DATA INTEGRATION USING WEIGHTS OF EVIDENCE MODEL: APPLICATIONS IN MAPPING MINERAL RESOURCE POTENTIALS

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ABSTRACT

Weights of evidence model is used to predict occurrence of an event with known evidences in a study area where training data are available to estimate the relative importance of each evidence by statistical methods. It provides a quantitative method for integrating multiple sources of evidences. It avoids subjective choice of evidences and subjective estimation of weights for evidences with comparing with other methods, such as Fuzzy logic method. This paper discusses our implementation of Weights of Evidence model as a data integration method in a GIS environment, and demonstrates working of the model using an application in the prediction of Sn-W-U mineral occurrence in the South Mountain Batholith in Nova Scotia, Canada. After introduction of the principal of weights of evidence model, the case study case is described, including data collection, data processing, and data integration with use of weights of evidence model. Finally, a Sn-W-U potential map with posterior probability values in the study area is generated and shown in this paper. Based on analysis of weights of five evidential maps and the final prediction result, it is concluded that the prediction result is successful and the model is useful in the study.

1. INTRODUCTION

The purpose of this paper is to demonstrate working of Weights of evidence model with using an application in the prediction of Sn-W-U mineral occurrence in the South Mountain Batholith in Nova Scotia, Canada. The research done here has two objectives: 1) to study the model for prediction of Sn-W-U deposits in the study area and 2) to evaluate analysis result of application of this model.

A Geographical Information System (GIS) is a "computer-based system which integrates the data input, data storage and management, data manipulation and analysis, and data output for both spatial and attribute data to support decision-making activities" (Malczewski, 1999). After over 40 years of development, GIS have been applied to serve important roles in many fields, such as environment monitoring, resources management, applications in commerce and business field, and different utilities. The ultimate purpose of GIS is to make evaluations or predictions with different specific data integration models to combine spatial and attribute data from various sources to provide support for decision-makers.

According to Bonham-Carter (1994), the data integration models in GIS are divided into two categories, data-driven and knowledge-driven models based on different methods for estimation of weights of different evidential maps. In data-driven models, the weights are calculated by using statistical methods and data of evidences in a training area to estimate the spatial relationships between the evidential maps and the final response maps. Data-driven models include Logistic Regression, Weights of Evidence, Neural Network, and so on, and the weights in those models are calculated from training data. While, the weights are estimated based on experts' opinions in knowledge-driven models. The knowledge-driven models include Fuzzy Logic, Dempster-Shafer Belief Theory and their weights are given with experts' opinions.

Weights of evidence model is used to predict a hypothesis about occurrence of an event based on combining known evidence in a study area where sufficient data are available to estimate the relative importance of each evidence by statistical methods. In the case of mineral resources assessment, the evidence consists of a set of evidential datasets (maps), and the model is used to predict the hypothesis about the occurrence of a given type of deposit in a study area. The weights are estimated from the measured association between known mineral occurrences and the values on the evidential maps. Based on combination of the evidential maps selected, the final result is extracted as a mineral potential map with a single index representing probability of occurrence of the given type of mineral deposit.

The model was originally developed for prediction of the probability that a new patient would be diagnosed to have a disease based on presence or absence of a set of symptoms (Kemp et al. 1999). Currently, it is still used in the medical fields (Zuyle. 2000; Johnson et al., 2001). The model has been applied in mineral resources assessment or geological survey with GIS together since the late 1980s (Agterberg, 1989,

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Agterberg, et al. 1993; Bonham-carter, 1991;Bonham-carter, et al. 1989). For example, this method was applied to predict occurrence of gold deposits in Nova Scotia (Bonham-carter, et al. 1988; Cheng et al., 1999) and other places (Harris et al., 2000; Raines, 1999). This model is also used in evaluation on distribution of other resources, such as copper deposits (Tangestani et al., 2001), fossil packrat (Neotoma) middens (Mensing et al., 2000), and archaeology sites in a portion of the Central Valley of California (Hansen, 2000). Currently, weights of evidence model has been implemented in ArcView GIS (Arc-WofE) (Kemp et al., 1999 and 2001). Arc-WofE has been widely used in mineral exploration and environmental assessments (Hansen, 2000; Zuyle, 2000).

In this paper, a procedure for prediction of Sn-W-U deposits by using weights of evidence model with GIS together to integrate different evidential datasets, such as anomalies of chemical elements, radioactive anomalies and geological data, is described and its analysis result is evaluated in the paper. Implementation of data processing using Principle Component Analysis and data integration were conducted in ArcInfo GIS software.

2. WEIGHTS OF EVIDENCE MODEL

Weights of evidence model uses a probability framework based on set theory (Bonham-Carter, 1994). One of the important concepts used in this approach is the idea of prior and posterior probability. In the situation of mineral resource assessment, assume that a hypothesis (H) about the probability of mineral deposits of a given type D of in a study area is related to a set of evidence X ($X = \{X_1, X_2, ..., X_n\}$, and $X_1, X_2, ..., X_n$ are conditionally independent with each other).

The prior probability ($P\{D\}$) is the probability of occurrence of mineral deposit of type D without consideration of any known evidence information. The posterior probability ($P\{D | X\}$), also named conditional probability, is the probability of occurrence of mineral deposit of type D given the condition of X existing in the study area.

Another concept used here is odd ($O\{D\}$), which is defined as a ratio of the probability that an event will occur, such as $P\{D\}$, to the probability that it will not occur, such as $P\{\overline{D}\}$. It can be expressed as following Equation:

$$O\{D\} = \frac{P\{D\}}{P\{\overline{D}\}} \tag{2.1}$$

As to the hypothesis H on D with given X , its odd is:

$$O\{D | X\} = O\{D\}\frac{P\{D | X\}}{P\{\overline{D} | X\}} \tag{2.2}$$

In ordinary weights of evidence model, each evidence X_i in X need be divided into two subsets which can be expressed in terms of set theory: A (presence or true) and $\overline{A}$ (absence or false). The two subsets have following properties:

1) $A \cup \overline{A} = X_i$ (A and $\overline{A}$ make up X_i), $i = 1,2,...,n$ (2.3)

2) $A \cap \overline{A} = 0$ (A and $\overline{A}$ are mutually exclusive. (2.4)

According to definitions and the properties of binary patterns introduced above, the following equations can be derived:

$$\begin{aligned} P\{D | X\} &= P\{D\}\frac{P\{X | D\}}{P\{X\}} \\ &= P\{D\}\frac{P\{X_1 | D\}}{P\{X_1\}}\frac{P\{X_2 | D\}}{P\{X_2\}}\cdots\frac{P\{X_n | D\}}{P\{X_n\}} \end{aligned} \tag{2.5}$$

$$\begin{aligned} O\{D | X\} &= O\{D\}\frac{P\{X | D\}}{P\{X | \overline{D}\}} \\ &= O\{D\}\frac{P\{X_1 | D\}}{P\{X_1 | \overline{D}\}}\frac{P\{X_2 | D\}}{P\{X_2 | \overline{D}\}}\cdots\frac{P\{X_n | D\}}{P\{X_n | \overline{D}\}} \end{aligned} \tag{2.6}$$

$$\begin{aligned} Log\{O\{D | X\}\} &= Log\{O\{D\}\} + Log\frac{P\{X | D\}}{P\{X | \overline{D}\}} \\ &= Log\{O\{D\}\} + Log\{\frac{P\{X_1 | D\}}{P\{X_1 | \overline{D}\}}\} + Log\{\frac{P\{X_2 | D\}}{P\{X_2 | \overline{D}\}}\} \\ &+ ... + Log\{\frac{P\{X_n | D\}}{P\{X_n | \overline{D}\}}\} \end{aligned} \tag{2.7}$$

If X_i is present, $\frac{P\{X_i | D\}}{P\{X_i | \overline{D}\}}$ is called sufficient ratio (LS). Otherwise, it is called necessity ratio (LN). Correspondingly, the natural logarithm of LS is the positive weight of evidence (W^+) and the natural logarithm of LN is the negative weight of evidence (W^-). For convenience, let W_0 denote the natural logarithm of $O\{D\}$. Thus, the Equation (2.6) and (2.7) can be written as:

$$O\{D | X\} = O\{D\}LS_1(orLN_1)LS_2(orLN_2).....LS_n(orLN_n) \tag{2.8}$$

$$\begin{aligned} Log\{O\{D | X\}\} &= W_0 + W^+{}_1(orW_1{}^-) + W^+{}_2(orW_2{}^-) \\ &+ ... + W^+{}_n(orW_n{}^-) = \sum_0^n W_i \end{aligned} \tag{2.9}$$

Then, the posterior probability $P\{D | X\}$ can be converted from the equation above as follows:

$$P\{D \mid X\} = \frac{\exp(Logit\{O\{D \mid X\}\})}{1+\exp(Logit\{O\{D \mid X\}\})} \tag{2.10}$$

The values of $P\{D \mid X\}$ calculated with using Equation (2.7) are identical to those calculated directly using Equation (2.5). The advantage of using weights (2.7 or 2.9 and 2.10), instead of directly using the conditional probability expressions (2.5 or 2.8), is that the weights are easier to be interpreted than the probability factors.

In most applications of ordinary weights of evidence model, the contrast C is defined as Equation (2.11) and is used to select the cutoff to divide continuous variables into binary patterns.

$$C = W_i^{+} - W_i^{-}, i = 1,2,...,n \tag{2.11}$$

3. PREDICTION OF SN-W-U MINERAL OCCURRENCES IN SOUTH MOUNTAIN BATHOLITH

Mineral resources assessment involves mapping the favourability of a type of mineral resources considered in a study area and ranking all sites in the study area according to their favourability. The mineral resources assessment is a decision-making process based on spatial information available to the study area. Generally, the assessment process is carried out with aid of GIS. This process can be summarized as three steps: database building, data processing and data integration modeling (Bonham-Carter, 1994). In this section, these three steps are described after introduction of characteristics of Sn-W-U deposits in the study area.

In this study, database building and evidential maps construction are carried out with aid of ArcInfo in terms of the geological and geochemical characteristics of Sn-W-U deposits in the study area. The evidential maps are integrated with weights of evidence model and the final potential map is generated and shown with posterior probability values of Sn-W-U mineral occurrences in the study area.

3.1 Characteristics of Sn-W-U deposits in the study area

Mineral deposits associated with granitoid rocks are divided into different categories based on their geological and geochemical characteristics. Sn-W-U deposits in the study area are categorized as "granophile-type", which often involves Sn, W and U mineralization (Strong, 1981). This type of deposits is genetically associated with quartz-rich leucocratic granitoids of later phase intrusions of a large granitoid bathlith. The hydrothermal alteration resulting in enrichment of Sn, W, and U elements in the deposits results in significant concentration of elements of Flourine (F), Lithium (Li), Niobium (Nb), Rubidium (Rb), Thorium (Th) and so on. Additionally, concentration of radiometric chemical elements, such as Th, U, and K, is associated with differential intrusion phases of the granitoid suite. Therefore, it is indirectly related to occurrence of Sn-W-U deposits.

The South Mountain Batholith in Nova Scotia is a granitoid batholith with area about 8000 km^2. The batholith consists of 13 plutons which can be divided into 2 formation stages, earlier stage and later stage (Xu, 2001). The later stage consists of monzogranite, leucomonzogranite and leucogranite, which are related to formation of Sn-W-U deposits in this study area. The petrographic and geochemical studies indicate that the South Mountain Batholith was formed by a continuous series from least evolved biotite granodiorite to most evolved leucogranite with a general incremental trend in trace elements Rb, U, Li, F, Sn, and W. Many economic geology studies indicate that lots of extensive and intensive hydrothermal fluid activities during the late- and post- magmatic period caused elements of Rb, U, Li, F, Sn, and W etc. to be further enriched and deposited in some geological sites spatially associated with small intrusive bodies of the later stage (O'Reilly et al. 1992; and Sangster, 1990) Numerous small deposits and mineral occurrences have been found in or around the South Mountain Batholith (Figure 1).

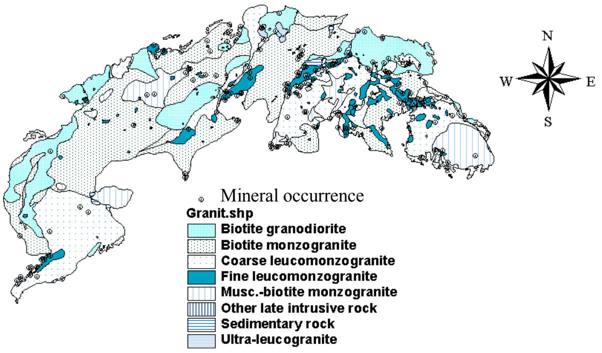

Figure 1. Geological Map of Sn-W-U mineral occurrence in the South Mountain Batholith in Nova Scotia, Canada

3.2 Datasets collected for the study

Data sets used in the current paper are mineral deposits and occurrence map, a geological map, two airborne radiometric anomaly maps, and 5 lake sediment geochemical anomaly maps (Xu, 2001).

The mineral occurrence map shows known Sn-W-U mineral deposits and occurrences in the study area. The geological map shows two granitoid phases in the study area. Later granitoid phases are favorite to occurrence of Sn-W-U mineral resources.

The two airborne radiometric anomaly maps are derived from the gamma-ray spectrometer datasets including images of eTh, eU and K, collected by Geological Survey of Canada from 1976 to 1983. According to previous research related to the study area, anomalies of the ratios eU/K and eU/eTh are associated with differentiation of granitoid phases (Xu, 2001), and they are also highly correlated with the evolved granitoid rock units, pervasive antometasomatic alteration, and granophile element mineralization (O'reilly et al. 1988).

The 5 lake sediment geochemical anomaly maps are derived from geochemical data of center-lake sediments. The anomaly maps include only anomalies of F, Li, Nb, Rb, and Th without W and Sn because the former 5 elements with relative high data quality are more suitable for spatial analysis than anomalies of W and Sn. Previous studies found that the relationship among the graniphile elements W, Sn, F, Li, Rb, Nb and radioactive element Th may reflect magmatic differentiation and hydrothermal solution activities (O'reilly et al. 1988).

Those data are used to delineate areas with significant late stage magmatic activity associated with Sn-W-U mineralization and alteration zones probably relative to Sn-W-U deposits.

3.3 Data Processing

According to the requirements on weights of evidence model, each evidential map can be binary pattern and conditionally independent each other in order to be integrated with weights of evidence model. Therefore, the collected data need to be preprocessed prior being integrated with Weights of evidence model.

It is found that most the 5 geochemical anomaly maps of lake sediments are correlated each other as shown in the correlation matrix of them (Table 1). The correlation coefficient between the two radiometric anomaly (eU/K and eU/eTh) maps is 0.24. To some extent, the two radiometric anomaly maps are correlated each other. Principle Component Analysis (PCA) method is respectively used to process the five geochemical anomaly maps and the two radiometric anomaly maps in order to get independent evidences. The first two principle components and the two principle components respectively generated from PCA of the five geochemical anomaly maps and the two radiometric anomaly maps are extracted as four evidential maps.

C	Li	F	Rb	Th	Nb
Li	1.00000	0.58701	0.57749	0.58250	0.22037
F	0.58701	1.00000	0.55676	0.57463	0.15430
Rb	0.57749	0.55676	1.00000	0.57285	0.14198
Th	0.58250	0.57463	0.57285	1.00000	0.13081
Nb	0.22037	0.15430	0.14198	0.13081	1.00000

Table 1 Correlation (C) matrix of the five geochemical anomaly maps

Suitable cutoffs for five evidential maps including a granitoid phase map and four principle component maps need to be set up in order to convert the five maps into binary patterns. After calculation of weights and studentized version of contrast C (Student (c)), which is equal to a ratio between contrast of a value and standard deviation of contrast of the value, of each value in each map, a value with the highest student(c) value is respectively used as cutoffs for each of the five evidential maps and convert them into binary patterns. For example, the value with the highest student(c) in the first geochemical anomaly component map is 12 (Figure 2), then favourite values in this map greater than or equal to 12 are converted into 1 and other values are converted into 0.

Additionally, distance to a contact between favorite granitoid phase, and the other phases is another useful evidence spatially related to Sn-W-U mineralization based on geologists' knowledge. A map representing the distance is generated by using "buffer" function in ArcInfo. Similarly, the distance map is converted in to binary in terms of a value with the highest student(c) value.

Pairwise test of conditional independence is carried out on the 6 binary evidential maps with use of Arc-WofE (Kemp et al. 1999). The results of pairwise Chi-square tests (significant at 95% level of probability, for which tabled χ^2 =3.8) are shown in Table 2. Table 2 shows that the two binary maps, representing the granitoid phases and the distance, are not conditionally independent each other. Therefore, the granitoid phase map is removed and the distance map is left based on their relative importance to prediction of Sn-W-U mineral occurrence.

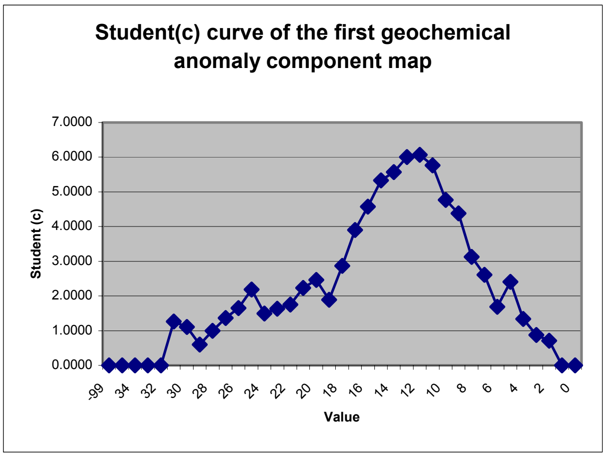

Figure 2. Student(c) curve of the first geochemical anomaly component map

Evidence	Radpc1	granbinw	ctactnw	chmpc2	chmpc1
radpc2	1.16	1.76	2.30	0.39	3.34
radpc1		0.95	1.74	0.16	1.33
granbinw			36.90	1.00	2.28
ctactnw				1.27	3.64
chmpc2					1.54

Where,

- granbinw is the binary map representing granitoid phases;
- ctactnw is the binary map representing the distance to the contact;
- chmpc1 is the binary map representing the first principle component from the 5 geochemical anomaly maps;
- chmpc2 is the binary map representing the second principle component from the 5 geochemical anomaly maps;
- radpc1 is the binary map representing the first principle component from the 2 radiometric anomaly maps;
- radpc2 is the binary map representing the second principle component from the 2 radiometric anomaly maps.

Table 2 Table of Chi-squared Statistics (significant at 95% level of probability, for which tebaled χ^2 =3.8)

3.4 Data integration with weights of evidence

The Sn-W-U occurrence map and the final 5 binary evidential maps including the distance map and four principle component maps are applied to calculate conditional probability of Sn-W-U mineral occurrence in the study area with the formulas 2.1, 2.9 and 2.10. It can be easily carried out with use of ArcInfo to generate a map of conditional probability in the study area (Figure 3).

It can be seen from Figure 3 that there are still some places with relative higher conditional probability which haven't been explored and may be taken as targets for future studies.

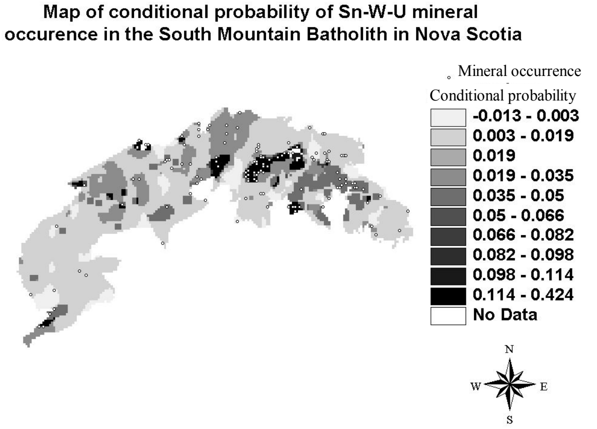

Figure 3. Map of conditional probability of Sn-W-U mineral occurrence in the South Mountain Batholith in Nova Scotia, Canada

4. DISCUSSIONS AND CONCLUSIONS

Generally, in case of mineral resources, evaluation of a prediction result is based on predictive ability of the prediction result. The best validation method is to see if the prediction result may be identical with newly discovered deposits. However, this is also the most difficult way to be executed and it takes much time and much money to test the result by this way.

Some practical evaluation methods are suggested by Raines (1999) as follows: 1) to test if the weights make sense; 2) to test if the known deposits are in the areas with high favourability; and 3) to compare the prediction results with the ones from other methods and to test if they agree with each other. In this paper, the first two methods are used to evaluate the prediction result.

It can be obviously seen from Figure 3 that most mineral occurrences are within areas with relative high probability. Table 3 summaries the weights, contrast, and student(c) results calculated for weights of evidence model. All of the five evidential maps has relative high contrast (greater than .5) and student(c) values (greater than 1), and they are conditionally independent each other at significant 95% level (Table 2). So, they are eligible to be applied in weights of evidence model.

Evidence	Class_field	W-	W+	Contrast	Student(c)
ctactnw	Value	-0.5526	1.2130	1.7656	9.2102
chmpc1	Value	-0.3829	0.7054	1.0883	6.0686
chmpc2	Value	-0.0203	1.7085	1.7288	2.9183
radpc2	Value	-0.4939	0.0856	0.5795	2.0312
radpc1	Value	-0.7474	0.0587	0.8061	1.9154

Table 3 Summary of evidential maps defined by weights of evidence model

The evidential map representing distance to the contact is the best evidence in terms of contrast and student(c) values. This evidence has highest contrast and student(c) values in the all 5 evidential maps. The three evidential maps, respectively representing the distance to the contact and the first two principle components of the 5 geochemical anomaly maps, have relative higher positive weights and student(c) values, therefore, their present patterns are useful to recognize sites where Sn-W-U mineral resources may occur. The two evidential maps, representing the two principle components of the two radiometric anomaly maps, have negative weights lower than those of the other three maps and positive weights close to zero, therefore, their present patterns are useful to recognize sites where Sn-W-U mineral resources may not occur.

Based on results of these two evaluation methods, it can be concluded that the prediction result with use of weights of evidence is successful and weights of evidence model is useful to predict Sn-W-U occurrence in the study area.

Weights of evidence model has both advantages and disadvantages. For example, this method is data-driven and can avoid subjective choice of evidences and subjective estimation of weights for evidences. In the other hand, with use of binary patterns (as a common case), some useful information in the continuous evidences may be lost after data conversion. Cheng and Agterberg (1999) developed Fuzzy weights of evidence method, based on a fuzzy membership function and weights of evidence method, in order to minimize the lost information from data conversion.

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