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Prospectivity Analysis of Granite-Related Polymetallic Mineralization in the Bushveld Complex, Using Knowledge- and Data-Driven Methods

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ABSTRACT

The Bushveld Igneous Complex is most well-known for its PGE-Cr-V mineralization but it has also been a significant source of polymetallic Sn and F associated with the granites of the Lebowa Granite Suite (LGS). A continuum of polymetallic mineralization is recognized with a wide range of assemblages (Sn-Mo-W-Cu-Pb-Zn-As-Au-Ag-Fe-F-U-REE), ranging from a higher to lower temperature magmatic hydrothermal mineralizing environment.

Two paths were selected to assess the regional prospectivity: 1) using fuzzy logic modelling along a knowledge-driven path, and 2) unsupervised cluster analysis along a data-driven path. Regional soil geochemical data (1 sample/km^2; n = 106,877) and the 1: 250 000 scale geological map were used in this study. The South Africa Mineral Database (SAMINDABA) was used to evaluate the predictive capability of the models developed in this study.

INTRODUCTION

The Bushveld Igneous Complex (BIC) of South Africa was historically a significant source of granite-related Sn and F mineralization (Crocker et al., 1988, 2001) but declining prices and demand led to the closure of most of the mines and cessation of production. Mining for Sn mineralization was confined to several tin fields including Zaaiplaats, Union, Elands, Rooiberg, Olifants and Moloto (Figure 1; Crocker et al. 2001), and fluorite was mined from the Buffalo, Vergenoeg, Ruigtepoort, Vischgat, and Zwartkloof deposits. Numerous small deposits and occurrences can be found but the focus of mining was for the higher grade deposits (Crocker et al. 1988).

Stratigraphically the BIC comprises the Rustenburg Layered Suite at the base, followed by the Lebowa Granite Suite (LGS), Rashoop Granophyre Suite and Rooiberg Group (Walraven et al. 1990). The overlying units, namely the Rooiberg Group and Rashoop Granophyre Suite, are commonly referred to as the roof rocks with respect to the LGS. The LGS comprises several granitic facies that can be identified by both color and texture at microscopic and macroscopic scales. Geochemically, the LGS show variable trends of fractionation (Walraven, 1988; Labuschagne, 2004). This is an important consideration in determining fluid focus within the cooling granite sheet. The apical granites, near the roof rocks, are most closely associated with polymetallic mineralization (Crocker et al. 2001). The LGS also exhibit variable geochemical signatures as a function of alteration and some local scale alterations are associated with mineralization (Pollard and Taylor, 1986; Pollard et al. 1989; McNaughton et al. 1993; Hunt, 2005).

MINERALIZATION

The LGS and associated roof rocks are host to numerous small- to medium-sized polymetallic deposits and occurrences (Figure 1; Crocker et al. 1988, 2001; Bailie and Robb, 2004; Kinnaird et al. 2004). The polymetallic mineralization exhibits various morphologies, although it is considered to represent a continuous, single mineralizing system from high temperature magmatic to low temperature hydrothermal mineralization (Freeman, 1998; Robb et al. 2000). It comprises a Sn-Mo-W-Cu-Pb-Zn-As-Au-Ag-Fe-F-U-REE assemblage and can be subdivided into three stages of ore formation: high temperature (> 400 °C) Sn-(Mo-W) mineralization, intermediate temperature (400–200 °C) Cu-Pb-Zn-As-Au-Ag mineralization and low temperature (< 200 °C) hydrothermal Fe-F-U-REE mineralization (Robb et al. 2000).

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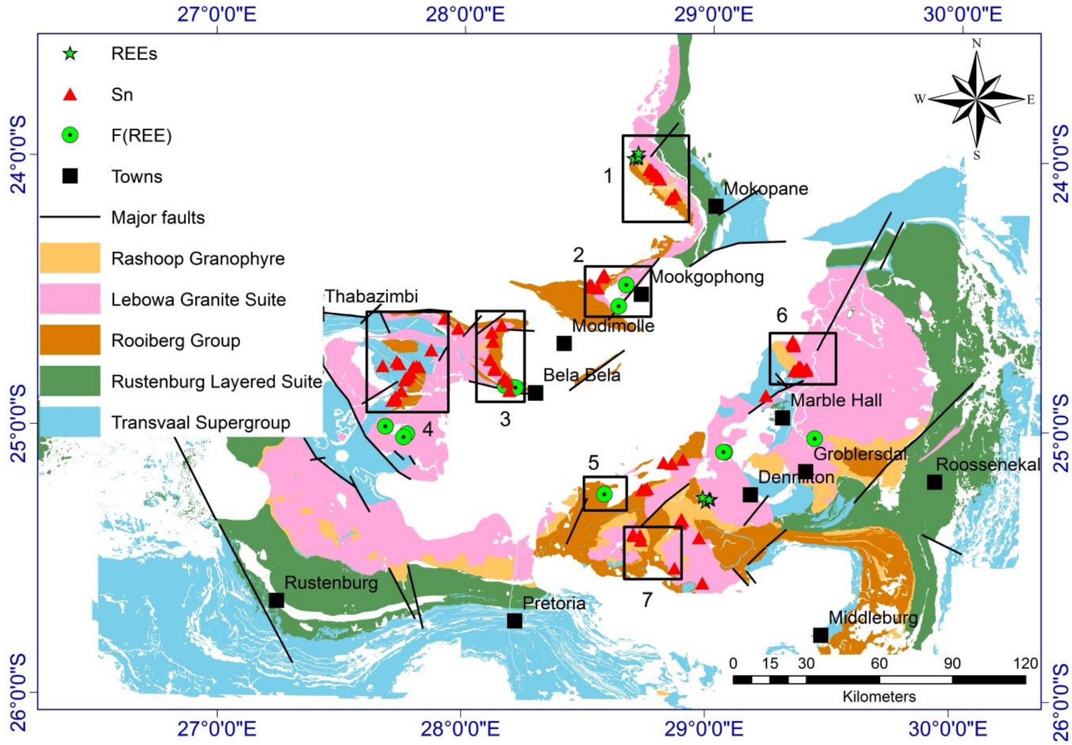

Figure 1: Spatial distribution of the main Sn-F deposits. 1) Zaaiplaats tin field (endogranitic Sn and REE mineralization). 2) Union tin field (exogranitic Sn deposits) and fluorite deposits (Buffalo and Vischgat deposits). 3) Elands tin field (exogranitic Zwartkloof Sn and F deposits). 4) Rooiberg tin field (exogranitic tin deposits). 5) Exogranitic fluorite deposit (Vergenoeg deposit. 6) Olifants tin field (exogranitic Sn deposits). 7) Moloto tin field (endogranitic Sn deposits).

KNOWLEDGE-DRIVEN MODEL

A minerals system approach was adopted to develop a conceptual geological model that could be used to inform a knowledge-driven Fuzzy Logic prospectivity model. Key to this was the identification of 1) sources of fluids and fluid focus mechanisms, 2) fluid pathways and barriers to flux, and 3) trap zones (Kreuzer et al. 2008 and references therein; Hagermann et al. 2016).

The crystallization of the Bushveld granites was accompanied by a long-lived hydrothermal system involving high fluid circulation in granites and associated roof rocks (Walraven et al. 1990; Pollard et al. 1991; McNaughton et al. 1993). The known polymetallic mineralization is closely associated with the most highly differentiated granites and these granites are considered to be the most likely source of metal-rich fluids, and as such, areas closest to the apical portions of the granites were assigned a higher fuzzy membership. This was combined with the Rb geochemical map, which was taken as indicative of the differentiation process and thus a proxy for fluid focus.

The fluid pathways could not be modelled directly using the soils data alone, however it was postulated that given the continuum of mineralization from higher temperature to lower temperature, the structures could be mapped by various metal assemblages, inferring the fluid pathway. Principal Components (PC) were derived from the 23 individual soil geochemical element input raster maps. PC maps were obtained for the low temperature F-Fe-REE end-member (using PC4: Y-Th) and for the high temperature Sn end-member (using PC14: Sn-W). The two PC maps were rescaled into fuzzy membership.

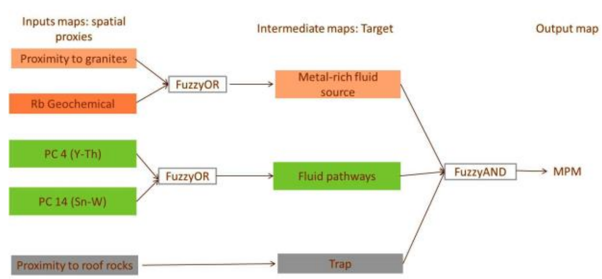

Figure 2: Flow diagram of two-staged integration matrix (or inference engine) used to combine the fuzzy evidential maps to produce a resultant mineral prospectivity map (MPM).

A number of suitable trap-sites for polymetallic mineralization exist, including 1) endo-granitic mineralization in apical portions of the granites themselves; 2) exogranitic mineralization in the roof-rocks including the Rooiberg Group volcanics, the Rashoop granophyres and the Transvaal sediments. Each should be considered individually, but for the purposes of this study all were considered as having equivalent prospectivity.

A two-staged integration matrix was designed using suitable fuzzy operators to integrate the fuzzy evidential maps to produce the prospectivity map for granite-related polymetallic mineralization (Figure 2). The first stage involved the generation of intermediate maps, and the second stage involved the combination of all intermediate maps to generate a mineral prospectivity map for polymetallic Sn-F-(REE) mineralization. The fuzzy score of the mineral prospectivity map was classified into three classes: low, moderate and high prospectivity (Figure 3). The upper limits of the low and moderate classes were defined using box-whisker and histograms plots.

DATA-DRIVEN MODEL

Unsupervised cluster analysis was undertaken to determine whether superior predictability could be achieved by considering more data simultaneously. PC analysis was undertaken as a first step to determine the most descriptive metal assemblages, and to reduce redundancy in the data. Only the granitic rocks were considered to limit background chemical variation. As might be expected, three groupings were established corresponding to the main metal assemblages, namely Sn-W-As, Cu-Pb, and Rb-Nb-Y-Th-U (Figure 4).

Using ioGAS geochemical modelling software, the unsupervised clustering method selected was Self-Organizing Maps (SOM), which is a type of artificial neural network that reduces the dimension of high dimensional data by grouping similar data together on a 2D map (Figure 5). The inputs to the SOM were the 10 PCs derived above.

The selection of the number of classifications of the SOM was selected using a K-Means Clustering graph which represents the sum of the squares of distances of the points from the mean of their respective cluster groups. In general, when the trend line of the sum of squares (SS) levels out there is little change in the number of clusters. Whilst a lower number of clusters could have been chosen, K = 9 was selected to try to represent the multiple rock types and the multiple styles of mineralization expected.

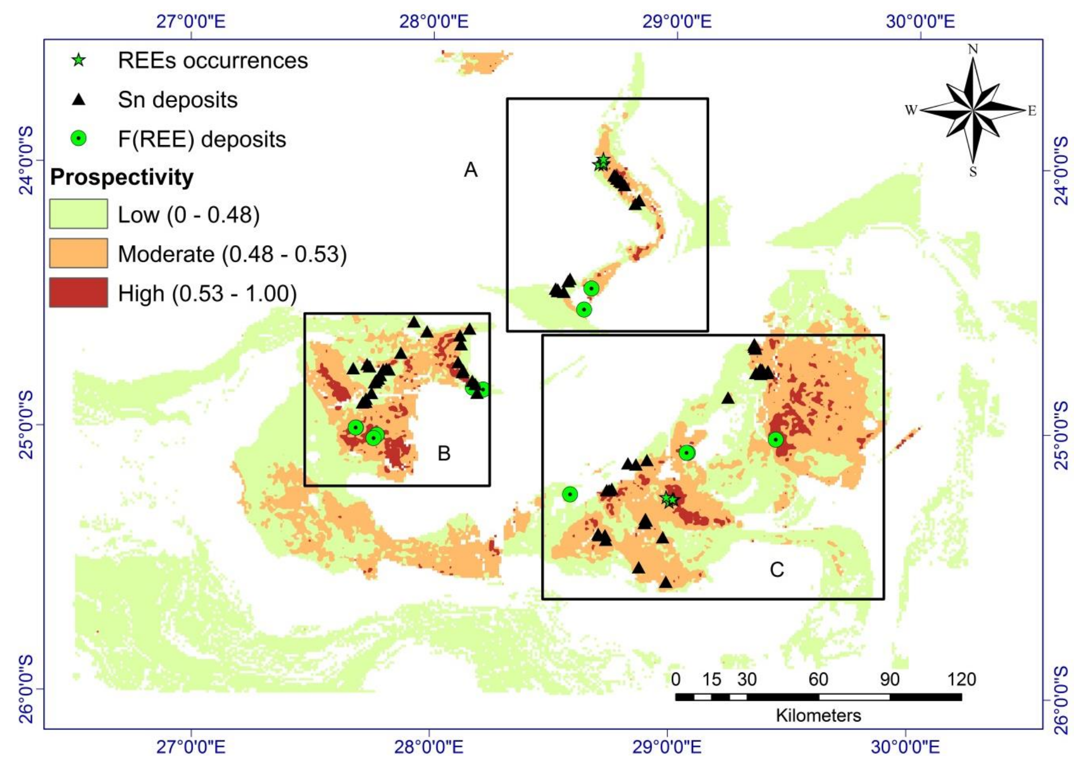

Figure 3: Mineral prospectivity map showing spatial relationship between highly prospective areas and known major Sn and F deposits within the BIC. Areas underlain by younger rocks and Older Archean rocks (see Figure 1) are masked out (white areas). Bordered areas A, B, and C designate Northern, Western and Eastern Limbs of the BIC respectively.

VALIDATION OF THE MODELS

In summary, 96 known occurrences and deposits were used to validate the model. The knowledge-driven prospectivity model predicted an average of 77% of known mineral occurrences within high prospectivity areas (i.e. 56 of 73 of the Sn occurrences, 12 of 15 of the F occurrences and 6 of 8 of the REE occurrences). The remaining 23% of mineral occurrences all plot on moderately prospective areas. No assessment could be made for the base metal occurrences because a suitable PC map could not be identified.

The data-driven models fared slightly better, with the PCA model predicting 83% of known mineral occurrences, but had the additional advantage of predicting the Pb-Zn-Cu base metal assemblages and fully doubled the number of anomalies, identifying an additional 140 anomalies which will require additional validation and verification. The SOM model predicted 80% of known mineral occurrences are provided more discrete targets.

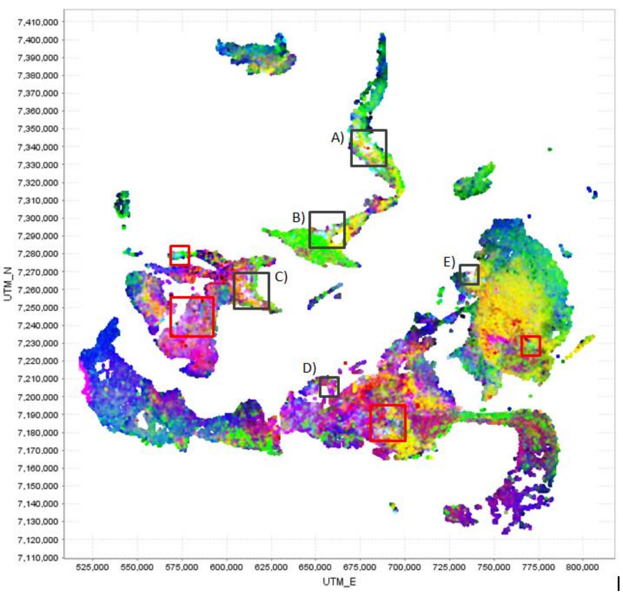

Figure 4: RGB map using principal components corresponding to (F-REE)-(Cu-Pb-Zn)-(Sn-W), highlighting areas of polymetallic mineralization in the Bushveld granites (light areas indicate highest combinations of the three components). Known deposits identified include: A) Zaaiplaats Sn district; B) Union Sn; C) Zwartkloof fluorspar; D) Vergenoeg F-Fe-REE; E) Mutue Fides-Stavoren Sn; areas of additional potential are indicated by red frames.

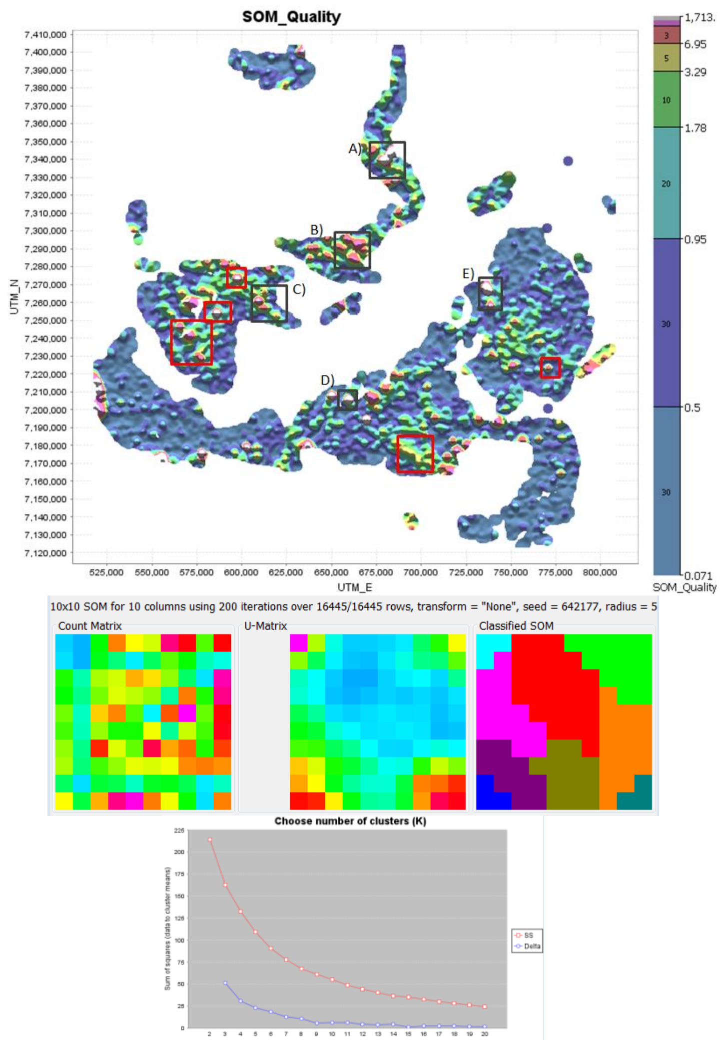

Figure 5: SOM analysis indicating number of samples mapped to each node, the Euclidean distance between neighboring nodes, the classified SOM and the K-Mean trend line used to select the number of clusters. The SOM Quality is a measure of "best-fit" between the given sample and the neuron, calculated in Euclidean distance units and is used here as a measure of multivariate "outlier-ness". Known deposits identified include: A) Zaaiplaats Sn district; B) Union Sn; C) Zwartkloof fluorspar; D) Vergenoeg F-Fe-REE; E) Mutue Fides-Stavoren Sn; areas of additional potential are indicated by red frames.

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