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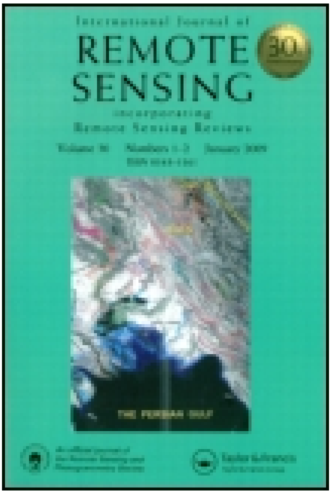

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Remote sensing and GIS for locating favourable zones of lead-zinc-copper mineralization in Rajpura-Dariba area, Rajasthan, India

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Remote sensing and GIS for locating favourable zones of lead–zinc–copper mineralization in Rajpura-Dariba area, Rajasthan, India

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Abstract. This paper reports the results of a pilot study carried out in Rajpura-Dariba area, Rajasthan, for locating favourable zones of lead–zinc–copper (Pb–Zn–Cu) mineralization using remote sensing, Geographical Information System (GIS) and geostatistical modelling techniques. Remotely sensed data, both aerial and satellite, were used to update the existing geological map. ATLAS GIS software and multivariate geostatistical techniques were used to analyse and integrate different types of geological and geophysical datasets. The Favourability Index (FI) maps prepared during this study show the occurrence of three favourable zones for Pb–Zn–Cu mineralization. They are: (i) around and north of Rawan ka Khera; (ii) isolated spots between Ruppura and Bhupalsagar; and (iii) north of Dhani. Selective geochemical sampling and resistivity profiling carried out in these favourable zones indicated the presence of geochemical anomalies (anomalous concentrations of Zn and Cu) and low/moderate resistivity zones, respectively. Recent drilling carried out by the Department of Mines and Geology (DMG), Rajasthan, at about 2.5 km north of Rawan ka Khera (one of the predicted favourable zones) indicated evidence of Cu mineralization at a depth of about 70 m.

1. Introduction

The biggest challenge before geoscientists today is to discover new mineral deposits, as most of the shallow deposits have either been located or are being exhausted (Rao 1996). The conventional methods of mineral exploration involve a high degree of risk, in addition to being time-consuming and cost-prohibitive. In order to overcome these limitations, innovative techniques for resource surveillance and data integration have to be used. Remote sensing and Geographical Information System (GIS) techniques have emerged as powerful tools in recent times for assessing/predicting mineral resources or isolating the favourable areas from

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unfavourable ones. Remote sensing data are mainly used to: (i) update the geological (lithological and structural) maps of the area; and (ii) map the hydrothermally altered minerals. GIS, on the other hand, is used to integrate and analyse different types of spatial datasets, such as geological, geophysical and geochemical maps. Advanced GIS packages bridge the gap between the traditional manual overlay approach and mathematical methods using multivariate statistics and image analysis (Bonham-Carter *et al.* 1988). The spatial information from multiple sources can be integrated using several methods; however, 'weights of evidence (or probabilistic)' and 'Dempster-Shafer (or evidential)' methods are more commonly used (Lee *et al.* 1987, Bonham-Carter *et al.* 1988, Kim and Swain 1989, Moon 1990, Shulman *et al.* 1992, Bhattacharya *et al.* 1993).

The well known Rajpura-Dariba multimetal deposit in Rajasthan witnessed probably the earliest (≈ 3000 years BP; Department of Mines and Geology, personal communication, Rajasthan) lead–zinc (Pb–Zn) mining in the world, as evident from the records of old workings. The main deposit was located by the Geological Survey of India (GSI) in 1963 (GSI 1977). Subsequent surface and subsurface exploration by the GSI between 1963 and 1970 proved the existence of a mineralized belt nearly 17 km long between Dariba and Bethumbi through Rajpura and Sindesar Kalan (Choudhary and Mathur 1973). The average Pb–Zn content of the ore is about 6.7% with subsidiary Cu, Ag, Sb, As and Hg (GSI 1977). The establishment of a well-defined ore deposit near Rajpura-Dariba encouraged many geologists to carry out detailed mineral exploration studies in surrounding areas for sulphide minerals.

With this background, the present study aimed to map the favourable locations of lead–zinc–copper (Pb–Zn–Cu) mineralization in the Rajpura-Dariba area of Rajasthan based on integration of geological and geophysical datasets using remote sensing, GIS and multivariate geostatistical modelling techniques. The work reported here pertains to part of the Indo-FRG collaborative project on mineral exploration.

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2. Study area

2.1. *Location*

The study area, covering parts of the Rajsamand and Chittaurgarh districts of Rajasthan, is located between latitudes 24°50′ and 25°05′ N, and longitudes 74°05′ and 74°15′ E. It falls on the Survey of India (SOI) toposheets no. 45 K/4 and L/1. The area forms part of the Mewar-Bhilwara plateau and, with the exception of two linear ridges—Dariba–Rajpura–Bethumbi in the west and Dhani-Rawan Ka Khera–Bhupalsagar–Matuniya in the east—the entire area is represented by an undulating pediplain with soil cover of varying thickness. Mining of lead–zinc minerals is in progress near Dariba. Udaipur, an important nearby city, is at a distance of about 84 km from Dariba by road. The area enjoys a semi-arid climate with extremely hot summers and cold winters. The mean daily maximum and minimum temperatures are about 39°C and 8°C, respectively. The mean annual rainfall is about 650 mm and is mainly restricted to monsoon months of July to September. The location map of the study area is shown in figure 1.

2.2. *Geology*

The belt of Rajpura-Dariba polymetallic sulphide mineralization runs for about 17 km from Dariba in the south to Bethumbi in the north through Rajpura, Sindesar Khurd and Sindesar Kalan. A number of preliminary accounts of the geology and the nature of mineralization at Rajpura-Dariba are available. Many geologists/

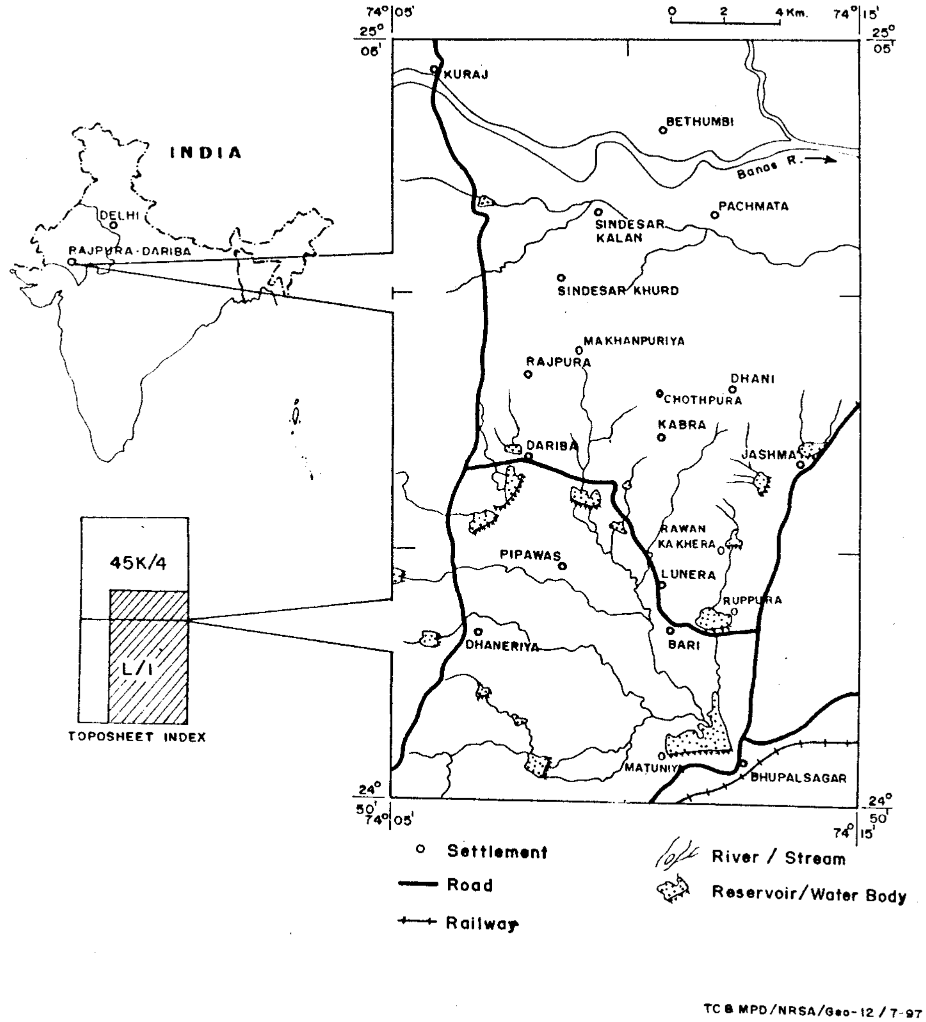

Figure 1. Location map of the study area.

geophysicists of GSI and other organizations have studied the area and have gathered information on geological and geophysical aspects of the entire region, and the Rajpura-Dariba area in particular (Gupta 1934, Gupta *et al.* 1980, Raja Rao 1967, 1970, Raja Rao *et al.* 1972, Choudhary and Mathur 1973, Sharma *et al.* 1978, Agarwal *et al.* 1980, Deb and Bhattacharya 1980, Roy *et al.* 1981, Samaddar and Bohra 1986, Patel 1987, Roy 1988). According to the workers of GSI, the sulphide bearing metasedimentary rocks in the Rajpura-Dariba area together constitute the 'Rajpura-Dariba Group', which are underlain by high grade metamorphites of the 'Mangalwar Complex'. The rocks of the 'Rajpura-Dariba Group' and 'Mangalwar Complex' together constitute the Bhilwara Super Group (pre-Aravallis). However, according to Roy *et al.* (1981) and Roy (1988), the rocks of the Rajpura-Dariba area form part of the Aravalli Supergroup. The chief litho-units constituting the 'Rajpura-Dariba Group' are sulphide bearing calc-silicates having dolomite/dolomitic marble, graphitic mica schists, calc-biotite schists and quartzites. The litho-units belonging

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to the Mangalwar complex include garnetiferous mica schists, migmatitic mica schists/gneisses and quartzites.

The general strike of the rock formations varies from N–S to NE–SW and dips are steep (> 65°) towards the east. The metasediments exhibit polyphase deformation and regional metamorphism corresponding to amphibolite facies (GSI 1977). The rock formations of the study area are reported to constitute part of a north-easterly plunging regional syncline, the closure of which is supposedly exposed near Bhinder in the south (Raja Rao *et al.* 1972). The Dariba-Rajpura-Bethumbi belt constitutes the western limb and the Bhupalsagar-Jashma belt constitutes the eastern limb of the regional syncline. There are, however, different views on the structure and status of different parts of the belt (Choudhary and Mathur 1973, Sharma *et al.* 1978, Samaddar and Bohra 1986, Agarwal *et al.* 1980, Ram Gopal and Agarwal 1993).

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3. Mineralization

Rajpura-Dariba ores demonstrate a classic multimetal association of Zn–Pb–Cu–Ag–Cd–As–P–F–S with minor Au, Mo, In and Hg. The major ore minerals are sphalerite and galena which are associated with chalcopyrite, pyrite and pyrrhotite (Mukherjee 1988). The average Zn–Pb content of the ores is about 6.7% with 5.5% Zn and 1.2% Pb (GSI 1977). The ore bodies occur as broad layers of mainly Pb–Zn–Cu sulphides conformable to bedding of associated graphite mica schists and calc-silicate rocks (Deb and Bhattacharya 1980 from Mukherjee 1988). Restricted occurrence of the Rajpura-Dariba ores to a typical sedimentary sequence, the presence of well-defined primary sedimentary features within it, the stratiform and finely laminated nature of the deposits prompted Poddar (1974) to ascribe a syn(dia)genetic origin of the ores. Initially, the concentration of ores took place during diagenesis. Further mobilization of ores occurred during the polyphase deformation and regional metamorphism (Deb and Bhattacharya 1980).

3.1. *Controls of mineralization*

The base metal sulphide deposit of the Dariba-Rajpura-Bethumbi belt is marked by its confinement to the following controls of mineralization (Choudhary and Mathur 1973):

1. A diagnostic *in situ* gossan and ferruginous chert breccia is formed in between Dariba and Rajpura. The gossan zone has a dip of 65–80° towards the east and strikes N–S. The depth of oxidation is as deep as 400 m below the surface.
2. The sulphide ore bodies are invariably associated with graphitic mica schists and calc-silicate rocks bearing dolomite/dolomitic marble belonging to the Rajpura-Dariba Group.
3. A N–S strike fault dipping 65–80° due east is indicated by the sheared graphitic mica schists along the eastern margin of the gossan. It extends from near Dariba in the south to Bethumbi in the north, and is parallel to the regional structural trend (N–S to NE–SW) of the major litho-units. The outcrops of diagnostic gossan and old workings along the graphitic schists-dolomite-chert horizon and the fault zone indicate that the mineralization is controlled by lithology and the workable lodes have been formed due to subsequent limited remobilization along the fault zone.

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3.2. *Exploration strategy*

In addition to the detailed account of geology and mineralization discussed above, geophysical surveys conducted by the GSI have also revealed different types of geophysical anomalies related to sulphide mineralization (Sharma and Singh 1976, Sharma *et al.* 1978, Agarwal *et al.* 1980). It has been shown that the Turam and Magnetic methods are an effective combination in locating the potential zones of sulphide mineralization in this area where graphitic mica schists form the main host rock. The Turam responses associated with moderate magnetic anomalies are indicative of sulphide mineralization at depth in view of the known occurrences of pyrrhotite with Pb–Zn–Cu sulphides invariably in this area.

Keeping in view the geological controls of mineralization and the results obtained through geophysical surveys over the mineralized areas, the exploration strategy for locating new zones of sulphide mineralization was essentially based on integrated analysis of geological, geophysical and geochemical parameters. In this context, the present study aimed to extract the geological information from remotely sensed data, and to analyse and integrate it with the available geophysical data in a GIS environment using suitable geostatistical modelling tools with the objective of locating the favourable zones of Pb–Zn–Cu mineralization in the surroundings of the known mineralized belt of Dariba-Rajpura-Bethumbi.

4. Used data and data processing

The following datasets were used in this study:

1. Satellite data (IRS-1A LISS-II, Landsat TM and SPOT PLA/MLA) and panchromatic aerial photographs to update the existing geological map at 1: 50 000 scale
2. Airborne electromagnetic data acquired during 'Hard Rock Operation' by GSI
3. Total field airborne magnetic data acquired during 'Hard Rock Operation' by GSI
4. Ground geological, geophysical and geochemical data
5. Survey of India (SOI) toposheets at 1: 50 000 scale.

The satellite data, after geocoding with reference to SOI toposheets, were digitally enhanced using linear contrast stretching, principal component analysis, Intensity-Hue-Saturation (IHS) transformation and ratioing techniques. PC-based ERDAS and EASI/PACE image processing software were used for this purpose. Then, the enhanced satellite images and aerial photographs at 1: 50 000 scale were visually interpreted in conjunction with field checks to update the existing geological map of GSI, which was used as a base. The major contribution of remotely sensed data was in mapping the graphitic mica schists, which form the host rocks for sulphide mineralization, at two hitherto unknown locations: (i) west of Bari village; and (ii) an extension of these rocks from near Bhupalsagar town to Ruppura village. In addition, the contacts between different formations were revised at several places in addition to identification and mapping of several faults/fractures/lineaments. It is worth mentioning here that it was difficult to map the faults/lineaments running parallel to the regional structural trend of the rock formations. In contrast, those oblique to the regional trend could be mapped very well on the satellite imagery. Aerial photographs facilitated identification and mapping of minor strike-slip faults across the quartzite ridges. The geological map of the study area (synthetic of information derived from remotely sensed data and existing geological map) is shown in figure 2. The lithostratigraphy is given in table 1.

In order to carry out the GIS-based data analysis/integration, lithological, structural, aeroelectromagnetic and aeromagnetic datasets were used as inputs. The lithological and structural details were taken from the geological map, shown in figure 2, in separate layers. The lithological layer consisted of 10 variables representing different litho-units including gossan, as shown in tables 1 and 2. The structural layer consisted of three variables: (i) faults; (ii) fractures/lineaments, and (iii) trend lines (table 2). The airborne electromagnetic data acquired by the GSI indicating channel anomalies is shown in figure 3. Contouring of original data was done in order to use them in the GIS. These data formed the important geophysical inputs as they indicate the conductivity of the rock formations and associated sulphide ore bodies. The total field aeromagnetic contour map was divided into six classes of magnetic highs and lows (figure 4). These are: (i) magnetic high (> 47 500 gamma); (ii) magnetic high (47 300–47 500 gamma); (iii) magnetic high (< 47 300 gamma); (iv) magnetic low (> 47 200 gamma); (v) magnetic low (47 000–47 200 gamma); and (vi) magnetic low (< 47 000 gamma). Further, magnetic high/low axes and discontinuities were interpreted and used as inputs (figure 5). These datasets were analysed and integrated using GIS and weighted modelling techniques, discussed in the next section.

5. GIS analysis

ATLAS GIS software, a PC-based software from Strategic Mapping Inc., USA, was used to integrate the geological (lithological and structural) and geophysical datasets. For this purpose, as discussed earlier, these datasets were digitized in the layered form, wherein each individual layer consists of several variables (table 2). In the case of line features, such as faults, fractures, magnetic axes, etc., buffer zones of 250 m were created. The width of the buffer zone was selected based on field conditions. Subsequently, the weighted modelling technique was used to prepare 'Favourability Index' (FI) maps showing the potential areas for Pb–Zn–Cu mineralization. The procedures suggested by Bhattacharya *et al.* (1993) were adopted for calculation of weightages (using a binary approach), Overall Associativity (OA) and Favourability Index (FI). The weightage (W_i) of each variable was computed by using two methods: (i) based on the binary approach and conditional probability

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Figure 2. Geological map of the study area (modified after GSI map). 1, Migmatitic mica schists/gneisses; 2, garnetiferous biotite-muscovite schists; 3, quartzites; 4a and b, calc-silicate rocks bearing (*a*) dolomite/dolomitic marble with minor quartz-chlorite-biotite schist and amphibolite bands and (*b*) quartz-chlorite-biotite schist with minor bands of dolomite and amphibolite; 5, calcareous biotite schists with minor dolomite/amphibolite bands; 6, kyanite-staurolite-garnet bearing graphitic mica schists with intercalatory quartzite bands; 7, Sindesar Kalan/Jashma/Bhupalsagar quartzites; 8, ferruginous chert breccia; 9, gossan (limonitised graphitic mica schist/silicified dolomite); —×—×—×— quartz vein; F——————F fault; —————— fracture/lineament; .... trend line; bedding; foliation/schistosity; ———— lithological boundary (confirmed); ---------- lithological boundary (inferred); ———— road; —|—|—|—|— railway line; ≈≈ river/stream; ▷, tank/water body; ● A, settlement. Settlement names: A, Kuraj; B, Bethumbi; C, Pachmata; D, Sindesar Kalan; E, Sindesar Khurd; F, Rajpura; G, Dariba; H, Dhani; I, Jashma; J, Lunera; K, Bari; L, Dhaneriya; M, Bhupalsagar.

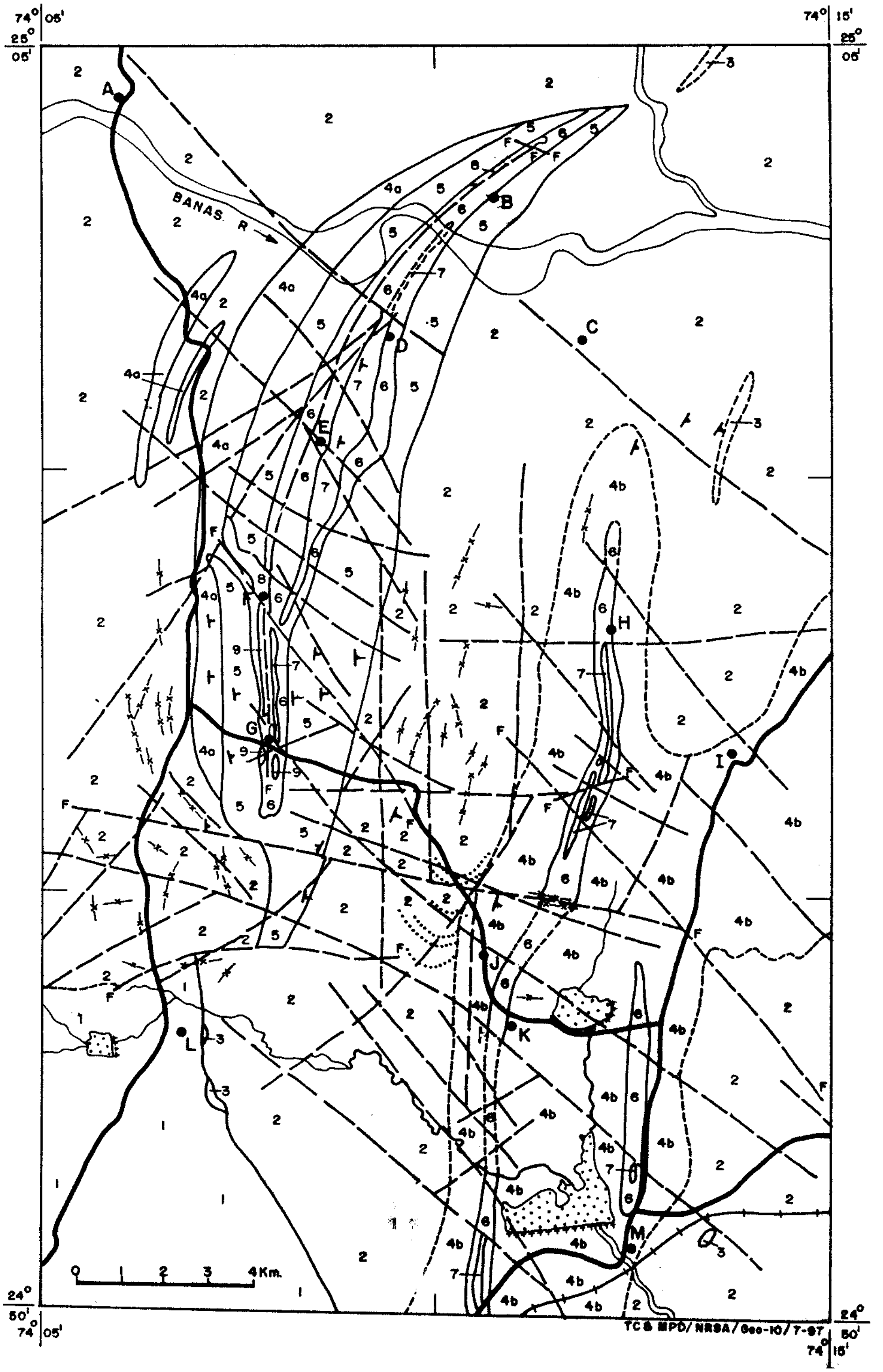

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Table 1. Lithostratigraphy of the Rajpura-Dariba area (based on GSI map).

Rajpura-Dariba Group	Quartz/pegmatite veins Gossan (limonitised graphitic mica schists/silicified dolomite) Ferruginous chert breccia Sindesar Kalan/Jashma/Bhupalsagar quartzites Kyanite-staurolite-garnet bearing graphitic mica schists with intercalatory quartzites Calcareous biotite schists with minor dolomite/amphibolite bands Calc-silicate rocks bearing (a) dolomite/dolomitic marble with minor quartz-chlorite-biotite schists and amphibolite bands and (b) quartz-chlorite-biotite schists with minor bands of dolomite and amphibolite
	Unconformity
Mangalwar Complex	Quartzites Garnetiferous biotite-muscovite schists Migmatitic mica schists/gneisses

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method; and (ii) based on the areal extent of each variable in the control (or known mineralization) area. In the first method, W_i is calculated using the following equation:

$$W_i = P\{(V_i \cap E)/E\} \tag{1}$$

where V_i is the ith variable and E is the event, i.e. mineralization. In the second method, W_i is calculated as the ratio of the areal extent of variable 'i' within the control area and the total areal extent of the control area. The weightages of different variables calculated using the above two methods are given in table 2. The weightages calculated by the two methods are different in absolute sense, however, their relative importance is maintained. This is because of the basic difference in data format and the method of weightage calculation. Since the binary approach is basically grid-based, the mere presence of a particular variable contributes towards the weightage, which is not true in case of the second method in which the weightage is calculated based on the areal extent of the variable within the known mineralized area.

After calculating the weightages of different variables, overlay analysis was performed in a GIS environment by taking two layers at a time, and FI maps were prepared. The FI values of the resultant units, obtained after overlay analysis, were calculated using the following equations:

$$\mathrm{FI} = \frac{\mathrm{OA}}{\text{maximum OA of the area}} \tag{2}$$

where,

$$\mathrm{OA} = \sum_{i=1}^{\mathrm{N}} (W_i \times V_i) \tag{3}$$

Further, the FI map was also prepared by changing the importance of lithological, structural, electromagnetic and magnetic data, and recalculating the weightage of each variable derived from the binary approach.

Essentially, the FI map indicates the percentage of the statistical similarity between an unknown area and the control area where the mineralization is present. It is also important to note that the FI map does not indicate whether a deposit is

Table 2. List of variables and their corresponding weightages.

Variable no.	Variable name	Weightage Method I*	Weightage Method II**
Geological			
V_1	Garnetiferous biotite-muscovite schists	0.0	0.0
V_2	Calc-silicates	0.6	0.4
V_3	Migmatitic mica schists/gneisses	0.0	0.0
V_4	Quartzites	0.0	0.0
V_5	Gossan	1.0	1.0
V_6	Graphitic mica schists with intercalatory quartzites	1.0	0.6
V_7	Calcareous biotite schists with dolomite bands	0.0	0.0
V_8	Sindesar Kalan/Jashma/Bhupalsagar quartzites	0.1	0.0
V_9	Quartz/pergmatite veins	0.0	0.0
V_{10}	Ferruginous chert breccia	0.0	0.0
V_{11}	Fault	0.8	0.2
V_{12}	Fracture/Lineament	0.1	0.04
V_{13}	Trend line	0.0	0.0
Airborne electromagnetics			
V_{14}	Channel 1 (in phase/quadrature ratio = > 3.0)	0.2	0.1
V_{15}	Channel 2 (in phase/quadrature ratio = 1.6–3.0)	0.7	0.4
V_{16}	Channel 3 (in phase/quadrature ratio = 1.5–0.75)	0.5	0.1
V_{17}	Channel 4 (in phase/quadrature ratio = < 0.75)	0.0	0.0
Airborne magnetics			
V_{18}	Magnetic high (> 47 500 gamma)	0.0	0.0
V_{19}	Magnetic high (47 500–47 300 gamma)	0.5	0.0
V_{20}	Magnetic high (< 47 300 gamma)	0.2	0.1
V_{21}	Magnetic low (> 47 200 gamma)	0.6	0.1
V_{22}	Magnetic low (> 47 200–47 000 gamma)	0.3	0.1
V_{23}	Magnetic low (< 47 000 gamma)	0.0	0.0
V_{24}	Magnetic high axis	0.3	0.1
V_{25}	Magnetic low axis	0.4	0.2
V_{26}	Magnetic discontinuity	0.2	0.1

* Based on binary approach.
** Based on areal extent.

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present. It only indicates that a particular area is more favourable than another (Shulman *et al.* 1992). The work reported here is an improved model compared with the previous one suggested by Bhattacharya *et al.* (1993), mainly because: (i) aero-electromagnetic data were used as additional inputs; and (ii) FI zones were more correctly defined spatially and follow the geometry of geological controls.

6. Results and discussion

The FI maps show that although the favourable zones in different models are more or less matching, their FI values are different in each model. The study of different FI maps indicates that the favourable locales for Pb–Zn–Cu mineralization can be grouped into two zones. The first zone falls in the Dariba-Rajpura-Bethumbi belt coinciding with the already lead–zinc mineralized belt, a part of which is under exploration by the Hindustan Zinc Limited (HZL) and a part under detailed exploration by the GSI. The second zone, a new zone, falls along the Dhani-Rawan

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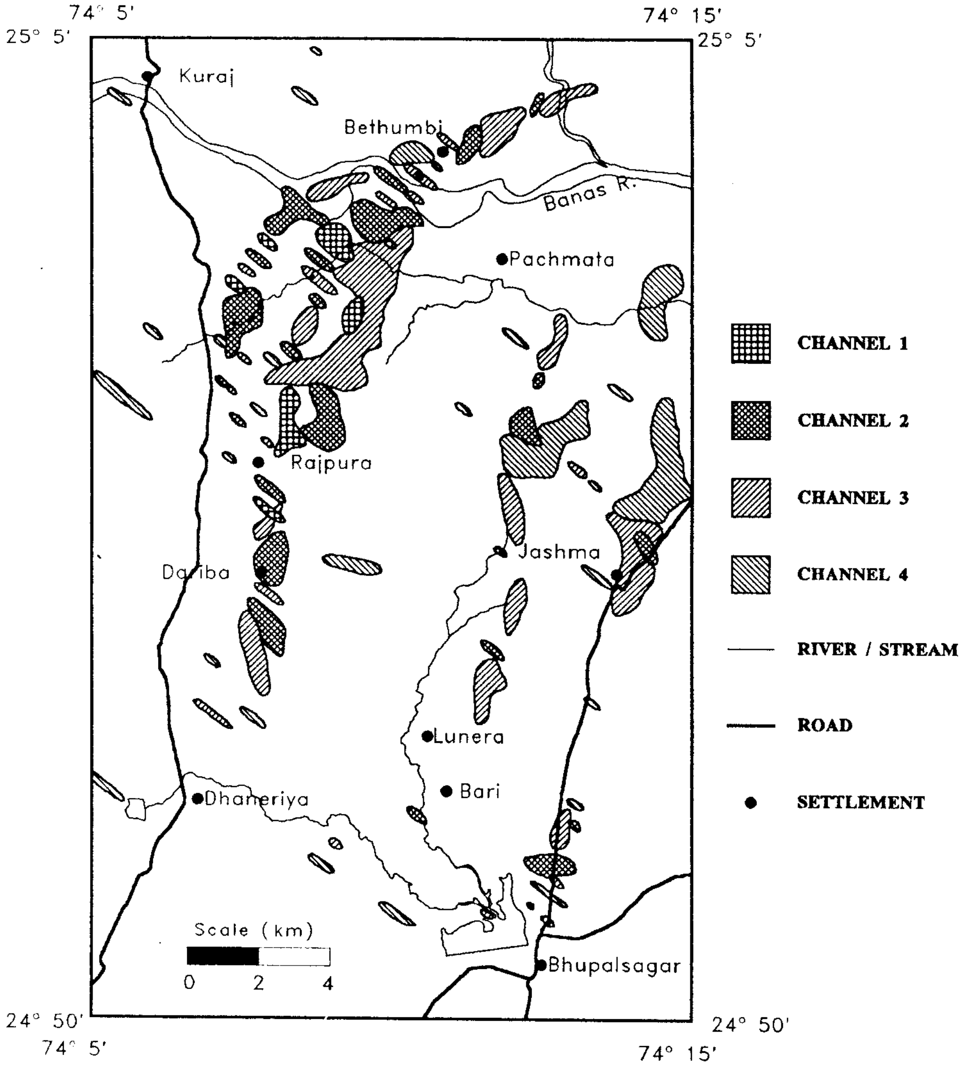

Figure 3. Map showing airborne electromagnetic anomalies (Source: GSI).

ka Khera-Bhupalsagar belt in the eastern part of the study area. The FI maps pertaining to different models were integrated and a map showing the favourable zones of Pb–Zn–Cu mineralization was prepared (figure 6), considering a proper FI value as a cut-off based on FI values over known mineralized areas. Thus, the favourable mineralized locales obtained along the Dhani-Rawan ka Khera-Bhupalsagar belt are: (i) around and north of Rawan ka Khera village (along Jashma ridge); (ii) isolated spots between Ruppura village and Bhupalsagar town; and (iii) north of Dhani village (along Jashma ridge). In the first zone, at about 2.5 km north of Rawan ka Khera village, a fault was noticed causing displacement in the graphitic schists-quartzites ridge. Subsequently, selective resistivity profiling was carried out around the first favourable zone, which showed low to moderate resistivity (or high to moderate conductivity) zones falling exactly over the favourable zones identified during this study. Further, a few stream/soil samples were collected over

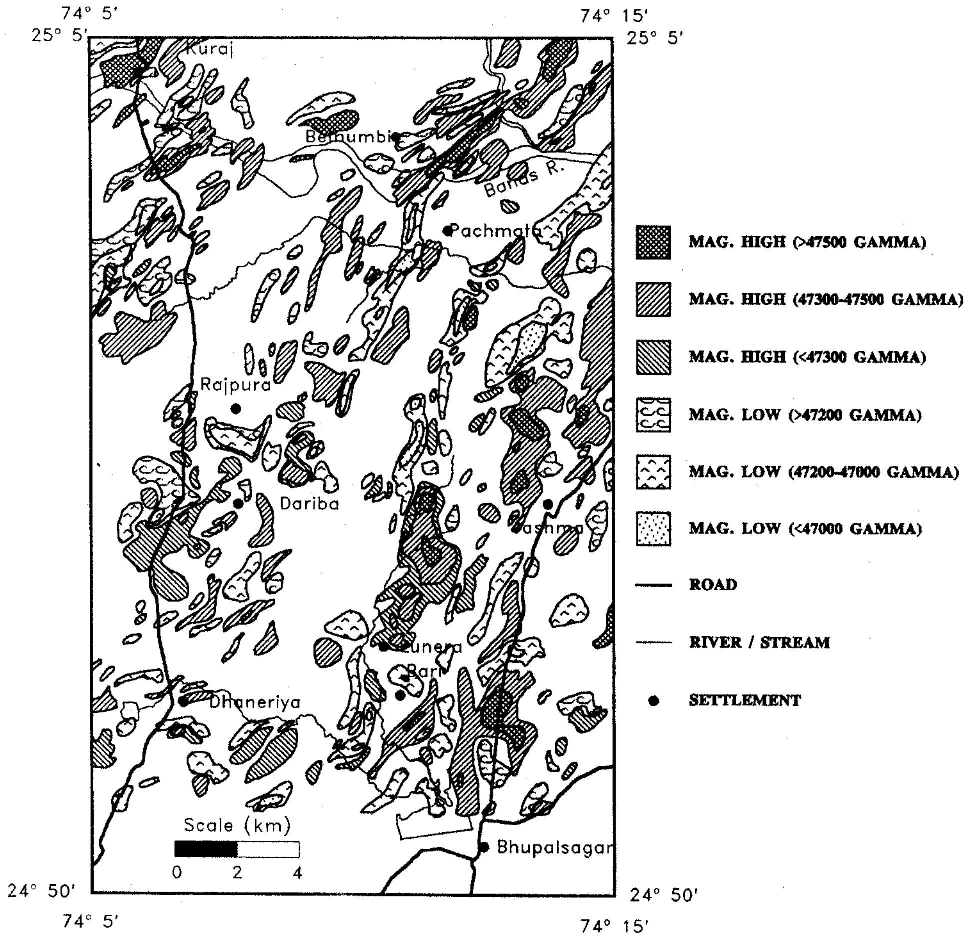

Figure 4. Airborne magnetic highs and lows interpreted from total field aeromagnetic map of GSI (Source: GSI).

the potential and surrounding areas, and analysed for Pb, Zn and Cu contents. The results indicate that the concentrations of Zn and Cu are anomalous near Bhupalsagar and at about 2.5 km north of Rawan ka Khera, respectively.

Recent drilling carried out by the Department of Mines and Geology (DMG), Rajasthan, in one of the favourable sites identified through the present study at about 2.5 km north of Rawan ka Khera along the graphitic schists-quartzites ridge, has indicated evidence of Cu mineralization at a depth of about 70 m (DMG, personal communication, Rajasthan). In view of the fact that in the Dariba-Bethumbi mineralized belt, Cu mineralization (poor grade) occurs at shallow depth and is followed by Pb–Zn mineralization at a deeper level, it is quite likely that even in this area with a similar geological environment Pb–Zn mineralization may be encountered at depth (DMG, personal communication, Rajasthan). Since this is the first borehole drilled by the DMG, Rajasthan, in this area, which itself has met with success, it has been suggested that a few more exploratory boreholes are drilled in other favourable locations identified during the present study after carrying out the necessary ground-based geophysical and geochemical surveys.

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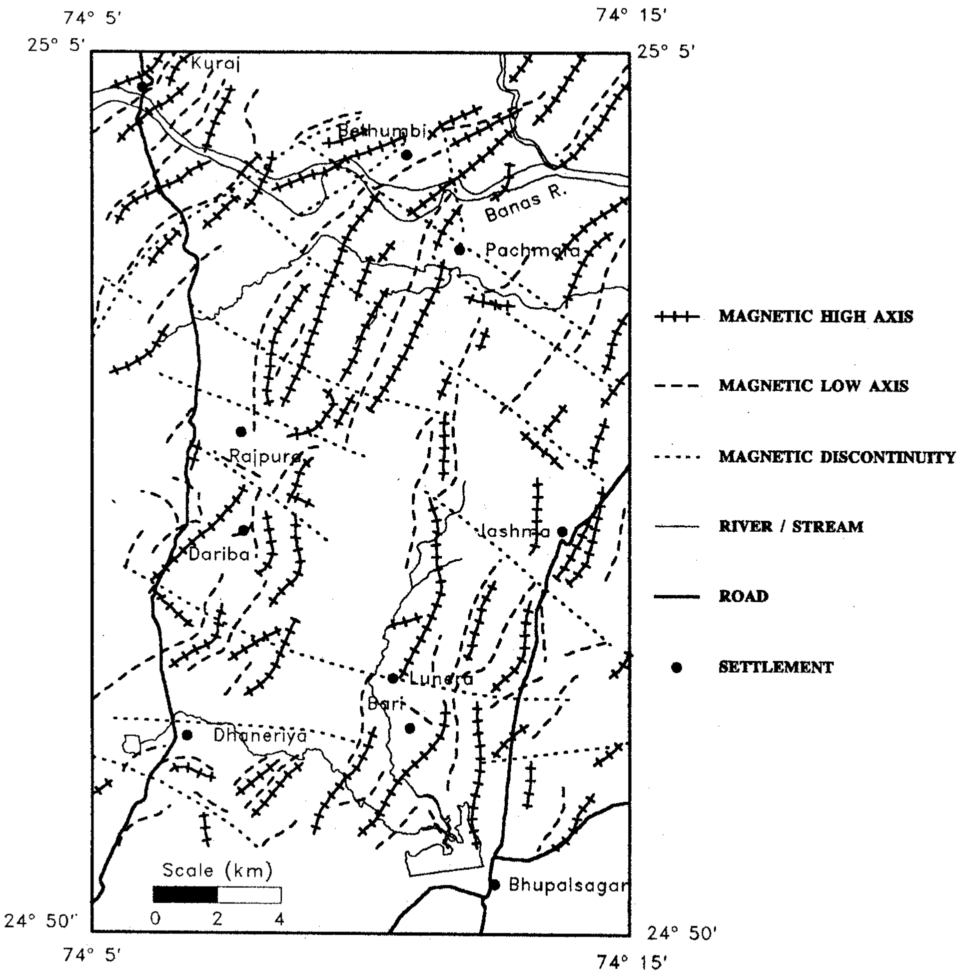

Figure 5. Airborne magnetic high/low axes and discontinuities interpreted from total field aeromagnetic map (Source: GSI).

This study has highlighted the use of remote sensing, GIS and geostatistical techniques for narrowing down the search areas for mineral prospecting.

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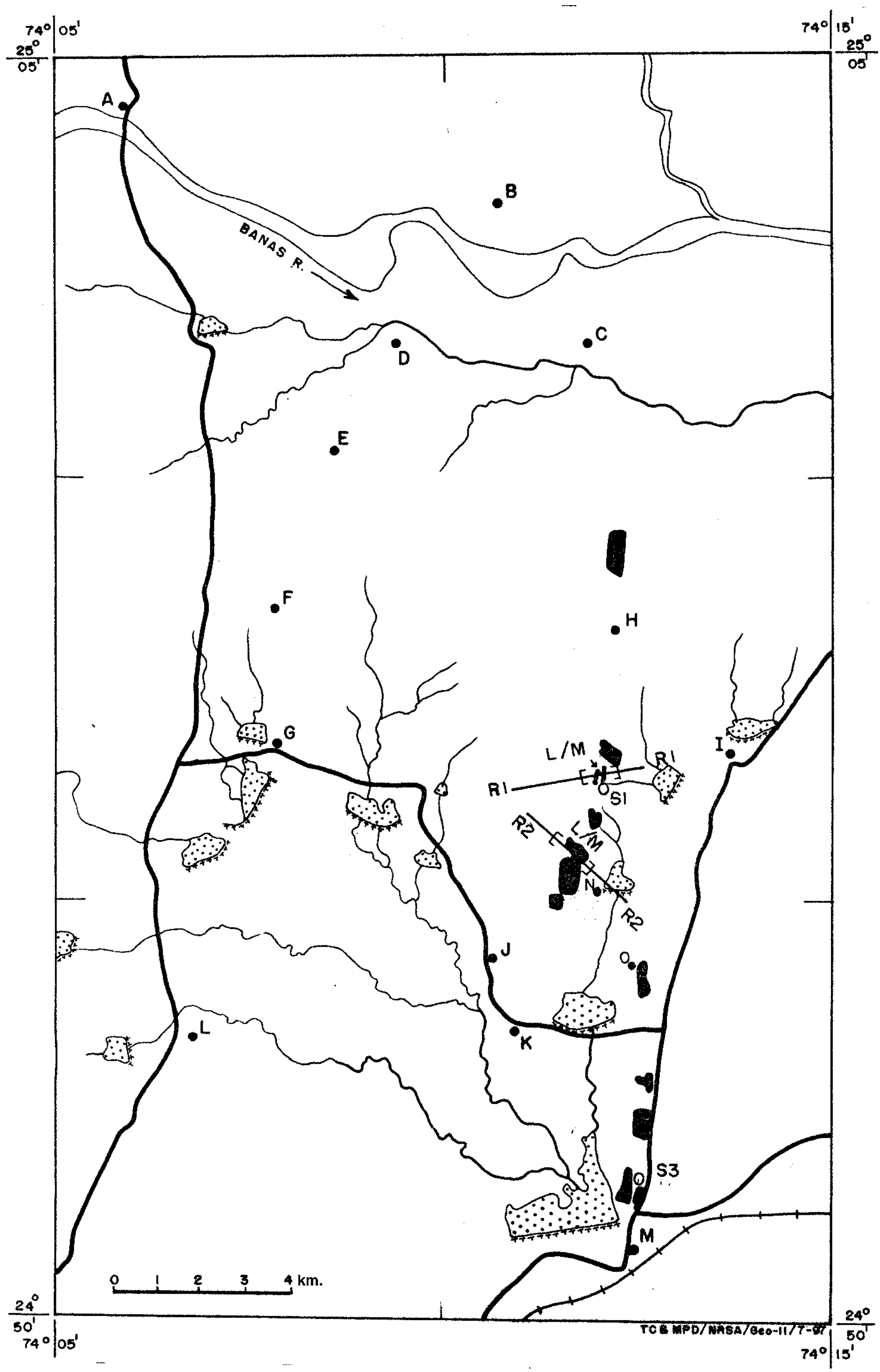
Figure 6. Map showing the favourable zones for Pb–Zn–Cu mineralization obtained through GIS-based analysis for planning detailed ground-based exploration. ■ Favourable zone; R1—[L/M]—R1, resistivity profile showing low/moderate resistivity zone; ○ S1, sample location having anomalous concentration of Zn/Cu; ———— road; —+—+—+— railway line; ≈≈ river/stream; ▷, tank/water body; ● A, settlement. Settlement names: A, Kuraj; B, Bethumbi; C, Pachmata; D, Sindesar Kalan; E, Sindesar Khurd; F, Rajpura; G, Dariba; H, Dhani; I, Jashma; J, Lunera; K, Bari; L, Dhaneriya; M, Bhupalsagar; N, Rawan ka Khera; O, Ruppura.



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