GIS-based mineral system approach for prospectivity mapping of iron-oxide apatite-bearing mineralisation in Bergslagen, Sweden

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Abstract. Bergslagen is one of the richest mineral districts in Sweden for base and precious/critical minerals and metals. In this work a mineral system approach for targeting of iron-oxide apatite-bearing mineralisation has been developed. GIS-based mapping of prospectivity for this type of mineralisation has been carried out with a focus on Ludvika mining area from Blötberget to Håksberg with known and high-quality iron-oxide deposits. According to spatial analysis on mappable criteria’s, strong positive airborne magnetic anomalies, density of structures and the contact between felsic volcanic rocks and granites are crucial for this type of mineralisation in the study area This GIS-based model will also be used in targeting of iron-oxide deposits at depth in the Blötberget area. However, the mineral systems approach considers the origin of deposits in the framework of lithospheric-scale processes from the time-honored aspects of the source, fluids, transport and physical and/or thermo-dynamical traps. Applied to exploration strategy, this approach allows for more predictive models. Rather than matching patterns, knowledge of the underlying geological processes and tectonic-structural setting can be used for identifying areas with higher probability of finding deposits of interest. Furthermore, this method can broaden the scope of prospectivity indicators and allows for earlier and more efficient fertility assessments.

1 Introduction

Iron-oxide (also sometimes apatite-bearing) deposits, in Sweden are today are mainly known from Kiruna and Malmberget mines in the north. However, iron-oxide deposits of similar quality and to a disputed origin can also be found in central Sweden in the so-called Bergslagen ore province/district. The largest of these being Grängesberg, Blötberget and Idkerberget mined for their quality iron ore until the 20th century some of which for over a few hundreds of years. Based on their overall mineralogy, geochemistry, geometry and relationships with the host rocks, these Bergslagen deposits are suggested to have Kiruna-type origin i.e., high temperature to magmatic origin (e.g. Jonsson et al., 2010). This type of mineralization locally may show some differences between style of mineralization, associated alteration and texture. Beside, iron in the form of magnetite and hematite, fluorapatite and associated rare earth-bearing phosphates and silicates in these ores may represent a significant potential reserve of REEs as well as of phosphorus (Sadeghi et al., 2019) requiring an elevated and renewed attention (Malehmir et al., 2017).

Wyborn et al. (1994) define a mineral system as “all geological factors that control the generation and preservation of mineral deposits, and stresses the processes that are involved in mobilising ore components from a source, transporting and accumulating them in more concentrated form and then preserving them throughout the subsequent history”. However, in most practical applications of the mineral systems approach in exploration targeting, these factors are ignored because they are generally difficult to map particularly for spatially variant datasets.

McCuaig et al. (2010) describe a four-step procedure for linking the mineral system with data available for practical exploration targeting. These steps include translation from (1) critical processes of the mineral system, to (2) constituent processes of the mineral system, to (3) targeting elements reflected in geology, and (4) targeting criteria used to detect the targeting elements directly or by proxy. This procedure is today used, implicitly or explicitly, in all mineral prospectivity modelling studies.

There is some restriction that prospectivity models are dependent on the input exploration data, and any targeting criteria that are not mappable in the available exploration data cannot be incorporated in modeling.

In this study, we focus to present a mineral system model for iron-oxide apatite ores in the Bergslagen from mining camp scale and imply the concept in the deposit scale (Blötberget) in the Ludvika mining area. The result of this model will be employed for 3D prospectivity modelling in the Blötberget and surrounding areas in follow up studies within the trans-European H2020-funded Smart Exploration project.

2 Study area

The study area is situated in the historical mineral district of Bergslagen in south-central Sweden extending from Grängesberg in the south Håksberg in the north (Fig. 1). The mineralisation in Bergslagen comprises of banded iron formation (BIF), skarn-type iron-oxide deposits andapatite-rich iron-oxide deposits, with the latter deposits accounting for more than 40% of the iron ore produced in Bergslagen (Magnusson, 1970, Stephens et al., 2000). The area of interest, Blötberget and areas north of it are
known for their iron-oxide apatite-bearing deposits. The mineralisation in Blöteberget is known to extend down to at least 800–850 m depth (Malehmir et al., 2017) in a moderately dipping (approximately 45-50 degree) manner.

Geologically, Bergslagen belongs to the Svecokarelian orogen in the Fennoscandian Shield. Metamorphosed volcano-sedimentary rocks of Palaeoproterozoic age (1.85-1.8 Ga) dominate the host rocks (Fig. 1). Metavolcanic rocks including feldspar porphyritic rocks show close spatial association with iron-apatite mineralisation. The rocks show metamorphic grades ranging from medium to upper amphibolite facies. Coeval dacitic, andesitic and basaltic dykes and subvolcanic intrusions, and syngneous, granitic to intermediate plutonic rocks cut the host rock and the mineralisation. Post-mineralisation intrusion of granite-aplite-pegmatite and metamorphism severely resulted in the deformation of these rocks (Allen et al., 1996; Ripa and Kübler, 2003). During their formation, the host rocks were variably hydrothermally altered. The origin of the apatite-rich iron-oxide deposits is considered to be syngneous, although this is disputed, with a new study favouring a magmatic-to-high-temperature hydrothermal origin (Jonsson et al., 2013).

3 Mineral systems approach target generation

In a data-driven mineral prospectivity model the model parameters are estimated based on statistical spatial relationships to a training dataset of the iron oxide apatite mineralisation in the study area (knox-Robinson and Wyborn, 1997). The data-driven weights of evidence method (WoE) have been used (Bonham-Carter et al., 1994), which is a statistical method for quantifying spatial association between mineral deposits and geological features. A weight of evidence is normally applied to exploration situations in which there is an adequate number of mineral deposits or occurrences already discovered (e.g., for brownfields). Simply, WoE is a data-driven method based on the Bayesian theory and its fundamental concept of prior and posterior probabilities.
### Table 1. Regional-scale iron-oxide apatite-bearing mineral system models listing targeting elements and relevant spatial proxies/predictor maps for the targeted apatite iron-oxide mineralisation deposit.

<table>
<thead>
<tr>
<th>Processes</th>
<th>Sub processes</th>
<th>Mappable ingredient</th>
<th>Predictor maps</th>
</tr>
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<tr>
<td>Fluids, Metals, and ligands</td>
<td>Magmatic-hydrothermal fluids</td>
<td>Geochemistry of rocks</td>
<td>Proximity and elemental map</td>
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<tr>
<td></td>
<td>Magmatic</td>
<td>The presence of iron-rich intrusive/extrusive rocks</td>
<td>Proximity of granitoid/rhyolitoid rocks</td>
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<td></td>
<td>Country rocks</td>
<td>The presence of iron-rich metal sedimentary rocks</td>
<td>Proximity of limestone/sedimentary rocks</td>
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<tr>
<td>Energy</td>
<td>Intrusive-volcanic complex</td>
<td>The presence of iron-rich intrusive/extrusive rocks</td>
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<td></td>
<td>Hydrostatic head for oxidised fluid</td>
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<td>Fluid pathway</td>
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<td>Regional scale structures (Geophysical data)</td>
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<td>Porosity</td>
<td>Bedrock and alteration</td>
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<td></td>
<td>Structural</td>
<td>Fault/ fold/ breccia zones</td>
<td>Proximity</td>
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<td></td>
<td>Chemical</td>
<td>Redox reaction between reduced rocks and oxidised fluid</td>
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</table>

Firstly, spatial association between training site (iron-oxide apatite-bearing mineralisation) and the mappable ingredient was calculated, secondly, evidential maps for prediction were optimised, and finally, predictor maps were combined based on mineral system approach to created favourability maps and target generated map produced.

Figure 2. Potential prospectivity map of iron-oxide apatite-bearing (IOA) mineralisation in the study area around Blötberget and Ludvika area. It is remarkable areas west of the city Ludvika with a strike SW-NE stands out as high probability.

### 4 3-D modeling of airborne magnetic data

In the summer of 2016-2017, the Geological Survey of Sweden (SGU) conducted a new airborne survey in the area along flight-lines of 200 m spacing with nominal flight-height of 60 m above the ground surface; an along flight-line sampling interval of 15 m was used. Different than earlier data from the 70s, this survey was designed to orthogonally (NW-SE directed) transverse the structures observed on earlier airborne data and surface geological mapping. The airborne magnetic data were modelled in 3D using the VOXI Earth modelling program developed by Geosoft®. The resulting model contains voxels each having the average susceptibility of material within the voxels' volume. The voxels have horizontal dimensions of 250 m by 250 m and a vertical dimension that increases logarithmically with depth starting from 25 m at the surface. Figure 3 shows iso-susceptibility surfaces of 0.05 (SI) generated from the voxel susceptibility model. The modelled iso-surfaces coincide well with the locations of known iron-oxide mineralisation in the area (e.g. Blötberget and Häksberg). Use of borehole information in the modeling of magnetic data as constraints can improve the accuracy of the method specially with depth. Such a model can be utilised for a 3D perspectivity mapping in the future. Moreover, at areas covered by water (e.g. the lake north of Blötberget) the model can facilitate planning reconnaissance drillings.
5 Conclusions

Based on spatial association of mappable ingredient with the IOA mineralisation in the Ludvika mining area, the highest spatial association with mineralisation is related to (i) proximity to the positive airborne magnetic anomalies, (ii) intensity of the structure, (iii) proximity to the contact between volcanic and granitic rocks and (iv) proximity to the dacite-rhyolite volcanic rocks. The data-driven spatial analysis in the area with several data and active mining and exploration activities (e.g. brown field) may help to adding values on knowledge of geological processes on mineralisation in district-camp scale. All this information may reveal new mineral system model(s) for better evaluation of targets for mineral exploration. There are other types of iron-oxide mineralisation in the study area (e.g. skarn type and BIF) and it is essential to remembers that the common practice of incorporating proxies of all mineral systems components (source, pathways and traps) in a single prospectivity model may not yield a deposit type-specific prospectivity map. The output of 2D mineral prospectivity and mineral system model can be applied in the 3D for calculation of exploration criteria’s and proximity to the ore deposit (target) in the 3D (e.g. proximity to the magnetic anomalies in depth and proximity of known mineralisation with contact between dacite-rhyolite and granitic rocks.

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References


