GIS-based regional scale prospectivity analysis of northern Finland for layered mafic intrusion related PGE-Cr-V-(Ni-Cu-Co) deposits

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Abstract -- A GIS-based prospectivity model is developed to delineate regional-scale target areas for follow-up exploration of layered mafic intrusion related PGE-Cr-V-(Ni-Cu-Co) deposits in northern Finland. A generalised mineral systems model was used to identify the mappable exploration criteria. Predictor maps were generated from public-domain exploration geodata to represent the components of the mineral system that were then combined in a fuzzy inference system (FIS), to obtain a PGE-Cr-V-(Ni-Cu-Co) prospectivity map.

Metals such as platinum group elements (PGEs), vanadium (V), chromium (Cr), cobalt (Co), and nickel (Ni) have significant applications in modern and eco-friendly industries. However, the current supply levels of these metals fall short of meeting the predicted demand. As a result, they are classified as "critical raw materials" and hold strategic importance. The importance of these metals in the industrial value chains and green sectors necessitates local production. The SEMACRET project is focused on promoting sustainable exploration of (critical) raw materials within the European Union (EU) to ensure a consistent supply during the green energy transition.

To demarcate potential areas for the occurrence of new deposits, this article describes the preliminary results of a computer-based prospectivity analysis of layered mafic intrusion related PGM-Cr-V-Co deposits in northern Finland using Fuzzy Inference Systems (FIS; [1]), a supervised, knowledge-based symbolic artificial intelligence technique.

The study area (Fig. 1a) is located in the northern part of Finland, within the Fennoscandian Shield, and is dominated by Archean and Proterozoic rocks of the Karelia craton. Its southern and western borders are defined by the Svecovefennian domain, while the northern and eastern boundaries are marked by the Caledonian and Kola domains, respectively. The study area hosts a diverse array of mafic–ultramafic intrusions of variable shape and size, that were formed over a period of approximately 600 million years, from 1.88 Ga to 2.5 Ga [2], under different tectonic conditions. Several globally significant PGE, Cr and V deposits such as Portimo and Penikat (PGE), Kemi (Cr) and Koillismaa (V, PGE) are hosted in the layered mafic intrusions that were formed during the 2.45 Ga magmatic event during the early stage of long rifting. Additionally, some of these deposits also contain small quantities of nickel (Ni), copper (Cu) and cobalt (Co).

PGE deposits are primarily found as stratiform or strata-bound reefs within large layered mafic-ultramafic intrusions that were extensively differentiated and emplaced during the late Archean and early Proterozoic. These intrusions were emplaced in stabilised, relatively sulphur-poor cratonic lithosphere, which enhances their preservation potential [3,4].

The parental magmas that gave rise to these intrusions are mostly derived from asthenospheric mantle sources, but some contributions from sub-continental lithospheric mantle are also suggested, as evidenced by the relative platinum enrichment in some major deposits. Mantle magmas that are fertile in terms of chalcophile metals are derived by larger degrees of mantle melting through the adiabatic melting of plumes. The host magmas are believed to ascend via intracratonic suture zones and trans-lithospheric breaks, where extension and rifting are limited [3]. The laterally continuous layering of these intrusions is consistent with their crystallization under conditions of low regional stress and limited magma-induced sagging, due to the underlying thick buoyant sub-continental mantle lithosphere. These potential host rocks are relatively easy to locate and delineate because of their large size (tens of kilometres) and the generally simple geometry of the host intrusions [4].

The mineralization process of the PGE-Cr-V-(Ni-Cu-Co) mineral system related to the layered mafic intrusions occurs mainly in the contact style (or marginal type at the base of the intrusion), and reef type between the lower ultramafic zone and the upper mafic zone, and among mafic rocks. The PGE mineralization is hosted mainly by sulphides (pyrrhotite–pentlandite–chalcopyrite), except in some chromitite reefs where the PGE are hosted mainly by platinum-group minerals [5]. The sulphide contents of the reefs are mostly low (<1–3%), but they have high metal tenors (hundreds of parts per million PGE). The host rocks to the reefs comprise the entire spectrum of mafic–ultramafic rock types (dunite, harzburgite, pyroxenite, norite–gabbronorite–gabbro, troctolite, anorthosite, chromitite, and magnetitite), but chromitite- and orthopyroxenite-hosted reefs tend to be more common. The critical processes involved in the formation of this mineral system are: (1) primitive, magnesium-rich rocks derived from the asthenospheric mantle (ultramafic and mafic rocks such as dunite, harzburgite, pyroxenite, norite–gabbronorite–gabbro, troctolite, anorthosite, chromitite, and magnetitite), which serve as the primary source of metal; (2) intracratonic suture zones and trans-lithospheric faults that act as pathways for magma, locally enhanced by varying compressional/extensional tectonic regimes; and (3) dilatational zones of high, fracture-related permeability and localized structures that act as physical traps leading to the emplacement of the layered mafic intrusions [6].

Based on the above mineral systems model, targeting criteria for the current study were identified, considering the scale of the study and the datasets available. This study mainly used openly available public domain geophysical datasets distributed by the Geological Survey of Finland (GTK; https://hakku.gtk.fi/en/locations/search). The targeting model and the datasets used are listed in Table 1.

Table 1: Targeting model for northern Finland and the datasets used in the prospectivity analysis. All datasets are sourced from the GTK except those referenced otherwise.

Process	**Primary data**	**Predictor map**
Source		
Convecting mantle and the lithospheric mantle	Tomography survey [7]	Distance to mantle
Lithologies of large igneous provinces - differentiated, Mg-rich, Mantle-derived rocks	Geological map	Distance to ultramafic and mafic rocks
PGE reside in olivine, PGE content of a mafic-ultramafic rock suite tends to increase with higher levels of MgO, thus greater potential to contain magmatic sulphides. MgO/(MgO + FeO) value indicates the amount of olivine crystallised in mafic and ultramafic rocks.	Rock Geochemistry	MgO/(MgO + FeO) ratio map
Pathways		
Trans-lithospheric faults	Structural map	Distance to trans-lithospheric faults
Magmatic sulphides are hosted in magma conduits such as dykes that additionally aid PGE mineralisation.	Geological map	Distance to dyke
Traps		
Damage zone indicates a higher degree of structural intricacy and greater availability of space, resulting in fluid accumulation - structural traps.	Structural map	Structure density map

Ultramafic magma fractionation - solid crystals precipitating to the floor of a fractionating magma chamber form cumulate rocks with high MgO. Further fractionation results in sulphide saturation and formation of magmatic nickel sulphide, chromium and PGE deposits (e.g., Great Dyke, Zimbabwe).	Common lithologies hosting/crystallising with cumulates, such as dunite and peridotites	Distance to cumulate map
Mafic-ultramafic rocks are dense and have a significant response to gravity	Bouguer anomaly data	Density anomalies
Abundance of metals and Fe rich minerals cause magnetic anomaly	High altitude aeromagnetic anomaly data	Magnetic anomalies
PGE deposits are often associated with Ni, Cr, V, Cu deposits in layered mafic intrusions	Surficial Geochemistry	Pt, Pd, Cr, Cu/Pd, Ni, Cu content maps

Spatial data processing and analysis tools were used to process primary geoscience data to map the targeting criteria by their spatial proxies in the form of predictor GIS layers. These predictor maps were integrated in a multi-stage FIS structured on the mineral systems model to generate the PGE-Cr-V-Co prospectivity map of the study area. In the first stage, a series of FIS were used to generate fuzzy prospectivity maps for individual components of the mineral system, namely, sources, pathways and traps, by combining their respective fuzzy predictor maps. In the second stage, the fuzzy prospectivity maps of the individual components were combined using the product operator to generate the PGE-Cr-V-Co prospectivity map of the study area (Fig. 1b).

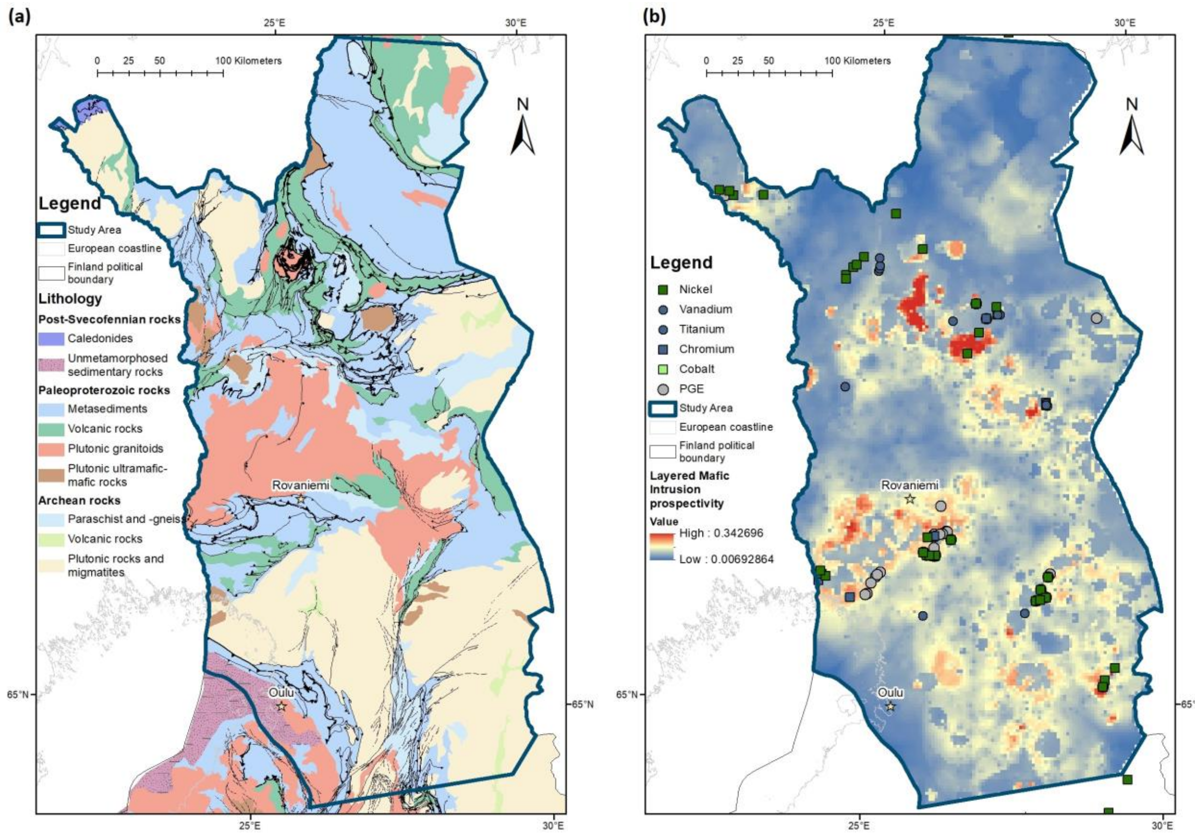

Fig. 1: (a) location and geology of the study area, (b) prospectivity map of northern Finland for layered mafic intrusion related mineralisation. Metal occurrences include all known magmatic occurrences.

The prospectivity map (Fig. 1b) shows good agreement with the known occurrences of PGE deposits. High prospective areas are identified in the north-central and western part of the study area for further detailed scale exploration to narrow down target areas for eventual ground exploration. In the western part, the significant deposits such as Kemi, Portimo and Penikat, occurring along the Archean and Paleoproterozoic boundary, are demarcated as a prospective high zone that extends further north. This indicates that there may be good potential to find more layered intrusions in the incipient rifting belt, which is now covered by younger supracrustal rocks.

It is also noteworthy that many Ni-Cu-dominated deposits that typically form conduit-type deposits are not marked with high prospectivity. It indicates that the prospectivity model is able to distinguish the layered mafic intrusion-related deposits from the conduit-type occurrences. With the inclusion of more predictor maps obtained from more data, this distinction is further expected to improve.

Since the Karelian craton, along with the Kola craton, were part of the Kenorland supercontinent [8] during the time of emplacement of these layered mafic intrusions at around 2.45 Ga, this model can be applied to areas that were part of Kenorland such as the Superior craton where similar occurrences are known.

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