Econ. Environ. Geol.
Vol. 32, No. 5 p. 537-544, 1999.

Data Fusion of Mineral Exploration Data Sets and Its Application Using Fuzzy Set Theory

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ABSTRACT: In mineral exploration, there are many data sets which need to be created, processed and analyzed in order to discover a favorable mineralized zone. Recently, with Geographic Information System (GIS), such exploration data sets have been able to be systematically stored and effectively processed using computer technologies. In this study, most exploration data sets were first digitized and then rasterized. Furthermore, they were integrated together by using fuzzy set theory to provide a possibility map toward a target hypothesis. Our target hypothesis is "there is a skarn magnetite deposit in this study" and all fuzzy membership functions were made with respect to the target hypothesis. Test area is extended from 37:00N/128:30E to 37:20N/128:45E, approximately 20 km by 40 km. This area is a part of Taebaeksan mineralized areas, where the Sinyemi mine, a skarn magnetite deposit, is located. In final resultant map, high potential or possibility area coincides with the location of the Shinyemi mine. In this regard, we conclude the fuzzy set theory can be effectively applied to this study and provides an excellent example to define potential area for further mineral exploration.

INTRODUCTION

Many geologists have applied their own methods to define a potential area for mineral exploration. In mineral exploration, each data set obtained from field or laboratory works is, to some extents, vague and incomplete. Therefore, it is difficult to predict or outline a favorable area toward a target mineral deposit by using each data set, individually. However, such vagueness or incompleteness can be improved if each data set would be fused together using a proper integration method. Geographic Information System (GIS) techniques allow us to process, analyze and integrate such an exploration data set. There are several methods to combine data sets together. Boolean Logic Models were introduced by Varnes (1974) and Robinove (1989), which were used to overlay each data set. Index Overlay Models are that each data set is assigned a different weight value depending on its significance to a given target hypothesis, which was applied by Reddy and Bonham-Carter (1991). Fuzzy Set Theory was also applied to outline a mineral habitat by An *et al.* (1991), An (1992) and Choi *et al.* (1999). In addition, weights of evidence was applied by Bonham-Carter *et al.* (1989) to map mineral potential and evidence belief function was used for integrating geological and geophysical data based on dempster-shafer method (Moon, 1990). Recently, Artificial Intelligence/Expert system and Neural network have been studied to overlay data sets together (Moon, 1993). In this study, we introduce the Fuzzy Set Theory that is able to systematically and effectively integrate the preexisting geologic data sets.

The objectives of this study are as follows; 1) To transform old exploration data sets to digital form for process, analysis, and integration on computers. 2) To provide a possibility map for a given hypothesis by integrating data sets. 3) To figure out which area has a high potential for further mineral exploration in the study area.

GENERAL GEOLOGY

The study area that is part of Taebaek-san mineralized area is located in the southwestern margin of the Baegunsa Syncline, and is largely divided into four major rock units (Fig. 1). The Precambrian basement rocks are composed of metasedimentary rocks, schist, and gneiss, which are exposed in the southern part of the study area (Fig.

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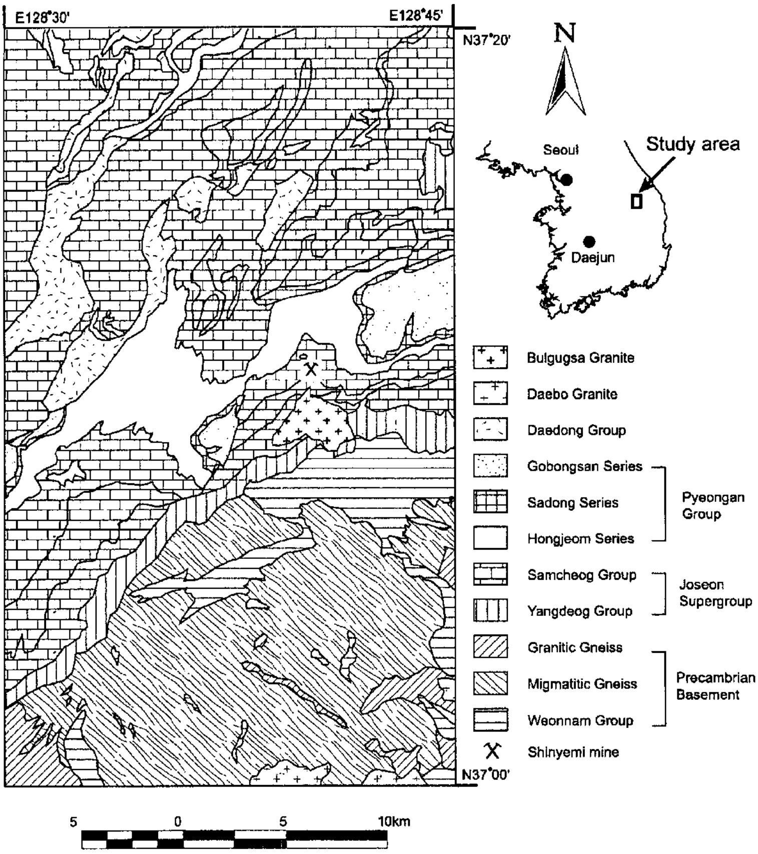

Fig. 1. Geologic map of the study area (after Chuncheon map sheet, 1973).

1). The overlying Cambro-Ordovician Joseon Supergroup consists of quartzite, limestone, and dolomitic limestones which are unconformably intruded by the Carboniferous-Triassic Pyeongan Group. Overlying the Pyeongan Group is the Jurassic sedimentary rocks of the Daedong Group which is intruded by the Cretaceous Bulgulsa and Shinyemi granites (Fig. 1). The geologic map of this study area is shown in Fig. 1, which was compiled by Geological and Mineral Institute of Korea (1973).

The Shinyemi mine, one of the largest skarn-type magnetite deposits in Korea, is located in Chodongri, Kangwon-do, Korea, about 1 km northern-east of Yemisan in the study area (Fig. 1), and closely related to Cretaceous granites. This mine was first exploited in 1961 and has been operated until the 1980s. We consider the location of Shinyemi as a ground-truth point toward the target hypothesis, there is a skarn magnetite deposit in the study area.

FUZZY SET THEORY

Many scientists have applied the fuzzy set theory to their study and proved that this theory is very useful to reflect natural phenomena or irregular behaviors. The fuzzy set theory was introduced by Zadeh (1965), which facilitates analysis of non-discrete natural processes or phenomena as mathematical formulas. In classical set theory, the membership of a set is assigned to 1 or 0 in value (true or false, respectively), while the membership of a fuzzy set can have any value from 0 to 1. That is, the former is just capable of 0 or 1, but the latter is capable of real value from 0 (full nonmembership) to 1 (full membership). A fuzzy set may be reviewed as a general form of a classical set whose membership only has two values {0,1}.

A fuzzy set, F, is represented as

$$F=\{\mu_{f(x)}|(x\in X)\}$$

where X is a collection of objects denoted generically by x, and $\mu_f(x)$ maps X to the membership space that is called the membership function of x.

A fuzzy membership function can be regarded as a possibility distribution function, where possibility distribution is similar but different from the mathematical probability distribution. Much of information on which natural phenomena are based is possibilitic rather than probabilitic (Zadeh, 1978).

Each data layer of target information denoted from fuzzy theory can now be integrated by using fuzzy operators. Even though a large number of fuzzy operators is available, most of them were basically designed for engineering applications and are not suitable for mineral exploration applications. Some of the useful fuzzy operators for mineral exploration application are comprehensively explained by An (1991), An (1992), and Bonham-Carter (1994).

The basic fuzzy operators considered in this study are as follows:

Fuzzy AND

$$\mu_{and}(x)=\mathrm{MIN}\{\mu_1(x),\mu_2(x),\mu_3(x),\ldots\}$$

The result obtained from fuzzy AND operator is the smallest value among contributing sets. This operator is usually used to be combined together when all of fuzzy sets are to satisfy a given hypothesis. This operator can also often be applied to creating an intermediate resultant set which will not have much effect on the resultant set later.

Fuzzy OR

$$\mu_{or}(x)=\mathrm{MIN}\{\mu_1(x),\mu_2(x),\mu_3(x),\ldots\}$$

The fuzzy OR operator is appropriate where any of fuzzy set supports a given hypothesis. Using this operator, the combined value is limited to the maximum value.

Fuzzy Algebraic Product

$$\mu_{product}(x)=\prod_{i=1}^{n}\mu_i$$

Fuzzy Algebraic Sum

$$\mu_{sum}(x)=\prod_{i=1}^{n}(1-\mu_i)$$

The fuzzy Algebraic Product operator makes the resultant set smaller than, or equal to, the minimum value among contributing fuzzy sets, while the fuzzy Algebraic Sum operator is the opposite, that is, the resultant set is larger than, or equal to, the maximum value among contributing fuzzy sets. One of the most significant differences between the former two operators and the latter two operators is that for the former two operators, only one of the contributing fuzzy sets has an effect on the resultant set while all the contributing fuzzy sets have an effect on the resultant set in the case of the latter two operators.

Fuzzy γ operator

$$\mu_\tau(x)=\left(1-\prod_{i=1}^{n}(1-\mu_i)\right)^{\tau}\times\left(\prod_{i=1}^{n}\mu_i\right)^{1-\tau}$$

where γ is a parameter value that can be in the range of 0 and 1. This operator was introduced by Zimmerman and Zysno (1980). The integrated information obtained from γ operator represents an information corresponding to somewhere between the fuzzy algebraic product operator and the fuzzy algebraic sum operator. Also it depends on the parameter value γ. If γ is equal to 1, the result will be same as the result would have been obtained from the fuzzy algebraic sum operator. If γ is 0, the result becomes equivalent to the result obtained from the fuzzy algebraic product operator. Fig. 2

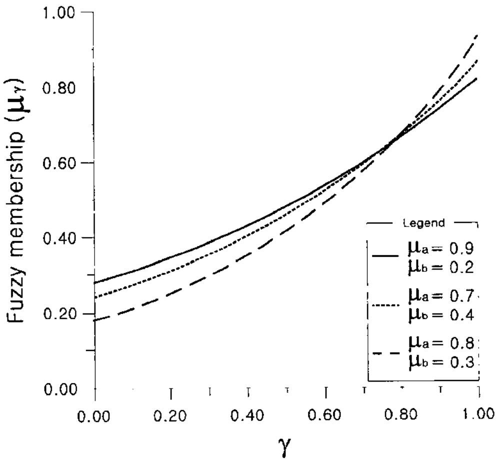

Fig. 2. Plot of μ_γ with given μ_a and μ_b. The horizontal axis represents γ value for integration of μ_a and μ_b using fuzzy γ operator. The μ_a and μ_b are fuzzy memberships for data set, A and B, respectively.

shows the effect of choosing different values of γ in the range between 0 and 1. As can be seen in Fig. 2, the choice of appropriate γ value make the result higher or lower potential toward a given target hypothesis. Value of γ which results in higher potential is different depending on the values of contributing fuzzy sets.

DATA SET AND DATA PROCESSING

All data sets used in this study were in analogue form (i.e. paper map). Prior to any further processing, these data sets must be converted to digital form. Paper maps were first digitized and then rasterized with Calcomp digitzer. Most data processing steps were carried out on GRASS 4.2 which is a cell-based system and has been distributed as a free of charge software (GRASS 4.2 Reference Manual). ER-Mapper 5.2 was also utilized in this study. Some functions which are not supported in these software but needed in this study were programmed by Choi, S. (1999) with the GNU gcc language. The detail descriptions of the utilized data sets in this study are as follows:

Geological data

Two geological maps were used in the study; one is a geologic map in 1973 on 1:250,000 scale, which was mapped by the Geological and Mineral Institute of Korea and the other is a compilation map in 1995 on 1:1,000,000 scale by Korea Institute of Geology, Mining & Materials. The former was basically digitized and the latter was only used to correct some errors in the former. The digitized map is converted into a raster map which consists of 3292 pixels by 2208 pixels and the resolution of each pixel is 10 units wide, 10 units high on Universal Transverse Mercator system. At this time, some similar geological units are combined together to make the later processing easier and simpler.

Geochemical data

In the case of geochemical maps, several elements are available in the study. Among them, Copper (Cu), Cobalt (Co), Lead (Pb) and Zinc (Zn) are selected and processed in this study because these four elements are usually used as pathfinder elements of skarn magnetite deposit (Rose, 1981). Geochemical data sets were first digitized and then interpolated to cover all study area by regularized spline method (Mitasova and Mitas, 1993). One of the interpolated maps is shown in Fig. 3A.

Geophysical data

Two types of geophysical survey data are available in the study area; total magnetic intensity (TMI) and γ-ray spectrometer maps (Park *et al.*, 1988). The anomalies of TMI can be considered as an indicator of magnetite deposit because magnetite deposit is mainly composed of several magnetic minerals. γ-ray spectrometer maps were also used to find unveiled granite rocks. All the geophysical data maps which were already preprocessed, interpolated and compiled as paper map sheet, were manually digitized and rasterized (Fig. 4A).

Data processing includes the following 4 steps. The first step is to convert all data sets into digital forms by using digitizer and scanner for further processing on the computer. Some data set, for example geochemical data, should be interpolated by using spline method, and re-sampled to cover the whole study area. Second step is to transform a vector format into a raster format because all data sets should be in a raster format to be processed in the study. At this time, the resolution of the data sets should be decided. A higher resolution data set has the more space and time for further processing. Therefore, the proper resolution should be considered and decided. In the study, the resolution of the data set is 3672 pixels by 2208 pixels, where the former is the number of rows, and the latter is the number of columns. Third step is to transform the data sets, which were processed through first and second steps, into fuzzy sets with respect to the hypothesis, "there is a skarn magnetite deposit", because the operators of data integration can applied to only fuzzy set in the study. To convert an exploration data set to a fuzzy set, a fuzzy membership function is defined for each data set that is assigned its fuzzy membership function later. Fuzzy membership function can be represented as a mathematical formula; i.e $y=x+b$, or tables of numbers. In this study, we employ table format as fuzzy membership function (Table 1). The final step is to

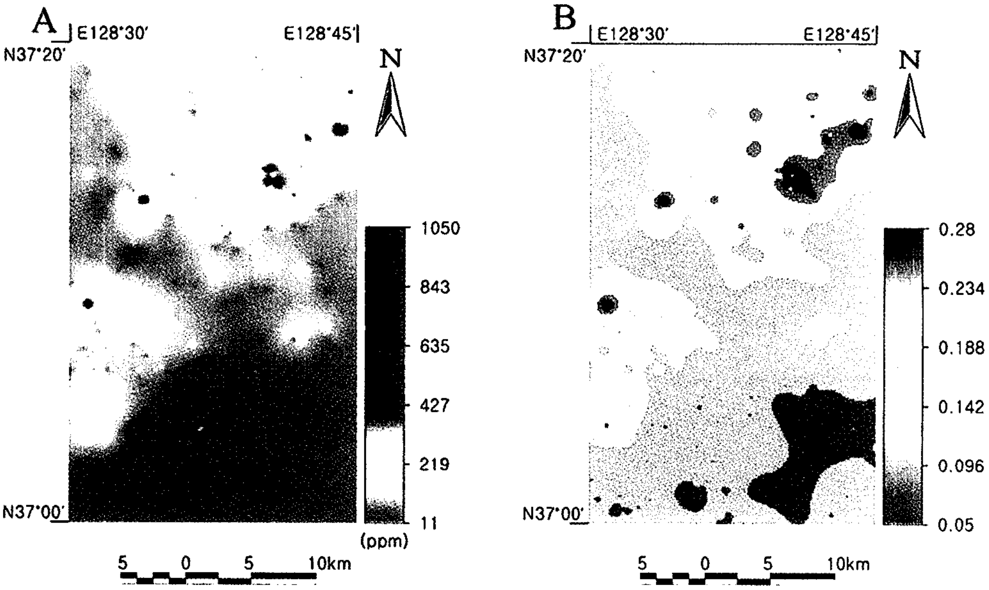

Fig. 3. (A) Preprocessed raster image of the geochemical data (Copper). (B) Fuzzy membership representation of the same data as shown in A.

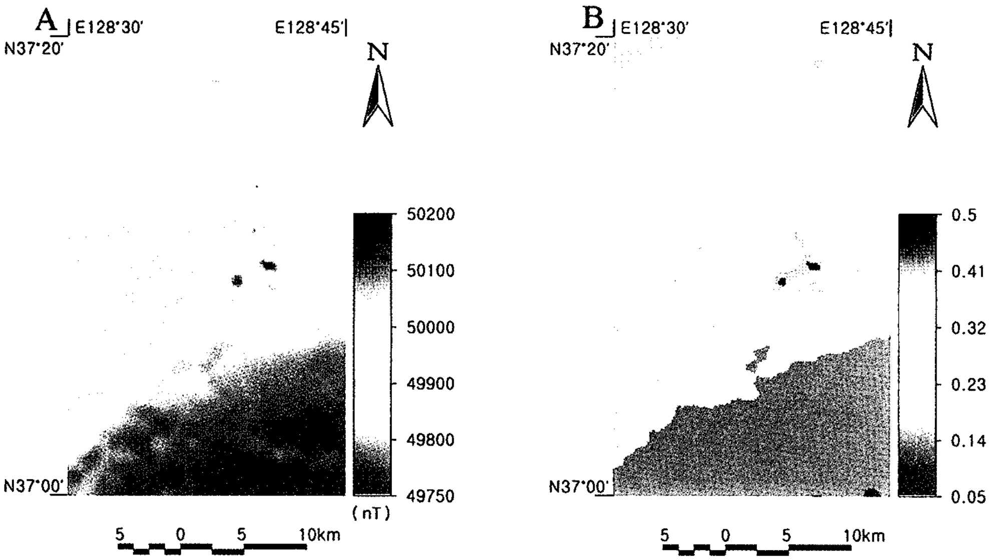

Fig. 4. (A) Preprocessed total magnetic intensity (TMI) data set. (B) Fuzzy membership representation of the same data as shown in A.

integrate all data set together by using several fuzzy operators to produce a possibility map toward the target hypothesis. Fig. 5 shows the inference steps toward the target hypothesis as network model, where a box and a circle represent a data set and a fuzzy operator, respectively.

DATA INTEGRATION

The following mineral deposit models were used in this study for data integration. 1) The contact zone between limestone and its intrusive granite plays an important role in a skarn magnetite deposit

Table 1. Membership function assignment of each data set with respect to the target proposition that there is a magnetite deposit in study area ($\mu_m(x)$).

Date Category			$\mu_{m(x)}$
Geological data	Limestone		0.2
	Others		0.05
	Granite		0.15
	Contact of Limestone and Granite	<100 m	0.3
		<500 m	0.25
		<1000 m	0.15
		<2000 m	0.1
		No contact zone	0.03
Geochemical data (ppm)	Co	>140	0.25
		97~143	0.20
		50~97	0.15
		3~50	0.10
		<3	0.05
	Cu	>241	0.25
		167~241	0.20
		92~167	0.15
		18~92	0.10
		<18	0.05
	Pb	> 730	0.25
		1830~2730	0.20
		830~1830	0.15
		30~ 830	0.1
		<30	0.05
	Zn	>284	0.25
		204~284	0.2
		124~204	0.15
		44~124	0.1
		<44	0.05
Total Magnetic Intensity (nT)	>50114		0.5
	50028~50114		0.41
	49942~50028		0.32
	49856~49942		0.23
	49770~49856		0.14
	<49770		0.05
Contact zones between γ-ray Spectrometer data and Limestone	<500 m		0.23
	500~1000		0.15
	1000~2000		0.1
	No contact zone		0.03

(Meinert, 1992). 2) Iron (Fe), copper (Cu), cobalt (Co), lead (Pb) and zinc (Zn) are considered as pathfinder elements for a skarn magnetite deposit. 3) In Korea, most deposits of skarn type are associated with Cretaceous granites (Choi, 1999). Two fuzzy sets associated with the contact zone were created and integrated together by using fuzzy OR operator. One is made by buffering the contact zone between limestone and granite extracted from the geologic map. The other is obtained by buffering the contact zone between limestone from the geologic map and anomaly areas which are produced by integrating γ-ray spectrometer data sets (K, Th, and U) with the fuzzy algebraic Product operator. We assume that the anomaly zones of γ-ray spectrometer data sets indicate the locations of undiscovered igneous rocks. Limestone and intrusive granitic rocks are considered as significant factors to be a skarn magnetite deposit. The fuzzy membership function of general geology is based on these factors and assigned to the geologic map. Total magnetic intensity (TMI) map is considered as an indicator of Fe, and is assigned the fuzzy membership function to be a fuzzy set (Fig. 3B). Four geochemical maps (Cu, Co, Pb and Zn) are fused together using the fuzzy γ-operator (γ=0.975), which is shown in Fig. 2B. As described above, four fuzzy sets are produced as intermediate processing. The first is about contact zones between limestone and granite, and the second is a general geology, the third a geochemical fuzzy set, and the last a TMI fuzzy set.

Several fuzzy operators were tested to combine these intermediate fuzzy sets together. The fuzzy γ-operator was more effective than in the fuzzy AND or OR operator because the results of the fuzzy AND or OR operators could not outline the ground-truth point, the Shinyemi mine. The result from the fuzzy γ-operator is shown in Fig. 7, which represents a possibility map toward the target hypothesis, there is a skarn magnetite deposit, in the study area.

Discussions & Conclusions

One of the time-consuming processes in this study is to convert the old exploration data to digital form. Once this work, however, is done, the other processes can be relatively quickly carried out on a computer. In this study, a geologic map, four geochemical maps, an airborne magnetic map, and three γ-ray spectrometer data were utilized to produce a fuzzy possibility map with respect to the target hypothesis. In the case of geochemical maps, the fuzzy γ-operator (γ=0.975) was chosen to integrate them because each geochemical map has a positive potential to be a skarn magnetite

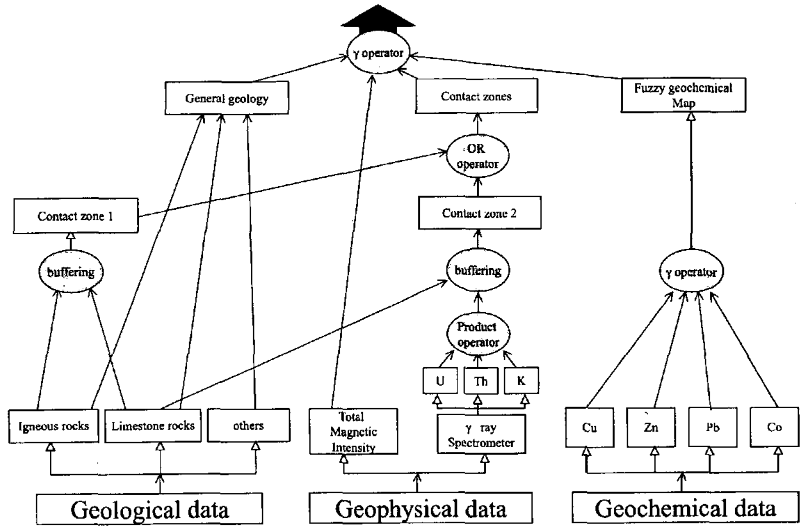

Fig. 5. A flow chart of the processing procedures in this study. A box and a circle represent a data set and a fuzzy operator, repectively.

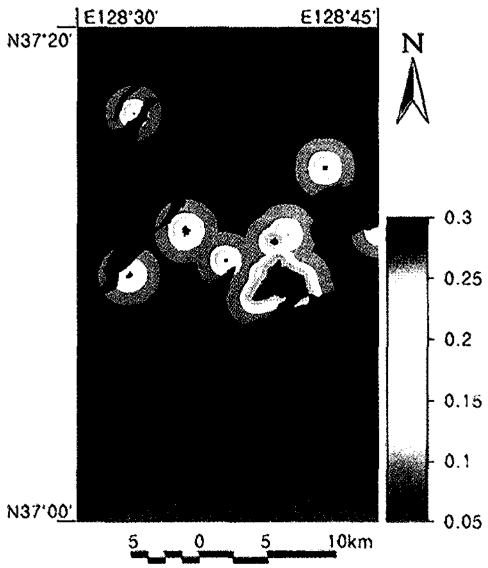

Fig. 6. Fuzzy membership representation of integrating the two fuzzy sets about contact zone by using fuzzy OR operator. One is from the contact information of limestone and the intrusive granite, and the other from the contact zone of limestone and the fuzzy set which obtained from γ-ray spectrometer data.

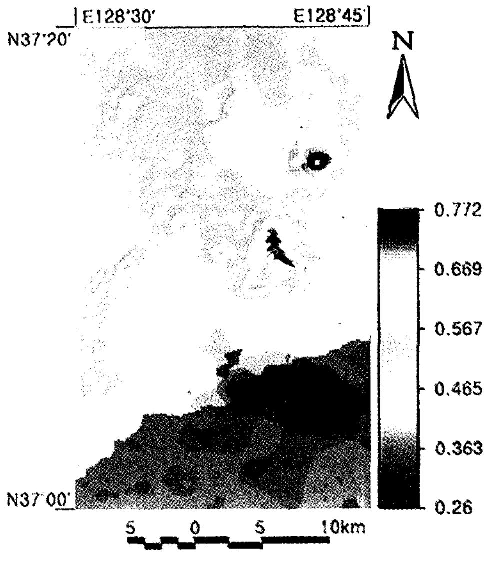

Fig. 7. Result of integrating the geological, geophysical, geochemical data using fuzzy γ-operators (γ=0.975). The mark represents the location of Shinyemi mine.

deposit, while the fuzzy OR operator was used to fuse two fuzzy sets associated with information of contact zone between limestone and granite because one is considered as a primary information and the other is a secondary information (Fig. 6).

As described above, four intermediate fuzzy sets were fused together with using the fuzzy γ-operator, γ=0.975. The last resultant map represents higher possibility or potential with respect to the target hypothesis (Fig. 7). In the final resultant map, the location of Shinyemi mine known as a skarn magnetite deposit, is represented as higher potential area. Therefore, we conclude that the possibility map outlines effectively high potential areas toward our target hypothesis, there is a skarn magnetite deposit. Also, some additional areas with high possibility, which are not clearly associated with known mine or deposit, are manifested in the map (Fig. 7). Such areas could be unveiled deposits, or any skarn magnetite deposit which has not been discovered or reported, yet.

ACKNOWLEGMENTS

This research is supported by Center for Mineral Resources Research (CMR). Also, the authors would like to thank Mr. Jin-Soo Shin for preparing some figures.

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1999년 6월 21일 원고접수, 1999년 7월 30일 게재승인.

광물자원탐사 자료에 대한 데이터 통합과 그 응용사례

최성원 · 소칠섭 · 최선규

요 약 : 금속광상은 지질학적 특성에 따라 여러 다양한 유형으로 형성되며, 특정원소나 특정광물종이 농집된다. 그러므로 광물자원탐사는 지질자료와 함께 많은 지구화학 및 지구물리자료를 종합하여 분석처리할 필요가 있다. 최근 지구과학정보시스템(GIS)이라는 개념이 도입됨에 따라, 다양한 지질자료를 보다 체계적으로 처리 할 수 있게 되었고 효율적인 광물자원탐사가 가능하게 되었다. 본 연구대상지역 (37:00N/28:30E~37:20N/128:45E)은 국내의 대표적인 광화대로 알려진 태백산 지역으로, 영남육괴의 변성암을 기반으로 하여, 조선계의 퇴적암과 중생대의 화강암으로 구성되어 있다. 본 연구에서는 이러한 지질자료와 함께, 기보고된 지구화학 및 지구물리 탐사자료들을 디지털화하고 이를 퍼지집합이론에 적용하여 데이터통합을 시도하였다. 본 연구의 결과로써 나타난 스카른 부존가능지역이 기존의 스카른 철광상으로 알려진 신예미 광산 위치와 잘 일치하고 있으며, 이는 본 연구에서 데이터 통합에 사용된 퍼지집합이론이 태백산 지역의 스카른 광상탐사에 효과적이었음을 시사한다.