Particularities of 5-component magnetotelluric soundings application for mineral exploration

Igor Ingerov*
Advanced Geophysical Operations and Services Inc. (AGCOS)
162 Oakdale Road, Toronto, Ontario, M3N2S5, Canada
ingerov@agcos.ca

Evgenii Ermolin
National Mineral Resource University (NMRU)
21-ya lin. Vasilyevskogo ostrova, 2, Sankt-Peterburg, Russia, 199106
ermolin_stud@list.ru

Sergei Belyakov
JSC "Kazgeology"
Dostyk Street 18, 17th floor, #1718, BC "Moscow"
Astana, Kazakhstan, 010000
bsergein@kazgeology.kz

SUMMARY

In the application of electroprospecting for mineral exploration, there are few clearly observed trends based on the development of electroprospecting technologies, hardware, software and computer technologies aimed at: a) the increase of electroprospecting application in comparison with other EM methods; b) application of electroprospecting at all stages of the exploration cycle; c) the increase of application of induction electroprospecting methods and, first of all, these which are based on the study of the natural EM field of the Earth (NEMFE). A special role here is played by the method of Broadband Magnetovariational Profiling (BMVP).

Three stages in the application of electroprospecting are quite clearly distinguished: a) exploration for new mining provinces according to the distribution of resistivity in the Earth's crust and upper mantle (the AusLAMP project, a revolutionary idea proposed by Australian scientists; deep MT, scale 1 : 5,000 000 – 1 : 1,000 000); b) exploration for large conductive ore bodies, areas with a prospecting survey square area of more than 100 km^2 by airborne geophysics, for areas with smaller size - 5-component AMT on a scale of 1 : 200,000 – 1 : 50,000; c) detailization and support of drilling operations, mapping of veins and dikes - 5-component AMT on the scale 1 : 20,000 – 1 : 5,000 in complex areas with induction and geometric soundings using control source if Induced Polarization is an exploration factor.

Key words: Magnetotellurics, deep crust, mantle, ore deposits, mining.

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) (Tikhonov, 1950, Cagniard, 1953, Berdichevsky, 1968). 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). In addition, there are several simplified versions of magnetotelluric soundings, which have been successfully applied since the 50s of the previous century to the present day (Berdichevsky et al., 1968, 2009). First of all, it is the Telluric Currents (TT or TC) method which is based on the study of relative (with respect to the fixed base station) amplitudes and phases of the two orthogonal horizontal electric components of the EM field (E_x, E_y). To date, the Magnetotelluric Profiling (MTP) method, which is a narrow-frequency band (0.02 - 0.006 Hz) version of MT, whose introduction into exploration for oil and gas was due to the existing 1960s-1970s hardware, has largely lost its relevance (Berdichevsky et al., 2009). The KMTZ equipment was used in the former USSR to designate MT surveys that were synchronous with the registration of the MT field at the fixed reference point (Remote Reference) (Berdichevsky et al., 1996, 2009). Since such technology allows to significantly suppress industrial and wind noise, as well as to calculate additional response functions (telluric (T) and magnetic (M) tensors), at present time the overwhelming majority of Magnetotelluric surveys of different scales are performed using this technology which is called Remote Reference Magnetotellurics (Gamble et al., 1979).
- 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). For the MVP method, the frequency gradation has not been officially introduced yet. The authors consider it expedient to introduce gradation similar to that used in Magnetotelluric methods, i.e. AMVP, MVP, LMVP, BMVP. The depth and scale of the objects under study essentially depends on the effective frequency band of the MVP method.

Of fundamental importance is the fact that Magnetotelluric methods map structures with sub-horizontal layers well, 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 inhomogeneities 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 us to investigate in detail complex geological cross-sections. Hence, the 5-component measurements are absolutely necessary for any type of AMT-MT survey (Berdichevsky et al., 2009).

In addition to the high sensitivity of this combination of methods, introduced into practice as a result of the discoveries by A.N. Tikhonov (1950) and L. Cagniard (1953) in the early 1950s, to the features of the geological section these methods have a unique capability to investigate the geoelectrical section over a large depth interval (from the first meters to 150 - 200 km) and to detect objects that are located away from the observation profile (Ingerov et al., 2014). 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.

EXPLORATION FOR NEW MINING PROVINCES

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 (Rokityansky, 1981) have identified the Carpathian anomaly of electrical conductivity (Figure 1). In later years, in the territory of Ukraine, the Kirovogradskaya, Ryasnopol'skaya and Donbas deep anomalies of electrical conductivity were also successively identified (Figure 1) by scientists of the Ukrainian Academy of Science lead by Prof. I.I. Rokitansky and State Geophysical Enterprise "Dneprogeophysica" lead by Dr. O. Ingerov (Dyakonova et al., 1986, Ingerov, 2004).

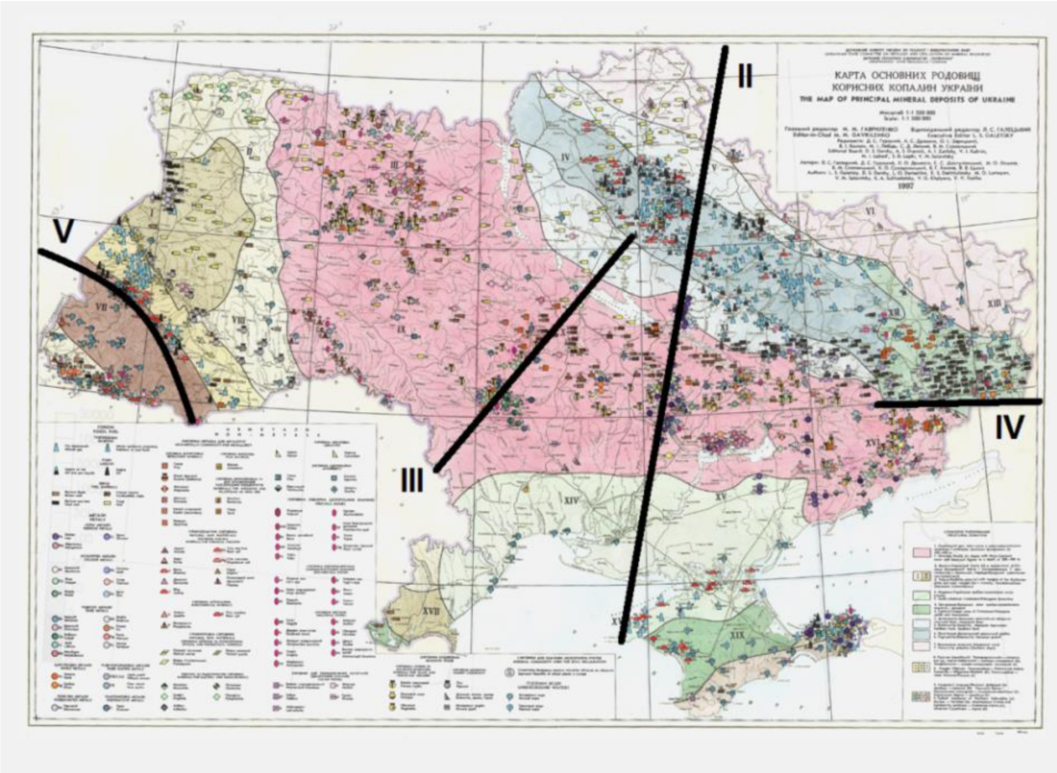

Figure 1: The map of Ukraine's existing mineral deposits with marked position of deep conductive anomalies axis's: I – Carpatian; II – Kirovogradskaya; III - Ryasnopolskaya; IV – Donbaskaya (according to O. Ingerov, 2004).

The idea of using the MT method for deep studies of the Earth's crust and upper mantle was expressed in the turn of 60s-70s of the last century by groups of Russian (Berdichevsky et al., 2009), and Ukrainian scientists (Rokityansky, 1970). In the 1970s, separate studies were conducted in different regions of the former USSR with CES-1 equipment (frequency range 10-3,600 sec). Consequently, in the area of the Kirovograd anomaly of electrical conductivity identified were more than 10km of high conductivity sediments in both Ukrainian Shield and in Dnipro-Donetsk basin (Rokityansky, 1981).

In the beginning of 1980s, the CES-2 equipment was developed with an extended frequency range (0.1-3,600 sec). In the former USSR a deep exploration program was announced, which included reference to superdeep boreholes with a depth of up to 15 km and connecting them geotraverses with field measurements using a suite of geophysical methods, where the main role was played by the methods of deep seismic and MT, whereas the auxiliary role was dedicated to gravity, magnetics, thermometry and spectrometry (Kozlovsky, 2008). MT was one of the first methods which was used to complete geotraverse 2 (Yalta-Warsaw) and geotraverse 8 (Odessa-Urengoy). The latter passed through the Krivoy Rog and Ural superdeep boreholes (Chekunov, 1988, 1993). The Ukrainian Ministry of Geology and the Academy of Sciences realized earlier than others the need to supplement geotraverses with regular mapping grid (Dyakonova et al.,1986). In the 1980s, regional surveys with scale of 1 : 5,000,000 and 1 : 2,500 000 were performed, and a 1 : 1,000 000 million scale survey was initiated only to be interrupted by the disintegration of the former USSR. At the beginning of the 1990s, a summative map of the location of deep MT sites on the territory of Ukraine (Figure 2) was composed (Ingerov, 2004). A simple superimposition of the axes of conductive anomalies in the Earth's crust onto the map of Ukraine's minerals shows a fairly close relationship (Figure 1).

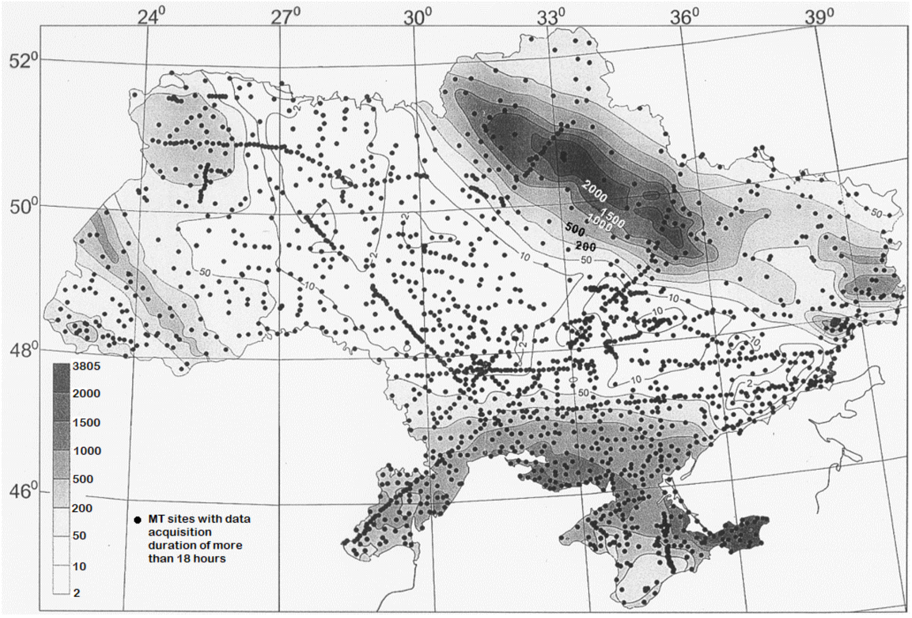

Figure 2: The map of sediments conductance to Precambrian basement for the territory of Ukraine (according to O. Ingerov, 2004).

Russia has continued regional MT surveys on geotraverses, particularly actively in the current century. Since 2002, CES-2 equipment has been replaced by Phoenix's equipment with a wider frequency range and portability (Aleksanova et al., 2009, Berdichevsky et al., 2009, Ingerov, 2004). Some results of these studies are given in the article by N.A. Palshin and a group of co-authors (Palshin, et al., 2017). As can be seen from Figure 3, the focus has recently been on Siberia. In 2015 Kazakhstan has also joined deep MT investigations.

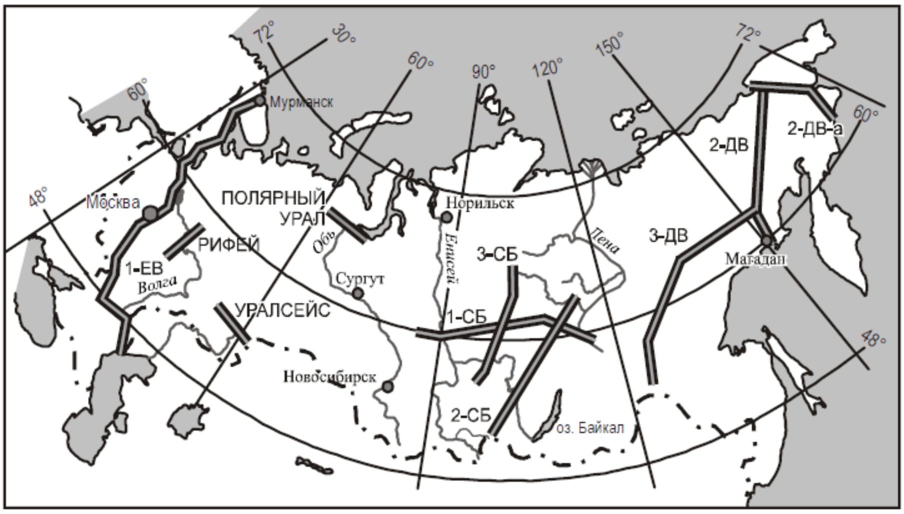

Figure 3: The map with marked position of the main regional MT profiles in Russia. Profile names are marked according to the program of complex geophysical investigations on geotraverses by the Ministry of Mineral Resources and Ecology of the Russian Federation (according to Palshin et al., 2017).

International projects such as EUROPROBE (Brasse et al., 2006), LITHOPROBE (Clowes, 2009), EMSLAB (Jiracek et al., 1989) 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 (Berdichevsky et al., 1996, 2009, Chekunov, 1988, 1993, Jones, 1992, Jones and Ferguson, 2001, Jones et al., 2001, Jones and Garcia, 2003, Parhomenko, 1989, Pushkarev, 2002, Spitchak, 2005, Zhamaletdinov, 1984, Zhdanov, 2009, Chave, 2012). The regional MT surveys conducted by the St. Petersburg Mining University at the Kola superdeep borehole area (Litvinenko et. al, 2014) and the unique natural phenomenon the Patom Crater in the Irkutsk region (Ingerov and Ermolin, 2011) have shown the high efficiency of the MT method for solving deep geological problems.

Thus, the great initiative of Australian scientists, the AusLAMP project (Chopping et al., 2016, Thiel et al., 2016), is supported by extensive experience and large amount of deep MT data collected in various parts of the world over the last 40 years.

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 it (Ingerov et al., 2014). In this case, the orientation of real induction vectors can show direction to the prospective objects. The results of 3-D modelling 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 4). 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 modelling 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).

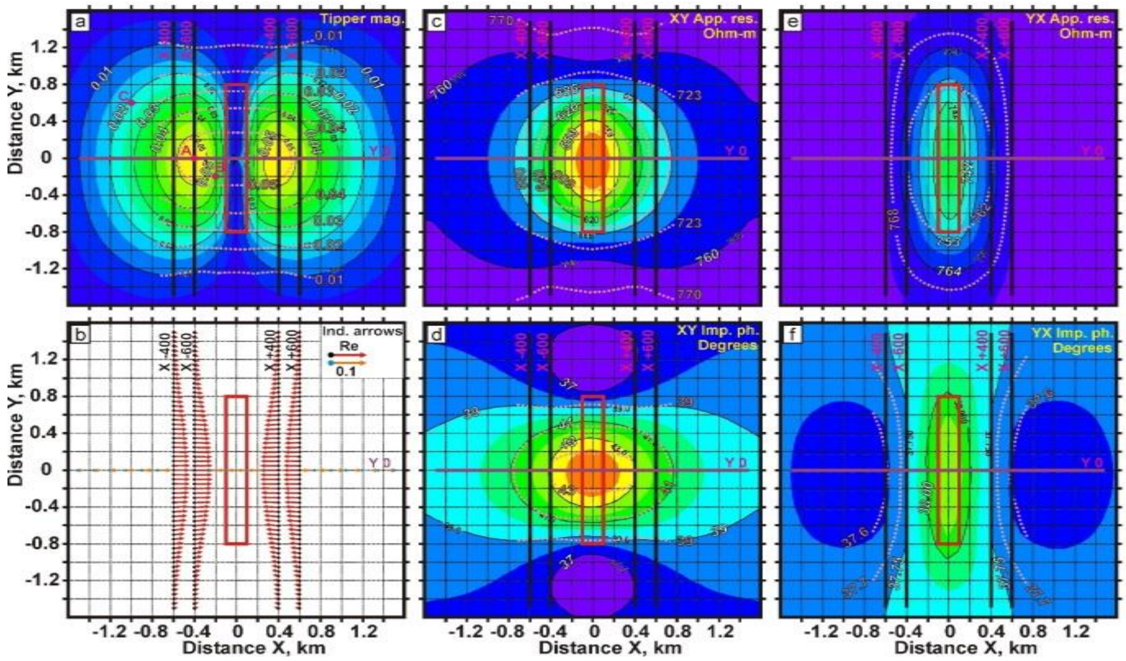

Figure 4: Results of 3-D MT modelling of deep conductive body; a - tipper amplitude, c – meridian apparent resistivity, e – longitudinal apparent resistivity, b – real induction vectors, d – meridian impedance phase, f – longitudinal impedance phase.

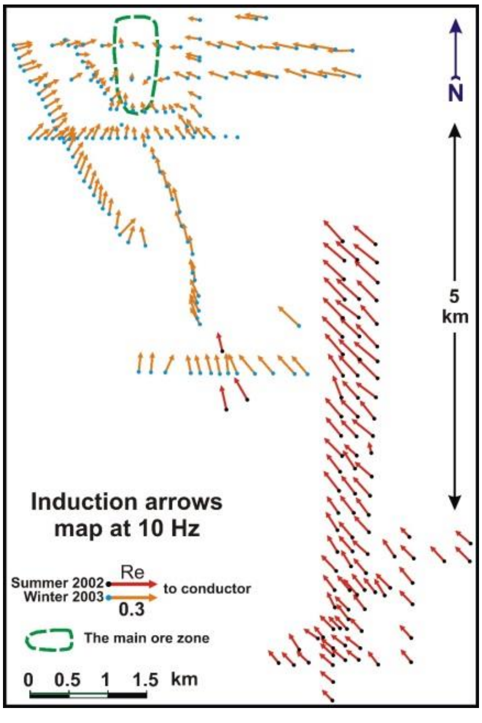

Figure 5: The induction vectors at 10Hz at Northern Quebec, Canada.

The classical example of prospecting and exploration survey is the AMT-MT survey conducted in the northern Quebec in 2002-2004 (Figure 5). 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. 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 the 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 (Ingerov, 2004). 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 5). 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.

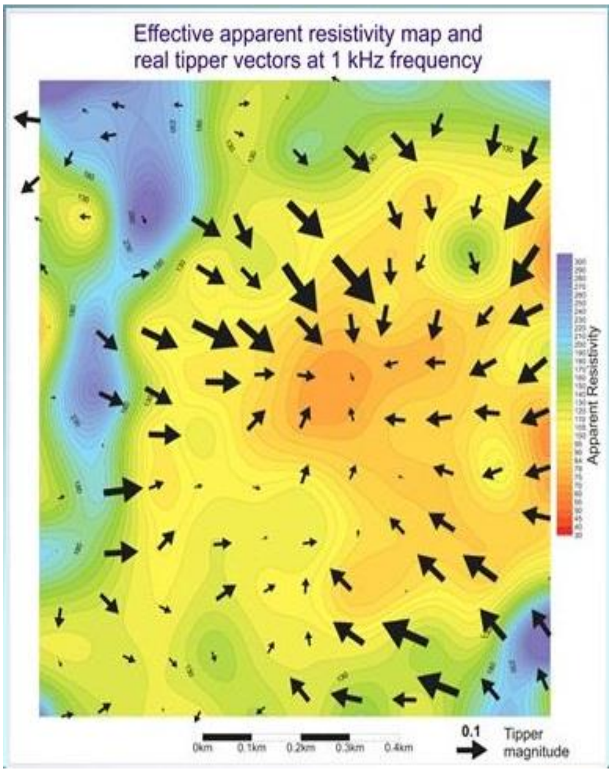

Figure 6: The map of induction vectors which lead to discovery of kimberlitic pipe in Arkhangelsk Region, Russia.

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 5th - 10th 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 6 shows the results kimberlitic pipe exploration in the Arkhangelsk region in Russian North-West (Ingerov et al., 2014). In this case, it was located by the 5-component AMT and was further confirmed by drilling. However, as can be seen from Figure 6, 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.

Another example of exploration survey for an object which is difficult to map by geophysical methods is shown in Figure 7 and Figure 8. The 5-component AMT measurements with 40m spacing along a series of sub-latitudinal profiles were conducted during additional exploration of the flanks of a large gold deposit in Chukotka, Russia (Figure 7). 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 8) as an area of lower phase values.

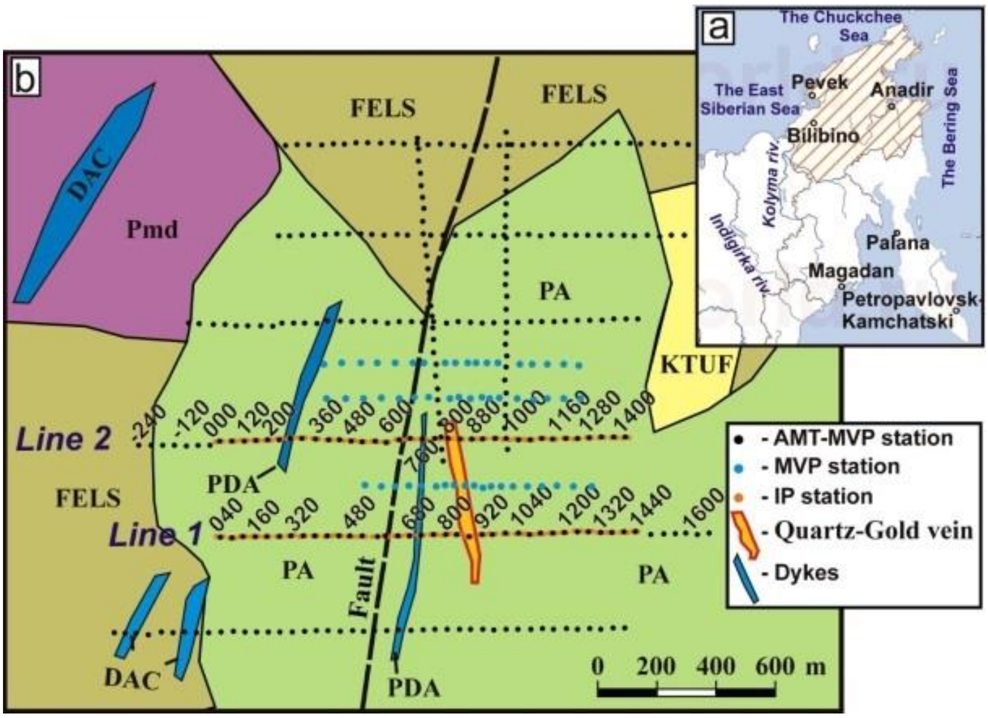

Figure 7: a) Chukotka region location; b) geology and scheme of investigation area with position of 5-component AMT and 3-component MVP measurement sites for gold deposit exploration in Chukotka, Russia in 2013-2014 (according to Ermolin et al., 2016).

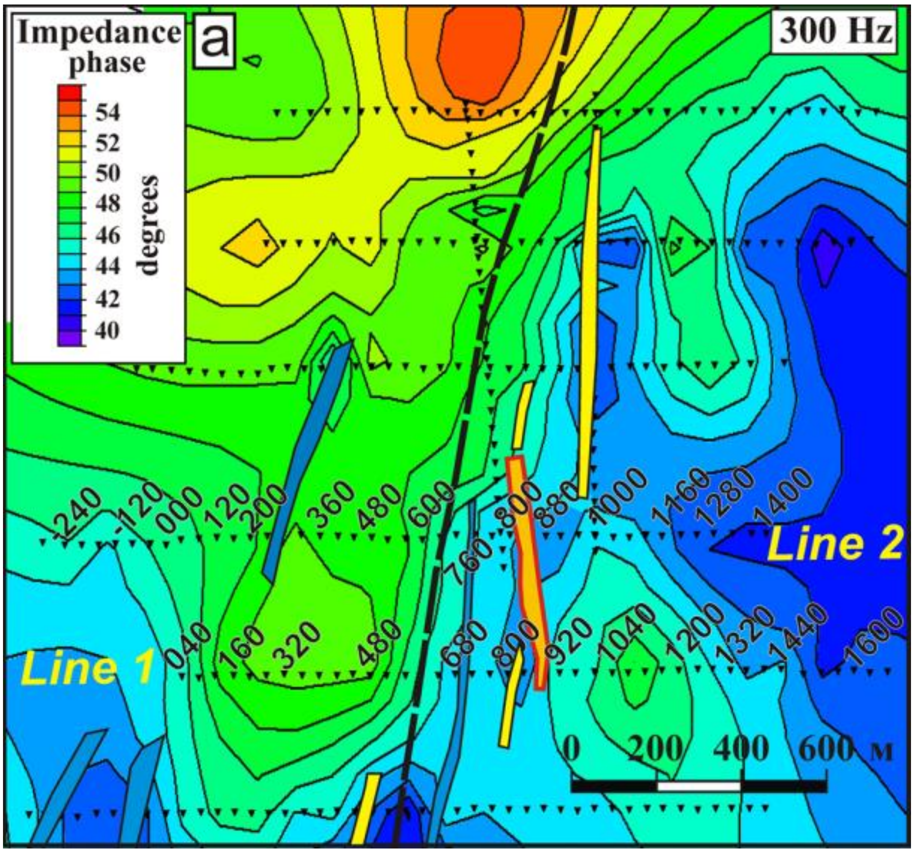

Figure 8: The map of invariant impedance phase at 300Hz and position of newly discovered gold bearing veins (according to Ermolin, 2016).

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, 2011). This equipment allows us to record the EM field with two types of sensors (AMT, MT), i.e. to cover a 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 separation 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, Ingerov et al., 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 modelling 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 (Berdichevsky et al., 2009, Chave et al., 2012, Vanyan, 1997, Zhdanov, 2009).

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).

ACKNOWLEDGMENTS

Authors acknowledge support and assistance during research provided by Advanced Geophysical Operations and Services Inc. (AGCOS).

REFERENCES

Aleksanova E.D., Alekseev D.A., Suleimanov A.K., and Yakovlev A.G., 2009, Magnetotelluric studies in salt-dome tectonic settings in the Pre-Caspian depression: First Break, vol. 7, no. 3, pp. 105-109.

Berdichevsky, M.N., 1968, Elecrtrical Prospecting by the method of Magnetotelluric Profiling: Moscow – Nedra, 1968.

Berdichevsky, M.N., Borisova, V.P., Golubtsova, N.S., Ingerov, A.I., Konovalov, Y.F., Kulikov, A.V., Solodilov, I.N., Chernyavsky, G.A., and Shpak, I.P., 1996, Experience of interpreting MT soundings in the mountains of the Lesser Caucasus: Moscow - Physics of the Earth, 1996, 4, 99-117.

Berdichevsky, M.N., and Dmitriev, V.I., 2009, Models and Methods of Magnetotellurics: Moscow – Scientific World, 2009.

Brasse, H., Cerv, V., Ernst, T., Hoffmann, N., Jankowski, J., Jozwiak, W., Korja, T., Kreutzmann, A., Neska, A., Palshin, N., Pedersen, L.B., Schwarz, G., Smirnov, M., Sokolova, E., and Varentsov, Iv.M., 2006, Probing electrical conductivity of the Trans-European Suture Zone - Eos Trans: AGU, 87 (29), 281-287.

Cagniard, L., 1953, Basic theory of the magnetotelluric method of geophysical prospecting: Geophysics 18, 605-635.

Chave, A.D., and Jones, A.G., 2012, The Magnetotelluric Method – Theory and Practice: Cambridge University Press.

Chekunov, A.V., 1988, Lithosphere of the central and eastern Europe – Geotraverses IV, VI, VIII: Kiev – Naukova Dumka, 1988.

Chekunov, A.V., 1993, Lithosphere of the central and eastern Europe – summary of results of investigation: Kiev – Naukova Dumka 1993.

Chopping, R. G., Duan, J., Czarnota, K., and Kemp, T., 2016, AusLAMP long period magnetotellurics: progress update and new insights into Victorian geology and mineral prospectivity: American Geophysical Union, Fall General Assembly 2016, abstract #GP41A-03.

Clowes, R.M., 2009, Initiation, development, and benefits of Lithoprobe — shaping the direction of Earth science research in Canada and beyond: Canadian Journal of Earth Sciences, vol. 47 no. 4, 291-314.

Dyakonova, A.G., Ingerov, A.I., and Rokityansky, I.I., 1986, Electromagnetic Soundings on the East European plato and Ural: Kiev – Naukova Dumka, 1986.

Ingerov, O., and Ermolin, E., 2011, The results of AMT survey at Patomsky crater: 73rd European Association of Geoscientists and Engineers Conference and Exhibition 2011 - Incorporating SPE EUROPEC 2011. 6. P.4325-4329, Extended Abstract.

Ermolin, E., Savichev, A., and Ingerov, I., 2016, Additional exploraiton of gold deposit in Chukotka by AMT and MVP: Proceedings of the 29th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Denver, Colorado, USA.

Gamble, T.D., Goubau, W. M., and Clarke, J., 1979, Magnetotellurics with a remote magnetic reference: Geophysics, Vol. 44, No. I (January 1979), 53-68.

Jiracek, G.R., Gurtis, J.H., and Ramirez, J., 1989, Two-dimensional magnetotelluric inversion of the EMSLAB Lincoln line: J.Geophys.Res., vol.94, 14145-14151.

Jones, A.G., 1992, Electrical conductivity of the continental lower crust: In Continental Lower Crust: Amsterdam-Elsevier, 81-143.

Jones, A.G. and Ferguson, I.J., 2001, The electric moho: Nature, 409, 331-333.

Jones, A.G. and Garcia X., 2003, The Okak Bay MT dataset case study - a lesson in dimensionality and scale: Geophysics, 68,70-91.

Jones, A.G., Ferguson, I.J., Chave, A.D., Evans, R.L., and McNeice, G.W., 2001, Electric lithosphere of the Slave Craton: Geology, 29, 423-426.

Ingerov, A., 2004, Magnetotellurics (MT) - Applications for hydrocarbon and mining prospecting: Invited paper at 32nd IGS, Florence, Italy, August 20-24, 2004.

Ingerov, A., 2011, Recent tendencies in onshore and offshore EM equipment development: Materials of the Fifth all-Russian workshop-seminar in the name of M.N. Berdichevsky and L.L. Vanyan on electromagnetic soundings of the Earth - EMS-2011, St. Petersburg, Russia, May 16-21, Abstract Book, Vol.1, 86-102.

Ingerov, I., and Ermolin, E., 2014, Application of magnetovariational profiling method (MVP) for geological mapping and mining exploration: 22nd EM Induction Workshop, Weimar, Germany, August 24-30, 2014, Extended Abstracts.

Ingerov, I., 2016, Multifunction 4 and 8 Channel Electroprospecting Instruments of the Generation 5+: Proceedings of the 29th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Denver, Colorado, USA.

Ingerov, I., Lozoviy, A., and Mendrii, Y., 2016, Frequency domain control source EM technology for mineral exploration: Proceedings of the 29th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Denver, Colorado, USA.

Kozlovsky, E.A., 2008, Deep investigations of the Earth crust – News about composition of the earth core: Center of Information Technologies and Natural Resources, 2nd Edition, 2008.

Litvinenko, V.S., Ermolin, E., Ingerov, O., Egorov, A.S., and Zhamaletdinov, A.A., 2014, Magnetotelluric investigation across the Kola Super Deep Hole area: 22nd EM Induction Workshop, Weimar, Germany, August 24-30, 2014, Extended Abstracts.

Palshin, N.A., Aleksandrova, E.D., Yakovlev, A.G., Yakovlev, D.V., and Breves, V.R., 2017, Experience and prospects of Magnetotelluric soundings application in sedimentary basins: Geophysical Invesigations, 2017, Vol. 18, 2, 27-54.

Parhomenko, E.J., 1989, Geoelectrical properties of minerals and rocks at high pressures and temperatures: Moscow – Nauka, 1989.

Pushkarev, P.Yu., 2002, Magnetotelluric investigations of Magnetotelluric studies of the Cascade subduction zone: Ph.D Thesis, Moscow State University.

Rokityansky, I.I., 1970, Investigation of the deep electrical conductivity: Geophys. Comm. Kiev, 38, 102–106.

Rokityansky, I.I., 1981, Induction Soundings of the Earth: Kiev – Naukova Dumka, 1981.

Spitchak, V.V., 2005, Electromagnetic Study of the Earth's interior: Moscow – Nauchny Mir, 2005.

Thiel, S., Heinson, G., Reid, A., and Robertson, K., Insights into lithospheric architecture, fertilisation and fluid pathways from AusLAMP MT: ASEG-PESA-AIG 2016 - 25th International Geophysical Conference and Exhibition, Adelaide, South Australia, August 21-24, 2016, Extended Abstract.

Tikhonov, A.N., 1950, About determining the electrical properties of deep layers of Earth crust and mantle, Abstracts of USSR Academy of Science, series № 1950, Vol. 73, №2, 295-297.

Vanyan, L.L, 1997, Electromagentic Soundings: Moscow – Scientific World, 1997.

Zhamaletdinov, A.A., 1984, Crustal anomalies of the electrical conductivity – Collection of the Scientific Works: Leningrad – Nauka, 1984.

Zhdanov, M. S., 2009, Geophysical electromagnetic theory and methods, Volume 43, 1st Edition: Elsevier Science.