Introduction

The discovery of Australian geophysicists (Dentith, 2012, Heinson, 2018) who established relation between the position of known large polymetallic mineral deposits and the presence of intensive conductivity anomalies located beneath them in Earth's lower crust and upper mantle caused a real revolution in mineral exploration approach. This discovery is based on 16 projects and approximately 3,000 wideband MT measurements completed by Australian geoscientists (Figure 1).

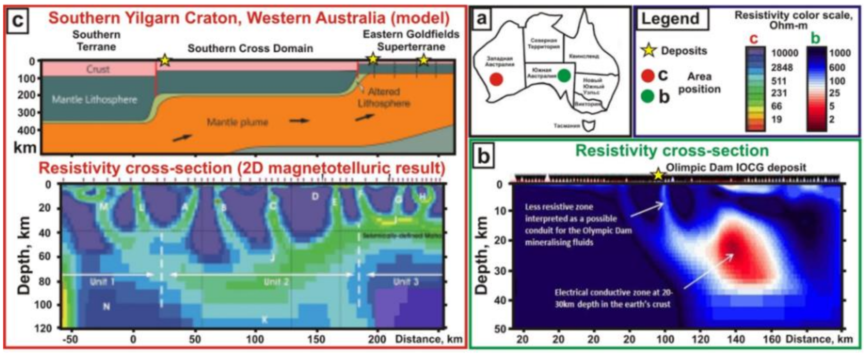

Figure 1 *The relation between mineral deposit position and distribution of conductivity in deep crust and upper mantle (modified from Dentith and Heison).*

In order to practically confirm established patterns, Australia began systematic survey of its entire territory on a scale of 1: 5,000,000 (AusLamp Project). Completed, in-process and planned MT stations of this project are shown in Figure 2.

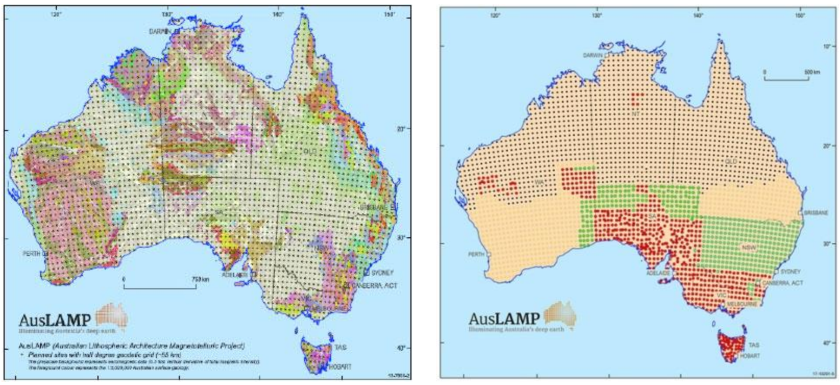

Figure 2 *Map of Australia showing distribution of 50 x 50km AusLamp stations; black – planned, red completed as of January 2017.*

Thus, when exploring for new mining provinces and large deposits, investigations of Earth's crust and the upper mantle electrical conductivity comes to the forefront. The most effective geophysical methods for solving this problem are Magnetotelluric soundings (MT) and Magnetovariational Profiling (MVP). These methods were introduced and actively developed since 1950 after publications by A.N. Tikhonov and L. Cagniard (Berdichevsky et al., 2009). While MT initially was primarily used for investigations of sedimentary basins, MVP from the outset was used to identify anomalous conducting objects in the Earth's crust and upper mantle. The 5-component soundings (E_x, E_y, H_x, H_y, H_z) are based on measurements of the natural alternating electromagnetic (EM) field of the Earth combine two methods: MT and MVP. Of fundamental importance is the fact that MT methods map structures with sub-horizontal layers well, whereas MVP methods do not respond at all to a horizontally layered medium. At the same time, MVP methods are very sensitive to horizontal inhomoginieties of the medium. Thus, the combination of MT and MVP methods allow 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 high sensitivity of MT-MVP methods combination to the features of geological section, these methods have a unique capability to investigate geoelectric section in wide depth intervals (from the first few meters to 150 - 200 km) and to detect objects that are located away from observation profiles (Ingerov et al., 2014).

Deep electromagnetic soundings application experience in the former USSR

Russia and Ukraine. The first deep MT in the territory of the former USSR was performed by N.V. Lipskaya in 1958 near town of Alushta, Crimea (Ingerov et al., 1999). According to the shape of the obtained curves, it was suggested that there is a conductive asthenosphere in this region. The idea of a broad application of MT and MVP for investigations of Earth's deep crust structure was put forward in 1970 by Russian and Ukrainian geoscientists (Rokityansky, 1970). The earthquake in the Vrancea zone, Romania in 1977 further stimulated interest for investigations of Earth's deep structure. In the mid-1980s, the USSR adopted a program for deep subsoil investigations (Kozlovsky, 2008) which included a network of super-deep boreholes and complex of connecting geophysical profiles (Figure 3a). Along with seismic prospecting, the 5-channel MT and MVP were used as the main investigative methods using CES-2 equipment. Russia further continued its work on this program (Figure 3b) and at the turn of the century CES-2 equipment (Ingerov, 2011) was replaced by portable Canadian equipment of the 5th generation. A summary of deep investigations results on the territory of Russia is given in recent paper by N. Palshin and group of co-authors (Palshin et al., 2017).

a) *b)*

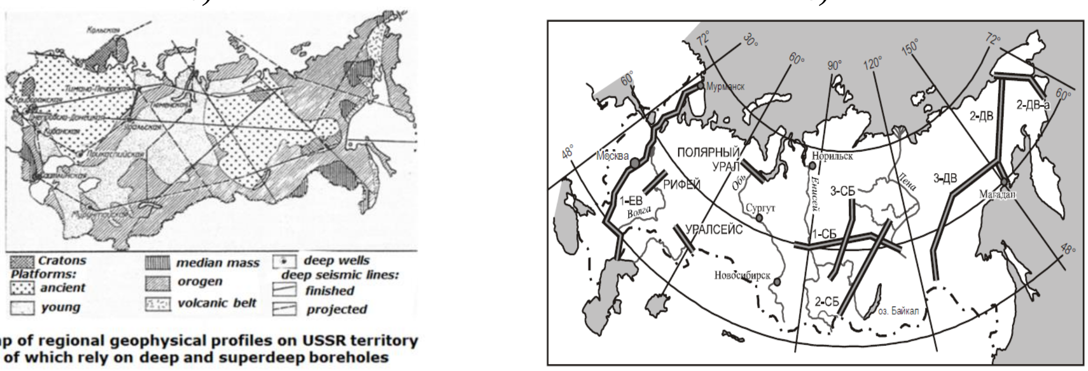

***Figure 3** a) The map of USSR deep boreholes and position of geotraverses (Kozlovsky, 2008, b) the main geotraveres presently completed in Russia (Palshin et al., 2017).*

In the 1960s, Ukrainian geophysicists together with scientists from neighbouring European countries delineated the Carpathian anomaly using the MVP method. In 1967, a group of scientists led by Dr. I.I. Rokityansky discovered the Kirovograd anomaly of electrical conductivity with MVP method (Rokityansky, 1982), and in 1986 in collaboration with Dneprogeofizika, they have discovered the Donbas anomaly of electrical conductivity with MVP and MT methods (Rokityansky et al., 1994). Since 1981, on the territory of Ukraine systematic deep MT investigations have been carried out on individual geotraverses, and since 1985, in addition to geotraverses, regional surveys have been consistently performed with 1 : 5 000 000, 1 : 2 500 000 and partially 1 : 1000 000 scales and measurements in 0.1 – 3 600 seconds frequency range (Ingerov et al., 1999). The map of the invariant apparent resistivity for the period of 150 seconds is shown in Figure 4. The map reveals total resistivity distribution in the Earth's crust, total conductivity of Precambrian sedimentary cover (layers) and position of Ukraine's large minerals deposits. Particularly interesting is the natural location of the deposits in low resistivity zones of the Earth's crust or on their boundaries. Thus, fairly dense Ukrainian MT-MVP data confirms the idea that investigations of the Earth's crust and upper mantle conductivity can considerably assist in forecasting new mineral deposits and, most importantly, significantly reduce survey costs and accelerate exploration.

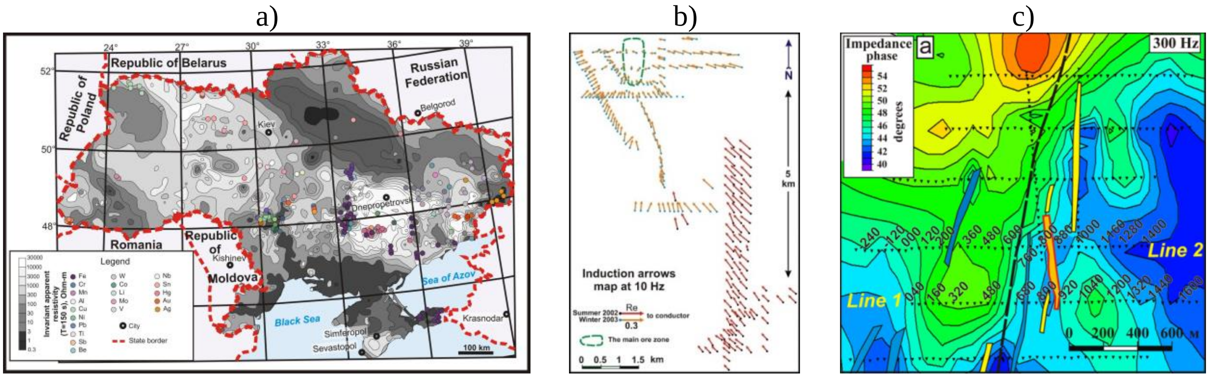

Figure 4 *a) Map of invariant apparent resistivity at period 150s and position of Ukraine's ore mineral deposits (Ingerov et al., 1999), b) induction vectors at 10Hz in Northern Quebec, Canada (Ingerov et al., 2014), c) map of invariant impedance phase at 300Hz and position of newly discovered gold bearing veins (Ermolin et al., 2016).*

MT and MVP methods application experience for prospecting and mapping ore bodies

In recent years, the application of MT-MVP methods around the world for mining exploration has increased substantially due to its depth resolution, high sensitivity, simple logistics and portability of equipment. In the forefront are Canada, Russia and Kazakhstan. Figure 4b shows an example of successful AMT exploration survey for massive sulphide ores in northern Quebec, Canada in 2002. The main network of three (3) N-S profiles completed on accessible in the summer part of the survey grid did not reveal promising anomalies. However, induction vectors at frequency 10Hz clearly indicate presence of a conducting object in the northwest part of the survey area. Detailed field measurements were performed primarily by the MVP method in the subsequent winter period when the surrounding lakes and marshes were frozen. As a result, the sought after object was delineated (Figure 4b). Figure 4c shows result of detailed AMT field survey (40m site stepping along the profiles) completed in 2013 in Chukotka, Russia. Objective of the survey was to locate northern and southern extensions of quartz low-sulphide gold-bearing vein (high-resistivity object in contrast to background). The task was complicated by the fact that the bedrock was covered by a 100m thick layer of low resistivity tuffs. Nevertheless, longitudinal fault separating survey area into two parts with different geoelectric properties is clearly observed on the map of invariant impedance phase at 300Hz. Quartz veins and the surrounding zones of thermal fluctuations are distinguished as areas of high resistivity. The position of these features on the map permits to suggest with high degree of probability that the southern part of the gold-bearing vein is shifted to the west, while the northern part is shifted to the east. Results of 2014 drilling program 100% confirmed geophysical forecast. Thus, the broadband MT-MVP equipment allows effectively realize all stages of mining exploration, starting from mapping the distribution of electrical resistivity in the Earth's crust and upper mantle up to discovery and precise mapping of individual anomalies.

Proposed stages of MT-MVP methods application for mineral exploration

1. The large scale regional surveys (1: 5 000 000, 1: 2 500000, 1: 1 000 000) and geotraverses with 1-5km increments. All field recordings must be wideband (10 000Hz - 3600s) with measurement of 5-components of EM field.
2. The AMT/MT-MVP exploration surveys in favourable regions, prospecting for conductive extensions leading to the surface from deep conductors or exploration of promising areas discovered using other geological and geophysical techniques.
3. The detailed exploration surveys to delineate individual ore bodies with 200 x 20(40)m and five (5) or three (3) component measurements in 10 000 (30 000) - 1 Hz frequency range.
4. The robust assessment of licensed areas. Commonly, the license holder does not have time to wait until the state completes the 1st stage. It is recommended to complete wideband (10 000 (30 000) - 0.001Hz)) 5-component MT-MVP surveys with one (1) station per 1-4 km^2 scale.

Conclusions

- A direct link between the distribution of mineral deposits and the conductivity of Earth's crust and upper mantle has been established.
- This link allows to significantly reduce costs and to accelerate exploration of new mineral deposits as well as quickly evaluate prospective licenced areas.
- Exploration and mapping surveys have to be carried out in 3 stages and MT-MVP measurements to be performed with registration of five (5) EM field components in a wide frequency range.
- Proposed MT-MVP technology could be the most cost effective and quickest solution for evaluating licensed areas potential.

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