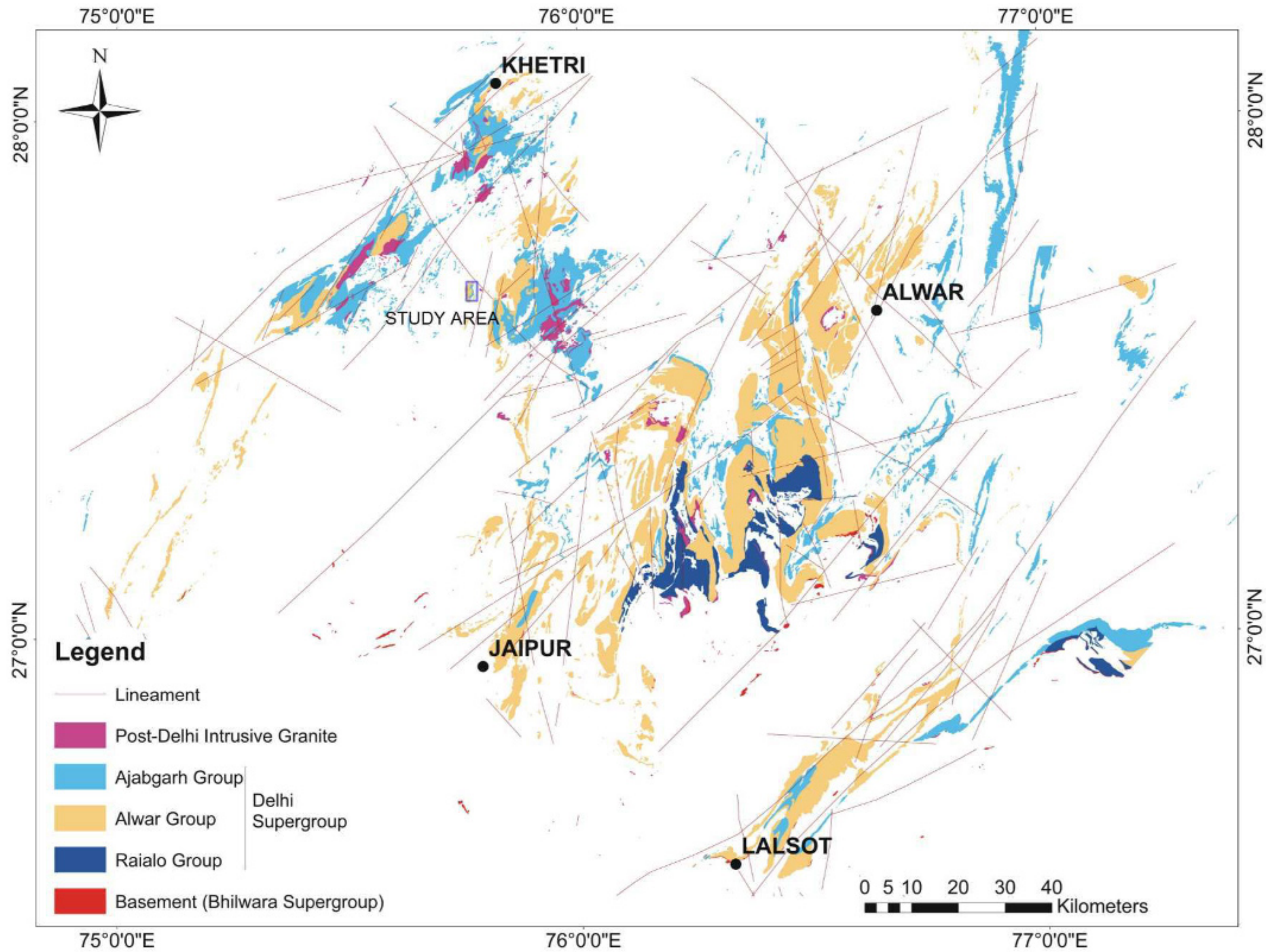

Fig.1. Geological map of North Delhi Fold Belt showing three main basins

sampling, rock chips were collected. About 1 kg of rock sample was collected from field, processed in the field by grinding to -80 mesh, cone and quartering. The reduced sample was later pulverized to -120 mesh and analyzed by AAS at Regional Chemical Lab, GSI, Jaipur with precision of 1ppm. The quantity and quality for each sample type was maintained to avoid contamination.

The surface litho-geochemical grid was carried out in the limited area, to establish the copper anomaly zone and confirmation of mineralization zone. A total of 44 nos. of grab bedrock samples collected randomly to find mineralization zones. The grid sampling was carried out on 100m x 25m interval. A total of 98 grid samples were collected along 19 traverse lines from an area of 2m radius from each sample point and composited to one representative sample.

GEOLOGY OF THE STUDY AREA

The rocks of the Pratapgarh Formation of the Alwar Group have sheared contact with the basement rocks as observed in the west of Bhudoli-Basari (Behera, 2008). Primary and secondary structures are well preserved in the rocks of the study area. The only clear primary structure recorded in the area is the bedding that is defined by colour and compositional banding. At some places crude cross bedding and ripples were also documented.

The rocks of study area have undergone greenschist facies to amphibolite facies regional metamorphism. The meta-sedimentary rocks of the Pratapgarh Formation of the Alwar Group and the Kushalgarh Formation of the Ajabgarh Group occupy most of the area. The Pratapgarh quartzite is represented by massive quartzite with bands of biotite schist. This unit is overlain by the Kushalgarh Formation of the Ajabgarh Group (Fig.4) with a sharp contact, which hosts copper mineralization and is represented by biotite-schist, impure marble and quartzite of the Kushalgarh Formation. Besides the Delhi Supergroup of rocks, post-Delhi intrusive in the form of pegmatite, amphibolite, albitite, calcite, epidote and quartz veins are present in the area.

Bedding (S_0) is the prominent primary structure, which is well preserved in the quartzite and impure marble, defined by colour and compositional banding. The general strike of bedding in the study area is N10°E-S10°W with steep dip on both sides, strike is sometimes E-W in northern part of the study area due to later deformations. Based on planar/linear structures, mesoscopic and macroscopic folds, three phases of deformation were identified in the study area. The lineation in the area is defined by mineral lineation, which is defined by the preferred orientation of long axes of tabular and acicular minerals.

Three phases of deformation have been identified with second deformation, as the most dominant one controlling the regional disposition of the rocks (Figs. 2, 3 and 4). The dominant planar fabric that has been observed during mapping is development of foliation or schistosity planes in the lithounits. The three foliations that have been identified: S_1, S_2 and S_3 in sequence of events of their development with the three major deformation event in the area. Deformation of first phase (D_1) has resulted in close to isoclinal and inclined to reclined folds (F_1), which are found rarely. The related S_1 axial planar cleavage of mesoscopic F_1 folds is represented by a schistosity, defined

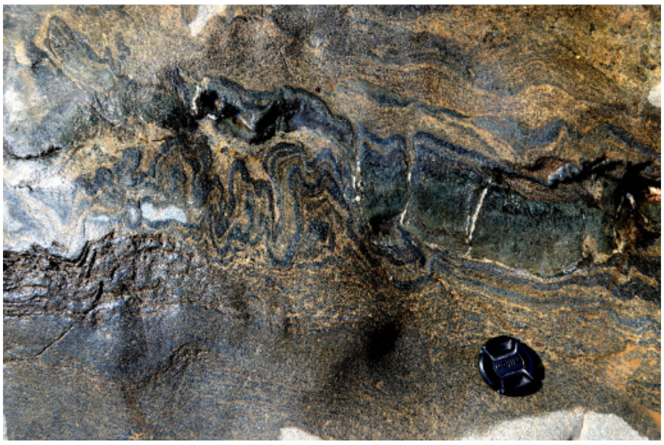

Fig.2. F_2 M/W fold developed within banded impure marble. Quartz veins are emplaced along S_2 plane and S_0 is parallel to S_1

Fig.3. F_2 plunging fold developed within impure marble. Orientation of S_2 is ~N-S

by the alignment of flaky minerals and as secondary banding. The L_1 lineation in the study area is defined by the mineral lineation and as intersection lineation (S_0^S_1), representing the linear structure (L_1) associated with the F_1 folding. The S_1 foliation is parallel to bedding (S_0) and strikes N-S to NNE-SSW with steep dip on either sides, but mostly towards east. The S_1 is usually parallel to S_0 except at the hinge of F_1 fold. Mesoscopic F_1 folds were observed at several places notably north of Khera Aga Ki Dhani in impure marble plunging moderately towards west to south-west. Deformation of second phase (D_2) led to second phase of folding (F_2), which forms the most dominant structure in the area and controls the disposition of lithounits. It is present usually in macroscopic scale with associated congruous folds in mesoscopic scale. Mesoscopic folds are usually close to tight in nature. The associated S_2 is represented as axial planar cleavage and as disjunctive cleavage usually in the hinge part of F_2 folds. The foliation (S_2) mainly strikes N-S to NNW-SSE and dips steeply towards west and is parallel to the S_0 and S_1 in general. The L_2 lineation is intersection lineation (S_0 and S_2), fold axis of minor congruous folds, crenulation axis and pucker axis. The lineation (L_2) pitches moderately towards SSW in the mapped area. The L_2 lineation is relatively parallel to L_1, though, at places, making an acute angle. Deformation of third phase (D_3) has resulted in F_3 folds, which are better perceived in siliceous lithology. These occur as open folds and warps. The S_3 surfaces (spaced cleavage) strike nearly E-W with moderate to steep dip on either side. In the mapped area, both F_1 and F_2 fold axes are usually parallel. The superposition of mesoscopic 'F_2' folds on the mesoscopic 'F_1' folds have produced hook shaped pattern, characteristically forming Type 3 interference on regional scale, north of Khera Aga Ki Dhani.

The principal rock types of the Kushalgarh Formation are given below.

Biotite-schist

This greyish-black lithounit comprises of biotite and quartz and is exposed in the central part of the area. The contact is gradational between biotite-schist and impure marble.

Quartzite

Light pink, fine to medium-grained quartzite band is exposed in the northeast of Bhudoli and comprises of quartz, sericite and grains of magnetite. Due to ferruginization, the rock occasionally shows light pink colour.

Impure Marble

This lithounit hosts copper mineralization and is composed of alternate bands of light grey to dark grey colour bands. It is fine to medium-grained rock composed of calcite, quartz, biotite, plagioclase, K-feldspar, chlorite, epidote and occasionally tremolite/actinolite.

The rock occasionally grades into medium to coarse-grained impure dolomitic marble, with substantial quartz and biotite, which occur as thin bands within the dolomitic marble unit. The calcite grains are subhedral and show interlocking texture with interstitial filling of fine quartz. At places, pink marble is emplaced along different planes. The D_2 stage quartz and calcite veins/veinlets also intrude the impure marble.

COPPER MINERALIZATION

A NNE-SSW trending copper mineralization zone having considerable strike length is present mainly over impure marble of the Kushalgarh Formation. Stream sediment sampling in the Bhudoli-Basari area shows moderate concentration haloes of Cu (Kumar and Sangwan, 2015) (Fig.5). Geological mapping in the area indicated that copper mineralization is evidenced by the presence of widespread and pervasive malachite-azurite stains, dissemination and veinlets of chalcocite and bornite within impure marble. Bedrock samples (random) collected from the malachite stain bearing zone analyzed copper content varying from 0.19% to 1.81% in 14 samples (Kumar and Sangwan, 2015). Occasionally, ore minerals are also concentrated along quartz and calcite veins (Figs. 7 and 8).

Mineralization is generally restricted within impure marble (greybeds) of the Kushalgarh Formation and stratigraphically, it is present above the Pratapgarh Formation or in other words, footwall of the mineralization is arenaceous in nature (redbeds in SSC).

Subsequent detailed geological mapping and sampling indicated disseminations and stringers of sulphides (Figs 7 and 8) within host rocks are also concentrated along/within quartz-calcite veins due to remobilization during subsequent deformation. In the area, four mineralized zones (MZ-I to IV) have been demarcated.

The mineralization is dominantly in the form of fine copper sulphide disseminations along the S_0^S_1 planes (Figures 7 and 8) of the host rock and occasionally as vein filling. The principal ore minerals are chalcocite-djurleite and associated minerals, bornite, covellite and chalcopyrite (Figs. 7, 8 and 11).

Petrographic studies revealed the following features:

1. Fine dissemination of chalcocite is restricted to grey impure marble.
2. Bornite and covellite occur as anhedral crystals within chalcocite.
3. Secondary malachite-azurite staining along the border of chalcocite.

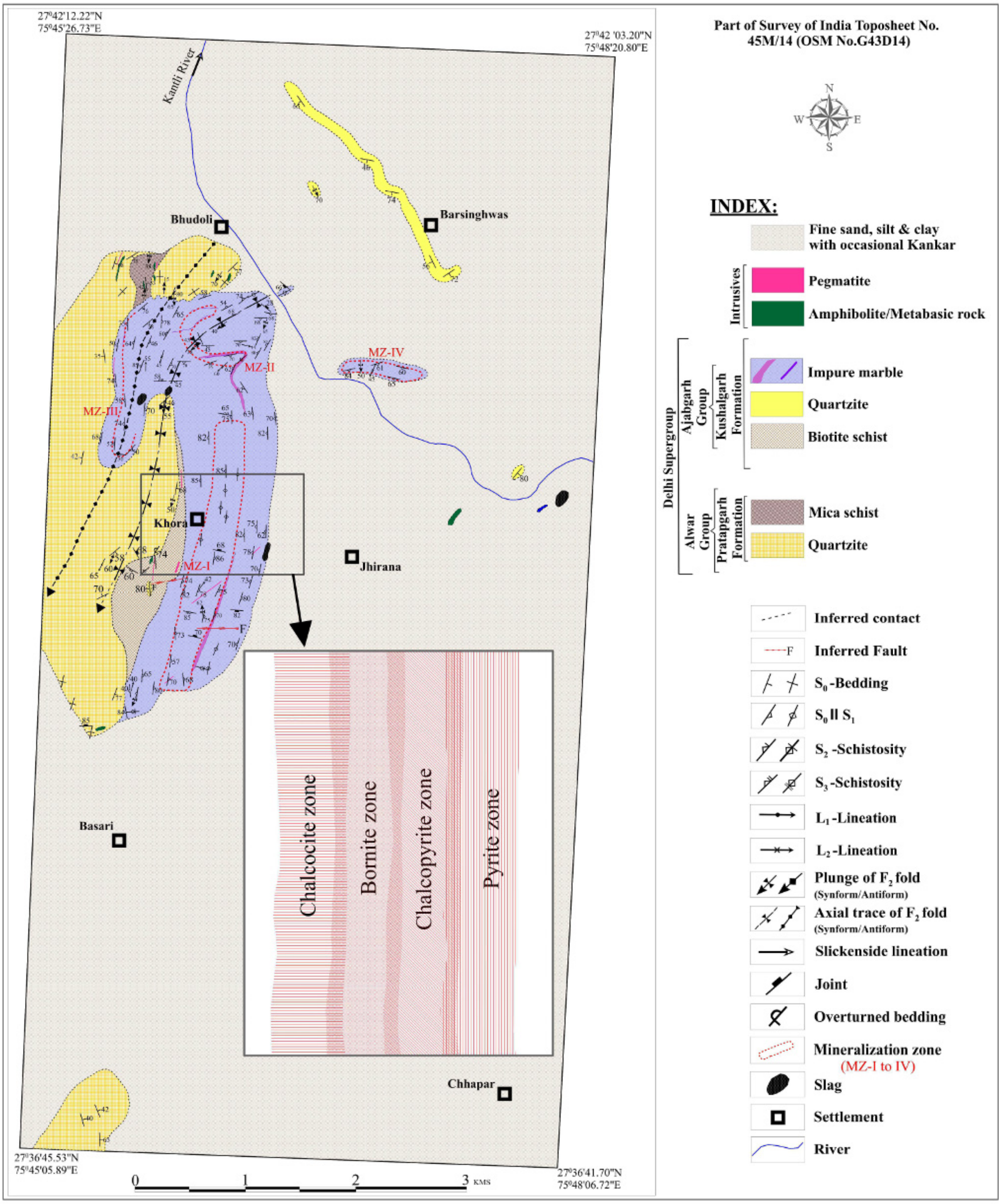

Fig.4. Geological map of Bhudoli-Basari area, district Sikar, Rajasthan showing copper mineralized zones and zoning of ore minerals (Kumar & Sangwan, 2016)

4. Deformational structures such as fractures and bent twin lamellae within chalcocite.
5. Fine specks of chalcopyrite were seldom recorded with chalcocite, but in abundance in other parts. Largely, the gangue minerals are calcite, quartz, feldspars, biotite, amphiboles etc.
6. Replacement of bornite by chalcocite in impure marble (Fig.8). However, bornite and chalcocite form solid solutions at temperatures from 175-225° (Wandke, 1926). Cleavage in chalcocite is indistinct in most of the observation, but rarely recorded in two directions.
7. Covellite exsolution is recorded within chalcocite The covellite is exsolved along specific planes and occasionally forming bulbous mass like features (Figures 8 and 10). Covellite may also be an alteration product of bornite. Usually, covellite grains are shapeless, occasionally laths like forming feathery texture within chalcocite and sometimes forming rims surrounding the

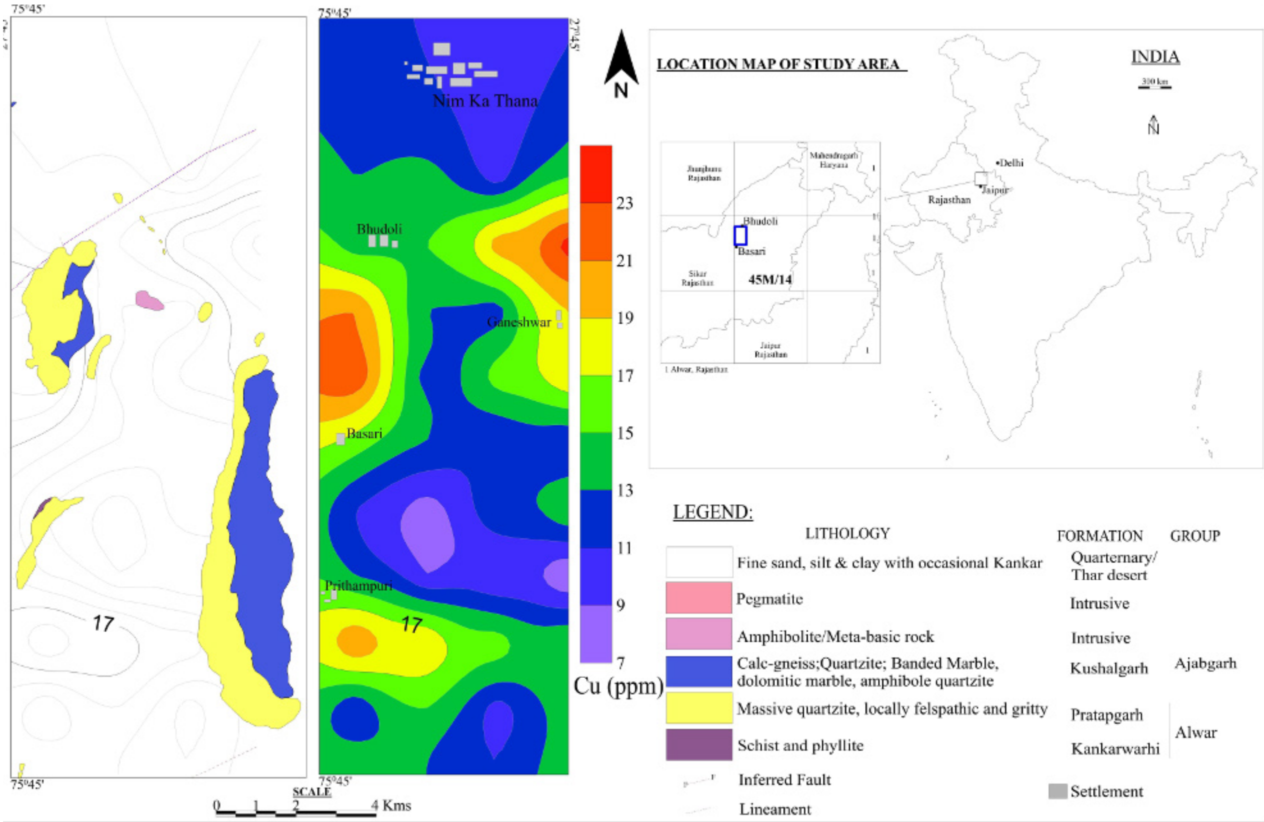

Fig.5. Elemental dispersion map of Cu (ppm) in stream sediments (no. of data= 50) overlain on geological map, Bhudoli-Basari area, Sikar, Rajasthan (Kumar & Sangwan, 2015) (Geology compiled by M & C, WR, GSI, Jaipur)

chalcocite, possibly by slow cooling. Covellite grains/laths are usually very small as compared to the grains of chalcocite and bornite, occasionally showing reticulated texture.

8. Gangue minerals malachite/azurite replace the Cu sulphides along definite planes (Figs. 8 and 10).
9. Chalcocite and covellite form solid solutions at low temperature of 70° to 75° (Bateman and Lasky, 1932). Covellite is readily exsolved by slow under-cooling within a narrow range below this temperature.
10. Zoning of ore minerals on surface is conspicuous, which is also corroborated by lab studies.

COPPER MINERALOGY-XRD STUDIES

Mineralized rock samples were analyzed by XRD method and the ore minerals identified are chalcocite (djurleite-$Cu_{31}S_{16}$), bornite and malachite. The major copper minerals present in the area are chalcocite, bornite, and covellite. But chalcocite-like phases (djurleite) are optically not easy to distinguish from chalcocite.

Studies of polished specimens of disseminated ore bearing samples reveal presence of chalcocite, bornite as main ore minerals whereas covellite and chalcopyrite occur as accessories. The different associations and features of (ore) minerals identified are summarized below:

1. Chalcocite
2. Chalcocite-bornite
3. Chalcocite-covellite
4. Chalcocite-bornite-covellite
5. Chalcocite-bornite-chalcopyrite-arsenopyrite
6. Chalcopyrite-pyrite
7. Pyrite

Some of the ore mineral assemblages mentioned above can be explained with the help of the Cu-Fe-S system depicted in figure 10. In Bhudoli-Basari area, the beds trend NNE-SSW, dipping steeply on either sides, therefore the impure marble in the westernmost part flanked by high quartzite ridges in west are enriched with fine dissemination of chalcocite and gradually the copper content decreases towards east as (preore?) pyrite. Dominance of dissemination type of zoned ore minerals points towards the sediment hosted stratiform copper (SSC) mineralization. The prospect is located on the reduced side of a transition from poorly sorted reddish (oxidized/haematitic) meta-sediments (Alwar Group) generally known as footwall redbeds in SSC to overlying fine-grained, grey impure marble/metacarbonates (Ajabgarh Group), collectively known as reduced greybeds. Generally, the redbed/greybed transition coincides with a continental to marine/lacustrine transition or redox boundary (Figs. 4 and 9).

The SSC deposits are typically stratiform and widespread along their sedimentary host and are confined to the basal portions of their host greybeds (Brown, 2014). The mineralization in the greybed-hosted SSC deposits consists mainly of bedding-parallel disseminations of fine-grained sulphides. The sulphides are typically zoned, with the most copper-rich sulfides (chalcocite, in present study also) adjacent to the redbed/greybed (redox) interface and progressively more iron-rich copper sulphides (towards chalcopyrite) arrayed and more distal from the redox transition, terminating the cupriferous zone with pyrite zone of the greybed (Brown, 2014, Brown and Trammell, 1965; White, 1960; etc.). Ore mineral zoning in the Bhudoli-Basari area is archetypal to SSC viz. the Kupferschiefer of Poland-Germany and the Central African Copper belt of Zambia. Zoning from Pratapgarh to Kushalgarh formations (west to east, about 600m wide on surface) is unexposed zone/soil - chalcocite - chalcocite + bornite + covellite - chalcopyrite + bornite - chalcopyrite + pyrite - pyrite - unexposed zone/soil (Fig.4).

Sediment-hosted stratiform copper deposits in toto require oxidized metal source beds (red beds), reduced facies to serve as metal traps,

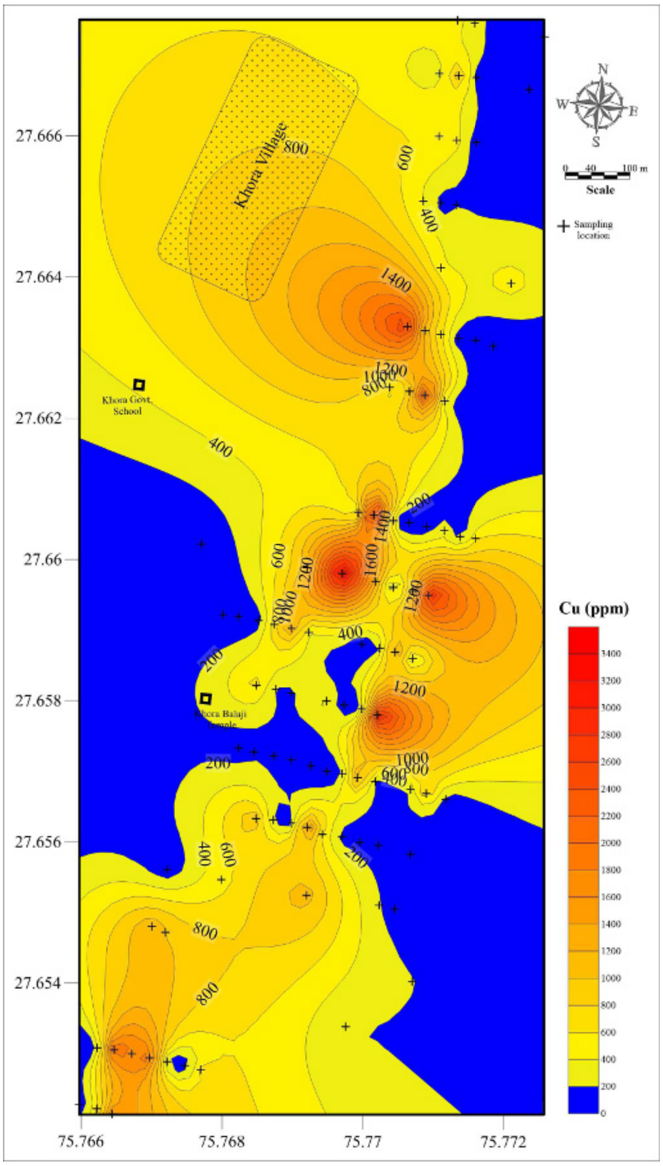

Fig.6. Geochemical contour map of Cu (ppm) in bedrock samples (no. of data= 98) of Khora area, Bhudoli-Basari area, Sikar, Rajasthan (Kumar and Sangwan, 2016)

and saline brines capable of leaching and carrying metals. Poorly sorted clastic sediments are an excellent source of labile minerals susceptible to diagenetic alteration and reddening by oxygen-rich brines from surroundings. This brine is suitable for the dissolution of copper as cuprous-chloride complexes from labile minerals. These copper chlorides may then be carried within the system or along crosscutting faults to sites of reduced rocks. When these cupriferous brine comes in contact with reduced sediments, stable copper and associated metals precipitate. The occurrence of secondary sulphides, oxides, malachite-azurite, and stains is due to later phase alteration, which is very common in surface exposures.

In passive margin setting, deposits are zoned from chalcocite to bornite to chalcopyrite to pyrite away from the shoreline toward anoxic deep water (Cox et al., 2007). However, the global tectonic framework as rifts was ideal for formation of intracratonic basins with basal, synrift red-bed sequences overlain by marine and/or lacustrine sediments occasionally with evaporitic strata (Hitzman, 2010). This setting of intracratonic basins against passive margin basins (which are fundamentally leaky) allowed the development of a hydrologically closed basinal architecture in which highly oxidized and saline, moderate-temperature basinal brines were produced that were capable of supplying reduction-controlled sulphide precipitation (Fig.9).

For a sediment-hosted copper deposit to form there must be an oxidized source rock. This rock must be hematite stable and must contain ferromagnesian minerals or mafic rock fragments from which copper can be leached. Leaching of copper from the source rock at moderately low pH may be described by equation

$$Cu_2O + 6Cl^- + 2H^+ = 2CuCl_3^{2-} + H_2O$$

Following the above equation, there must be a source of brine to mobilize copper. Any sedimentary environment in which evaporation exceeds rainfall will produce brines. Brines may also form by evaporation of seawater, where connection with the open sea is restricted as in rift valleys. The brines are generally rich in sodium, because other cations (K, Ca and Mg) are removed during formation of clays, sulfates, and carbonates. There must be a source of reduced fluid to precipitate copper and form a deposit. Sulphide in the form of finely disseminated pyrite is commonly found in reduced host sediments. The lower stratigraphic limit of mineralization is defined by the contact between continental redbeds and marine/lacustrine greybeds enriched with chalcocite (sometimes native copper) and the upper limit of mineralization is defined by disseminated chalcopyrite which grades upward into disseminated pyrite.

The minerals commonly form in zones with chalcocite deposited closest to the interface between brine and reduced fluid (Ripley *et al.*, 1985). Covellite occurs in the transition zone between oxidized and reduced sediments. Pyrite occurs outside of the chalcopyrite zone. Cobalt, common in the African Copper belt, is most abundant in the chalcopyrite zone, and galena and sphalerite in the Kupferschiefer of Poland mainly occur with pyrite (Oszczepalski, 1999). The presence of cobalt, silver, lead and zinc in some deposits and not in others suggests that sedimentary exhalative processes may be important (Brown, 1984). High temperature deep basinal fluids introduced through basin-margin faults may overprint or mix with copper-rich brines to produce copper deposits with valuable byproducts.

EPMA STUDY

EPMA studies have been carried out to determine the chemical composition of the ore minerals. EPMA study has been carried out on a CAMECA SX 100 Electron Probe Micro Analyzer at EPMA Laboratory, GSI, Hyderabad, Telangana. The analytical conditions were as follows: accelerating voltage, 15-20 kV and probe beam current 20 nA. Both line and spot analyses on the samples were performed to know the variation of elemental concentration.

The predominant ore mineral phases belong to chalcocite series (Cu_2S to Cu_9S_8) (Fig. 11). The Cu content of chalcocite series ranges from 72.9% to 81.4%, with variance in Cu content in the same crystal also. Therefore, it can be deduced that this differential content is due to presence of solid solution series of chalcocite. Other Cu-S phases identified are bornite and covellite, which are tarnished to malachite and azurite. The bornite host phase is replaced by chalcocite. The exsolutions of covellite in chalcocite are observed at several places along specific directions (figure 8c).

The variance in electron reflectivity (clearly visible in BSE-FCC, Fig. 11F) within a crystal is inferred as the change in Cu and S content in solid solution series of chalcocite.

DISCUSSION

The nature of mineralization in Bhudoli-Basari area, Nim Ka Thana is archetypal of SSC. The ore petrographic studies reveal that, the principal ore minerals are chalcocite, bornite and covellite. Chalcocite (series) occurs mainly as disseminations, occasionally as specks and stringers in impure marble, later remobilized phases are also recorded. The nature of the sulphides and their association with quartzo-felspathic

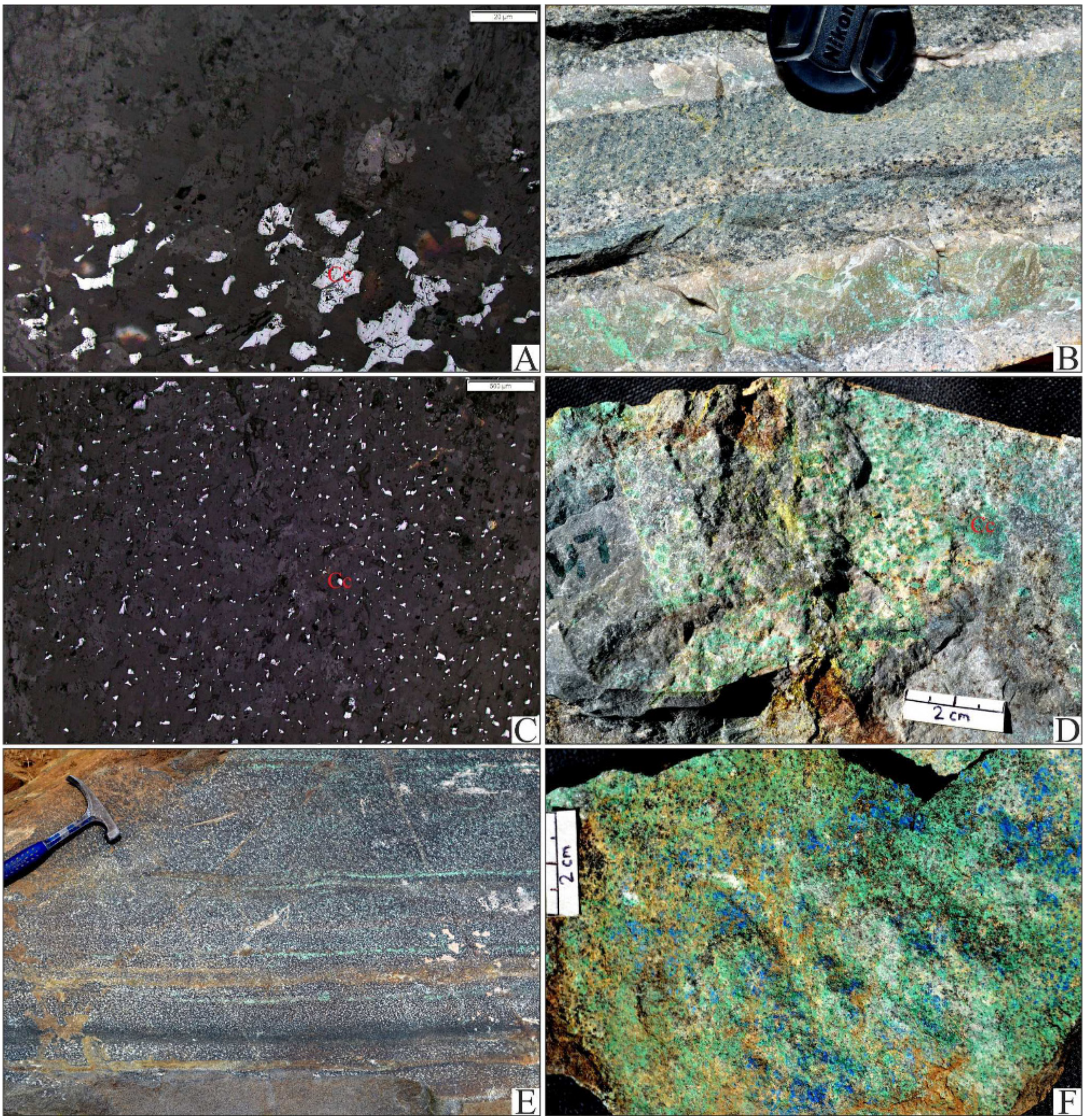

Fig.7. A. Stratiform chalcocite within banded impure marble (Photomicrograph) B. Stratiform copper mineralization within banded impure marble. C. Disseminated chalcocite within banded impure marble (Photomicrograph) D. Disseminated chalcocite & malachite within banded impure marble. E. Disseminated and layer parallel malachite within banded impure marble. F. Malachite and azurite stains within banded impure marble(Cc- Chalcocite)

and calcite veins also validates that a part of the mineralization is remobilized and deposited along the weak planes during the post depositional metamorphic and/or other hydrothermal activities (Figs. 7, 8 and 10). Similar type of mineralization was reported from Dokan-Baniwala Ki Dhani-Dariba area, about 10kms east of present study area. (Mukhopadhyay, 2014).

Based on field and lab studies, mineralization can be categorized into two distinct genetic types:

Diagenetic Type (SSC)

Sulphide mineralization of diagenetic type is evidenced from the nature of occurrence of disseminated discrete grains of sulphides within the host rocks. In impure marble, sometimes blebs and square-shaped chalcocite, bornite occur as discrete grains, often linearly arranged or forming thin laminae and even occasionally concentrated in layers parallel to stratification, suggesting stratiform nature of mineralization (Fig.7). Detrital sulphide is conspicuously absent. The intimate association of chalcocite and bornite indicates that these primary sulphides were precipitated from copper-bearing brines (cuprous chlorides) typical of SSC (Fig.9).

Following are the attributes of SSC (Brown, 2005, 2009, 2011, 2014; Hitzman, 2005, 2010; Kirkham, 1989) and their comparison with the SSC prospect of Bhudoli-Basari area:

1. Low-temperature (generally 120°C or less) constituents, especially apparent in temperature-sensitive sulphides (e.g., djurleite, orthorhombic chalcocite, sulphur-rich bornite; Brown, 1971) and silicates. In Bhudoli-Basari area, chalcocite series (djurleite etc.) bornite are the main ore minerals, as inferred from

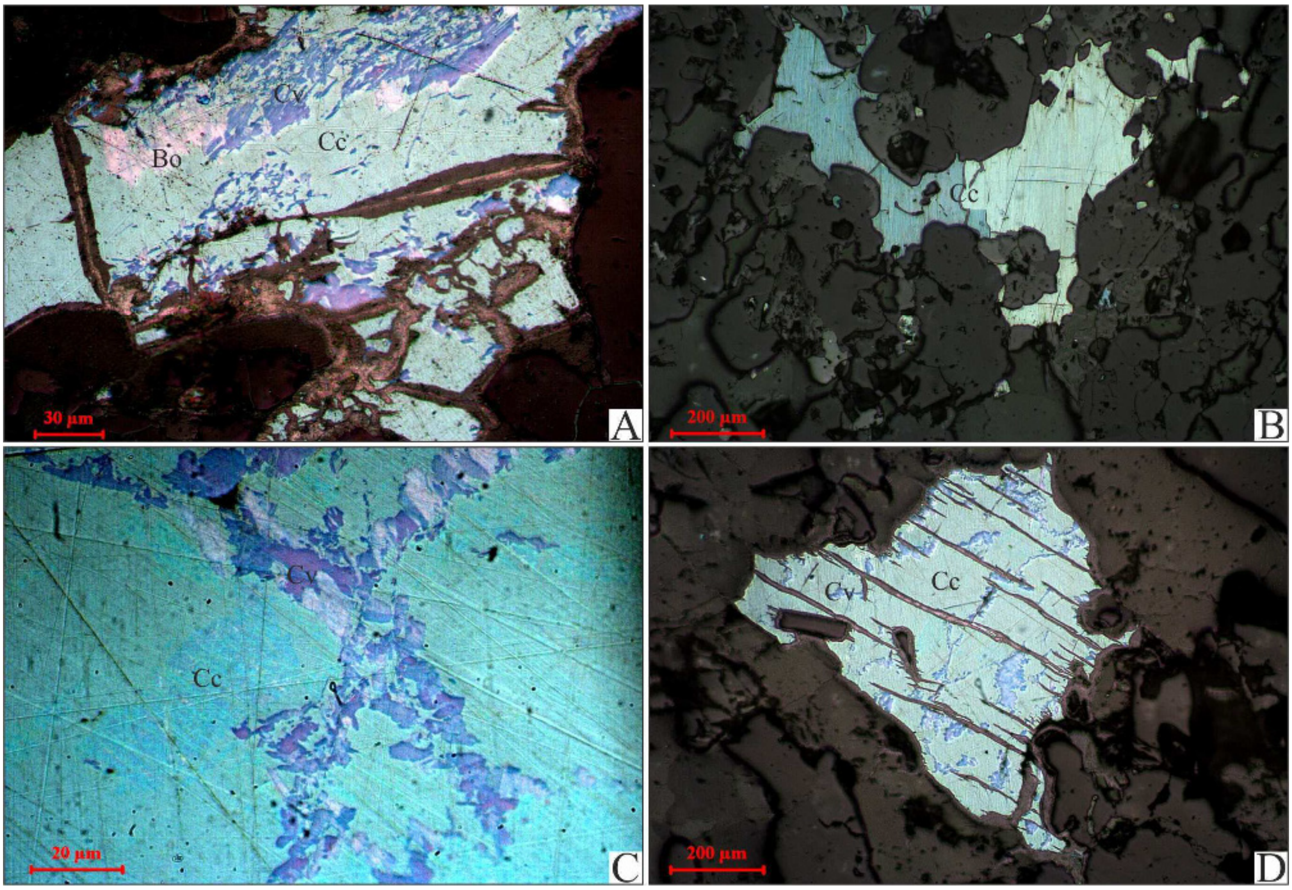

Fig.8. A. Exsolved covellite in chalcocite-bornite within banded impure marble (Photomicrograph)B. Imperfect cleavage of chalcocite showing variation in colour due change Cu contentC. Exsolved and altered covellite in chalcocite within impure marble (Photomicrograph)D. Exsolved and altered covellite in chalcocite within impure marble. Also showing malachite (gangue like appearance) replacing the chalcocite (Photomicrograph)(Cc- Chalcocite, Cv- Covellite & Bo- Bornite)

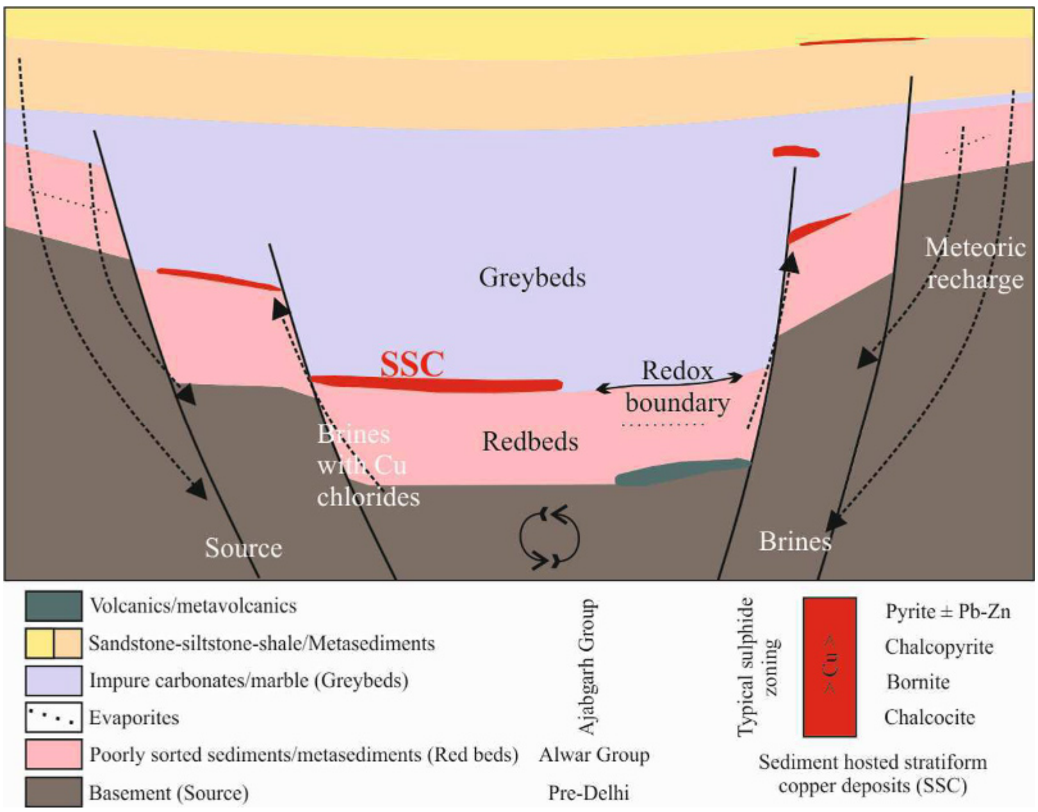

Fig.9. Genetic model for sediment-hosted stratiform copper mineralization at basin-scale (modified after Brown, 2014 and Hitzman, 2010)

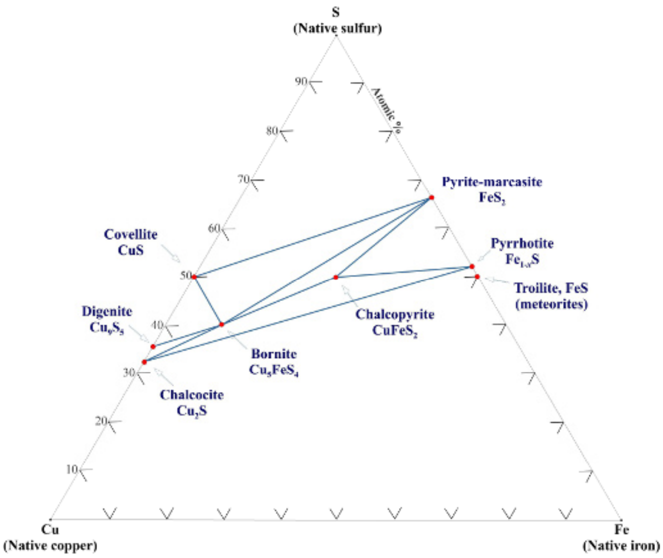

Fig.10. Some of the most common sulphides represented by the Cu-Fe-S system. Many of these sulphides show some solid solution of especially Cu and Fe. Tie lines connect commonly occurring pairs of minerals. Triangles indicate coexistence of three sulphides. (Hurlbut and Klein, 1977)

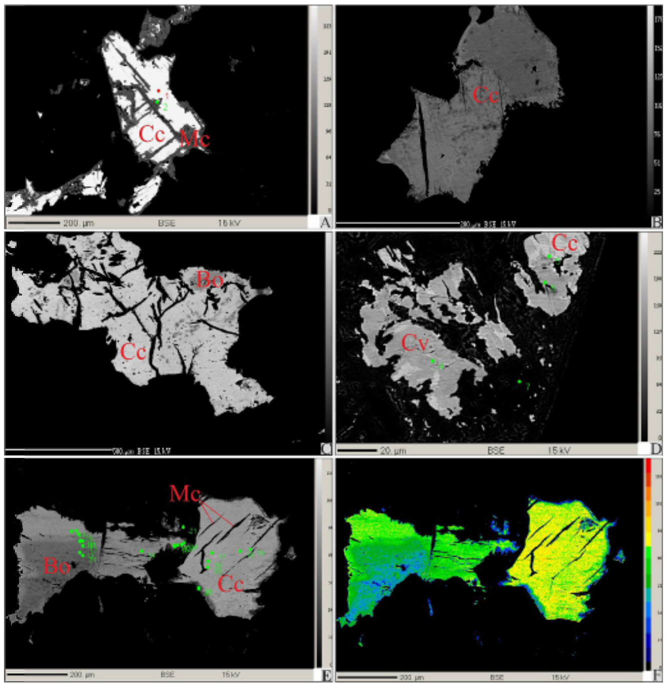

Fig.11. A- Back Scattered Electron (BSE) image showing association of corrosion of chalcocite (1) by malachite (2). Note the definite planes of alteration. B- Chalcocite, C- Chalcocite and bornite, D- Chalcocite and covellite, E- Chalcocite-malachite and bornite, F- BSE-False color composite (FCC) show different phases of the system, blue-bornite and rest are chalcocite series (Cu_2S to Cu_9S_8). Cc- Chalcocite; Bo- Bornite; Cv- Covellite; Mc- Malachite.

petrological, EPMA and XRD studies (Figs. 7, 8 & 11).

2. Disseminated copper sulphide mineralization restricted to reduced fine-grained basal greybeds immediately overlying oxidized (haematitic) coarse grained footwall redbeds. The fine dissemination of chalcocite-bornite-chalcopyrite is restricted to grey impure marble of the Kushalgarh Formation, just above the quartzite-biotite schist of the Alwar Group and gniesses of pre-Delhi basement (Fig.7a).
3. Carbonaceous host greybeds, which in fact vary in color from greenish grey to light buff, and which typically range from fine-grained clastic sediments (shales, siltstones, or fine sandstones) to shallow-water carbonates. Economically SSC mineralization is within the cupriferous greybeds, typically following distinctly favourable beds. The host lithology in Bhudoli-Basari area is greenish grey impure marble, which is typical of greybeds of SSC (Figs. 2 & 3).
4. Laterally widespread stratiform cupriferous sulphide mineralization along the base of the greybeds. In the present study area, the surface manifestations of copper mineralization in the form of malachite and azurite stains are widespread, but the fresh copper sulphides are limited and are concentrated towards the contact of redbeds and greybeds i.e. redox boundary (Figs. 4, 7 & 9).
5. Laterally extensive non-mineralized greybeds characterized by fine-grained disseminations of syndiagenetic pyrite in those greybeds extending far beyond the zones of copper mineralization. In Bhudoli-Basari area, towards east or away from redox boundary the copper sulphides gradually changes to iron sulphide i.e. pyrite, which is extensively abundant laterally in all other directions (Fig.4).
6. Disseminated primary (ore-stage) mineralization consisting mainly of fine grained sulphide minerals (e.g., chalcocite, bornite, and chalcopyrite ± galena-sphalerite). In the present study area also, copper mineralization occurs mainly in the form of disseminations, and rarely streaks, veins and chunks of chalcocite-bornite-covellite and associated malachite-azurite stain within calcareous facies rocks, i.e. within impure marble of the Kushalgarh Formation of the Ajabgarh Group of the Delhi Supergroup (Fig.4).
7. Distal zones of lead and zinc sulfides extending abruptly or gradually beyond the cupriferous zone (rarely important, except in the Kupferschiefer where lead even surpasses copper in overall abundance, although rarely in economic amounts). The lead and zinc sulphide are not recorded in the Bhudoli-Basari area, however galena and sphlarite in the Nim Ka Thana copper belt, which is about 10kms east are observed in the similar lithopackage and basinal setting (Misra, 1977; Bhaise, 2010)
8. Minor amount of ore-stage sulphides along bedding veinlets and cross-cutting veins and veinlets, all within or close by the cupriferous zone. The calcite/quartz/feldspar veins/veinlets carrying copper sulphides are copious in the Bhudoli-Basari area (Fig.8).
9. Possibly supergene redistribution of copper. Occasionally temperature-sensitive copper sulphides may also show characteristics of secondary mineralization, commonly accompanied by covellite (CuS). In Bhudoli-Basari area, covellite exsolutions are recorded commonly within chalcocite, which appear to be exsolved along specific planes and occasionally forming bulbous mass like features. Usually, covellite grains are shapeless, occasionally laths like forming feathery texture within chalcocite and sometimes forming rims surrounding the chalcocite, possibly by slow cooling. Covellite grains/laths are usually very small as compared to the grains of chalcocite and bornite, seldom showing reticulated texture (Figs. 8 & 11).
10. Zoned sulphide mineralogy which exhibits a paragenetic sequence trending from preore-stage syndiagenetic pyrite to cupriferous sulphides, typically trending from chalcopyrite to bornite to digenite to chalcocite. Bornite may include stoichiometric bornite as well as sulphur-rich bornite (Brett and Yund, 1964). Chalcocite and digenite are difficult to distinguish, and also include an series of optically similar sulphides with

Table 1. EPMA analytical results (sulphides weight %) of samples collected from Bhudoli-Basari area, Rajasthan, India

DataSet	Zn	Ni	Co	Fe	S	Pb	Cu	Total	X	Y	Z	Remarks	Point#
TPS9	0.00	0.00	0.02	0.00	31.78	0.25	65.12	99.40	-2496	19252	342	Covellite	4
TPS9	0.00	0.00	0.02	0.09	33.54	0.11	67.24	101.11	-2441	19291	345	Covellite	6
TPS9	0.00	0.06	0.00	0.02	0.00	0.04	44.82	48.29	-2453	19242	344	Malachite	7
TPS9	0.00	0.00	0.00	0.67	22.33	0.02	75.92	99.13	1772	21259	353	Chalcocite	8
TPS9	0.00	0.06	0.04	1.81	23.14	0.17	75.84	101.11	1786	21228	353	Chalcocite	10
TPS9	0.07	0.00	0.00	0.00	20.86	0.00	78.61	99.95	2219	21192	357	Chalcocite	17
TPS9	0.18	0.00	0.00	0.02	0.07	0.07	50.80	51.44	2124	21276	355	Azurite	21
TPS9	0.00	0.00	0.02	2.07	22.86	0.07	73.87	99.15	-1784	21393	354	Chalcocite	26
TPS9	0.00	0.10	0.03	0.70	22.03	0.03	75.18	98.16	1779	21248	354	Chalcocite	29
TPS9	0.00	0.02	0.00	3.71	23.34	0.12	72.94	100.38	1784	21223	355	Chalcocite	30
TPS9	0.00	0.09	0.02	11.00	25.16	0.11	61.67	98.16	1794	21179	354	Bornite	31
TPS9	0.04	0.01	0.00	0.02	31.95	0.12	66.49	98.65	2117	21218	357	Covellite	33
EPMA6	0.00	0.08	0.02	0.00	20.52	0.02	77.19	97.95	-5382	-35734	382	Chalcocite	1
EPMA6	0.00	0.00	0.00	0.00	21.27	0.00	79.44	100.95	-5397	-35812	382	Chalcocite	2
EPMA6	0.00	0.08	0.07	10.49	24.88	0.00	62.80	100.57	-5526	-35744	379	Bornite inclusion in chalcocite	3
EPMA6	0.00	0.01	0.03	0.02	20.63	0.09	78.54	99.47	-5229	-36948	383	Chalcocite	4
EPMA6	0.03	0.03	0.03	0.03	21.39	0.04	75.56	98.95	-6415	-36229	377	Chalcocite	7
EPMA6	0.00	0.00	0.00	0.04	32.41	0.00	66.38	98.84	-6416	-36221	377	Covellite replacing chalcocite	8
EPMA6	0.00	0.00	0.00	0.00	20.59	0.08	77.08	99.30	-7243	-35481	375	Chalcocite	9
EPMA6	0.20	0.06	0.00	0.05	20.83	0.02	78.42	100.12	-7311	-35440	375	Chalcocite	10
EPMA6	0.00	0.01	0.06	10.62	25.30	0.12	63.39	99.51	-7364	-35417	375	Bornite	11
EPMA6	0.00	0.02	0.00	10.40	25.58	0.06	63.30	101.37	-7395	-35418	375	Bornite	12
EPMA6	0.00	0.05	0.02	0.04	20.97	0.06	79.28	100.50	-7273	-34714	375	Chalcocite	13
EPMA6	0.26	0.00	0.01	0.01	20.77	0.00	76.94	100.45	-5196	-33947	378	Chalcocite	16
EPMA6	0.00	0.02	0.01	0.25	20.50	0.08	77.85	98.79	-150	-31904	384	Chalcocite	18
EPMA6	0.00	0.03	0.00	10.37	24.60	0.02	61.66	100.77	-199	-31934	384	Bornite inclusion in chalcocite	19
EPMA6	0.05	0.00	0.02	0.89	1.37	0.00	53.37	56.95	-54	-31875	384	Azurite developing at the margins of chalcocite	20
EPMA6	0.00	0.00	0.00	0.04	20.28	0.07	77.67	98.30	1423	-32017	388	Chalcocite	21
EPMA6	0.00	0.07	0.04	10.30	24.03	0.18	62.09	98.70	4121	-32245	387	Bornite	29
TPS13	0	0.02	0.058	0.52	21.69	0.114	75.806	98.337	-4157	-34953	332	Chalcocite	31
TPS13	0	0	0.003	0.594	21.808	0.096	76.859	99.794	-4181	-34908	332	Chalcocite	32
TPS13	0	0.094	0	0.342	21.752	0.119	77.855	100.255	-4260	-34865	332	Chalcocite	33
TPS13	0	0	0.042	0.011	22.177	0.033	77.884	100.583	-4393	-34600	332	Chalcocite	35
TPS13	0.048	0	0	0.019	32.095	0	67.244	99.728	-4355	-34606	328	Covellite exsolutions in chalcocite	38
TPS13	0.045	0	0.033	0.987	22.099	0	75.31	98.715	-4927	-34146	335	Chalcocite	39
TPS13	0	0	0.024	0.18	31.471	0.012	67.104	99.081	-4888	-34112	335	Covellite	42
TPS13	0.161	0	0	0.022	21.73	0	76.347	98.568	-6085	-33842	337	Chalcocite	43
TPS13	0.047	0.04	0.048	0	22.042	0	78.194	100.439	-6129	-33886	338	Chalcocite	44
TPS13	0	0.008	0	0.005	32.335	0.017	65.905	98.342	-6146	-33943	337	Covellite	45
TPS13	0	0.02	0	0.27	21.434	0.121	76.2	98.129	-6635	-34386	337	Chalcocite	46
TPS13	0	0.057	0.065	0.317	21.516	0.023	76.927	99.192	-6617	-34366	337	Chalcocite	47
TPS13	0	0	0	0.311	22.304	0.075	78.423	101.209	-8116	-35624	337	Chalcocite	48
TPS13	0	0	0	0.228	22.425	0.034	77.705	100.602	-8085	-35623	337	Chalcocite	49
TPS13	0	0.072	0.01	0.041	21.879	0.198	77.005	99.317	-4396	-34606	332	Chalcocite	50
TPS13	0	0.036	0.077	0.143	21.338	0.146	76.342	98.591	1761	-38539	294	Chalcocite	56
TPS13	0	0.025	0.031	10.456	24.624	0	62.141	97.614	1775	-38309	293	Covellite exsolutions in chalcocite	58
EPMA5	0.042	0	0.038	0.041	20.682	0.009	78.073	99.207	-380	31225	414	Chalcocite	60
EPMA5	0	0.023	0	0.011	32.091	0.174	66.563	98.903	-370	31227	414	Covellite exsolved from chalcocite	61
EPMA5	0.067	0	0	0.032	0.011	0	53.124	53.259	-416	31231	414	Azurite	62
EPMA1	0.00	0.00	0.00	10.48	24.42	0.08	62.32	97.46	1653	-21175	296	Bornite host phase	1
EPMA1	0.00	0.06	0.00	1.09	22.15	0.00	76.16	99.72	2258	-22739	291	Chalcocite	13
EPMA1	0.00	0.00	0.06	0.50	20.50	0.01	76.04	97.13	2258	-22824	291	Chalcocite	14
EPMA1	0.00	0.03	0.06	1.88	21.89	0.00	75.16	99.25	2990	-21591	295	Chalcocite series	15
EPMA1	0.23	0.09	0.00	10.80	25.17	0.19	63.21	99.76	1683	-21014	298	Bornite host phase rimmed by chalcocite (djurleite)	19
EPMA1	0.00	0.01	0.00	1.55	22.22	0.10	75.90	100.01	1717	-20964	298	Chalcocite series	20
EPMA1	0.03	0.01	0.00	1.63	22.40	0.10	76.68	100.94	2920	-21643	295	Bornite host phase	22
EPMA1	0.19	0.00	0.00	0.56	21.48	0.06	75.80	98.09	2959	-21644	295	Chalcocite series djurleite	23
EPMA1	0.20	0.05	0.00	0.94	22.42	0.00	76.72	100.34	-3137	-27064	316	Djurleite host phase	25
EPMA1	0.00	0.07	0.00	12.06	25.19	0.00	60.84	98.21	-3172	-27031	316	Bornite inclusion in djurleite	26
EPMA1	0.04	0.00	0.03	0.81	21.73	0.11	75.81	99.04	-3137	-26998	316	Djurleite host	27

similar compositions to that of chalcocite, such as djurleite (Brown, 1971) and anilite (Vaughan and Craig, 1997). In the present study also, paragenetic sequence from chalcocite to pyrite is observed comparable to archetypal of SSC (Figs. 4 & 9). EPMA studies also corroborate the occurrence of chalcocite series of minerals and XRD studies endorse the specks of djurleite within chalcocite from the surface samples. Though, anilite and digenite are not recorded in the present study area, but are recorded from the extension areas of the same basin within few kilometres (~10 kms) in Baniwala area (Mukhopadhyay, 2014).

Epigenetic Type

Chalcocite, bornite, covellite and chalcopyrite are present as grains of varying sizes in quartz and calcite veins. Predominant gangue minerals are calcite, quartz, biotite and amphibole. Except for some bornite and chalcocite grains, the vein filling grains are usually irregular-shaped. In quartz vein, chalcocite occurs as massive grains, sometimes as fine grains and stringers. Thin stringers and grains of bornite are sometimes aligned in a preferred orientation within vein quartz. The epigenetic sulphides occur in association with vein quartz and calcite emplaced post-to the first phase of deformation as evidenced by their orientation.

Cu, Pb and Zn are the main metallic elements which are present in SSC along with the major oxides. Of these, Cu dominates over the two other elements in the study area. The values of Pb and Zn are of no economic importance as observed in many Cu±Pb±Zn deposits of the world.

Occasionally the vein-filled and stringers of copper sulphide modify the primary textures form dissemination to veins and stringers. Therefore, copper mineralization seems to be overprinted on its host sedimentary units during their diagenesis and subsequent metamorphic events, which may have resulted into high-temperature overprints of copper mineralization on earlier low-temperature diagenetic mineralization. These type of genetic models are in refinement stages.

GEOTECTONIC EVOLUTION AND ORE GENESIS

The origin of Mesoproterozoic SSC mineralization in Bhudoli-Basari area within the Ajabgarh Group is a result of specific geotectonic set-up prevalent during that time along with source rock. Presence of red beds (hematite quartzite) in the Pratapgarh Formation, presence of dolomite, dolomitic marble, barite and marialite within the Kushalgarh Formation, reveal that an arid to semi arid environment was prevalent during the time of deposition of the Alwar and the Ajabgarh Groups of rocks and imply subtropical conditions. The global tectonic framework as rifts was ideal for formation of intracratonic basins with basal, synrift red-bed sequences overlain by marine and/or lacustrine sediments occasionally with evaporitic strata (Hitzman, 2010). This setting of intracratonic basins allowed the development of a hydrologically closed basinal architecture in which highly oxidized and saline, moderate-temperature basinal brines were produced that were capable of supplying reduction-controlled sulphide precipitation (Fig.9). The climate of the region played an important role in the process and type of sedimentation, selective leaching of the metals from the source rocks and subsequent mineralization. Pre-Delhi Basement rocks and mafic rocks of the Raialo Group are the most probable source for copper.

HIGHLIGHTS

The copper mineralization in the Bhudoli-Basari area is an example of Middle Proterozoic sediment hosted stratabound copper (SSC) mineralization. The sedimentary rocks of the Kushalgarh Formation were deposited in tropical to sub-tropical climate within the intra-cratonic Alwar basin. Copper minerals are deposited as fine disseminations, which are modified and remobilized during compaction, metamorphism and subsequent deformations. Chalcocite, bornite, covellite and chalcopyrite are the prominent ore minerals. Metals were remobilized and concentrated along with the emplacement of quartz and calcite veins. All these characters support a diagenetic origin of SSC mineralization. Sediment-hosted stratiform copper mineralization are located in greybeds overlying intracontinental rift redbeds. Copper was typically deposited as zoned fine-grained sulfide disseminations in the basal greybeds.

Copper leached from poorly sorted first-cycle clastic sediments of footwall redbeds, associated meta/volcanics of the Raialo Group and basement rocks during their progressive diagenetic alteration by moderate-temperature oxygen rich brines.

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