Sustainable exploration of (critical) raw materials in orthomagmatic ore deposits

Yang S., SEMACRET consortium*

[1]Oulu Mining School, University of Oulu, 90014 Oulu, Finland

Abstracts The SEMACRET project try to develop sustainable exploration methods for orthomagmatic ore deposits hosted (critical) raw materials. The starting point is refining ore deposit models following the Mineral Systems Approach (MSA) concept. New exploration criteria will be defined and represented by geographic information system (GIS) based geodata, followed by prospectivity modelling. In local scale, different methods will be combined together including litho-geochemistry, geophysics, surficial geochemistry and artificial intelligence.

Ore model refinement following the Mineral Systems Approach

The Mineral Systems approach considering fundamental source-pathway-sink processes to identify regions of high exploration potential. However, there remains considerable controversy for each component.

(i) Source. The nature of the mantle source to the parent magmas of major magmatic ore deposits remains controversial, with either plume mantle or sub-continental lithospheric mantle (SCLM) being considered [1]. We will use multiple isotope systems, including Re-Os isotopes as a tracer of the mantle source of magmas and ore deposits, relying on the fact that SCLM tends to have negative γOs, lower than typical plume mantle [2]. A large dataset of isotope geochemistry from large igneous provinces (LIP) and related intrusions will be collected. In addition, we will perform numerical modelling using the MELTS platform [3] to simulate partial melting of SCLM samples from our Finland reference site to test whether partial melting of SCLM can form metal-rich magma.

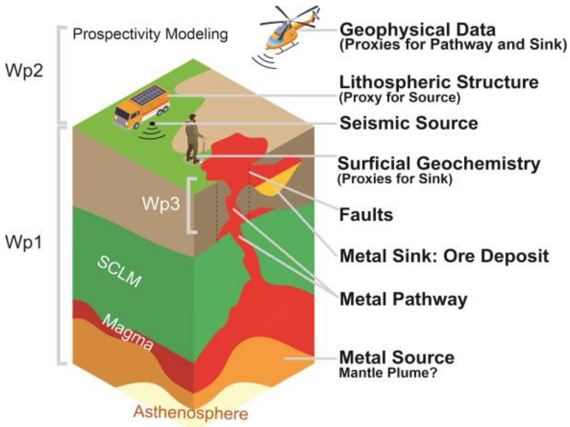

Fig. 1 Mineral systems approach and regional scale exploration targeting

(ii) Pathway. Many major Ni-sulfide deposits (e.g., Voiseys Bay, Sakatti) occur within relatively small intrusive bodies which have evidently served to focus large fluxes of relatively unevolved magmas [4]. Conduits used by the parent magmas to magmatic ore deposits appear to be particularly dynamic, characterized by high magma flux rate and assimilation of the wall rocks, which together favour saturation of the magma in ore metals as well as entrainment and hydrodynamic concentration of ore phases [1]. This concept has been applied to exploration targeting by using proximity to major faults as well as craton and terrane boundaries as a vector to ore [5]. However, new methodologies are needed to identify feeder conduits which may, in many respects, be indistinguishable from narrow closed-system sills and dykes. Potential tools that have been used in the past include the recognition of relatively unevolved magma (e.g., by high Mg# and Ni contents), anomalous/dynamic crystallization conditions (e.g. reflected by highly variable metal contents of silicates and oxides, an abundance of xenoliths and autoliths, and complex zoning of silicate minerals) and unusually slow cooling rates (determined by geothermometry). In this study, we will apply these tools holistically to identify highly dynamic magma conduits.

(iii) Sink. Mafic intrusions likely formed an evolving 4-dimensional framework of melts, crystal mushes, and solidified cumulates that determined how, where and when mass was transported

*Contact person of partner: Maier W.D., Jesus A.P., Wertich V., Rosowiecka O., Iacono-Marziano G., Filzmoser P., Pospiech S., Kobow J., Viezzoli A., Mononen T., Fiandaca G., Fernandez I., Carranza J., Jackson M., Datar B.

within these bodies [6]. We will study both highly mineralized intrusions in the EU (e.g., Akanvaara, Finland) and sub-economic intrusions (e.g., Rookjärvi, Finland). We will employ high-precision geochronology and microtextural visualization techniques (e.g., FESEM, micro XRF, X-ray computed tomography), combined with advanced numerical modelling of magmatic reactive flow (e.g., [1]) and high-temperature experiments to study the crystallization history of the intrusions [8] thereby constraining the mechanism of ore formation in mafic-ultramafic intrusions in the EU.

The importance of magma contamination will be quantified by high-precision lithogeochemistry of the orthomagmatic rocks, including analysis of incompatible trace elements, Re-Os, O, Nd, and Sr isotopes, in combination with high-temperature experiments simulating orthomagmatic processes while controlling pressure, temperature, redox conditions, and the composition of the magma (including volatile elements). A particular target will be how the assimilation of anhydrite and black shale trigger sulfide saturation, Especially, the role of sulfide-bearing black shale and anhydrite in the formation of orthomagmatic sulfide deposits will be investigated in detail, which may have played a key role in the ore formation in Lapland, and thus has critical application in exploration in the highest potential region in the EU. This approach is crucial to understand the importance of chemical and physical processes during magma-rock interactions which constitutes a key component of an improved ore model.

Developing methods for regional-scale exploration targeting

Critical ore-formation factors are translated under the scope of the Mineral Systems Approach to mappable proxies using multiple geoscience datasets including geophysics, geology and geochemistry [9]. The multiple data layers can then be integrated on a GIS platform to generate prospectivity maps distinguishing areas of low and high exploration potential. In the present project, based on the refined ore model, we will define proxies reflecting all the components of the Mineral Systems Approach including 'source', 'pathway' and 'sink' to guide regional exploration targeting for orthomagmatic deposits. Abundant deep penetration geophysical studies have been conducted across the EU, providing information on the 3D structure of the lithosphere (e.g., [10]), but these data have not been applied to mineral exploration.

Proxy reflecting 'source' component of ore model may be reflected by lithospheric structure. The POLENET/LAPNET (Polar Earth Observing Network) broadband seismic network was deployed in northern Fennoscandia (Finland, Sweden, Norway, and Russia), consisting of about 60 seismic stations [11]. The upper mantle beneath the northern Fennoscandian Shield was imaged using high-resolution teleseismic P wave tomography [12], P- and S- receiver function analysis [13]. The studies revealed a highly heterogeneous and thick (down to 200 km) lithospheric mantle beneath the northern Fennoscandian Shield. In addition, a large elongated negative velocity anomaly (up to − 3.5 %) at the depth range of 100–150 km was revealed in the central part of the network. This low-velocity zone separates three high-velocity regions corresponding to the cratonic units in the region. The low-velocity region may correspond to a Paleoproterozic rifting belt. In this project, we will study the spatial links between the lithospheric architecture and mafic-ultramafic magmatism in northern Finland.

Proxy reflecting 'pathway' component of ore model: We will use terrane and craton boundaries as well as faults as proxies for magma pathways [14, 15]. In this study, the trans-lithospheric deep structures revealed by the large-scale seismic surveys (mentioned above) and results of deep crustal studies using controlled source seismic methods [16] will be extracted from the published databases and given higher weight as proxies of province-scale magma pathways. Relatively shallow faults indicated in digitized bed rock maps will be considered as proxies to magma pathways at the local scale.

Proxies reflecting 'Sink' component of ore model: (i) Identifying favorable host rocks - Mafic-ultramafic rocks tend to have high density and gravity anomalies which can be used as proxies for favorable host rocks. We will use the country-wide, open access, density and gravity database of northern Finland as a component of our prospectivity modelling. (ii) Geochronology to identify the source of sulfur: The prolonged rifting resulting in the formation of the Central Lapland Greenstone

Belt (CLGB) caused multiple episodes of mafic-ultramafic magmatism (2.45 Ga, 2.3 Ga, 2.2 Ga, 2.15 Ga, 2.06 Ga). A recent study has shown that the latest magma pulse (2.06 Ga) has the highest potential to form sulphide-rich deposits [17]. This provides an opportunity to investigate the role of regional geology in controlling ore formation. The formation of most orthomagmatic ore deposits requires the addition of external sulfur [4].

Similarly, existing regional surface geochemical data sets of till (and soil) had not been fully deployed for exploration due data analytical challenges. In this study, we will use these datasets to constrain the 'source' and large scale 'pathway' of fertile magmas. We will also further study the mechanisms to trigger metal deposition in so-called 'sinks' including the mechanism of sulfide melt saturation. These new data will allow us to generate improved prospectivity maps for Cr-PGE-V-(Ni-Cu-Co) and Ni-Cu-(PGE-Co) deposits, and to validate the ore model and prospectivity model in reference site where there are abundant mineralization occurrences and a large geo-database available for study.

Integration of multiple proxies via prospectivity modelling: Prospectivity modelling can be classified into two main categories including knowledge-driven (fuzzy logic) and data-driven (weight of evidence and artificial neural network) approaches. The data-driven approach requires a large number of known occurrences of mineralization [14]. This is difficult to achieve in the EU due to the limited number of known occurrences of orthomagmatic ore deposits in almost all metallogenic belts. Hence, fuzzy logic modelling is adopted in all reference sites. However, the identified mappable criteria of the Canadian and Australian studies can be referenced in our prospectivity modelling, especially considering the similar geology between Finland, Canada and Australia. In addition, we aim to improve the mappable criteria with better understanding of ore deposit model.

Developing methods for brownfield exploration targeting

In this study, we will improve existing techniques (notably surficial geochemistry) and develop new techniques (notably 3-D modelling and inversion of ground and airborne geophysics), and introduce new machine learning tools for 3D prospectivity modelling.

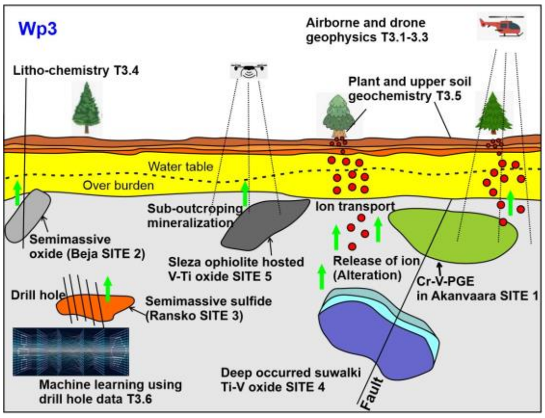

Fig. 2 Multidisciplinary approach for local scale exploration

Surficial geochemical exploration (upper soil, plant chemistry) allows to delineate geochemical domains and anomalies with low to zero environmental impact. It can be applied as well in agricultural used areas as in environmental protection areas. In this study, the focus lies on testing under different surface conditions with different host rocks how the use of surface media can be calibrated to find hidden mineralization of Ni-Cu dominated sulphide deposits and Cr-V-PGE dominated deposit. We will develop new data analytical tools and improve existing concepts, code and guidelines to better filter relevant information for exploration from the highly variable surface geochemical data. Modelled data of all three approaches, litho-geochemistry, geophysics and surface geochemistry, can then contribute to be used in the integrative approach.

Ground-based and airborne geophysical methods have been successfully applied in various brown-field exploration projects. Potential fields methods (gravity, magnetic) and electro-magnetic methods including MT and IP (Magneto-Telluric and Induced Polarization) (EM) methods are particularly effective both for studying the structural geological setting and for direct targeting of mineral systems. However, different mineralization styles of the orthomagmatic deposit group pose different chal-lenges and require different methodologies. In this study, we will explore optimized solutions combining different methods together for different mineralization styles represented by different reference sites. These include: combining magnetotelluric and full tensor magnetic gradiometry (FTMG) to better constrain the deep occurrence of oxide ores; 3D inversion for electromagnetic data of sulfide ores; using passive seismic to constrain local structure and surficial geochemical data interpretation; integrating airborne and ground polarization (IP) for oxide ores.

3D prospectivity modelling: An essential component of this methodology is 3D geological modelling for improved understanding of geological controls on mineral deposit occurrence at local to deposit scales. 3D geological modelling is a computer-based procedure whereby geological data (from cross-sections and drill cores) and suitable geophysical datasets are typically analyzed and integrated to predict locations of geological features in the subsurface. Another essential component of the methodology is 3D modelling of ore bodies, which is a traditional procedure in mining. The availability of a 3D geological model and a 3D orebody model allows for the quantification of spatial relationships of known ore-bodies and certain geological units. The quantified spatial relationships are used for 3D predictive delineation of new exploration targets in the subsurface, which likely contain undiscovered ore bodies. Thus, 3D prospectivity modelling can potentially help the mineral industry to identify future resources, though successful delineation of prospective targets for exploration in a brownfield continues to be a tough challenge. Besides, unlike linear methods used earlier for 3D prospectivity modelling (e.g., [18]), machine learning algorithms can capture intrinsic non-linear spatial relationships between mineral deposits and geological features.

Traditionally, resource estimation has relied on intensive drilling. The main challenge is to predict metal grade in three dimensions, especially in complex ore bodies, where the continuity of mineralization is not always guaranteed. Supervised machine learning methods have been successfully applied to resource modelling [19], increasing the accuracy of resource estimation compared to the traditional geostatistical methods (e.g., kriging. In this study, we will apply machine learning to improve resource estimation in magmatic ore deposits.

Overall, the SEMACRET project will develop sustainable exploration methods from regional scale to local scale for orthomagmatic ore deposits, which has low environmental and societal impact.

This work is co-funded by the European Union and UKRI (SEMACRET, GA101057741).

References:

[1] Barnes SJ et al. (2016) Ore geology reviews 76:296-316
[2] Shirey SB and Walker R (1998). Ann Rev Earth Planet Sci 26:423-500
[3] Ghiorso MS et al. (2002) Geochem Geophy Geosys 3:1-35
[4] Naldrett AJ (2004) Springer Science Business Media
[5] Joly A et al. (2015) Ore Geol Rev 71:673-702
[6] Sparks RSJ et al. (2019) Philosophical Trans Royal Soc A 377:20180019
[7] Jackson MD et al. (2018) Nature 564:405-409
[8] Iacono-Marziano G et al. (2017) Ore Geol Rev 90:399-413
[9] McCuaig TC et al. (2010) Ore Geol Rev 38:128–138
[10] Prodehl C and Mooney WD (2012) Geol Soc Amer 208
[11] Kozlovskaya E et al. (2007) Geophy J Intern 171:761-779
[12] Silvennoinen H et al. (2016) Solid Earth 7:425-439
[13] Vinnik L, Oreshin et al. (2016) Tectonophy 667:189-198
[14] Lawley CJ et al. (2021) Ore Geol Rev:103985
[15] Nykänen V et al. (2015) Ore Geol Rev 71:853-860
[16] Silvennoinen H et al. (2014) Geo Res J 1-2:19-32
[17 Moilanen M et al. (2021) Ore Geol Rev:104044
[18] Farahbakhsh E et al. (2020) Geochem: Explor, Environ, Anal 20:480-495
[19] Kaplan UE, and Topal E (2020) Miner 10:847