Deformation and metamorphism of gold-sulphide lodes in the Bhukia–Jagpura gold prospect, Rajasthan: Implications for ore genesis

S DEOL*, A CHATTOPADHYAY and M DEB

Department of Geology, University of Delhi, Delhi 110 007, India.

**Corresponding author. e-mail: swatideol@yahoo.com*

The role of polyphase deformation in controlling the emplacement of gold-quartz lodes in dilational regimes is demonstrated from the Proterozoic Bhukia–Jagpura gold prospect in south Rajasthan. Earlier researchers deciphered the gold-sulphide mineralisation event as synchronous to the second phase of deformation (D_2) without convincing microstructural or metamorphic evidences. In this contribution, we correlate the deformation and metamorphic imprints in the host rocks with those in the gold-sulphide mineralised zone, and present a new interpretation for the relative timing of gold emplacement *vis-à-vis* deformation. The ore-forming process first involved layer-parallel influx of ore-bearing hydrothermal fluids along S_1 schistosity in the host rocks, synkinematic with respect to the first phase of deformation (D_1). This initial ore concentration experienced metamorphism isofacially ($\sim 500^\circ\text{C}$ at 5.3 kb) along with its host rocks during D_1 , and subsequently underwent extensive remobilisation, giving rise to gold-bearing silicified lodes along the hinges and axial surfaces of F_2 folds during D_2 .

1. Introduction

In terrains with lode gold deposits, structures produced during regional deformation, especially faults/shear zones, etc., play an important role in localisation of gold by controlling the flow of the ore fluid and precipitation of the metal. Deformation and metamorphic signatures of the host rocks of gold-sulphide ores in turn help to correlate ore genesis and its emplacement with regional (and/or local) tectonothermal events. Important examples of such studies worldwide include Hill End gold field, Australia (Windh 1995); Meguma gold deposit, Nova Scotia, Canada (Horne and Culshaw 2001; Kontak and Horne 2010) and Sigma Mine, Val d'Or, Quebec (Robert and Poulsen 2001), amongst others. In Indian gold deposits, focused study on this aspect is relatively less, except in parts

of Dharwar Craton (Kolar, Hutti and Ajjanhalli), where genetic relationships between structural elements and gold have been studied (Ziauddin and Ramachandra 1963; Kolb *et al.* 2004a, b, 2005). Chattopadhyay (2010) has recently reviewed the structural characteristics of orogenic gold deposits, with special reference to Indian gold deposits, and had pointed out the need for further research in this area.

The present contribution is an attempt to analyse the influence of deformation and metamorphism on the Proterozoic lode gold-type mineralisation (*cf.* Partington and Williams 2000) in Bhukia–Jagpura area (lat.: $23^\circ 52'$; long.: $74^\circ 21'$), Banswara district, south Rajasthan. The gold-sulphide mineralisation in Bhukia area has been intensively explored since their discovery (Grover and Verma 1993). However, the relative timing and

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mode of emplacement of quartz-gold lodes have remained a matter of debate. Garhia *et al.* (2001) have suggested that sulphide-hosted gold mineralisation and associated hydrothermally altered zones characterised by intense carbonatisation, amphibolitisation and tourmalinitisation formed synchronous with early to late F_2 deformation. However, the detailed field and microstructural observations recorded in the present paper do not support this inference. Moreover, the detailed microstructural study of ore and host rocks, which is key to understand the effect of deformation on movement of ore-bearing fluids, were not dealt with in the earlier work mentioned above. The present work examines the relationship between deformation, metamorphism and gold-bearing sulphide mineralisation in the area from a holistic approach, and reinterprets the relative timing of ore emplacement in the context of the regional tectonothermal events. This also enhances our general understanding of the genesis of a structurally controlled gold-sulphide mineralisation.

2. Geological setting of Bhukia–Jagpura prospect

The Bhukia–Jagpura is located in the extreme southeastern part of Aravalli–Delhi Orogenic Belt (ADOB) (figure 1). The geology of ADOB comprises an Archean basement, the Banded Gneissic Complex (BGC), overlain by Proterozoic cover sequences (Gupta 1934; Heron 1953). In the Udaipur region, the Paleoproterozoic succession of the Aravalli–Jharol belt constitutes the type Aravalli Supergroup of rocks (figure 1). The lowermost part of the Aravalli Supergroup, lying close to its contact with the BGC, hosts the gold-sulphide mineralisation in Bhukia–Jagpura area. Sinha-Roy (1996) named this lowermost sequence as Delwara Group and subdivided it into a lower Jakham Formation and an upper Bhukia Formation. The Bhukia Formation, that hosts the gold-sulphide mineralisation, mainly comprises a carbonate sequence along with pelites and quartzites (inset in figure 1). Roy and Jakhar (2002), on the other hand, considered the lithology of Bhukia–Jagpura area to be the southeastern extension of the Jhamarkotra Formation of the lower Aravalli Group overlying the lowermost Delwara Formation. A Pb–Pb model age of galena separated from barite lenses in the Negeria volcanics was between 2150 and 2075 Ma (Deb and Thorpe 2004), and is the best age constraint available so far for the basal Aravalli mafic volcanic rocks of the Delwara Formation. U–Pb zircon and titanite analyses from quartz-albite rocks from the Bhukia mineralised zone gave an age estimate between

~1820 and ~1740 Ma (Deb and Thorpe, unpubl. data).

Dolomitic marble, well bedded calc-silicate rocks, and meta-pelites (garnet-staurolite-aluminosilicate-bearing mica schist), constitute the lithology of Bhukia–Jagpura area, along with some finely laminated tuffaceous units, tourmaline-bearing rocks, bedded albite-bearing rocks, and scarce quartzite and carbon phyllite. Scanty exposures of amphibolites and meta-ironstones are also present. The rocks in the area are intruded by a number of pegmatitic and granitic bodies. Within this lithologic package, the gold-sulphide mineralisation is associated with dolomitic marble, calc-silicate rocks, tuffaceous quartz-albite rocks, albite-rich rocks and tourmaline-bearing rocks.

Sengupta (1976) described three generations of folding (figure 2a), of which the second generation folds (F_2) control the regional structural pattern. Later Garhia *et al.* (2001) described the first folds (their AF_1) as reclined with high amplitude/wavelength ratio, and a penetrative S_1 schistosity parallel to the bedding (S_0). This schistosity is the form surface of the second generation (AF_2) asymmetric to overturned, doubly plunging folds controlling the regional map pattern, with N–S to NNW–SSE striking S_2 schistosity. F_3 has been described as broad open warps with widely spaced fracture cleavage. A major NNW–SSE striking dislocation zone (Ghatol thrust) has been described from this area, which formed between the F_2 and F_3 folding (Garhia *et al.* 2001). Mineralogical and genetic studies on this prospect have been carried out by Guha (2004) who suggested that “the sulphide–Au mineralisation was, in part, syn- to post depositional to the host rocks, and were metamorphosed later”. Golani *et al.* (1999, 2002) suggested that mantle carbon, permeating through deeper faults, was probably responsible for the gold transport and its subsequent deposition in an evaporitic repository of carbonates and quartzofeldspathic rocks. In sharp contrast, recent studies on geological characteristics of this prospect have suggested a magmatic hydrothermal process of genesis, with gold concentration taking place during regional metamorphism (Deol *et al.* 2010, 2012).

3. Deformation and metamorphism of host rocks in the mineralised zone

Deformation and metamorphism of the ores and the host rocks have been elucidated in this section at the outcrop and the microscopic scale. The effects of deformation are best manifested as penetrative foliations (e.g., S_1 and S_2 schistosity) in micaceous rocks, whereas the marble units lack any

Figure 1. Geological map of the Aravalli-Delhi orogenic belt (modified after Heron 1953 and Deb and Sarkar 1990). Inset shows geological map of Bhukia-Jagpura area, southeastern Rajasthan (modified after GSI 1994).

prominent foliation and show pervasive annealing and recrystallisation. However, superposed folds on silicate layers in impure marble units, reflect

the effect of polyphase deformation on these rocks. The earliest deformation D_1 resulted in tight to isoclinal, and commonly reclined F_1 folds at the

Figure 2. (a) Structural map of Bhukia and its adjoining area (modified after Sengupta 1976). A stereographic projection showing bedding plane poles of the F_2 folds from (b) Kundli and (c) Gundlapara. (d) The stereonet plots of the data collected from the old workings along with their sketches; old workings are mainly located within intercalated carbonate rock/calc-silicate rock and quartzite.

outcrop scale (figure 3a). As the F_1 folds are isoclinal, the S_1 schistosity is generally parallel to bedding (S_0) except at the F_1 hinges. F_1 has a

variable orientation due to reorientation by large scale F_2 folding. The second generation folds (F_2) are upright to steeply inclined (figure 3b) and show

Figure 3. Field photographs of (a) isoclinal F_1 folds in calc-silicate rock. (b) Steeply inclined F_2 fold. (c) Type II interference of F_1 and F_2 folds. The smaller fold (top of the photograph) is a boomerang-shaped interference pattern. The larger fold is also a boomerang with one side eroded out. (d) Type III hook-shaped interference of F_1 and F_2 folds. (e) Chilled margins at the contact of carbonate rock and granite comprising altered minerals parallel to the margin (near Bhukia–Ghatol road crossing). (f) A large old working subparallel to the F_2 axial plane.

moderate to steep plunge (50° – 75°) towards NNW or SSE. These folds are disharmonic in nature and are locally polyclinal, which is more common in impure laminated marble with high competency contrast between the layers (figure 3b). F_2 folds are commonly associated with silicification. F_3 folds are represented by open warps oriented at a high angle with F_2 axial planes. A set of widely spaced pressure-solution bands occur parallel to the F_3 axial planes at outcrop scale.

Excellent examples of superposed folding are observed in outcrops of dolomitic marble, west of

Bhukia. The competent silica-rich layers within carbonate matrix are deformed by both F_1 and F_2 folds and this resulted in Type II and Type III interference patterns (Ramsay and Huber 1987) depending on the local orientation of F_1 folds. Non-coaxial, non-coplanar overprinting of F_2 folds over F_1 folds leads to a non-planar, non-cylindrical (Type II) interference pattern, whereas coaxial, non-coplanar interference results in cylindrical non-planar (Type III) interference folds. The Type II superposition (*cf.* Ramsay and Huber 1987) forms mushroom-shaped or

Figure 4. Photomicrographs showing: (a) alternate parallel bands (parallel to S_0/S_1 surfaces) of carbonate-rich, albite-rich and biotite-rich layers in a highly altered carbonate rock (under transmitted light). (b) Flattened grains of albite, muscovite, tourmaline, quartz and fine opaque grains displaying S_1 schistosity (under transmitted light). (c) Tremolite-rich rock showing blade-shaped grains of tremolite arranged in an irregular manner (under transmitted light). (d) Spaced foliation, where quartzofeldspathic mass (microlithons) alternates with the phyllosilicates (crenulation cleavage). Relict folding (on S_1) is present in between the parallel layers of phyllosilicates (S_2). Folding of S_2 during third phase of folding is seen as broad warps (under transmitted light). (e) Subhedral to anhedral coarse porphyroblasts of highly fractured arsenopyrite within a mass of pyrrhotite. Fractures in arsenopyrite are filled up by pyrrhotite (under reflected light). (f) Thin veins comprising chalcopyrite and pyrrhotite within highly fractured and deformed grain of arsenopyrite. Fine grain of gold ($\sim 2.5 \mu\text{m}$) is present, within the veins, in association with chalcopyrite (under reflected light). (g) Remobilisation of chalcopyrite along F_2 fold axis in a quartz-albite rock (under transmitted light). (h) Remobilisation of pyrrhotite mass along the hinges and axes of F_2 micro-folds in a tourmaline-bearing rock (under transmitted light).

boomerang-shaped outcrop pattern (figure 3c), in which both the hinge line and the axial surface of F_1 folds are curved. In Type III hook-shaped interference pattern, the hinge lines of F_1 and F_2 folds are straight and parallel, but the axial surface (S_1) is curved/folded (figure 3d).

Regional structural mapping was beyond the scope of the present study. However, different structural features (e.g., fold axis, bedding, cleavage) measured during regional traverses in the study area are consistent with that of the regional fold patterns described by earlier researchers such as Sengupta (1976). The bedding plane (S_0/S_1) poles for Kundli hill, lying south of Bhukia, fall on a somewhat diffused girdle, showing a best-fit β -axis plunge of $53^\circ \rightarrow 189^\circ$ for the large scale (F_2) folds (figure 2b). Stereo-net plots of bedding/cleavage data of F_2 folds from the northern part of Bhukia show a southerly plunge of the F_2 axis (figure 2d), while F_2 folds from Gundlapara show northerly axial plunge (figure 2c). These variations of F_2 fold axes on regional scale indicate large scale non-cylindrical nature of F_2 folds, consistent with the observations of Garhia *et al.* (2001). It may be noted here that F_2 folds are non-cylindrical in outcrop scale also, mainly due to superposition of open F_3 folds over F_2 .

Geothermobarometric calculations using metapelitic mineral assemblage of garnet + biotite + muscovite + plagioclase + chlorite + quartz, (defining S_1 fabric) indicate that peak metamorphism was synchronous with the first phase of deformation (D_1) at $\sim 500^\circ\text{C}$ and 5.3 kb, suggesting amphibolite facies regional metamorphism (see Deol *et al.* 2010 for details). Multi-equilibrium geothermobarometry of the late cross cutting calcite veins, associated with Ca-amphibole, chlorite, biotite, plagioclase, talc and sulphides (pyrite, pyrrhotite and arsenopyrite), gave P–T estimates of 470°C and 3.2 kb and represent late stage retrogression with hydrothermal activity (Deol 2010). In the absence of an unambiguous textural relationship between D_2 and the retrograde metamorphic mineral assemblage, it can only be suggested that D_2 post-dated the regional peak (syn- D_1), metamorphism and occurred on its retrograde metamorphic path.

4. Nature of hydrothermal alteration and gold-sulphide mineralisation

Carbonate-rich rocks, calc-silicate-, albite- and tourmaline-bearing rocks are the most common host rocks for gold-sulphide mineralisation in Bhukia–Jagpura prospect, which are gradational with each other at all scales (Deol *et al.* 2010). The whole metasedimentary sequence is intruded

by a number of synkinematic pegmatite and granite bodies often present along the S_1 schistosity (figure 3e).

Protoliths of the host rocks were affected by hydrothermal alteration, represented by multiple phases of Na-, B- and Si-metasomatism. The presence of cross cutting veins of tourmaline and albite in tourmaline-bearing quartz-albite rocks, and alternate bands of very fine and fine albite grains in albite-rich rocks suggests the possibility of more than one phase of albitisation and tourmalinitisation. Albitisation of the host rocks is ubiquitous, which is also seen in the clastic country rocks, such as in the metapelites. The alteration minerals, such as calcic-amphibole, phlogopite, muscovite, chlorite, secondary calcite, epidote, allanite, titanite, and flattened albite, tourmaline as well as ilmenite and rare magnetite, are arranged parallel to S_0/S_1 surfaces (figure 4a and b). This style of alteration often shows sharp contact, varying from μm to cm scale, and is associated with scanty silicification. However, at places, these alteration bands do not maintain parallelism and show undulatory and diffused contacts. Radiating to irregular, decussate arrangement of graphite, muscovite and calcic-amphiboles represent relict signature of a thermal effect, possibly due to the granitic intrusion in the area. These domains are not overprinted by otherwise pervasive S_1 schistosity (figure 4c).

In borehole samples, four styles of mineralisation were identified: (1) patchy/stringery, (2) banded, (3) vein, and (4) massive type. Patchy/stringery type mineralisation (figure 5b) contains irregular masses of pyrrhotite, arsenopyrite, and rare chalcopyrite within albite-bearing calc-silicate rocks. Banded type mineralisation (figure 5a) is present as fine to medium alternating bands of pyrrhotite or arsenopyrite within calc-silicate or tourmaline-rich host rocks. It is also associated with hydrothermal alteration parallel to the S_1 -surface in the carbonate host rocks, showing fine parallel bands of calc-silicate minerals. Vein type mineralisation (figure 5c) includes veins of fine- to medium-grained quartz and sulphides (pyrrhotite) that cut the host rock fabric at a high angle. Massive type mineralisation (figure 5d) contains greater than 60% sulphides represented by pyrrhotite, chalcopyrite, and coarse-grained arsenopyrite, with coarse to medium grained patches of quartz and various host rock fragments.

5. Deformation and metamorphism in the ore zone

Due to the paucity of exposed ore bodies and absence of proper mine face in the area, the old workings have been used to deduce the

Figure 5. Borehole samples showing (a) sharp contact of calc-silicate rock and dolomitic marble; at the contact boudinaged amphibole-rich layer can be seen. Pyrrhotite, within calc-silicate rock and albite veins, is present parallel to S_0/S_1 surfaces. (b) Patches of pyrrhotite and calc-silicate minerals within dolomitic marble. (c) Vein of quartz, along with pyrrhotite, cross cutting the calc-silicate rock. (d) Rounded and ellipsoidal grains of arsenopyrite in association with rounded patches of host rocks in massive pyrrhotite showing durchbewegt texture.

3-dimensional disposition of the mineralised zones and its relation with the structures. About 50 old workings and prospecting pits are reported within a 6 km² area around Bhukia village (Grover and Verma 1993), covering all the three potential prospects, Bhukia, Jagpura and Gundlapara. On a regional scale, the old workings generally follow a NNW–SSE trending linear pattern on the map, parallel to the axial traces of the F_2 folds (figure 6). On a transverse section, these old workings appear to have been dug along the axial planes of F_2 folds plunging either to the NNW or SSE. This is highlighted in an ENE–WSW oriented geological section (figure 7), where the ore bodies appear irregular, lensoid and subparallel to the S_2 (striking N–S) with the largest ore body having a surface expression in a large old working, about 70 m in length and 10 m in width (figure 3f). A set of circular to elliptical shaped old workings have also been observed at the hinge zone of F_2 folds especially

along the contact of calc-silicate and quartzite litho units (figure 2d). These observations suggest that in 3-dimension, these old workings are parallel to the axial plane (S_2) and are possibly elongated parallel to F_2 fold axis.

Mesoscopic and microscopic observations from drill core samples reveal the imprints of D_1 and D_2 on the host rocks and associated Au-bearing sulphides. The patchy/stringery and banded types of mineralisation, discussed above, are stratiform and are accompanied by hydrothermal alteration parallel to S_0/S_1 surfaces. Silicification is rarely observed in these stratiform ores. In contrast, the vein and massive type mineralisation occur as medium to coarse-grained sulphides transecting the S_0/S_1 surfaces and are mainly associated with the large scale silicification. The last two styles of mineralisation are often associated with brecciation, where mineralisation is present within the intergranular spaces of brecciated clasts. Rounded and ellipsoidal

Figure 6. Plan view of some of the old workings in Bhukia mineralised zone (after Metal Mining India Ltd.).

grains of arsenopyrite along with rounded patches of rolled host rocks in massive pyrrhotite mass (figure 5d) define a ‘durchbeweget’ texture (Vokes 1969).

Under the microscope, the schistose metapelitic rocks display well-developed spaced cleavage (S_2), where unfoliated microlithons (quartz and plagioclase) alternate with strong cleavage domains (muscovite + chlorite). Relict microfolds, representing folded S_1 schistosity, are present in the microlithons of S_2 confirming S_2 is a second generation crenulation cleavage. Weak folding of S_2 indicates the imprints of later D_3 deformation (figure 4d). Parallel bands of sulphides, viz., arsenopyrite, pyrrhotite and chalcopyrite; oxides, viz., ilmenite, magnetite and titanite along with silicates and carbonates suggest hydrothermal alteration and concomitant stratiform mineralisation parallel to S_0/S_1 (figure 4a and b).

The discordant style of mineralisation (vein- and massive-types) exhibits deformation, recrystallisation and coarsening of the sulphides and

the associated silicate and carbonate minerals. The deformation-induced recrystallisation resulted in coarsening and grain growth of arsenopyrite, pyrrhotite and chalcopyrite, and also caused development of triple junction points in pyrrhotite. Due to continued deformation, the recrystallised coarse grained arsenopyrites were affected by brittle fracturing and protoclastic granulation along the margins (figure 4e). However, the softer minerals like pyrrhotite and chalcopyrite showed ductile behaviour during deformation, relocating themselves within the fractures in arsenopyrite (figure 4e), thereby manifesting contrasting deformation behaviour due to rheological difference. Such highly fractured coarse grains of arsenopyrite and the development of deformation lamellae in the subgrains of pyrrhotite suggest that the deformation outlasted grain growth and recrystallisation.

Gold is present as fine grains either as inclusions within coarse grains of arsenopyrite or within the fractures of arsenopyrite, in association with pyrrhotite and chalcopyrite (figure 4f). Within

Figure 7. Transverse section showing the disposition of ore bodies at depth, subparallel to the trend of the F_2 fold axis. Dashed/dotted lines indicate conjectured orientation of the regional F_2 folds.

arsenopyrite, gold is often found as inclusions along with loellingite, pyrrhotite, wehrlite (Bi–Te alloy), and maldonite (Au–Bi alloy) (Deol *et al.* 2012). Pyrrhotite/chalcopryrite is also seen along the axial planes (figure 4g) and at the hinge zones of F_2 micro-folds (figure 4h), further confirming the remobilisation of the sulphides during D_2 .

In the studied samples of the Bhukia–Jagpura prospect, invisible gold is identified by LA-ICPMS only in pyrites with low Ni:Co ratio (Ni:Co < 1), and in Co-rich arsenopyrites and loellingite (Deol *et al.* 2012). This trace element signature precludes the possibility of these Au-bearing pyrites being sedimentary-diagenetic in origin (Loftus-Hills and Solomon 1967; Mookherjee and Philip 1979). In contrast, sedimentary-diagenetic pyrites (Ni:Co > 1) are very rarely observed in these samples and they are completely devoid of invisible gold. This strongly supports the idea that the Au-mineralisation in Bhukia–Jagpura area is epigenetic hydrothermal and not syn-genetic in nature.

On the basis of association and mineral chemistry, two different varieties of arsenopyrite (I and II) have been identified: arsenopyrite-I as inclusions within loellingite, rimmed by pyrrhotite,

representing the prograde metamorphic assemblage (*cf.* Tomkins and Mavrogenes 2001), and arsenopyrite-II forming a reaction rim surrounding loellingite, in turn rimmed by pyrrhotite, characteristic of the retrograde metamorphic assemblage (*cf.* Neumayr *et al.* 1993). Using arsenopyrite thermometry (formulations of Kretschmar and Scott 1976; Sharp *et al.* 1985), the temperature obtained from the prograde assemblage ranges between 550° and 530°C, whereas the retrograde assemblage yields temperature range between 460° and 474°C (Deol *et al.* 2012).

Thus it can be suggested that patchy and banded styles of mineralisation accompanying hydrothermal alteration in the host rocks occurred by fluid ingress along pervasive S_1 schistosity during early syn- D_1 phase. The metamorphic fabric and the peak metamorphic temperature obtained from the ores (490°–570°C), which is comparable to those obtained from silicate thermometry of the host rocks (~500°C at 5.3 kb), indicate that the ore and the host rocks were isofacially metamorphosed during D_1 at amphibolite facies conditions.

Massive and vein type mineralisation, on the other hand, are mainly associated with large scale

silicification discordant to S_0/S_1 fabric and parallel to S_2 indicating their syn- D_2 development. Presence of sulphides within the fractures of arsenopyrite and intergranular spaces of silicate and carbonate minerals, and along axial traces and hinge zones of F_2 crenulations in microscopic scales is suggestive of remobilisation of the ore during this phase. The occurrence of fine gold grains within the fractures of arsenopyrite healed by pyrrhotite and chalcopyrite possibly suggests the extraction of the metal from arsenopyrite host and its subsequent remobilisation with the ductile sulphides during D_2 . Old workings in the area also strike parallel to the axial trace of the F_2 folds and are elongated along their hinge zones. The mineralisation is not specific to any lithological type and is observed along the lithological contacts suggesting that these contacts have acted as favourable conduits for the mobilisation/remobilisation of the ore fluid. The retrograde P–T condition of the host rocks is estimated at $\sim 470^\circ\text{C}$, 3.2 kb and retrograde temperatures for ores range between 460 and 474°C . It needs to be mentioned that the exact position of D_2 on the metamorphic retrograde path cannot be constrained due to the lack of retrograde textures in silicates. The lowest retrograde metamorphic temperature of the ores can be further traced to 241°C and to $\sim 116^\circ\text{C}$ (Deol *et al.* 2012).

6. Discussion

Although the Bhukia–Jagpura gold-sulphide prospect has been the subject of research by various researchers, the ore genetic study has not been

dealt with a holistic approach. So far, the relationship between ore and host rocks, the extent and effect of metamorphism in the area, the role of structure in the formation/transformation of ore, timing of ore emplacement *vis-à-vis* deformation and metamorphism, etc., are not clearly established. In this respect, the relationship between regional deformation, metamorphism and gold-sulphide mineralisation in Bhukia–Jagpura area has been established in the present study from the spatial distribution of mineralised zones with respect to the macroscopic, mesoscopic and microscopic structural patterns, as described above.

Compiling all the observations documented in this paper, it is suggested that gold-sulphide mineralisation in Bhukia–Jagpura area is emplaced by structurally controlled epigenetic processes. The gold-bearing sulphides accompanying hydrothermal alteration formed parallel to S_1 during the first deformation (D_1). The sulphides, silicates and carbonates underwent isofacial regional metamorphism under amphibolite facies conditions during D_1 (figure 8a). The S_0/S_1 parallel arrangement of alteration minerals, such as calcic-amphiboles, biotite, muscovite, and flattened albite and tourmaline, confirms that alteration is early syn- D_1 and did not post-date the D_1 metamorphism. The presence of calcic-amphiboles and albite, showing enhancement of An component (up to 11%) (Deol 2010), suggests that the alteration assemblage was stable at the P–T conditions of D_1 metamorphism under amphibolite facies.

The syn- D_1 granite intrusion possibly acted as a local heat source for hydrothermal fluid circulation. The decussate texture of graphite, muscovite and

Figure 8. Cartoon showing relationship of mineralisation with different phases of deformation and associated metamorphism.

calcic-amphiboles are not overprinted by otherwise pervasive S_1 schistosity (figure 4c). This indicates that thermal effects from granite emplacement may have outlasted D_1 deformation.

The sulphides were later remobilised and further concentrated during the subsequent phase of deformation (D_2) at the hinges and along the axial planes of F_2 folds (figure 8b). This is in contrast to the views of previous authors, such as Garhia et al. (2001), who suggested that mineralisation and associated hydrothermal alteration were synchronous with early to 'late F_2 -deformation', and Guha (2004), who negated the hydrothermal replacement hypothesis of metal genesis and its concentration.

The inferences regarding structural control of gold-sulphide mineralisation and their remobilisation, as brought in the present contribution, will be useful during future regional exploration and eventual exploitation of the prospect, and for the understanding of its genesis.

7. Conclusions

- Gold-sulphide mineralisation in the Bhukia-Jagpura is structurally controlled. Preferred orientation of sulphide grains and associated alteration along S_0/S_1 surfaces, presence of syntectonic granite (with respect to D_1) and temperatures of $\sim 550^\circ\text{C}$ calculated from the metamorphosed ore assemblages indicate that alteration related mineralisation, peak phase of metamorphism and granite intrusion are broadly early synchronous to D_1 , and not synchronous to D_2 as suggested by some researchers previously.
- The gold-sulphide mineralisation was remobilised during subsequent D_2 -deformation and concentrated as silicified lodes at the hinge zones and along the axial planes of the F_2 folds. These sites can be the favourable targets for the exploitation of ore in future.

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