GEOLOGICAL APPLICATIONS OF THE VLF METHOD

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1. Introduction

Just like in the case of any electromagnetic (EM) method, the electrical properties of the ground affect the behaviour of radio waves as well. The first EM measurement using radio frequencies applied wave-tilt techniques and was made at relatively high frequencies with shallow penetration depth [1]. The earliest EM measurement with radio waves of 3-30 kHz was carried out in 1963 with the aim of ore prospecting [2]. In the late sixties commercially available ground very low frequency (VLF) instruments were introduced into near-surface exploration. These instruments can be used to observe either the magnetic field and/or to determine the terrain's apparent resistivity. Over 1D half-space the magnetic field at the surface is linearly polarized. However, in the presence of a lateral conductivity inhomogeneity – situated between the surface and skin depth – the total magnetic field at the surface will be elliptically polarized due to the induced magnetic field. Usually the induced vertical magnetic field component is small compared with the primary azimuthal magnetic field component. In this case the ellipticity of the magnetic polarization ellipse is approximately equal to the quadrature component of the ratio of the vertical and the azimuthal magnetic component, and the tilt angle of the ellipse approximately equals the real component of the same ratio [3]. If the radial electric field and the azimuthal magnetic field component are known the apparent resistivity at the VLF frequencies can be derived.

Takács was the first in Hungary to develop the radiokip method with instruments to apply the EM fields of distant LF transmitters for near-surface geological explorations [4]. The VLF method was introduced and intensively used in Transdanubian Central Range bauxite exploration by ELGI [5]. In the frame of this work Farkas developed the VLF invariant resistivity method based on the concept of the magnetotelluric impedance tensor [6]. The VLF method utilizes the frequency range of 10 kHz-30 kHz, providing poor depth resolution. To overcome this resolution problem this frequency range was extended and in addition to the VLF carrier waves the low frequency (LF) signals from civilian radiotransmitters are also utilized by the RMT (Radiomagnetotelluric) method. Takács carried out and interpreted the first RMT soundings in Hungary in the range of 18.3 kHz and 630 kHz. He measured both the electric and magnetic field components and MT 1D inversion was applied [7]. The radiofrequency resistivity (RF-R) device measuring in the range of 12 kHz-240 kHz was successfully applied to delineate karst structures [8]. In 1973 Tilsley applied a portable VLF transmitter as a supplementary source to the regular VLF transmitters [9]. To cope with the interpretation problem arising from the mutual position between transmitter and structural strike direction or to overcome the poor coupling with the target the use of a portable transmitter can be recommended. For the determination of sufficient distance between the portable VLF transmitter and VLF profiles numerical modelling is also needed [10].

2. VLF resistivity response over layered half-space

If the VLF wave impedance – which is the ratio of the radial electric and the horizontal azimuthal magnetic field component – is independent of the transmitter

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direction, the geology can be considered as 1D down to the penetration depth. The apparent resistivity of the inhomogeneous ground (ρ_a) can be defined as:

$$\rho_a = \frac{1}{2\pi f_{VLF}\,\mu_0}\left|\frac{E_r}{H_\phi}\right|^2 \tag{1}$$

In equation (1) f_{VLF} stands for the frequency, μ_0 denotes the absolute permeability of a vacuum. In the carrier wave transmitted into the homogeneous ground the horizontal radial electric field component leads the horizontal magnetic field perpendicular to the transmitter bearing in phase by 45°. The phase difference between E_r and H_ϕ can furnish information about the changes of conductivity in a vertical sense till approximately the penetration depth. Assuming a horizontally stratified half-space with a lower layer more resistive compared with the upper one, the phase angle $\Phi(E_r, H_\phi)$ will be less than 45°, and it is greater than 45° if there is an increase in conductivity with depth. In practice a 1D assumption can be applied to geology with slow variations in geometry. Locally 1D approximation proved to be successful in the exploration of covered communal waste (in Nyékládháza) and fault localization (in the Csanyik Valley of the Bükk Mountains). For the interpretation the 1D inversion method given by [11] was applied.

3. VLF method for elongated conductivity structures

Although one encounters 3D conductivity structure with anisotropy in general, locally 2D approximation without anisotropy can frequently be applied. First the theoretical background is presented.

3.1. Basic equations for E and H polarization

Maxwell's first equation states that an electric field is induced by the time-varying magnetic field and this electric field is proportional to the negative rate of change of magnetic flux. This can be written in a cylindrical coordinate system as:

$$\frac{1}{r}\frac{\partial E_z}{\partial \phi} - \frac{\partial E_\phi}{\partial z} = -\frac{\partial B_r}{\partial t} \tag{2}$$

$$\frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} = -\frac{\partial B_\phi}{\partial t} \tag{3}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rE_\phi) - \frac{1}{r}\frac{\partial E_r}{\partial \phi} = -\frac{\partial B_z}{\partial t} \tag{4}$$

Maxwell's second equation expresses that every current flow produces a magnetic field and it is proportional to the total current flow, i.e. the sum of the conduction and displacement current. It has the following form:

$$\frac{1}{r}\frac{\partial H_z}{\partial \phi} - \frac{\partial H_\phi}{\partial z} = j_r + \frac{\partial D_r}{\partial t} \tag{5}$$

$$\frac{\partial H_r}{\partial z} - \frac{\partial H_z}{\partial r} = j_\phi + \frac{\partial D_\phi}{\partial t} \tag{6}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rH_\phi) - \frac{1}{r}\frac{\partial H_r}{\partial \phi} = j_z + \frac{\partial D_z}{\partial t} \tag{7}$$

If we assume that r coincides with the structural strike and there is an $e^{i\omega t}$ time dependent EM field variation, furthermore we neglect the effect of the displacement current, we shall get simpler component equations, mainly because all partial derivatives with respect to r can be approximated by zero. Actually at greater distances from the transmitter constant EM fields can be observed along profiles parallel to the transmitter bearing. Note that these statements are valid only for elongated (at least locally 2D conductivity) structures. Taking into account the constitutive relations between magnetic induction and magnetic field intensity, and between electric current density and electric field for homogeneous, isotropic earth, instead of (2)-(4) we can write:

$$\frac{1}{r}\frac{\partial E_z}{\partial \phi} - \frac{\partial E_\phi}{\partial z} = -i\omega\mu H_r \tag{8}$$

$$\frac{\partial E_r}{\partial z} = -i\omega\mu H_\phi \tag{9}$$

$$\frac{1}{r}\frac{\partial E_r}{\partial \phi} = i\omega\mu H_z \tag{10}$$

Similarly, instead of the Maxwell's second equations:

$$\frac{1}{r}\frac{\partial H_z}{\partial \phi} - \frac{\partial H_\phi}{\partial z} = \sigma E_r \tag{11}$$

$$\frac{\partial H_r}{\partial z} = \sigma E_\phi \tag{12}$$

$$-\frac{1}{r}\frac{\partial H_r}{\partial \phi} = \sigma E_z \tag{13}$$

If equations (8), (12), (13) are taken into one set of equations, it contains only H_r, E_ϕ, E_z components and similarly, in the set of equations consisting of (9), (10), (11) the three remaining components – E_r, H_ϕ, H_z – can be found. In order to get the simplest partial differential equation to be solved in the first case, the values of the electric field components from (12) and (13) into (8) have to be substituted. After some operations:

$$\frac{\partial^2 H_r}{(r\partial\phi)^2} + \frac{\partial^2 H_r}{\partial z^2} = i\omega\mu\sigma H_r \tag{14}$$

In the second set of equations the values of the magnetic field components have to be substituted from (9) and (10) into (11) and we can obtain:

$$\frac{\partial^2 E_r}{(r\partial\phi)^2} + \frac{\partial^2 E_r}{\partial z^2} = i\omega\mu\sigma E_r \tag{15}$$

Equation (14) describes the H-polarization and (15) corresponds to the E-polarization case. The physical-mathematical significance of this is that independently of the angle of the incident plane wave the EM field can be divided into two parts which can be treated separately. An additional conclusion is that – depending on the mutual position of the transmitter bearing and strike direction – we can encounter pure E- and H-polarization cases. The basic equations derived here can be finite differenced and depending on the boundary conditions different linear equation systems will have to be solved.

3.2. VLF measurements over elongated geological structures

The VLF method is a useful tool in geological mapping [12] and it may even have geothermal, environmental and geophysical engineering applications as well. Here special emphasis is put on elongated conductivity structures, where locally 2D approximation can be applied. When restricted to 2D conductivity inhomogeneities there are two modes. This classification is based upon the angle between the transmitter bearing and the structural strike. If they coincide with each other, then the term of E polarization or TE mode is used. In this mode current channelling in the conductive part can be experienced. In the case of elongated conductive targets with finite geometry the magnetic field perpendicular to the strike induces closed-loop eddy currents in the targets and their magnetic fields are added to that of the galvanic current flow. If the structural strike is perpendicular to the transmitter bearing, the case is called H polarization or TM mode. In TM mode a galvanic effect can be observed. As a result a secondary electric field of the oscillating electrical charge accumulation on the interfaces perpendicular to the primary electric field can be measured. For this reason both modes can be effective tools to locate near-surface vertical or nearly vertical contacts and embedded conductivity inhomogeneities. In a poor 2D situation an induced vertical magnetic field can be measured only in E polarization.

Several attempts were made to locate caves in the Bükk Mountains and in Esztromos Hill [13]. VLF measurements made over known caves and numerical modelling proved that cave localization is possible if the cave is situated within the skin-depth range. Instead of the cave, sometimes the fault along which the cave was forming could be detected, because it was closer to the surface and it suppressed the EM response due to the cave. By means of VLF measurements we also managed to assess the limestone from a mining point of view.

Owing to the geographical position of the Bükk Mountains and taking into account the dominant strike direction, the VLF EM field due to GBR transmitter approximately meets the H polarization condition in the Bükk Mountains. The geological surroundings of a spring were investigated with apparent resistivity and its phase measurements.

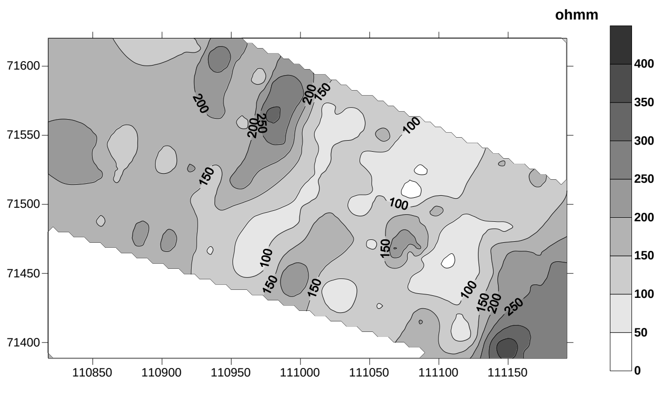

Figure 1. VLF apparent resistivity map due to GBR at Köpüs Spring

The resistivity (in Fig. 1) and phase (in Fig. 2) anomalies show similarities for the neighbouring profiles parallel to the transmitter bearing. This correlation is more pronounced in the case of the phase map, because apparent resistivity is disturbed by thin surface inhomogenities, while phase is hardly influenced by it. The interpretation can be considered as an underestimated problem because the number of unknowns is greater than the measured data available (there are three geological formations characteristic of the surroundings of Köpüs Spring). For TM mode we applied finite difference grids using rectangular elements with 39 columns and 49 rows [14]. A classical trial-and-error method was used: the parameters were changed until the best fit between the measured data and computed data was reached along all profiles. The geology for the southern-most profile is presented in Fig. 3. The impermeable mudstone behaves like a “barrier” and determines the position of the spring.

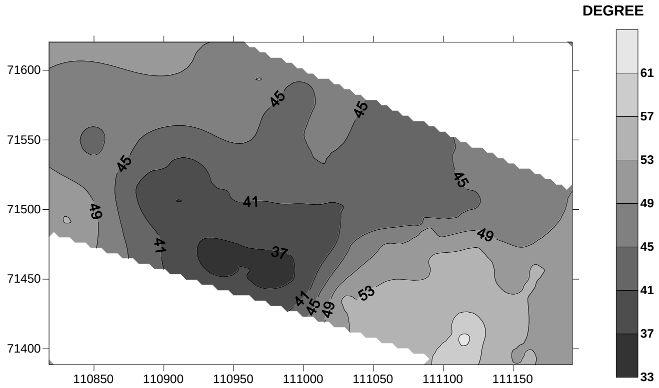

Figure 2. VLF apparent resistivity phase map due to GBR at Köpüs Spring

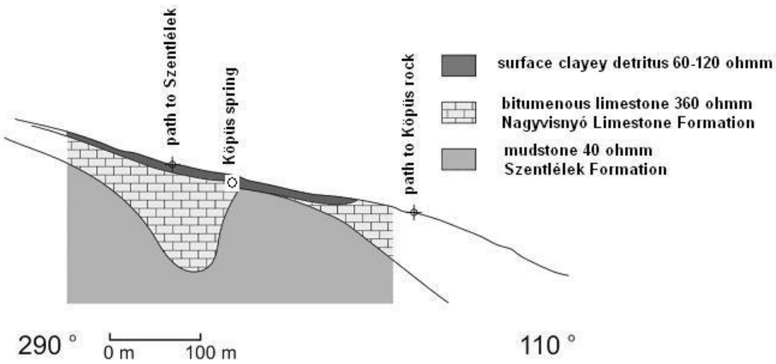

Figure 3. Interpretation based on resistivity and phase at Köpüs Spring

With a FUX 18.3 kHz transmitter at Szögszéktető (also in the Bükk Mountains) the approximate position of a metavolcanic rock hosted in Triassic limestone was determined.

Due to the mutual position of the strike of the conductive body and the French VLF transmitter the situation could be approximated by E-polarization and a simplified inversion was applied for interpretation. It is based on the fact that the secondary vertical magnetic field is generated by discrete, stationary current lines inside the targets [15].

4. Conclusions

VLF method can be an effective tool in near-surface exploration. The interpretation of the elongated structures is relatively easy if the structural strike coincides with the transmitter direction or they are perpendicular to each other. If there is no distant transmitter meeting this condition, the use of a portable VLF transmitter is recommended.

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