A PREDICTIVE MODEL FOR BASEMETAL EXPLORATION IN A GIS ENVIRONMENT

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ABSTRACT

A predictive model for mineral potential mapping based on fuzzy set theory is described. It is tested in the south-central part of the Aravalli province (western India), which hosts a number of conformable sediment-hosted basemetal deposits. Recognition criteria for basemetal mineralisation were identified on the basis of published work on metallogenesis in Aravalli province. A regional GIS was then established in ArcView GIS software using several public-domain geodata sets. These were reviewed, processed, reclassified and gridded to generate multi-class lithological, stratigraphic, structural, magnetic and lineament-density maps. Weights were assigned to each evidential map, and also to each class of the maps, on the basis of their significance as guides to the occurrence of basemetal mineralisation. These were used to calculate fuzzy membership values for all classes. The values thus determined were combined using fuzzy algebraic sum and fuzzy algebraic product operators to generate basemetal favourability maps for the province. It was observed that the fuzzy algebraic sum operator gives excessive areas of high favourability, while the fuzzy algebraic product operator tends to diminish favourability. The values obtained from these operations were therefore combined using fuzzy gamma operators to generate final favourability maps. Known basemetal occurrences were overlaid on the favourability maps to validate the procedure. It was found that most of the known mineral occurrences correlate with areas of high-predicted favourability, although there are several areas of high favourability that do not have any mineral occurrences. Work is continuing to check whether such areas genuinely represent areas warranting further exploration, or whether the modelling techniques used need further refinement.

1 INTRODUCTION

Most statistical and probabilistic approaches to mineral potential modelling are based on the use of binary evidential maps, while real-world geodata is usually multi-class in nature. This necessitates reclassification of multi-class data into binary data, which may result in loss of valuable information. Moreover, the reclassification principles are normally based on available information, and may change, as more information becomes available. Models based on fuzzy set theory accept multi-class data and are sufficiently robust to assimilate the “informational fuzziness” (Zimmermann, 1985) that is inherent in most geodata. The input parameters can be selected either by using empirical methods based on statistical (or heuristic) evaluation of the spatial association of various geodata with mineral deposits or by using a genetic model. In this study the second approach was used, the fuzzy membership values of the model parameters being assigned subjectively by experts. For building and testing the model, the south central part of the Aravalli metallogenic province in Rajasthan, western India, was selected (see Fig. 1). The area has been relatively well explored and this work is documented in the literature. An area of about 37500 sq. km, falling between latitudes 23°30′ N and 26° N and longitudes 73°30′ E and 75° E is used. This area includes a number of major Zn-Pb-Cu and Pb-Zn deposits and many small and minor occurrences of basemetals as well as abandoned mining pits.

1.1 Geology and mineralisation of the test area

Heron (1953) interpreted the geology of the Aravalli province in terms of three major Proterozoic orogenic cycles, represented by the Banded Gneissic Complex (BGC), the Aravalli Supergroup and the Delhi Supergroup. His scheme has remained the basic framework of reference for all subsequent revisions (e.g., Raja Rao, 1976; Roy, 1988; Sudgen et al., 1990; Gupta et al., 1995). The region is characterised by evidence of repeated tectonic deformation, metamorphism and magmatism (Roy et al., 1971; Naha and Halyburton, 1974; Roy, 1988; Sharma, 1988; Srivastava, 1988).

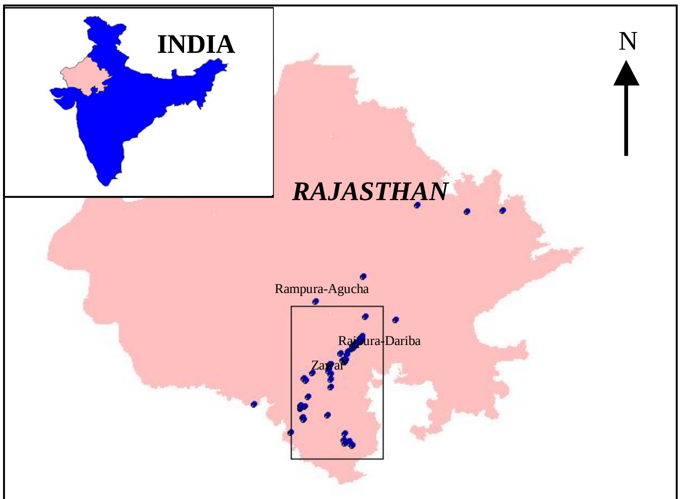

Fig. 1 Location map of the test area

Conformable, stratabound, sediment-hosted basemetal deposits in the area are hosted by Lower to Middle Proterozoic supracrustal rocks of the Aravalli supergroup, and by Pre-Aravalli(?) metasediments of the Bhilwara area. These deposits exhibit a marked preference for non-clastic carbonates and graphitic rocks (Deb, 1982). Major concentrations of mineralisation in the Bhilwara area occur in the Rampura-Agucha deposit and in the Pur-Banera-Rajpura-Dariba belt. Rampura-Agucha is a Zn-Pb-(Ag) deposit with the highest combined metal grade (about 15%) of all basemetal deposits in India. In the Rajpura-Dariba area, the Zn-Pb-Cu-(Ag-Sb-Cd-As-Au) mineralisation is located in a 17 km long belt running from Bethumni in north through Rajpura to Dariba in the south, with a lean pyrite zone to the south of Dariba. There is another lean polymetallic zone to the northeast, known as the Pur-Banera zone. Copper, gold and uranium mineralisation occurs in the basal sequences of lower supracrustals (Lower Aravalli group) between Udaipur and Banswara. The Upper Aravalli group hosts the Zn-Pb mineralisation of the Zawar belt, which comprises the deposits of Mochia Magra-Balaria, Zawarmala and Baroi Magra.

1.2 Overview of the approach

Recognition criteria for basemetal mineralisation in the study area were identified on the basis of published work on metallogenesis in Aravalli province. A regional GIS was then established using several public-domain geodata sets for this area. These were reviewed, reclassified and gridded to generate a series of multi-class evidential theme maps. Fuzzy membership values for each evidential map were derived using weights assigned subjectively. Finally, the fuzzy membership values of the evidential maps were combined using the fuzzy gamma operator to generate favourability maps.

2 RECOGNITION CRITERIA AND EVIDENTIAL MAPS

The mineral deposits in the area have been interpreted as exhalative-sedimentary deposits. Deb and Sarkar (1990), in a review of these deposits based on detailed field, fluid inclusion, stable isotope and other geochemical data, have explained metallogenesis in Aravalli province in a framework of extensional tectonism. According to these authors, the Zn-Pb(-Cu) sulphide deposits at Rampura-Agucha and in the Rajpura-Dariba and Pur-Banera belts were formed by convective sea water circulation in zones of crustal extension. The metal content of the exhalative brines was precipitated in troughs with high biological activity. The Zn-Pb deposits of the Zawar belt were formed close to a basement inlier, in second order basins with biological activity, by hydrothermal fluids convecting through a heterogeneous source.

On the basis of the published studies on metallogenesis in the Aravalli province, lithology, stratigraphic position, proximity to major fold axes and evidence of deformation were identified as key recognition criteria for the basemetal deposits. The first two criteria were based on the syngenetic nature of mineralisation, while the last two were selected on the basis of the extensive remobilisation of mineralisation by subsequent deformation, especially in the Zawar belt.

An extensive regional scale GIS was compiled in ArcView GIS software by digitising lithostratigraphical map (Heron, 1953), structural map (Gupta et al., 1980), total intensity aeromagnetic map (GSI, 1981), magnetic zones (GSI, 1981), gravity map (Reddi and Ramakrishna, 1987) and lineament density map. The mineral locations were compiled from various sources and digitised as point features in the GIS. Based on a consideration of the genetic model, we selected five thematic maps, which were deemed most likely to provide useful evidence for the presence of recognition criteria for basemetal deposits in the study area. The evidence maps selected were the lithological, stratigraphic, structural, magnetic zones and lineament density maps.

The lithostratigraphic map was reclassified into two independent maps, viz., lithological map and stratigraphic map. The structural map of the Aravalli region was classified according to the fold type and deformation phase. The fold axes were buffered to a distance of 1 km on the basis of visual inspection of spatial association between fold axes and the known mineral occurrences

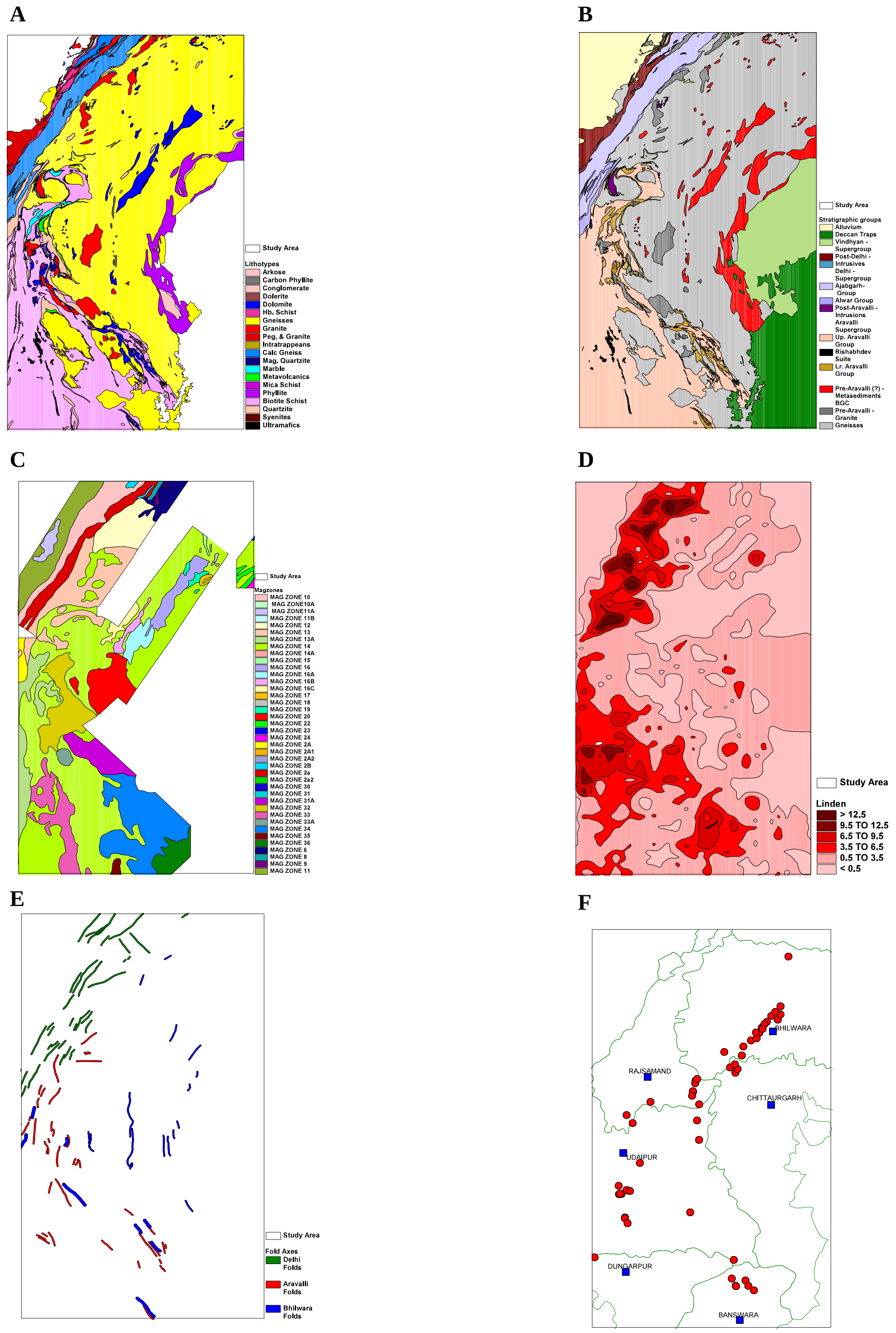

Fig. 2 Input evidential maps: A. the lithological map, B. the stratigraphic map, C. the magnetic zones map, D. the lineament density map, E. the structural map; F. basemetal distribution in the study area.

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Landsat TM images were interpreted to generate a lineament map. A 1 km^2 moving window was overlaid on the lineament map and the density of lineaments per square km was determined and contoured. As the lineament density largely depends on the extent of deformation, this was used as an evidence of deformation intensity.

The major part of the Aravalli province was covered by airborne magnetic surveys (1967-72) at flight intervals of 500 m and 1 km and at an altitude varying from 60 m to 130 m. These data were processed and visually interpreted by the Airborne Mineral Surveys and Exploration (AMSE) wing of the Geological Survey of India, who divided the entire region into 37 magnetic zones on the basis of magnetic intensities, patterns and features in relation to the geology and structural features as displayed on the geological map (GSI, 1981). Each magnetic zone can therefore be interpreted as a lithologic-tectonic-metallogenic association with a characteristic magnetic response. The spatial association of magnetic zones and base metal deposits was studied both empirically and genetically, and it was found that mineralisation tends to associate with particular magnetic zones. The magnetic zones map was, therefore, selected as one of the evidential maps.

The evidence theme maps, which were originally digitised and reclassified as polygon shapes, were converted into grid themes with a grid size of 100 metres. The grid size was decided on the basis of resolutions (or scales) of input maps. The input evidence grid maps and the mineral distribution in the area are shown in Figs. 2 (A to F)

3 FUZZY MODEL

If X is a multi-class evidential data set whose classes are denoted generically by x, then a fuzzy set $\tilde{A}$ in X, consisting of favourable indicators of mineralisation, can be defined such that

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) \mid x \in X\}$$

$\mu_{\tilde{A}}(x)$ is called the membership function or grade of membership (also degree of compatibility or degree of truth) of x in $\tilde{A}$ which maps X to the membership space M (Zimmermann, 1985). When M contains only two points 0 and 1, $\tilde{A}$ is non-fuzzy and $\mu_{\tilde{A}}(x)$ is identical to the characteristic function of a non-fuzzy set.

Given two or more multi-class maps with fuzzy membership values for each class, these can be combined using a variety of fuzzy set operators. Zimmermann (1985) gives a variety of combination rules based on fuzzy mathematics. An et al. (1991) discuss five operators that were found useful for combining exploration datasets, viz., fuzzy AND, fuzzy OR, fuzzy algebraic product, fuzzy algebraic sum and fuzzy gamma (γ) operator. Bonham-Carter (1994) gives a review of these operators.

We used fuzzy the γ operator function (Zimmermann and Zysno, 1980) for combining the maps. This operator is defined as follows:

$$\mu_{\tilde{A}_{i,comp}}(x) = \left(\prod_{i=1}^{m} \mu_i(x)\right)^{(1-\gamma)} \left(1 - \prod_{i=1}^{m}(1-\mu_i(x))\right)^{\gamma}, \tag{1}$$

where $x \in X$, $0 \leq \gamma \leq 1$

The γ operator is a combination of the fuzzy algebraic product and fuzzy algebraic sum operators. At $\gamma = 0$, the operator is equivalent to the fuzzy algebraic product, while at $\gamma = 1$, it is equivalent to fuzzy algebraic sum. This operator tends to compensate the "decreasive" tendency of fuzzy algebraic product with the "increasive" effect of fuzzy algebraic product.

We used the following function to calculate fuzzy membership values:

$$\mu_{\tilde{A}}(x_{ij}) = \begin{cases} 0 & \textit{for } S_{ij} = S_{min} \\ \dfrac{S_{ij} - S_{\min}}{S_{\max} - S_{\min}} & \textit{for } S_{max} > S_{ij} > S_{min} \\ 1 & \textit{for } S_{ij} = S_{max} \end{cases} \tag{2}$$

The Score (S_{ij}) measures the effective weight of the i^{th} class of the evidential map j, and was calculated using following relation:

$$S_{ij} = \frac{W_i \times W_j}{\sum_{j=1}^{n} W_j} \tag{3}$$

Here W_i is the weight of the i^{th} class and W_j is the weight of j^{th} map. These weights were assigned subjectively, based on past exploration experience and opinion of the experts. The scores and fuzzy membership values for each of the input maps are given in Table 1.

Map/Class	Weight	Score	Fuzzy Membership	Map/Class	Weight	Score	Fuzzy Membership
Lithological map (Map weight 10)				**Structural Map (Map weight 2)**			
Alluvium	0	0.00	0.0	AF1 Antiform	4	0.27	0.08
Arkose & Conglomerate	1	0.33	0.1	AF2 Antiform	4	0.27	0.08
Basalt	0	0.00	0.0	AF2 Overturned Antiform	10	0.67	0.20
Carbonaceous Phyllite	8	2.67	0.8	AF2 Synform	6	0.40	0.12
Conglomerate	0	0.00	0.0	BF1 Overturned Synform	8	0.53	0.16
Dolerite Intrusion	0	0.00	0.0	BF1 Synform	4	0.27	0.08
Dolomite	10	3.33	1.0	BF2 Antiform	6	0.40	0.12
Epidiorite & Hb Schist	2	0.67	0.2	BF2 Overturned Antiform	10	0.67	0.20
Gneisses & Schists	0	0.00	0.0	BF2 Overturned Synform	10	0.67	0.20
Granite	0	0.00	0.0	BF2 Synform	6	0.40	0.12
Granite & Pegmatite	0	0.00	0.0	DF2 Antiform	4	0.27	0.08
Lst, Calc Gneiss & Schist	3	1.00	0.3	DF2 Overturned Antiform	6	0.40	0.12
Magnetite Quartzite	8	2.67	0.8	DF2 Overturned Synform	6	0.40	0.12
Marble	5	1.67	0.5	DF2 Synform	4	0.27	0.08
Metavolcanics	8	2.67	0.8	Shear Zone	6	0.40	0.12
Mica Schist	6	2.00	0.6	**Magnetic zones Map (Map weight 6)**			
Missing Data	0	0.00	0.0				
Phyllite	0	0.00	0.0	MAG ZONE 2	2.0	0.4	0.12
Phyllite & Biotite Schist	0	0.00	0.0	MAG ZONE 2A	1.0	0.2	0.06
Quartzite	2	0.67	0.2	MAG ZONE 2B	4.0	0.8	0.24
Serpentinites	0	0.00	0.0	MAG ZONE 6	4.0	0.8	0.24
Soda Syenites	0	0.00	0.0	MAG ZONE 8	6.0	1.2	0.36
Vindhyan Formations	0	0.00	0.0	MAG ZONE 9	6.0	1.3	0.39
Stratigraphic Map (Map weight 10)				MAG ZONE 10	4.0	0.8	0.24
				MAG ZONE 11	3.0	0.6	0.18
Ajabgarh Group	6	2.00	0.6	MAG ZONE 11A	3.0	0.6	0.18
Alluvium	0	0.00	0.0	MAG ZONE 12	6.0	1.2	0.36
Alwar Group	4	1.33	0.4	MAG ZONE 13	5.0	1.0	0.30
Banded Gneissic Complex	2	0.67	0.2	MAG ZONE 13A	5.0	1.0	0.30
Deccan Traps	0	0.00	0.0	MAG ZONE 14	3.0	0.6	0.18
Lower Aravalli Group	8	2.67	0.8	MAG ZONE 15	4.0	0.8	0.24
Post-Aravalli Intrusions	0	0.00	0.0	MAG ZONE 16	8.0	1.6	0.48
Post-Delhi Intrusives	0	0.00	0.0	MAG ZONE 16A	8.0	1.6	0.48
Pre-Aravalli Granite	0	0.00	0.0	MAG ZONE 16B	8.0	1.6	0.48
Pre-Aravalli Metasediments	10	3.33	1.0	MAG ZONE 16C	8.0	1.6	0.48
Rishabhdev Suite	0	0.00	0.0	MAG ZONE 17	6.0	1.2	0.36
Upper Aravalli Group	6	2.00	0.6	MAG ZONE 18	4.0	0.8	0.24
Vindhyan Supergroup	0	0.00	0.0	MAG ZONE 19	8.0	1.6	0.48
Lineament Density Map (Map weight 2)				MAG ZONE 20	2.5	0.5	0.15
				MAG ZONE 22	4.5	0.9	0.27
< 0.5	0	0.00	0.00	MAG ZONE 23	6.5	1.3	0.39
0.5 To 3.5	2	0.13	0.04	MAG ZONE 24	3.5	0.7	0.21
3.5 To 6.5	4	0.27	0.08	MAG ZONE 31A	7.0	1.4	0.42
6.5 To 9.5	6	0.40	0.12	MAG ZONE 32	7.5	1.5	0.45
9.5 To 12.5	8	0.53	0.16	MAG ZONE 33	8.5	1.7	0.51
>12.5	10	0.67	0.20	MAG ZONE 33A	8.0	1.6	0.48
				MAG ZONE 34	9.0	1.8	0.54
				MAG ZONE 35	4.0	0.8	0.24
				MAG ZONE 36	5.5	1.1	0.33

Table 1 Weights, scores and fuzzy membership values for the evidential maps

The fuzzy gamma operator function (Equation 1) was then used for combining fuzzy membership values and generating final favourability maps. The algebraic product term in the right hand side of the equation, viz., $\prod_{i=1}^{m} \mu_i(x)$, returns a value of 0 for most of the area, because the fold axes map has a value of "no data" for all grids except for the grids which fall on the buffers of fold axes. This results in a combined fuzzy membership value of zero on multiplication for all these areas. This map was therefore omitted, and the algebraic product term was computed using four maps only. Several values of γ were tested, and it was found that large values of γ give excessive areas of high favourability (eg. Fig. 3C, $\gamma = 1$). Figs. 3A and 3B show the favourability maps generated using $\gamma = 0$ and $\gamma = 0.500$, respectively.

A			B			C		
Fuzzy Membership	No. of Deposits	%	Fuzzy Membership	No. of Deposits	%	Fuzzy Membership	No. of Deposits	%
0.00 - 0.10	3	5.0	0.00 - 0.19	2	3.3	0.00 - 0.20	0	0.0
0.10 - 0.19	1	1.7	0.19 - 0.37	0	0	0.20 - 0.40	0	0.0
0.19 - 0.29	10	16.7	0.37 - 0.56	0	0	0.40 - 0.60	0	0.0
0.29 - 0.38	3	5.0	0.56 - 0.74	1	1.7	0.60 - 0.80	0	0.0
0.38- 0.48	43	71.7	0.74 - 0.93	57	95.0	0.80 - 1.00	60	100.0

Table 2 Distribution of deposits with respect to the combined fuzzy membership classes derived using different values of the fuzzy gamma operator (A. $\gamma = 0$, B. $\gamma = 0.500$, and C. $\gamma = 1$)

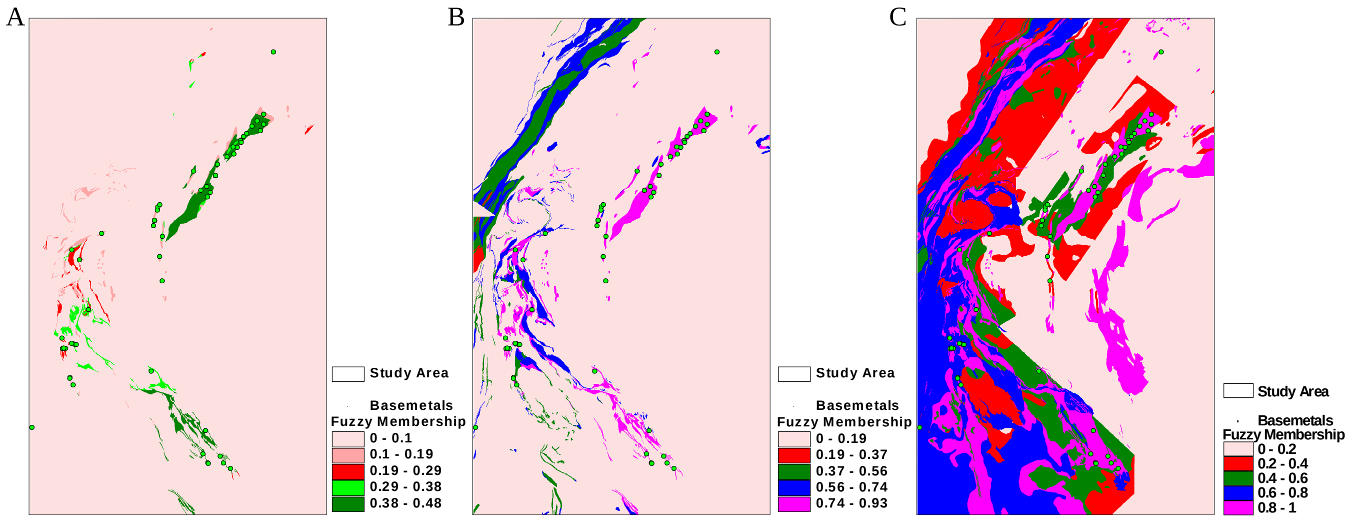

Fig. 3 Favourability maps generated using different values of fuzzy gamma operator (A. $\gamma = 0$, B. $\gamma = 0.500$, C. $\gamma = 1$)

4 DISCUSSION

The fuzzy model at $\gamma = 0.500$ predicts 95% of the known mineral deposits in high favourability areas (Table 2B, Fig. 3B). At $\gamma = 1$ (the fuzzy algebraic sum operator), the model predicts all mineral deposits in high favourability area, but it also predicts unrealistically large areas of high favourability (Fig. 2C). On the other hand, the fuzzy algebraic product operator ($\gamma = 0$), predicts most of the known mineral deposits in low to moderate favourability areas (Fig. 2A).
In addition, several areas with high favourability, which contain no known basemetal occurrence, are mapped. Especially notable is a moderately-high favourability belt with combined fuzzy membership value of 0.56-0.74 in the north-western part of the study area, which is predicted by the model when a γ value of 0.5 or larger is applied. This belt is occupied by meta-carbonates and meta-basites of the Delhi supergroup and contains no significant mineral occurrence. Similar rocks host important copper and polymetallic mineralisation outside the study area. Work is continuing to verify whether these areas genuinely represent favourable areas warranting further exploration, or whether the modelling techniques used need further refinement.

5 SUMMARY AND CONCLUSIONS

A GIS-based fuzzy model was developed and tested for predictive mapping of basemetal deposits in the Aravalli province. The membership values for the input evidential maps were derived using subjectively assigned weights and were combined using a fuzzy gamma operator with different values of γ. The resulting favourability maps predicted most of the known basemetal occurrences in the study area. However, very low and very high values of γ yield unrealistic favourability maps. Moderate values of γ (about 0.5) are most suitable for combining maps using fuzzy gamma operator. The model also predicted new areas that can be possible targets for further exploration in the area.

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