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The Sargipali sulphide deposit of Orissa, India: its atypical lead-high character and genesis

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ABSTRACT

The sulphide deposit of Sargipali, in the Proterozoic fold belt of Gangpur, is strikingly lead dominant in character. It has an ore reserve of 2.06 million tonnes with an average grade of 6.73% Pb and 0.33% Cu, with a little Ag (about 50 ppm). The Zn content in the ore is insignificant (<0.5%), below recoverable limit.

The unusual compositional character of the deposit will be evident when compared with that of many known sulphide deposits. Pb- and S- isotope studies reveal extreme uniformity of Pb isotope composition, along with high source μ ($^{238}U/^{204}Pb$) value of Pb,which suggest a single- stage lead, derived from isotopically homogeneous, uranium enriched, felsic upper crustal source, though sulphur was derived from reduction of contemporary sea water sulphate source. However,the Pb- isotope study may well indicate that the Sargipali is a 1682-1695- Ma- old sedimentary- exhalative (SEDEX) deposit. The petrographic and chemical studies of ore and host rocks indicate the metamorphosed synsedimentary-exhalative genesis of the deposit.The abnormal enrichment of Pb in the residual fluid is suggested to have caused by the buffering of metal containing hydrothermal fluids by mica present in the felsic rocks or sediments, to a low pH at relatively low temperature. Pb-Pb ages of ores (ranging between 1682-1695 Ma) suggest that mineralisation occurred during the closing phase of sedimentation in the Gangpur basin.

The present study may help in throwing new light about the genesis of similar sediment- hosted Pb-rich deposists in terms of the SEDEX model.

INTRODUCTION

The sulphide deposit of Sargipali occurs in the Proterozoic fold belt of Gangpur in eastern India, south of the northern mobile belt (Fig. 1). The mineralisation at Sargipali is known from the ancient past, as evidenced by the presence of numerous old workings and slag heaps scattered along an arcuate belt in the area. Ball (1877) first reported the occurrence of galena pebbles from south-east of Sargipali. Later, Krishnan (1973) located the deposit at Sargipali. From 1966 to 1972 the Geological Survey of India undertook the systematic exploration programme, and then Hindustan Zinc Limited took over the operation in 1974. From 1983, the production of ore was carried out.

Exploration carried out so far, has confirmed the presence of a potentially mineralised zone at Sargipali having a strike length of about 2.5 km. The mine extends from Bharatpur (22° 05' N: 83° 56' E) in the east to Lokdega (22° 02' N: 83° 55' E) village in the west covering a strike length of approximately 2 km of the mineralised zone (Fig. 2). A depth of 90 m from the surface has already been reached through five levels. The ore reserve, based on the toal drilling coverage of 14,087 m in 100 boreholes, is of the order of 2.06 million tonnes having an average grade of 6.73% Pb, 0.33% Cu and about 50 ppm Ag (unpublished report of HZL; Pattnaik and Raju 1990). The Zn content in the ore is insignificant (the average grade being 0.4%, Sarkar 1974), below recoverable limit. The Pb/Zn ratio of the ore is unusually high and geochemically rare, in comparison to many other sulphide deposits (Fig. 3). The deposits of primary sedimentary affiliation and the SEDEX deposits commonly contain more Zn in proportion to Pb (Sangster 1990) than does the Sargipali deposit. In Stanton's classification (Stanton 1972) the Pb-Cu association is also not common in the stratiform sulphides of marine and marine- volcanic association. Also, volcanogenic massive (VMS) deposits do not usually show such high Pb content relative to the contents of Zn and Cu (Franklin 1986). For this reason, the subject of evolution of the deposit is still a matter of discussion. Two extreme views persist about the origin of the deposit, *viz.* an epigenetic and a syngenetic one. On the basis of composition alone, one would judge that Sargipali must not be a SEDEX deposit. Because one would expect Mississippi Valley type deposits, some of which have significant Cu and relatively little Zn, that has been sheared out during intensive deformation. One would consider it could posibly be a metasomatic type of deposit, similar to some of the skarn deposits in Mexico that are very stratiform and termed 'mantos'. The Pb-(Cu) character of the Sargipali deposit also resembles to the vein type Pb-Cu-(Zn) deposits of the world. However, Pb-rich deposits in sediments occur often close to a granitic basement (Laisvall, SE Missouri) or in magmatic hydrothermal deposits.

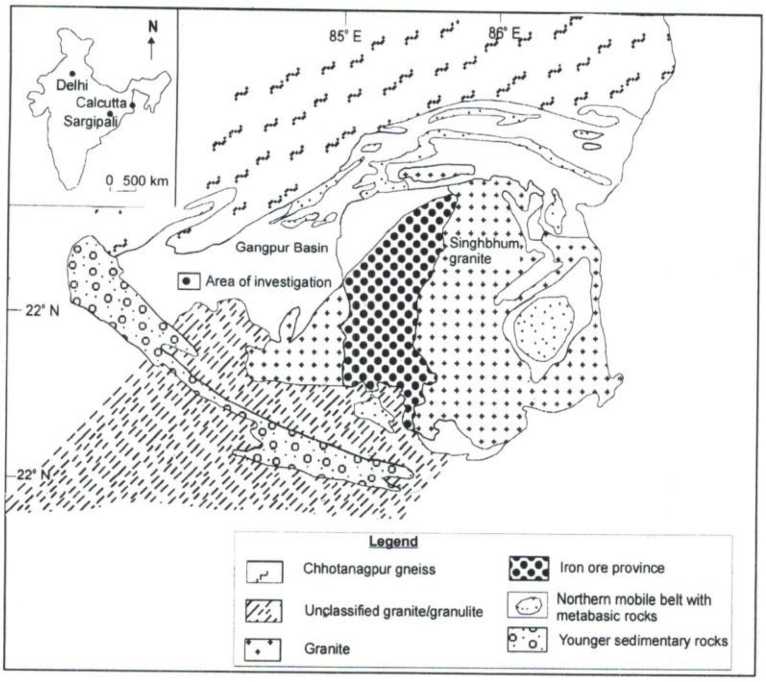


Fig. 1: Generalised geological map of eastern Indian shield (after Naha and Mukhopadhyoy 1990) showing the area of investigation around Sargipali.

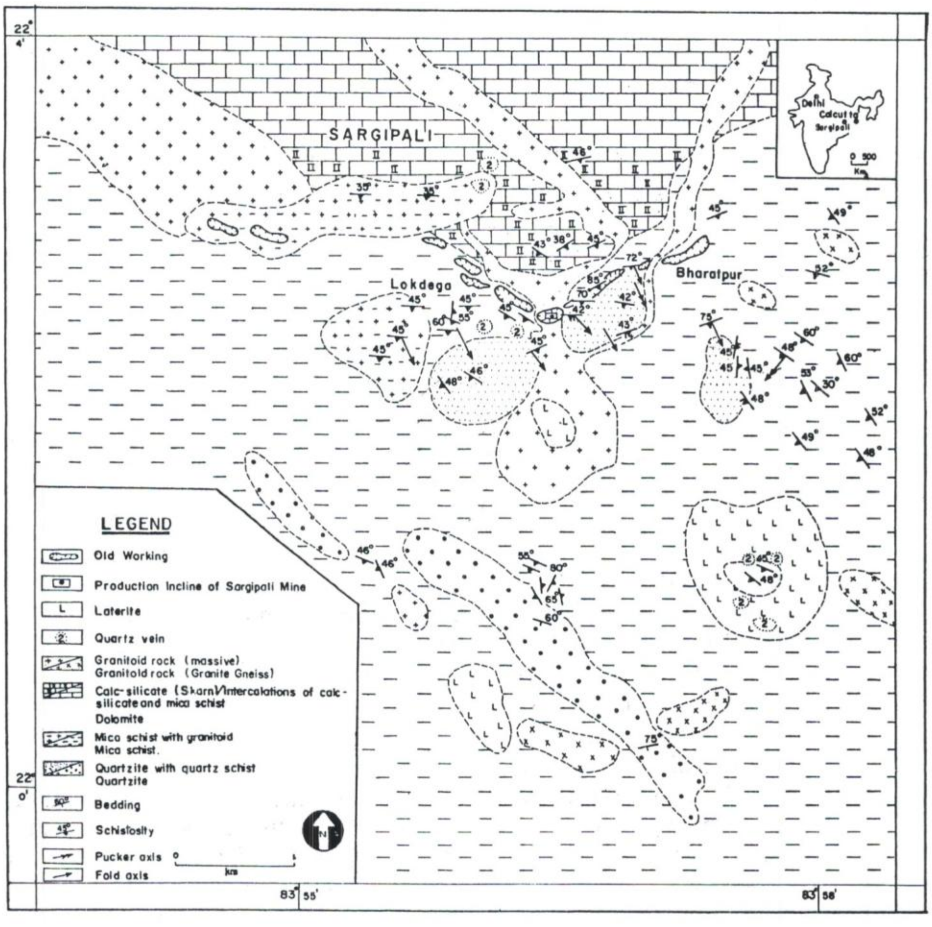


Fig. 2: Geological map of the Sargipali area showing intrusive nature of granitoid.

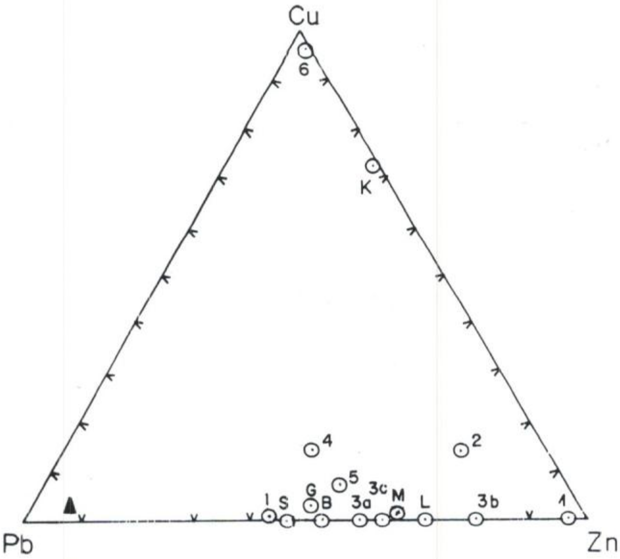


Fig. 3: Pb-Zn-Cu ternary diagram showing the plots of some important sulphide deposits (after different sources) and also of Sargipali deposit. Indian deposits: 1. Rampura-Agucha; 2. Rajpura-Dariba; 3. Zawar- (a) Nadia (b) Balaria and (c) Zawarmala; 4. Ambaji; 5. Deri; 6. Khetri; ▲: Sargipali; Other deposits:- Australia-Mt. Isa, M: Mc. Arthur, L: Lady Lortta Loretta, B: Broken Hill; Canada-S: Sullivan; Japan-K: Kuroko; Greece-G: Madem Lakkos.

Considering the geological-tectonic and mineralogical-geochemical relationship of the host rock and the ore, Rajarajan et al. (1968), Rajarajan (1978), Roy (1983), and Roy et al. (1994) suggested a hydrothermal metallogenic model for the Sargipali sulphide deposit. Rajarajan et al. (1968) and Rajarajan (1978) suggested that the hydrothermally originised quartz-pegmatite veins serve as the ore-carriers for the mineralisation along a suspected shear zone. Roy (1983) apparently interpreted the 'granite' as albite-greisen, and considered the deposit to be of metasomatic-greisen origin. Later Roy et al. (1994) suggested a pneumatolitic hydrothermal environment of formation of the deposit.

On the contrary, considering the stratified and stratabound nature of the Sargipali deposit, the isofacial metamorphism of ore and host rock, variation of ore mineals with variation of sedimentary facies, and the absence of wall rock alteration, Kar Ray (1973), Sarkar (1974) and Pattnaik and Raju (1990) suggested a syngenetic ore depositional model. Though Sarkar (1974) described it as strictly a stratabound syngenetic deposit, and according to him the remobilisation and reconcentration of the ore was not influenced by the granitic activity in the area, from his figure 1, the relationship of the ore body to granitoid rocks is puzzling and nebulous. Sarkar (1974) further suggested that the ore material may be derived from adjacent terrestrial sources during the weathering cycle, but based on Pb- and S-isotope studies Vishwakarma and Ulabhaje (1991) and Ghosh et al. (1999) suggested a synsedimentary- exhalative (SEDEX) genesis of the deposit, in which single-stage lead, derived from isotopically homogeneous, uranium enriched, felsic upper crustral source, though sulphur was derived from reduction of contemporary sea water sulphate source.

As the deposit has unusual compositional character, and diverse opinions have been expressed on the genesis of this deposit, the present study aims to understand the nature and origin of sulphide mineralisation of the Sargipali area with particular reference to its lead dominant character. A satisfactory work not only solve the above-mentioned problems of this deposit, but also may help in throwing light about the genesis of the similar Pb-rich deposits.

GEOLOGICAL SETTING

The pioneering contribution was made by Krishnan (1973) on various geological aspects including stratigraphy, structure, metamorphism and mineralisation in the Gangpur basin. Later Rajarajan (1978), Kar Ray (1973), Kar Ray et al. (1971), Sarkar (1974) and Roy (1983) made some studies on the geology of the Sargipali area with reference to sulphide mineralisation.

The rocks of the area belong to the upper part of the Gangpur 'Series', and stratigraphically overlie the 'Iron Ore Series' of rocks (Kanungo and Mahalik 1967; Sarkar 1968). These rocks are chiefly represented by a metaseimentary sequence of pelitic, psammitic and calc-silicate units, with granitoid intrusives. The contacts of all the rock types are gradational, except the granitoid rock which has sharp contact with the other rocks. Presence of a thin band of epidote-chlorite schist in the deeper mine level to the north of the mineralised schist indicates its basic affinity. Endoskarn has been developed at the contact of dolomite and granitoid rocks. The conspicuous feature of this area is the presence of tourmaline-quartz schist (Tourmalinite) in which tourmaline- sulphide layers alternate with the quartz layers, cherty laminations and rich proportions of actinolite minerals in quartzite. Primary sedimentary structures like current bedding are preserved in the quartzites. The truncated top of this current bedding is directed to the opposite of the dip direction of the quartzites, indicating reverse stratigraphy of the area (Table 1).

Mica schist

This rock is widely distributed in the present area, but often covered by soil and laterite. Mica schist in the mineralised zone is garnetiferous, while south of the mineralised zone, garnet is totally absent in the mica schist. Mineralogically, the rock is divisible into eight sub- units which are not mappable in the field. These sub-units vary from muscovite-biotite schist to biotite-muscovite schist with presence or absence of various minerals like garnet, kyanite, sillimanite, chlorite, potash feldspar and plagioclase. The garnet- biotite schist is the host rock of all economic concentrations of ores. Two schistosity planes (prominent S_1 and crude S_2) are present in the mica schist. S_1 is defined by the parallel alignment of biotite, muscovite, chlorite,

Table 1: Geological succession of rocks of the Sargipali area

Recent		**Soil and alluvium**
Sub-Recent to Recent		**Laterite**
		Unconformity
PRE-CAMBRIAN (PROTEROZOIC)	GANGPUR GROUP	Pegmatite and quartz vein
		Granite and Pegmatoid granite
		Epidote - chlorite schist (? metamorphosed amphibolite)
		Dolomite interbanded with limestone, hornblende-hornfelses and skarns (developed at the dolomite-granitoid contact)
		Intercalations of mica schist and calc-silicate skarn;dolomite and schist interlayered
		Mica schist with variants e.g., garnet-biotite schist, epidote -quartz-mica schist, biotite-muscovite schist, muscovite-biotite schist, chlorite-mica schist, garnet-chlorite-quartz-sericite-muscovite schist and garnet-kyanite-sillimanite-mica schist.
		Intercalations of mica schist and quartz-tourmaline schist (tourmaline).
		Quartzite and Quartz schist
	Basement not exposed	

tourmaline and porphyroblastic aggregates of fine fibrous sericite which is the pseudomorph after kyanite (Ghosh 1998), and S_2 is defined by the parallel alignment of biotite, muscovite, tourmaline, kyanite and sillimanite. This schistose rock is the metamorphosed product of pelitic and semi-pelitic rocks ranging in composition from quartzwacke to qurtzose clay, and aluminium rich clay and shales to feldspathic clay (Ghosh 1998).

Quartzite and quartz schist

Quartzite, grading occasionally to quartz schist, occurs in the ridges and hillocks of the Sargipali area. Quartzite is very fine grained and cherty in nature. Laminations of cherts also occur in the quartzites. Quartz schists often show bands alternating quartz-rich and tourmaline-mica- rich laminae (thickness ~ 1cm) parallel to the lithological layering. Rounded to subrounded tourmaline grains with modal content of more than 20% in this schist resembling a similar situation as in the bedded tourmalinite (Plimer 1986), and the rock indicates relict primary sedimentry bedding. Quartzite and quartz schist are barren to any sulphide mineralisation, but tourmalinite in the ore zone show close association of tourmaline needles with the disseminated galena. Presence of cherty laminations, actinolite (with epidote and chlorite) and albitic plagioclase in quartzite and quartz schist indicate the derivation of these rocks from greywacke that initialy had a significant component of volcanic rock fragments (William et al. 1985).

Dolomite and calc-silicate skarn

Dolomite occur in the northern part of the area, but not well- exposed on the surface. The rock consists chiefly of dolomite with subsidiary calcite, tremolite diopside, quartz, microline and a little ilmenite. Interestingly, buff coloured skarn rocks which are usually massive, but also grade to a schistose variety near to the ore zone, have developed at the dolomite-granitoid contact. From the petrographic as well as petrochemical study, metasomatic alteration of dolomite forming endoskarn, at the contact of granitoid rock appears clear (Ghosh 1998). These rocks are lacking of economic sulphide mineralisation. Minor pyrite and chalcopyrite are the only sulphides associated with this stage of metasomatism. The presence of minor ilmenite has also been noted in the garnet-diopside-actinolite-sphene-plagioclase-microcline assemblage.

Granitoid rock

Granitoid rock, an important lithounit of this area, shows well developed foliation in the marginal eastern part but appears massive in the western part. However, it has an overall intrusive relationship with other rock types including mineralised mica schist, and barren to sulphide mineralisation. It divides the ore body into eastern and western zones. Mineralogical variation and geochemical parameters indicate that this granitoid rock is a true 'granite' and is calc-alkaline in character showing distinct trend of fractionation. This rock exhibits 'S'-type geochemistry and is probably derived from psammopelites which are quite often observed in the area of study. The granitic melt could be formed in a compressional tectonic regime indicating compressive orogenic set up (Ghosh 1998).

Sarkar (1980) suggested that sedimentation in Gangpur belt took place between 1700 Ma and 2000 Ma. It has also been suggested that the age of granitoid intrusion is about 850 Ma (Sarkar 1972; 1983).

The rocks of the Sargipali area constitute the limb of a major fold. This major fold is a regional structure, the exact nature of which cannot be determined in the study area due to granitoid intrusion and the recent alluvial cover. However, Krishnan (1973) suggested that the rocks of the Gangpur basin are folded into an ENE-WSW trending anticlinorium pitching towards east. Banerjee (1968) is of opinion that an easterly plunging regional reclined fold later re-folded into an antiform. While later workers (Kanungo and Mahalik 1967; Sarkar 1968; Chaudhuri and Pal 1983) proposed an opposite view suggesting that the Gangpur rocks are folded into a synclinorium plunging westward. The synclinal nature of the main fold is suggested in the present study by the northerly younging direction of the southern limb (direction of the truncated top of the current bedding is opposite to the dip direction of the southern limb).

In the Sargipali area the axial plane schistosity (S_1) strikes WNW -ESE to NNW-SSE in the extreme eastern part with moderate dip towards SW, then the direction changes to N-S in the central part, and dipping moderately towards in both E and W. Then S_1 again takes a turn toWNW in the western part and finally to E-W with a moderate to steep dip towards SW and S. Therefore, a swinging pattern of schistosity indicates the presence of a major fold, with the direction of S_1 changing to N-S at the fold closures (Fig. 2). Colour and compositional banding as seen in a few quartzites and quartz schists may be considered to represent relict primary bedding (S_0) which is almost parallel to S_1. On the basis of K-Ar radiometric data, Sarkar et al. (1969) suggested that the time of deformation corresponds to either 893-993 Ma (determined on whole-rock biotite-phyllite) or 866-912 Ma (determined on muscovite of muscovite schist).

The rocks of the area are metamorphosed, the metamorphism ranging from greenschist facies to amphibolite facies. The mica schist of the ore zone (characterised by the abundance of spessartine-rich almandine, and the presence of occassional kyanite and sillimanite, absence of primary chlorite and staurolite) and dolomite, north of the ore zone (abundance of diopside in the skarns) show amphibolite-facies metamorphism. Presence of both kyanite and sillimanite in the mica schist under the same P-T regime would indicate that the maximum temperature and pressure conditions of metamorphism attained in the area are between 500° to 600° C and 5 to 6 kb, respectively. Quartz schist and other mica schist which occur south of the ore zone, indicate quartz-albite-muscovite-chlorite subfacies of green-schist facies metamorphism. The retrogressive effects are not very conspicuous in the area. The indications of thermal metamorphism in the area are noted in the mica schist at its contact with granitoid. The fine grained massive hornblende-hornfels which occur near to the granitoid contact seems to be the early thermal metamorphic product of impure carbonate lithologies.

At the last stage of granitoid intrusion, which gave rise to pegmatites, locally metasomatism of mica schist and dolomite took place at the immediate contact of the granitoid. Metasomatism of dolomite at the contact of granitoid caused the formation of endoskarn.

ORE BODIES

Ten stratabound ore lenses constitute the ore body whose central part is characterised by large scale granitoid activity. Apophyses of this granitoid rock are also present both in the eastern as well as in the western parts (Fig. 4). The strike of the ore lenses changes from NNE-SSW in the extreme eastern part to ENE-WSW in the eastern part with moderate dip towards SE. In the central part the srike of the ore lenses is almost E-W which finally turns towards WNW-ESE in the western part with moderate dip towards SW. Individual lenses usually extend from about 100 m to a little over 600 m and the width varies from 4 m to 14 m. Because of the presence of granitoid body which widens along depth, the length of the ore lenses decrease with depth. Out of the 10 lenses, the W-4 lense represent the main ore body at Sargipali, and the present study is confined mainly to this lense.

The ore lenses are conformable with the host schists (Fig. 5a, b). The mineralisation is mainly banded, which is characterised by an alternate disposition of sulphide and silicate layers even in micro scales (Fig. 6a, b) reflecting a stratiform nature. Locally, however, ore veins occur discordant to the schistosity, filling fractures of host rocks. Some sulphides also occur associated with coarse quartz aggregates. Besides, minor disseminations of sulphides are

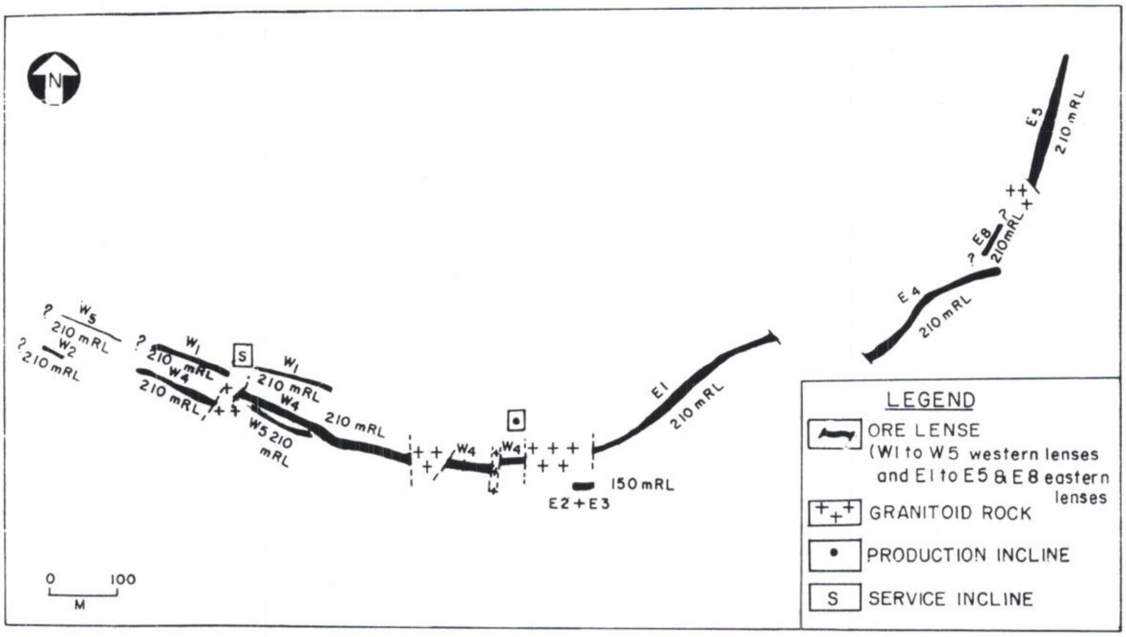


Fig. 4: Ore body disposition at Sargipali mine (after Pattnaik and Raju 1990).

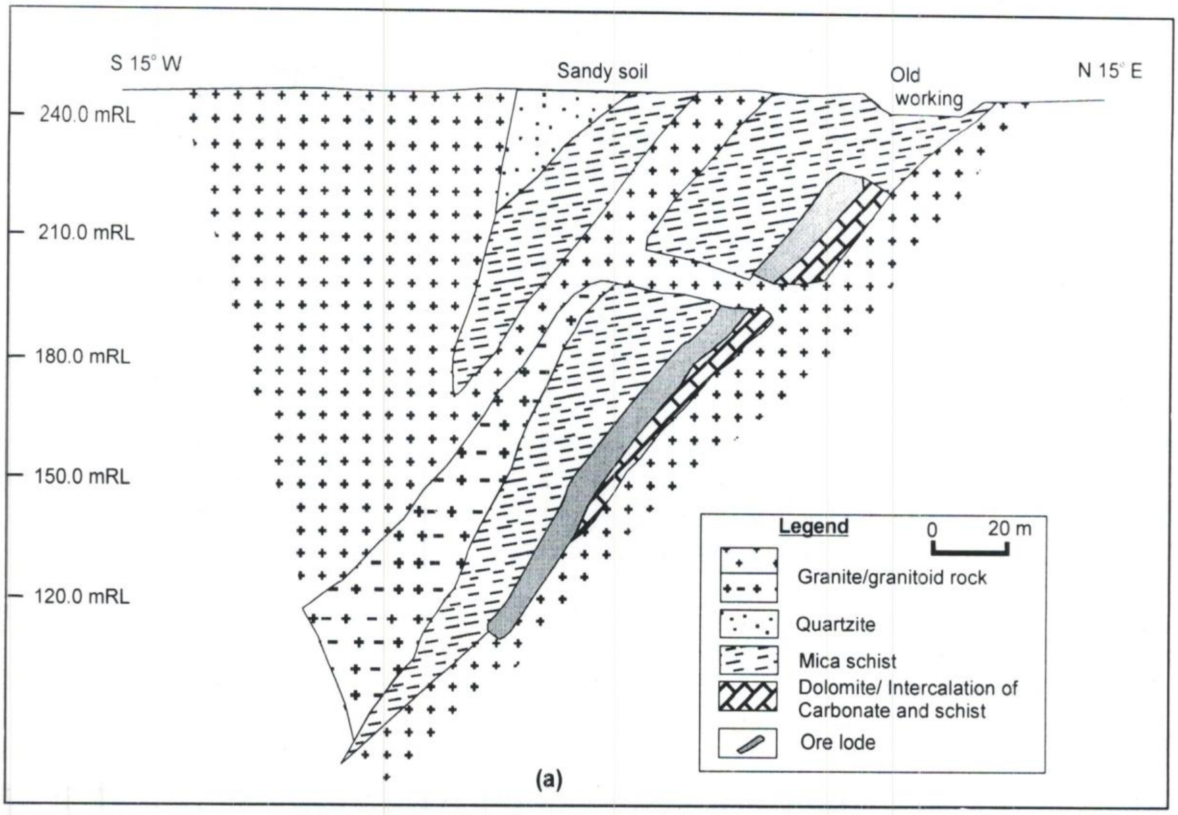
present in the vicinity of the ore lenses in mica schist as well as in adjacent dolomite and calc-silicate skarn.

The economic concentration of sulphide minerals are confined within the garnet-biotite schist which occurs in between dolomite and quartzite. Fine-grained tourmaline layers associated with disseminated galena alternate with quartz layers in the 'tourmalinite'. Skarn rocks and granitoid rocks at the immediate contact of the ore body show higher concentration of ore minerals, but they are very local, and do not serve as favourable host rocks of sulphide mineralisation. There is no visible wall rock alteration of the host schist.The Sargipali ore has a rather simple assemblage of a fewer sulphide minerals. The most abundant mineral is galena, with a little chalcopyrite and some sphalerite. Other associated ore minerals are pyrrhotite, pyrite and marcasite. Tetrahedrite, loellingite, rammelsbergite, breithauptite, bournonite, vallerite and stromeyerite are present in traces. Non-sulphide minerals contain quartz, micas, garnet, tourmaline,epidote with occassional chlorite and apatite.

Stratabound and stratified sulphides showing evidence of soft sediment deformation (primary sedimentary contortion of both ore and host rock layers) appear to reflect the primary sedimentary and diagenetic processes (Fig. 6a). Superimposed on these are the structures and textures mainly due to recrystallisation and annealing in response to subsequent metamorphism.

Plastic deformation of galena and chalcopyrite are evidenced by the fracture filling of silicates by these minerals (Fig. 7a). Mechanical deformation feature in coarse galena grains is identified by serrated boundaries and bent cleavages which possibly developed under low temperature (below 200° C) and pressure conditions (Mc Clay 1980). Martensitic blebs which are common in Sargipali galena (Fig. 8b) might have formed due to shear deformation (Smith 1964; Shewmon 1969). Skeletal galena (Fig. 7b) might have formed by autogenous fragmentation (Lawerence 1973). Microbrecciation is discernible through smoother boundaries exists between galena and silicates (Fig. 7c) which form pseudographic intergrowth (Lawerence 1973) of galena and silicates. The indistinct wavy trails of fractures of some chalcopyrite grains could be due to mechanical deformation of the mineral. Thinner, parallel sided twin lamellae locally revealed in etched chalcopyrite (Fig. 9a) indicate polysynthetic deformation of the mineral, which according to Kelly and Clark (1975) would have started as low as 100° C reducing the strength of chalcopyrite substantially. The features of chalcopyrite "flowage" developed at temperature above 500°C (Kelly and Clark 1975). Deformational features in sphalerite include the development of sub-grains with incomplete grain boundaries as well as rare rectangular grain shapes (Fig. 9b, c). The flexed nature or the comb structured pyrite may be a response to deformation caused by pressure solution (Mc Clay and Ellis 1983).

The effects of metamorphism are clearly recognised in the Sargipali sulphides.Recrystallisation and annealing are shown by the polygonal fabric and triple point junctions of galena, sphalerite, chalcopyrite and pyrrhotite (Fig. 8a; 9b, c, d). Experimental deformation showing recrystallisation of pyrrhotite reported to take place at temperatures above 450° C (Clark and Kelly 1973) and that of sphalerite at temperatures near about 600°C (Gill 1969; Stanton and Willey 1971), accompanied by the development of growth twins and granoblastic texture. Disseminated chalcopyrite occuring along the twin planes, triple point junctions and



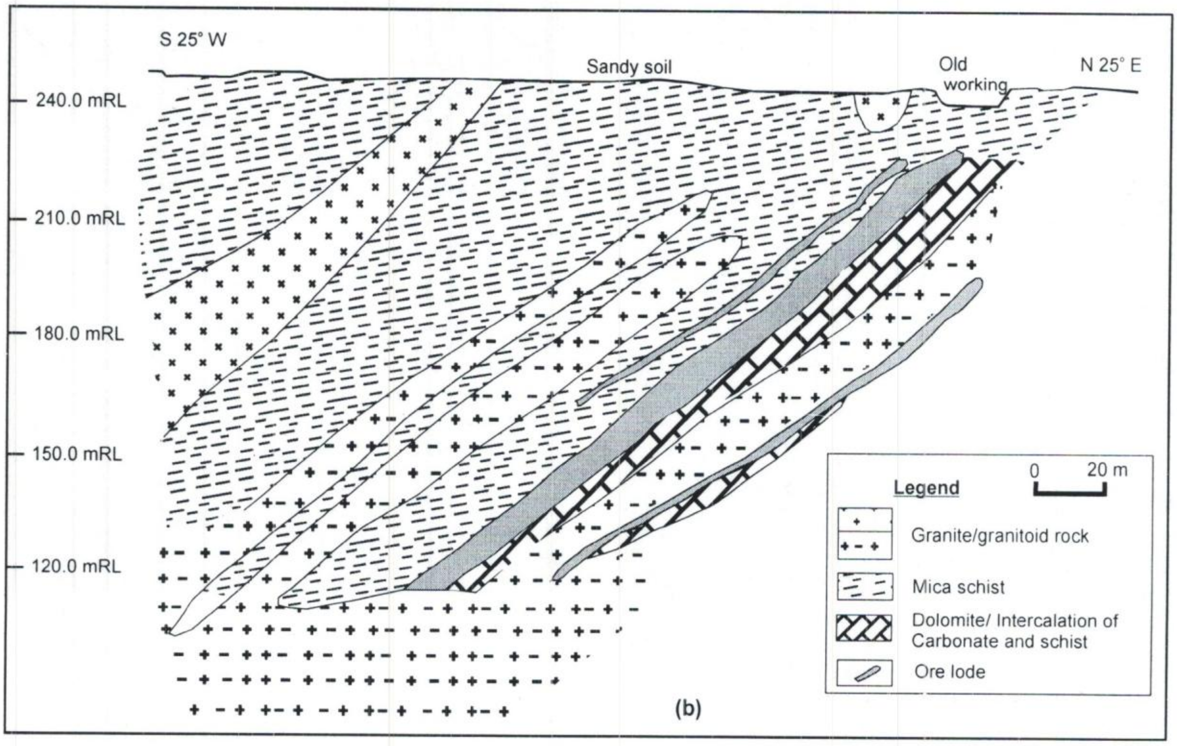


Fig. 5: Cross sections along Production Incline (a) and Service Incline (b) showing the behaviour of the ore bodies at depth (after pattnaik and Raju 1990).

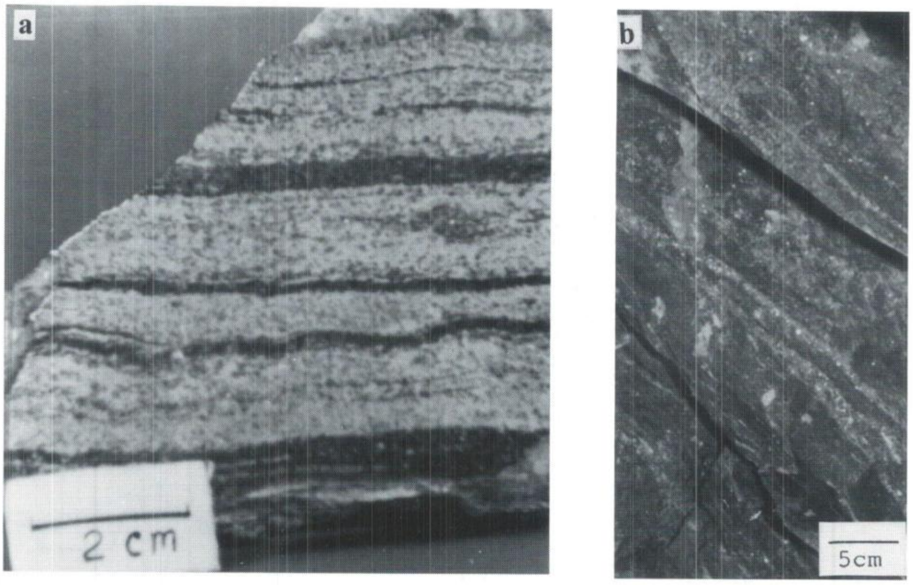


Fig. 6: Exposures of banded ore at 120 mRL, Sargipali mine. a: alternate layering of ore (black) and host schist (bluish white). Note synsedimentary contortions of layers (towards bottom); b: Thin layers of galena (white) in host schist (dark grey).

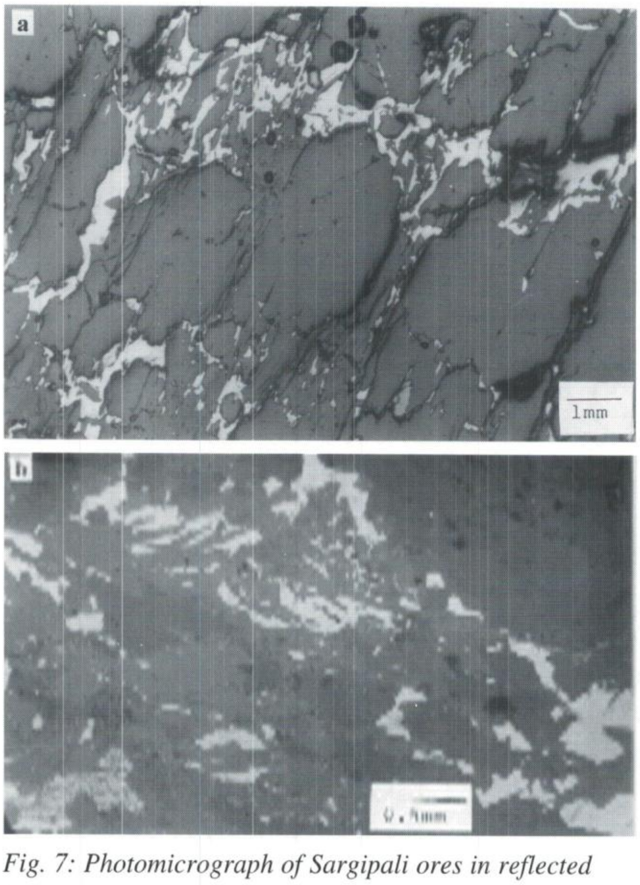


Fig. 7: Photomicrograph of Sargipali ores in reflected light: a: Fracture filling of host schist by galena and chalcopyrite; b: Skeletal galena in silicate matrix.

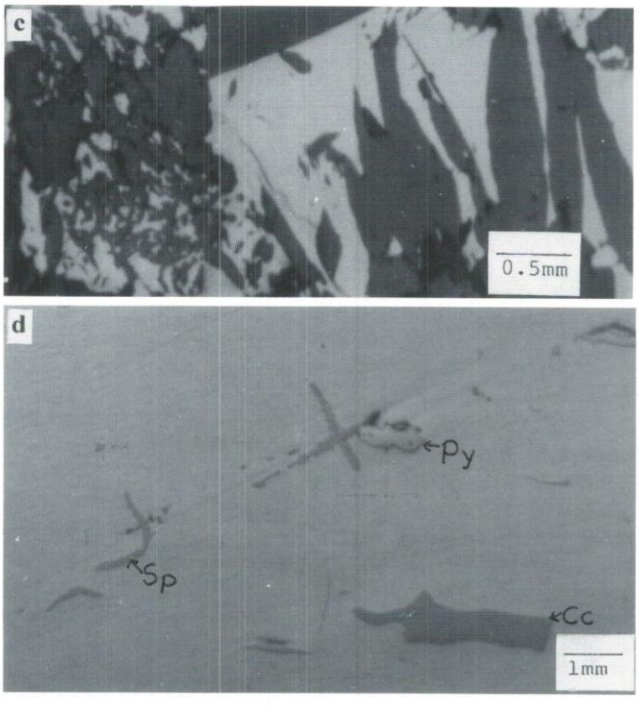


Fig. 7c: Pseudo-graphic intergrowths of galena and the silicates in the left side, and in the right side, mutual boundary and cleeavage replacement textures of chalcopyrite and silicates are present; d: Star shaped inclusions of sphalerite (grey) in chalcopyrite (yellow). A few inclusions of pyrrhotite (pink) occur closely associated with sphalerite stars.

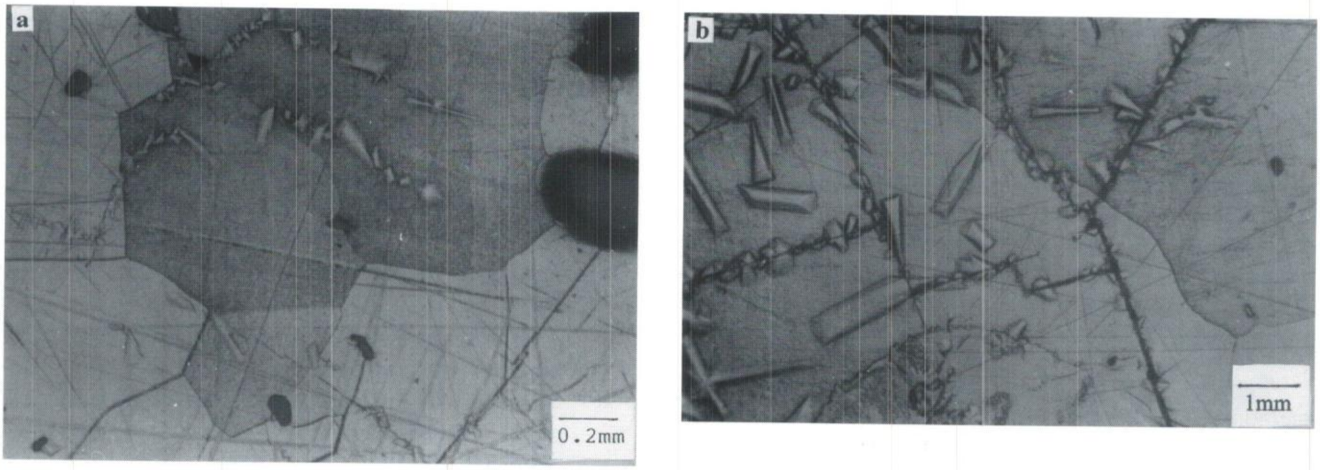


Fig. 8: Photomicrographs of Sargipali galena in reflected light (etched with thiouria +HCl). a: Polygonal galena with triple point junctions; b: Large to small martensitic (?) blebs and plates in galena. Larger blebs are randomly oriented, while most of the smaller blebs appear preferentially concentrated along galena cleavages.

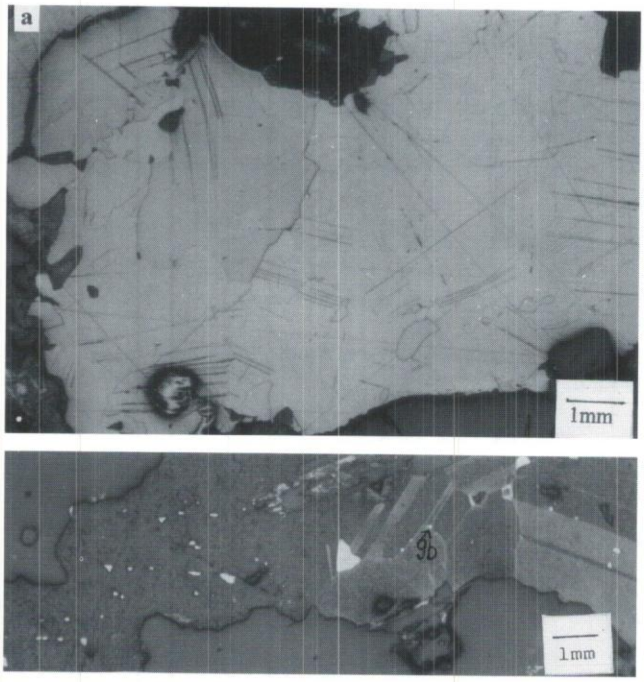


Fig. 9: Photomicrograph of Sargipali ores in reflected light (etched with saturated chromic acid solution):
a: Thin parallel-sided polysynthetic deformatonal twin lamellae in chalcopurite terminating abruptly at grain boundaries.
b: Sub-grains of sphalerite with triple point junctions and straight annealing twins, and adjustment of grain boundaries through grain-boundary bulging (gb) of sphalerite. Note, the small chalcopyrite blebs (yellow) mostly occuring along the sub-grain boundaries, triple-point junctions and twin planes of sphalerites.

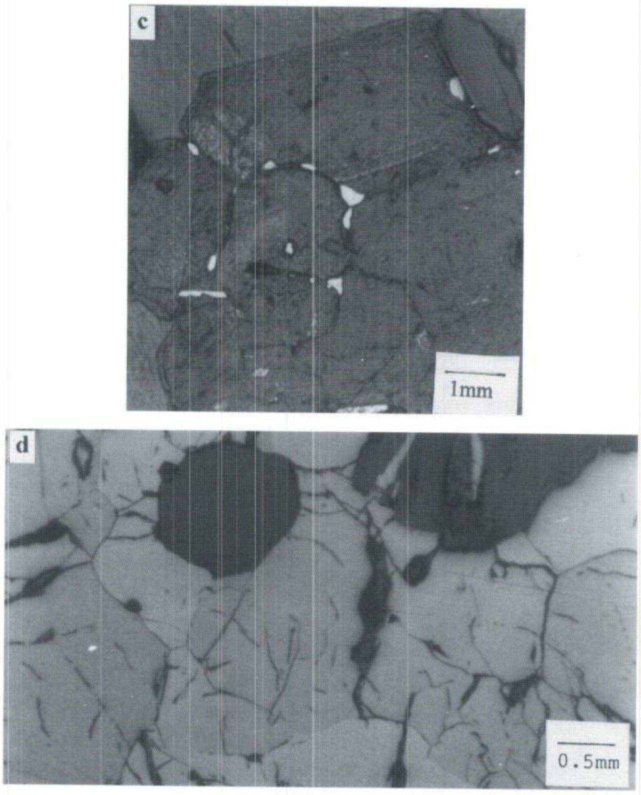


Fig. 9c: Sphalerite sub-grains showing rectangular grain shapes and also triple point junctions. Chalcopyrite blebs (yellowish white) occur at sub-grain boundary intersitces.
d: Ligtly etched patches of hexagonal pyrrhotite occuring along with dark etched (brown) monoclinic pyrrhotite. Arrays of etch pits in pyrrhotite formking sub-grain walls, indicating the onset of polygonisation.

grain boundaries of sphalerite (Fig. 9b) indicate replacement of sphalerite by chalcopyrite at a temperature of about 600°C (Bortinikov et al. 1991). Sphalerite stars in chalcopyrite (Fig. 7d) indicate exsolution texture at about 500°C. The ores locally contain the invarient assemblages of pyrite+ pyrrhotite+ arsenopyrite, the temperature of which is around 600°C. Hence it may be suggested that the ore was possibly metamorphosed to a maximum temperature of 600°C. This is consistent with the amphibolite facies conditions for the enclosing host rocks, and indicates that the sulphide ore was metamorphosed together with its host rocks.

Eight galena samples were analysed by spectrographic methods for the determination of the contents of Pb, Zn, Cu, Ag, Co, Ni, Sband Bi. To obtain galena separates, ore samples were crushed, and galena grains were then handpicked under a magnifying lens, and to ensure uniformity and purity, the final fraction was microscopically checked. Element concentrations were determined by using the Pye Unican model SP-200 Atomic Absorption Spectrophotometer in the laboratories of Hindustan Zinc Limited at Sargipali, Orissa (Pb, Zn, Cu, Ag, Co, Ni) and at Tundo, Bihar (Sb, Bi). The trace elements (Sb, Ag, Cd and Bi) of Sargipali galena have been compared with that from some other sulphide deposits (Chowdhury and Ghosh 2001) representing various genetic types (Table 2), and the following observations appear noteworthy.

1. The average Ag content (468 ppm) and Sb/Ag ratio (3.28) in Sargipali galena are similar to that in galenas from the metamorphosed synsedimentary deposit of Madem Lakkos,Greece (440 ppm and 3.47).
2. Sb content (average 1536 ppm) is comparable to that in galena from the metamorphosed sedimentary deposit of Broken Hill, Australia (1,010 ppm) and of Madem Lakkos (1,530 ppm), as well as of carbonate-hosted strata-bound deposit of Fankou, China (1,210 ppm), and of skarn hydrothermal deposits of Shuikouohan, China (1,580 ppm).
3. Cd content of the present samples (average 32 ppm) is also not far from the content of this element in Fankou galena (50 ppm);
4. The average Sb/Bi ratio (25.86) in galena from Sargipali is much lower than that of British Island (very large) and Wood River (180.1), lower than Madem Lakkos (66.52), and higher than that of all other deposits.

Table 2: Minor elements in galena from various deposits (in percentage).

No.	Ag	Cd	Sb	Bi	Sb/Ag	Sb/Bi	References
Metamorphosed sedimentary Pb-Zn deposit							
1.	0.0618	-	0.101	0.0135	1.63	7.48	Broken Hill, Australia (Both 1973)
2.	0.073						Aguilar, Argentina (Gemmell et al. 1992)
3.	0.044	-	0.153	0.0023	3.47	66.52	Madem Lakkos, Chalkidiki, Greece (Nebel et al. 1991)
4.	0.046	0.0032	0.153	0.0058	3.28	25.86	Sargipali, India (Present Study)
Carbonate-hosted stratabound and stratiform Pb-Zn deposit							
5.	0.0003	0.0008	bld	-	6	-	Upper Mississippi valley, U.S.A. (Hall and Heyl 1968)
6.	0.164	0.005	0.121	0.012	0.74	12.1	Fankou, China (Xuexin 1984)
7.	0.0224	0.0009	0.0211	0.0035	0.93	6	Cantabria, N.W. Spain (Diaz Rodriguer and Fernandes 1988)
Syngenetic galena							
8.	0.001	-	0.008	bld	0.8	very large	The British Island (El Shazly et al. 1956-57)
Volcano- hydrothermal polymetallic deposit							
9.	0.0577	0.009	-	-	-	-	Xiaotieshan, China (Xi Yeliu, Unpublished Data, complied after Xuexin 1984)
Hydrothermal Pb-Ag/ Pb-Zn deposit							
10.	0.3683	0.0019	0.3783	21	1.03	180.1	Wood River, Idaho, U.S.A. (Hall and Cramanske 1972)
11.	0.0574	0.0013	0.0338	-	0.58	-	Benue, Nigeria (Olade and Morten 1985)
Skarn-hydrothermal Pb-Zn/ Fe-Cu deposit							
12.	0.1076	0.015	0.158	0.086	1.47	1.84	Shuikoushan, China (Xiang Ye, Unpublished Data, complied after Xuexin 1984)
13.	0.086	0.0089	0.0016	0.75	0.019	0.002	Lw. Md. Yangtze Valley (Fe-Cu), China (Su Yeyan, Unpublished Data, complied after Xuexin 1984)

- = not determined bld = below the limit of determination

The Sb-Bi-Ag atomic ratios for galena from Sargipali and other deposits (Fig. 10) show that the Sargipali galena is likely to be compositionally similar to the metamorphosed synsedimentary deposit of Madem Lakkos,and may not be sharply different from that of Broken Hill, which is also a metamorphosed sedimentary deposit (Chowdhury and Ghosh 2001).

The extreme uniformity of lead isotopic composition even in the banded as well as in the vein galena (Table 1 in Ghosh et al. 1999) along with high source μ (^{238}U/ ^{204} Pb ratio) value of lead (μ=11.748 to 11.781) may suggest a single-stage lead, derived from isotopically homogeneous uranium enriched, felsic upper crustal source. However, vein galena ores may represent the remobilisation product of early existing lead, as proposed by Sarkar (1974) and Vishwakarma and Ulbhaje (1991). The galena ages range between 1682 and 1695 Ma, which is not far from the probable age of the upper part (hosting the deposit) of the Gangpur Sequence (1700 to 2000 Ma).

The moderate spread of δ^{34}S values for Sargipali galena in the range -3.2 to +7.6 0 /00 (Ghosh et al. 1999; Vishwakarma 1996) probably indicates a sediment sulphur source. The isotopic variation between two levels of Sargipali mine and between foot wall and hanging wall of the same level indicate that the amphibolite-facies metamorphism have not homogenised the primary distribution of δ^{34}S values (Ghosh et al. 1999; Von Gehlem et al. 1983; Parr 1992).

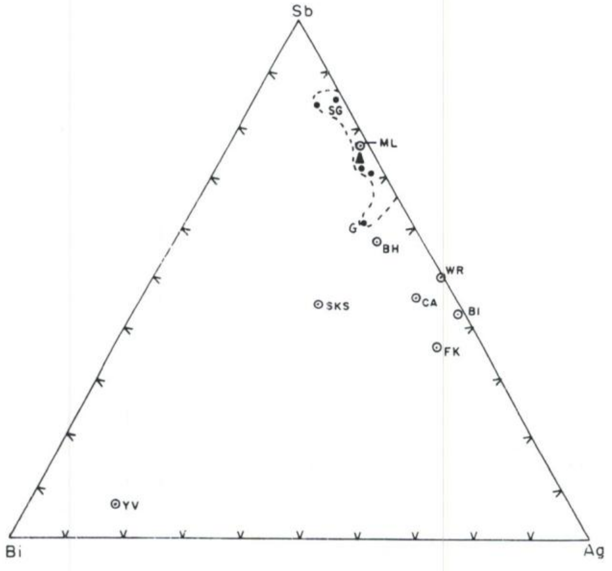


Fig. 10: Sb-Bi-Ag atomic ratios for galena from Sargipali and other ore fields. SG: Sargipali, India; BH: Broken Hill, Australia; WR: Wood River, USA; BI: British Island; FK: Fankau, China; SK: Shuikoushan, China; YV: Lower-Middle Yangtze Valley, China; ML: Madem Lakkos, Greece; △: average of 9 analyses fo Sargipali galena.

DISCUSSION

Geological features observed above indicate that the sediment-hosted lead-dominant sulphide deposit of Sargipali is strictly stratabound and stratified in nature. The ore lenses are parallel to the compositional layering of the associated metasedimentary rocks. The ore laminae alternate with the layers of the host schist. Textural studies did not give any evidence to suggest that the ore layers selectively replaced the silicate layers anywhere. On the other hand, the silicate layering is primary, supported by the presence of rounded tourmaline grains. Frequent contortions of both the ore and the silicate layers (Fig. 6a) are strongly indicative of the effects of diagenesis, and these above mentioned features indicating their exhalative origin (Murry 1975; Taylor and Andrew 1978).

The distinctive feature of the deposit is the repetition of ten stratiform sulphide ore lenses formed in a basin having a strike length of about 2.5 km (Fig. 4), which is considered to be characteristic of many sediment-hosted sulphide deposits. Referring to other sediment-hosted sulphide deposits, it may be noted that Mount Isa , Mc Arthur River and Hilton (Australia) have at least 34, 8 and 7 ore lenses, Navan (Ireland) 5, and the Aguilar (Argentina) 10 ore lenses.

There is no field evidence to suggest the existence of any shear zone or fault plane localising sulphide mineralisation at Sargipali, as was earlier suggested by Rajarajan et al. (1968), Kar Ray et al. (1971) and Roy et al. (1994). There is also no visible wall-rock alteration in the host rock which is indicative of the epigenetic mineralisation, where ore-fluid reacts with the host rock. The granitoid rock of the area can be outright rejected to be a source of mineralisation because of its intrusive nature, much younger age (~ 850 Ma) in comparison to the host rock (~ 1700 Ma) and the contained ore (range between 1682 Ma and 1695 Ma). The skarn rocks which are formed by metasomatic alteration of dolomite at the contact of granitoid are barren. Also Pb-Zn-Ag x1000 triangular diagram (Fig. 11) shows that sulphide mineralisation of Sargipali has no relationship with skarn type deposits.

A feature of the sediment-hosted deposits is the presence of anomalous, apparently syngenetic metal values in footwall sediments. Manganese appears first, followed higher in the footwall sequence by zinc ± lead, iron and exhalative chert. The footwall sediment of Sargipali is enriched in lead, but at deeper mine level (120 mRL) the sulphide footwall is characterised by pyrrhotite- rich bands and laminations like the sediment-hosted sulphide deposit of Sullivan, Canada (Ransom 1977). Locally bedded chert (Vishwakarma 1996) and tourmalinite of exhalative origin (Willner 1992) are closely associated with the ore zone.

The vertical distribution of copper in sediment-hosted deposits contrasts with that in volcanic- hosted orebodies. Copper is not restricted to the stratigraphic footwall as in the case in the volcanic-hosted deposits. Relatively late

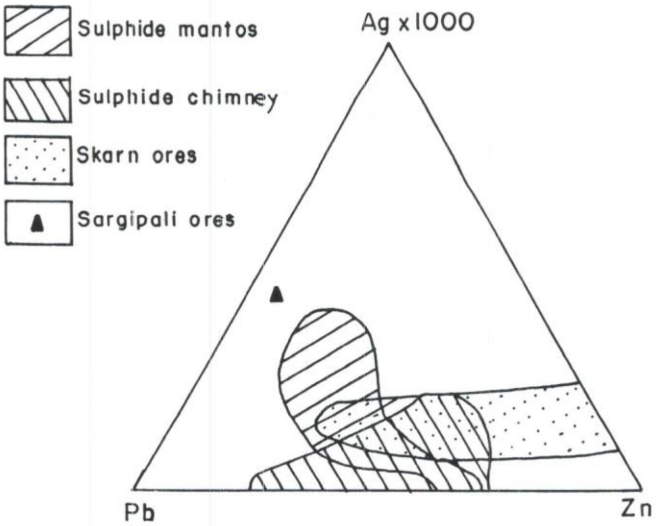


Fig. 11: Pb-Zn-Ag plot of Sargipali ore, in relationto various skarn type deposits (after Megaw et al. 1988).

copper enrichment is observed in many exhalative deposits (Mathias et al. 1973; Whitcher 1975). In Sargipali hanging wall rocks are richer in chalcopyrite.

Metal zoning which is a common feature of the volcanic-hosted deposit, is lacking in the Sargipali deposit. The Sb/Ag ratio and Sb-Bi-Ag atomic ratio for Sargipali galena (Chowdhury and Ghosh 2001) are very similar to those for galena from the metamorphosed synsedimentary sulphide deposit of Madem Lakkos, Greece, and are only slightly different from the metamorphosed sedimentary lead-zinc deposit of Broken Hill.

The extremely homogeneous lead-isotopic composition and high m value of lead of Sargipali galena (Ghosh et al. 1999) indicate the derivation of lead from uranium-enriched felsic upper crustal source. The sulphur- isotope values of galena show a moderate spread indicating inorganic or biogenic sediment source of sulphur (Ghosh et al. 1999). According to Vishwakarma (1996) there may be the possibility of a sulphur source mainly from inorganic reduction of seawater sulphate at a temperature of ~ 300°C. Presence of pyrrhotite-rich bands and laminations in the deeper mine levels also indicate the reducing environment of ore deposition. The absence of oxidised zones around the ore body supports this view.

From the above discussion, it appears that the lead-dominant Sargipali mineralisation contain well homogenised lead, derived possibly from upper crustal felsic terranes below or adjacent to (?) the basin, and the metal was discharged through hydrothermal vents to the basin floor. Franklin et al. (1981) and Franklin (1986, personal communication) suggested that the metal content of the hydrothermal fluids, as envisaged here, is established by the buffering capacity of the source rocks, as well as possibly by the actual metal content of these rocks. During cooling, provided that the fluid is always reduced and the pH is acidic, copper, then zinc will precipitate leaving the residual liquid relatively enriched in lead. In Sargipali lead is considered to have been derived from uranium enriched, felsic upper crustal source (Ghosh et al. 1999; Vishwakarma and Ulabhaje 1991). Frankling (1986, personal communication) suggested that phase separation of a fluid can change its metal ratios, as well as its complexing characteristics. Hydrothermal fluids in felsic rocks or sediments are buffered by mica to a low pH at relatively low temperature (Ca. 300°C). Deposits in such terranes will be, therefore, more lead rich (relative to copper and zinc) as in the case at Sargipali. The metal-rich hydrothermal fluid, as envisaged, acquired reduced sulphur available in the basin (which is according to Vishwakarma 1996 is mainly derived from inorganic reduction of sea-water sulphate at a temperature of ~300° C) and, as a result, sulphides precipitated conformably with the sediments, representing synsedimentary mineralisation. Some remobilisation of pre-existing minerals, mostly the ductile phases took place during regional metamorphism. But this mobilisation involved limited transport distances of the order of millimeters to meters.

In summery, therefore, the lead-dominant sulphide mineralisation of Sargipali represents sedimentary exhalative (SEDEX) mode of origin, which later remobilised and reconcentrated due to high grade metamorphism. According to Vishwakarm and Ulabhaje (1991), and Vishwakarma (1996) lead was derived from the "upper continental crust", the source rock possibly being the 2.20-Ga-old Singhbhum soda-granite which was initially rich in U-Th-Pb.

The SEDEX origin of the lead-dominant Sargipali sulphide deposit contradicts the idea that the SEDEX deposits are always zinc rich, and this study may help in throwing new light about the genesis of similar sediment-hosted Pb-rich deposists in terms of the SEDEX model.

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