Application of the FINDER System to the Search for Epithermal Vein Gold-Silver Deposits : Kushikino, Japan, A Case Study*

Donald A. SINGER** and Ryoichi KOUDA***

Abstract : The FINDER system employs geometric probability, Bayesian statistics, and the normal probability density function to integrate spatial and frequency information to produce a map of probabilities of target centers. Target centers can be mineral deposits, alteration associated with mineral deposits, or any other target that can be represented by a regular shape on a two dimensional map. The size, shape, mean, and standard deviation for each variable are characterized in a control area and the results applied by means of FINDER to the study area. The Kushikino deposit consists of groups of quartz-calcite-adularia veins that produced 55 tonnes of gold and 456 tonnes of silver since 1660. Part of a 6 by 10 km area near Kushikino served as a control area. Within the control area, data plotting, contouring, and cluster analysis were used to identify the barren and mineralized populations. Sodium was found to be depleted in an elliptically shaped area 3.1 by 1.6 km, potassium was both depleted and enriched locally in an elliptically shaped area 3.0 by 1.3 km, and sulfur was enriched in an elliptically shaped area 5.8 by 1.6 km. The potassium, sodium, and sulfur content from 233 surface rock samples were each used in FINDER to produce probability maps for the 12 by 30 km study area which includes Kushikino. High probability areas for each of the individual variables are over and offset up to 4 km eastward from the main Kushikino veins. In general, high probability areas identified by FINDER are displaced from the main veins and cover not only the host andesite and the dacite-andesite that is about the same age as the Kushikino mineralization, but also younger sedimentary rocks, andesite, and tuff units east and northeast of Kushikino. The maps also display the same patterns observed near Kushikino, but with somewhat lower probabilities, about 1.5 km east of the old gold prospect, Hajima, and in a broad zone 2.5 km east-west and 1 km north-south, centered 2 km west of the old gold prospect, Yaeyama.

Key Words : Artificial Intelligence, Kushikino, Epithermal veins, Geometric probability, Bayesian statistics, Targets, Anomalies, Exploration

1. Introduction

In a practical use of Artificial Intelligence in exploration, a method (FINDER) that integrates spatial and frequency information (Singer, 1985) is tested on the Kushikino epithermal veins and on the surrounding areas (Fig. 1). In an earlier test on kuroko-type deposits (Singer and Kouda, 1988), FINDER was able to identify all of the major known deposits and suggest several other favorable areas. In one of these, a discovery of a new kuroko deposit (Nurukawa) was subsequently announced. The main purpose of this analysis is to determine whether FINDER can locate the main Kushikino veins and to identify other areas to explore that are similar to Kushikino. A secondary purpose is to learn more about how to discover

mineral deposits. The FINDER system employs geometric probability, Bayesian statistics, and the normal probability density function to integrate spatial and frequency information to produce a map of probabilities of target centers. The target centers can be mineral deposits, alteration associated with mineral deposits, or any other target that can be represented by a regular shape on a two dimensional map. The size, shape, mean, and standard deviation for each variable are characterized in a control area and the results applied by means of FINDER to the study area. In addition to circular, elliptical, and annular shaped variables available in the original version of FINDER, sectors of annuluses and rectangles with offset centers have been added. Application of FINDER to the Kushikino area is presented after consideration of the geology of the Kushikino area and the mathematical basis of this analysis.

2. Geology of Kushikino

Located in the southwestern part of Kyushu, the Kushikino deposit is one of the oldest of a group of gold- and silver-bearing epithermal vein deposits that

* Orally presented at International Symposium on Mineral Exploration: -The Use of Artificial Intelligence, 1990 (ISME-AI '90, Tokyo and Tsukuba)

** U. S. Geol. Survey, 345 Middlefield Rd., Menlo Park, CA 94025, USA

*** Geol. Survey of Japan, 1-1-3 Higashi, Tsukuba 305, Japan

Fig. 1. Location of the study area, Kushikino veins, Mt. Crown, and other nearby gold prospects.

range in age from 5 Ma to 0.4 Ma and generally young to the northeast (Izawa and Urashima, 1987). The most recent discovery, Hishikari, was formed about 0.78 ~ 1.05 Ma (Urashima and others, 1987). The Kushikino deposit consists of groups of quartz-calcite-adularia veins that produced 55 tonnes of gold and 456 tonnes of silver since 1660. The veins are hosted in middle Miocene andesite lava and pyroclastic rocks (Fig. 2) which locally contain the alteration minerals sericite, kaolinite, smectite, and chlorite (MITI, 1986). Gold mineralization has been dated at 4.0 ± 0.3 Ma (MITI, 1986). A felsite dike about 4 km east of the veins in the Mt. Crown (Kammuridake in Japanese) area, dated at 4.2 ± 0.5 Ma (MITI, 1986) is probably related to the gold mineralization. Fluid inclusion data show that the Mt. Crown area was a thermal center with temperatures greater than 250°C and that temperatures decreased to $200^{\circ} \sim 230^{\circ}\text{C}$ at the Kushikino deposit (Izawa, 1987). Oxygen isotopes suggest that the hydrothermal fluid flowed from the direction of Mt. Crown, toward Kushikino (Matsuhisa and others, 1985).

Surrounding the window of andesites that contain the exposed Kushikino veins is a group of Pliocene volcanic rocks variously classified as dacite, pyroxene andesite, and dacite-rhyolite. These volcanics are approximately the same age as the gold mineralization at Kushikino. A younger sedimentary unit consisting of siltstone and sandstone underlies irregular areas 10 to 20 km east of the Kushikino deposit. Widespread Pleistocene units of andesite, welded tuff, and basalt overlie the mineralized rocks on the northeast and northwest.

3. Mathematical Basis

In this paper we present an application of a recently developed method, FINDER (Singer, 1985), that can be used to aid in the selection of target areas on the basis of one or more geologic, geochemical, or geophysical variables, and any spatial distribution of samples. The method combines Bayesian statistics and geometric probability in an area of influence procedure (Singer and Drew, 1976).

In order to show how the methods presented in this paper work, we first construct a simple artificial example; later we examine a real example. In a well-studied control or training area there is a circular shaped geochemical pattern that has a radius R centered on a mineral deposit (Fig. 3). The pattern is recognized in a separate study by means of discriminate analysis or related methods before the use of FINDER, and can be represented in two dimensions. Both the background and mineralized populations have been sampled sufficiently to produce the respective frequency distributions (Fig. 3). If there are only two populations, background and mineralized, then it is possible to estimate the probability for either population that any particular sample in a study area exceeds a particular value based on the relative frequency histograms. From the observed relative frequencies in the control area, the probability of observing a value at least as great as X_i , given that a sample is from the background group, is $P(X_i | \text{background})$; the probability of observing a value at least as great as X_i , given that a sample is from the mineralized population, is $P(X_i | \text{mineralized})$. What is really desired is to be able to calculate the probabili-

Fig. 2 Generalized geology of study area (Modified after MITI, 1986).

ty of being from the mineralized population given a particular sample, $P(\text{mineralized} | X_i)$, which is different from the above probabilities and is discussed below. For example, a sample having a value of 10 or less would have a low probability of occurring if it came from the background population and a very low probability of occurring if it came from the mineralized population; by examination of the lower left graph of Figure 3 it would appear to belong to the background population. Similarly, a sample with a value of 50 or more would appear to belong to the mineralized population; samples with values between 25 and 35 could have come from either population. A sample that had a value of 35 or more would have a small probability of occurring if it came from the background population and a much higher probability of occurring if it came from the mineralized population. Because we assume that the general geological conditions, frequency distributions, and associated anomaly sizes for the control area represent the conditions in the study area (Fig. 3), we can map the probabilities of sample values occurring from each population onto the study area. In the extreme case where the probability of being from the mineralized population is very close to zero and the probability of belonging to the background population is very close to 1.0, we can map a circle of radius R around the study area sample locations, A and B (Fig. 3), and say that the probability that a mineralized target is cen-

tered within each radius is close to zero. Similarly, values of samples located at C and D have very high probabilities of occurring given the mineralized population and low probabilities of occurring given the background population (Fig. 3) and the revised probability of being from the mineralized population should be high for C and for D. Because the circles about C and D do not overlap (Fig. 3), we can say with a high probability that the center of a deposit is located within each of these circles.

The probability that a cell belongs to the mineralized population, given one or more samples, can be calculated by means of Bayes Theorem (Raiffa, 1968) as follows:

$$P(\text{mineralized} | X) = \frac{P_m P(X | \text{mineralized})}{P_m P(X | \text{mineralized}) + [1 - P_m] P(X | \text{background})} \quad (1)$$

where;

$P(\text{mineralized} | X)$ is the revised probability of belonging to the mineralized population, given the observation X ;

P_m is the prior probability of being from the mineralized population, typically a small number like 0.01 or 0.001 is used initially;

$P(X | \text{mineralized})$ is the probability of sample value X occurring given the mineralized population; and, $P(X | \text{background})$ is the probability of sample value X occurring given the background population.

Where there are multiple samples, parts of

Fig. 3. Left side : Control area showing mineralized area within radius R and associated frequency distributions for samples taken within radius R and beyond radius R . Right side : Study area showing mapping of circles of radius R on sample sites and probabilities of mineralization calculated with Bayes Theorem.

Equation (1) can be expanded to :

$$P(X_1, \dots, X_n | \text{mineralized}) = P_m \prod_{i=1}^n P(X_i | \text{mineralized}), \text{ and}$$

$$P(X_1, \dots, X_n | \text{background}) = P_m \prod_{i=1}^n P(X_i | \text{background}) \quad (2)$$

where;

P_m is the same as above;

$\prod P(X_i | \text{mineralized})$ is the product of the probabilities of each sample value occurring given the mineralized population, that is $P(X_i | \text{mineralized})$;

$\prod P(X_i | \text{background})$ is the product of the probabilities of each sample value occurring given the background population, that is $P(X_i | \text{background})$; and n is the number of samples or variables.

For the study area each part of Equation (2) is applied separately for the number of samples that are applicable and, in fact, the same equations are used (with different subscripts) for cases where multiple variables are applicable. The assumptions of Equation (2) are that the probabilities entering the equations are independent of each other. By substituting Equation (2) into Equation (1), we obtain :

$$P(\text{mineralized} | X_1, \dots, X_n) = \frac{P_m \prod_{i=1}^n P(X_i | \text{mineralized})}{P_m \prod_{i=1}^n P(X_i | \text{mineralized}) + [1 - P_m] \prod_{i=1}^n P(X_i | \text{background})} \quad (3)$$

where;

$P(\text{mineralized} | X_1, \dots, X_n)$ is the revised probability of belonging to the mineralized population, given the observations $X_1, \dots, X_n$;

P_m is the same as above;

$\prod P(X_i | \text{mineralized})$ is the same as above;

$\prod P(X_i | \text{background})$ is the same as above; and

n is the number of samples or variables.

For points near sample C in Figure 3, Equation (3) can be used to estimate that the revised probability of belonging to the mineralized population, $P(\text{mineralized} | X_C)$, equals 0.808 based on a prior probability (P_m) of 0.05, a probability of 0.40 that a value of 38 or more could occur given the mineralized population $P(X_C | \text{mineralized})$, and a probability of 0.005 that a value of 38 or more could occur given the background population $P(X_C | \text{background})$; for points near sample D, $P(\text{mineralized} | X_D)$ equals 0.929 based on a probability of 0.25 of observing a value of 41 or

Fig. 4. Study area and location of surface samples and control area.

more given that the sample came from the mineralized population $P(X_D | \text{mineralized})$, and a probability of 0.001 of observing a value of 41 or more given the sample came from the background population $P(X_D | \text{background})$.

In cases where there is overlap of the radii about the samples, the probabilities $P(X_i | \text{mineralized})$ and $P(X_i | \text{background})$ associated with each sample are used in Equation (3) to calculate the probability of belonging to the mineralized population for the part of the study area where the overlap occurs. This is the key to the use of spatial information derived from the locations of samples in the study area and the mapping of the target size and shape from the control area allows this revision of estimated prior probabilities.

The prior probability that a cell belongs to the mineralized population may be estimated from external sources of information such as historical data. Typically, a small number is used because even in known mining districts, the deposits comprise a small proportion of the total area that is favorable. Initially the small prior probability is assigned to all of the study area and the information from samples is then used to revise the probabilities near the samples. In the program FINDER (Singer, 1985), the two normal probability distribution functions ($P(x_i; \mu_b, \sigma_b)$ and $P(x_i; \mu_m, \sigma_m)$) are used to estimate the probabilities of sample values occurring given both the background or barren, $P(X_i | \text{background})$, and the mineralized, $P(X_i | \text{mineralized})$, populations respectively.

In general :

$$P(x_i | \mu, \sigma) = \frac{\int_z^\infty \exp \left[-\frac{z^2}{2} \right] dz}{\sqrt{2\pi}} \quad (4)$$

where :

$P(x_i | \mu, \sigma)$ = probability of at least x , for $P(X_i | \text{mineralized})$ or $P(X_i | \text{background})$,

x = an observation,

$$z = \frac{x - \mu}{\sigma},$$

μ = population mean, and

σ = population standard deviation.

From the control area, the estimated population means and standard deviations of the background and of the mineralized samples are calculated and used with the normal probability distribution function, Equation (4), to calculate probabilities used in the Bayes Theorem (Equation (3)). Bayes Theorem allows the effects of multiple samples and multiple variables to be represented in the estimated probability. It is important to note, however, that both the variables and the samples should satisfy the conditional independence conditions of Equation (2). The independence of variables may be tested by standard correlation methods. By spatial independence, we mean that knowledge of the value of a sample in space does not help predict the value of a nearby sample in space. The fact that the samples within the mineralized population tend to be high and the samples within the background population low does not violate the independence requirement because the effect of the induced correlation is only apparent on the margin of the mineralized population and not in the center. Thus, for properly transformed variables, a mechanism is provided for integrating multiple vari-

ables and samples to make a probabilistic estimate of the likelihood that an area contains the center of a mineralized target.

In practice, the computer program, FINDER, divides the study area into a number of small cells, assigns the prior probability of being from the mineralized population to each cell, and calculates the revised (posterior) probabilities for each cell based on the spatial arrangement of the samples, the sample values observed, and the size and shape of the target sought. The map patterns of many variables related to mineralized areas can be approximated by circles, ellipses, annuluses, or annular ellipses. The mapping of the target onto sample locations allows probabilistic statements to be made about possible centers of any of these variously shaped patterns of variables.

For targets having circular shapes, any cells within the radius of the circle have their prior probabilities modified by means of Equation (3). The input probabilities are calculated with Equation (4) from the samples within the radius. For elliptically shaped targets the same reasoning that is used for circles is applied; points or cells farther away than the variable semimajor axis (a) from a sample are not modified by the information from the sample and points closer than the variable semiminor axis (b) from a sample are treated in the same manner as circular variables discussed above. For points between the semimajor and semiminor axis lengths away from the sample, effects of orientation must be considered. The central angle of possible orientations affected, ϕ , is calculated (Drew, 1966; Singer and Drew, 1976) as follows :

$$\phi = (2 \tan^{-1}) \frac{b}{a} \sqrt{\frac{(a^2 - d^2)}{(d^2 - b^2)}} \quad \text{for } a > d > b \quad (5)$$

where, a is the length of the semimajor axis of the variable ellipse, b is the length of the semiminor axis of the ellipse, and d is the distance between the sample and the point or cell being considered. The angle ϕ can vary from 180 degrees for distances equal to the semiminor axis to zero degrees for distances equal to the semimajor axis. Equations (3) and (4) are applied to the possible orientations affected to calculate the probabilities for each orientation. If it is assumed that all orientations of the ellipse of interest are equally likely, then the sum of the probabilities within ϕ divided by 180 degrees provides an estimate of the probability for a cell.

All cells and orientations initially are assigned the prior probability, thus only cells within a distance equal to the radius or semimajor axis of a sample location have their prior probability modified by new

information.

Another way to look at the way FINDER works is to assume that a geographic template representing, say, one elliptically shaped variable is centered over each of the grid cells. If there are no samples located under the template, then the prior probability for that cell is not changed. If there is only one sample located under the semiminor axis of the ellipse, then the probability associated with that sample is used in Equation (3) to modify the prior probability for that cell. Two samples under the semiminor axis of the ellipse would result in the probabilities of two samples to be used in Equation (3) to modify the prior probability of the cell. A single sample close enough to the cell to have the elliptical template cover the sample location only in some orientations would result in the probabilities associated with the sample to be applied in Equation (3) only to the range of orientations identified by Equation (5). Once all sample locations covered by the template are considered, the FINDER program would move on to consider the same template over the next cell.

4. Application of Finder to Kushikino

Part of a 6 by 10 km area near Kushikino served as a control area (Fig. 4). Based on the control area analysis, the potassium, sodium, and sulfur contents from 233 surface rock samples (MITI, 1986) were each used as variables in FINDER to produce probability maps for the 12 by 30 km study area which includes Kushikino (Fig. 4). Chemistry of other elements were also available and could have been used, however, most of the other variables examined by us did not show interesting patterns. By interesting pattern we mean a spatial clustering of values of a vari-

Fig. 5. Scatter diagram showing the effect of mixing mineralized and barren populations on the correlation between sodium content and the absolute value of the normalized potassium content.

Fig. 6. FINDER output for sodium where probability is greater than or equal to 0.5.

Fig. 7. FINDER output for potassium where probability is greater than or equal to 0.5.

able that could be related to the mineralization process. For example, plots of gold, mercury, arsenic, and fluorine all display one to three sample anomalies near or east of Kushikino, but in each case, the number of samples above background values is so small that statistical characterization is not possible. The results of X-ray analyses of the samples were not in digital form in time for this study. Subsurface samples were not used because they were for the most

part restricted to the Kushikino deposit and therefore would be of little use away from Kushikino.

Within the control area, data plotting, contouring, and cluster analysis were used to identify the barren and mineralized populations. Sodium was found to be depleted in an elliptically shaped area 3.1 by 1.6 km, potassium was both depleted and enriched locally in an elliptically shaped area 3 by 1.3 km, and sulfur was enriched in an elliptically shaped area 5.8

Fig. 8. FINDER output for sulfur where probability is greater than or equal to 0.1.

Fig. 9. FINDER output for sodium, potassium, and sulfur combined, where probability is greater than or equal to 0.5.

by 1.6 km. The “mineralized” populations are displaced up to several kilometers east of the Kushikino deposit except for part of the sulfur ellipse which overlaps some of the veins. Logarithms were used to reduce the skewness of the distribution of sulfur content. Spatial plots of potassium content showed very high values adjacent to very low values in the area east of Kushikino. Therefore, potassium was transformed to the absolute value of the number of stan-

dard deviations of the value from the mean in order to reflect the high local variability of potassium in altered areas. Correlations observed among variables are due to the mixing of the altered and unaltered populations. For example, Figure 5 shows that the correlation coefficient between sodium and transformed potassium is 0.05 for the barren Na control samples, but 0.49 when the mineralized control samples are also used. Thus, the correlations observed

between variables in this analysis do not violate the assumptions required for proper use of Bayes Theorem. The spatial independence of samples was not tested; visual examination suggested no spatial correlations and none should be expected except perhaps in the mineralized population.

Probability maps were prepared using separate FINDER runs for sodium (Fig. 6), potassium (Fig. 7), and sulfur (Fig. 8) individually and together (Fig. 9). In each case, all 233 samples in the study area were used. High probability areas for each of the individual variables are over and offset up to 4 km eastward from the main Kushikino veins. Probability values greater than 0.5 are located adjacent to the Kushikino veins in the analysis of sodium and potassium. The high probability areas for sodium (Fig. 6) cover the Hajima prospect and project out into the sea, as do the high probability areas for sulfur (Fig. 8). Although some of the high probability areas for sodium and potassium could be related to rock type, the presence of high probability areas for both variables near Kushikino and near the two gold prospects suggests that these variables are usually representing alteration. These high probability areas exclude the Mt. Crown area where temperatures were too high for gold deposition. The only case where FINDER actually identified the Kushikino veins was with sulfur where the probability level was as low as 0.1 (Fig. 8). In general, high probability areas identified by FINDER are displaced from the main veins and cover not only the host andesite and the dacite-andesite that is about the same age as the Kushikino mineralization, but also the younger sedimentary rocks, andesite, and tuff units east and northeast of Kushikino. Some of the samples from these younger sedimentary rocks and volcanics east of Kushikino have low sodium, high sulfur, and highly variable potassium suggesting the passage of hydrothermal fluids with potential to deposit gold/silver because this is not an upwelling zone as at Mt. Crown. The evidence of hydrothermal fluids in younger rocks in the area of Yaeyama is consistent with the general trend of younger epithermal gold-silver deposits to the northeast. The close proximity of sedimentary rocks and approximately coeval volcanics near Yaeyama suggest there may have been local uplift and faulting which would provide conduits for hydrothermal fluids and perhaps local heat sources.

One of the features of FINDER is that it can extrapolate and interpolate under cover because it focuses on the center of targets. This benefit is shown in this analysis by the high probability area two kilometers northeast of Kushikino which is in part co-

vered by alluvium (Figs. 6 and 9). Another feature is FINDER's ability to identify clusters of desirable samples where there is significant local variability making it possible to use potassium, despite considerable local variability.

Attempts to use FINDER's new two dimensional target shapes, sectors of annuluses and rectangles with offset centers, were unsuccessful. In FINDER runs using these shapes, the Kushikino veins were covered by a very broad area of low to moderate probabilities that was not specific to the veins. The veins were not discriminated from other areas with these new shapes.

5. Concluding Remarks

In order for FINDER, or any other system for that matter, to locate a deposit, at least one variable must be centered on the deposit. This variable, or combination of variables, can be, in the simplest case, an alteration zone or geochemical anomaly centered on the deposit. More complicated cases include the deposit located between anomalies from two different variables such as gypsum/anhydrite and sericite anomalies bracketing kuroko deposits (Singer and Kouda, 1988), or a variable displaying a trend that points to the deposit. Fluid inclusion data which pointed to the productive veins at Kushikino were not available outside the control area. Thus, if the fluid inclusion data had been used, they would have only worked for the Kushikino deposit and would have been useless elsewhere. FINDER was successful in identifying areas where hydrothermal fluids were not concentrated in large veins.

Thus the test of locating Kushikino succeeded in that the main veins are on the edge of the high probability alteration maps. However, if high probability areas are to cover the main Kushikino veins, one or more new variables are required that are centered on the veins or are on the other side of the veins from the high probability areas presented here. Mineralogical variables not studied here may fulfill this need.

High probabilities representing alteration are also shown for two minor gold producing areas on the map. The maps display the same patterns observed near Kushikino, but with somewhat lower probabilities, about 1.5 km east of Hajima and in a broad zone 2.5 km east-west and 1 km. north-south centered 2 km west of Yaeyama. In addition, there are high probability areas based on sodium and potassium located 2 km north-northeast and 10 km east-northeast of the main Kushikino veins. These other areas should be considered for exploration.

Acknowledgements : Jim Rytuba suggested using potassium and reviewed a short version of this paper. C. Chung, Dennis Cox, Kate Johnson, and Steve Ludington provided helpful reviews. This study is the result of a cooperative project called "Resource assessment of deep seated ore deposits" between the Geological Survey of Japan and the U.S. Geological Survey. We wish to thank both organizations for their continued support. Ministry of International Trade and Industry (MITI) kindly allowed us to use the data in a publication book on the regional exploration of Hokusatsu-Kushikino conducted by Metal Mining Agency of Japan (MMAJ).

References

- Drew, L. J. (1966) Grid drilling and its application to the search for petroleum. Unpub. Ph.D. thesis, Pennsylvania State University, 141p.
- Izawa, E. (1987) The Kushikino gold-silver deposit : In Gold deposits and geothermal fields in Kyushu, Guidebook 2 (Urashima, Y., ed.), *The Soc. of Mining Geologists of Japan*, 23-26
- Izawa, E. and Urashima, Y. (1987) Geology and tectonic setting of the epithermal gold and geothermal areas in Kyushu : In Gold deposits and geothermal fields in Kyushu, Guidebook 2 (Urashima, Y. ed.), *The Soc. of Mining Geologists of Japan*, 1-12.
- MITI (1986) Report on the regional exploration researches of the Hokusatsu-Kushikino region (1985). *Japanese Ministry of International Trade and Industry*, Tokyo, 641p. (in Japanese).
- Matsuhisa, Y. Morishita, Y. and Sato, T. (1985) Oxygen and carbon isotope variations in gold-bearing hydrothermal veins in the Kushikino mining area, southern Kyushu, Japan. *Econ. Geology*, **80**, 283-293
- Raiffa, H. (1968) Decision analysis : Introductory lectures on choices under uncertainty : Reading, Massachusetts, *Addison-Wesley*, 309p.
- Singer, D. A. (1985) Preliminary version of FINDER, a Pascal program for locating mineral deposits with spatial information, *U. S. Geological Survey Open-File Report*, **85-590**, 24p.
- Singer, D. A. and Drew, L. J. (1976) The area of influence of an exploratory hole. *Econ. Geology*, **71**, 642-647
- Singer, D. A. and Kouda, R. (1988) Integrating spatial and frequency information in the search for kuroko deposits of the Hokuroku District, Japan. *Econ. Geology*, **83**, 18-29
- Urashima, Y., Ibaraki, K. and Suzuki, R. (1987) The Hishikari gold-silver deposit : In Gold deposits and geothermal fields in Kyushu, Guidebook 2 (Urashima, Y. ed.), *The Soc. of Mining Geologists of Japan*, 27-38

(Received 8 January 1991; accepted in revised form 7 May 1991)

要 旨

浅熱水鉱脈型金銀鉱床探査のための FINDER システムの応用：日本の鹿児島県串木野地域における事例研究
：ドナルド A. シンガー・古宇田亮一

FINDER システムは、幾何学的な確率とベイズ統計、および正規確率密度関数を用いて、空間と頻度の情報を統合し、対象中心のモデル出現確率分布図を作成する。対象中心のモデルには、例えば、特定の型（モデル）の鉱床があり、又は、鉱床に伴う変質帯や、そのほか、平面図状に正規の形として表現できるどんなものでもよい。モデルは、制御領域における規模、形、平均値、標準偏差値によって表現され、研究対象地域にその結果が適用される。串木野鉱床は石英、石灰石、カリ長石を伴う鉱脈群からなり、1660年以來これまでに金を55トン、銀を456トン産出してきた。串木野鉱床近傍の南北に6 km 東西に10kmの部分領域が、モデルの制御領域として使われた。この制御領域の中で、データ図化、等高線図、クラスタ解析によって、母集団を鉱床不毛帯と、鉱床帯に分類した。ナトリウムは、長軸3.1km短軸1.6kmの楕円形領域の溶脱帯を形成していた。カリは3 kmと1.3kmの楕円形領域の中で、あるいは溶脱しあるいは逆に富化し、いずれにしても組成が変化していた。硫黄は5.8kmと1.6kmの楕円形領域の中で富化していた。ナトリウム、カリ、硫黄の分析データがある地表岩石試料233個を用いて、串木野鉱床を含む12km対30kmの対象領域から FINDER システムにより鉱床分布高確率領域を推定した。ナトリウム、カリ、硫黄のそれぞれにおける高確率領域は、串木野主鉱脈の東方4 km付近に相互に重なるか、ずれて分布していた。一般的に、FINDER システムが指摘する高確率領域は、主鉱脈からずれ、串木野鉱脈とほぼ同じ時期の安山岩と石英安山岩—安山岩にかかるだけでなく、串木野の東と北西に当たるより新しい堆積岩や安山岩、凝灰岩層にもかかっている。鉱床賦存高確率領域は、串木野鉱脈近傍に同じパターンで見られるし、1.5km東の古い金鉱化帯である羽島地域や、串木野鉱脈より18km西にある古い金鉱化帯の八重山地域から西へ2 kmの所に中心を持つ東西2.5km南北1 kmに広がった地域にも同じ様な高確率のパターンが見られた。

キーワード：人工知能、串木野、浅熱水鉱床、幾何学的確率、ベイズ統計、探査対象、異常帯、探査

(1991年1月8日受付, 1991年5月7日受理)