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Geology of the Copper Mineralization in Proterozoic Ajabgarh Meta-Sediments of, Dokan-Dariba Belt, Sikar District Rajasthan Northwestern India

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Abstract

The Khetri copper belt is a well-known metallotect in northern part of Delhi fold belt in Rajasthan. On the eastern margin of the Khetri sub basin of North Delhi basin separated by a basement high, another sub basin Alwar-Ajabgarh sub basin exposes that a thick sequence of Ajabgarh group of rocks overlies a thick arenaceous sequence of Alwar group of Delhi Super Group of rocks. The Ajabgarh meta sediments here in the Neem Ka thana area are characterized by presence of Bornite dominated copper mineralization with silver association and minor presence of Pb. The mineralization has been described by various workers as strata-bound, hypogene and IOCG. But these inferences are based on part information and the inference drawn is sectorial in nature. The current study includes a holistic study based on exploration over a period of more than two decades and the data generated suggest thereof, that this syngenetic sulphide mineralization associated with the sedimentation of marl and carbonate rocks. Subsequently it has been relocated during 2nd deformation accompanied by epigenetic component of mineralization depicted in terms of vein filled coarse grained aggregates of bornite and chalcopyrite disposed across the general disposition of litho-package. The EPMA and fluid inclusion data generated from the area indicate association of typical hydrothermal environment minerals like, Perkrite, Wittchenite, Aguilarite, Molybdnite etc. The mineralizing fluids have been trapped between the temperature ranges of 130˚C to 375˚C with average being 250˚C to 300˚C. The fluid salinity also varies from near pure hot water to moderately saline fluid indicative of multi-episodic mineralization of syngenetic nature coupled with epigenetic component. The ore textures indicate 500˚C temperature range; certain intergrowths of minerals like specular hematite and bornite suggest the occurrence of hypogene environment induced due to emplacement of granite/pegmatite on the eastern and southern margins of the belt. The strata bound nature suggests the euxogenic environment facilitated by carbonate facies of rocks. The parallelism of sulphide with the rock fabric was attained during first deformation and the epigenetic component coupled with the hypogene assemblage was deposited during the D_2 deformation in the brittle ductile shear zones and limb shears, between the temperature ranges of 130˚C to 570˚C as deduced from petrochemical data. Hence a comprehensive model is suggested here on evolution of process of mineralization in the Neem Ka Thana belt.

Keywords

Proterozoic Copper Mineralization, Ajabgarh Meta Sediments, Dariba-Dokan Belt, Neemka Thana. Northwestern India

1. Introduction

The Neem ka thana area, Sikar district, Rajasthan is known for copper mineralization from early period because of the presence of the Baleshwar copper deposit, which was, an old mine where from the copper was mined and exported to Johannesburg during the British rule in India. The Archaeological records suggest Baleshwar mine, as source of copper for even Harappan culture as referred in [1] [2]. The area adjacent to Baleshwar has many known copper prospects including the Chiplata and Tejawala, which Geological Survey of India [3] explored during the Period 1976-1979 and proved small resources of copper, with good mineable grade. Prospects like Ahirwala, Tejawala and Chipalata were also explored and drilled by GSI, [4] in the Neem ka Thana along with Baleshwar during early eighties but had poor copper mineralization [5] [6] [7] [8]. Work was also carried out in the area south east of Kharagbinjpur for Pb-Zn mineralization [9] in Baleshwar area. ***It was a chance discovery of Bornite mineralization in the year* 2000 *that chunks of Bornite were encountered during a well deepening, near Dokan on the Neem Ka thana-Kotputli road and was reported to a Geologist from Geological Survey of India, working in adjacent area. This is how the bornite dominated copper mineralization came to the light***. Post this discovery of bornite mineralization, extensive exploration over a strike length of more than 20 km has been done; a sizeable resource has been established by the Geological survey of India. The copper mineralization here is unique, as bornite is dominant over other sulphides of copper in occurrence. Various publications are available from this belt. [10]-[17] but these publications do not provide a holistic view about this mineralization. Though the exploration details are available in the form of unpublished reports of the Geological Survey of India, for all the explored blocks, a comprehensive account of this bornite dominated proterozoic sediment hosted copper silver mineralization is lacking. Here in this paper author has compiled the information available in the form of unpublished GSI reports besides the available publications. The author's own work of over a decade as field geologist and project leader, has been synthesized with the other existing views and a comprehensive model has been proposed on genesis of mineralization, after examining surface geochemical indications, study of several kilometers of borehole core, hundreds of samples of thin and polished surfaces of ore and host rocks from the belt. The paper includes data from the older reports besides first hand work experience of all the co workers who have worked in the belt.

2. The Geological Overview

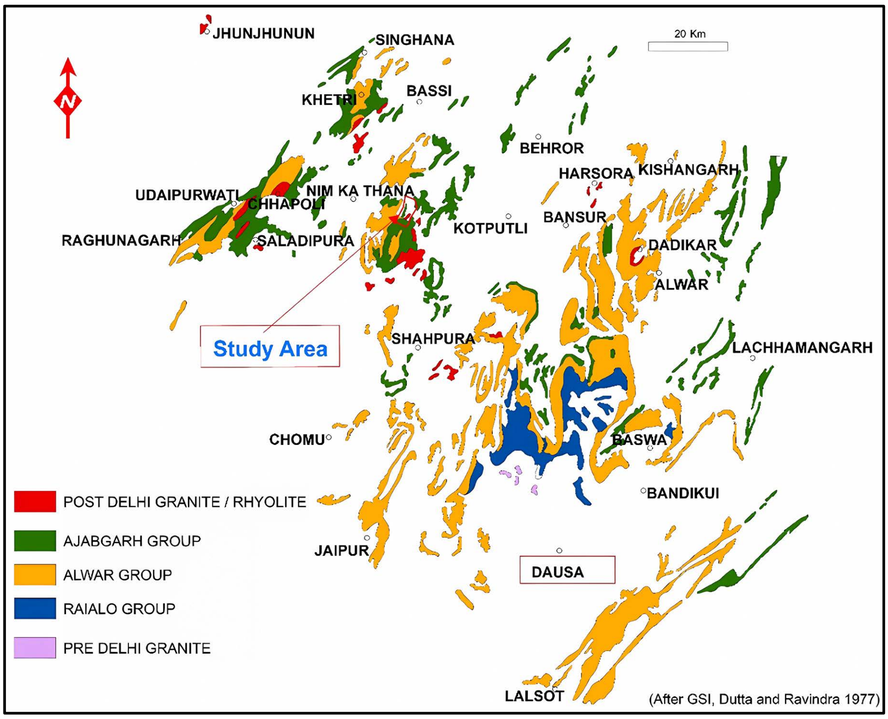
The pioneer work in the area [18] [19] classified the rocks of the area in to Delhi "System" the Alwar "Series" and the Ajabgarh "Series". Subsequently there has been several generations of mapping by Geological survey of India during different times, [20] [21] [22] [23] [24] carried out in various parts of the area under study. The detailed geological mapping of Patan area [25] recorded three successive phases of deformation. The first and second phases of folds are generally co-axial. Expression of last phase of folding is mild and extremely localized, [3] as resulted from detailed geological mapping and geochemical sampling in Patan area. The base metal investigation in Baleswar area was also initiated by the same authors [3]. The general stratigraphic succession established during 2007, by GSI workers, [26] in the area is adopted here.

The latest geological setup worked out during thematic mapping by Geological survey of India is adopted here as under in **Table 1**.

Table 1. Stratigraphic succession of Neem Ka Thana belt by Behra, *et al.*, [26].

Intruvises		Quartz veins, Quartz Kynite veins, Calcite veins, Epidote, Pegmatite, Albitite and Amphibolite
Ajabgarh Group	Kushalgarh Formation	Tremolitic marble with brecciated and ferruginous cherty quartzite and carbon phyllite Slate, phyllite with carbon phyllite Marble Banded biotite amphibole marble with mica schist, Quartzite and carbon phyllite Biotitic marble Garnetiferous staurolite mica schist Massive quartzite Micaceous quartzite Quartzite intercalated with mica schist Garnetiferous mica schist
Alwar Group	Pratapgarh Formation	Gritty to pebbly quartzite
Pre-Delhi		Pelitic gneiss Impure marble; garnetiferous biotite schist; banded white marble intercalated with mica schist

Regionally speaking the North Delhi fold belt, (which is considered as store house of Copper gold mineralization, [27] [28]) is sub divided in to three sub basins [29]. The Khetri sub basin, Alwar-Ajabgarh sub basin and Lalasot-Bayana sub basin. (**Figure 1(i)**). The study area falls on the western margin of the Alwar Ajabgarh sub basin and is separated by a basement high from Khetri sub basin. The Basement rocks (Mangalwars) are not exposed in the study area, and so does the Raialos. Hence the thick Arenaceous rocks of the Alwar group of DSG form the base here for the host litho package "Ajabgarhs". Topographically the area displays two linear ridges one running from Mahawa to Patan, in the east-west direction and nearly marks the northern limit of the mineralization, while another ridge extends in the North south direction from Baleshwar to Chiplata separating a vast, plain soil covered area to its west and a rolling topography with very good intensity of exposures on its east. The northern ridge is folded along the N-S trending F_2 axial planes and exhibits macroscopic syn-forms and anti-forms named as Mahawa Synform, Bharala Antiform, Bageshwar Synform and Dokan Antiform from west to east (**Figure 1(ii)**). After Dokan, the ridge takes a north-easterly swing and is described as a flexure by earlier workers, [25] and there after continues up to Patan all along the road. The Baleshwar ridge, which extends from Baleshwar to Chiplata and has a domal structure, is composed of white to dirty whitish grey coloured crystalline, mature ferruginised and brecciated quartzite belonging to Alwar Group of Dehli Super Group of Rocks. This ridge on its east has a vast exposed expense of Ajabgarh Group of meta-sediments mainly composed of impure dolomite, Calc silicate, Calcareous quartz biotite schist and banded calc-semipelite, besides having lensoid bodies of carbonaceous phyllite. This marl-semi-pelitic intercalated sequence is inter-layered with quartzite, which is mature but less crystalline then the quartzite of Alwar Group. The Quartzite being the dominant lithology in Alwar Group, forms ridges and constitutes the limb parts of the two major map scale structures, ***The Dokan Antiform in the north and the Dariba Antiform*, *in the south.*** The Dokan, Baniwala ki Dhani and Dokan north block, carved out for the convenience of exploration comprise of dolomite, biotite bearing dolomite, amphibole bearing dolomite, calcareous quartz biotite schist and banded calc-semipelite rock and amphibole quartzite, representing Ajabgarh meta sediments. This package is dipping due west as well as due east, at steep dips and deformed by polyphase folding. Pegmatites, Quartz veins, Amphibole veins, calcite veins and Quartz tourmaline rocks occur as intrusive in this area. The eastern limb of Dokan antiform here in the Dokan area takes a regional flexure (**Figure 1(ii)**) and extends further in the Panchokharkhara and Mina Ka Nangal area. ***The Dariba Antiform*** is a large structure with its axial zone extending for about 500 m in width, in Dariba area, where it is best exposed and depicts the corrugated sheet like formed surface due to formation of mullions and pervasive fold axis lineation. The plunge of this regional fold is moderate to gentle varying between 25˚ to 40˚ due south. The western limb of this antiform is the major repository of the copper mineralization,



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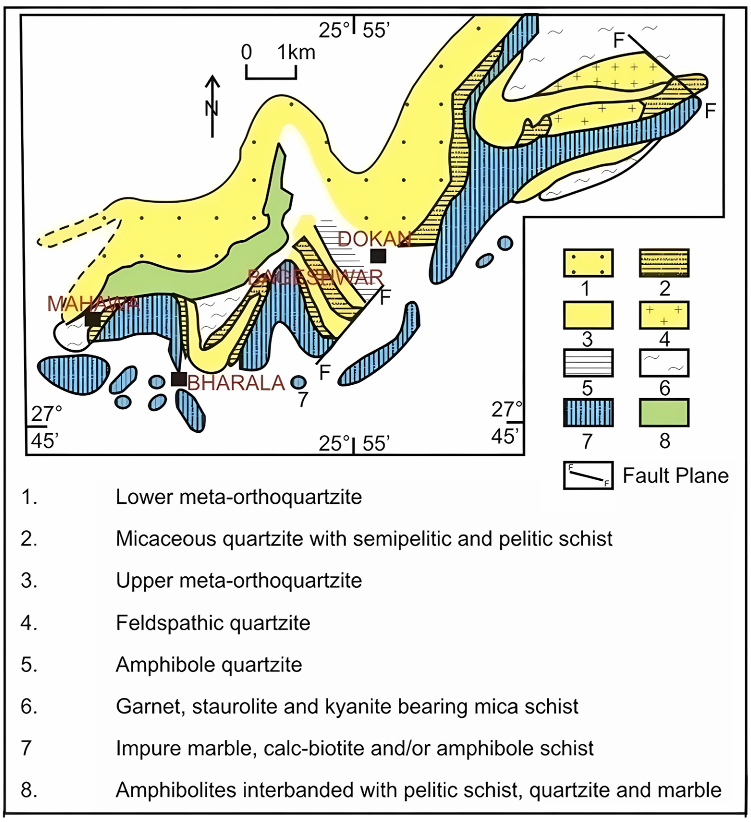

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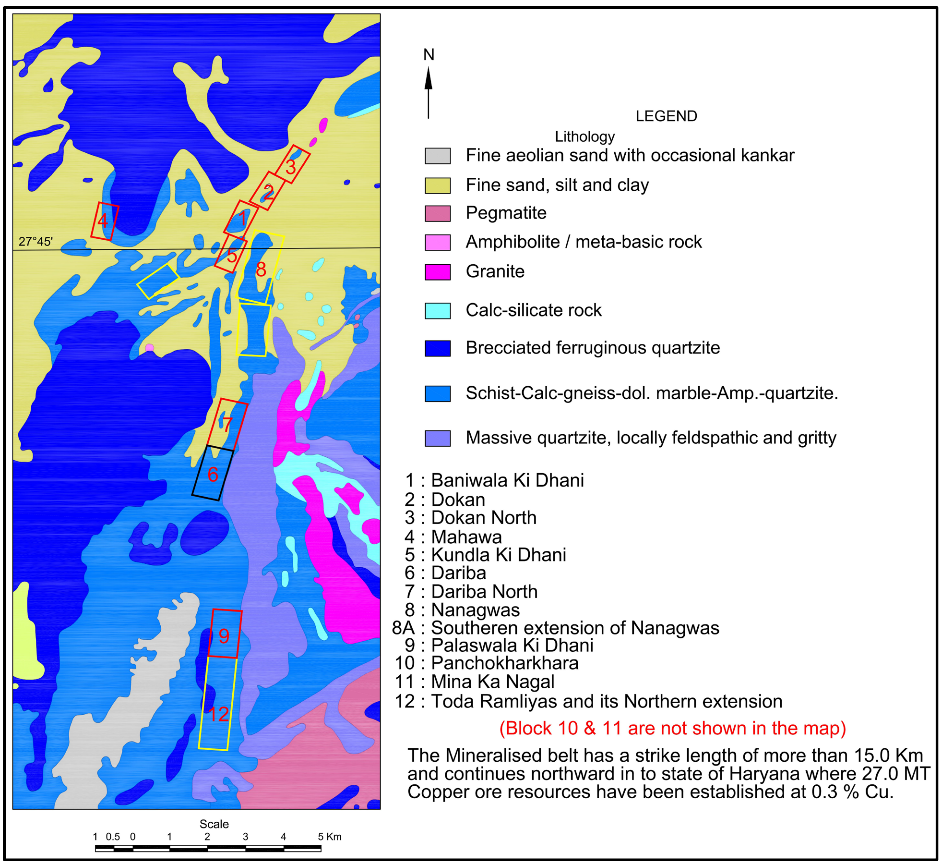
Figure 1. (i) Simplified geological Map of North Delhi fold belt (modified After Datta and Ravindra, GSI, 1977); (ii) Regional Lithological Map of Patan area, Northern part of the belt (Ray, 1983).

which is confined to the limb shears parallel to the axial planar shears. The eastern limb is overturned and dips steeply together with western limb towards west and the axial plane is disposed in the NNE-SSW direction. Both the limbs of the Dariba antiform exhibit evidences of being tectonised and sheared in nature. South of the closure of Dariba antiform, the eastern limb is further refolded in to a map-scale synform called Palaswala Ki Dhani synform. [30] [31]. This is a northerly closing southerly plunging synform, the western limb of this synform is mineralized and resources have been proved in this block. This limb extends further south displaying mesoscopic folds of the same generations and significant resources have been proved in the Toda Ramliyas area under the Teliwala-Ramliyas and Toda-Ramliyas blocks, [32] [33].

The 20 km long belt, where exploration has been done, is divided in to several blocks, for the convenience of exploration and they are depicted in **Figure 2(i)**.

2.1. Host Litho-Package

The sulphide mineralization in the belt is not confined to a single lithology, instead it is a litho-package which is mineralized and this package is conspicuously calcareous in nature and is typically Marl. The principal facies of metamorphosed marl, hosting the sulphide mineralization are; Impure dolomite/marble, calcareous quartz biotite schist and to lesser extent calc silicate rock, besides



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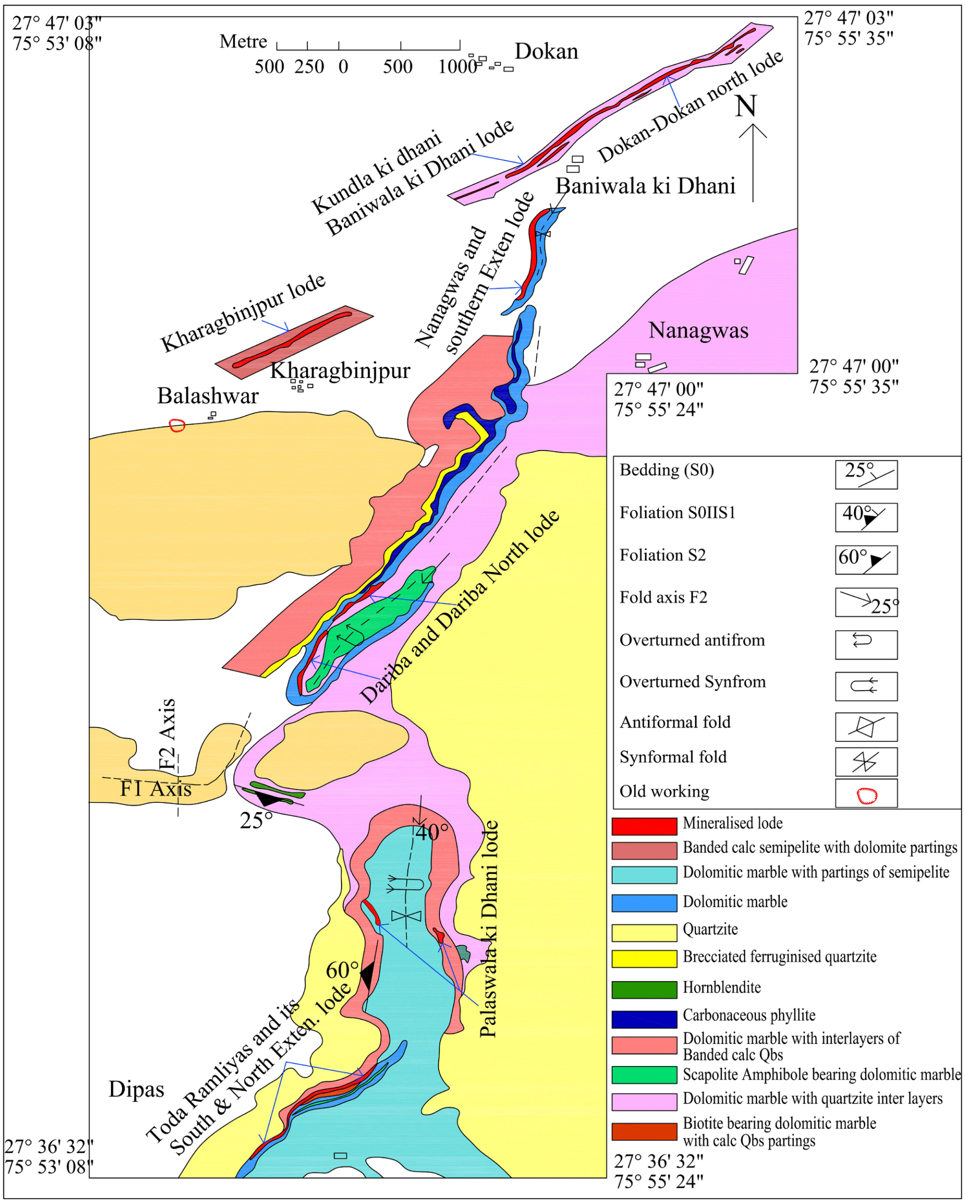

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Figure 2. (i) Geological Map of the part of the belt with location of various explored blocks. (Modified after compiled GSI map, part of T.S.45M/13 & 14); (ii) Large scale map of host litho-facies of the Mineralized belt with disposition of surface projection of lodes in various blocks in the Neem Ka Thana belt, Sikar District. Raj (Mapped by Sharma *et al.* 2017).

carbon phyllite which contains occasional layer parallel pyrite and pyrrhotite but no copper mineralization. The host lithlogy mentioned above have been discussed and the same has been mapped on large scale to elaborate on structures produced and their control on the mineralization, on map scale. (**Figure 2(ii)**).

The impure dolomite (includes *amphibole bearing dolomite*, *biotite bearing dolomite* and *dolomite with intercalations of calc quartz biotite schist*. And calc silicate (**Figures 3(A)-(H)**). Dolomite occurs as well bedded massive to semi massive, comparatively extensive subunit of the Ajabgarh Group of rocks in the

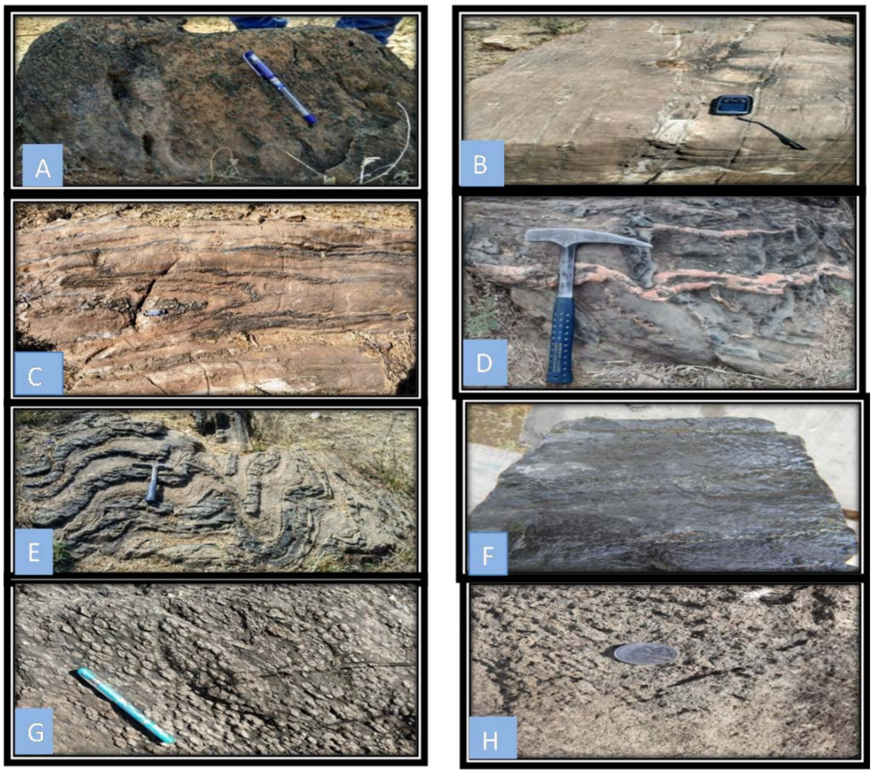


Figure 3. Host lithologies as they appear in hand specimen, from various parts of the belt. (A) Amphibole dolomite. (B) Biotite bearing dolomite/marble. (C) Biotite bearing marble with Calc QBS partings, (D) Dolomite QBS inter layered strata intersected by Pink calcite vein. (E) Calc. QBS-dolomite inter layered lithounit. (F) Carbonaceous phyllite wtih layer parallel pyrite mineralization. (G) QBS with scapolite defining mineral lineation. (H) Typical calc silicate rock.

area. The average thickness of dolomite band varies from 30 m to more than 100 m at places. Characteristically the impurities in the dolomite, control the mineralization. The dolomite without impurities is typically barren. The abundance of amphibole bearing dolomite could be witnessed in the Baniwala ki Dhani block. On the other hand, the Dokan and Dokan North blocks have biotite bearing dolomite as the major mineralized lithology. Similarly, Dariba, Dariba north, Palaswala Ki Dhani and Toda Ramliyas blocks also have the dolomite as the predominant host but it is tremolite bearing marble here with partings of calc quartz biotite schist. Dolomite in the Toda Ramliyas, Palaswala Ki Dhani, Dariba and Dariba north blocks is also silicified in nature and traversed by subsequent quartz, carbonate, amphibole and chlorite veins, besides specularite veins. In the Dokan North block the dolomite is ferruginised in nature. Crystalline coarse grained variety of dolomite/dolomitic marble is also seen exposed in the Palaswala Ki Dhani and Dokan North block. This unit also exhibits occasional development of oxidised zones in terms of upper tough crust of ferruginous goethite material and very rarely crude psiolites of iron. Possible manganiferous coatings are also noticed on the surface of dolomite near Gursali ki Dhani village.

At few places the dolomite when becomes rich in tremolite, muscovite, and chlorite and assumes banded nature with bands of green minerals grading in to calc silicate rock, but it becomes difficult to separate these units, because of inter fingering nature of facies variation.

Calcareous Quartz biotite schist and biotite schist

Calcareous quartz biotite schist is another most prominent host lithology for copper mineralization, (has been referred as Calc QBS elsewhere) is exposed extensively as bedded lithology with well-developed schistosity. It generally exhibits spotted appearance at the expense of presence of coarse-grained plagioclase grains and also sometimes due to presence of scapolite. Rounded grains of calcite and quartz are also noticed as spots on the weathered surfaces. This unit seldom contains garnet porphyroblasts of varying dimensions. Frequency distribution as well as size of the scapolite porphyroblasts varies in large limits throughout the area. Scapolite defines a mineral lineation in Nanagwas and Dokan north blocks, while the smaller sized grains occur in the quartz biotite schist throughout the belt. The concentration of the calcite in this rock, after which it derives its calcareous nature, has large variation, it occurs as primary grains as well as secondary calcite as coating along the grain boundaries. The Calc QBS is so intricately intercalated with dolomite and biotite schist that it becomes very difficult some times to provide a nomenclature to the lithology, (**Figure 3(D)**, **Figure 3(E)** and **Figure 3(G)**, depicting various modes of occurrences and field expressions of Calc QBS)

Cal silicate rock

The calc silicate rock is well exposed on the eastern limb of the antiform in Dariba and Dariba north block; it is also well exposed in the Toda-Ramliyas block and in Palaswala ki Dhani block. This unit shows lateral facies variation from amphibole marble to calc-silicate rock. (**Figure 3(H)**). This mixed litho-unit has been termed as the inter-bedded calc silicate rock with calc quartz biotite schist. It is thinly bedded rock with greenish grey colour, having well defined scapolite rich bands and actinolite, epidote, calcite rich bands. The pink calcite veins emplaced parallel to these bands and litho-contacts are noted from this area. This unit is mineralized in Palaswala ki Dhani block where as it is barren in the northern parts of the belt.

Carbonaceous phyllite.

This litho unit occurs as intercalations within the Calc QBS and is rarely exposed on the surface. It is tuffaceous, very fine grained, soils the hand and ash grey in colour (**Figure 3(F)**) Very finely banded and thinly laminated. Generally, oxidised and contains non uniformly distributed red spots all over the rock surface, indicating presence of oxidised pyrite grains. In some of the areas like Dokan North block, Nanagwas block and Mahawa block this litho-unit contains a well-defined pyrite-pyrrhotite mineralized zone at a shallower level but does not contain any copper mineralization anywhere in the area in this zone. In some of the boreholes the carbon phyllite is intersected as sandwiched between quartzite and calc quartz biotite schist and contains graphitic development.

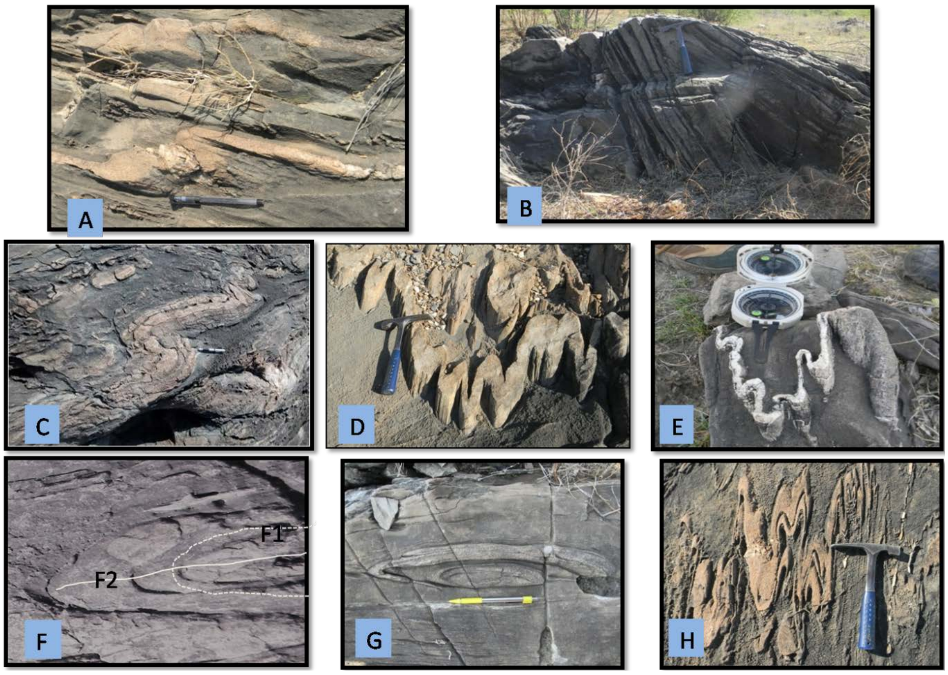
2.2. Structure

The general disposition of the litho-units in the area is North-North-East-South-South-West with steep to very steep dips on either side *i.e.* NW as well as NE direction. The rocks are intensely folded and preserve mesoscopic folds in calc silicate, Calc QBS, in dolomite and also in banded calc-semi-pelite litho-units besides the quartzite. Three principal planar surfaces are very well developed in the rocks of the area besides the bedding. The first foliation is parallel to the bedding and is comparatively less pervasive then the second. The $S_o$llS_1 has an acute inter-cleavage angle of about 15^0 to 20^0 with S_2 and both are steeply dipping. The direction of the dip keeps on swinging around the verticality. The third cleavage is widely spaced disjunctive in nature and least pervasive, does reflect refraction in various lithologies, and has nearly East-West trend. The area exposes and preserves three phases of folding very distinctly and profusely preserved on various scales.

The mesoscopic first folds; are, tight to isoclinal in geometry, (**Figure 4(ii)**) rootless, have various orientations indicating first deformation, and are recorded occasionally from the area. The first foliation is axial planar to the F_1 and is largely parallel to the bedding. Stripping lineation, mineral lineation defined by elliptical grains of scapolite, form the L_1 lineation. The F_1 folds can also be seen as intra-folial folds beautifully preserved in the Calc QBS and banded calc biotite schist. Stretched grains of sulphide and layer parallel mineralization recorded long the S_1, might suggest mineralization pre F_1 and alignment of the mineral bodies along s_1 during first deformation.

Second phase of folding: The Second fold is the most dominant structure in the area which controls the disposition of litho-units. It is preserved on macroscopic and mesoscopic scale in various lithologies. Mesoscopic F_2 folds are usually tight to isoclinal (**Figure 4(i)**) in nature. S_2 is represented as axial planar crenulation cleavage in mica schist and as disjunctive cleavage usually in the hinge part of F_2 folds in competent rock types. S_2 strikes N-S to NNE-SSW and is vertical to sub vertical towards west or west-northwest. The associated lineation (L_2) is recorded as intersection lineation (of S_0 and S_2), crenulation axis, minor congruous fold axis (S, Z, M-W folds, **Figure 4(i)**) and pucker axis. The lineation (L_2) pitches moderately towards S to SSW in the area. Displacement of S_0 is noted along the axial planar S_2 cleavage in competent rocks.

Macroscopic overturned F_2 folds are seen around Panchokharkhara, Patan, Mahawa, Bharala, Bageshwar, Baleshwar, Nanagwas, Dariba, Palaswala and Toda Ramliyas. In the Mahawa-Bharala-Bageshwar area, Mahawa synform is followed on the east by Bharala antiform, which is again followed by Bageshwar synform and thereafter by Dokan antiform (**Figure 1(ii)**). The second phase of folding has the major control over mineralization as the limb shears and axial planar shears parallel to the NNE–SSE trending axial planes are the prominent locales of the remobilized ore bodies. Besides the brittle ductile shearing, sympathetic to the D_2 deformation has also produced significant open spaces for the migration and deposition of the remobilized mineralizing fluids.



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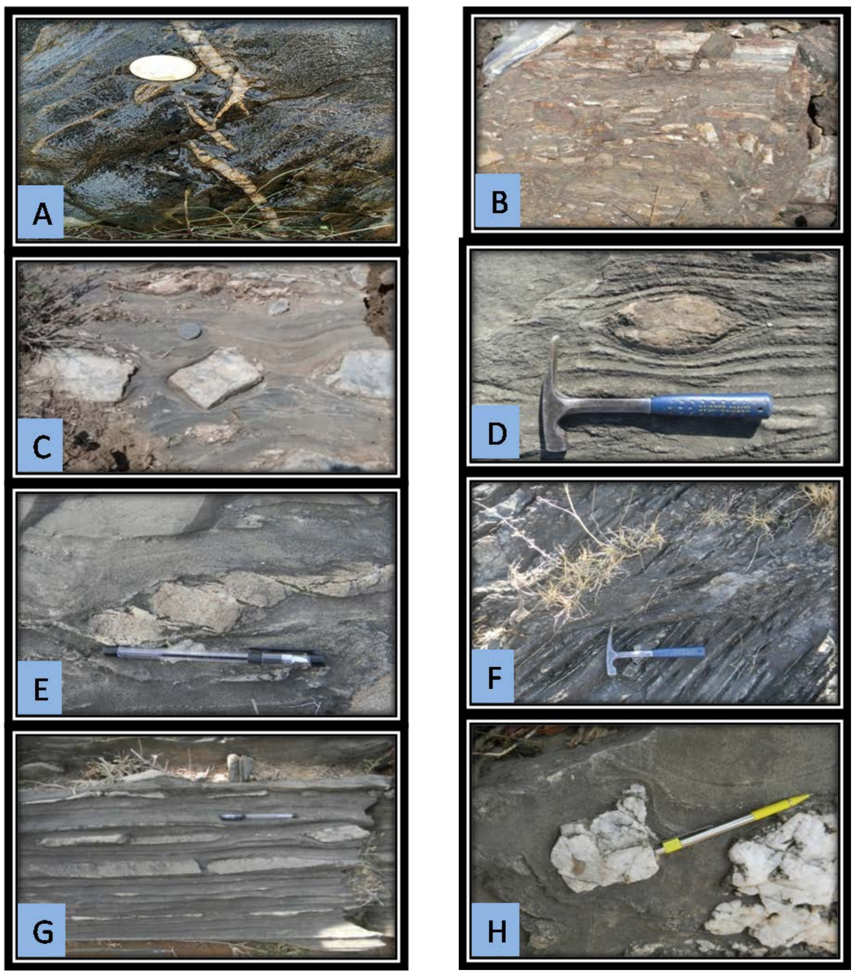

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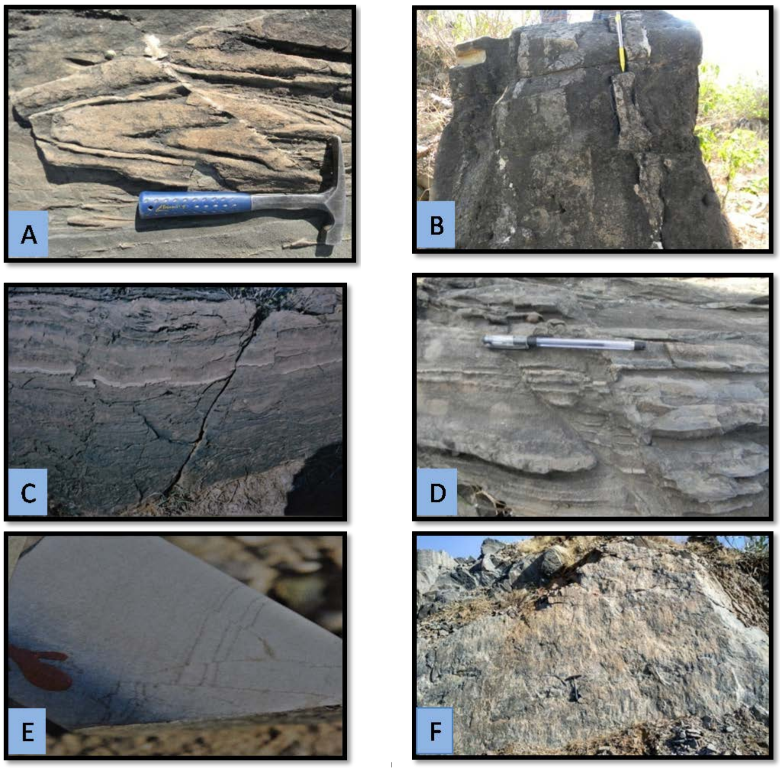

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Figure 4. (i) Depicting Mesoscopic folds in the studied area. (A) Mesoscopic F_1 fold, Dariba North. (B) Overturned F_2 fold Palaswala ki Dhani. (C) Mesocspic S fold, Dariba block. (D) M-W folds in Hinge zone of a large antiformal F_2 fold. (E) Mesocspic M/W folds, in Quatrz vein. Dariba block. (F) Refolded fold F_1 is coaxial to F_2. (G) Domical folds in quartzitic layers within siliceous dolomite, Dariba area. (H) M-W folds in hinge zone of a large antiformal F_2 fold depicting thicknenning of hinges and attuanation of limbs due to shearing; (ii) Shearing eveidences form different parts of the belt. (A) Forked Tension Gashes, Toda Ramliyas. (B) Brittle shearing of multiple quartzite bands, note the plastic deformation of matrix. Off Bichhu ki Dhani. Evidences of more than one deformation are also recorded here. (C) Chocolate boudins (torn boudins), Indicating brittle deformation while the matrix is plastically deformed and folded, Dhabala [34]. (D) Fish mouth boudin, suggesting less viscosity contrast between the boudin and host, margins deformed. (E) Shear band like boudin, synthetic slip along the inter boudin surface, Dariba north. (F) Shearing oblique to foliation producing sigmoidal boudins in Quartz vein along the shear plane, Dariba. (G) Multilayer boudinaging of Semipelite producing torn boudins, Dariba. (H) Drawn boudin produced in Quartz vein, the enveloping surface is folded due to plastic deformation of host dolomite, Dhabala [35]. (iii) The mesoscopic scale faults and drags observed in the Dokan-Dariba belt. (A) mesoscopic fault sympathetic to third fold. (B) Mesoscopic step faults. (C) Step faults producing graben and horst structurec in Ajabgargh lime stone. (D) Cuonjugate set of faults sympathetic to third deformation. (E) Step faulting variously oriented as recorded in borehole core of dolomite. (F) Slicansides on mesoscopic dipslip fault plane (sympathetic to F_2,) parallel to S_2 foliation in TodaRamliyas.

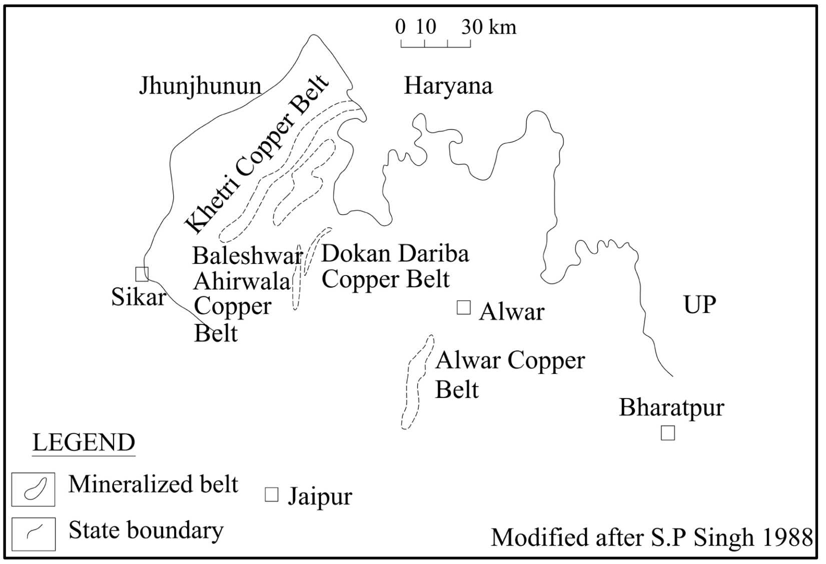
Third phase of folding: The third phase of folding in the area is marked by broad warps and open folds along nearly E-W striking axial plane and has also caused swinging of linear quartzite ridges. While this has not been seen on the surface but the curvilinear disposition of the ore lodes might suggest effect of the third phase of folding on mineralization.

Shearing: Evidences of shearing in NNE-SSW to N-S direction are profusely recorded in the area preferably in quartzite. The eastern and western contact of the Ajabgarh Group of rocks in the Valley with the Alwar Group of meta-sediments has a tectonised and sheared manifestation, evidenced by stretched pebbles of conglomerate, exposed West North West of Baleshwar temple, where the pebbles exhibit down dip lineation. Profuse silicification, epidotization, ferruginization and brecciation of the litho-units along the contact, and stretching of the grains and development of sigmoids and boudins in quartz veins support the tectonised nature of contact. A prominent brittle-ductile shear passing through the axial region of the antiform, which runs from Dariba to the Nanagwas block, here probably it enters subsurface and reappears in the Dokan-Baniwala and Dokan North block, displayed by brecciation, ferruginization and presence of tension gashes. Limb shears are also developed especially on the western limb of the Dariba antiform parallel to main shear plane. The bulk of the mineralization is also concentrated within these shear zones during deformation due to remobilization.

Faults: Major faults are not recorded from the area except for the ones reported earlier [3] in the Baleshwar area and the one reported [25] along the eastern limb of the Dokan antiform. East-West trending faults, north of Dariba and north of Gursali ki Dhani were recorded [36]. Besides this there are evidences of dragging along East-West direction in Bichhu Ki Dhani village, where drags could be observed in the carbon phyllite. Conjugate faults of mesoscopic nature have also been observed in Dariba, (**Figure 4(iii)(B)**, and **Figure 4(iii)(D)**) Toda Ramliyas block and also at many other places, in the southern part of the studied area. In The Toda Ramliyas and Palaswala ki Dhani blocks conjugate set of faults disposed at an acute angle to the main fault plane which is East-West have been witnessed in the pits exhibiting slicken slides and indicating right lateral movement, are observed. The east west trending faults of the various intensities and dimensions are sympathetic and parallel to the axial planes of the third deformation. Some of these minor faults might have affected the ore body to go down on the eastern side is recorded during the drilling in Toda Ramliyas blocks and truncation of the lode in case of Southern extension of Nanagwas block.

2.3. Historical Account of Mineralization

The area forms part of the Alwar-Ajabgarh sub basin of the North Delhi Fold Belt and is important for hosting mineralization, dominantly base metals. Khetri Copper Belt is located west of the area and is separated by basement rocks. The area under study was known for Baleshwar copper deposit, which is the earliest mineralization known from this belt (**Figure 5(i)**). The principal minerals found in and around Baleshwar include Copper, Barite, Iron, Bismuth and REE, besides reported occurrences of gold and off course silver is associated with the copper. Calcite, feldspar and albitite veins are also reported from the area. The mining activity in this area probably dates back > 3000 B.C. as indicated by the



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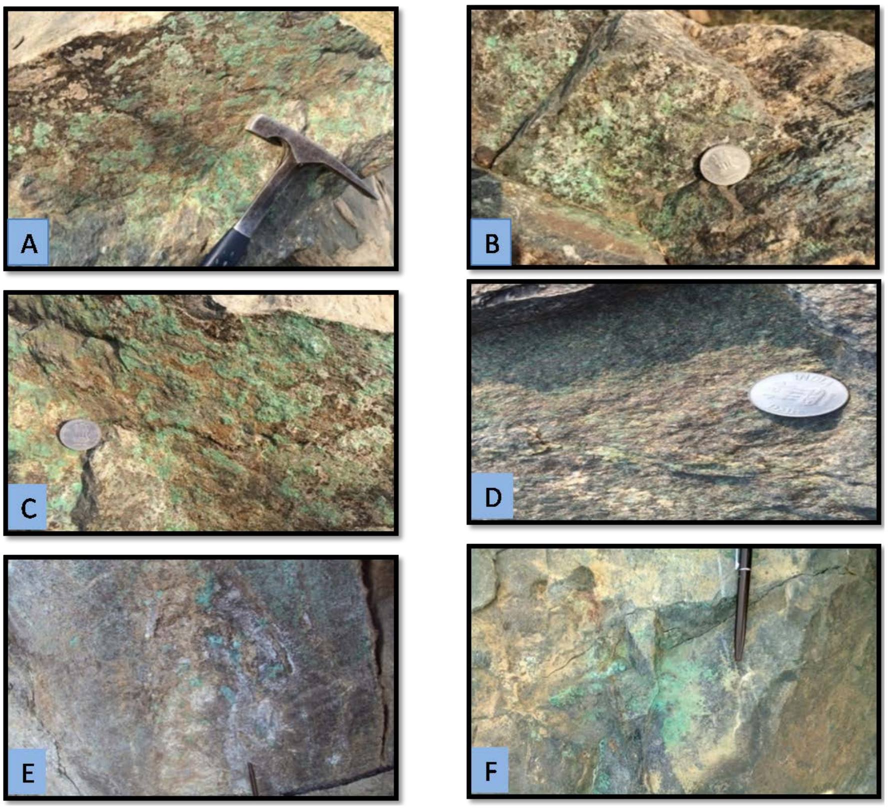


(ii)

Figure 5. (i) Location of newly discovered mineral belt Dokan Dariba belt, vis-a vis, other known mineralized belts in Ajabgarh basin. (Modified after Singh *et al.* 1988); (ii) Evidences of surface mineralization in various lithologies and location from the belt. (A) Profuse malachite staining in calcareous quartz biotite schist, Dariba area. (B) Malachite staining in Carbonate rock, Dariba area. (C) Malachite staining in Biotite bearing marble Dokan area. (D) Pervasive malachite staining in Scapolite bearing tremolite marble, Nanagwas area. (E) Malachite staining in Calc silicate rock Toda Ramliyas area. (F) Malachite staining in Quartz vein, from Nanagwas.

recent archaeological findings [1]. Considering the literary records, the mining is very well known from the Akbar's period, since there is a mention of mining of Detha (Cobalt) from the Akwali Mine near Khetri, in Aiene Akbari, and the Baleshwar-Dariba is contemporary to Akwali. The Dariba village; 6 kilometres south from Baleshwar, is settled on the small mound of slag bears the testimony to the principal smelting site for ore from contemporary Baleshwar mine, besides having slag heaps at Baleshwar. The earliest geological record of the report of old working from the area is contained if references [20] [21]. Subsequently the exploration work by Geological Survey of India, from 1973-78, established mineralization to extend over a strike length of 1.5 km, as impersistant lenses and 1.59 million tones of reserves were estimated, at 0.84% Cu at 0.50% Cu, cut off [3]. Old workings for barite which is hosted within the impure marble and calc silicate rock and controlled by the F_2 deformation, is exhausted now; is located at Sami ki Dhani area and is known as Kharagbinjpur Barite deposit [37]. Calcite, Iron and feldspar are also mined from the Raipur area, near Nanagwas [37]. The iron deposit is located south East of the Baleshwar and nearly 4 km south west of Raipur, which is 10 m - 50 m wide and nearly 500 m in strike length, has a very high content of magnetite with some hematite. Significant hematite quartzite bands are also reported from the area under study in the Toda-Dipas transect, having an exposed width of about 35 m and strike extension of about 2 km each of these en'echelon disposed bands, [38] [39]. Bismuth ore occurs in Narda [40] in earthy and lumpy form as segregation, within pegmatite with values of the order of 2% to 4% Bi. The Bismuth values from 50 ppm to 3000 ppm occur in a variety of rock types including pegmatite and albitite around Narda hill and in the adjacent Nim-Ka-Thana area. The study of bismuth in this area assumes more significance since upto 7000 ppb Au and 1000 ppm Ag have been recorded from the ore. Albitite and magnetite veins are also reported from the Narda area besides Native Gold and Bismuth. Drilling carried out for Bismuth in the same area however could not prove any resource [41]. The surface geochemical mapping by GSI, established a prominent zinc anomaly in the area, South East of Kharagbinjpur and few boreholes were drilled [42] [43] [44]. Occurrence of Gold and REE mineralization has been reported in EPMA studies from the Toda Ramliyas block [33]. *Despite the area having* 2000 *year old mining history and the copper mineralization being worked out in detail by GSI, during late seventies at Baleshwar, the bornite dominated copper mineralization hosted within the impure dolomite and calc silicate, occurring as disseminated and fracture filled mineralization remained un discovered till the year* 2000. *Ever since this mineralization has been unraveled it is being explored continuously till date by Geological Survey of India, Jaipur, of which the present author was part of, along with other workers whose works are reported here. Which has augmented the national copper resources significantly and the area has emerged as one of the important copper silver mineralized belt, on Mineral map of Rajasthan.*

3. The Exploration

Surface Exploration; Occurrence of a prominent false gossan zone extending from west of Dariba to Gursali ki Dhani, trending in NNE-SSW direction and exhibiting brecciation and ferruginization, was traced for a six kilometer strike length, along the axial plane of Dariba antiform [21]. However subsequent work suggested this zone to be located on western limb of Dariba Antiform rather than along the axial plane [42]. The occurrence of Bornite dominated copper mineralization in the Baniwala ki Dhani village [41], was followed a thematic mapping by GSI, [38] [45] brought out several locations with feeble to profuse malachite staining in a package of rocks which is marly in nature which remains, the only surface indication for the bornite bearing copper mineralization (**Figures 5(ii)(a)-(f)**) Brecciation and silicification are other associated evidences occur here. The surface geochemical evaluation of the area was done in the entire belt by taking up litho-geochemical and pedo-geochemical sampling on grid pattern, besides pitting and trenching and surface geochemical profiling along the proposed boreholes in all the blocks. The entire belt has been covered by geochemical sampling block by block, over several years and the details of surface geochemical exploration of the individual blocks are available in various unpublished reports of GSI, WR, Jaipur. This was achieved by collecting a total of 2815 number of grid samples on 200 m × 50 m grid, besides detailed mapping of an area of 11 sq. km on 1:2000 scale, in the belt to know the host rock; control of the mineralization and detailed mesoscopic structural features in the area during last two decades by various workers including the author. The grid geochemical sampling as well as detailed mapping has brought out comprehensively the disposition of the mineralized zone on surface, in various blocks in the entire belt of 20 km strike length (**Figure 2(ii)**). The mineralized zone as delineated sector wise from north to south based on the various map scale and/or macroscopic structures to which these mineralized blocks are confined. The area from North to south contains three major structures, the Dokan antiform and its contemporary synforms and antiforms, forming the **Northern Sector**, the **Central Sector** is basically defined by the Dariba antiform and the **Southern Sector** is located within the Palaswala synform and Toda Ramliyas antiform (**Figure 2(ii)**). The major part of the mineralized zone as disposed on the surface has been depicted in the large scale map on 1:10,000 scale covering the belt from Toda Ramliyas to west of Nanagwas block. The other four significant blocks including Dokan North, Dokan-Baniwala ki Dhani and Kundla Ki Dhani have been shown as a separate block as they are not in strike continuity but are disposed in en echelon pattern. The northern most part of the belt containing Panchokharkhara [46] and Mina ka Nangal [47] blocks could not be included in the large scale map, because there is a gap area where exploration has not been done due to pinching of host litho-package and very poor surface shows of mineralization. The western fringe of the mineralized belt represented by the Mahwa block (**Figure 2(i)**) and other two marginally positive blocks could not be depicted in a single large scale map due to nearly 20 km horizontal distance between the eastern and western end of the belt.

3.1. Mode of Occurrence of Mineralization

The mineralized zone/sulphide zones as studied from the borehole cores and surface are characterized by presence of disseminations of bornite, chalcopyrite, covellite and chalcocite. Occasional clusters of the coarse grained bornite within quartz, carbonate, chlorite and amphibole veins are noticed besides the stringers of various sulphides. Occurrence of small sigmoid and lenticular bodies of quartz and carbonate, containing disseminations of sulphides and aligned parallel to the banding in the marble and along the foliation in the calc-quartz biotite schist, (S_oIIS_1), have been observed in various borehole drill cores throughout the area. The fracture filled and vein filled sulphides within the quartz and calcite veins are recorded in considerable proportion from the area. Very fine grained dusty disseminations of bornite and sometimes chalcopyrite are also recorded specifically from the biotite bearing rocks. Pyrite in general occurs as poor disseminations all along the drilled depths of various boreholes. Occasional pyrite veins are also recorded. A well defined layer parallel pyrite mineralized zone occurs at shallow level in almost all the boreholes drilled in Dokan and Dokan north blocks. Specular hematite occurs as vein filling, fracture filling cutting across the foliations besides wide spread disseminations in various rocks all through the area. Galena associated with the pyrite and specularite occurs in Nanagwas block and random veins in other places. Covellite occurs as vein fillings and as coatings along the pyrite and bornite besides streaks and stringers. Foliation parallel bornite streaks and stringers are frequently observed. Pyrrhotite also occurs as wide spread mineral and very often associated with the bornite. The co-existence of bornite and chalcopyrite is not always seen but very often they occur together. Larger chunks of coarse grained bornite and pyrrhotite occurring together have been observed. In Mahawa block the shallower level mineralized zone is richer in bornite while the deeper level (comparatively; otherwise both the zones are within 100 m depth from the surface) contains more of chalcopyrite than bornite. Such variations and aberrations to generalization are noticed throughout the belt in various blocks but the general mode of occurrences include, disseminations, streaks, stringers, vug filling, cavity filling, layer parallel and co-folded pyrite and pyrrhotite veins (**Figure 6** & **Figure 7**). The presence of vein fillings of bornite-chalcopyrite, covellite, and chalcocite suggest remobilized and epigenetic component of mineralization. Occurrence of smears of bornite, (**Figure 6(A)**) chalcopyrite, pyrite and other sulphides suggest circulation of mineralizing fluids along the fracture planes.

3.2. Control of Mineralization

The mineralization in the area is characterized by over lapping signatures of litho and structural control. The mineralization primarily is hosted within the

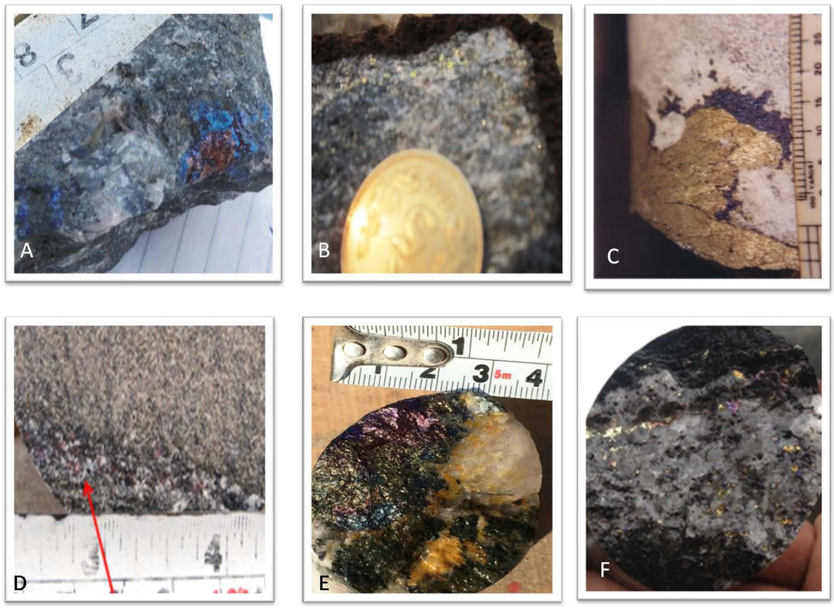


Figure 6. Drill cores exhibiting various modes of occurrence of sulphide Mineralization. (A) Vein/cavity filled bornite and covellite within calcareous quartz biotite schist. (B) Disseminated chalcopyrite in impure dolomite, Kharagbinjpur-Dhabala area. (Observe the thick oxidised layer on litho unit. (C) Occurrences of pyrrhotite adjacent to bornite suggest to different episodes of sulphide mineralization. (D) Fine disseminations of bornite within quartz biotite schist, Toda Ramliyas block. (E) Vein filled coarse grained bornite-chalcopyrite and covellite with in calc QBS. (F) Streaks and disseminations of bornite and chalcopyrite within biotitic partings in dolomite.

Figure 7. Drill cores and hand specimens exhibiting various modes of occurrences of mineralization. (A) Layered sulphides co folded with host indicating sediment hosted strata-bound nature of sulphide mineralization. (B) Layered pyrite mineralization in QBS suggesting syngentic nature of sulphide mineralization. (C) Vug/cavity filled bornite and chalcopyrite within biotite bearing dolomite. (D) Foliation parallel streaks of chalcopyrite, besides sulphide mineralized quartz vein emplaced also parallel to foliation impure dolomite. (E) Disseminations and clusters of chalcopyrite along carbonate vein with in calc QBS. (F) Coarsely crystalline Chalcopyrite within the carbonate vein emplaced with in biotite bearing dolomite.

calcareous facies by and large. The impurities in marble/dolomite are in terms of varied proportion of biotite, amphibole and calc silicate minerals. Another litho-unit containing the mineralization is calc-quartz-biotite schist and/or calc-biotite amphibole schist with or without garnet and scapolite. Occurrence of wide spread, dusty and impregnated disseminations of bornite, chalcopyrite, covellite and specular hematite within various calcareous rocks, layer parallel pyrite and pyrrhotite mineralization, sulphide veins co-folded with the host lithology (observed in drill cores in Mahawa area) suggest the nature of primary mineralization to be of syngenetic in origin, as one of the modes of mineralization in the area. However, the significant proportion of the mineralization is observed as coarse grained aggregates and chunks associated with quartz and calcite veins. These veins are emplaced oblique to the banding, indicating the epigenetic/remobilized component of mineralization. The occurrence of coarse grained bornite and chalcopyrite in these veins suggest recrystallization. Besides the occurrence of mineralization associated with the calcareous rocks, carbonaceous phyllite and phyllite also found to be containing some layer parallel pyrite and pyrrhotite mineralization.

The mineralization is mostly associated with the hybrid type of rocks *i.e.* scapolite bearing amphibole marble intercalated with dolomitic marble, dolomitic marble with biotite partings, calc quartz biotite schist, calc quartz biotite schist with partings of amphibole marble and scapolite bearing amphibole marble with calc quartz biotite schist and calc silicate partings. This mixed kind of litho-package suggests that the mineralization is preferably localized along the zones of depositional facies variation. The sulphides were precipitated during the deposition of lithofacies. The coarsely crystalline nature of the sulphides and their association with amphibole, quartz and calcite veins indicate that a part of the mineralization is remobilized and relocated along the weak planes during the post depositional diagenetic/metamorphic and/or deformational activities. Occurrence of zeodes of quartz, associated with the mineralization, suggests hydrothermal epigenetic origin of the sulphide mineralization. Yet another feature observed from the drill cores, *i.e.* occurrence of foliation parallel stringers and veins of the sulphide co folded with the foliation suggests its origin to be syn to pre F_2 or D_2 deformation, in this area.

The restricted occurrence of silver in the Dokan, Baniwala ki Dhani and Kundla ki Dhani blocks, which are on the northern end of the belt and in the Toda Ramliyas block on the southern end of the mineralized belt and conspicuous absence of silver from the central and middle part of the belt, might indicate a typical basin configuration. It is known that silver goes preferably in to the lattice of chalcocite by its geochemical affinity, as chalcocite forms the earliest mineral in a sedimentary basin grading from deeper parts through chalcocite-bornite-chalcopyrite-pyrite-pyrrhotite and hematite in the last, towards the outer shallower parts of the basin. These blocks namely Baniwala ki Dhani, Dokan, Kundla ki Dhani in the north and Toda Ramliyas block in the southern end contain considerable amount of chalcocite meaning there by the Dokan and Baniwala ki Dhani and Kundla ki Dhani was the deepest part of the basin during the time of deposition, hence it is restricted to these three blocks. Similarly silver association is repeated in the Toda Ramliyas area which is the southernmost part of the Dokan-Dariba mineralized belt, where hypogene environment of mineralization has been suggested [16]. The enrichment in Chalcocite and occurrence of hematite bornite ex-solution in this area along with silver association suggest occurrence of a horse shoe type of structure where the southern and northern parts of the areas indicate deeper part of the basin having richer mineralization while the middle part/central part of the area is shallower part, where the mineralization is weaker. The mineralization beyond Toda Ramliyas is not seen in south, which appears to be truncated by the profuse pegmatite intrusion which has eaten away the already weak mineralization. These Pegmatites and Granites possibly have facilitated the induction of hypogene environment.

Hence the mineralization here in this entire area is syn sedimentary, which was remobilized and scavenged and relocated within the structurally favourable locales like brittle shear zones by the mineralizing fluids during the deformation. The epigenetic hydrothermal component of mineralization is represented by mineralized veins disposed oblique to the lithology and might have its source in the hydrothermal fluids derived from the granitic and pegmatite plutons present in the area, which is substantiated by EPMA studies also. The absence of deformation textures in ore minerals might point towards the syn to post D_2 deformation emplacement of the epigenetic component of the mineralization. The preferential occurrence of mineralized zones within the brittle ductile shear zones, which are sympathetic to the main NNE-SSW shear zone, disposed parallel to the axial zone of the major F_2 folds in the area, suggest structural control on mineralization. Hence the sulphide mineralization in the area is primarily lithologically controlled and has been re-concentrated in the present locales, during metamorphism and/or deformation and these mineralized zones are thin, parallel and disposed in en-echelon pattern within the axial zone to western limb of the major F_2 structures in the area.

3.3. Petrography of Host Rock Vis a Vis Mineralization

It has been observed that the mineralization in this belt is confined to the marly package, and by very nature of environment of deposition the marly package has facies variation, accordingly the host lithologies are also exhibiting a mixed kind of mineral composition of the rocks exposed in the area. These litho units include dolomite which has graded to marble at some places and is characterized by varying proportions of various impurities, which leads to the facies as *Tremolite bearing dolomite/marble*, *Amphibole bearing marble/dolomite*, *Biotite bearing Marble/dolomite and siliceous dolomite/marble. Similarly other predominant lithology*, *which is largely mineralized across all the blocks is the calcareous quartz biotite schist*, *which has been referred as calc QBS in the text at many* *places.* This QBS occurs with or without scapolite, and garnet. The thin laminas like partings of calcareous quartz biotite schist occur within dolomite. As one moves southward in this belt the calc silicate rock is also mineralized, where as in the blocks falling in the north within the mineralized belt calc silicate is almost barren.

The petrographic studies of a large number of thin sections of the various lithology intersected in boreholes, as well as from the surface has been done, here in the following section a summarized account of the observations and representative photomicrographs have been presented to represent the petrographic characteristics of the host lithology and their relation with the mineralization. It is recorded that there is a predominance of minerals like biotite, chlorite, actinolite and tremolite indicating upper green schist facies of metamorphism in general but isolated occurrence of garnet and hornblende in some cases indicates that the metamorphism touched the pressure temperature conditions of amphibolite faces, though not as uniform and wide spread. The host rocks are, coarse to medium grained in nature, and the sizeable portion of the rock, sometimes is purely composed of calcite and actinolite indicating profuse carbonate and amphibole venation in the area. The important lithology with reference to mineralization is marble/dolomite which contains nearly 10% to 15% and even more biotite, (**Figures 8(A)-(F)**) actinolite and tremolite (in various different localities) along with minor chlorite. Scapolite occurs associated with biotite rich marble bands (**Figure 8(E)**). The actinolite clusters are very common in the marble (**Figure 8(D)**). Secondary calcite in the form of veins and coarsely crystalline aggregate are also observed (**Figure 8(A)**). The feldspar, primarily the potash feldspar, mostly orthoclase depicting sericitization and containing profuse inclusions of quartz has been observed very commonly (**Figure 8(D)**). The principal minerals which occur in the quartz-biotite schist are quartz-biotite and feldspar (potash feldspar mostly orthoclase) and sub ordinate plagioclase of calcic type. The biotite occurs as primary grains showing preferred orientation and imparts schistosity to the rock (**Figures 9(A)-(G)**). The schistosity is generally poor except for the portions richer in biotite displaying well developed schistosity. Secondary biotite mostly occurs as cloudy grains, masking other optical features and lying oblique to the principal foliation, is observed (**Figure 8(F)**). The characteristics of various minerals which are often psedumorphed by sulphides are depicted in **Figures 9(A)-(F)** and **Figures 10(A)-(F)**. Quartz which is the next most important mineral occurs as equigranular to irregular in shape and displays saccrohidal texture and wavy extinction. Tourmaline occurs as accessory mineral with rounded to stub like porphyroblasts, irregularly distributed throughout the rock mass. Garnet and Scapolite also recorded from the Calc-QBS, having a large size range (**Figure 9(G)** & **Figure 9(A)**). Occurrence of preferred alignment of prismatic grains of opaques indicates syngenetic type of mineralization (**Figure 9(D)** & **Figure 10(C)**).

The opaques occupying the cleavage planes of hornblende and alignment of

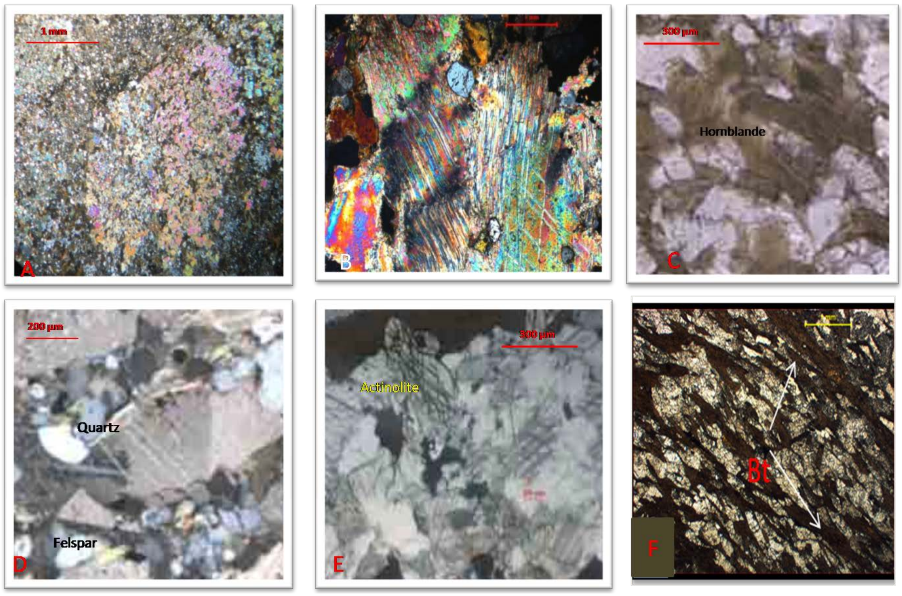


Figure 8. (A) Photomicrograph showing large porphyroblast of scapolite within the dolomitic marble (2.5×, XPL); (B) Folding of cleavage in calcite in dolomitic marble (CPL 5×); (C) Hornblande grains in calc-QBS (under PPL 10×). (D) Impure marble with feldspar and quartz grains (under CPL 10×); (E) Actinolite marble with opaque (under PPL 10×). (F) Photomicrograph exhibiting biotite defining the schistosity and lying oblique to it also suggests two generations of biotite primary and secondary. (5×, CPL).

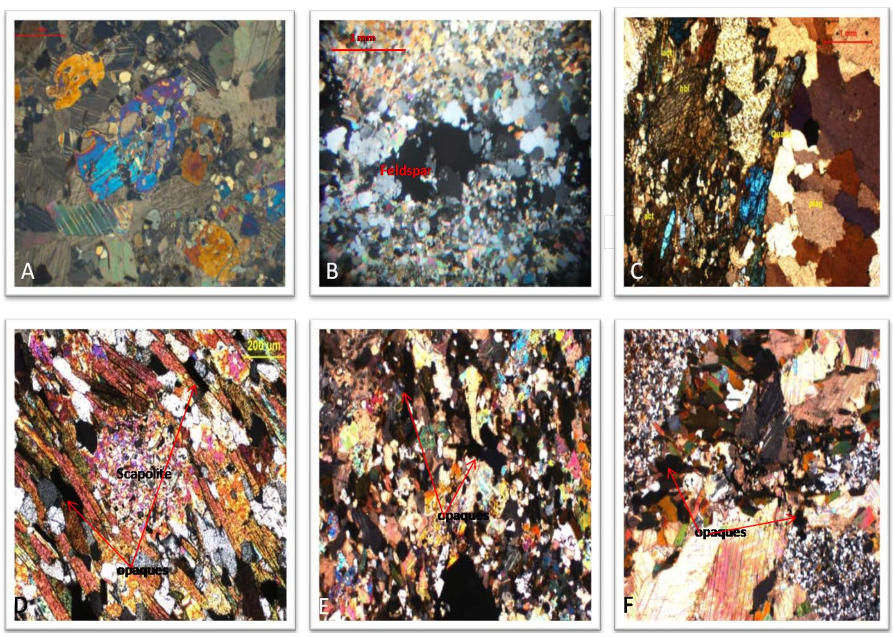


Figure 9. (A) Photomicrograph of scapolite with high interference colour within calcareous quartz biotite schist (CPL 5×) (B) Bimodal crystallinity of Quartz and feldspar in QBS also contain opaques. (under CPL). (C) Fine grained QBS with recrystallized quartz grains having irregular boundaries (under CPL5×). (D) Scapolite porphyroblasts in impure biotite amphibole rich dolomite, biotite books are defining schistosity and opaque are aligned parallel to it. (Under CPL 10×). (E) A crossed polar view of a thin mineralized quartz vein within the biotite rich semipelite and sericitised feldspar grains (CPL 10×). (F) Coarse grained calcite vein containing sulphides (black) within fine grained QBS (2.5×, CPL).

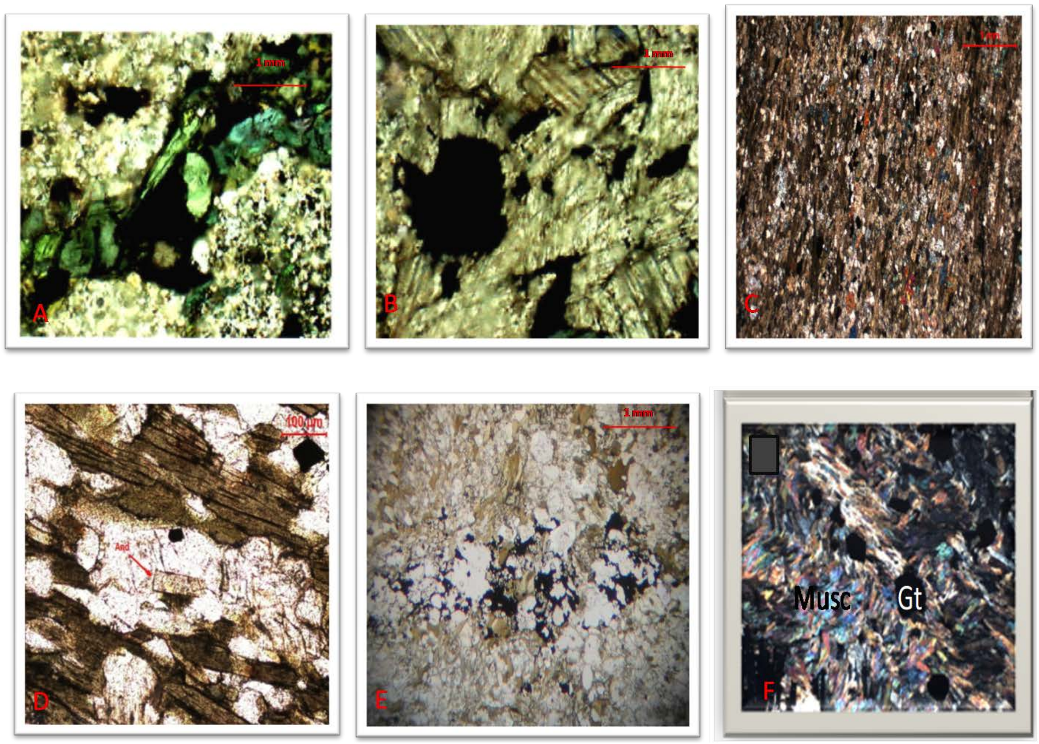


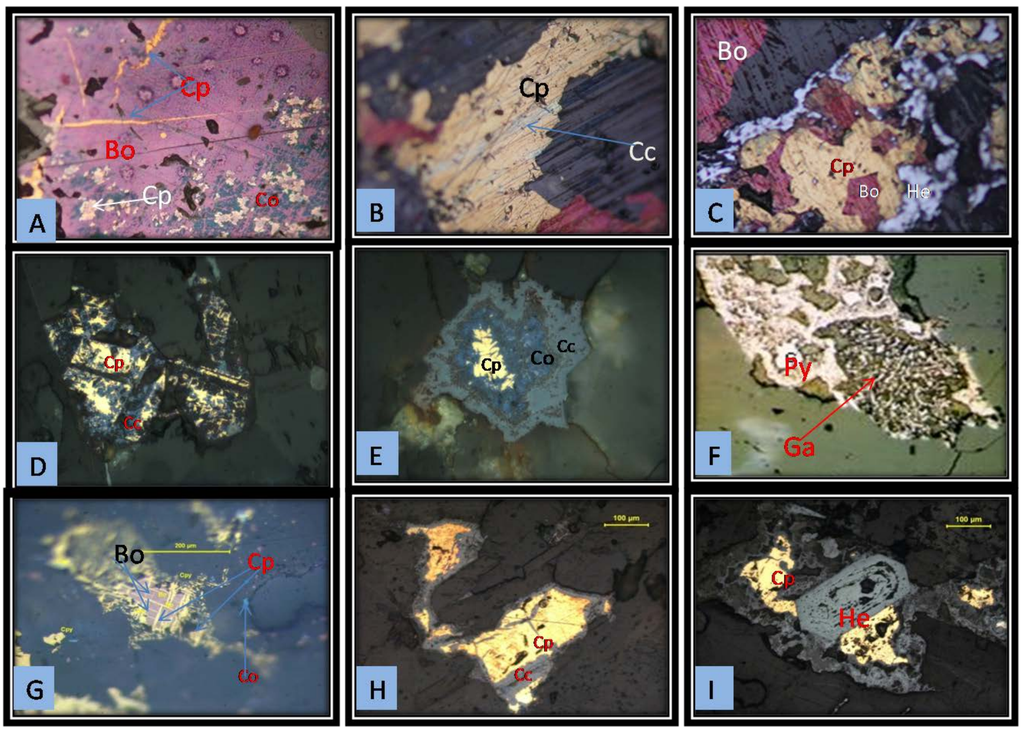
Figure 10. (A) Amphibole gangue pseudo morphed by opaque (Ore mineral) in QBS in Kundla Ki Dhani block (under PPL 20×). (B) Carbonate vein containing Sulphides (Opaques) Intruding Impure dolomite Dokan block (Under PPL 20×). (C) Fine grained biotite schist from Dhabala area depicting impregnated dissemination of sulphides as Opaque (under PPL 5×). (D) Epidote porphyroblast Calc QBS rich in amphibole. Northern extension of Toda Ramloyas block (Under PPL 10×). (E) Irregularly shaped opaque representing sulphide mineralization in quartz vein (Under PPL5×), Nanagwas block. (F) Crystallization of tiny garnet crystals along the crenulation axix in various schists. Toda Ramliyas extension block (Under PPL 5×).

the same along both the schistosity and vein fillings of sulphides healing the weak planes are suggestive of the epigenetic nature of mineralization (Figure 10(A) & Figure 10(E)). Occurrence of crenulation cleavage has been observed in micaceous rocks, in some of the cases the crenulation axis is very well demarcated by the crystallization of epidote, sericite and garnet along it (Figure 10(F)). Minute plagioclase grains are also noted from this litho unit. The calc silicate rock becomes important as it is mineralized in Toda Ramliyas and its northern extension blocks. This is coarse grained rock with well developed schistosity. The mineralization is mostly in the form of vein filling, with occasional clusters of sulphides. A litho unit similar to the calc silicate rock has been recorded from the Baniwala ki Dhani block which is a calcareous rock but at places contains nearly 10% to 20% amphibole and has been marked as amphibole marble is mineralized profusely in Baniwala ki Dhani block [48]. Besides amphibole the rock contains scapolite and other calc silicate minerals, plagioclase and secondary calcite. Such rock has not been repeated anywhere in the belt. The characteristics of calc silicate rock are depicted in Figure 9(A), Figure 9(C) & Figure 9(F).

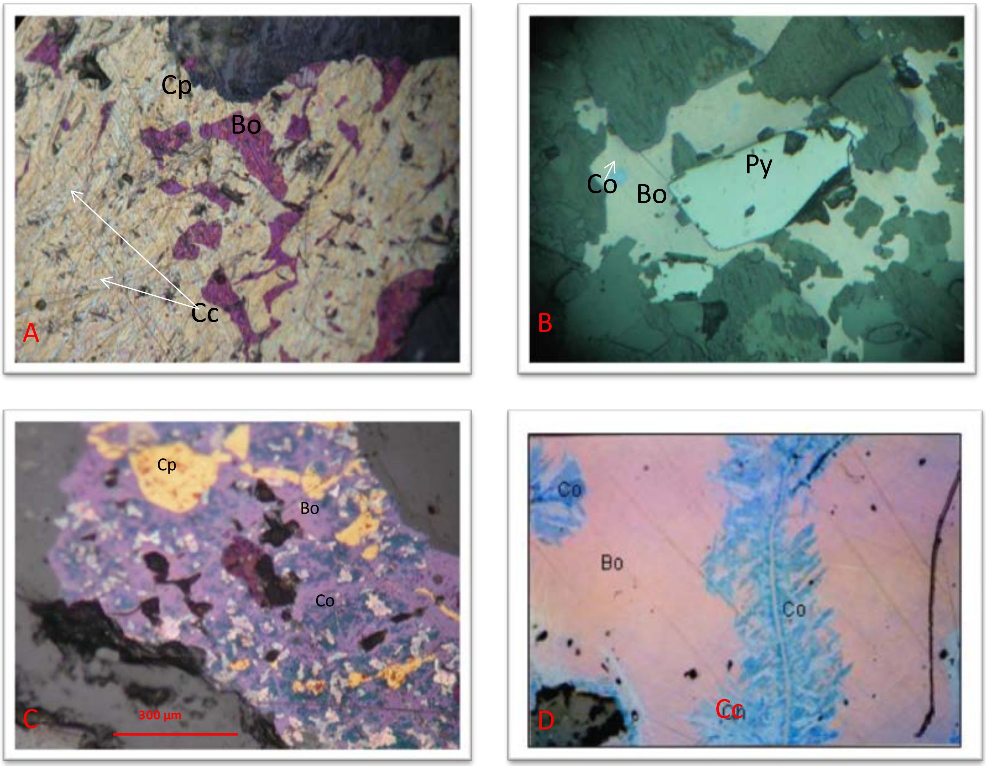
3.4. Petrography of Ore

Exhaustive petrography of the host rock as well as the ore lumps has been done in the entire belt under various blocks; the nature of mineralization as exhibited by ore petrography indicates nearly similar textures throughout the belt except some variations in the southern sector. Here a summarized account of the vast amount of observations made has been presented, taking all salient features from various blocks, to make the study and behaviour of the mineralizing fluids representative of the mineralized belt.

The ore petrography study depicts occurrence of bornite, chalcocite, diginite, covellite, chalcopyrite, cubanite, pyrrhotite, pyrite and specular-hematite, magnetite, besides the occasional grains of galena. The Allanite has also been reported from the area. The bornite occurs mostly in the form of large coarse grains with irregular boundaries in association with other sulphides, occurring as islands within the chalcopyrite and vice versa, suggesting reverse paragenesis (**Figure 11(ii)(A)**, & **Figure 11(ii)(C)**). The normal and reverse paragenesis is evident in the area suggesting towards the disruption of paragenesis during the post depositional remobilization of the ore fluids. It also occurs as bold grains adjacent to pyrite indicting eutectic crystallization (**Figure 11(ii)(B)**). Bornite has also been recorded being traversed by the veins of other minerals like chalcopyrite (**Figure 11(ii)(A)**. Bornite occurs in exsolution and intergrowth with chalcopyrite, (**Figure 11(i)(F)**) covellite, chalcocite and specular hematite. The intergrowth with hematite (**Figure 11(i)(C)**) suggests presence of hypogene environment of ore formation. The covellite by and large occurs mostly as alteration product,



(i)



(ii)

Figure 11. (i) Evidences of remobilization and replacement from Dokan and Dariba block, Sikar District Rajasthan; (A) Veins of chalcopyrite invading large porphyroblast of bornite indicating hydrothermal remobilization; (B) Chalcocite laminae along cleavage planes of chalcopyrite indicating replacement; (C) Islands of bornite within chalcopyrite which is rimmed by hematite; (D) Chalcopyrite being replaced by chalcocite along the crystal boundary and cleavage planes (PPL 10×) [34] (E) Typical Alteration sequence; chalcopyrite altering to covellite in turn to chalcocite; (F) Myrmekitic galena adjacent to pyrite from Nathuwala area; (G) Chalcopyrite lamellae along the cleavage planes of bornite, Ex-solution texture. covellite blebs also appear from gangue in the background; (H) Bold chalcopyrite porphyroblast rimed by chalocite indicating replacement of chalcopyrite. Photomicrographs under PPL, 20×, [34]; (I) Euhedral Hematite crystal having straight grain boundary with the chalcopyrite suggesting eutectic crystallization, also gangue lined along the growth rims of Hematite crystal. (ii) Various textures exhibited by bornite and chalcopyrite from different parts of the belt. (A) Islands of bornite within the chalcopyrite, suggesting early crystallization of bornite, chalcopyrite contains exsolved chalcocite. (B) Bold grain of pyrite adjacent to bornite suggesting simultaneous crystallization (Eutectic crystallization). (C) Islands of chalcopyrite within bornite suggests early crystallization of chalcopyrite. (D) Covellite and chalcocite along the cleavage planes of bornite, producing an alteration tree.

preferably confined to the cleavage plains of bornite (Figure 11(ii)(D), but incidences of independent grains of covellite have also been noted (Figure 11(i)(F). Chalcocite and covellite in some cases occur side by side as simultaneously crystallized grains. Pyrite and pyrrhotite showing normal and reverse paragenesis with bornite are observed, as islands of bornite within chalcopyrite and pyrite and islands of pyrrhotite and pyrite within large crystals of bornite are observed (Figure 11(i)(A) and Figure 11(ii)(C). In general the bornite grains are coarse and have irregular and straight grain boundaries with the other associated minerals. This indicates simultaneous crystallization, but veins of pyrite as well as that of bornite cross cutting each other are also observed. Chalcopyrite is also significant mineral which is associated with the other sulphides, though the relative abundance is less than bornite. Chalcopyrite grains generally become significant, when they are bold large porphyroblasts sharing straight grain boundaries with other sulphides and occur as fracture fillings. Besides this commonest mode of occurrences, the fine disseminations, stringers and streaks of the chalcopyrite-bornite are common mode of occurrence.

Remobilization evidences are beautifully depicted by hair thin veins of chalcopyrite originating from a larger grain and cutting across various other sulphide and gangue. (**Figure 11(ii)**) Healing of fractures in gangues and within the other sulphide minerals are also some of the abundant mode of disposition of the chalcopyrite ore bodies. Typical replacement textures depicting chalcopyrite altering to covellite to chalcocite is observed from the area (**Figure 11(i)(E)**) features like exsolution, and various replacements of minerals by each other are depicted in **Figures 11-15**. The effect of post depositional deformation is preserved in the form of fractures and occasional granulation of above all ore minerals. Most commonly exhibited texture is the cataclastic grains of pyrite and pyrrhotite (**Figures 16(B)-(D)**). Some deformed grains of pyrite and chalcopyrite have also been observed; never the less, evidences of significant post depositional deformation of ore are seen restricted to the above observations, in the entire belt. The predominant gangue minerals are biotite, epidote, hornblende, tremolite, actinolite, quartz, calcite and scapolite. Occurrence of short prismatic grains of pyrite and pyrrhotite aligned parallel to the foliation in the rocks of the area does point towards the syngeneic nature of the mineralization. Similar features have also been observed in the borehole cores in hand specimens, where the layered pyrite and pyrrhotite is co-folded with the foliation suggesting the syngeneic nature of mineralization. Contrary to that there are several incidences of the mineralization being in the form of fracture filling and vein filling cutting across the foliation indicating towards the epigenetic and or diagenetic nature of the mineralization in the area. Hence the area hosts the evidences of both the syngenetic as well as the epigenetic and diagenetic nature of mineralization. Most common textures observed are the intergrowth, exsolution and replacements.

Besides the above summarized and generalized characters of the ore under microscope from the belt, there are salient observations made regarding the variation in the behaviour of the ore minerals from north to south in the belt, which merit a mention here and can lead to significant contribution in the modeling for the genesis and localization of mineralization in the belt.

1) The predominant sulphide minerals found in the area and recorded during the ore petrography are; pyrite-pyrrhotite-bornite-diginite-chalcopyrite-covellite-chalcocite with occasional presence of galena. Hematite as prominent oxide phase with magnetite and Ilmenite.

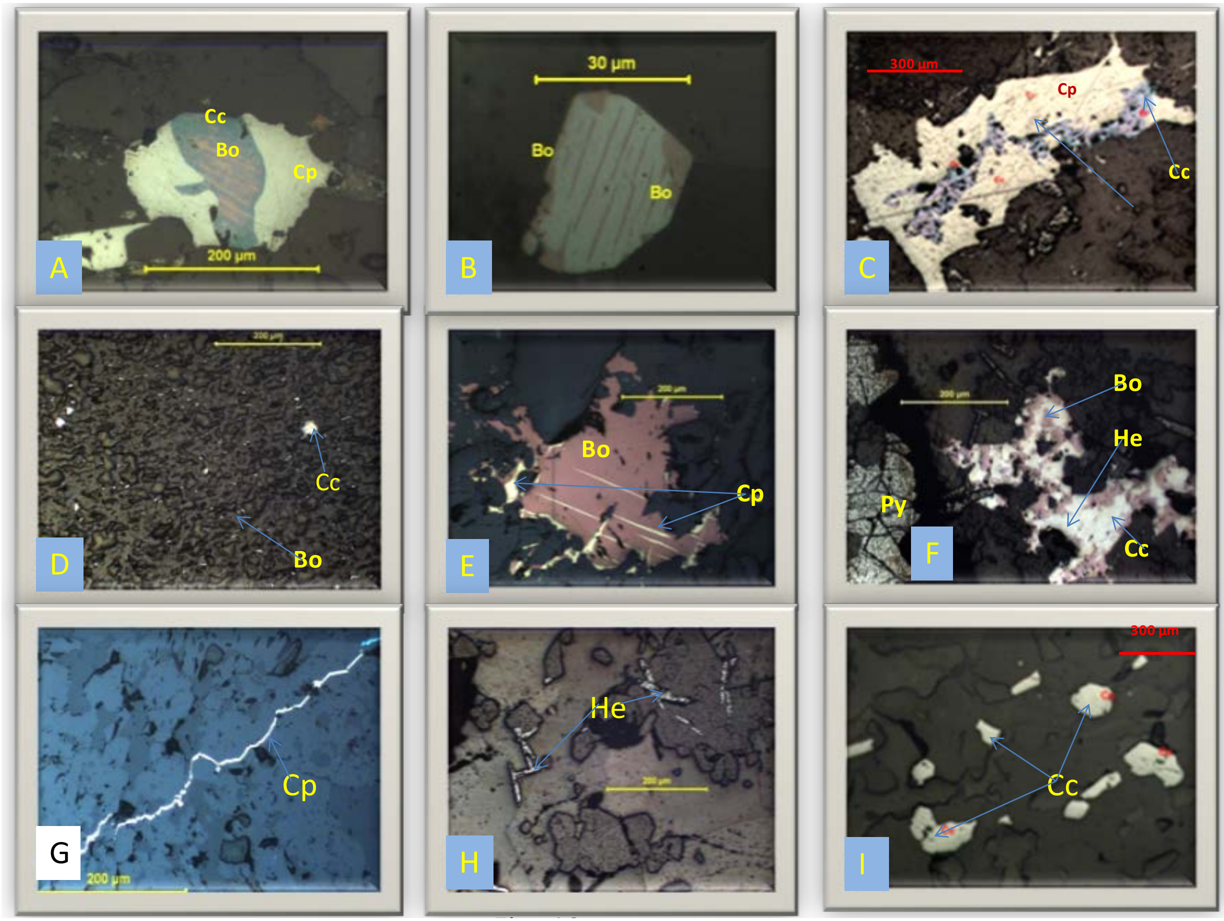
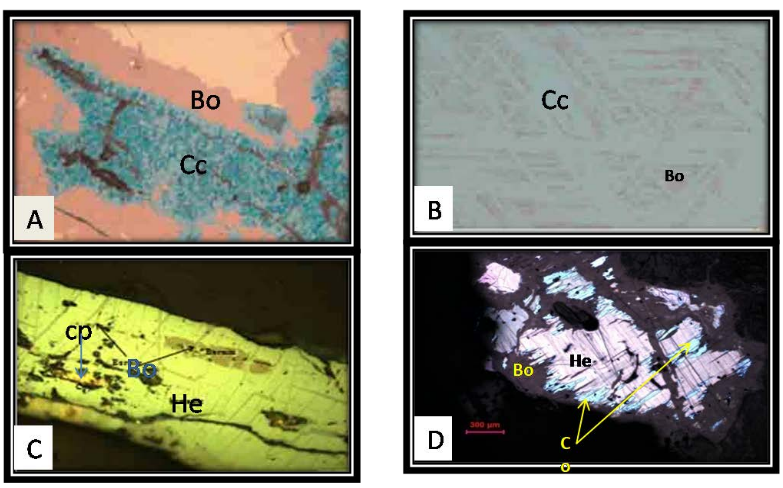


Figure 12. Replacement textures and other modes of occurrences of sulphides from various parts of belt. (A) Chalcocite (greyish blue and bornite shows unmixing (exsolution) along with simple intergrowth with chalcopyrite; (B) Bornite exsolved out of chalcocite, in lamelleas along cleavage planes. (C) Exsolution texture depicting bornite and chalcocite unmixing out of chalcopyrite. (D) Dusty disseminations of bornite and chalcocite, an indication of syngenetic nature of sulphides. (E) Chalcopyrite lamellae along bornite cleavage plane depicting perfect exsolution. (F) Bornite, chalcocite and specular hematite intergrowth with adjacent porphyroblasts of pyrite, depicting hypogene environment. (G) Chalcopyrite vein, pervading gangue indicates remobilization of sulphide mineralization. (H) laths of specular haematite scattered in groundmass/gangue. (I) Disseminations of independent grains of chalcocite in groundmass, yet again indication of hypogene environment.



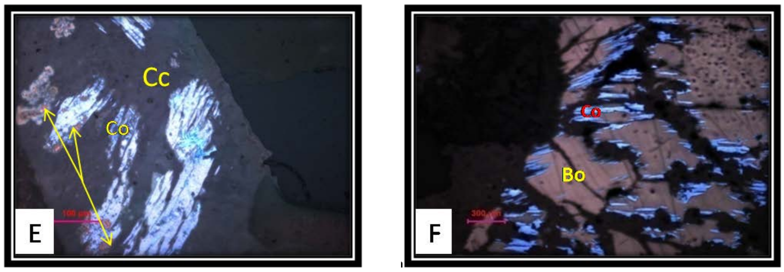


Figure 13. Various replacement textures exhibited by ore sections from the belt. (A) Subhedral chalcocite replacing bornite and being replaced by covellite (under PPL 50×) Dokan Baniwala ki Dhani; (B) Lamillar chalcocite replacing bornite (under PPL 50×) Dokan block; (C) Exsolution of chalcopyrite and bornite in hematite (under PPL 20×) indicating hypogene environment, TodaRamliyas block; (D) Replacement, mutually by each other; Bornite, covellite and specular hematite, indicating hypogene environment (PPL 20×); (E) & (F) Indicators of hypogene environment of mineralization (intergrowth and mutual replacement of bornite, covellite and specular hematite, by each other, Toda Ramliyas Block, [33].

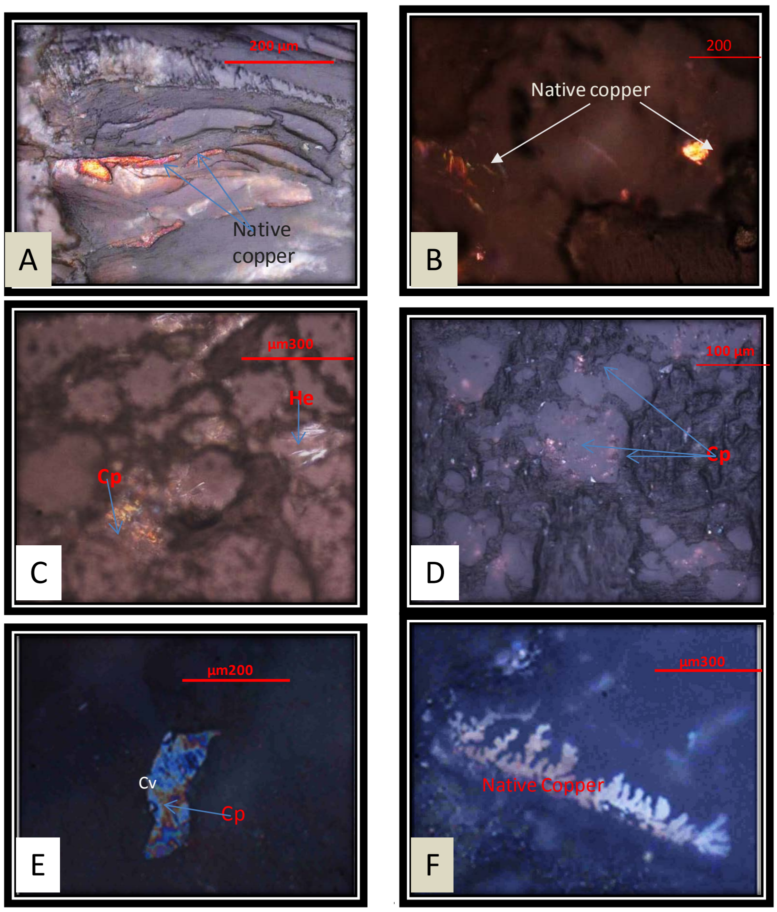


Figure 14. Various modes of occurrences of native copper in the belt, from Dariba block (All the photomicrographs are in PPL 20×), [52]. (A) Straek of native copper hosted within Quartz Amphibole vein. (B) Fine disseminations of native copper in dolomite. (C) Smears of chalcopyrite in dolomite. (D) Very fine/dusty disseminations of chalcopyrite in dolomite. (E) Near total replacement of chalcopyrite by covellite. (F) Dendritic, native copper indicating pressure solution conditions.

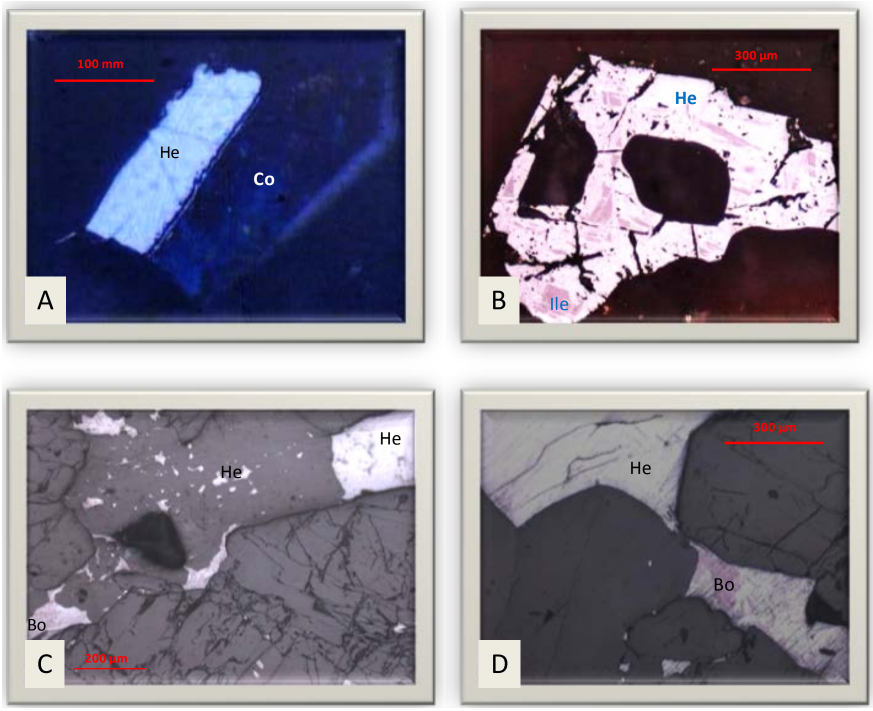


Figure 15. Various intergrowth and replacement features from Dariba area of the belt (all photomicrograph under PPL20×). (A) Sutured grain boundary of hematite indicating replacement by covellite. (B) Hematite ilmenite exsolution. (C) Vermicular and vispy Heamatite in gangue. (D) Wisps of hematite within ganung and large grains of hematite exhibing intergrowth with bornite.

2) The predominance of bornite over other sulphides, remains a common feature throughout the area, but within this setup there are certain variations, for example in Mahawa area/block the bornite and chalcopyrite are found in separate zones indicating a possible mineral zoning. The proportion of bornite is maximum once again in Baniwala ki Dhani-Dokan blocks, it still maintains pre-dominant in other blocks located within Dariba antiform and Dokan antiform but the proportion of chalcocite gains significance as one moves from north to south in the area, *i.e.* South of Dariba antiform. The chalcocite is predominant over bornite and chalocopyrite in the Toda Ramliyas and its adjacent blocks, while it is insignificant in Palaswala ki Dhani block, where chalcopyrite is the main ore mineral.

3) The occurrence of Galena in the form of Lead lode is restricted to the West of Nanagwas block, while lead values have also been recorded from Mahawa block and myrmekitic galena from Nathuwala area.

4) The association of silver is restricted to the Baniwala Ki Dhani [47] Dokan blocks only as Cu-Ag lodes, [48] while stray incidences of silver are also reported from the Panchokharkhara [49] [50] and Toda Ramliyas (N) blocks [51].

5) The occurrence of hematite as impregnated disseminations of prismatic grains in groundmass in the host rock have been seen throughout the area, but from the Dariba block further south the intergrowth of Hematite and Bornite

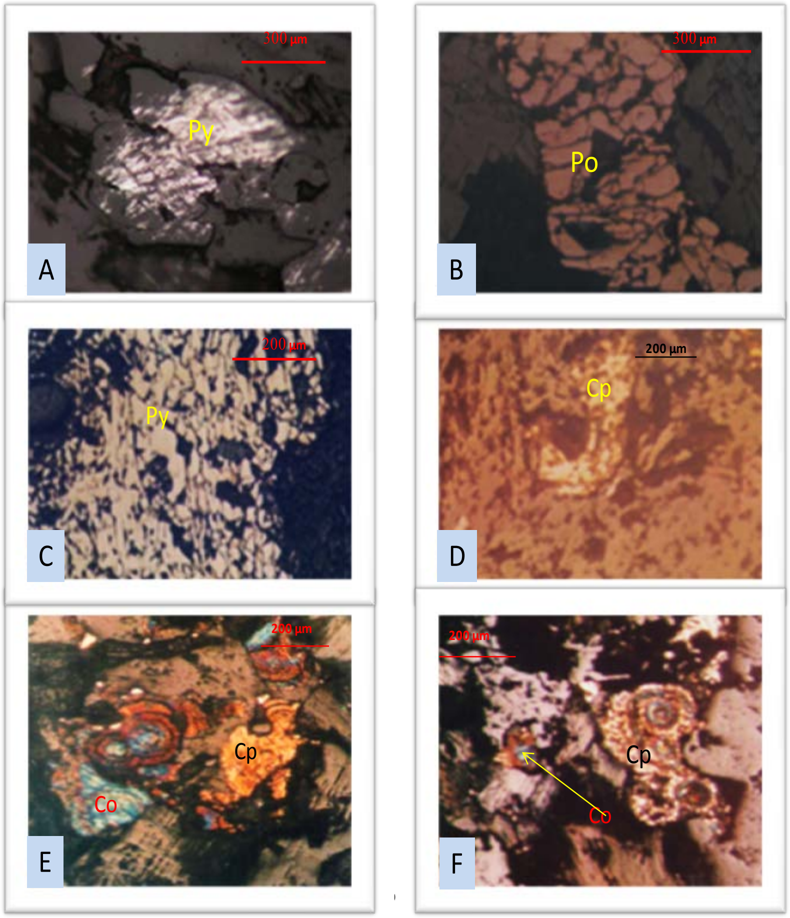


Figure 16. Post emplacement deformation textures and depositional environment indicators from Dariba block from the belt. (A) Feathery pyrite. (B) Cataclastic pyrrhotite. (C) Cataclastic pyrite. (D) Mildely deformed chalcopyrite grain. (E) & (F) Colloidal precipitates of copper sulphides indicating low temperature deposits. (Photos under PPL at 20×)

has become more significant. The intergrowth of hematite and bornite, predominance of chalcocite and occurrence of silver supported by presence of REE bearing minerals xenotime and allanite from southern sectors of the belt together suggest the establishment of hypogene environment of ore formation in this part during the emplacement of Plutons (Granites and pegmatites) syn to post D_2 deformation [16].

6) Though the plutonic intrusive activity is responsible for partial enrichment of the mineralization with depth in the southern most sector (observed in Toda Ramliyas block) of the belt, reflected in terms of marginally higher grade of Cu, yet the same intrusive phase is also responsible for termination of the mineralization further south, where it has disrupted the host litho-package and totally eaten out the mineralization at the expense of profuse pegmatite emplacement.

4. The Petrochemical Studies and Interpretations Thereof

The petrochemical studies including the Electron probe micro analysis, Fluid inclusion studies have been done for a large number of representative samples from all the three sectors from the mineralized zone and inferences regarding the genesis of the mineralization have been made.

4.1. EPMA Studies

The electron probe micro analysis studies of the ore sections from the belt have been carried out on CAMECA-SX-51 & CAMECA-SX-100 instrument at Geological Survey of India EPMA Lab Faridabad and Kolkata, over a period of two decades under different blocks and projects, here in the present paper only representative data has been presented. The EPMA results of Northern part of the belt including the Dokan Block, Baniwala-Kundla ki Dhani and that of west of Nanagwas Block have been discussed here. The studies have been carried out in Dariba and southern extension of Nanagwas Block also but that data does not show significant genetic signatures of sulphide or association of depositional environment indicator minerals. The southern sector encompassing Toda Ramliyas block and Northern extension of the same has some significant indications; these have been discussed here to arrive comprehensively at some genetic model. The analytical studies are carried out on the polished ore surfaces from Dokan, Kundla Ki Dhani and Dokan North blocks suggest large variation in the physicochemical conditions of crystallization of copper and silver associated with other sulphides. The detailed elemental composition of various sulphide ores are depicted in the Tables 2-5. The temperature of the minerals recorded in the electron probe studies indicate, derivation of some minerals from pegmatite on one hand, while other minerals suggest a normal epigenetic hydrothermal depositional

Table 2. Mineral chemistry of various phases of ore minerals recorded from Dokan North-Dokan and Kundla ki Dhani block, Sikar District Rajasthan (Observe the Silver association).

%	Cu-Ag-Pb sulphides			Bornite	Bornite	Bornite	Bornite	Bornite	Bornite	Bornite
Au	0.000	0.000	0.083	0.012	0.118	0.000	0.020	0.000	0.000	0.017
Pb	42.424	54.971	53.237	0.119	0.043	0.000	0.104	0.057	0.168	0.143
Sb	0.000	0.000	0.000	0.013	0.000	0.000	0.000	0.000	0.000	0.000
Ag	1.394	4.818	4.876	9.443	9.535	0.109	0.090	0.000	0.082	1.317
As	0.074	0.000	0.000	0.000	0.000	0.000	0.052	0.000	0.000	0.014
Ga	0.000	0.085	0.048	0.000	0.000	0.003	0.000	0.022	0.000	0.012
Zn	0.028	0.000	0.000	0.026	0.000	0.000	0.042	0.000	0.000	0.012
Cu	26.933	16.885	17.815	51.347	51.119	57.939	63.988	63.721	63.632	61.358
Ni	0.008	0.000	0.000	0.028	0.000	0.000	0.000	0.000	0.000	0.000
Co	0.033	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.026
Fe	9.326	4.193	6.149	7.294	7.520	11.141	10.897	10.830	10.877	11.367
S	19.722	15.854	15.999	21.884	21.906	23.787	25.217	24.840	25.759	26.457
Total	99.942	96.806	98.207	90.166	90.241	92.979	100.410	99.495	100.518	100.717

Table 3. Mineral chemistry of ore minerals from Dokan, North-Dokan and Kundla ki Dhani blocks, Sikar District Rajasthan Signifying hydrothermal environment.

%	Corrollite	Witchenite	Witchenite
Bi	0.000	13.642	12.882
Pb	0.048	0.038	0.000
Te	0.026	0.000	0.000
Au	0.004	0.021	0.000
Sb	0.000	0.009	0.000
Ag	0.040	0.540	0.498
Se	0.000	0.000	0.000
As	0.008	0.009	0.000
Ga	0.000	0.000	0.000
Zn	0.000	0.000	0.015
Cu	14.205	42.848	43.290
Ni	11.099	0.018	0.000
Co	17.810	0.000	0.047
Fe	1.194	0.398	0.953
S	55.566	42.476	42.315
Total	100.000	99.999	100.000

Table 4. Mineral chemistry of ore minerals from Dokan, North-Dokan and Kundla ki Dhani blocks, Sikar District, Rajasthan Signifying hydrothermal environment and Silver association.

%	Chalcopyrite	Aguilarite	Argentite	Argentite	Argentite	Parkerite	Parkerite	Parkerite
Fe	29.729	1.633	0.376	0.616	0.299	0.189	0.548	0.652
Co	0.000	0.000	0.010	0.000	0.000	0.008	0.000	0.000
Ni	0.037	0.000	0.026	0.017	0.047	26.005	26.036	25.720
Cu	35.264	0.324	0.382	0.548	0.219	0.792	1.540	2.430
Zn	0.014	0.025	0.000	0.024	0.000	0.024	0.011	0.049
Ga	0.000	0.000	0.010	0.027	0.000	0.000	0.000	0.000
As	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Se	0.000	19.399	0.000	0.000	0.000	0.000	0.000	0.000
Ag	0.084	73.519	82.413	80.456	82.831	0.008	0.000	0.000
Sb	0.000	0.000	0.000	0.000	0.000	0.056	0.093	0.052
Te	0.000	0.090	0.093	0.000	0.057	0.000	0.000	0.000
Pb	0.110	0.025	0.000	0.000	0.031	0.093	0.060	0.000
Au	0.000	0.000	0.024	0.000	0.000	0.103	0.034	0.000
S	33.529	10.361	11.163	10.070	11.858	8.943	9.110	9.477
Bi	0.000	0.000	0.010	0.000	0.000	62.627	61.453	60.523
Total	98.784	105.376	94.507	91.758	95.342	98.848	98.885	98.903

Table 5. Mineral chemistry of ore minerals from Dokan North-Dokan and Kundla ki Dhani block, Sikar District, Rajasthan Indicating natural affinity of Silver with bornite.

%	Copper Metal			Chalcocite		Chalcopyrite		Bornite	Bornite	Bornite	Bornite	Bornite
Au	0.013	0.000	0.119	0.036	0.000	0.092	0.000	0.000	0.000	0.007	0.000	0.000
Pb	0.000	0.000	0.006	0.075	0.079	0.128	0.190	0.046	0.012	0.0127	0.046	0.012
Sb	0.000	0.002	0.030	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ag	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.068	0.954	0.863	0.682	0.954
As	0.000	0.000	0.000	0.010	0.030	0.077	0.000	0.023	0.000	0.017	0.023	0.000
Ga	0.000	0.000	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Zn	0.058	0.050	0.023	0.011	0.032	0.000	0.016	0.000	0.000	0.000	0.000	0.000
Cu	96.370	95.124	93.172	78.807	75.161	34.666	34.441	62.087	61.110	60.910	62.087	61.110
Ni	0.000	0.000	0.001	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.000	0.000
Co	0.000	0.000	0.000	0.000	0.000	0.040	0.022	0.010	0.008	0.000	0.010	0.006
Fe	2.416	2.778	1.634	1.046	4.915	29.378	29.326	11.108	10.957	11.187	11.108	10.957
S	0.124	0.125	1.365	19.867	18.461	34.432	34.139	25.279	25.121	26.569	26.279	26.121
Total	98.981	98.158	96.350	99.853	98.678	98.824	96.237	100.235	99.162	99.680	100.235	99.162

environment. Some of the sulphide minerals are observed to occupy the lattice of the bornite at high temperature besides silver. These minerals having minor occurrences mostly occur as exsolution, hydrothermal veins and vermicular wisps in the bornite. Silver is most commonly associated with the chalcocite, (Figure 17) occurs as native grains but also found to be associated with many sulphides including ***wittichenite, parkerite, aguilarite and carrollite*** (Figure 18).

The electron probe studies from the area have recorded some of the sulphide minerals for the first time, besides, identifying various associations of known minerals. The sulphides include bornite, chalcopyrite, chalcocite, covellite, galena, parkerite, wittichenite, carrollite, aguilarite, enargite and argentite besides, Ag-Cu sulphides, Ag-Cu-Bi sulphides and Ag-Cu-Fe sulphides (Figure 18). The above associations of sulphides and silver call for the existence of many geochemical systems operating together during the process of sulphides precipitation and emplacement in this belt. The geochemical systems operating during the process are Copper-Sulphur system, which has produced principally covellite and chalcocite. Another important system is Copper-Iron-Sulphur system producing the Bornite-Chalcopyrite-Pyrite minerals. These are the crystallization systems which have controlled the bulk of the sulphide mineralization in the belt, but there are small and less common but important geochemical systems operated in various parts of the belt are Nickel-Bismuth-Sulphur system, Cobalt-Nickel-Silver system, Copper-Bismuth-Silver system, Copper-Cobalt-Sulphur system, besides, native silver has also been found in the probe (Figure 18 & Figure 19). It could be observed with confidence that besides the above mentioned various geochemical systems, there has been large scale substitution of various elements in different proportions which has allowed the crystallization of various

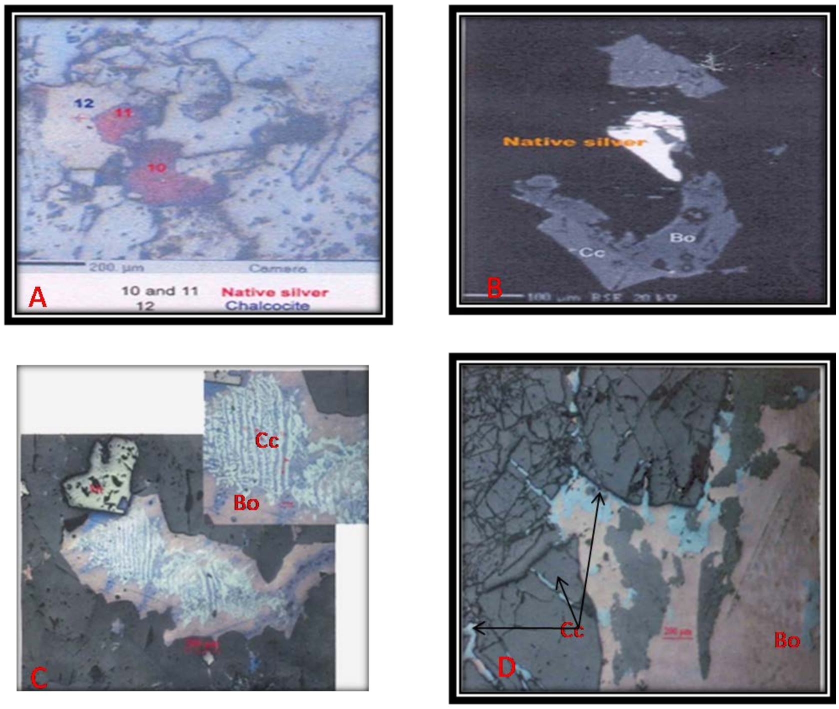


Figure 17. EPMA studies of ore from Baniwala Ki Dhani [53], from the belt. Indicating association of silver with chalcocite and bornite. (A) BSE images of association of silver with chalcocite. (B) Bornite from Baniwala Ki Dhani area, adjacent native silver grain. (C) Bornite-chalcocite myrmikitic intergrowth indicating simultaneous crystallisation. (D) Bornite-chalcocite veins pervading the gaunge indicating remobilization.

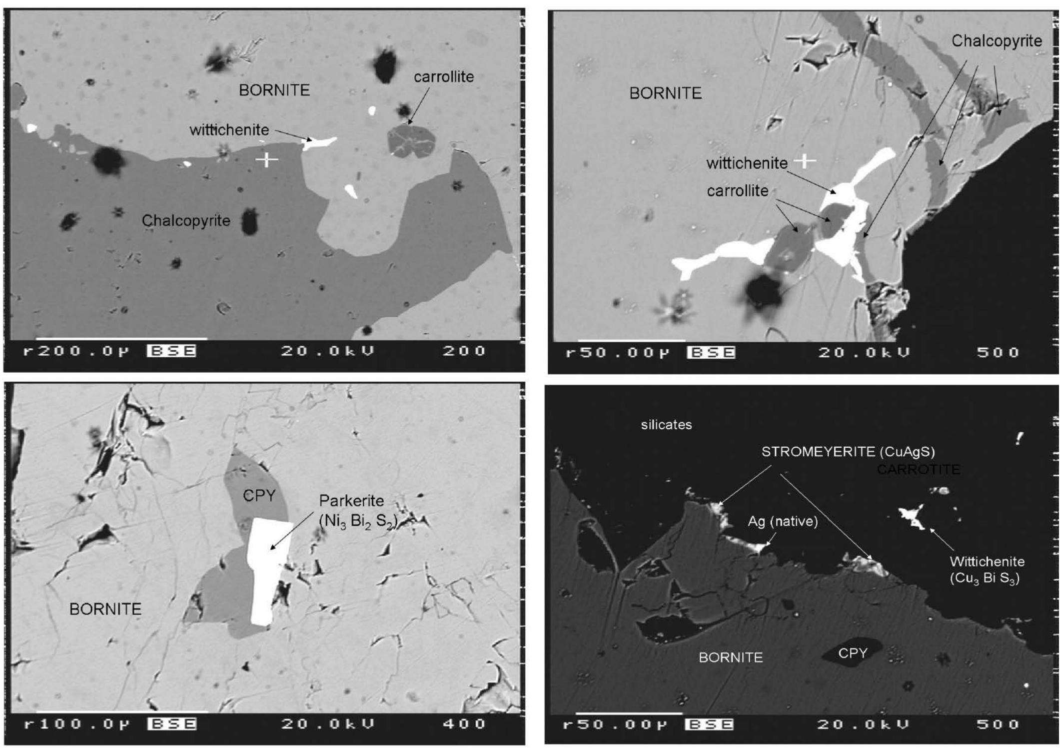


Figure 18. BSE Images of sulphide minerals from Dokan-Dokan North & Kundla ki Dhani block. Sikar District, Rajasthan [14].

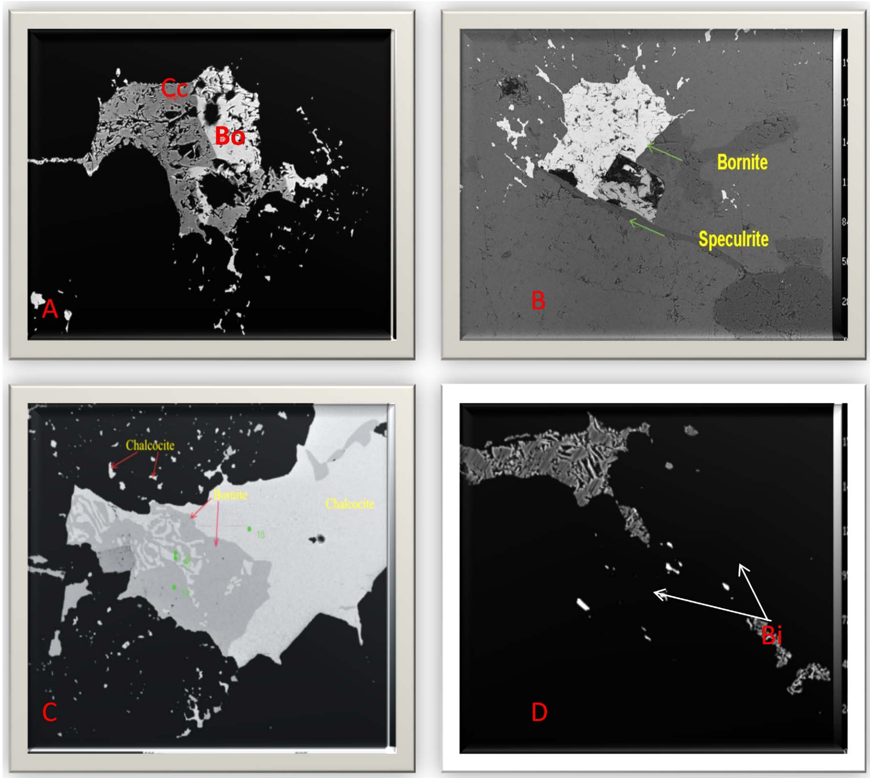


Figure 19. BSE of replacements and intergrowths from Nanagwas block, from the belt. (A) Back scattered image (BSE) showing replacement of bornite by chalcocite. (B) Inter growth of specular hematite and Bornite suggesting hypogene environment. (C) Bornite-chalcocite replacement texture. (D) Native bismuth and ilemanite disseminations suggesting high temperature environment.

minerals, which are not generally in equilibrium with the common systems controlling the bulk of the mineralization. The common solid solutions and intermediate solid solutions (*iss*) allow a limited substitution of the element in equilibrium at various temperatures as in a copper-iron system, only 3 atom % of copper in pyrrhotite is permitted at 700˚C [54] [55], similarly the highest content of copper in pyrite can occur at lower temperature than at higher temperature [56]. The presence of Zn in Copper-Iron-Sulphur system can significantly alter the phase relations at high temperature, but at low temperature zinc will exsolve as sphalerite. The solid solution with ZnS, so stabilizes the *iss* that chalcopyrite becomes incompatible with the sphalerite just below 500˚C [57]. The geochemical system Copper-Iron-Nickel-Sulphur is very important for the magmatic segregation deposits, but not so important for the hydrothermal deposits, occurrence of copper, nickel, cobalt and sulphides of selenium in combination with copper and silver suggest the presence of either hydrothermal or high temperature metamorphic environment of formation of such minerals. The silver is hosted in pentlandite due to stability of its structure having the composition Iron-Nickel-Silver sulphide and Argentinean pentlandite is the principal host of silver in many magmatic deposits [58]. But, in the present case the silver metal is exsolved from bornite and occurs in the various combinations of copper sulphur system of crystallization suggests that the bulk of the present mineralization is not a magmatic segregation deposit. However, the occurrences of other minerals like Wittichenite which crystallizes at 527˚C (high variety) and 290˚C (low variety) in the form of hydrothermal veins in association with other Bismuth minerals. Aguilarite, Argentite, Parkerite and Carrollite do indicate the presence of hydrothermal environment of deposition having a varied temperature range. Carrollite crystallizes in Copper-Cobalt-Sulphur system and is found to occur in association with chalcocite, covellite, bornite, tetrahedrite, chalcopyrite and digenite, besides pyrite, sphalerite and calcite. It has been found that carrollite co-exists with chalcocite at 500˚C and is more copper rich. Parkerite mostly found in Nickel-Bismuth-Sulphide system associated to pegmatite or marginally magmatic nickel ferrous Pyrrhotite, where it is associated with the pentlandite, chalcopyrite, cubanite and galena and bismuth telluride. Argentite occurs as epigenetic veins near surface in association with galena, sphalerite, pyrite, chalcopyrite and native silver in hypogene process. Aguilarite, predominantly silver selenium sulphides with minor Cu and Pb are low temperature hydrothermal mineral and occurs associated with the copper-sulphur geochemical system indicates the substitution of Ag by Cu as well as by Pb in a hydrothermal environment. The principal combinations and associations of mineral phases in the northern sector, based on petrography and electron probe study combined can be summed up as:

Pyrite-pyrrhotite:	Major phase
Bornite:	Major phase in the form of veins and recrystallized large porphyroblasts
Bornite-Chalcopyrite:	In intergrowths and islands of each other mutually
Bornite-Covellite-Chalcocite:	As alteration along the cleavage planes of bornite and as exsolution

Parkerite and Carrollite, Aguilarite, Wittichenite, Argentite and other minerals could only be identified as blebs and fresh fills within the bornite and as thin hydrothermal veins traversing the bornite porphyroblasts so also native silver shows exsolved nature from bornite and chalcocite by electron probe. Besides these sulphides, oxides like Magnetite and Specular Haematite also have been observed from the area. These occur as intergrowths with bornite.

The electron probe analysis of the samples from the West of Nanagwas block indicates peculiar and uncommon intergrowth of sulphide and oxide where a bornite grain contains a lath of a euhedral shaped specularite (Hematite) (**Figure 19(B)**). Similar intergrowth has been noticed from the Dariba and Toda Ramliyas block even under ore petrography. This intergrowth may be attributed to **hypogene formation in an oxidizing environment** [57] Hematite, ilmenite (**Figure 15(B)**), a native bismuth grain has also been observed in the BSE images of a sample from the southern part of the block. The association of ilemenite is significant as it is a geologic thermometer and indicates the deposit touched at least 500˚C temperature during its formation [57]. The geochemical systems operating during the process are Copper-Sulphur system, which has produced principally covellite and chalcocite, another important system is Copper-Iron-Sulphur system producing the Bornite-Chalcopyrite-Pyrite minerals. It is observed that the bornite of Dokan block appears enriched in iron which ranges between 10.1% to 11.1%, in comparison to bornite analysis from Nanagwas block, which has a larger range from 5.30% to 11.5%. Titanium association with bornite is reported from Nanagwas area [60] [61]. The points with high bismuth values show anomalous values of tin also.

The EPMA study of sulphides from Dariba north which forms part of the Central sector located within the main antiform structure; the Dariba antiform indicates that sulphides are present in the form of fine to very fine disseminations. The ore minerals such as chalcopyrite, chalcocite and bornite occur as fine disseminations and at most of the sections studied indicate chalcocite, bornite replacement [62]. The rhombic, cubic shaped pyrite shows sieved texture. Sphalerite and galena show close association with the chalcopyrite. Thin slender grains of magnetite occur as discrete grains within the matrix of biotite.

The electron probe analysis of the samples from the southern sector; Toda Ramliyas block and its extension comprising the southern sector of the belt, have been carried out for selected core samples collected from different depths. The elements analyzed are Fe, Co, Cu, Zn, Ag, Bi, Au and S. The copper mineralization in Toda-Ramliyas block [33] occurs not only in the form of fine disseminations of Chalcocite, Bornite, Chalcopyrite and occasional Chalcocite but also along the secondary quartz & calcite vein. The samples show replacement texture exhibiting replacement of bornite by chalcocite (**Figure 20**). A good association of chalcocite and bornite has been noted almost in all samples. One yttrium (Y)-bearing phosphate phase (Xenotime) has been identified in one sample in association with chalcocite and bornite. Xenotime is a rare-earth phosphate mineral, the major component of which is yttrium ortho-phosphate (YPO_4). Fine disseminated magnetite also identified along with the other sulphide minerals. Intergrowth of sulphide and oxide has been observed, here also like Nanagwas and Dariba (Bornite-Hematite intergrowth).This intergrowth may be attributed to hypogene formation in an oxidizing environment [57]. A very good intergrowth texture of bornite and chalcocite has also been identified in a sample. Besides magnetite, ilmenite, native silver (Ag), Grains of galena (PBS) have been noticed in the samples, Bismuth (Bi) phase also identified An allanite grain in BSE image and by wavelength-dispersive-spectrometry (WDS) has been identified in (**Figures 20(A)-(D)**). Allanite is a sorosilicate group of minerals within the broader epidote group that contains a significant amount of rare-earth elements. The above associations of sulphides indicate the existence of more than one geochemical systems operating together during the process of sulphides precipitation/emplacement. The chalcocite occurs here in two different modes; one as alteration product of bornite and second as independent bold

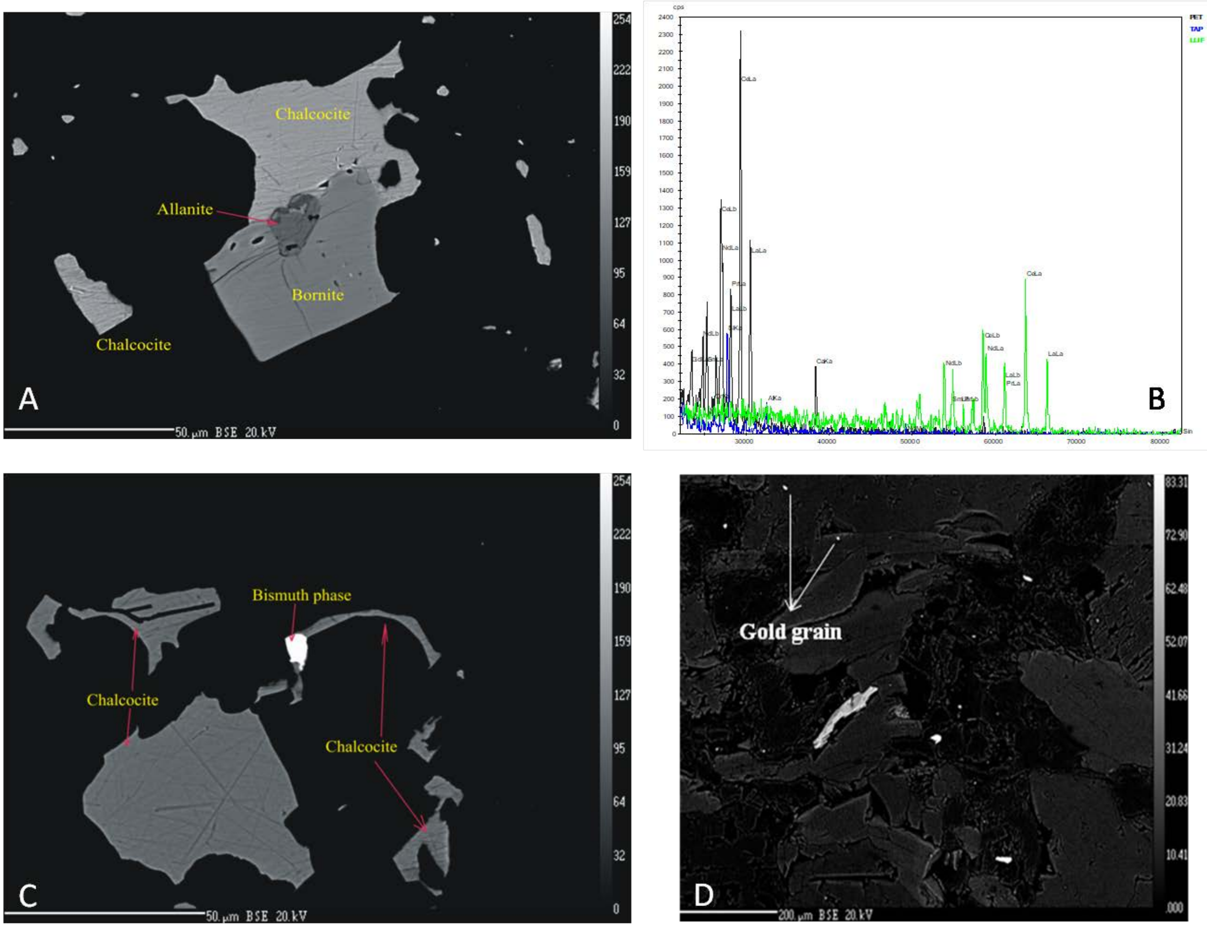


Figure 20. (A) BSE Images exhibiting associations of sulphide and Allanite from Toda Ramliyas block. (B) Wave-length-Dispersive-Spectrometry (WDS) showing allanite which contains rare-earth elements [33]. (C) Back scattered image (BSE) showing Bismuth (Bi) phase in association with chalcocite [33]. (D) BSE Image of Galena also indicating tiny Gold grains in the Gangue Nanagwas area [59].

grains occurring separately. Such independent grains might suggest hypogene origin of chalcocite apart from chalcocite as alteration product of bornite.

The various geochemical systems discussed and mentioned above have their specific temperature stability range and these stability fields of various minerals decide the exsolution and iss. Here the mineral having the largest stability range in terms of temperature is bornite as well as pyrrhotite. Besides this Ilmenite also determines the temperature range as it is completely miscible with hematite above 600˚C temperature while separates out at 500˚C, [57]. The pyrrhotite and pyrite are inter-convertible at various temperatures; hence they occur associated to bornite and chalcopyrite both and do not actually signify any particular temperature range for the deposit where they are occurring. But the occurrence of Aguilarite, defines the lower temperature range at 133˚C, while the upper range as indicated by the presence of wittichenite, which requires a temperature of about 570˚C. Hence, the sulphide mineralization has been deposited between 133˚C and 570˚C temperature, as deduced from the electron probe studies of sulphides from the belt.

4.2. Fluid Inclusion Studies

Fluid inclusion studies can define the temperature and pressure conditions of the emplacement of ore fluids besides indicating the nature of the fluid which helps indirectly to infer as what could have been the source of the fluids causing mineralization. Such studies have been carried out in various blocks of the mineralized belt. The significant observations have only been made in two blocks namely Baniwala ki Dhani block which could be taken as representative for the other three blocks including the Dokan north block, Dokan block and Kundla ki Dhani block, because the nature of mineralization, correlation of sulphide zones as well as copper lode is achieved with the high degree of similarity in these four blocks. Another significant block where fluid inclusion studies have been carried out is the West of Nanagwas block which is confined to an independent mesoscopic structure and mineralized lodes do not lie in the exact strike continuity of the other four blocks has been discussed here. However it forms part of the Northern sector.

Fluid Inclusion studies have been carried out in Central Petrological laboratories, Geological Survey of India, Kolkata using Leica DMLP (TMS 94), GSI for micro thermometry studies of samples and temperature was controlled with the Linksys software.

Total 22 samples were collected both from mineralized and non-mineralized part of cores of different boreholes of West of Nanagwas area. Thin wafers were prepared at Petrological lab, WR, Jaipur. 22 samples have been studied and out of 22 samples workable inclusions have been found only in 4 samples. The inclusions observed in the samples are both primary and secondary mono-phase & bi-phase. Carbonic inclusions are dominantly mono-phase although few bi-phase carbonic inclusions have also been noticed. Secondary inclusions are smaller which show rounded, sub-rounded and faceted shapes and have been seen along healed fractures in linear fashion. Trails of very fine inclusions also are observed. Primary bi-phase inclusions are too small to use. The size of the vapour phase in the form of bubble ranges in size from 0.070 to 1.887 µm. The size of workable bi-phase aqueous-vapour inclusions varies from 4.2 µm to 11.15 µm. Observation after Micro thermometry of Bi-phase aqueous-vapour inclusions [63] [64].

Te which is the initial melting temperature ranges from 20.2˚C to −31.2˚C with an average of −25.7˚C which indicates presence of NaCl ± KCl salt in the fluid inclusion assemblage and it has also been observed that the major dissolved component in the aqueous phase is NaCl and attributes to a compositional system of $NaCl\text{-}H_2O \pm KCl$ for the fluids.

T_{fice} which is the final ice melting temperatures of the aqueous phase in these inclusions vary between −0.2˚C and −2.9˚C with an average value of −1.5˚C simply indicates that the fluid is marginally saline.

T_h (homogenization temperature): Three different sets of range of homogenization temperature (T_h) of the aqueous vapour rich fluid inclusions have been found:

1st set - 134.8˚C to 150.5˚C (average 142.65˚C).

2nd set - 169.8˚C to 182.3˚C (average 176.05˚C).

3rd set - 205.6˚C to 220.1˚C (average 212.8˚C).

Salinity is 0.33 to 4.54 wt% NaCl equivalent (average 2.435 wt% NaCl equivalent).

Density of the inclusions varies from 0.86 to 0.96 g/cm^3.

Observation after Micro thermometry of Biphase aqueous-vapour inclusions: Carbonic inclusions are most likely heterogeneously trapped inclusions and that's why they do not homogenize at the same temperature as the aqueous inclusions. The melting temperature of CO_2 ranges from −57.1˚C to −58.2˚C and the maximum depression of melting temperature of CO_2 is −58.2˚C which indicates the fluid contains only CO_2. These aqueous carbonic inclusions homogenized between −6.8.7˚C to 9.7˚C into liquid CO_2 phase. The fluid pressures vary from 1.9 kbar to 2.5 kbar.

The temperature of homogenization vs. salinity plot of aqueous-vapour fluid inclusion suggests **mixing between "main fluid" and cooler fluids/heated meteoric water possibly of same salinity.** Hence, it may be concluded that the high temperature populations of isochore (205.6˚C to 220.1˚C) main fluid when this fluid enters into the host rock, because of pressure reduction the fluid starts boiling which is indicated by 169.8˚C to 182.3˚C isochore. 134.8˚C to 150.5˚C isochore indicates mixing of cooler fluids/heated meteoric water possibly of same salinity with the main fluid.

The studies were carried out from Baniwalaki Dhani, [53] by collecting a large number of samples from various depths and various modes of sulphide occurrence. Their findings are as follows from the northern part of the belt in Baniwala ki Dhani block.

1) The moderate to high saline gas poor fluids were responsible for Cu-Ag mineralization in the area.

2) The homogenization temperature ranged between 130˚C to 375˚C with average temperature of entrapment being 250˚C to 300˚C.

3) The fluids were emplaced at a pressure of 1.7 Kb and exhibit a mixing with the slight cooler fluids during emplacement.

4) The ore textures and sulphide phases however are indicative of entrapment temperature of the order of 500˚C, indicates extraneous heat source probably a granitic intrusion.

While comparing the fluid inclusion data of both the blocks following observations/interpretations can be made.

1) There is difference in the range of temperature of entrapment/homogenization, the elevated temperature in Baniwala could be due to the fact that there might have been more epigenetic component of mineralization at the expanse of some pegmatitic intrusions, as the association of Molybdnite has been noticed only from Baniwala ki Dhani block.

2) There is marginal difference in salinity of the fluids in both the blocks. The

Baniwala ki Dhani fluid studies point towards a moderate to high saline fluid, while the Nanagwas area fluids suggest only marginally saline fluids. This again either can be due to the fact that the population studied in case of Nanagwas is only secondary inclusions suggesting there by that it represents only a subordinate event may be associated with the deformation and not exactly with the entrapment of fluid or these two blocks have mineralization emplaced at different stage of deformation.

3) Besides these two anomalies the average fluid entrapment temperature appears to be the same in both the blocks which is 130˚C to 220˚C and non-isothermal mixing of hot aqueous fluid with cooler fluid has been recorded in both the cases.

4) The above situation/anomalies could be explained by convective hydrotherms which is a rule rather than exception in the strata-bound deposits. The fact that silver is restricted to the Baniwala-Dokan area supports this observation, as the comparatively higher gradient of temperature in the deeper part will facilitate deposition of silver in association with chalcocite as per the paragenitic sequence of deposition of sulphides in a sedimentary basin, which goes Chalcocite-bornite-chalcopyrite-Pyrite/Pyrrhotite and Hematite from the deeper parts outward.

5. Conclusion and Discussions

The Proterozoic rocks of Ajabgarh group of Delhi Super group, are exposed in Dokan-Dariba copper belt, are characteristically marly in nature. The sediments pertaining to the Dokan-Dariba belt were deposited in the intra-cratonic long furrowed basin developed after the Aravalli orogeny [29]. The biotite rich basement granitic rocks, which acted as provenance for the deposition of the calcareous sediments with profuse biotite component, facilitated deposition of the sulphides in the country rock. As suggested by the experiments of [63] [64], the elements such as Fe, Zn, Cd, Cu and Mn are strongly partitioned into chloride rich hydrothermal fluids. These elements are leached out of the rock forming minerals from the host and enter the fluid phase. It is observed that a litho-some containing hornblende, chlorite, biotite and feldspar would also contain substantial metallic content. For example it is estimated that a biotite + hornblende + chlorite may contain up to 50% of Cu in a Granodiorite associated to a porphyry copper mineralization [65]. The setting up of convective hydrotherms due to thermal gradient in the brines, resulted in the leaching of the sulphides and precipitation of the same in favourable locales due to change in the Eh and Ph conditions of the brines, at the expense of prevailing eu-exogenic environment and reduction of the biogenic components in the restricted shallow basins, supporting partial lagoonal marine environment exhibited by occurrence of orbicular sulphides and scapolite. The sulphides in a basin get deposited in the order chalcocite-bornite-chalcopyrite-pyrite-magnetite, from deeper to shallower and from centre towards margin of the basin. The restricted occurrence of silver in the Baniwala ki Dhani-Dokan and Kundla ki Dhani block indicates that these sediments formed the deepest part of the basin, as the silver preferably enters into the lattice of Chalcocite and bornite which precipitate in the deeper part of the basin as per the normal paragenitic depositional sequence. The sediments, such deposited, contained sulphides as indicated by the presence of layer parallel pyrite and pyrrhotite. Wide spread distribution of very fine nearly dusty disseminations of bornite chalcopyrite and oxides in a large variety of calcareous facies of rocks, colloidal precipitates of copper (recorded from Dariba area), co folding of sulphide veins with the lithology recorded from Mahawa area are strong evidences suggesting syngenetic component of the sulphide mineralization. These were subjected to the metamorphism and deformation, facilitating remobilization of the more aqueous fluids, derived from the metamorphic process and relocalization of the sulphides along the weak planes/shear zones. The un-deformed and coarsely crystalline nature of the vein and cavity filled component of the mineralization suggests the remobilization and relocalization of mineralization here in this belt is syn to post D_2 deformation. The only deformation recoded is in the form of some fracturing of the ores. Occurrence of minerals typical of the hydrothermal environment suggests the presence of epigenetic hydrothermal activity of sulphide mineralization in the area. Occurrence of Parkerite, Native bismuth, Molybdenum with the sulphides, suggests their derivation from the Pegmatite/granite intrusions and the same holds good, as there are lots of granite and Pegmatite bodies present in the surroundings of this belt (**Figure 2(i)**). The observation that the mineralization is syn to post D_2 deformation is further supported by the fact that the granite/pegmatite bodies are emplaced during the F_2 folding as syn-kinematic to D_2 deformation in the entire area. These granitic and pegmatitic intrusions during the deformation have given rise to establishment of hypogene environment in the area recorded in terms of high temperature mineral assemblage and sulphide oxide intergrowth. Hence it can be convincingly and comprehensively interpreted that bornite rich sulphide mineralization in the area is laid down in the narrow third order sub basin within the Alwar-Ajabgarh basin, having marine to lagoonal environment, precipitated due to hot brines, subsequently remobilized by metamorphic process containing the aqueous fluids and located along the shear zones. This was followed by the epigenetic hydrothermal influx of the sulphides deposited during the granite/peg-matite intrusions mostly during the waning stage of the D_2 deformation. The mineralization has a temperature of deposition ranging between 130˚C to 570˚C as estimated from fluid inclusion studies. There are evidences of hypogene environment of mineralization in terms of occurrence of hematite-bornite intergrowth, presence of chalcocite, bornite and chalcopyrite-bornite exsolution and association of REE bearing minerals like allanite and yettrium.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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