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Mineragraphic Studies of Pb-Zn Ore Deposits of Rampura-Agucha Area, Bhilwara Belt, Rajasthan

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Abstract: **The Sediment hosted massive Pb-Zn sulfide deposit at Rampura-Agucha area, district Bhilwara, Rajasthan, has been studied. It is in the Mesoproterozoic meta-sedimentary rocks belonging to the Bhilwara supracrustal belt of Aravalli-Delhi orogen. The ore body at Rampura-Agucha is hosted by an enclave of graphite-biotite-sillimanite schist which is found within the garnet-biotite-sillimanite gneiss country rock. It contains bands of amphibolite, pegmatite, calc-silicate rocks and aplite in the proximity of the ore zones. The host and associated rocks encountered in the study area are metamorphosed to mainly upper amphibolite to granulite facies. In this work, an attempt has been made to emphasize on the mineralogy, texture and mode of the occurrence of lead and zinc ore and other ore minerals of the study area. The ore and gangue minerals are identified with the help of the X-ray diffraction analysis and ore microscopic studies. The mineralogical studies of ore samples revealed the presence of sphalerite, galena, pyrite, pyrrhotite, chalcopyrite, arsenopyrite, canfieldite and argentopyrite along with the gangue minerals such as quartz, graphite, kyanite, haycockite as recorded in the X-ray diffraction pattern. Sphalerite and galena are present in most of the samples. The sphalerite is broadly categorized into groups, on the basis of shape, size, and frequency of inclusions and their textural relationships; (a) Sphalerite devoid of inclusions, (b) Sphalerite with minor inclusions of galena, pyrite, and pyrrhotite, (c) Sphalerite with graphite fragments. Existence of deformation texture, brecciated texture and curved cleavage pits in the samples are the suggestive of the post-depositional brittle and ductile deformation in the area.**

Index terms: **Graphite-biotite-sillimanite schist, Ore microscopy, Pb-Zn mineralization, Rampura-Agucha, Rajasthan, X-ray diffraction.**

I. INTRODCTION

The massive Pb-Zn sulfide deposit at Rampura-Agucha area found in the Mesoproterozoic meta-sedimentary rocks in the district Bhilwara, Rajasthan, which belongs to the Bhilwara supracrustal belt of Aravalli-Delhi orogen (Deb and Sarkar, 1990). The geology of this significant deposit deposit was first studied by the Gandhi et. al. (1984). According to Deb et al (1989), the stratigraphic status of the ore body was assessed based on the Pb-Pb model age of about 1.8 Ga. This deposit is situated around 220 km away in the south west direction from the state capital, Jaipur. The area is famous for its largest Pb-Zn deposit and also one of the lowest cost producers of Zn globally, where the ore body is reaching out over a length of about 1.55 km with a normal width of 60 m while at places the width increases and goes up to 100 m. The estimated Pb-Zn ore reserve in the study area is around 63.65 million tonnes with an average content of Zn-13.38%, Pb-1.9% and Fe-9.58% (Gandhi et. al., 1984). The host and associated rocks encountered in the present study area are metamorphosed to mainly upper amphibolite to granulite facies, estimated by Deb & Sarkar (1990) and Ranawat et. al. (1988). Mineralogical and textural studies of ore minerals are crucial to establish the mineralogical assemblages concerning the time at different P-T paths. It also discloses the paragenetic sequences of ore minerals and their depositional history. It plays a significant role in the genetic interpretation of ores. Textures may provide evidence for the nature of processes such as initial ore deposition, post-depositional re-equilibration or metamorphism, annealing, deformation, and meteoric weathering. However, the extent to which ore minerals preserve their compositions and textures which formed during the initial processes varies widely. The morphological investigations and inclusion patterns inside the refractory ore minerals such as pyrite may show the initial high-temperature conditions. While, the coexisting pyrrhotites may have equilibrated to intermediate temperature and pressure conditions during cooling, and minor sulfosalts or native metals may have equilibrated down to the very low ambient temperatures. Thus, complete textural interpretation involves not only recognition and interpretation of the individual textures but also their placement in the time framework of the evolution of the deposit from its initial formation to the present day. The author reviewed the work done by the pioneer workers like Deb (1992), Deb and Sehgal (1997), Gandhi (1992),

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Genkin and Schmidt (1991), Holler and Gandhi (1995), Holler and Stumpfl (1995), Holler et. al. (1996) & Ranawat and Sharma (1990). Though, the area is under study for a long time, the complete mineralogical assessment of lead and zinc ore minerals in these deposits and a relative explanation are lacking. In this piece of research work, an attempt has been made to emphasize on the mineralogy, texture and mode of occurrence of lead and zinc ore minerals in the Rampura-Agucha opencast and underground mines of the study area.

II. GEOLOGICAL SETTING

The early Proterozoic Bhilwara supracrustal belt which forms a significant constituent of Aravalli-Delhi orogenic belt in the Precambrian of northwest India, is economically important in terms of several major base metal deposits found in it (Deb, 1982 & Powar and Patwardhan, 1984). In northwestern India, the Aravalli-Delhi orogenic belt is about 30-200 km wide and spreads for a length of about 700 km in NE-SW direction from Delhi through Haryana and Rajasthan to Gujrat. Most of the modern studies in this orogenic belt based on the work of Coulson (1933), Gupta (1934) and Heron (1935 & 1953) and later re-interpretations on a regional scale were presented by Gupta et. al. (1980), Naha and Halyburton (1974), Rao et. al. (1971), Roy (1988) and Sen (1970). This orogen is separated into two different terrains by a fundamental lineament which passes through the Rakhabdev lineament. To the east, the Archaean crust represented by the Banded Gneissic Complex and Bundelkhand massif is overlain by the mid-Proterozoic Aravalli and Bhilwara supracrustal belt or the sediments of Vindhyan Supergroup of upper Proterozoic age. To the west of the lineament, Jharol belt and Delhi belt occur comprising the metasedimentary and metavolcanic rocks encroached broadly by granitic suites.

The Bhilwara belt has been formed by incipient divergence interpreted on the basis of the geological evidence by Sugden et. al. (1990). The Bhilwara belt is occuring between the Banded Gneissic Complex (BGC) in the west and the Vindhyan sediments to the east; it is about 100 km wide towards north. The main part of this belt is about 200 km long with NE-SW trends and it meet to the eastern boundary of rocks belongs to Aravalli belt. The Bhilwara belt contains numerous subparallel to linear metasedimentary zones with intervening region of migmatised gneisses. The metamorphism grade of the bhilwara metasediments raises to upper amphibolite facies along the interaction of northern block of Banded Gneissic Complex. According to Gandhi et. al. (1984), the ore body of Rampura-Agucha is a doubly plunging synformal structure. The ore body at Rampura-Agucha is hosted by an enclave of graphite-biotite-sillimanite schist within garnet-biotite-sillimanite gneiss country rock. It contains the bands of amphibolite, pegmatite, calc-silicate rocks and aplite in the proximity of the ore zones (Fig.1). Along the western footwall side of the ore body, a marked zone of mylonitization of the gneissic rock is present on a regional scale which varying from 15-40m in width. The rocks in the study area have been subjected to polyphase deformation and metamorphosed up to high grade with zones of mylonite (H.Z.L, 1992). In the study area, the ore and host rock have been isofacially metamorphosed under upper amphibolite to granulite facies conditions (Deb and Sehgal, 1997). According to Ray (1982), the area around the Rampura-Agucha ore body has suffered three-phase of deformation namely-

i-An initial isoclinal folding with a variable plunge and axial plane that produced WNW-ESE trending folds;

ii-Subsequent isoclinal folding which folded the S1 axial plane about a NE-SW axis;

iii-A weak, local phase of upright, steeply plunging fold.

The stratigraphic position of this deposit is problematic due to difficulties in separating between the member of Banded Gneissic Complex and the high grade metasedimentary rocks of Bhilwara belt (Sinha-Roy, 1989).

III. METHODOLOGY

The ore and gangue minerals are identified with the help of the X-ray diffraction (XRD) analysis and ore microscopic studies. For X-ray diffraction analysis, samples are powdered up to –200 mesh size to get the excellent diffraction patterns of the ore and gangue minerals. A Xpert-Pro Philips instrument with Ni filtered Cu Kα radiation operated at the current 40kV-30mA along with an angular scan range 10° to 90° with a step size 0.05°/second was used at department of Mechanical Engineering, A.M.U., Aligarh. The obtained XRD patterns were used for the identification of ore minerals, following X'pertHighscore plus and Origin Pro 8.5 software. For ore microscopic studies, the cutting of the ore samples and their rubbing and polishing was carried out on several grade emery papers with different grades of diamond paste at Section Cutting Lab and Economic Geology Lab, Department of Geology, Aligarh Muslim University, Aligarh. The microscopic study of polished blocks was done under reflected light using an advance version of ore microscope (Leica DM 2700P Polarizing Microscope fitted with DFC 550 Digital camera and LS analysis software kit) in the Department of Geological Sciences, Jadavpur University, Kolkata, West Bengal.

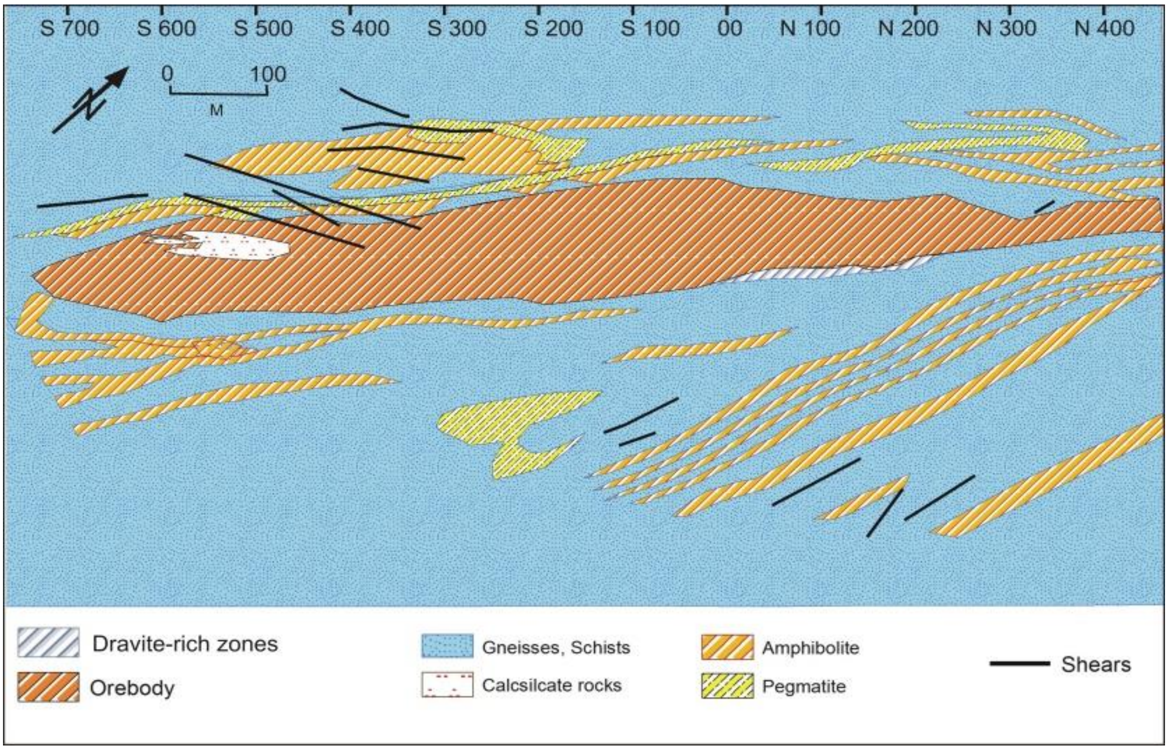

Fig. 1. Simplified geological map of Rampura-Agucha ore body and surrounding rocks (after Holler & Gandhi, 1997).

Table I. Proterozoic lithostratigraphy of Aravalli-Delhi belt, India (Director General, G.S.I, 1977).

	Unit	Sub-unit and lithology
	Post-Delhi granitoids (950-635 Ma, and 1660-1480 Ma)	Erinpura-Abu-Idar granite Baireth-Khetri granite
	---------Delhi orogeny (~1600 Ma)---------	
	Delhi Supergroup (2000-1600Ma)	Ajabgarh Group: dolomites, marbles, calc-schists and gneisses slates, phyllites, mica schist; amphibolites and quartzites. Alwar Group: quartzites and mica schists with basal grit and conglomerates.
	---------Aravalli orogeny (~2000 Ma)---------	
	Aravalli Supergroup (2500-2000 Ma)	Jharol Group: quartzites, mica schists and phyllite Udaipur Group: basal quartzites, and conglomerates; metavolcanics; crystalline limestones and phyllites; mica schists with gneisses.
	~~Unconformity~~~~~~~~	
Archaean	Bhilwara Supergroup (3500-2500 Ma)	Banded Gneissic Complex, Berach granite, Untala granite

IV. RESULTS AND DISCUSSION

A. Microscopic Study

The detailed studies of the lead and zinc ore of the study area reveal that the sphalerite, pyrite, pyrrhotite, galena are the most common minerals present in almost every polished ore blocks with the minor occurrence of sulphosalts.

1) Ore mineralogy

a) Sphalerite (ZnS)

It is the most dominant sulphide ore mineral of zinc in the study area. Grain size of sphalerite differs from very fine grained material admixed with galena to coarse-grained crystalline concentrations. Sphalerite also occurs as veinlets in association with pyrrhotite and pyrite. Sphalerite is present in almost every polished block and usually occurs as an irregular aggregate intergranular to silicates gangues. Under the microscope, sphalerite grains show grey to greyish white color, low reflectance with brownish red internal reflections. However, not all grains of sphalerite show the internal reflections. Internal reflections in the sphalerite grains are best seen under crossed polar and with high illumination. Internal reflections in the spahlerite grains can increase with the assistance of high-power magnification and an oil immersion objective (Craig and Vaughan, 1994). Sphalerite grains reveal annealing twins, and frequently contain the inclusions of galena and pyrrhotite. The sphalerite is broadly categorized on the basis of shape, size, and frequency of inclusions and their textural relationship into the following segments;

a. Sphalerite devoid of inclusions.
b. Sphalerite with minor inclusions of galena, pyrite,and pyrrhotite (Fig. 3).
c. Sphalerite with graphite fragments.

Coarse-grained sphalerite shows the evidence of metamorphic recrystallization. Sphalerite grains show incipient alteration along narrow cracks and grain boundaries. Sphalerite along with pyrrhotite and chalcopyrite also occurs in the veins and fractures developed in silicates gangue. It is found in close association with galena and pyrrhotite (Fig. 2). In some polished block, the sphalerite grain shows the mutual boundary texture and straight boundary relationship with pyrrhotite and pyrite of first generation.

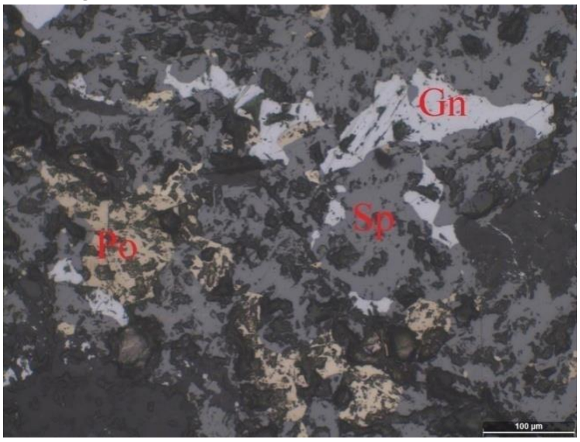

Fig. 2. Photomicrograph showing the association of pyrrhotite (Po), galena (Gn) and sphalerite (Sp) from Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

Presence of this type texture indicates simultaneous crystallization of these minerals from the same medium. Sphalerite grains in the study area show a classic example of chalcopyrite disease in which very fine grains of chalcopyrite are disseminated throughout the sphalerite grains. The presence of chalcopyrite disease in the sphalerite grains results from the exsolution of previously existing single phase (Barton and Bethke, 1987).

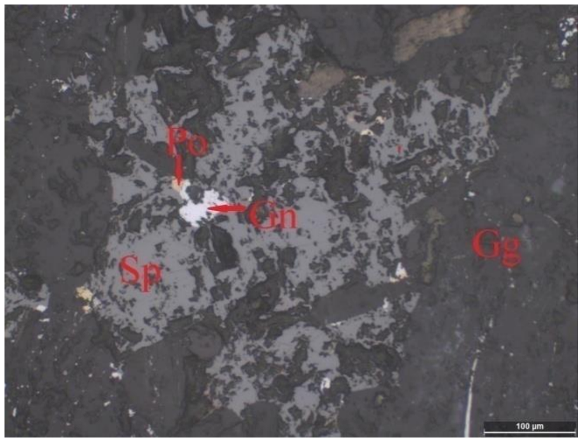

Fig. 3. Photomicrograph showing the inclusions of galena (Gn) and pyrrhotite (Po) in the sphalerite (Sp) from Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

b) Galena (PbS)

In the study area, galena is the next most important ore mineral after sphalerite. A polished section containing the grains of galena displays scratches due to its softness relative to the other associated ore minerals. The polishing hardness of galena grains is much lower than the chalcopyrite grains; consequently it displays the depressions in the polished section under the microscopic studies. It occurs as fine to medium-grained disseminations and veinlets in the main ore zone. It is identified by its higher density, reflected through its bright greyish white colour, cubic habit, and three sets of perfect cleavages under the macroscopic study. Microscopically, galena is white, high reflectivity and isotropic with characteristic triangular cleavage pits. The characteristics triangular pits in the galena grains formed due to the plucking action at the intersections of its perfect 3- sets cleavage directions. However, galena will resemble smooth without any pits, if a grain in sample is polished parallel to anyone of its cleavage directions. Galena and sphalerite occur in close association in most of the polished section, sphalerite being a major phase. Galena grains are relatively devoid of inclusions in most of the samples (Fig. 6). An isolated grain of sphalerite also occurs as an inclusion within the galena occasionally. Coarse grained galena is displaying the curved triangular cleavage pits. The curved triangular pits in galena grains are the indication of plastic deformation after the deposition of galena and it uses frequently as a measure of distortion in the deposit. The principal deformation mechanisms in galena are translation gliding and associated kinking (Salmon et. al., 1974). Accordingly, galena is a good indicator of deformation in the low temperature and pressure condition. The remobilizations of galena with chalcopyrites grains are common in the fissure which is developed within silicate gangue. Galena along with sphalerite and pyrrhotite grains is also occurred in the veins and fractures created in silicate gangues. It found as inclusions within sphalerite grains in few polished blocks. Galena show perfect euhedral shaped grains within sphalerite in some specimen (Fig.6). It has cross-cutting relationship with graphite grains (Fig.5). In few polished blocks, galena is found as a sub-rounded to rounded grains throughout the silicate gangues (Fig.4). Galena shows mutual boundary relationship with pyrrhotite and sphalerite which is indicating that these minerals were crystallized at the same time.

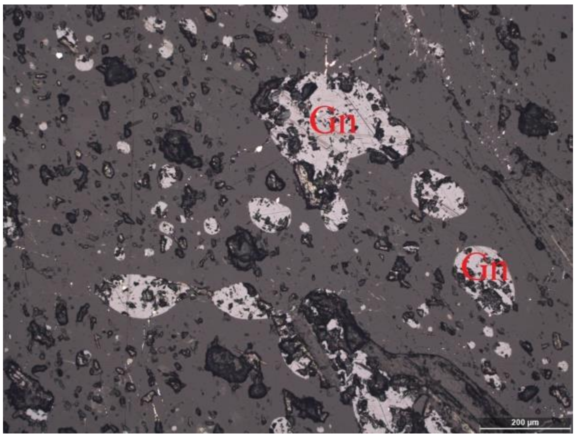

Fig. 4. Photomicrograph showing the dispersed rounded shaped galena (Gn) in silicate gangue from Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

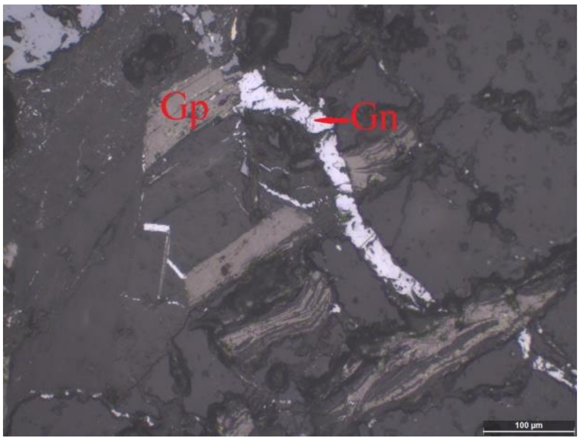

Fig. 5. Photomicrograph showing the cross-cutting emplacement of galena (Gn) in the graphite (Gp) grains, Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

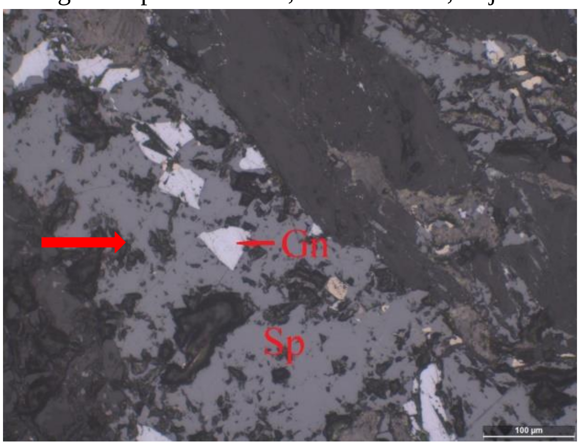

Fig. 6. Photomicrograph showing the perfect shaped galena (Gn) arrow pointing,embaded in the ground mass of sphalerite (Sp) from Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

c) Pyrite (FeS_2)

Pyrite contains the most normally available siderophile element and is stable over a wide range of pressure-temperature conditions and oxygen fugacity consequently pyrite is the most widespread and typical of the sulphide minerals (Craig, 2001). Pyrite and pyrrhotite occur in different proportions in the main lode. The pyrite grains shows yellow color precisely distinct from chalcopyrite, isotropic, high reflectivity and high polishing hardness, mottled surface and absence of internal reflection under the microscopic studies. The pyrite grains have the most fixed tendency to form the idiomorphic crystal as shown in figure 8. There are two groups of pyrite in the ore deposit of the study area, identified on the basis of the mode of occurrences. The pyrite grains of the first generation shows large homogeneous, euhedral grains which are enclosed and rarely transverse by pyrite of the second generation .The second generation pyrite grains are granular in form. The first-generation pyrite is also occured in a granular groundmass of pyrrhotite (Fig.7) and found to be intergrown with pyrrhotite. The large euhedral porphyroblast of pyrite grain shows brittle fractures which are later occupied by the other sulfide mineral and silicate gangues (Fig.7). According to the Graf and Skinner (1970), pyrite is basically twisted by brittle processes at all conditions. While Barrie et. al. (2011) proposed that the crystal-plastic deformation is possible at temperatures as low as 200°C-260°C. However, pyrite is still one of the most mechanically resistant sulphide mineral; it shows the brittle deformation mechanism which is manifested by numerous occurring deformed pyrite

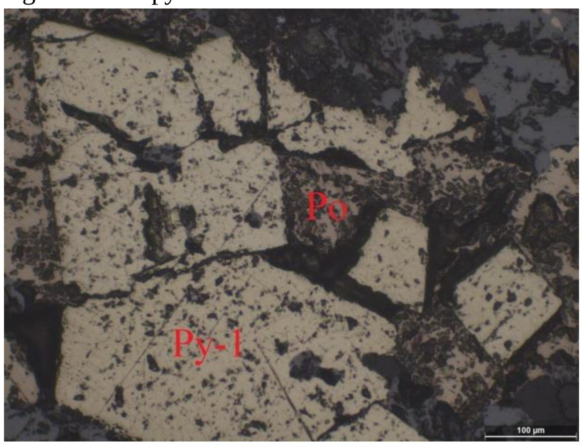

Fig. 7. Photomicrograph showing the coarse euhedral pyrite grain (Py-1) growing in granular mass of pyrrhotite (Po), Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

during the greenschist to amphibolite regional metamorphic conditions (Craig and Vokes, 1993 & Vokes and Craig, 1993). Mutual boundary relationship exists amongst the pyrite of the first generation, sphalerite and pyrrhotite. The pyrite grain shows the development of sub-grains with 120° triple junction, called dynamic recrystallization texture. Presence of dynamic recrystallization texture in the samples of study area indicates the metamorphism under upper amphibolite to granulite facies condition. Usually, Pyrite is found in association with the pyrrhotite in most of the polished blocks but rarely associated with sphalerite. The large euhedral porphyroblast of pyrite grain contain the inclusion of sphalerite, while small euhedral pyrite grains are found in the groundmass of sphalerite (Fig.8).

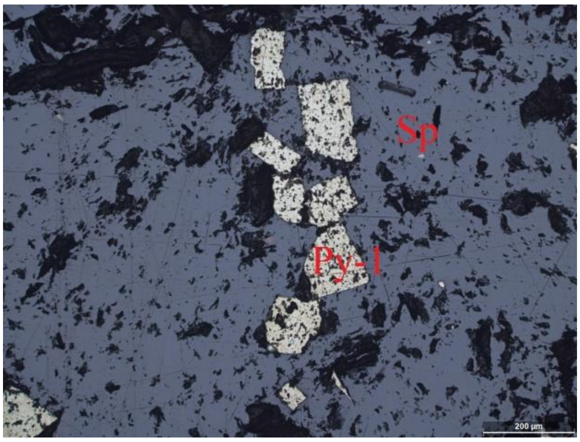

Fig. 8. Photomicrograph showing the euhedral pyrite grains of first generation (Py-1) within the sphalerite (Sp), Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

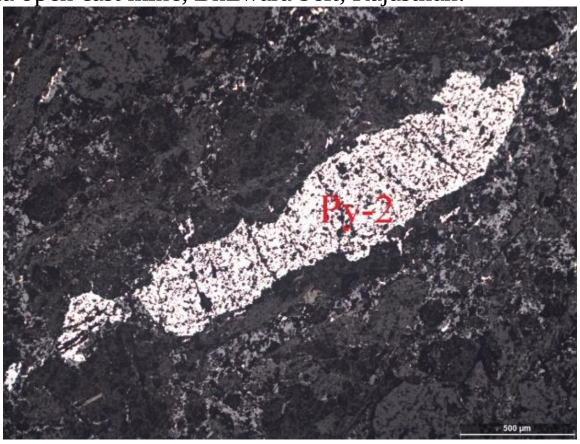

Fig. 9. Photomicrograph showing the elongated pyrite of second generation (Py-2) within the silicate gangue from Rampura- Agucha underground mine, Bhilwara belt, Rajasthan.

d) Pyrrhotite [$Fe_{(1-x)}S$]

The pyrrhotite occurs in lesser amount as compared to sphalerite, galena and pyrite in the study area. It is a comparatively hard mineral with a flat surface. Fine-grained pyrrhotite is found as granular aggregates of numerous quantities and associated with sphalerite and pyrite. The polishing hardness of pyrrhotite is more than the chalcopyrite but less compared to pyrite. The pyrrhotite is anisotropic, low reflectivity without any internal reflection under the microscope. The pyrrhotite is easily recognized in polished sections by its strong brown to reddish brown pleochroism. Exsolved blebs of pyrrhotite of variable sizes founds in sphalerite grains (Fig.10). The pyrrhotite grains are often partially or completely fragmented into a granular product comprising of pyrite. Pyrrhotite shows ductile behavior at temperatures as low as 100°C (Graf & Skinner, 1970). Pyrrhotite along with sphalerite and negligible chalcopyrite occur in fracture that developed in silicate gangue. The pyrrhotite also shows the straight boundary relationship with pyrite of first generation. Most of the pyrrhotite behaviour is same as chalcopyrite but pyrrhotite is more sensitive to pressure while chalcopyrite is susceptible to temperature. The pyrrhotite is easily deformed as galena under the regional metamorphism i.e., up to greenschist to amphibolite facies condition (Marshall & Gilligan, 1987). Pyrrhotite also exists as a rounded/anhedral form in the sphalerite ground mass. In few samples, pyrrhotite occurs in the vein developed in the silicate gangue. Pyrrhotiteis also found together with sphalerite and galena (Fig.11).

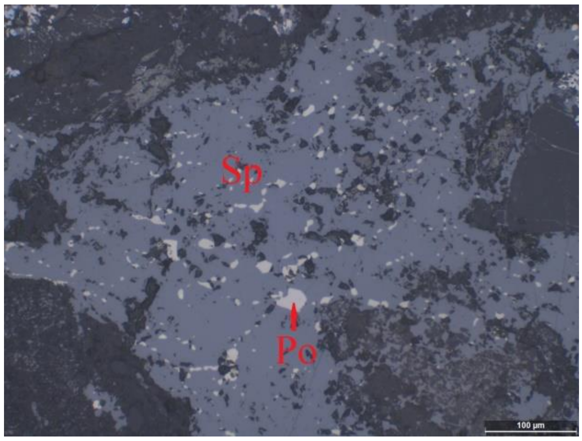

Fig. 10. Photomicrograph showing the inclusions of pyrrhotite (Po) in the sphalerite (Sp), Rampura-Agucha underground mine, Bhilwara belt, Rajasthan.

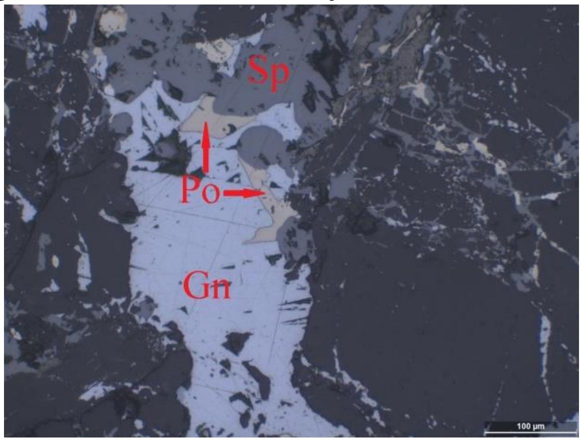

Fig. 11. Photomicrograph showing association of the galena (Gn), pyrrhotite (Po) and sphalerite (Sp), Rampura-Agucha underground mine, Bhilwara belt, Rajasthan.

According to Deb and Sehgal (1997), the pyrrhotite found with sphalerite contains marginally higher Fe (47.2-48.5 atomic %) than those pyrrhotite found in association with sphalerite and pyrite (44.6-47.7 atomic %).

e) Chalcopyrite ($CuFeS_2$)

Chalcopyrite is a minor component in the study area and found as dispersed anhedral grains interstitial to the sulphides and silicates. Chalcopyrite grains are easily recognized by its representative golden yellow to brass yellow colour under the microscope which tarnishes to deep yellow colour owing to the air etching on exposure to the atmosphere. The polishing hardness of chalcopyrite is more than the galena but less as compare to pyrite.

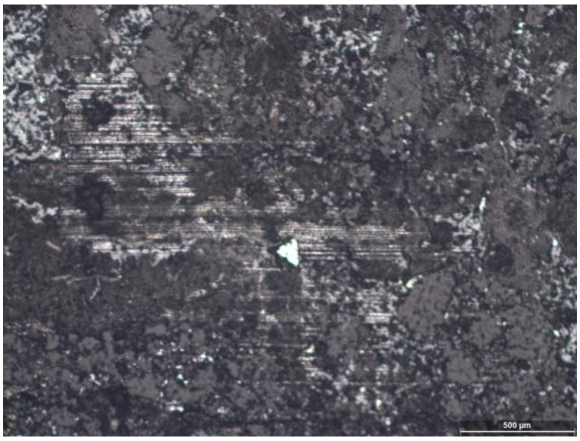

Fig. 12. Photomicrograph showing polysynthetic twinning in chalcopyrite (Cp) from Rampura-Agucha underground mine, Bhilwara belt, Rajasthan.

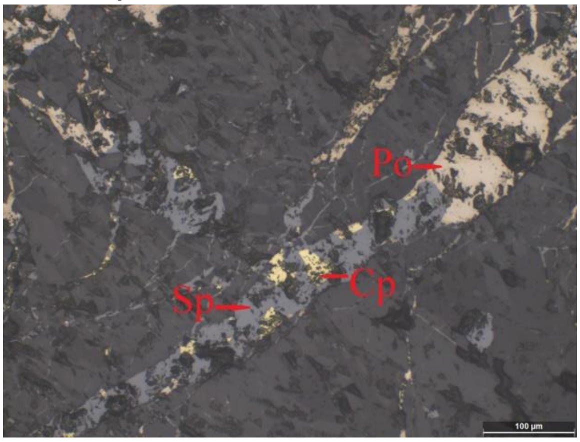

Fig. 13. Photomicrograph showing the fracture in the silicate gangue infilled by sphalerite (Sp), chalcopyrite (Cp) and pyrrhotite (Po), Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

The chalcopyrite grain gets easily polished and shows low reflectivity. Reflection pleochroism and anisotropism effects are deprived of chalcopyrite and internal reflection is not seen. Being more mobile, during deformation and metamorphism of the host rocks in the study area, chalcopyrite flows out to cracks and interspaces in the silicates. Polysynthetic twinning is common and seen in a large grain of chalcopyrite (Fig.12). It is observed that the fine-grained chalcopyrite inclusions in the sphalerite aggregate are seen in some polished blocks. Chalcopyrite is typically showing the association with sphalerite, pyrrhotite and rarely with galena. It also occurs in the fractures along with sphalerite and pyrrhotite(Fig.13).

f) Arsenopyrite (FeAsS)

Arsenopyrite is comparatively minor sulphide mineral in the study area. Arsenopyrite is mainly occured as disseminated small subhedral to euhedral grains. Arsenopyrite displays the idiomorphic crystals with anisotropism and high reflectivity under the microscopic studies. Arsenopyrite is found as euhedral crystals in the sphalerite mass that are flattened parallel to foliation in few polished blocks(Fig.14). It occurs in the form of bends in a polished block which reveal the proof of plastic deformations. Arsenopyrite is a competent mineral with behavior similar to pyrite (Gilligan and Marshall, 1987).

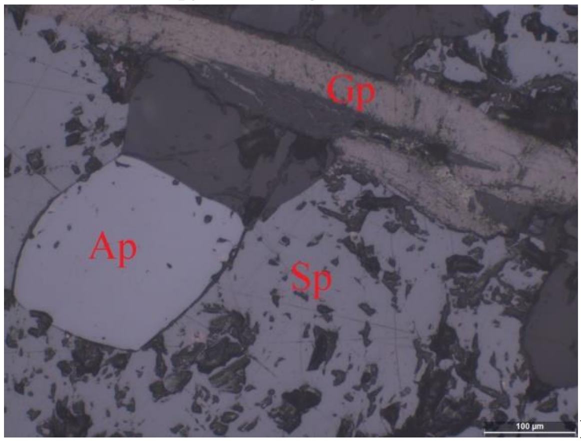

Fig. 14. Photomicrograph showing the arsenopyrite (Ap) in the sphalerite (Sp) and elongated graphite (Gp) from Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

B. X-ray Diffraction studies

X-ray diffraction is the direct method for assessing the mineralogy of a sample. Its unique X-ray diffraction pattern identifies each phase (mineral). The lead, zinc and associated major ore and gangue minerals recognized by the X-ray diffraction technique using d-spacing and intensity of 2θ position. The XRD analysis of ore samples reveals the presence of galena, sphalerite, pyrite, pyrrhotite and chalcopyrite along with few peaks of argentopyrite, wurtzite and canfieldite. The gangue minerals which are found in association with major ore minerals are quartz, graphite, kyanite, haycockite as recorded in the XRD spectrum. Galena and sphalerite is found in almost in every X.R.D pattern of ore samples.

C. Textures and Microstructures

The study of textures and microstructures is the most significant part of the microscopic study. It reveals the most important information about the oxidation, hydration, weathering and metamorphism etc., which assist to know the origin and depositional history of an ore deposit. As per the Guilbert and Park (1986), “Textural analysis can assist helps in determining the time connections of progressive mineral assemblages, environment of formation and the way of deposition in an ore deposit.” Here, we will focus on the inter-relationships of ore mineral grains. Different textures and microstructures identified in the ore of the study area are described as under;

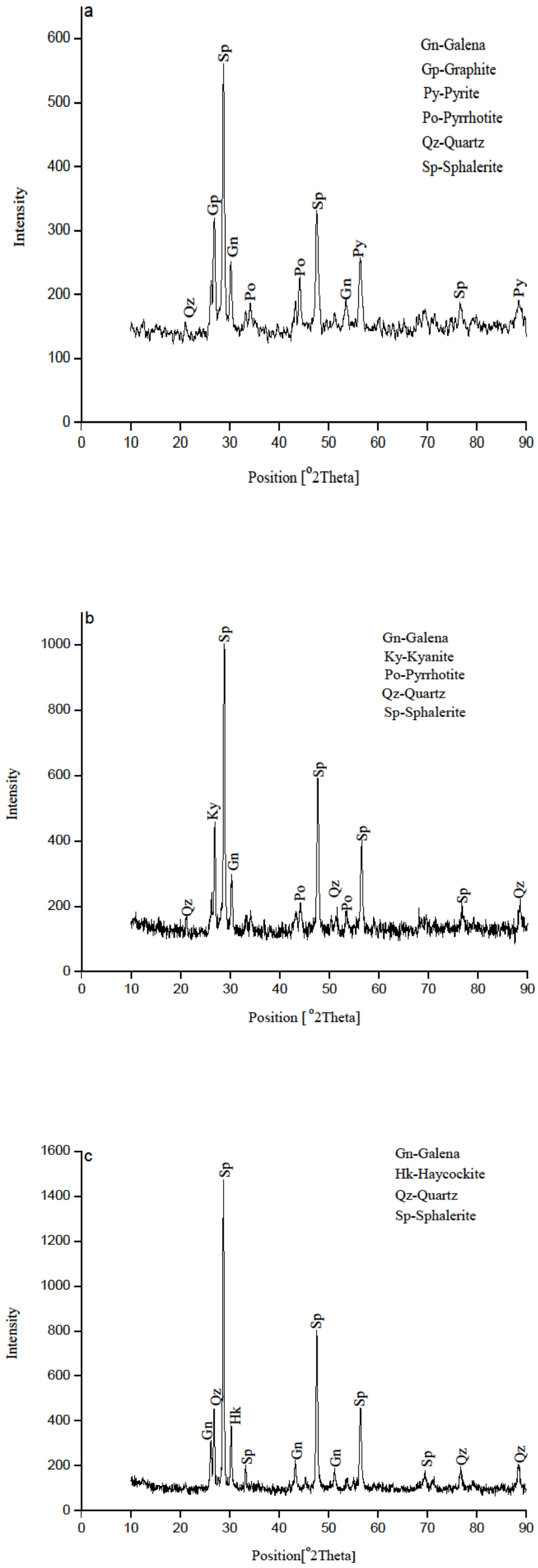

Fig. 15 (a-c) X-ray diffraction pattern showing 2θ position of various ore and gangue minerals of Rampura-Agucha opencast mine, Bhilwara belt, Rajasthan.

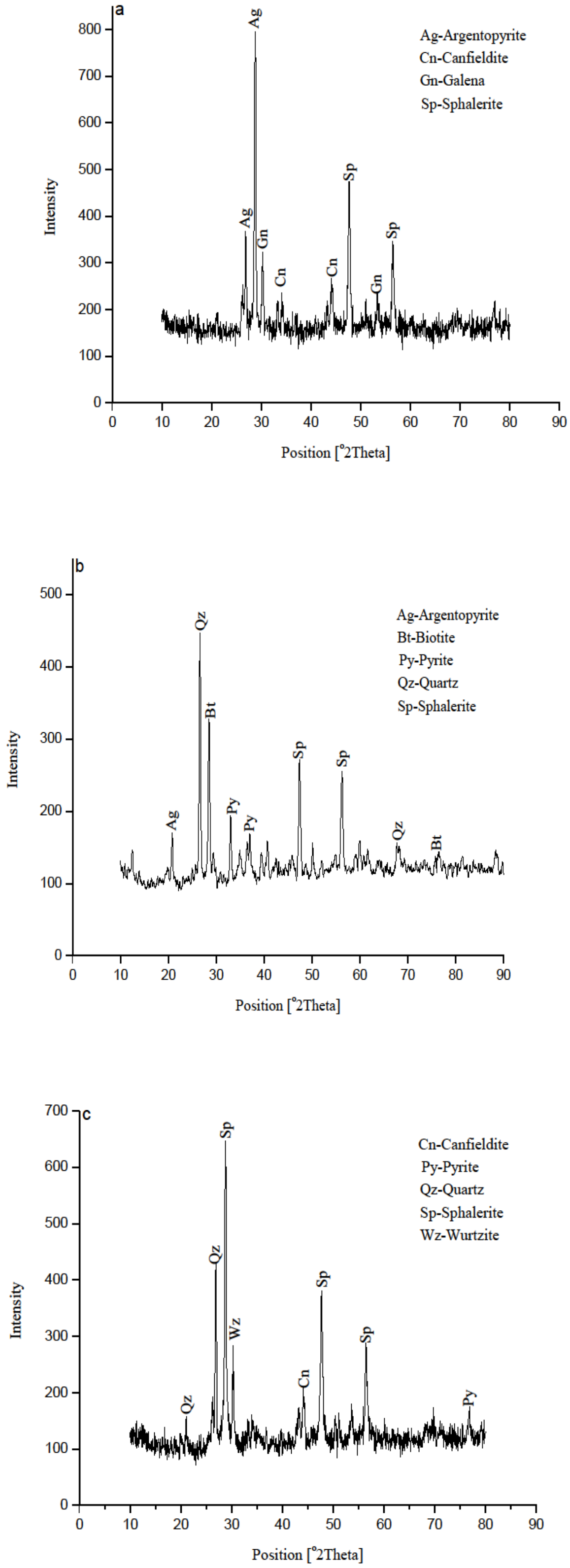

Fig.16 (a-c) X-ray diffraction pattern showing 2θ position of various ore and gangue minerals of Rampura-Agucha underground mine, Bhilwara belt, Rajasthan.

1) Replacement texture

Replacement is mainly restricted to easier pathways of movement limited to the microfractures developed in the initially formed minerals and along the edge of minerals grains (Siddiquie, 2004). The replacement textures of initially formed ore phases found along the fissures, fractures, grain boundaries and cleavage planes. The replacement of sphalerite grain by the galena results in the development of atoll structure (Fig.17). Atoll texture is also called as core texture. The features such as irregularities in distribution, concentration along the edge of grains, enclosing lenses of sphalerite are the expressive of replacement textures. The fracture produced in the silicate gangues offers a structural weakness that assists in the replacement by galena and sphalerite.

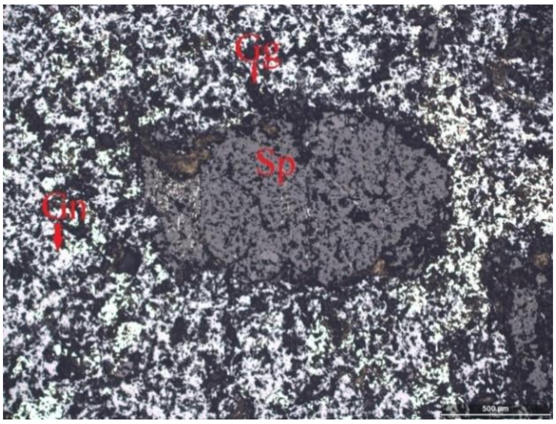

Fig. 17. Photomicrograph showing the replacement of sphalerite (Sp) grain by the galena (Gn) forming the atoll structure, Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

2) Brecciated texture

Pyrite being more resistant as compared to the associated sulphide such as galena, sphalerite and pyrrhotite, is angular to sub angular in shape (Fig.18). The pyrite grains are found to be extremely deformed and the intergranular spaces are occupied by the less resistant mineral i.e, sphalerite and silicate. The brecciated texture is also known as crushed texture or exploding bomb texture, categorized as a secondary ore texture (Schwartz, 1951 and Siddiquie, 2004 & 2008, Siddiquie et al., 2015).

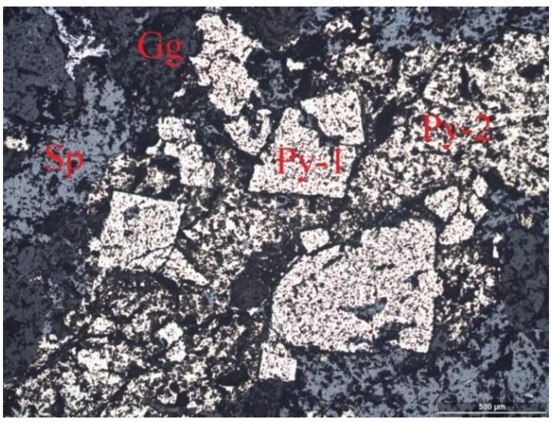

Fig. 18. Photomicrograph showing the broken of first generation pyrite (Py-1), Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

3) Mutual boundary relationship

The mutual boundary relationship is principally shown by the sphalerite, pyrite and pyrrhotite. The pyrite and pyrrhotite are displaying the sharp straight contact along their grains boundary while the contact is curvilinear in nature between the pyrrhotite and sphalerite grain boundaries (Fig. 19).

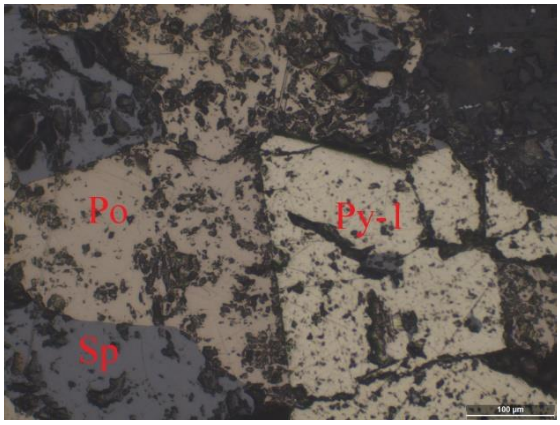

Fig. 19. Photomicrograph showing the mutual boundary relationship among pyrrhotite (Po), sphalerite (Sp) and first generation pyrite of (Py-1), Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

4) Veined texture

Galena and sphalerite in association with other sulphide minerals is witnessed in the form of veins. Sphalerite and pyrrhotite is found as an irregular vein in the silicate gangues. Presence of galena in the veins is rare (Fig.20).

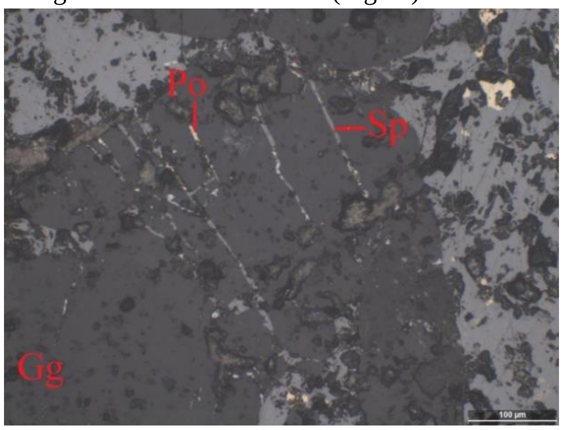

Fig. 20.Photomicrograph showing the vein of sphalerite (Sp) and pyrrhotite (Po) in the silicate gangue (Gg) from Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

5) Deformation texture

A primary factor which defines the mineral characters in terms of deformation is its hardness and other factors like temperature, associated minerals and deformational processes. Pyrite grains are highly crushed and produced interspaces are filled by silicate gangues. While in some sections, silicates are highly shattered and their interspaces

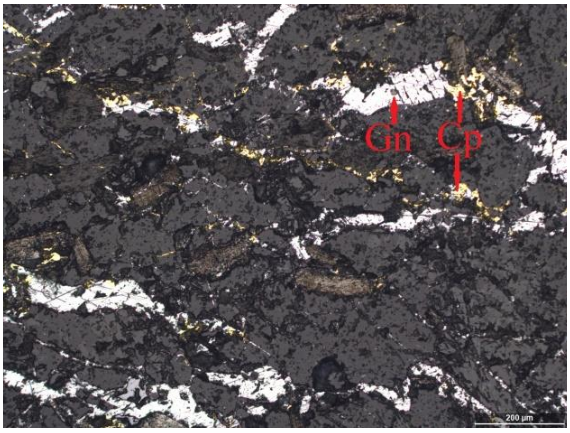

Fig. 21. Photomicrograph showing the folded fractures in the silicate occupied by galena (Gn) and chalcopyrite (Cp) from Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

are occupied by galena and sphalerite. Fractures produced in the silicate gangues occupied by galena and are highly folded observed in the ore of study area (Fig.21).

6) Curved Cleavage pits

Triangular cleavage pits are investigative in the recognition of galena which commonly assists in the measurement of deformations in the ore deposit. The curved triangular cleavage pits are detected in the galena ofstudy area (Fig.22). The existence of curved triangular cleavage pits in galena is the suggestive of the plastic deformation after deposition of the ore deposit (Craig and Vaughan, 1994).

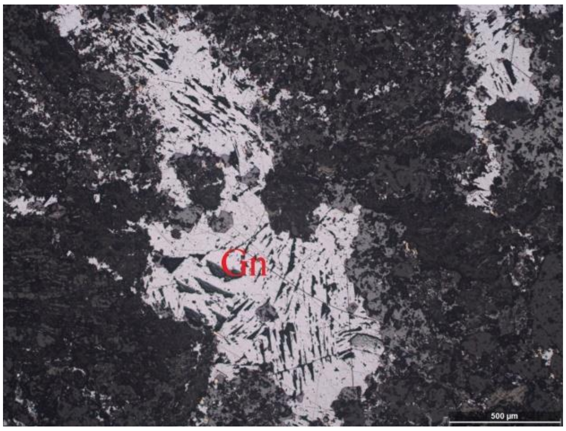

Fig. 22. Photomicrograph showing the curved cleavage pits produced due to stress in galena (Gn), Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

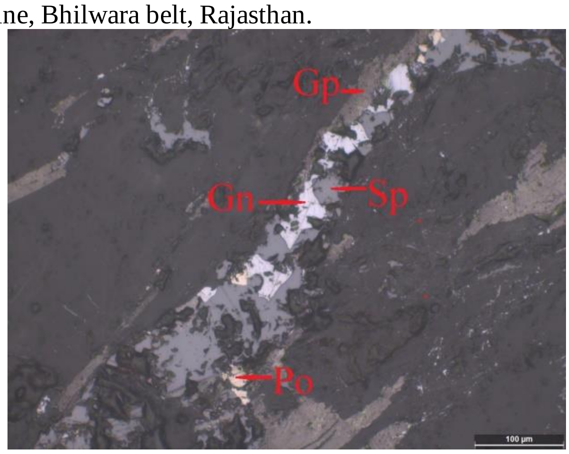

Fig. 23. Photomicrograph showing the fracture occupied by galena (Gn), pyrrhotite (Po) and sphalerite (Sp) in the silicate gangue, Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

7) Fracture filling

Fracture filling microstructures are normal in the study area. The fractures are frequently occupied by the association of galena and sphalerite (Fig.23). It is also occupied by pyrrhotite, chalcopyrite and sphalerite associations.

8) Chalcopyrite disease

This type of texture is revealed by sphalerite grains in the study area. In this texture, very fine chalcopyrite grains are distributed throughout the sphalerite, results in the formation of the chalcopyrite disease in the spahlerite (Fig.24). Chalcopyrite disease was first entitled by Barton and Bethke (1987) in the sphalerite grain. Existence of this type of texture is explaining that it formed from the exsolution of previously existing single phase.

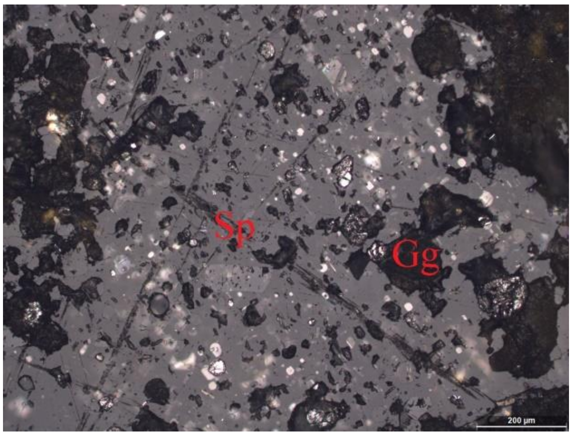

Fig. 24. Photomicrograph showing the chalcopyrite disease in sphalerite (Sp), Rampura-Agucha open cast mine, Bhilwara belt, Rajasthan.

Table II. Ore mineral assemblage of study area observed in microscopic and X-ray diffraction studies.

Name of Mine	**Ore Minerals**
Rampura-Agucha Mine	Galena+Sphalerite+Pyrrhotite, Sphalerite+Pyrite+Pyrrhotite+Galena, Pyrrhotite+Chalcopyrite+Sphalerite +Galena, Sphalerite+Galena+Arsenopyrite, Associated ore and gangure minerals are canfieldite and argentopyritealong with quartz, graphite, kyanite and haycockite.

D. Mineral assemblage

On the basis of microscopic and X-ray diffraction studies of the ore samples from the different location of the study area reveals the different mineral assemblages given below;

CONCLUSION

The mineralogical studies of ore samples of the study area revealed the presence of sphalerite, galena, pyrite, pyrrhotite, chalcopyrite, arsenopyrite, canfieldite and argentopyrite along with the gangue minerals such as quartz, graphite, kyanite and haycockite as recorded in the X-ray diffraction pattern. Ore minerals occur as veins, stringers and fracture fillings. The textures and microstructures in the ores are characterized by replacement texture, brecciated texture, mutual boundary relation, veined texture, deformation texture, curved cleavage pits, fracture filling and chalcopyrite disease. The mutual boundary relationship is shown by the sphalerite, pyrite and pyrrhotite, indicating that the simultaneous crystallization of these minerals from the same medium. Sphalerite grains in the study area show a classic example of chalcopyrite disease in which very fine grains of chalcopyrite are disseminated throughout the sphalerite grains interpreted that it is resulting from the exsolution of previously existing single phase. Presence of deformation texture, brecciated texture and curved cleavage pits in the samples are suggestive of the post-depositional brittle and ductile deformation in the area.

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REFERENCES

Barrie, C. D., Pearce, M. A., & Boyle, A. P. (2011). Reconstructing the pyrite deformation mechanism map. *Ore Geology Reviews*, *39*(4), 265-276.

Barton, P. B., &Bethke, P. M. (1987). Chalcopyrite disease in sphalerite; pathology and epidemiology. *American Mineralogist*, *72*(5-6), 451-467.

Coulson, A. L. (1933). *The geology of Sirohi state, Rajputana*.Geological Survey of India.

Craig, J. R. (2001). Ore-mineral textures and the tales they tell. *The Canadian Mineralogist*, *39*(4), 937-956.

Craig, J. R., &Vokes, F. M. (1993). The metamorphism of pyrite and pyritic ores: an overview. *Mineralogical Magazine*, *57*(386), 3-18.

Craig, J.R., & Vaughan, D.J. (1994). Ore Microscopy and Ore Petrography. Second edn., *John Wiley and Sons, Inc*, New York, 167–274.

Deb, M. (1982). Crustal evolution and Precambrian metallogenesis in western India.*RevistaBrasileira de Geociencias*, 12(1-3), 94-104.

Deb, M. (1992).Lithogeochemistry of rocks around Rampura-Agucha massive zinc sulphide ore-body, NW India-Implications for the evolution of a Proterozoic Aulacogen. In *Metallogeny related to tectonics of the Proterozoic mobile belts*. 1-35.

Deb, M., &Sarkar, S. C. (1990). Proterozoic tectonic evolution and metallogenesis in the Aravalli-Delhi orogenic complex, northwestern India. *Precambrian Research*, *46*(1-2), 115-137.

Deb, M., &Sehgal, U. (1997). Petrology, geothermobarometry and COHS fluid compositions in the environs of Rampura-Agucha Zn-(Pb) ore deposit, Bhilwara District, Rajasthan. *Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences*, *106*(4), 343-356.

Deb, M., Thorpe, R. I., Cumming, G. L., & Wagner, P. A. (1989). Age, source and stratigraphic implications of Pb isotope data for conformable, sediment-hosted, base metal deposits in the Proterozoic Aravalli-Delhi orogenic belt, northwestern India. *Precambrian Research*, *43*(1-2), 1-22.

Director-General, Geological Survey of India (1977). Geology and mineral resources of the states of India, Part XII: Rajasthan. *Geol. Surv., India*, Misc. Publ., 30: 1--75.

Gandhi, S. (1992). Mineral characterization and chemistry in the Gossan Zone of Rampura-Agucha deposit, India. In *International geological congress*.

Gandhi, S. M., Paliwal, H. V., &Bhatnagar, S. N. (1984). Geology and ore reserve estimates of Rampura-Agucha zinc-lead deposit, Bhilwara district, Rajasthan. *Journal of the Geological Society of India*, *25*(11), 689-705.

Genkin, A., & Schmidt, S. (1991). Preliminary data for a new thallium mineral from the lead-zinc ore deposit, Agucha, India. *N Jb Mineral Abh*, *163*, 256-258.

Gilligan, L. B., & Marshall, B. (1987). Textural evidence for remobilization in metamorphic environments. *Ore Geology Reviews*, *2*(1-3), 205-229.

Graf, J. L., & Skinner, B. J. (1970). Strength and deformation of pyrite and pyrrhotite. *Economic Geology*, *65*(2), 206-215.

Guilbert, J. M., & Park Jr, C. F. (1986). The Geology of Ore Deposits Freeman. *New York*, *985*.

Gupta, B. C. (1934). *The geology of central Mewar*.Office of the Geological Survey of India.

Gupta, S.N., Arora, Y.K., Mathur, R.K., Iqballuddin, Prasad, B., Sahai. T.N. and Sharma, S.B. (1980) Litho-stratigraphic map of the Aravalli region, Scale 1:100000. Geological Survey of India, Calcutta.

H. Z. L. (1992). Rampura–Agucha mine. *Min Mag*, *167*, 372-375.

Heron, A. M. (1935). Synopsis of the pre-Vindhyan geology of Rajputana. *Trans. Nat. Inst. Sci. India*, *1*(2), 17-33.

Heron, A. M. (1953). The geology of central Rajputana. *Mem. Geol. Soc. Ind.*, *79*.

Hoeller, W., & Gandhi, S. M. (1995). Silver-bearing sulfosalts from the metamorphosed RampuraAgucha Zn-Pb-(ag) deposit, Rajasthan, India. *The Canadian Mineralogist*, *33*(5), 1047-1057.

Höller, W., & Gandhi, S. M. (1997).Origin of tourmaline and oxide minerals from the metamorphosed RampuraAgucha Zn-Pb-(Ag) deposit, Rajasthan, India. *Mineralogy and Petrology*, *60*(1-2), 99-119.

Holler, W., &Stumpfl, E. F. (1995). Cr-V oxides from the RampuraAguchaPb-Zn-(Ag) deposit, Rajasthan, India. *The Canadian Mineralogist*, *33*(4), 745-752.

Höller, W., Touret, J. L. R., &Stumpfl, E. F. (1996). Retrograde fluid evolution at the RampuraAguchaPb-Zn-(Ag) deposit, Rajasthan, India. *MineraliumDeposita*, *31*(3), 163-171.

Marshall, B., & Gilligan, L. B. (1987). An introduction to remobilization: information from ore-body geometry and experimental considerations. *Ore Geology Reviews*, *2*(1-3), 87-131.

Naha, K., &Halyburton, R. V. (1974) Early Precambrian stratigraphy of central and southern Rajasthan, India.*Precambrian Research*, *1*(1), 55-73.

Powar, K. B., &Patwardhan, A. M. (1984). Tectonic evolution and base-metal mineralisation in the Aravalli–Delhi belt, India. *Precambrian research*, *25*(1-3), 309-323.

Ranawat, P. S., & Sharma, N. K. (1990). Petrology and geochemistry of the Precambrian Pb-Zn deposit Rampura-Agucha, India. *Regional Metamorphism of Ore Deposits, Verlag*, 197-227.

Ranawat, P. S., Bhatnagar, S. N., & Sharma, N. K. (1988) Metamorphic character of Rampura–Agucha lead-zinc deposit, Rajasthan. *Mem Geol. Soc. India*, *7*, 397-410.

Rao, C. R., Poddar, B. C., Basu, K. K., &Dutta, A. K. (1971). Precambrian stratigraphy of Rajasthan—a review. *Rec. Geol. Surv. India*, *101*(2), 60-79.

Ray, J. N. (1982). An evaluation of the tectonic framework of Rampura-Agucha zinc-lead deposit, Bhilwara district, Rajasthan; *India Minerals,* 34(4), 19-22.

Roy, A.B. (1988). Stratigraphic and tectonic frame work of the Aravalli Mountain Range. In: Roy, A.B. (Ed.), Precambrian of the Aravalli Mountain Rajasthan, India, *Geological Society of India Mem*. 7, pp. 3-31.

Salmon, B. C., Clark, B. R., & Kelly, W. C. (1974). Sulfide Deformation Studies; II, Experimental Deformation of Galena to 2,000 Bars and 400 degrees C. *Economic Geology*, *69*(1), 1-16.

Schwartz, G. M. (1951). Classification and definitions of textures and mineral structures in ores. *Economic Geology*, *46*(6), 578-591.

Sen, S. (1970). Some problems of Precambrian geology of the central and southern Aravalli range, Rajasthan. *J. Geol. Soc. India*, *11*(3), 217-231.

Siddiquie, F. N., &Bhat, S. H. (2008).Mineragraphic Study of the Manganese Ores in Vizianagram Manganese Ores Belt (AP) India. *Journal of the Indian Association of Sedimentologist*, *27*, 87-98.

Siddiquie, F. N., Burhamuddin, K., Shaif, M., &Alam, S. (2015). Manganese ore minerals assemblages and mineral paragenesis with the help of ore petrography and XRD studies of Balaghat District, (M.P) India. *Global Journal of Science Frontier Research: Environment & Earth Sci*, *15*(3), 21-34.

Siddiquie, F.N. (2004) Metallogenesis of Manganese ores of Srikakulam- Visakhapatnam belt. *Icon Publication Pvt. Ltd*. New Delhi, 213. ISBN:81-88086-08-8

Sinha-Roy, S. (1989). Strike-slip faults and pull-apart basins in Proterozoic fold belt development in Rajasthan. *Indian Minerals*, *43*(4), 226-240.

Sugden, T.J., Deb, M. &Windley, B.F. (1990). The tectonic setting of mineralisation in the Proterozoic Aravalli–Delhi orogenic belt, NW India S.M. Naqvi (Ed.), Precambrian Continental Crust and its Economic Resources, Elsevier, New York, 367-390.

Vokes, F. M., & Craig, J. R. (1993). Post-recrystallisation mobilization phenomena in metamorphosed stratabound sulphide ores. *Mineralogical Magazine*, *57*(386), 19-28.

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