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Receiver operating characteristics (ROC) as validation tool for prospectivity models — A magmatic Ni–Cu case study from the Central Lapland Greenstone Belt, Northern Finland

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ABSTRACT

A prospectivity model for magmatic Ni–Cu deposits was created by integrating spatially referenced geophysical and geochemical datasets based on a simple and practical exploration model. The study area is the Central Lapland Greenstone Belt, Northern Fennoscandian Shield, Finland. Magmatic nickel deposits are related to rock types that are typically characterized by local magnetic and gravity anomalies. These deposit types can also be a source of nickel, copper and cobalt anomalies in the overlying glacial till cover. This straightforward exploration criterion was translated into a fuzzy logic prospectivity model. The model validation is an essential step in justifying the validity of the prospectivity model. This was accomplished by using receiver operating characteristics (ROC) technique. We used the known Ni–Cu occurrences and deposits as true positive cases and other deposit type locations or random points as true negative cases in the validation process. It appears that the ROC technique provides a robust model validation and optimization technique, providing that suitable validation data exists.

1. Introduction

Validation of a predictive spatial model is a vital part of any prospectivity modeling. There are several established methods used for validating a mineral prospectivity map, including cross-validation (Agterberg and Bonham-Carter, 2005; Chung and Fabbri, 2008; Fabbri and Chung, 2008) and jack-knifing (Bonham-Carter, 1994; Nykänen and Salmirinne, 2007). The common requirement for all these techniques is that a set of known mineral occurrences that were not used as input to a model is used as an independent variable for testing the performance of that model. The receiver operating characteristics (ROC) technique can also be used to test the validity of a spatial predictive model (Nykänen, 2008; Robinson and Larkins, 2007). It has been increasingly used in machine learning and data mining research (Fawcett, 2006). This validation technique also requires known locations of the modeled phenomena. These locations represent "true positive" sites (i.e. locations of known mineral occurrences), adopting the terminology from the medical sciences. In addition a set of "true negative" sites representing areas where no mineral occurrences are found is required to generate the receiver operating characteristics (ROC) curves. Finding a representative set of "true negative" sites can be a challenge. In mineral exploration these could be derived from the locations of other deposit types within the study area. Alternatively, as we propose in this paper, the true negative sites can also be generated as random locations within the study area. In that case these points do not represent real "true negative" sites but rather a set of random points. The locations of the random points can also be constrained by lithology if required or applicable. If the number of known deposits allows, one can also run weights-of-evidence or logistic regression prospectivity model and use the low probability areas to constrain the location of the random points. This would cause, however, dependency between the true positive and true negative sites. Furthermore we can also use drilling sites that appear to be barren as true negative sites as these areas have been tested geochemically.

The aim of the current paper is to demonstrate the use of the ROC technique as a validation technique for prospectivity mapping. This is accomplished by using a case study where geophysical and geochemical datasets were integrated based on a simple exploration model for magmatic Ni–Cu deposit type using the fuzzy logic technique.

We constructed a prospectivity map that integrates datasets considered favorable for magmatic Ni–Cu deposits. Subsequently we tested the performance of the predictive model by comparing the resulting

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prospectivity map with the current Ni–Cu exploration activity within the area and also with the location of drilling sites with elevated Ni or Cu values. The selection of validation sites is challenging due to the lack of adequate number of known nickel deposits within the study area.

2. Study area

The Central Lapland Greenstone Belt (CLGB) is located in the Northern Fennoscandian Shield, approximately 100 km north of the Arctic Circle (Fig. 1). The selection of the CLGB area for this study was based on two main reasons: 1) it is an active Ni–Cu *greenfields* exploration terrain with a significant new discovery and 2) availability of geochemical and geophysical data. The geology of the central part of the CLGB and its surroundings (Fig. 2.) consists of Palaeoproterozoic volcanic and sedimentary cover (2.5–1.97 Ga) on the Archaean granite gneiss basement (3.1–2.6 Ga) (Hanski and Huhma, 2005; Lehtonen et al., 1998). Rifting events of the Archaean continent from 2.5 Ga to 1.97 Ga resulted in mostly tholeiitic and komatiitic mafic to ultramafic intrusions, dykes and lavas. These rock types are characteristic hosts for the magmatic Ni–Cu deposits (e.g. Markwitz et al., 2010; Naldrett, 2004). One nickel mine, Kevitsa (Mutanen, 1997), is currently operating within the CLGB. However, active nickel exploration is going on in the surrounding areas and a promising recent exploration success is discovery of the Sakatti deposit approximately 20 km SW from Kevitsa.

As described by Rasilainen et al. (2012) the majority of known Ni–Cu deposits in Finland can be divided into three deposit types: 1) deposits associated with Svecofennian (c. 1.89–1.87 Ga) mafic–ultramafic intrusions, 2) deposits associated with Archaean (c. 2.8 Ga) or Palaeoproterozoic (c. 2.05 Ga) komatiitic rocks or 3) deposits associated with Palaeoproterozoic (c. 2.45 Ga) mafic–ultramafic-layered intrusions. The latter two age groups of rocks occur within the current study area defining the expected deposit types.

3. Input datasets

Naldrett (2011) divides magmatic sulfide deposits into two main groups: 1) sulfide rich Ni- and Cu-deposits; and 2) sulfide poor PGE-deposits. Magmatic sulfide deposits form as segregation and concentration of sulfide liquid droplets from ultramafic or mafic magma, and partitioning of chalcophile elements into these droplets from the silicate magma forming the ultramafic or mafic rocks. Mafic and ultra-mafic rocks typically have higher density and magnetic susceptibility than surrounding felsic rock. Therefore the former are characterized by positive magnetic anomalies and/or positive gravity anomalies. When outcrops of magmatic sulfide deposits are weathered, glacial dispersal can cause elevated values of chalcophile elements in till deposits. Thus the exploration model we used for predicting magmatic nickel deposits requires that the host rocks containing Ni deposits are characterized by local magnetic and gravimetric anomalies and there is a Ni–Cu–Co anomaly in till cover (Fig. 3). There is a possibility of Ni depletion as well in the prospective host magma. This feature could perhaps be also used as an input in a prospectivity model if adequate geochemistry of hosting lithological units was available. A high-pass filter was applied to the gridded magnetic and gravity data to suppress long wavelength regional anomalies and enhance the locally derived anomalies possibly caused by mafic–ultramafic intrusions and associated mineral deposits (Hinze et al., 2013). In a GIS, filtering can be undertaken using a moving window of a fixed radius across the study area to calculate the local median value, which is subtracted from the original data values (e.g., Nykänen et al., 2008b). The resulting residual grid is then used as the input to the magmatic Ni–Cu prospectivity modeling. This filtering was applied to the magnetic field total intensity, regional gravity and

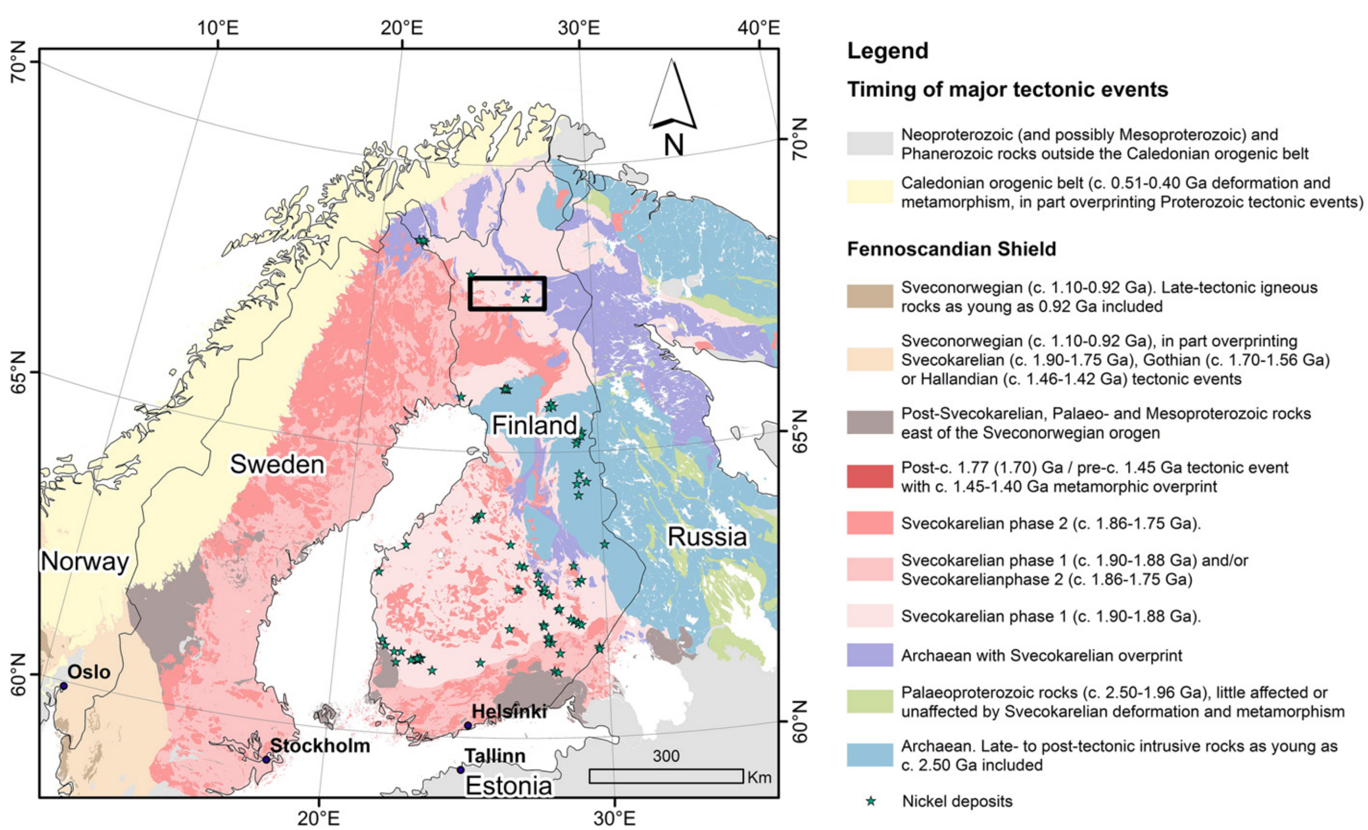

Fig. 1. Location of the study area. Nickel deposits in Finland marked with green stars are from the FINNICKEL database (Makkonen et al., 2009). Generalized bedrock map is modified from Koistinen et al. (2001).