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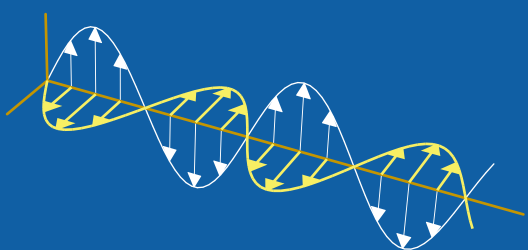

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Abstract

A comparison between experimental measurements of the electromagnetic field in boreholes and a mathematical model is made. The transmitting antenna is a rectangular wire loop on the ground and the three orthogonal components of the magnetic field are measured below the ground in the borehole. In the mathematical model the ground is assumed to be a stratified half space with a rectangular wire antenna on the ground. Excellent agreement was found between the experimental results and the theoretical ones in most cases and where deviations were found, the assumption of a stratified ground was inaccurate due to present conductive inhomogeneities. The method presented in this paper is capable of determining an ore body within a radius of 100 m from the borehole. The position (direction and distance) of the target can be estimated from the measurements in the borehole. The impact on the economical effectiveness of a drilling programme is considerable when a prediction of the location of additional boreholes can be made. In the case of reconnaissance drilling of a geological structure or trend the distance between adjacent boreholes can be considerably enlarged.

1 Introduction

The exploitation of outcropping ore bodies is the basis for the nine productive mines in the Skellefte field in northern Sweden. The massive sulphide ore bodies of the Skellefte field are generally steeply dipping and have a high conductivity. Consequently, they are most ideal targets for electromagnetic exploration techniques. To maintain the ore reserves beyond the year 2000 the performance of the exploration techniques has to be improved to be able to reveal concealed deposits.

Boreholes play an important role in the exploration of deeper targets. To achieve maximum information from such holes there is a need for an improvement of the geophysical borehole technique and interpretation algorithms. An improved geophysical borehole system should be able to localize a massive sulphide deposit of economical size at a distance of 50–100 m around the hole and to find the attitude of and the direction to the target. One of the requirements on the system is the usage in an operating mine. In this paper a brief presentation of our geophysical borehole system and some basic results are given.

In order to locate distant anomalies and to be able to interpret the information in the measured field components, a mathematical model has been developed. This model is also important for calibration purposes. In the next section, a short description of the experimental equipment is given. In Section 3 a model for a time harmonic source in the presence of a stratified lossy ground is analyzed. A simplified model based on the static solution, which reduces the need of computer capacity, is also used. This approximate approach is used in areas of well known bed-rock properties. Examples from both models will be given in Section 4.

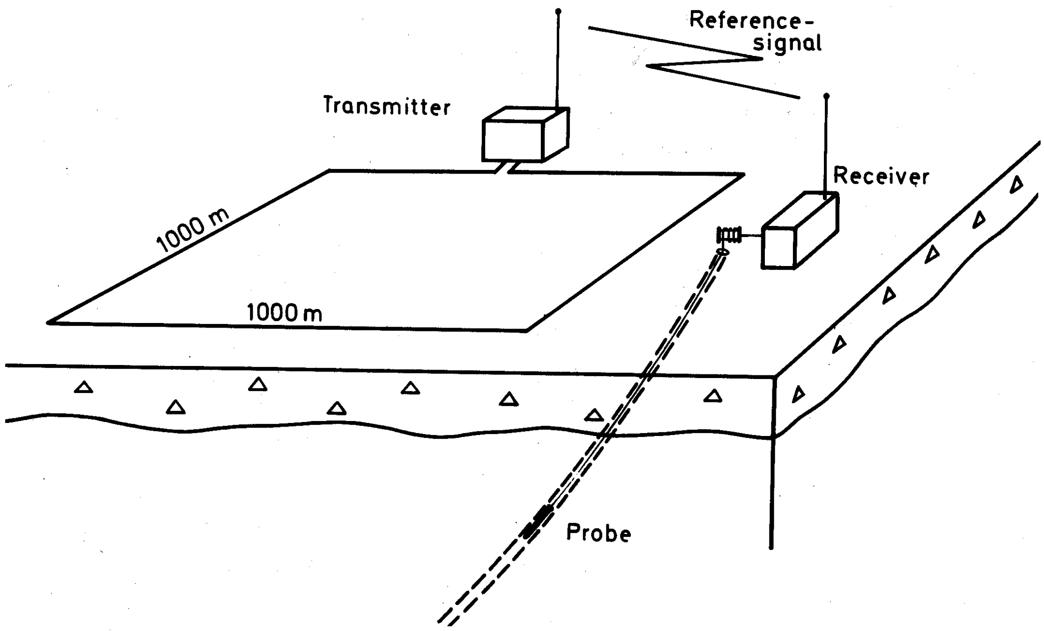

Figure 1: A sketch of the layout in a field application.

2 Equipment

Basically, the experimental set-up consists of a large ground loop transmitter and a receiver measuring the magnetic field. A sketch of the system is given in Figure 1.

The transmitting ground loop is of a characteristic size of 1000 $\times$ 1000 m^2 and is fed with an alternating current of up to 4 Ampère. Its maximum power is 1000 W and it operates at two frequencies, 200 and 2000 Hz. In a more recent configuration the equipment is operating at 223 and 2230 Hz.

The probe, which is 32 mm wide, consists of three coils measuring the magnetic field in three perpendicular directions. The coils form a right handed coordinate system. One coil is fixed with its axis parallel to the hole. The other two are naturally fixed on a movable frame carefully journalled in bearings. The frame uses gravity as a reference, giving one horizontal component, see Figure 2.

A reference signal is transmitted to the receiver, which is located on the ground, from the transmitter by a radio communication link. The signals from the three coils are pre-amplified and transmitted to the ground in a coaxial cable. The coils are tuned to a bandwidth of 150 Hz. In the receiver the signals are processed and the amplitude and phase of the three components are computed. To improve the signal to noise ratio the bandwidth of the detector is reduced to 1 Hz. The accuracy of the device is of the order of $\pm$ 2 % in amplitude and $\pm$ 2° in phase within the range 0.01–16 nT. The data of the equipment are collected in Table 1.

After the measurements are completed the data are sent directly to the central computer via a modem link to a mobile telephone. Together with information about the attitude of the borehole the measured components are transformed to a coordinate system suitable for presentation.

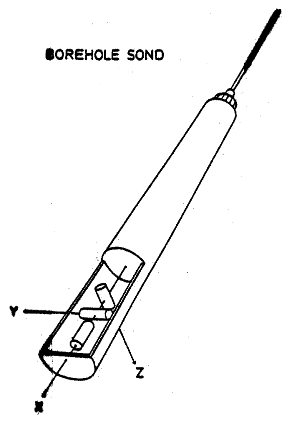

Figure 2: The definition of the x-, y- and z-direction.

Frequencies	223, 2230 Hz
Current	0–4 A
Power	1000 W
Range	0.01–16 nT
Bandwidth	1 Hz
Resolution: amplitude	2%
phase	2°

Table 1: Data of the experimental equipment.

3 Theoretical model

A brief description of the general mathematical model which is used for the interpretation of the measured results is now given. The geometry shown in Figure 1 is modeled by a stratified ground with homogeneous layers. The source is a wire antenna driven by an alternating current of frequency f. Problems related to this geometry has been studied by Wait (1981). However, the intention here is to treat the square loop antenna and to solve the problem in a more general setting. The mathematical details of this approach are omitted in this short review, but can be obtained from Kristensson (1983).

In order to explain the basics of the theory a less complicated geometry is assumed. This simplified medium is assumed to be completely homogeneous and isotropic with constant permittivity ε, permeability μ, and conductivity σ. In a finite volume V a current density $\boldsymbol{j}(\boldsymbol{r})$ of fixed frequency f is assumed. A factor $e^{-i\omega t}$, where $\omega = 2\pi f$, can therefore be suppressed from all field quantities. The magnetic field $\boldsymbol{H}(\boldsymbol{r})$, that is generated by the current density $\boldsymbol{j}(\boldsymbol{r})$, can be represented as a volume integral over the volume V, i.e.,

$$\boldsymbol{H}(\boldsymbol{r}) = \iiint_V \boldsymbol{j}(\boldsymbol{r}') \times \nabla' \frac{\exp(ik|\boldsymbol{r} - \boldsymbol{r}'|)}{4\pi|\boldsymbol{r} - \boldsymbol{r}'|}\, dV'. \tag{3.1}$$

The wave number k is defined by

$$k^2 = \varepsilon\mu\omega^2 + i\mu\sigma\omega \tag{3.2}$$

and the magnetic field $\boldsymbol{H}(\boldsymbol{r})$ in (3.1) satisfies radiation condition at large distances from the sources in V.

The presence of a planar interface in the model introduces mathematical difficulties. The reason for this complication is that the waves have different propagation properties in the two regions and that boundary conditions on the interface are to be met. These conditions are not inherent in (3.1). The boundary conditions at the interface are continuity of the horizontal electric and magnetic fields, $\boldsymbol{E}$ and $\boldsymbol{H}$, respectively. In terms of the magnetic field $\boldsymbol{H}$ the boundary conditions are:

$$\left.\begin{array}{c} \boldsymbol{H}\times\hat{n} \\ \dfrac{\mu}{k^2}(\nabla\times\boldsymbol{H})\times\hat{n} \end{array}\right\} \text{continuous over the interface,} \tag{3.3}$$

where $\hat{n}$ is a normal vector to the interface. The latter expression in (3.3) is obtained from Ohm's law $\boldsymbol{j} = \sigma\boldsymbol{E}$, (3.2) and the Maxwell equation

$$\nabla\times\boldsymbol{H} = \boldsymbol{j} + \frac{\partial}{\partial t}(\varepsilon\boldsymbol{E}) = \frac{k^2}{i\mu\omega}\boldsymbol{E}.$$

For a general source configuration above the earth this boundary value problem is not easy to solve. However, if the source generates a plane wave the problem is simple. In this case, the incident plane wave generates a reflected and a transmitted plane wave such that the boundary conditions are met. The amplitudes and phases of the reflected and transmitted waves are given by the reflection and transmission coefficients of the interface, respectively, and the directions of propagation are given by Snell's law. This fact is employed in the general source case, where the radiating magnetic field $\boldsymbol{H}$ in (3.1) is decomposed in plane waves.

The starting point in the general case is thus a plane wave representation, i.e.,

$$\boldsymbol{H}(\boldsymbol{r}) = \iint h(\boldsymbol{k})\boldsymbol{\phi}(\boldsymbol{k};\boldsymbol{r})\,d\boldsymbol{k}, \tag{3.4}$$

where $\boldsymbol{\phi}(\boldsymbol{k};\boldsymbol{r})$ is the plane vector wave and $h(\boldsymbol{k})$ is its amplitude. In order to avoid complicated notation the integration limits are suppressed in (3.4). The superposition in (3.4) can be viewed as a Fourier integral in the Fourier variables corresponding to the horizontal space coordinates. The field $\boldsymbol{H}(\boldsymbol{r})$ in (3.1) can now be generalized to include the effect of an interface. The incident, reflected, and transmitted fields all have plane wave representations similar to (3.4). If $h(\boldsymbol{k})$ is the amplitude of the incident wave, then the reflected and transmitted field amplitudes are simply $h(\boldsymbol{k})$ multiplied by the total reflection and transmission coefficients of the overburden, $R(\boldsymbol{k})$ and $T(\boldsymbol{k})$, respectively. Thus,

$$\boldsymbol{H}(\boldsymbol{r}) = \iint h(\boldsymbol{k}) \left\{ \begin{array}{c} R(\boldsymbol{k}) \\ T(\boldsymbol{k}) \end{array} \right\} \boldsymbol{\phi}(\boldsymbol{k};\boldsymbol{r})\,d\boldsymbol{k}, \tag{3.5}$$

for the reflected and transmitted field, respectively. The incident field above the interface is represented by (3.4). Above the interface the magnetic field is thus given by the sum of (3.4) and the upper part of (3.5). The lower part of (3.5) gives the magnetic field below the interface. The remaining unknown quantity, which is the incident wave amplitude $h(\boldsymbol{k})$, can be expressed as a volume integral over the sources $\boldsymbol{j}(\boldsymbol{r})$ in V

$$h(\boldsymbol{k}) = 2ik \iiint_V \boldsymbol{j}(\boldsymbol{r}) \cdot \left\{\nabla \times \boldsymbol{\phi}(\boldsymbol{k};\boldsymbol{r})\right\} dV \tag{3.6}$$

This equation is essentially the Fourier transform of (3.1).

For a wire antenna the volume integral in (3.6) reduces to a single integral. For some simple shapes of the wire loop, such as the horizontal circular and rectangular loops this single integral can be evaluated exactly. The remaining step in the calculation of the total magnetic field is the synthesis of the plane waves, given by (3.4) and (3.5). For the wire antennas mentioned above, this synthesis eventually reduces to a single integration over an infinite interval and has to be evaluated numerically.

In some parts of this work, where interactive interpretation is necessary, a simplified model is used, provided the frequency f is sufficiently small. In this model the effect of the interface is neglected. The medium is thus totally homogeneous and isotropic. The magnetic field in this case is obtained by letting $k \to 0$ in (3.1), i.e.,

$$\boldsymbol{H}(\boldsymbol{r}) = \iiint_V \boldsymbol{j}(\boldsymbol{r}') \times \nabla' \frac{1}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|}\, dV'. \tag{3.7}$$

This equation reduces to the well known Biot-Savart law when the current density $\boldsymbol{j}(\boldsymbol{r})$ becomes a line current I.

4 Results

In the first two examples an approximate homogeneous geology is considered. The measured fields are compared with the theoretical model. These comparisons are very important because the modeling of the background is the basis for the determination of the shape and the size of any anomaly.

In the Finnsjö area in Central Sweden there are a number of 600 m deep holes in a large homogeneous granitic body. The geometry is shown in Figure 3. The transmitting ground loop, 500×600 m^2, is placed almost symmetrically around the vertical borehole No. 6 (Bh 6). In the figure a second hole, Bh 5, dipping about 50° towards the edge of the loop, is also shown.

A comparison between the general theoretical model and the measured data for the x-component (the component along the borehole) from Bh 6 is shown in Figure 4. The apparent resistivity used is 10 kΩm which corresponds well with the medium value surveyed with a down hole Schlumberger array. The agreement between the model and the measured data is almost perfect for both the amplitude and the phase. However, a small difference between the curves for the x-component in Bh 5 is seen in

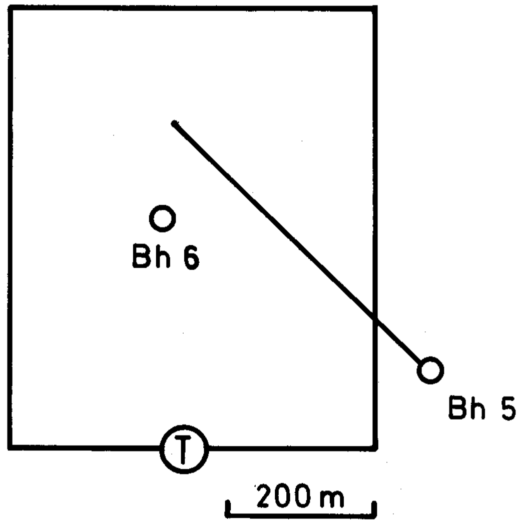

Figure 3: Finnsjön area. The horizontal projection of the ground loop and the boreholes.

Figure 5. It is probably caused by the small topographical irregularities of the area or small uncertainties in the position of the measuring probe. The topographical irregularities are of the order of 10 m. The results show that the theoretical model can also handle the situation very close to the edge of the loop.

A second test in more conductive rocks is made in the Kankberg area. Here the acid volcanics have a typical apparent resistivity of 1 kΩm. Borehole 109, Figure 6, intersects an alteration zone at the depth of 600 m. The zone has an apparent resistivity of 0.1 kΩm. In this case the transmitter is a square loop with the size 800 × 800 m^2. At the frequency of 200 Hz there is a good correspondence between the measured data and the theoretical result, see Figure 7. Using the higher frequency, 2000 Hz, the influence from the alteration zone becomes stronger as expected, see Figure 8. In the first 500 m of the homogeneous bed-rock, the phase of the y-component agrees reasonable well with the model as seen from Figure 9. However, 100 m from the conductive zone, there is a strong shift in the phase. Thus, measuring and modeling the phase improves the interpretation.

In a third example, also taken from the Kankberg area, a buried conductive target is included, see Figure 10. This target is a massive sulphide body mainly composed of pyrite and pyrrhotite bearing traces of Cu, Zn and Pb. Electromagnetic measurements have been carried out in the exploration holes 101–105 towards the deeper parts of the ore body. The figure shows a vertical projection of the ore and an interpretation of the conductive alteration zone. The points where the holes are intersecting or passing through the mineralized zone are marked by dots in the figure.

In this example the simplified model for the calculations is used, i.e. calculations based upon (3.7). A horizontal projection of the ore body is given in Figure 11.

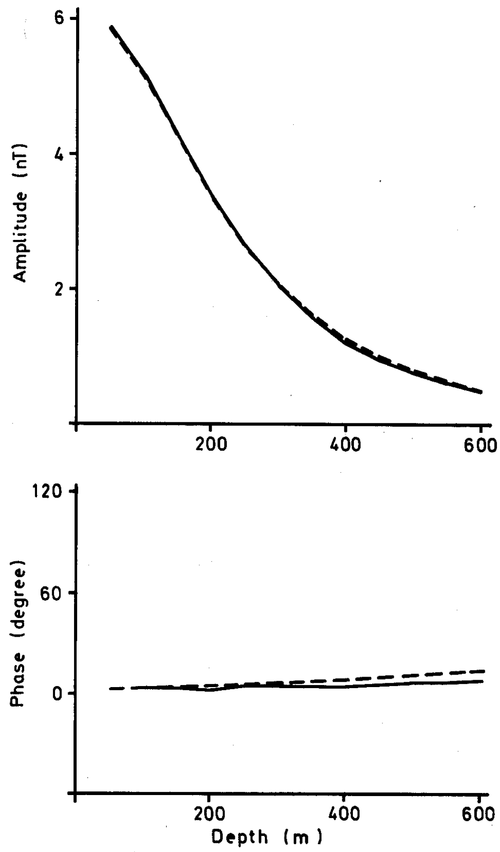

Figure 4: Finnsjön Bh 6. A comparison between the theoretical model and the measured data of the x-component at the frequency 2 000 Hz. The solid line represents the measured data and the broken line the theoretical model.

The boreholes intersect the alteration zone at the depth of about 350 m. The vectors shown in the figure are representing a horizontal projection of the residual field. The residual field is the difference between the total field and the field in the ground without the alteration. It is obvious that the boreholes 101, 102 and 104 are intersecting a good conductor, while Bh 103 passes to the right of the conductive body. From the residuals in Bh 103 it is also possible to see that the conductor consists of two parallel structures.

Borehole 105 intersects the alteration zone at the depth of 500 m. In Figure 12 the horizontal projections of the residual vectors show that the borehole passes to the right of the conductor. Here again, two parallel structures show up very clearly in the diagram of the residual vectors.

In Figure 13, the residuals of Bh 103 are measured in the x, y and z system of the probe, as described in Section 2. In this coordinate system the x-component is directed along the direction of the borehole and the y-component is horizontal, see Figure 2. The residual of the y-component is antisymmetric and zero at the point where the residual of the x-component has its maximum. The amplitude of the residual of the z-component is very small. This implies that the edge of the

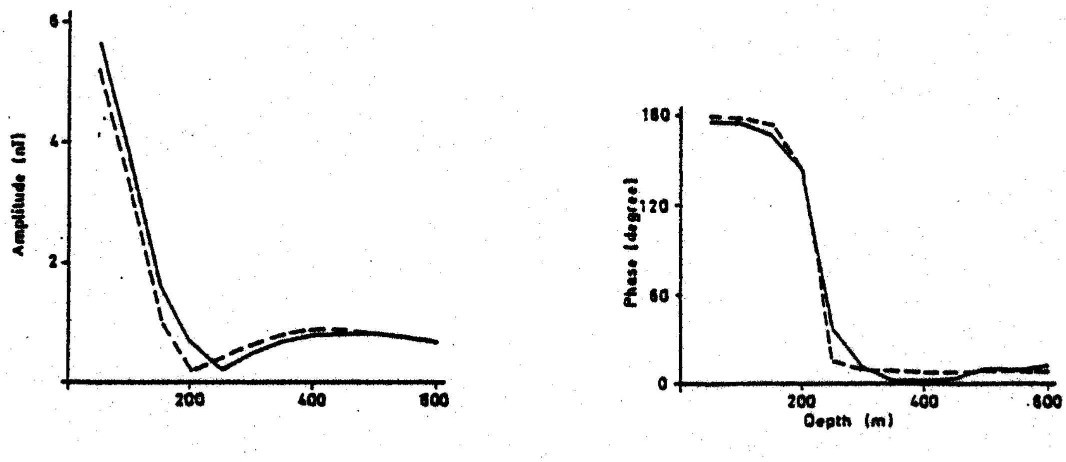

Figure 5: Finnsjön Bh 5. A comparison between the theoretical model and the measured data of the x-component at the frequency 2 000 Hz. The solid line represents the measured data and the broken line the theoretical model.

conductor is almost parallel to the z direction in the borehole system.

By comparing the residuals of the y- and z-components in Bh 105 it is seen that their peak to peak values are of the same size, see Figure 14. This means that the edge of the conductor is dipping about 45° in the borehole system. From the positions of the peaks of the three field components, it is possible to locate the conductor. The conductor is situated to the left of the hole and it is dipping about 45° down to the left. The half width of the x-component or half of the distance between the positive and negative peaks of the y- and z-component gives a rough estimate of the distance of approximately 30 m.

The results discussed so far are measured at the frequency of 200 Hz. Since the Kankberg ore body is surrounded by pyrite dissemination it is instructive to show the differences between the two frequencies 200 and 2000 Hz and how these frequencies can provide information about the conductivity of the targets.

Figure 15 shows the corresponding residuals at 2000 Hz from Bh 105. In this case it is found that the borehole intersects the conductor about 40 m from its right edge. The 200 Hz residuals show that the hole passes about 30 m to the right of the conductor, see Figure 12. Combining the results from the two frequencies it can be concluded that the borehole intersects the outer parts of a pyrite dissemination and that there is a much better conductor at approximately 30 m to the left. This conductor is almost perpendicular to the borehole and it is plunging about 45°, see Figure 16.

In the example, shown in Figure 17, measurements from boreholes made under the known deposit of Långsele are shown. Electromagnetic measurements were carried out in five boreholes drilled from the 610 m level in the Långsele mine. The holes were drilled in order to investigate deeper parts of the ore body about 70 m below the deepest level of earlier investigations. None of the boreholes struck any ore. However, the results of the electromagnetic measurements gave a very

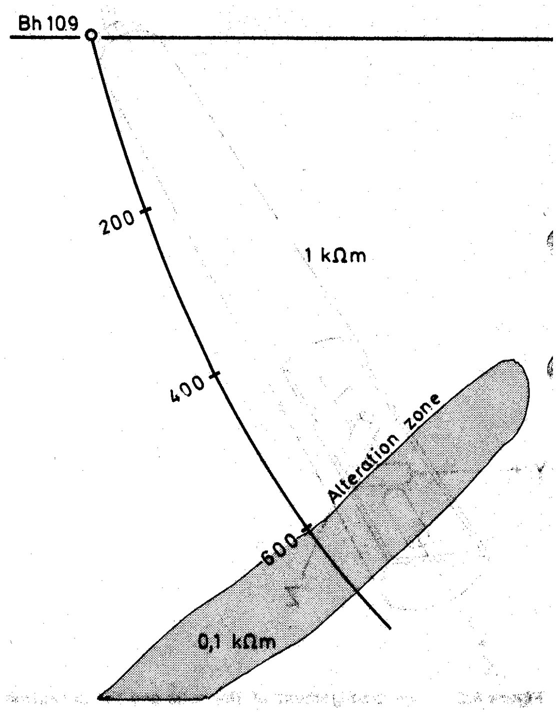

Figure 6: Kankberg Bh 109. Vertical projection.

unexpected pattern of residual vectors as shown in Figure 17. The source of this residual field was interpreted to lay behind the boreholes. To check the anomaly Bh 733 was drilled. It showed that there was about 20 m of massive pyrite.

The final example shows measurements made from Petikäs. Three boreholes, Bh 19, 23 and 27, are shown in Figure 18 together with the estimated form of the deposit. The measurements are made at the frequency 223 Hz. The figure shows the residual magnetic field in the boreholes. The ore body starts at 300 m below the ground level and continues downwards. Three additional boreholes, not shown here, also support this interpretation. Borehole 19 intersects the ore body 430 m below the ground, while the other two boreholes, Bh 23 and 27, pass the body 350 m and 480 m below the ground, respectively. Bh 23 passes close to the west of the deposit while Bh 27 passes approximately 30 m to the east of the deposit. The measurements at Petikäs presented here were made as the boreholes were drilled. The location of any new borehole was determined by previously estimated positions of the anomaly. In this respect the measurements acted as a guide to the entire drilling programme.

Over the last six years of operation the system has been very useful in many situations. The possibility to determine the direction to and the attitude of conductive targets are of great importance for the geological interpretation and the economical evaluation of an exploration project. It also improves the cost effectiveness of drilling in exploration work.

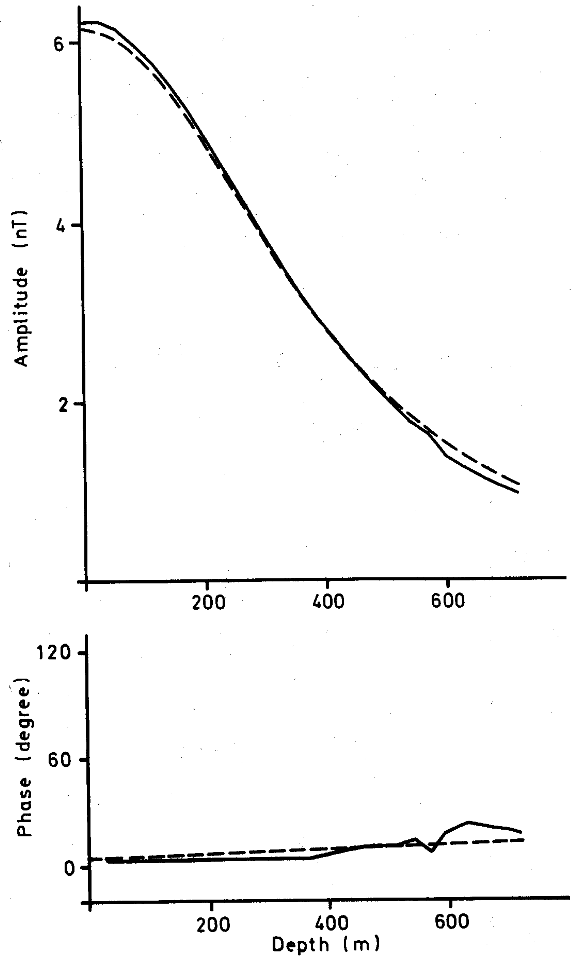

Figure 7: Kankberg Bh 109. A comparison between the theoretical model and the measured data of the x-component at the frequency 200 Hz. The solid line represents the measured data and the broken line the theoretical model.

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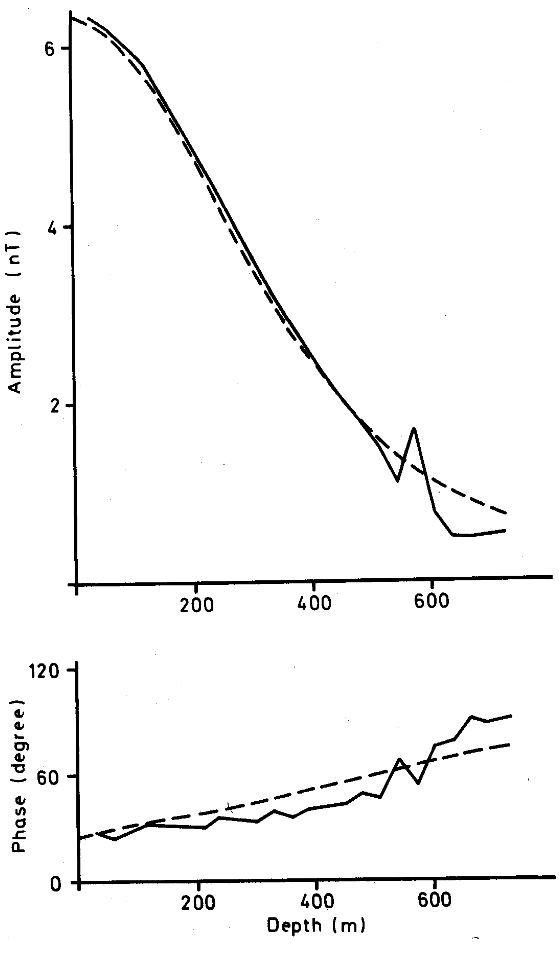

Figure 8: Kankberg Bh 109. A comparison between the theoretical model and the measured data of the x-component at the frequency 2 000 Hz. The solid line represents the measured data and the broken line the theoretical model.

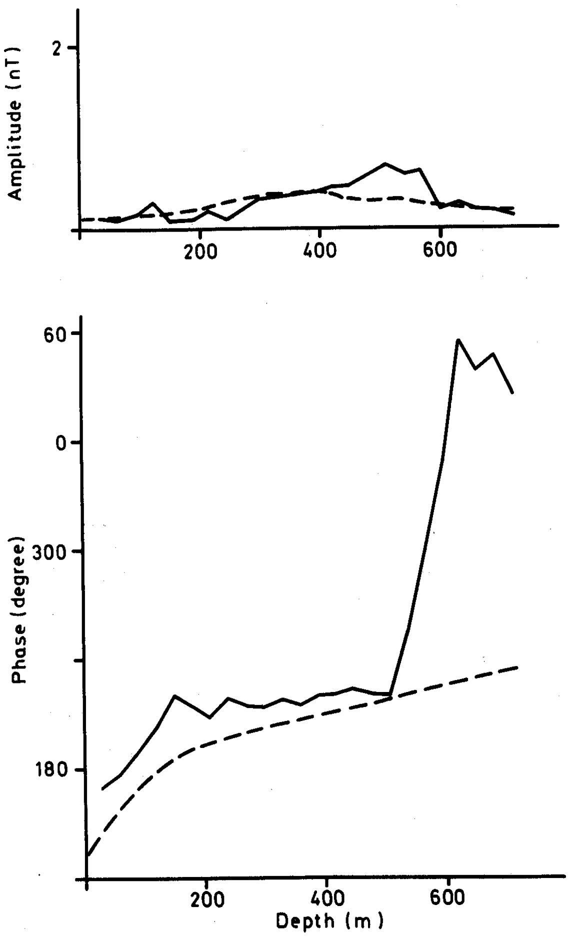

Figure 9: Kankberg Bh 109. A comparison between the theoretical model and the measured data of the y-component at the frequency 2 000 Hz. The solid line represents the measured data and the broken line the theoretical model.

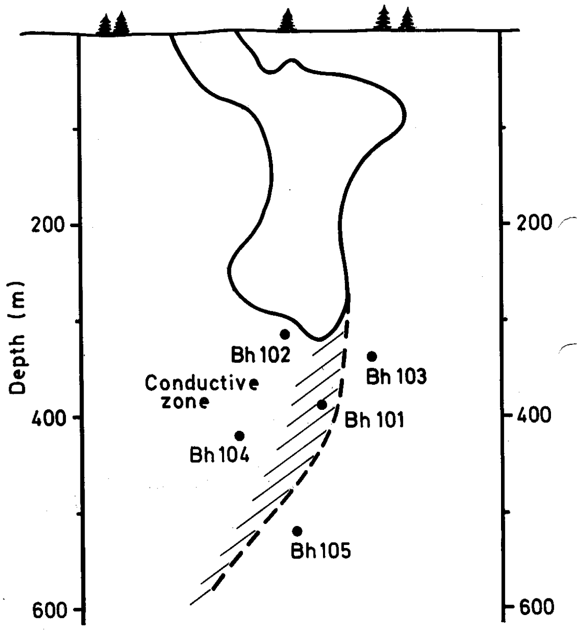

Figure 10: Vertical projection of the Kankberg ore body and an interpretation of the conductive alteration zone. The points where the boreholes are intersecting the mineralized zone are marked by dots.

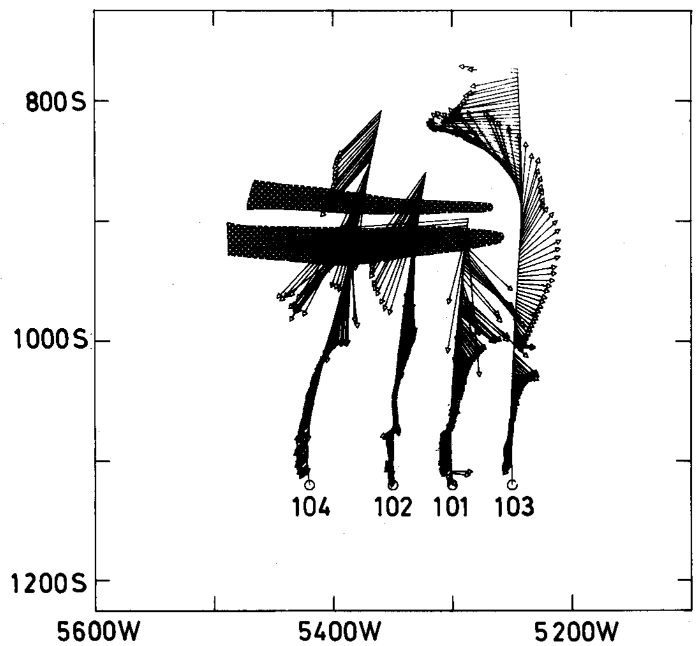

Figure 11: Horizontal projection of the Kankberg ore body at about 350 m level. The vectors are representing the in-phase residuals at the frequency 200 Hz. The interpreted good conductors are shaded.

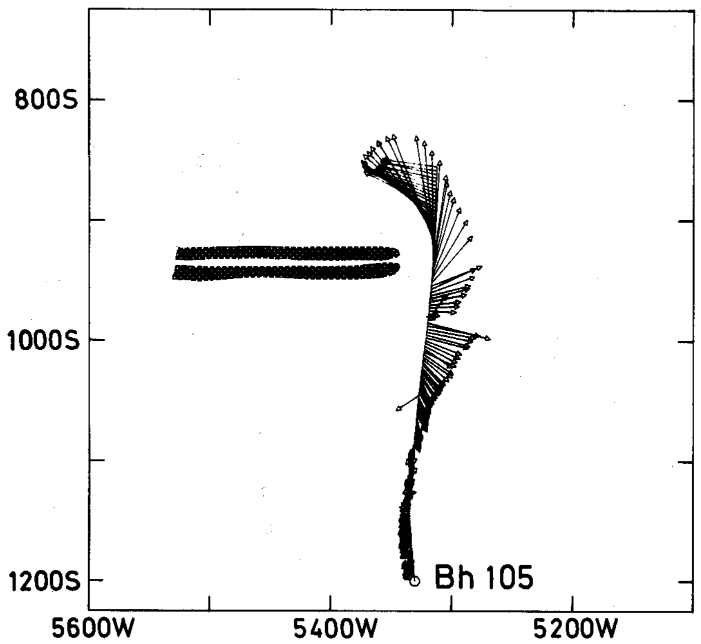

Figure 12: Horizontal projection of the in phase residuals at 200 Hz in Kankberg Bh 105. The residuals are represented by vectors. The interpreted good conductors are shaded.

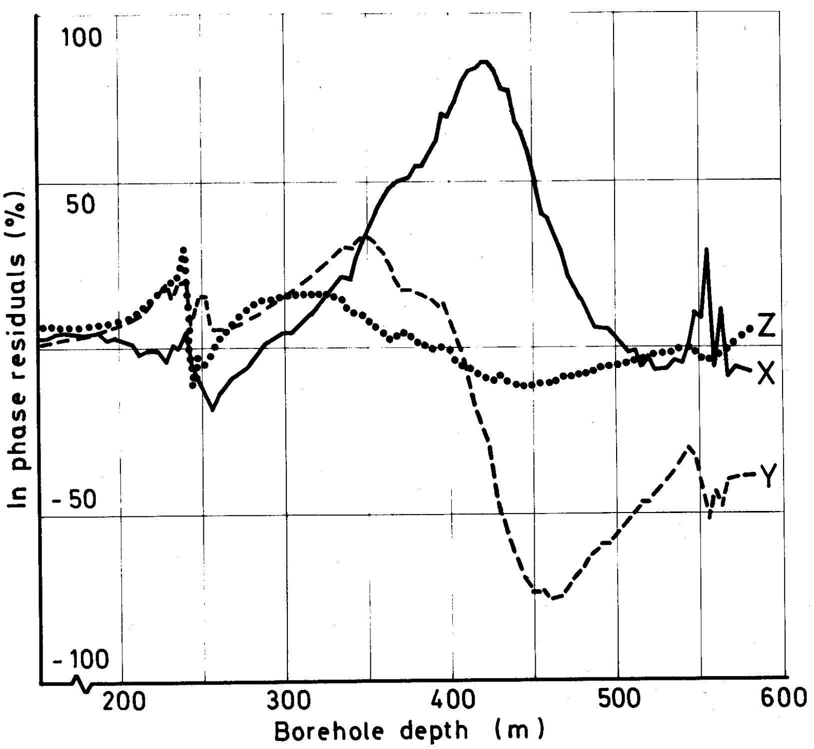

Figure 13: Kankberg Bh 103. In-phase residuals for the x-, y- and z-component at the frequency 200 Hz.

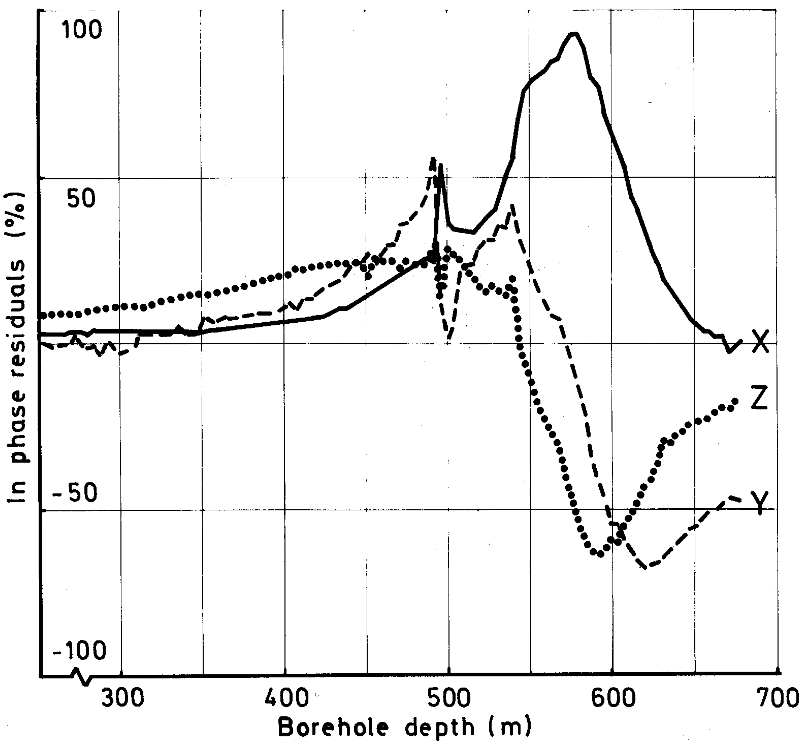

Figure 14: Kankberg Bh 105. In phase residuals for the x-, y- and z-component at the frequency 200 Hz.

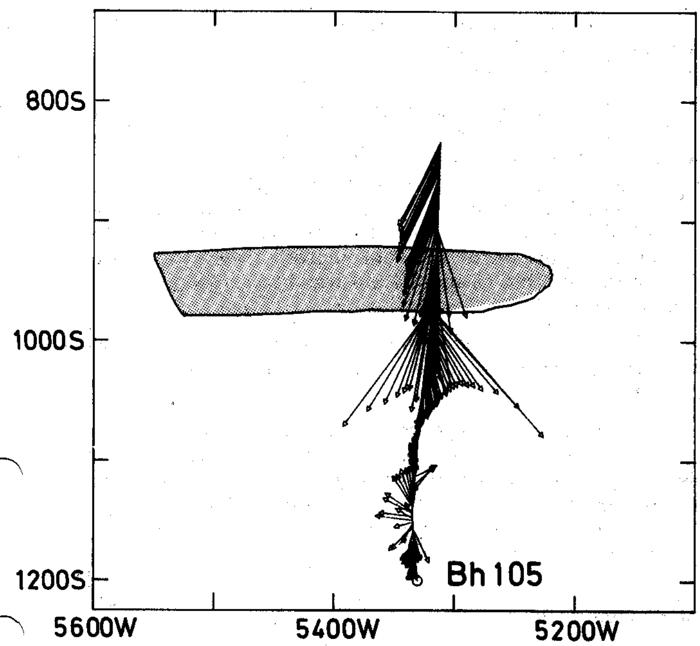

Figure 15: Horizontal projection of the in phase residuals at 2 000 Hz in Kankberg Bh 105. The residuals are represented by vectors. The interpreted alteration zone is shaded.

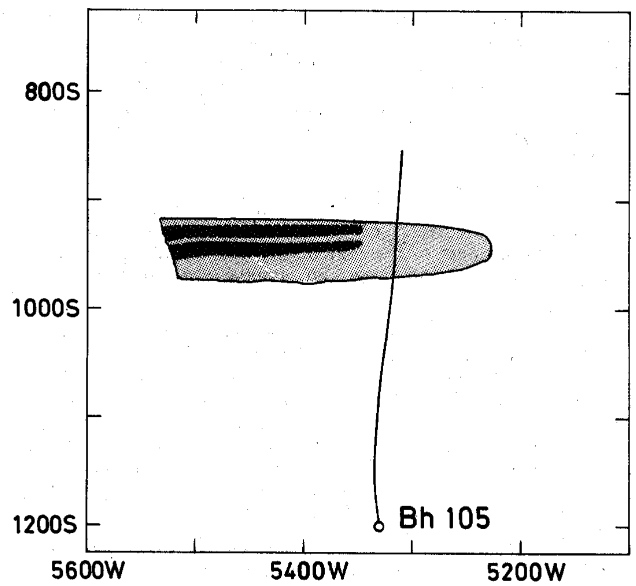

Figure 16: Horizontal projection of the interpreted situation around Kankberg Bh 105. The alteration zone is shaded and the structures of high conductivity are black.

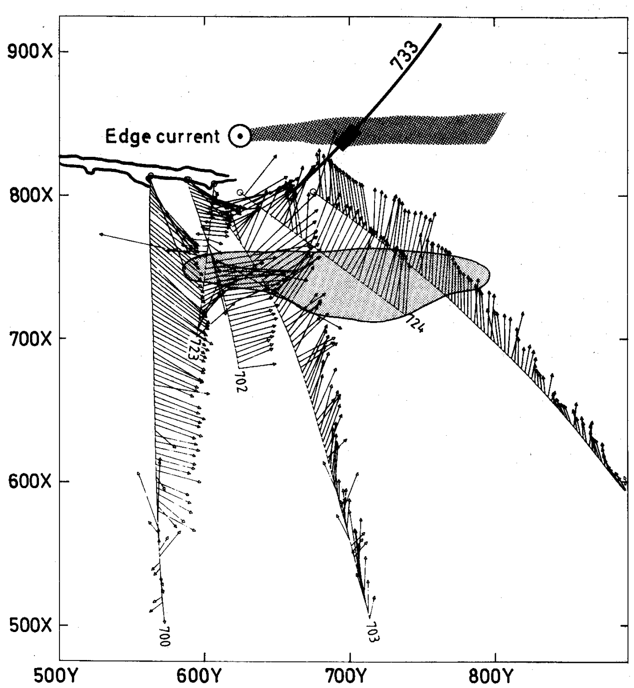

Figure 17: Horizontal projection of the 610 m level in the Långsele mine. The vectors are representing in-phase residuals at the frequency 2 000 Hz. The lowest level of the ore body, coloured grey, is situated about 70 m above the measured boreholes. The interpreted conductive target is coloured black.

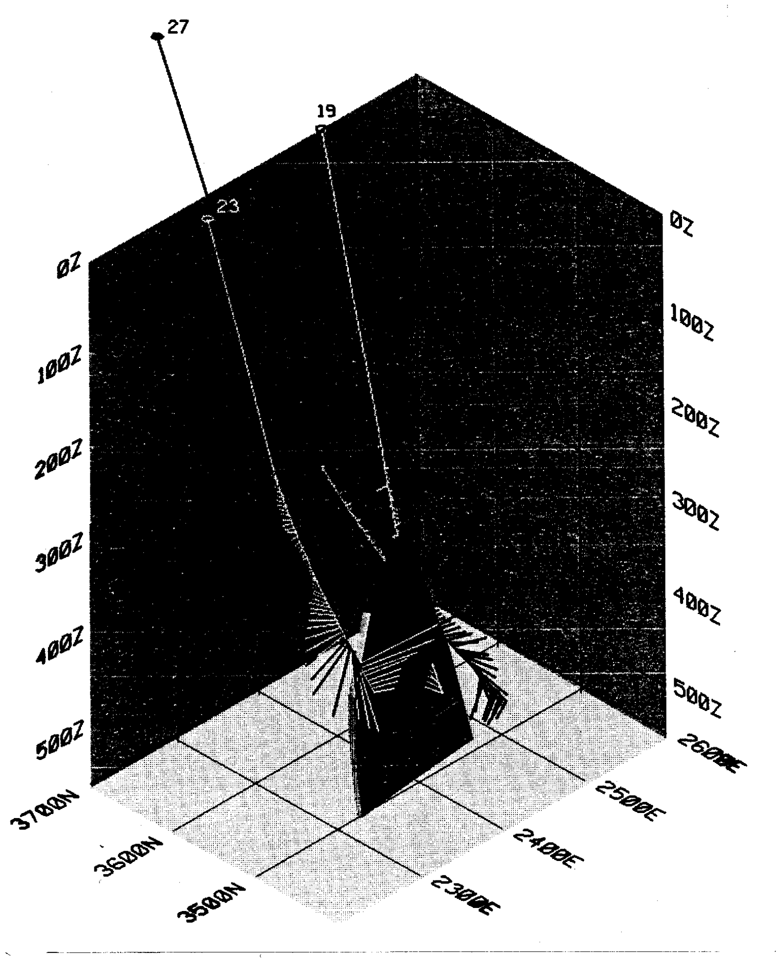

Figure 18: Petiknäs Bh 19, 23 and 27. Residual magnetic fields and the estimated position of the deposit.