ABSTRACT: The gravity and magnetic data may be analysed by geostatistical methods. The obtained models may be used to interpolate the magnetic and gravimetric measurements to maps. In addition, geophysical measurements and maps can be used to validate the geostatistically simulated geological models. The paper presents few examples of using geophysical methods in a study of the Kutemajärvi and Pampalo gold deposits in southern Finland.

1 Introduction

Kutemajärvi and Pampalo gold deposits are situated in different geological domains (Fig. 1). The Pampalo deposit in eastern Finland is in the Archaean domain and the Kutemajärvi deposit in southern Finland is in the Svecofennian domain. Both gold deposits consist of subvertical structures.

Figure 1. K Kutemajärvi gold deposit and P Pampalo gold deposit on the Geological map of Finland (Geological Survey of Finland, http://www.gsf.fi).
Kutemajärvi gold deposit consists of five economic, subvertical lodes (Fig. 2). The length of the biggest lode is greater than 300 metres. The horizontal extent of the pipes is 10 - 20 metres times 20 - 50 metres. The deposit is situated in the Tampere schist belt that is Palaeoproterozoic. The rocks are volcano-sedimentary in the central part of the Svecofennian (1.75 - 2.0 Ga) domain. The deposit is in a sequence comprising, felsic, intermediate and mafic metavolcanic and volcanogenic metasedimentary rocks. The altered and mineralized area is in the intersection of NW-SE and E-W trending faults. The geology of the Kutemajärvi deposit has been described by several authors, e.g., Kojonen et al. (1999) and Luukkonen (1994).

Figure 2. Plan and cross sections at Kutemajärvi after Kojonen et al. (1999).
Pampalo deposit in eastern Finland has three pipe-like, high-grade, subvertical, NE-trending bodies (Nurmi and Sorjonen-Ward, 1993). The lodes are 5 - 10 metres wide, 50 - 80 metres in height and extend more than 200 metres. The mineralisation is in the central part of the Hattu Schist Belt (Fig. 3). The host rocks form a deformed sequence with tholeiitic metavolcanic rocks. Gold is associated with secondary shear zones between the main shear zones in the Pampalo shear system (Fig. 3).

Figure 3. Regional geological map from Pampalo surroundings (Nurmi and Sorjonen-Ward, 1993).

The data consisted of drill hole data from the Kutemajärvi and Pampalo gold deposits. The orebody V from the Kutemajärvi deposit (Fig. 2) is dealt in the present paper. In addition, magnetic survey data from the Kutemajärvi area were used in the study.

The main host rocks were mapped using sequential indicator simulation and geological interpretations at the Kutemajärvi and Pampalo gold deposits. The continuity of the host rocks was studied by a variogram analysis on indicator variables defined by a simple relation:

\[ i_q(x) = \begin{cases} 
1 & \text{if host rock prevails at the location } x; \\
0 & \text{else.} 
\end{cases} \]

Sequential indicator simulation (Gomez-Hernandez and Srivastava, 1990; Alabert, 1987) was used to map the host rocks using the obtained variogram models. In the sequential indicator simulation conditioning is extended to include all data available...
within a search neighborhood, including original data and previously simulated values. The geostatistical simulations were done by ISATIS software and GSLIB Fortran codes (Deutsch and Journel, 1999).

The magnetic measurements were used to interpolate the magnetic map for the Kutemajärvi area. The magnetic survey data was interpolated to a magnetic map using kriging interpolation. Kriging is a generalized regression technique that minimizes an estimation variance (e.g. Journel and Huijbregts, 1978). Kriging is based on the modelled variograms i.e. on the covariance structure of the dataset.

Traditionally, gravity and magnetic measurements have been used to interpret the anomalies appearing on the geophysical maps. This is called inverse modelling. In forward modelling the geophysical anomalies of the known geological models are calculated. In the present paper the magnetic and gravity anomalies for the geostatistically simulated models were calculated and modelled using MATLAB and geophysical modelling software ModelVision.
2 Kutemajärvi gold deposit

At the Kutemajärvi deposit the main host rocks are quartz rocks and sericite quartz schists (Fig. 4). The modelled spatial continuity of the quartz rock is in accordance with the geological interpretations. Two geostatistically simulated models of the ore-body V are shown in the Figure 5. The grid size was 2 metres and vertical dimension of the model is 300 metres

![Boxplots of gold contents. In the plot: 1 - quartz rock, 2 - quartz schists and 3 - sericite schists.](image)

The density of the quartz-rich hostrocks are low. The density of quartz is about 2.65 kg/m$^3$ and the density of micas are 2.8 – 2.9 kg/m$^3$ (Olhoeft and Johnson, 1989). The rock density can be calculated as a weighted average of the densities of the constituent minerals. The weights are the mineral contents. So, the density of the orebodies was evaluated to be about 2.7 kg/m$^3$ that do not differ considerably from the density of the country rocks, that are mainly felsic volcanites. However, the the density contrast between the quartz-rich rocks and sericite schists may be used to map the quartz rocks.

Magnetic susceptibility is the fundamental parameter in magnetic prospecting, since the magnetic response of rocks and minerals is determined by the amount of magnetic materials in them. There exist a rough linear dependance between content of ferromagnetic minerals such as magnetite and magnetic susceptibility. If the rock contains mainly quartz and feldspars the magnetic susceptibility may be negative and the rock is classified diamagnetic. Most of the rocks are paramagnetic having the magnetic susceptibility from 0 to $10^{-4}$ SI. For example, micas, pyroxenes and amphiboles are paramagnetic minerals. Accordingly, the quartz rocks are nearly diamagnetic having a low magnetic susceptibility value compared to the surrounding schists that can be classified as paramagnetic, and locally as ferrimagnetic containing magnetite and having a magnetic susceptibility value greater than $10^{-4}$ SI.
In the Figure 6 these physical properties are used to calculate corresponding gravity and magnetic anomalies for the two simplified geological models - quartz rocks were modelled to occur as tabular bodies. It was assumed that top of these models are at the surface. The magnetic and gravity anomalies have different shapes reflecting the different geological models for the quartz rocks distribution in the deposit. The used density contrast was $50 \text{kg/m}^3$ and the magnetic susceptibility contrast $600 \cdot 10^{-6}\text{SI}$. It is possible to use this kind of calculations to validate the obtained simulated geological models. In this case, however, the needed measurement interval should be under five metres, that is economically possible for magnetic measurements but not for the gravity surveys. Magnetic surveying is fast and cheap. In contrast, every single gravity measurement takes a long time, and, so, the gravity surveys are expensive. However, the clear density difference may be used by $\gamma - \gamma$ logging of the gold critical rocks in drill holes.

Figure 5. Vertical sections (S-N) of two simulated geological models of the host rock distribution in the orebody V (Fig. 3).
Figure 6. A The calculated gravity (blue) and magnetic (red) anomaly for the simulation 1 (Fig. 5) and B the calculated gravity (blue) and magnetic (red) anomaly for the simulation 2 (Fig. 5).

The magnetic survey has been done (Outokumpu Mining) with a line spacing of 10 metres and a sample spacing of 5 metres. The Figure 7 shows the variogram models. The magnetic field values have a maximum continuity along the geological formations. This model was applied to krige the magnetic field values into a magnetic map (Fig. 8). The ore bodies are located beside the positive magnetic anomalies that could be interpreted as vertical magnetic formations that dip to the north, so, that the weakly magnetic orebodies III, IV and V are below them.
Figure 7. Experimental variograms calculated from the magnetic measurements and corresponding spherical variogram models.
3 Pampalo gold deposit

At Pampalo deposit gold has been enriched in porphyry rocks and andesites (Fig. 9). Geological models (Fig. 10) were simulated using sequential indicator simulation. The grid size was 60 x 110 x 44. Every grid element had a size of $5^3 m^3$. The variogram model is in agreement with the northeastern trend in the area.

The host rocks are lighter than the surrounding schists, amphibolites and komatiites. The density of the lightest country rocks, talc chlorite schists, is approximately $2800 kg/m^3$ and the density of andesitic and porphyritic rocks are about $2700 kg/m^3$ based on the mineral compositions of these rocks. Thus, the density contrast of $100 kg/m^3$ was applied in calculations. The gravity anomaly was calculated as a sum of the effects.
of the cubic $5 \times 5 \times 5 m^3$ elements. Figure 10 shows the resulted anomaly for one of the geological models. Based on for example on the visual examination it is possible to validate the simulated geological models, in case, the gravity field were measured. However, only the features near the surface can be checked because the deep structures can not be interpreted in detail using gravity measurements (e.g. Parasnis, 1996) These field values are mainly inversely proportional to a squared distance from the source. The similar approach could be applied to calculate the magnetic fields for the simulated geological models. The calculation is more complicated but the magnetic surveying is fast and cheap.

Figure 9. Boxplot of gold content distribution at the Pampalo gold deposit. 0 - not determined, 1 - iron formation, 2 - metasediments, 3 - basic and intermediate volcanites, 4 - quartz-rourmaline-carbonate veins, 5 - andesites, 6 - porphyrites, 7 - skarns, 8 - talc chlorite rocks, 9 - biotite chlorite rocks, 10 - fractures.
4 Conclusions

Magnetic and gravity anomalies can be calculated for the geostatistically simulated geological models and the corresponding geophysical fields may be compared with the real geophysical measurements in order to validate the simulated models. In the case of the Kutemajärvi and Pampalo gold deposits, the host rocks are consisting of rocks that differ petrophysically from the country rocks. The proposed approach of checking the geostatistically simulated geological models could be economic by using magnetic surveying that is cheap. In this case, the interpretation may be difficult because the magnetic properties are not simply correlated to the mineral composition as it is the case with the rock densities.

Geostatistical estimation methods may used to interpolate the geophysical measurements to maps. For example, at the Kutemajärvi area the kriged magnetic map shows the locations of the orebodies in relation to the magnetic anomalies clearly.

Finally, the calculated anomalies for the geostatistically simulated geological models may be used to characterize geophysical properties of ore deposits.

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REFERENCES


INTERNET REFERENCES