EXPLORATION OF HIGH RESISTIVITY BASEMENT USING ELECTRICAL AND MAGNETIC FIELDS OF QUASI-STATIC POINT SOURCES*

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ABSTRACT


Determination of thickness of sediments (usually of high conductivity) overlying a high-resistivity basement is one of the basic problems of electrical exploration methods. This paper proposes to determine horizontal electrical conductance on the basis of impedance calculated from electrical and magnetic fields of distant quasi-static (low-frequency) point sources. Using the proposed method, horizontal conductance of the sediments can be determined also from artificial quasi-static noise-impulses coming from sources of unknown position and intensity. The results of analogue modeling and field examples prove the potential of the proposed technique.

INTRODUCTION

One of the basic problems of geophysical exploration is to determine thickness of high conductivity sediments overlying a high resistivity basement. Several geoelectrical methods can be used to solve this problem.

Using DC methods with artificial source the high-resistivity basement is indicated by the rising part of the sounding curves. In magnetotellurics, a resistive layer is indicated by the so-called S-interval of the sounding curve. When using conventional DC methods, the current intensity and the position of the source electrodes are to be known. The intensity of the source is not of importance in magnetotellurics, only its geometry: the primary source is considered to be a plane wave.

For an infinitely high resistivity basement, the parameters of the quasi-static point sources need not to be known. The connection between the impedance

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$Z_{\text{point}} = E_s/H_s$ and the horizontal conductance $S$ is derived by a detailed study of the magnetotelluric $S$-interval.

ON THE QUASI-STATIC APPROXIMATION

In the case $\rho_0 \gg \rho_1$, where the subscripts 0 and 1 mean the air and the homogeneous conducting half-space, respectively, the quasi-static range is generally described by the condition

$$|k_1 r| < \eta, \text{ where } \eta \ll 1,$$

(1)

$k_1$ is the quasi-stationary wave number of the first layer with $k_1^2 = \imath \omega \mu / \rho_1$, and $r$ is the distance between the transmitter and the receiver dipoles.

According to (1) the quasi-static range depends on frequency $f = \omega / 2 \pi$, permeability of the air $\mu$, resistivity of the first layer $\rho_1$, and distance $r$.

Relation (1) is exactly valid only for electric dipoles. Using sources of another type (e.g., two distant electrodes) the quasi-static range changes slightly. In case of high resistivity basement ($\rho_0 \gg \rho_1 \ll \rho_2$), the thickness of the conducting layer has also a significant influence. Hence, for the frequency $f$ and the resistivity $\rho_1$ only an approximate relation can be obtained from (1) for a given $r$ and given limit or error $\eta$:

$$f/\rho_1 < (10^7/8\pi^3) \cdot (\eta/r^2),$$

(2)

In the case of suitable $\rho_1$ and $r$ the induction effects of low-frequency signals satisfying the approximate relation (2) are negligible with respect to their DC effects. Such signals can be called quasi-static. The period of the quasi-static signals occurring in field research must be in general at least several tenths of second.

INTERPRETATION OF THE MT S-INTERVAL AS A FIELD OF A HORIZONTAL, INFINITELY LONG DC LINE SOURCE

In the MT $S$-interval the geomagnetic pulsations have periods in the range in which the upper layer becomes saturated with current, but the effect of the electromagnetic induction generated in incidental well-conducting structures below the high resistivity basement cannot be yet observed. Therefore in the $S$-interval there is an almost homogeneous quasi-static current density in the upper layer.

The direction of the electric field-strength vector points in the direction of the current and the direction of the inphase magnetic field is perpendicular to it. According to Berdichevsky (1968) the quotient of the absolute values of the components $E_s$ and $H_s$ is

$$Z = E_s/H_s = 1/S,$$

(3)

where $S$ is the horizontal electric conductance of the upper layer, i.e., the quotient of the thickness $h$ and the resistivity $\rho_1$. The magnetotelluric mapping of a high resistivity basement can be made using (3).
The electromagnetic field in the magnetotelluric S-interval can be interpreted as the field of an infinitely long, horizontal DC line source situated very far away. The electric potential of a line source situated on the surface of a two-layered half-space with a resistive basement is according to Szigeti (1980):

$$U(x) = \ln \left[ \exp \left( \frac{\pi x}{h} \right) + \exp \left( -\frac{\pi x}{h} \right) \right] + \text{const}$$  \hspace{1cm} (4)

As it can be seen from (4), the potential becomes a linear function of $x$ for $x > 1.3 \ h$, that means the field-strength is homogeneously distributed.

The homogeneous DC field (in accordance with Biot-Savart's law) produces a homogeneous magnetic field distribution perpendicularly to the direction of the current, so the analogy between the field relations in the magnetotelluric S-interval and those of a distant, horizontal, infinitely long DC line source is complete.

As the vectors $\mathbf{E}$ and $\mathbf{H}$ have a simple connection with the parameters of the layer for the case of a line source, one can expect a similarly simple relation for sources of other types.

The sources of artificial DC fields used in geophysics are usually point- or dipole sources. In the following chapter the relation between the impedance and the horizontal electric conductance will be deduced for these cases.

### The S-Interval of a DC Point Source

The electric potential of a DC point source situated on the surface of a low resistivity ($\rho_s$) sediment covering a basement of high resistivity ($\rho_s < \rho_b$) has a cylindrical symmetry. When the reflexion coefficient equals 1, then

$$U(r) = \frac{\rho_s I}{2\pi} \left[ \frac{1}{r} - \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{\sqrt{r^2 + (2nh)^2}} \right].$$ \hspace{1cm} (5)

At a distant measuring point ($r > 2h$) the potential varies as the logarithm of $r$ that means for the electric field-strength is a function of type $1/r$, contrary to the constant electric field-strength distribution of the DC line source. This can be seen directly by expressing the current density on the surface of a cylinder with the point source on its axis having height $h$. At points $r > 2h$ the current density is constant, therefore

$$E_r = \rho_s \frac{Ih}{2\pi r} e_r$$ \hspace{1cm} (6)

The magnetic field of the current spreading from a point source at the surface in the soil when the underground structure has a cylindric symmetry around the source can be calculated not only from the Biot-Savart’s law, but also from Ampère’s law. Edwards (1974), when elaborating the basis of the magnetometric resistivity method (MMR) derived the following relation for the horizontal magnetic field-strength:

$$H_r = \frac{1}{4\pi r} e_r$$ \hspace{1cm} (7)
This relation is valid for each structure satisfying the cylindric symmetry around the point source, therefore it is also valid in horizontally layered media. From (6) and (7), it follows that for \( r > 2h \) the impedance calculated from the electric and magnetic field-strengths of the direct current spreading from a point source:

\[
Z = \frac{E_y}{H_y} = \frac{2}{S}.
\]  

(8)

The horizontal electric and magnetic fields of several point sources can be superimposed, therefore (8) remains valid also for more complicated sources whose field can be replaced by a finite sum over the fields of point sources.

The effect of cables connecting the electrodes may cause some distortion in the magnetic field, because the superposition of the magnetic fields requires the superposition of the whole current carrying circuit, including also the cables. If it is presumed that the cables are horizontal and the measurements are made in the horizontal plane of the cables, there is no horizontal magnetic component deriving from the cable current. Edwards (1974) based his MMR method on a similar hypothesis.

It must be mentioned that the quasi-static point sources can be at any depths in the upper layer if the cable section connecting the buried electrode and the surface is vertical. According to Edwards (1974) \( H_y \) in relation (7) includes the effect of this vertical cable section. Concerning \( E_y \), at distant measuring points where the current distribution does not depend on the depth, it is naturally insignificant whether the source is at the surface or somewhere in the layer itself.

In the sense of (8) the horizontal conductance of the upper layer can be also determined from the impedance calculated from the electric and magnetic fields of distant quasi-static sources of unknown position and intensity.

For the application of the proposed method these sources have to fulfil two requirements:

1. According to (6) the distance between the source and the measuring point must be at least twice the expected depth of the high resistive basement (for nearer sources the impedance would also depend on distance).

2. The field generated by point- or dipole sources has to be quasi-static and the period of the signal has to fulfil the requirements of the \( S \)-interval. (If the high resistivity basement is very thick, the periods might have practically only a lower limit. When the high resistivity layer is thin and there is some high conductivity structure below the resistive basement, the periods are limited on both sides).

**Geoelectrical Mapping of a Horizontally Inhomogeneous High-Resistivity Basement**

To determine the relief of the high-resistivity basement in the Hungarian basins, initially the fast and simple potential mapping (PM) is used (i.e., measuring of the electric field distribution on the surface between two distance point sources).

Recently measurements have been carried out of the magnetic field of a direct current originating from point sources and flowing into the earth. This method
called magnetometric resistivity (MMR), was proposed by Edwards (1974) for ore prospecting.

The two independent geophysical methods are combined for geological situations with high-resistivity basement by (8). In other words, the horizontal conductance of the covering layer can be determined by a combination of the PM and MMR methods.

The potential or geoelectrical mapping of high resistivity inhomogeneities in the basement has been examined by analog modeling using the PM and MMR methods. Figure 1 shows results obtained over a fault in high resistivity basement. The angle between the direction of the current electrodes and the strike direction was 45°. Figure 1a illustrates the well-known phenomenon that the electric field distribution depends not only on the geological structure but also on the direction of the feeding electrodes. In the PM method this distortion effect can be eliminated using several layouts in different directions (fig. 1c).

Figure 1b shows the distribution of $H_y$ over the fault. According to fig. 1d the $S$-map determined from the $E_x$ and $H_y$-field distributions of only one layout also

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Fig. 1. Results of analog modeling using the quasi-static field of point sources above a fault in the resistive basement. (a) Relative $S$-map of the potential mapping method using only one layout, (b) $H_y$-map of the magnetometric resistivity method, (c) $S$-map of the PM method using two perpendicular layouts, (d) $S$-map of the combined PM-MMR method.
reflects the geological structure. The anomaly itself is influenced by the angle between the layout and the strike, but from this point of view the $\hat{S}(E^1_x/H^1_y)$-map gives also somewhat better result than the $\hat{S}(E^1_x, E^2_x)$-map.

APPLICATION OF A QUASI-STATIC FIELD OF UNKNOWN ARTIFICIAL ELECTRICAL NOISE SOURCES FOR THE EXPLORATION OF HIGH RESISTIVITY BASEMENT STRUCTURES

The horizontal electrical conductance of the sediments covering a high resistivity basement in the sense of (8) can be determined using not only the quasi-static field of controlled point sources but also that of unknown, distant point- or dipole sources.

The geoelectrical field measurements are often disturbed by artificial electrical noise, mostly of industrial origin, from distant point- or dipole sources. Among the impulses of irregular length there are always impulses where the period of the fundamental harmonic (which gives the main part of the energy in the noise-impulses) is in the $S$-interval. Therefore (8) has a practical significance in this case too.

Geoelectrical noise always has both electrical and magnetic components. The magnetic field of the spatial current-density $\mathbf{j}(r')$ in the volume $V''$ is determined by Biot–Savart’s law. According to Stratton (1941)

$$\mathbf{H}(r) = \frac{1}{4\pi} \int_{V''} \mathbf{j}(r') \times \text{grad} \frac{1}{|r - r'|} \, dV'' \quad (9)$$

In the sense of (9) the quasi-static artificial electrical noises have also measurable magnetic components, with the exception of local sources of small intensity. The electrical and magnetic impulses caused by industrial noise sources can be studied especially well on analog records of MT measurements.

For a high-resistivity basement the impedances calculated from (3) and (8) can be written as

$$Z_{\text{point}}/Z_{\text{MT}} = 2. \quad (10)$$

If one interprets the noise impulses as magnetotelluric pulsations, the relation

$$\rho_{\text{point}} = 4\rho_{\text{MT}} \quad (11)$$

holds.

A divergence between apparent resistivities calculated from the electromagnetic field of point sources and of geomagnetic pulsations was studied also by Goldstein and Strangway (1975). Relation (8) gives a simple physical explanation for this divergence in the $S$-interval.
FIELD EXAMPLES

Numerous field examples could be found in the analog magnetotelluric records of the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences to support statements made in the paper.

1. At a magnetotelluric deep sounding at Breitenbuch in the Graz basin, Austria (for details see Ádám, Márcez, Verő, Wallner, Duma and Gutdeutsch 1980) some irregular noise impulses of durations of several seconds were observed mainly in the $E_x - H_y$ pair.

   Figure 2 shows a several minute long section of the analog magnetotelluric records of components $E_x$ and $H_y$. The quasi-sinusoidal magnetotelluric pulsations are often disturbed by rectangular impulses of unknown origin. Several of them are denoted by arrows.

   In Ádám et al. (1980) the MT pulsations and these impulses were also interpreted by the MT processing method. Figure 3 shows the MT sounding curve $\rho_{\text{max}}$ at Breitenbuch together with the determined curve points where the relative weights of reliabilities of MT values are also denoted. The upper curve was determined from the “noise” impulses. It was found that apparent resistivities $\rho^{\text{MT}}_{\text{noise}}(\sqrt{T})$ in the $S$-interval run parallel to the MT sounding curve, and the resistivity values were just four times the magnetotelluric ones.

   In the sense of (11) this divergence must have been due to the character of these noise-impulses, which were derived from some distant point- or dipole source. Using (8) the correct value of the horizontal electric conductance can be obtained.

2. During MT soundings in the western fore-land of the Bakony Mountains, Hungary (Ádám 1980) unusual artificial distortions of electrical and magnetic field were recorded which were due to electromagnetic rectangular signals (fig. 4).

![Fig. 2. Noise impulses of unknown origin (several of them are denoted by arrows) on analog MT record of components $E_x$ and $H_y$ at the Breitenbuch MT site.](image-url)
Fig. 3. Magnetotelluric sounding curve $\rho_{\text{max}}$ at the Breitenbuch MT site with the apparent resistivities obtained from noise-impulses using the MT processing method (after Ádám et al., 1980). (△) Noise: (●, ○, ×, ·) MT values with weights 8, 4, 2, and 1.

Fig. 4. Rectangular impulses of a distant artificial frequency-sounding disturbing the analog MT records of the horizontal electric and magnetic components at the Dabronc MT site. The beginning of the disturbed section is shown by large arrows.
I. Depth of the structural elements (blocks)

- 100
- 300
- 500
- 800
<= -800 Below -800 m

II. Geological formations

\( \text{\textsuperscript{2}}T_3 \) Formation of Kössen
\( \text{\textsuperscript{2}}T_3 \) Formation of Main Dolomite
\( T \) Triassic

Tectonic elements younger than Upper Cretaceous

MTS

0 1 2 3 4 5 km

Fig. 5. Depths of formations below Senonian at the south-western part of the Transdanubian Middle Mountains in Hungary (according to J. Haas, personal communication, 1982) and the four MT measuring sites (denoted by full points).
As it was found later, our MT records were disturbed by resistivity sounding surveys (1/30 Hz < f < 30 Hz) carried out by the Hungarian Geophysical Enterprise. They used an electric dipole of about 2 km length as transmitter. The output of their generator was 450 V × 60 A. The current electrodes were about 20 km north of our measuring area.

Figure 5 shows the four MT measuring sites (denoted by full points) and the geological map of the exploration area. At these measuring sites the effective impedances

\[ Z_{\text{eff}} = \sqrt{E_x^2 + E_y^2} / \sqrt{H_x^2 + H_y^2} \]  

were calculated from the noise impulses. In spite of relatively large errors due to the small magnetic components the effective impedances are in close connection with the approximate depths of blocks of the high-resistivity Triassic limestone basement at the four points, as seen on table 1.

Table 1. The value \( S \) calculated from artificial noises and the depths \( h \) of the high resistivity Triassic basements at the four MT sites

<table>
<thead>
<tr>
<th></th>
<th>( S [\Omega^{-1}] )</th>
<th>( h [\text{m}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ötvös</td>
<td>25.7 ± 2.5</td>
<td>800 &lt; ( h_1 )</td>
</tr>
<tr>
<td>Dabronc</td>
<td>13.3 ± 1.3</td>
<td>100 &lt; ( h_2 ) &lt; 300</td>
</tr>
<tr>
<td>Gogánfa</td>
<td>15.2 ± 1.5</td>
<td>300 &lt; ( h_3 ) &lt; 500</td>
</tr>
<tr>
<td>Ukk</td>
<td>19.1 ± 1.9</td>
<td>300 &lt; ( h_4 ) &lt; ?</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The quasi-static field of distant point- and dipole sources can be used in exploration of high resistivity basements in the same way as in magnetotellurics. Due to the derivation of the impedance from the horizontal vectors \( E \) and \( H \) the necessity for information concerning the position of the sources and current intensity is eliminated. This result offers several advantages in the exploration of the high-resistivity basement using quasi-static (or DC) controlled point-sources.

It has also been demonstrated that the horizontal electrical conductance of the upper layers can be obtained from noise-impulses coming from distant industrial point- or dipole sources. It may be possible to obtain the value of \( S \) in a district of about 20–30 km from any high-power point- or dipole source. Neglecting this phenomenon may cause a systematic error when processing this type of noise as geomagnetic pulsations during digitally recorded magnetotelluric measurements. Knowing the origin a correction can be made to eliminate this distortion effect.

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REFERENCES


Szkgili, G. 1980, Application of the conform transformation method for determination of the electric field above cylinder-like structures arising from the high-resistivity basement (in Hungarian), Magyar Geofizika 21, 121–133.