Introduction

The 5-component soundings (E_x, E_y, H_x, H_y, H_z) based on measurements of the natural variable electromagnetic (EM) field of the Earth combine two methods:

- Magnetotelluric soundings (MT), which are based on the study of four horizontal components of the EM field: two horizontal electrical components (E_x, E_y) and two horizontal magnetic components (H_x, H_y) (Berdichevsky and Dmitriev 2009, Chave and Jones 2012). Depending on the depth of the investigations and the frequency range, distinguished are audiomagnetotelluric soundings (10,000 - 1 Hz, AMT), magnetotelluric soundings (300 - 0.001 Hz, MT), long period magnetotelluric soundings (1 - 0.00001 Hz, LMT) and broadband magnetotelluric soundings (10,000 - 0.00001 Hz, BMT). Remote Reference Magnetotellurics (Gamble et al. 1979) technology allows to significantly suppress industrial and wind noise, as well as to calculate additional response functions (telluric (T) and magnetic (M) tensors).
- Magnetovariational Profiling (MVP), based on the study of three orthogonal magnetic components (two horizontal, H_x, H_y and one vertical, H_z) of the natural alternating EM field of the Earth (Rokityansky 1981).

Of fundamental importance is the fact that Magnetotelluric methods map well structures with sub-horizontal layers, whereas Magnetovariational Profiling methods do not respond at all to a horizontally layered medium. At the same time, Magnetovariational Profiling methods are very sensitive to horizontal inhomogeneity's of the medium. Thus, the combination of Magnetotelluric and Magnetovariational Profiling methods realized in 5-component measurements of the natural EM field of the Earth allows to investigate in detail complex geological cross-sections. Geological tasks that could be successfully resolved by MT - MVP complex of methods at different stages of the geological exploration are further discussed in this paper.

Regional magnetotelluric investigations

Historically, the first investigations of the Earth's deep crust were carried out by the MVP method. Using this method, scientists from Hungary, Romania, Czech Republic, Slovakia, Russia and Ukraine have identified the Carpathian anomaly of electrical conductivity. In the 1970s, separate studies were conducted in different regions of the former USSR with CES-1 equipment (frequency range 10-3,600 sec). In the beginning of 1980s, the CES-2 equipment was developed with an extended frequency range (0.1-3,600 sec). Russia has continued regional MT surveys on geotraverses, particularly actively in the current century. Since 2002, CES-2 equipment has been replaced by MTU equipment with a wider frequency range and portability. International projects such as EUROPROBE, LITHOPROBE, EMSLAB and others provided rich information on the structure of the Earth's crust and upper mantle in terms of the nature of the deep distribution of electrical properties. The regional MT surveys were also conducted by the St. Petersburg Mining University at the Kola superdeep borehole area.

Mining prospecting MT field surveys

The 5-component MT can sense objects located not only under the observation profiles, but also the ones located away from them (Ermolin et al. 2014). In this case, the orientation of real induction vectors can show direction to the prospective objects. The results of 3-D modeling show that deep 3-D body (located at more than 600m depth) could be detected by MT even if it is situated away from the MT survey profiles (Figure 1). Expected position of anomaly could be estimated by the real induction vector direction as well as the tipper amplitude map (two maxima positive anomaly) and impedance phase map (positive anomaly). The conclusion from the analysis of modeling results could be that it is practical to carry out AMT-MVP prospecting with random grid (0.5 - 2km) of 5-component AMT profiles with relatively dense spacing between sites along profile (0.1 – 0.5km).

The classical example of prospecting and exploration survey is the AMT-MT survey conducted in the northern Quebec in 2002-2004 (Figure 2). Customer has singled out three North-South observation profiles at the most promising area from his point of view at the southwest part of the survey area.

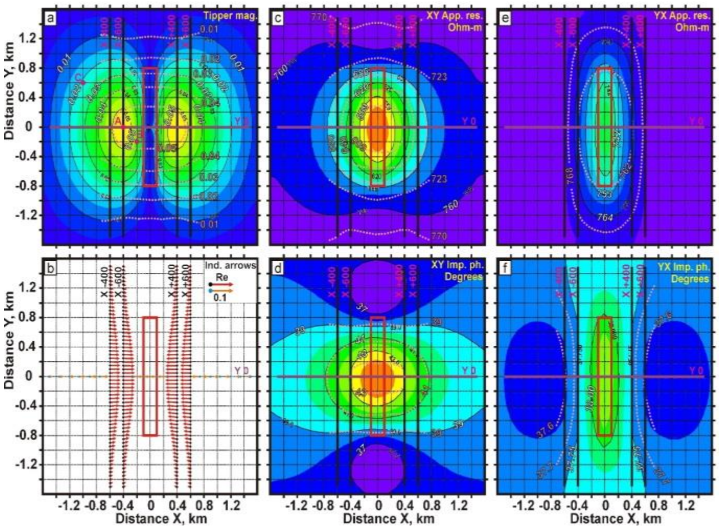

Figure 1 *Results of 3-D MT modeling of deep conductive body; a - tipper amplitude, c – meridian apparent resistivity, e – longitudinal apparent resistivity, b – real induction vectors, d – meridian impedance phase, f – longitudinal impedance phase.*

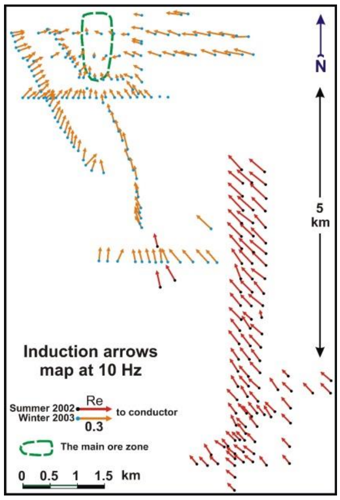

Figure 2 *The induction vectors at 10Hz at Northern Quebec, Canada.*

All three profiles were located overland (around the lake or swamps), although the relief was quite challenging and the movement from one measurement site to the next required significant amount of time, despite the low weight of equipment. At the initial stages of the survey, there were no significant anomalies with reduced resistivity detected. However, the real induction vectors at frequency 10 Hz pointed to the presence of a strong conductive object located to the northwest of the initial survey area. Due to the conditions of the terrain at the newly discovered area of interest it was not possible to conduct additional investigations during the summer. In the following winter, the 3-component MVP measurements (with 20 minutes recording time at each site) with just the induction sensors for measurement of three orthogonal magnetic components of EM field were carried out and massive conductive polymetallic sulphide deposit was contoured in the North-West part of the survey area (Figure 2). Estimation of the Nickel-Copper ore body properties was done by two latitudinal 5-component AMT profiles.

Thus, at this stage, the 5-component MT-AMT (MT) is the main exploration method. The existence of AMT data (frequency range 10,000 – 1Hz), in principle, eliminates the need for follow-up measurements with any other EM method to control the S-effect. It is advisable to construct survey grid with a series of parallel profiles located across the strike of geological structures. The spacing between AMT-MT-MVP measurement sites along the profiles is commonly between 100-500m depending on the depth, size and contrast of the investigated objects, whereas the distance between the profiles is normally 500-2,000m. It is reasonable at each 5^{th} - 10^{th} site to have a wide frequency band data (10,000 – 0.001Hz) to control base structure and crust conductivity.

MT-AMT exploration surveys

Their implementation is appropriate for the anomalies or prospective areas identified in the previous stages of exploration. The main frequency range is 10,000 - 1 Hz, with auxiliary (every 5^{th} - 10^{th} measurement site) being 10,000 - 0.001 Hz. All observations are made with 5-component EM field measurements. The step between measurements sites along the profiles, depending on the size of the investigated objects, is 20-100m, the distance between the profiles is 200-500m. It is important to note that with 5-component AMT not only polymetal sulphide deposit exploration but also much more complex geological exploration tasks could be solved. Figure 3 shows the results kimberlitic pipe exploration in the Arkhangelsk region in Russian North-West. In this case, it was located by the 5-component AMT and was further confirmed by drilling. However, as can be seen from Figure 3, the applied survey grid density is noticeably redundant, and reduction of the number of measurement sites by at least a half, would have still ensured the detection of this object.

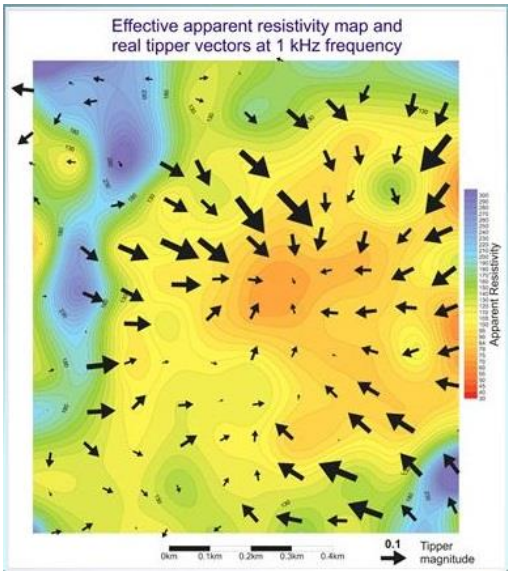

Figure 3 *The map of induction vectors which lead to discovery of kimberlitic pipe in Arkhangelsk Region, Russia.*

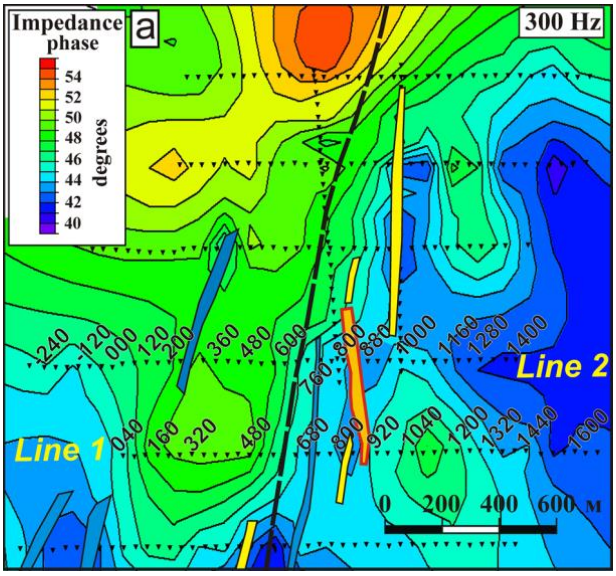

Figure 4 *The map of invariant impedance phase at 300Hz and position of newly discovered gold bearing veins (according to Ermolin 2016).*

Another example of exploration survey for an object which is difficult to map by geophysical methods is the 5-component AMT measurements with 40m spacing along a series of sub-latitudinal profiles which were conducted during additional exploration of the flanks of a large gold deposit in Chukotka, Russia. As a result, gold-bearing dikes displaced in tectonic disturbances in the north and south of the area were located. Dykes and the surrounding hydrothermally altered rocks best manifest themselves as zones of increased resistivity. Quite accurately, the zones of gold bearing dikes exit to sufficiently powerful low-resistivity strata overburden (50-100m, resistivity - 50 Ohm) with a sharp change in the tipper sign on pseudo-sections according to the data from the observation profiles (Ermolin et al. 2016). These alteration zones are also very clearly observed at the map of the invariant phase (Figure 4) as an area of lower phase values.

Field equipment and data interpretation capabilities

At the present day, all three stages of exploration have been provided with serially produced equipment. For all three stages, 5 or more channel equipment (ADU-07, MTU-5 or GEPARD-8) completely satisfies all the technical requirements (Ingerov 2016). This equipment allows to record EM field with two types of sensors (AMT, MT), i.e. to cover very wide frequency range. Individual elements of the field measurement cycle can also be done with GDP-32, Stratagem, KMS-820 and other instruments.

The most optimal way to integrate geophysical methods is to use the 2-3 spacing FDEMS to detect anomalies caused by induced polarization and the parameters of surface inhomogeneity's. In certain cases, such surveys can be performed with the same recording instruments from the first three manufacturers (Ingerov 2016). The application of TDEM method for such tasks is clearly an obsolete idea for more than 30 years.

The software for calculating response functions of the medium, their analysis, 1-D, 2-D and 3-D modeling and interpretation is very well developed and has been extensively tested over the years during a number of scientific and exploration surveys in different parts of the world.

Conclusions

To date, the present state-of-the-art for the field instrumentation and post-processing software have provided MT-MVP with significant advantages compared to other electroprospecting methods for the geoelectrical section investigations in the 30 - 200,000m depth interval. It is also possible to clearly distinguish three MT-MVP technology application stages for the mineral exploration:

1. Exploration for new mining provinces – surveys with a scale of 1 : 5,000 000 and individual cross-reference profiles with 5-10km spacing between sites (frequency range 10,000 - 0.0001 Hz).
2. Mining prospecting MT field surveys at the areas:
   - Detected by the airborne methods;
   - Less than 100km^2 areas;
   - Deep investigations in the areas with operating mines (interval 200-2000m). The scale of the surveys is 1:200,000 - 1:50,000. It is preferable to perform observations with 0.5-1 km spacing between measurements sites along the profiles (frequency range 10,000 - 0.001 Hz).
3. Separate profiles with spacing 20-200m across the strike of the investigated structures. The main frequency range is 10,000 - 1 Hz, the additional frequency range is 10-20% of the total number of measurement sites (10,000 - 0.001 Hz).

A natural complementary exploration technology of the MT-MVP is the FDEMS-IP method which allows to map high-resistivity objects with high degree of accuracy and to detect induced polarization anomalies (Ingerov et al. 2016).

Acknowledgements

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