Predictive GIS Model for Potential Mapping of 
Cu, Pb, Zn Mineralization

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ABSTRACT  The geologic features indicative of Cu, Pb, Zn mineral deposits in an area are fractures (structure), and host rock sediments. Datasets used include Cu, Pb, Zn deposit points record, geological data, remote sensing imagery (Landsat TM5). The mineral potential of the study area is assessed by means of GIS based geodata integration techniques for generating predictive maps. GIS predictive model for Cu, Pb, Zn potential was carried out in this study area (Weixi) using weight of evidence.

The weights of evidence modeling techniques is the data driven method in which the spatial associations of the indicative geologic features with the known mineral occurrences in the area are quantified, and weights statistically assigned to the geologic features. The best predictive map generated by this method defines 24% the area having potential for Cu, Pb, Zn mineralization further exploration work.

KEYWORDS  geographic information system; weights of evidence; mineral resource prediction

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Introduction

China is the third richest country in the world of mineral resources with a total potential value of 11 trillion USdollars. Yunnan Province is one of the important metallogenic belts for non-ferrous and precious metal deposits[1].

Mineral source potential mapping is a complex analytical procedure, which require simultaneous consideration of a number of spatial evidence such as geological, geomorphological, structural, geochemical, geophysical, etc. The capability of GIS to manipulate such classified spatial information through amalgamated layers make it a unique tool for delineating potential locales [2].

One of the major strength of GIS is the ability to integrate and combine multiple layers of geosciences data into predictive mineral potential maps showing areas favorable for mineral exploration[2]

The distribution of known Cu, Pb, Zn occurrences was examined in term of spatial association with series of evidence maps derived from the geological, geophysical and remote sensing data. Using GIS and weights of evidence modeling techniques has predicted areas of high potential deposits for further Cu, Pb, Zn exploration.

1 Geology

Yunnan Province is situated in a compound position of Tethys-Himalayan and marginal Pacific tectonic domain with complex geological structures. The strata were fully developed, containing abundant fossils and biotas in different areas, and the series were alternately grown in these strata with various sedimentary types and fully complicated environments.

Weixi study area lies in the northwest part of Yunnan Province. It is the combining part of Eurasia plate and Gondwana plate, the Three
River area has complicated tecto-genesis and magma volcano activities and is well-known as the earth dynamic, key to solving global structure problems, especially solution to Tethyan geosyncline [1].

The main rock associations in the region include variable composites of metavolcanics, principally metatuff, schist, rhyolites and sediment rocks such as limestone, sandstone, shale and conglomerate, and igneous rock. The different kinds of rocks and formation in the studied area are concisely described as follow.

1) Cenozoic era, represented by conglomerate, mudstone, rhyolite include lava breccia and dark micaceous granite.

2) Mesozoic era, represented by the following kind of rocks: siltstone, shale. Upper part of Triassic period represented by gray dark oolitic limestone muddy. Early Triassic include intrusive volcanic rock and metamorphic rock, lava body.

3) Paleozoic era including Permian igneous bodies, which are represented by basalt rock. Devonian period is represented by sandstone and siltstone rock.

2 Mineralization

Comprehensive geological surveys at various scales, launched in 1950s, have resulted in the discovery of 171 mineral commodities, with proven reserves being established for 156 commodities. More than 200 000 metal and industry mineral deposits and occurrences, including 25 000 sizable and 87 giant deposits, have been identified in various parts of the country. A significant mineral potential remains to be discovered, particularly in the largely unexposed area of west of China [1].

The prospecting area is located at Sanjia, the area spans two secondary tectonic units of Yunlin fold system and Lanping-Simao middle depression. There are two ore belts: east and west ore belts.

Many ore bodies have been found in the area. Being exposed and controlled, the metal reserves of Cu 400 000 t at average grade Cu 1. 31%, Pb + Zn 380 000 t at average grade Pb 1. 28%, Zn 0. 52% and Ag 6. 090 t at average Ag grade 132. 77 g/t, Co 1 544 t at average Co 0. 04%.

The ore belt is effected by northeast Huachangshan thrust fault. Triassic Jurassic limestone and silty shale at the east side of Huachangshan fault has been pushed westwards over lower Tertiary. This fracture zone and its secondary fractures at the upper side are ore-control (host) rock of this ore belt.

Most of nonferrous precious metallic deposits in the study area have been considered to be associated with sedimentary strata bound mineralization, which are basically controlled by three factors of basin, facies and position and closely associated with the condition of sources, transportation and reservoir.

The host rocks are varying in geological age, excluding the Silurian, Pb, Zn and Ag bearing position are well devoloped, Cu, Au, Ag and Sb mineralization have mostly been found in post Devonian strata. The mineralization age is generally younger than that of host rocks except for some deposits associated directly with volcanic rocks. The mineralization has been considered to be centered in the period of late Paleozoic, late Triassic, late Cretaceous and Paleogene.

3 GIS dataset

GIS data involves a number of steps; data must be collected and converted into digital formate acceptable for input to the GIS, and the data should be projected to the same coordinate system. GIS data include the following factors.

1) Landsat TM image path 132 row 42 was georeferenced for ground control points identified both on the image and topographic map. The studied area (Weixi) is situated in northwest of Yunnan Province, it lies in the region of high mountains, vegetation in the area are not very high in most parts, so the rocks unit are well exposed.

2) Host rocks were digitized from the 1 : 500 000 scale topographic map of Yunnan Prov-
ince, the lithological units were added into the attribute table using Arc/Info software. The information constituted one layer represents host rock evidence.

3) Major fault within the selected area is digitized from 1:500 000 scale geological map of Yunnan Province, other structures are derived from the interpretation of gravity and magnetic field data carried out by Geophysical Bureau of Yunnan Province. These sets were merged into one layer as the first structural evidence.

4) Major lineaments are therefore extracted from the available geological map and image. The extracted structural map obtained from surface geological mapping provides surface lineaments information. The result represents remote sensing structural evidence.

4 Weights of evidence

Weights of evidence is a quantitative method that was originally developed for spatial application of medical diagnosis. This method developed by Geological Survey of Canada, and adapted for mineral potential mapping with GIS has been in use since the late 1980s [4].

Mineral exploration companies increasingly use GIS technology to combine spatial data and make predictive mineral potential maps. Weights of evidence is a discrete multivariate method first applied to this problem [5]. It is based on the application of Bayes rule [6], the Bayesian approach to the problem of combining multiple predictor variable (datasets) uses probability framework. One of the concepts in this approach is the idea of prior and posterior probability. Starting with prior probability of mineral deposit occurring in a unit area, a posterior probability is calculated based on the weights of evidence for the presence and absence of predictor variable.

The GIS based mineral potential mapping process can be divided into four main steps.

1) Building a special digital database.

2) Extracting predictive evidence for a particular deposit type based on an exploration model.

3) Calculating weights for each predictive map or evidential theme.

4) Combining the evidential theme to predict mineral potential.

Weights of evidence methodology is normally applied to explore situation in which there is an adequate number of mineral deposit or other location data that can be used as training points for calculating weights. However, the extension should be so designed that the user can calculate weights with training point data.

Modeling typically proceeds in three phases: specification, prediction, and testing. The specification of the model begins with the definition of a set of sites where some phenomena, such as mineral deposits, earthquake epicenters, or other points objects have been observed. Other specification required for the model include a defined study area, preparation of data for use in evidential themes, exploration of spatial associations between potential evidential themes and training points, and the generalization of evidential themes. The tools provided by the Arc-Wofe extension are particularly valuable for spatial data exploration and generalization.

A pixel size of 100 m×100 m is used for rasterizing the mineral occurrence point map and the input binary evidence map, derived from geological, geophysical and remote sensing data, for the creation and calculation of weights of binary predictor maps. This size is chosen to ensure that only one mineral occurrence is present in any given pixel. The spatial association of each evidence map is assessed with respect to the location of known Cu, Pb, Zn occurrences. A pair of weights \((W^+, W^-)\) are determined from the degree of overlap between the known Cu, Pb, Zn deposits and the binary evidence map. For rasterized maps representing host rocks features and linear structures faults and lineaments features of heat source rocks, the optimum distance within which the spatial association of these features with the Cu occurrence is optimal was determined by calculating the weights \((W^+, W^-)\) and contrast \(C\) for successive distances away from the geological features and examining variations in \(C\) or in studentized \(C\). Different buffer
zone intervals were experimented in order to determine the optimum buffer intervals.

Distance map showing relative distances by dilating (buffering) around these formations in successive zones at distances of 150 to 250 m with increment of 150 m was generated. Because the distance map has multiple classes, optimal spatial association between the known Cu, Pb, Zn mineral occurrences and favorable host rocks should be calculated to define the potentially favorable lithologies that may be covered by unfavorable lithologies. The highest C usually indicates the optimum cutoff distance at which the predictive power of the binary pattern is maximized. However, in cases where there are only a small number of occurrence points or small area, the uncertainty of weights might be so large that C is meaningless.

The studentized C was useful for choosing the cutoff distance because it serve as a measure of the certainty and uncertainty of the contrast, the variation in the contrast for cumulative distances from the outline of host lithologies with respect to the known Cu, Pb, Zn prospects.

5 Pairwise test for conditional independence

Bayes rule requires that all input maps should be conditionally independent of one another with respect to the mineral occurrences. If this rule is violated, the resultant predictive map will be biased and under or over estimates the undiscovered mineral deposits. The following relationship is satisfied if two binary maps conditionally independent.

\[
N(B_1 \cap B_2 \cap D) = \frac{N(B_1 \cap D)N(B_2 \cap D)}{N(D)} (0,1)
\]

The left side of the equation is the observed number of occurrences in the overlap zone of \(B_1\) and \(B_2\). The right side is the predicted number of deposits in overlap zone. A contingency calculated table is used for test to conditional independence of two binary patterns, and the following equation was applied for test to all possible map pairs.

\[
X^2 = \sum_{i=1}^{t} \frac{(o_i - p_i)^2}{p_i}
\]

where \(o_i\) is observed data; \(p_i\) is predicted data. Because the mineral occurrences are considered as points or single unit cell, the resulting values of \(X\) are unaffected by the units of area measurement. The calculated values can then be compared with standard values of \(X\) to verify if the conditional independence hypothesis holds at 95% probability with one degree of freedom.

The \(X\) values for each pair of binary predictor maps for all two overlap conditions can be calculated from contingency table. A sum of these two \(X\) values gives the total \(X\) values for each possible pair of the binary patterns.

6 Application of weights of evidence to Weixi

The weights of evidence analysis method is applied to the 19 known mineral occurrences in Weixi to generate a predictive model. The extracted geologic features whose spatial association with the mineral occurrence are first quantified are the favourable rocks, structure.

6.1 Calculating the weights of evidence of favorable rocks

Favorable host rocks are described under the deposit recognition criteria. Favorable host lithologies are buffered in order to define the potentially favorable lithologies that may be covered by unfavorable lithology. The mineral occurrence point map is rasterized and crossed with a multiclass raster distance map of favorable host lithology to calculate the weights of evidence \((W^+, W^-)\) for cumulative distance away from the favorable host lithology.

The optimum cutoff distance is selected at 1 400 m away from the outline of host lithology on the basis of that the studentized value of C is estimated at this distance. Contrast \((W^+, W^-)\) at this distance indicates a positive and strong spatial correlation between the mineral occurrences and host lithology domain with a 1 400 m
buffer zone. Table 1 shows the value of weights of evidence analysis of the favorable host lithology domain, and 10 out of 19 occurrence. Fig. 1 shows map of host lithology domain with mineral occurrence.

The weights of this favorable domain used for the final model are \( W^+ = 0.267 \) if it is in a favorable host rock domain, \( W^- = -1.344 \) if it is not in a favorable host rock domain.

### Table 1 Weights of evidence analysis of the favorable host lithology domain

| Class | Area/km² | Points | W⁺ | S-W⁺ | W⁻ | S-W⁻ | Contrast | S-Contrast | Student |
|-------|----------|--------|----|------|----|------|----------|------------|---------|
| 100   | 2 485.23 | 8      | 0.846 | 0.354 | 0.410 | 0.335 | 1.256 | 0.486 | 2.583 |
| 200   | 2 014.59 | 8      | 0.795 | 0.354 | 0.397 | 0.335 | 1.192 | 0.484 | 2.451 |
| 300   | 2 764.63 | 8      | 0.739 | 0.354 | 0.381 | 0.335 | 1.120 | 0.486 | 2.304 |
| 400   | 2 882.53 | 8      | 0.697 | 0.354 | 0.359 | 0.335 | 1.066 | 0.484 | 2.192 |
| 500   | 3 028.52 | 8      | 0.647 | 0.354 | 0.353 | 0.335 | 1.001 | 0.486 | 2.058 |
| 600   | 3 133.12 | 9      | 0.731 | 0.333 | 0.459 | 0.357 | 1.191 | 0.486 | 2.450 |
| 700   | 3 232.38 | 9      | 0.700 | 0.333 | 0.448 | 0.357 | 1.149 | 0.486 | 2.363 |
| 800   | 3 343.18 | 9      | 0.666 | 0.333 | 0.436 | 0.357 | 1.103 | 0.486 | 2.268 |
| 900   | 3 451.23 | 9      | 0.634 | 0.333 | 0.424 | 0.357 | 1.059 | 0.486 | 2.178 |
| 1 000 | 3 554.00 | 10     | 0.711 | 0.316 | 0.546 | 0.378 | 1.257 | 0.493 | 2.549 |
| 1 100 | 3 637.23 | 11     | 0.783 | 0.302 | 0.691 | 0.408 | 1.474 | 0.507 | 2.903 |
| 1 200 | 3 716.49 | 12     | 0.849 | 0.289 | 0.864 | 0.447 | 1.713 | 0.532 | 3.216 |
| 1 300 | 3 815.40 | 13     | 0.903 | 0.277 | 1.075 | 0.500 | 1.979 | 0.572 | 3.459 |

### Table 2 Weights of evidence analysis of favorable structural domain

| Class | Area/km² | Points | W⁺ | S-W⁺ | W⁻ | S-W⁻ | Contrast | S-Contrast | Student |
|-------|----------|--------|----|------|----|------|----------|------------|---------|
| 100   | 693.820 | 1      | 0.040 | 1.000 | 0.002 | 0.250 | 0.043 | 1.031 | 0.041 |
| 200   | 1 091.34 | 2      | 0.281 | 0.707 | 0.032 | 0.258 | 0.313 | 0.753 | 0.416 |
| 300   | 1 555.17 | 3      | 0.332 | 0.577 | 0.058 | 0.267 | 0.391 | 0.638 | 0.615 |
| 400   | 1 937.97 | 4      | 0.400 | 0.500 | 0.096 | 0.277 | 0.497 | 0.572 | 0.868 |
| 500   | 2 430.79 | 5      | 0.397 | 0.447 | 0.128 | 0.288 | 0.525 | 0.532 | 0.985 |
| 600   | 2 787.84 | 8      | 0.738 | 0.351 | 0.379 | 0.335 | 1.109 | 0.486 | 2.281 |
| 700   | 3 130.51 | 8      | 0.614 | 0.354 | 0.342 | 0.335 | 0.958 | 0.484 | 1.967 |
| 800   | 3 523.07 | 9      | 0.616 | 0.338 | 0.416 | 0.353 | 1.030 | 0.485 | 2.119 |
| 900   | 3 901.09 | 10     | 0.617 | 0.316 | 0.505 | 0.378 | 1.123 | 0.507 | 2.278 |
| 1 000 | 4 261.30 | 11     | 0.624 | 0.301 | 0.616 | 0.408 | 1.240 | 0.507 | 2.443 |

### Fig. 1 Host rock map with mineral deposit

6.2 Calculating the weights of evidence of favorable structure

Faults have spatial association with known mineralization in the area. Successful representation of lineament features in shaded relief depends on the choice of illumination azimuth (preferably perpendicular to the linear features).

The resulting structural domain was rasterized, buffered at distances of 100 m and crossed with the raster mineral occurrence point map to estimate weights of evidence of the domain. The optimum buffer, that is resulted from the maximum studentized value of \( C \), was defined at 1 100 m. The resulting buffered structural domain covers the area. Table 2 shows the values of the weights of evidence analysis of favorable structural domain, 8 out of 19 occurrences are present in this domain (Fig. 2). The weights of evidence analysis reveals a strong correlation between the structural domain and mineral occurrences. The weights used in the final model are \( W^+ = 0.30 \) if it is in a favorable structural domain, \( W^- = -0.61 \) if it is not in a favorable structural domain.
6.3 Predictive map of studied area

The predictive exploration model was generated by summing the weight of evidence of three binary maps representing the epithermal Cu, Pb, Zn recognition criteria in the Weixi area. The various overlap combinations of the binary maps resulted in the highest cumulative weights in the area where all of the recognition criteria exist. The lowest weights are located in the areas with a scarcity of favorable conditions. The predictive weights range from maximum of 0.326 to a minimum of −1.95, this model assumes conditional independence of the input recognition criteria binary maps [1]. Fig. 3 shows the predictive map of Weixi.

7 Conclusions

The processing techniques of the Arc-Wofe extension within GIS Arcview software are particularly suited for building the database, modeling the spatial correlations between geological features and known Cu, Pb, Zn occurrence, map calculations, and displaying the result that are required in the quantitative mapping of mineral potential.

The final predictive exploration GIS Wofe model has placed high prospective areas for Cu, Pb, Zn occurrences, it was 14 out of 17 of the Cu, Pb, Zn mineral deposit points of the studied area. The predictive potential map highlights some other new unrecognized favorable area. The favorable areas extracted by applying Arc-Wofe extension are located in the southwest part of the studied area and other small areas in different places.

This model and characterization of the detailed relationship between layers can be applied to the adjoining and less geologically explored areas. Consequently, this not only reduces the cost of detailed exploration but also benefits for generating a predictive GIS model in the similar tectonic-stratigraphic set up.

REFERENCES

[1] Geological and Mineral Exploration Bureau of Yunnan Province (1990) Regional geology of Yunnan Province[M]. Beijing, Geological Publishing House
[2] Harris J, Wilkinson L, Heather K, et al. (2001) Application of GIS processing techniques for producing mineral prospectivity maps—a case study, mesothermal Au in Swayze greenstone belt, Ontario, Canada[J]. Natural Resources, 10(2):91-123
[3] Bonham-Carter G F (1994) Geographic information systems for geoscientists: modeling with GIS[M]. New York, Pergamon, 398
[4] Bonham-Carter G F, Wright D, Agterberg F (1989) Weights of evidence modeling: a new approach to mapping mineral potential[M]. Canada, Geological Survey of Canada
[5] Chung C F, Agterberg F P (1980) Regression models for estimating mineral resources from geological map data[J]. Mathematical Geology, 12 (5) : 473-488
[6] Agterberg F P (1992) Combining indicator patterns in weights of evidence modeling for resource evaluation[J]. Nonrenewable resources, 1(1), 39-50