Optimization of Ground Electroprospecting Survey Techniques for Mining Exploration

I. Ingerov, "AGCOS Inc.", Toronto, Canada & **E. Ermolin**, "National Mineral Resource University" (SPMI), St. Petersburg, Russia

Introduction

Recent advances in airborne EM geophysics, which confidently explores at the depth range of 0 – 400m, particularized the list of tasks facing ground electroprospecting surveys. These can be summarized in the following main objectives :

- Precise mapping of anomalies detected during airborne surveys and optimization of borehole coordinates;
- Prospecting and exploration of small objects (dikes, veins, sills, faults, etc.), which cannot be detected by airborne EM surveys;
- Exploration and characterization of deep ore bodies (depth to the upper limit of 300 – 400 m).

Based on these objectives, an optimal set of electroprospecting methods has been developed. It includes electroprospecting methods AMT/MVP (implemented 5-component measurements AMT (2E+3H) and one of the IP method modifications. These methods implement different physical characteristics of ore bodies from the host medium, taking into account parameters of apparent electrical resistivity (ρ) and induced polarization (Δφ, η) that register the presence of a two-phase environment polarized by the flow of an electric current.

Due to recent technological advancements in electronic component base, computer technologies and software, the AMT method (5-component) has become the main tool for finding subsurface objects that differ in apparent resistivity, mainly due to its:

- High portability (2 crew members can service 1 set of equipment with spacing between the sites more than 200 m or 2 sets spacing less than 200 m);
- High sensitivity;
- High productivity (8-25 sites per day for 1 crew);
- Large depth of investigations (2-3 km);
- Environmental compliance and the ability to carry out all-season field surveys on any terrain or soil conditions (due to the application of precision tripods for induction magnetic sensors);
- Long-range sensitivity (several kilometres) to the presence of conductive anomaly.
- When combined with AMT data (Ex, Ey, Hx, Hy), the MVP method (Hx, Hy, Hz) adds the following:
- Ability to distinguish small objects;
- Ability to determine the sensitivity (direction) of objects located far away from the observation profile;
- Ability for rapid anomaly assessment at the field camp (without carrying out inversion);
- Ability to determine the total longitudinal conductivity of an object (G),
- Ability to determine the shape of the body and its depth (H).

The total longitudinal conductivity cross-section of the body (G =σ × a1 × a2) mainly depends on the frequency (period) of tipper extreme and the real induction vector. The depth of the body is mainly determined by the distance (d) between the two tipper extremes. The ratio of vertical and horizontal dimensions of the anomalous body is determined by the shape of the tipper anomalies. The angle of inclination of the body is also uniquely determined by the form of the tipper anomaly.

Development of a New Technique: Some History

In the early 1950s, three induction EM methods were being intensively developed in former USSR counties:

- MT (Berdichevsky, Dmitriev)
- LowTEM (Vanyan)
- FDEM (control-source) (Vanyan , Enenshtein, Svetov, Molochnov).

The MVP method is related to the publications of Weise, Parkinson, Shmukker, Vozoff, and Rokityansky dating back to the 1960s and 1970s.

First experiments using the MVP (Magnetovariational Profiling) method took place in the 19th century. Significant strides were made in the 1960s and 1970s, with the theoretical basis being further developed for low frequencies, and the development of low-frequency field equipment. Regional and deep crustal studies were undertaken, with several large conductive anomalies discovered in Central and Eastern Europe (including the Carpathian & Kirovogradskaya anomalies). The response functions (3H measurements), such as tipper and induction vectors (real and imaginary), were defined, and simple techniques were developed for total conductivity (G) estimation of the anomalous body section for 2D conductive anomalies).

The two conventions for induction vector (real part) representation are:

- Weise-Schmucker
- Parkinson

$$H_z = \vec{W}\vec{H}_\tau(f) = W_{zx}H_x + W_{zy}H_y$$

$$W = [W_{zx}\ W_{zy}]$$

$$\vec{w}^2 = W_{zx}^2 + W_{zy}^2,\quad |\vec{w}|^2 = |W_{zx}|^2 + |W_{zy}|^2$$

$$\mathrm{Re}\vec{W} = \mathrm{Re}W_{zx}\vec{1}_x + \mathrm{Re}W_{zy}\vec{1}_y$$

$$\mathrm{Im}\vec{W} = \mathrm{Im}W_{zx}\vec{1}_x + \mathrm{Im}W_{zy}\vec{1}_y$$

$$\mathrm{Re}\vec{W} = -\mathrm{Re}W_{zy}\vec{1}_x,\ \mathrm{Im}\vec{W} = -\mathrm{Im}W_{zy}\vec{1}_y$$

$$\nu = \frac{|H_z|}{\sqrt{|H_x|^2 + |H_y|^2}}$$

In the 1960s–1980s, further theoretical, modelling and field investigation work was conducted and more convenient 3- and 5-channel field equipment was developed. Rokityansky (1975) showed that total conductivity of 2D conductive bodies can be estimated by frequency (period of the maxima of frequency characteristic).

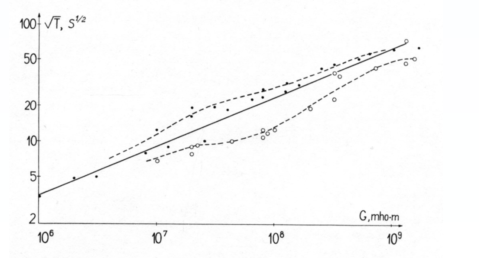


Figure 1. Period T_0 of maximal modulus of the anomalous field (or of phase sign change) as a function of longitudinal conductivity G of the anomaly

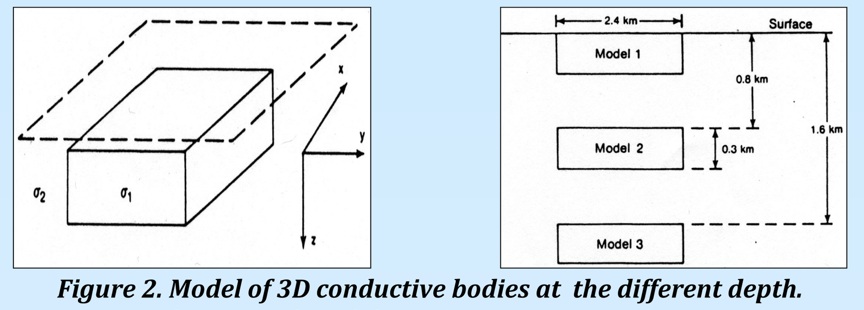


Figure 2. Model of 3D conductive bodies at the different depth. The general model: σ_1=5.0Sm^{-1},σ_2 = 0.005 Sm^{-1}

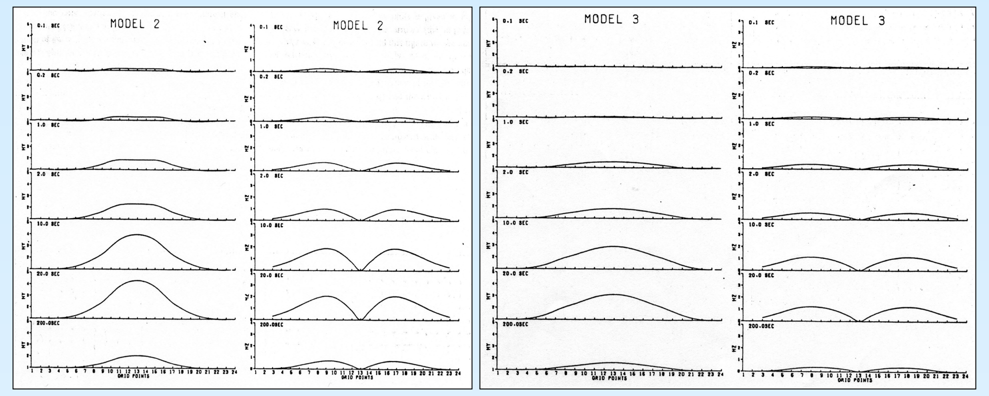


Figure 3. Tipper amplitude frequency response for model 2 and 3 (Figure 2)

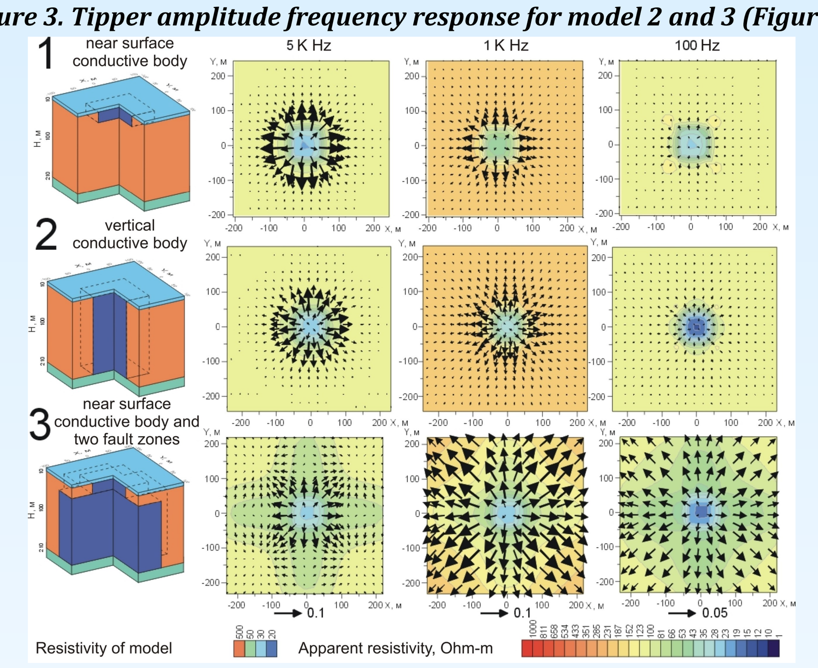


Figure 4. Three models with various different body conductivity, depth and configuration.

The results of modeling clearly show that MVP parameters are closely connected to the size, structure, depth and conductivity of the anomalous bodies, which means that MVP parameters can be used for exploration in the appropriate frequency band. However, for any exploration technique, we need to have:

- A source of the normal field;
- Understanding the physics of anomalous fields;
- Portable, wide dynamic and frequency band recording field equipment;
- Portable wide band magnetic sensors;
- Accessories for quick and precise magnetic sensor installation and orientation in three orthogonal direction;
- As well as quick deinstallation and comfortable transportation to the next observation site.
- The interpretation technique has to provide accurate and robust information about position and parameters of the anomalous body.

Energy Source (Magnetotellurics)

Nature gives us a perfect powerful source of energy in the form of a solar wind, which interacts with the magnetic field of the Earth to create an alternating electromagnetic (EM) field with a10 – 0.000001 Hz frequency band (Figure 5). In its turn, this field creates an electric currents in the ionosphere and in the earth (telluric currents). The distribution of telluric current in the ground depends on the conductivity structure of the Earth.

Figure 5. The Interaction of the solar wind and the magnetic field of the Earth

Energy of Long-Range Thunderstorms (Audiomagnetotellurics)

For the audio frequency band, tropical thunderstorms, which occur constantly on Earth, play the role of an energy source. They create EM energy, propagated between the ionosphere and the Earth's surface, inducting high frequency 20 000 – 8 Hz telluric currents in the earth (Figure 6). These currents perfectly highlight conductive anomalies by creating anomalous EM fields and especially, magnetic components of these fields.

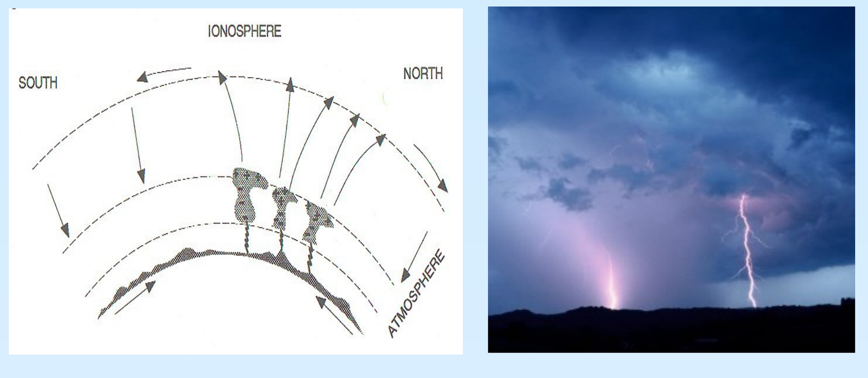
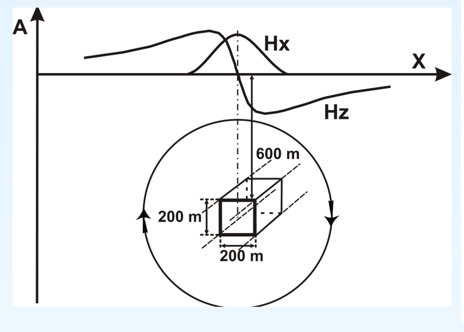


Figure 6. Propagation of EM energy thunderstorms between the Earth's surface and the ionosphere. Thunderstorms are the source of EM natural energy for audiomagnetotellurics

Physics of MVP Anomalies

Any electrical current flowing through a conductor creates an alternating magnetic field around the conductor. In 2D situations, this field will have two orthogonal components: vertical (Hz) and horizontal (Hx), which would be orthogonal to the conductive body strike (Figure 7). If Hx anomaly is very local, it will have only one positive sign and good location of the position of anomalous body. If the Hz anomaly is very wide, it will have two signs: negative and positive (which allow to sense an anomaly located far from its location). Hz changes its sign exactly above the epicenter of the conductive anomaly, which allows to precisely mark the position of the epicenter. Hz also has two extremes (negative and positive) and the distance between these extremes provides the information about the depth of the anomalous body.



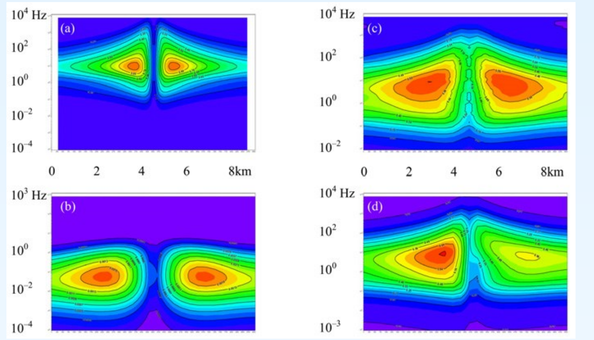


Figure 7 (left). The anomalous Hz and Hx above 2-D conductive ore body
Figure 8 (right). Tipper amplitude pseudo-section for: a)-isometric body, b)- horizontal body, c)- vertical long body, d)- inclined long body

A tipper amplitude pseudo-section carries lot of useful information (Figure8). It allows one to estimate the form of the section of anomalous body as well as to calculate the depth and conductivity of the section.

Field Work

A standard field procedure at the site includes moving a set of equipment to the location of the site, installing the equipment (from transportation to working position), laying out sensors according to Figure 9, and turning on the recording unit with an automatic synchronization to GPS.

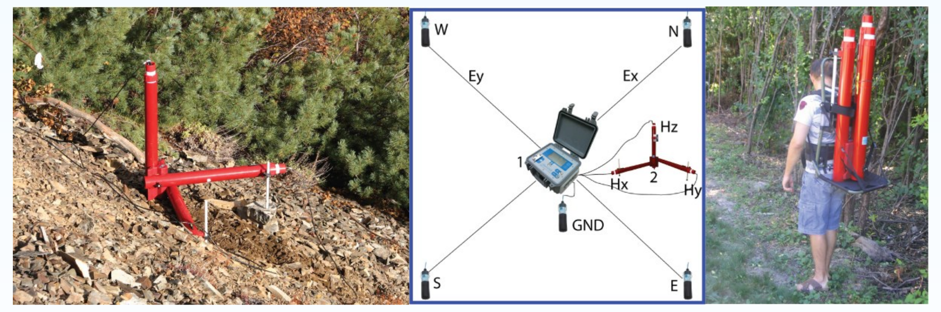


Figure 9. Induction magnetic sensors in a tripod during recording, layout of AMT/MVP equipment at the observation site, induction magnetic sensors prepared for transportation in a transportation frame

During 5-component AMT/MVP measurements, the profile grid can be sparse since induction vectors will show the exact direction to the possible target, which can be detailed later.

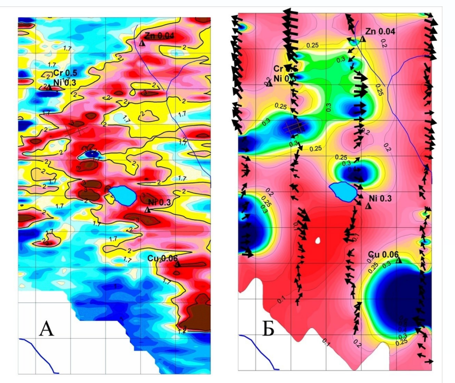


Figure 10. The results of the AMT/MVP and IP surveys in the South Kovdor area (Cola Peninsula, Russia, "Nord-West" Ltd.). A map of chargeability (η_κ), IP data - (A), a map of total conductivity (S) (AMT/MVP data - (Б). Induction vectors are in Wiese convention

Two anomalies of η_κ, 2-3% (normal phone is 1.5 %) connected to a sulphide ore. Several contrast anomalies of conductivity are marked on the left map by AMT-MVP data.

Recording Equipment

Any 24-bit 5-channel (or more) recording equipment with a frequency band of 10,000 – 10 Hz can be used as a field recording unit. Standard AMT/MT software can be used to control the recording and later for data processing. An example of a recording instrument is shown below in Figure 11.

Figure 11. A typical recording instruments for AMT/MVP – A) 4-channel EM receiver; B)8 -channel EM receiver. Both are equipped with IP data acquisition function.

Magnetic Sensors

Highly-sensitive wide-band magnetic coils could be used for AMT-MVP field survey. Figure 12 shows an example of suitable magnetic sensors:

Figure 12. Highly-sensitive wide-band magnetic coils sensors. AMS-15 has frequency band 50 000 – 0.1Hz, AMS-37 - 1000 – 0.0001 Hz.

Precision Tripods

These high precision mechanical instruments have revolutionized AMT/MVP field surveys at the beginning of this century, significantly increasing field productivity, accuracy, and the ability to carry out all-season field surveys on any terrain and in any climate. Other important features of these tripods are the temperature stability of the sensors, the safety of the connector, and the safety and convenience of the induction sensor transportation. Widely used in the industry, several tripod models are shown in Figure 13.

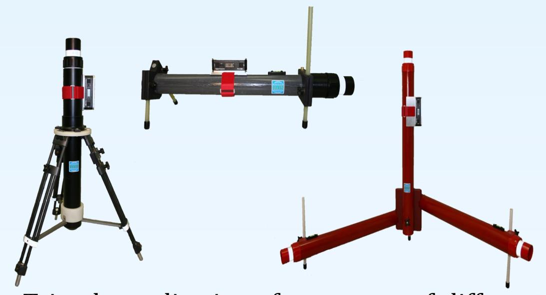


Figure 13. Main types of precision tripods for induction magnetic installation. Left – one axis vertical, middle – one axis horizontal; right – most popular 3-axis collapsible.

Tripods applications for surveys of different scales and in different environments are shown in Figure 14.

Figure 14. Field application of precision tripods

Robust Interpretation Technique

Data processing, editing and analysis can be done at the field camp on the same day field data acquisition is completed. Hence, the main advantage of the MVP method is the ability to quickly determine a conductive' body position and to estimate its main parameters.

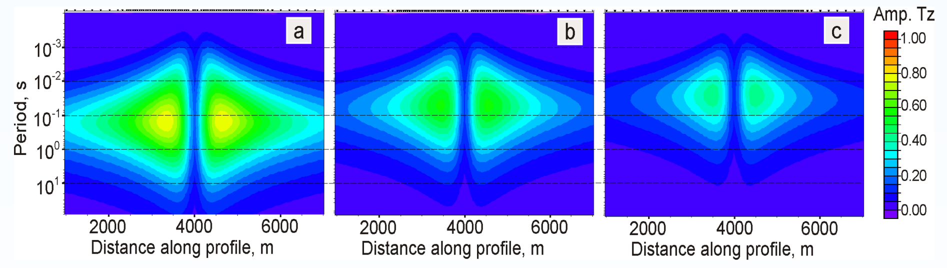
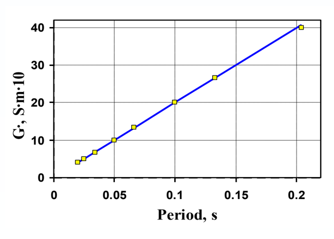


Figure 15. Reflection in tipper amplitude pseudo-section conductive bodies with different total conductivity of the section (G): a) high conductivity; b) middle conductivity; c)-low conductivity

Figure 15 shows the trend: the bigger the G, the correspondingly bigger the Tmax (1/f)max. Figure 16 shows the quantitative relation between G and T max (1/f)max



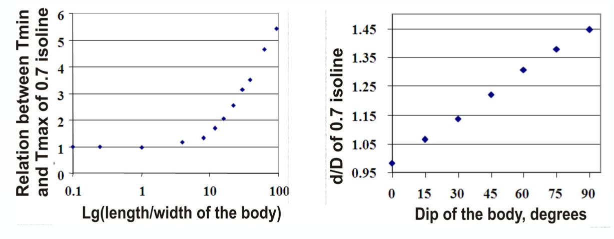


Figure 16. The graph of dependence of the frequency (period) of tipper maxima on the total conductivity of the body's section G.

Figure 17. Estimation of the relation of length/height and inclination of anomalous body

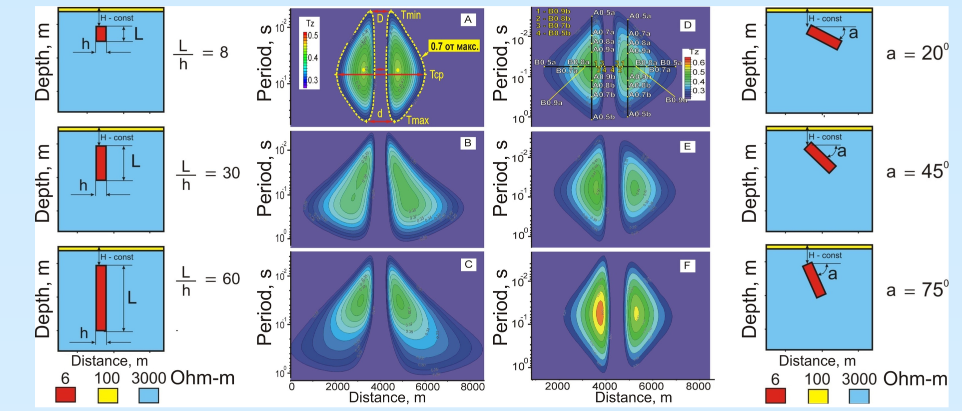
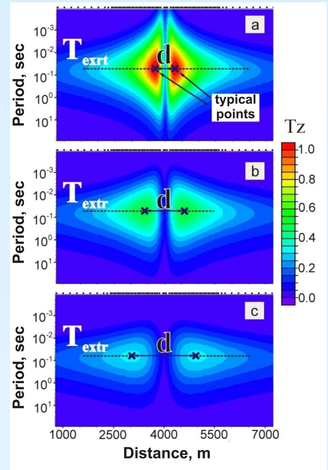


Figure 18. The models of conductive bodies and correspondent tipper pseudo-section

The graph in Figure 17 demonstrates the estimation of the form of the body and its inclination using forms of double anomalies at tipper pseudo-sections. All three graphs shown in Figure 19 demonstrate the estimation of the depth of the conductive body using the distance along the profile between two extremes.



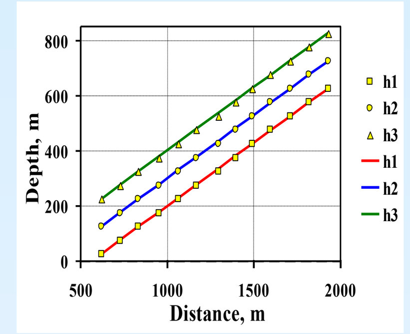
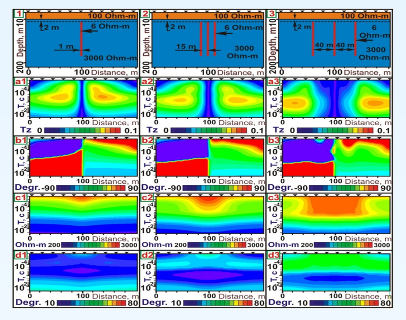


Figure 19. The dependence of the position and form of the tipper amplitude anomaly using the depth of the anomalous body

Thin objects, such as dikes, veins and small faults, represent very special situations. Figures 20 and 21 show how they could be detected using the tipper and resistivity data.



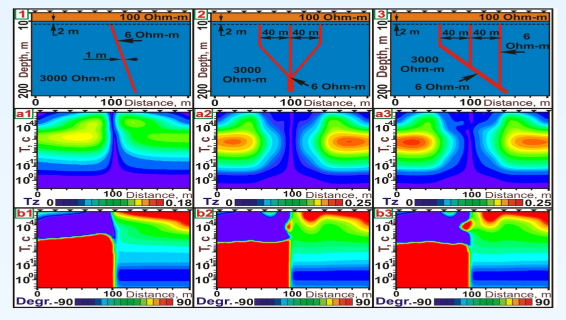


Figure 20. Vertical dikes with different distances between them

Figure 21. Inclined dike and dikes having a common route

Application Examples

Since the beginning of this century, different countries around the world have accumulated positive experience in mining exploration and geological mapping using a combination of AMT (MVP) + IP technologies.

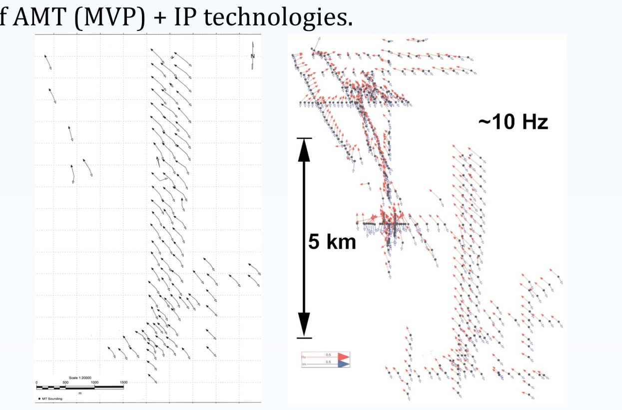
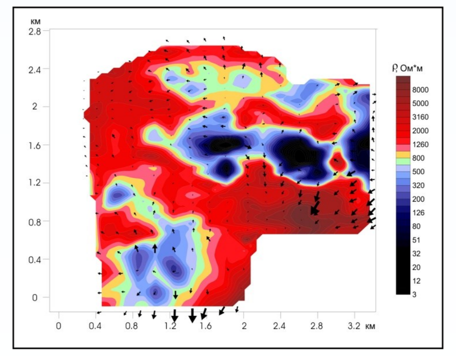


Figure 22. An induction vector allowed the identification and further exploration of a conductive body situated outside the original field survey grid



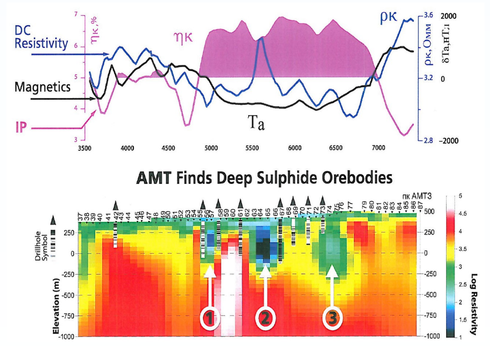


Figure 23. (left) Polymetallic ore exploration by AMT method located southeast from Baikal Lake (East Siberia, Russia, 2008)
Figure 24. (right) Strategic deposit discovery at Chukotka (Russia)

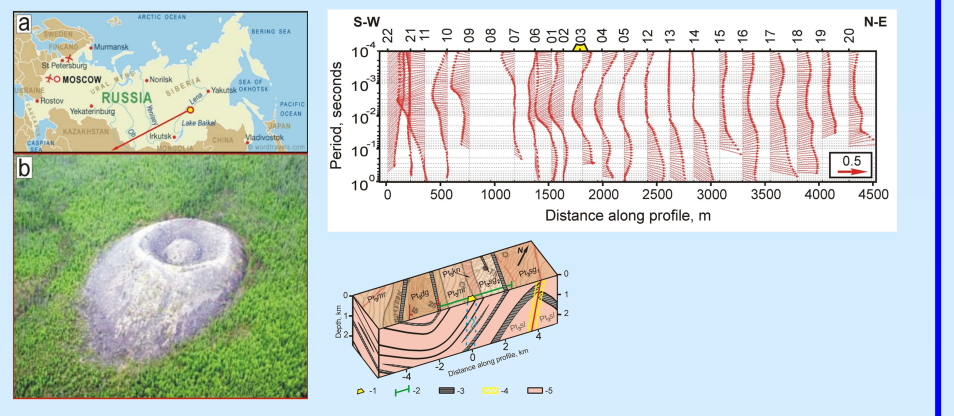


Figure 25. Investigation of the Patomsky crater nature in the middle of East Siberia (Russia)

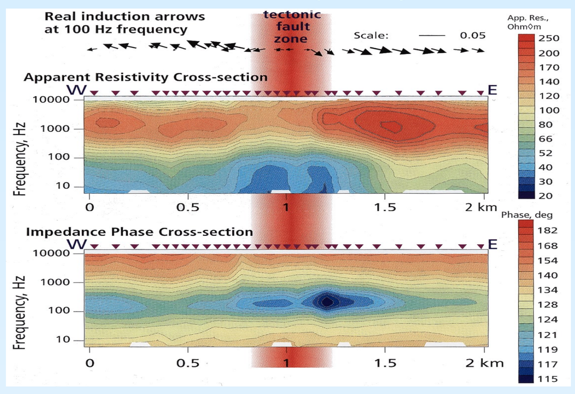


Figure 26. Location of prospective faults by ALROSA company at East Siberia (Russia)

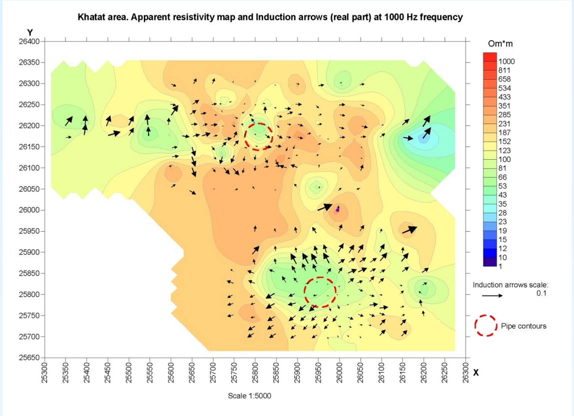


Figure 27. Diamond Exploration by ALROSA at East Siberia (Russia). Two small kimberlitic pipes at the Hatat polygon.

Conclusion

At the present time, the high frequency variant of MVP (AMT frequency band) technology has been developed and extensively tested during various field surveys. Besides the ability to resolve a wide range of exploration tasks and scope of investigations, from mapping of thin dikes and veins overlaid by sediments near the surface to deep ore bodies at depths of 1-3 km, unique distinct features of this technique are:

- Ability to sense ore bodies and to determine their direction far away from the exploration profile (several depths). Such capability allows a substantial decrease in the amount of necessary data acquisition sites via a determination of potentially perspective regions using a sparse network of exploration profiles (sites);
- Environmentally friendly, portable and compact field instrument installation;
- Quick installation and removal, as well as ease of transportation by foot by just two field crew members;
- High sensitivity and accuracy;
- High productivity with application of high precision tripods for induction magnetic sensor installation;
- Ability to carry out field surveys year around.

It is highly recommended to carry out 5-componnent field surveys for mining exploration tasks using the AMT/MVP method.

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