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A MAGNETOTELLURIC METHOD FOR DETERMINING AQUIFER DEPTHS

by

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ABSTRACT

A magnetotelluric method for determining aquifer depths is described, which was tested along the "Blue Road Traverse" in central Sweden. It was necessary to choose a sampling interval as low as 0.04s, to ensure that thin aquifers were not missed in interpretation. The depth of the "Blue Road" aquifer was estimated to be about 38m, for a depth of about 1km investigated. The merits of the magnetotelluric method over other methods of investigating aquifer depths are discussed.

1. INTRODUCTION

In the magnetotelluric (MT) technique of conductivity investigation, observations are made only at one station, and the time variations of two orthogonal components of both electric and magnetic fields are recorded. The method for deriving conductivity distribution with depth proposed by Cagniard (1953) assumes that the earth is one-dimensional, that is, that conductivity varies only with depth. However, noting that many structures are multi-dimensional, Wright (1970), Weildelt (1975), and Haak (1972) proposed methods of interpreting such structures. Inductive methods such as MT and geomagnetic deep sounding (GDS) are superior to galvanic methods, that is, to methods in which current is applied to the earth by grounded electrodes, in that in inductive methods, much greater depths can be investigated. The energy source for inductive methods is the natural variation of the geomagnetic field.

Some of the materials which affect electrical resistivity within the earth are water content, temperature, mineral composition, and porosity (Kellér & Frischneckt, 1966; Green, 1972; Shankland, 1975; and Duba, 1972). The relative importance of these parameters is depth dependent. For instance, water content greatly influences conductivity in the upper crustal layers while temperature is of major significance below the crust.

2. A BRIEF ACCOUNT OF THE STRUCTURAL GEOLOGY OF THE STATION

The field work reported in this paper was carried out in central Sweden, along the "Blue Road Traverse" (figure 1). The main rock groups are the archean rocks which are uplifted by faults, and traversed by valleys carved out by postilurian erosion. The hill tops rise to the same average height over wide areas even when the rocks are of widely varying composition and structure. The main bulk of the formation consists of reddish-brown sandstones. Their thicknesses attain a maximum of about 80m in the south and thin out towards the north. Thin intercalations of chocolate-coloured shale are frequently met within the upper horizons, and conglomerates are usually present in the bottom layers. The clays within the Scandinavian archean area are generally washed out products of moraine, principally composed of crushed but not decomposed species of primary rocks.

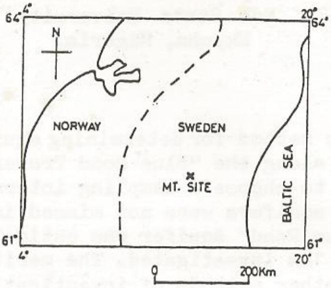

Fig. 1: Magnetotelluric Site

3. FUNDAMENTAL THEORY

The relevant Maxwell's equations are:

$$\nabla \times \underline{E} = -\partial \underline{B}/\partial t = -\mu \partial \underline{H}/\partial t \quad (1)$$

$$\nabla \times \underline{H} = \underline{J} + \partial \underline{D}/\partial t = \sigma \underline{E} + \varepsilon \partial \underline{E}/\partial t \quad (2)$$

Cagniard (1953) proposed an impedance relationship of the form:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} 0 & Z_{xy} \\ Z_{xy} & 0 \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \quad (3)$$

Eq (3) assumes that the impedance is a scalar quantity. However, in areas of lateral conductivity variations, this relationship does not give interpretable, meaningful, or consistent results. Berdichevski (1963), followed later by other workers, expressed the relationship between the $\underline{E}$ and $\underline{H}$ fields in the form of an impedance tensor:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \quad (4)$$

A common acceptance criterion for MT data is that coherence between one telluric component and one, or both, of the magnetic components should be above a minimum level. However, there is no rigidity as to what constitutes an acceptable level. Rather, the idea is to analyse the best available data. If X(t) is the input and Y(t) the output of stationary time series with power spectra $P_{xx}(f)$ and $P_{yy}(f)$ respectively, and cross-spectrum $P_{xy}(f)$, the coherence between the two time series is defined as

$$C^2_{xy}(f) = |P_{xy}|^2/P_{xx}P_{yy} \quad (5)$$

where $0 \leq C_{xy}(f) \leq 1$.

Another problem encountered in data analysis is to decide whether the structure is one-, two-, or three-dimensional. This is often determined by computing the skew, defined by

$$\text{skew} = (Z_{xx} + Z_{yy})/(Z_{xy} - Z_{yx}) \qquad (6)$$

A site is regarded to be one-, two-, or three-dimensional if skew is zero, less than 0.4, or greater than 0.4, respectively. In a practical situation, we wish to find the direction of strike and compute impedances parallel and perpendicular to it. This reduces the data to what would be expected for a one-dimensional **structure**, a situation which is relatively easy to analyze. For this purpose, Reddy and Rankin (1971) suggested maximizing

$$Z_{xy}(\theta)^2 + Z_{yx}(\theta)^2,$$

while Swift (1967) preferred minimizing

$$Z_{xx}(\theta)^2 + Z_{yy}(\theta)^2,$$

where θ is the strike angle. These two methods were used in numerical methods for estimating strike angle.

An approximate depth interpretation formula, given by Keller and Frischknecht (1966), is

$$h_1 = 800(\rho_a/\omega)^{\frac{1}{2}} \qquad (7)$$

where the permeability of the earth is taken as $\mu = 1.5 \times 10^{-6}$ H/m, $\omega = 2\pi f$ = angular frequency of the field oscillation, and ρ_a is apparent resistivity. A curve fitting method of depth estimation is given in some detail by Asokhia (1979).

4. EQUIPMENT FOR THE MT MEASUREMENT

The instrument for the MT measurements was constructed in Kiruna, north Sweden. The total weight was 113kg. Details of the construction are given in Asokhia (1979). The major components, by weight, are: (i) a three-component magnetometer of the variable-mu type, constructed by the Electro-Mechanics Company, Austin, Texas, USA, which was used for measuring the magnetic field. Two loops were used along with it for measurements involving high frequencies. The total weight of the magnetometer was 36kg. (ii) The electric signal from the earth electrodes and the magnetic signal from the loops are both in the range 10 to 1000 µV. It is necessary to amplify these signals by 60 to 80dB before they are recorded on magnetic tape, and all the amplifiers used for this purpose weighed about 31kg. (iii) Either lead or copper electrodes could be used in the field. However, lead electrodes have an advantage over copper in that lead electrodes need not be immersed in solution. The copper electrodes have to be checked regularly for leakages. A typical copper electrode used for this project is illustrated in figure 2. It weighs about 6kg. (iv) The recorders have two components, namely tape recorder and paper chart recorder. The recorders are of make Telefunke, model MS-54. The tape recording equipment consists of a 4-channel FM unit. The total weight of the recorders is about 27kg. (v) Single conductor cables are preferable. Where cables are joined to make up the required length, epoxy glue is properly spread at the soldered junctions. The total length of the ca-

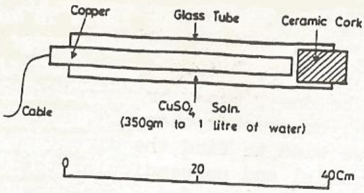

Fig. 2: Copper electrode for experiment.

ble used for this project was 60m, and the weight was 13kg.

5. DATA ACQUISITION AND PROCESSING

Figure 3 shows the layout of sensors at the measuring site. The common electrode is used as ground, and connected to the instrument chassis. It is useful if the direction of the other two electrodes coincide with the geomagnetic north-south and east-west directions because, then, the direct qualitative comparison between orthogonal magnetic and telluric records is possible. However, it is possible to record telluric variations with non-orthogonal axes which are not coincident with geomagnetic axes. The vectors can then be resolved into the desired orientation at the first stage of data reduction on the computer. The electrodes are buried for some time to

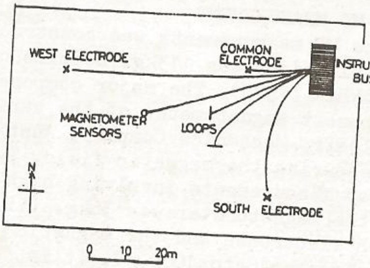

Fig. 3: Layout of sensor at the measuring site

allow them to stabilize before recording. The cable length used was 60m, and they were buried in shallow trenches to reduce temperature fluctuations and possible disturbance by animals. (The reindeer was common in the region of investigation.) The instrument incorporates digitization of the data, although analog record could always be produced with photographic developing instruments for inspection in the field. Figure 4 shows typical signals for the electric and magnetic fields. The raw data, in the form of voltage histories, were recorded on magnetic tape using the American code for information interchange (ASCII). The analog record was digitized at sampling interval I given by

$$I = P/RS$$

where P = play-back speed, R = recording speed, and S = sampling rate. A sampling interval as small as 0.0449s was used to ensure that very thin aquifers, as thin as 1m, were observed. The digitized data were retained in ASCII. However, the IBM computer at the Uppsala data centre which was used for analyzing the data does not operate in ASCII. It was necessary to convert the ASCII to external binary coded decimal interchange code (EBCDIC) for this computer. A FORTRAN program was written to do this conversion and to print out the values. The data were then visually edited, and linear trends removed. The response data were then transformed from time domain into complex frequency domain, using Fourier transform, given by

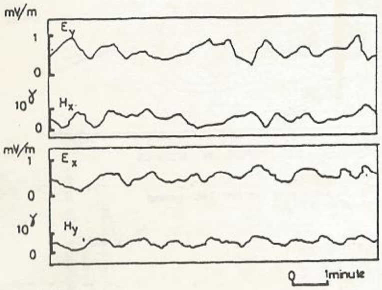

Fig. 4: Typical signals. The signals E_x and E_y from the earth electrodes and H_x and H_y from the magnetometer. Band width is 0·01 - 3Hz

$$X(f) = \int_{-\infty}^{\infty} X(t)e^{-i\omega t}dt \qquad (9)$$

so as to estimate frequency-dependent characteristics such as conductivity, impedance, etc. Finite Fourier transform was actually used since signal records were limited. Impedance analysis was performed using eq (4), while coherence was computed using eq (5). The strike angle was calculated by the method of rotating tensor impedance. Eq (6) was used for estimating the skew. Depth estimation was achieved by using eq (7), and by curve fitting for comparison. Other details of MT data analysis are given in Asokhia (1979).

6. RESULTS AND INTERPRETATION

Figure 5 shows a graph of coherence versus log period, for electrodes buried in the E-W and N-S directions. Mean coherence was about 0.6, showing that the records were fairly good. The graph of strike angle versus log period is shown in figure 6. The results obtained by minimizing the sum of square of diagonal terms of tensor impedance and by maximizing the anti-diagonal terms were identical for periods longer than about 0.6s. At shorter periods, the difference was generally less than 10 degrees. This type of marginal difference is permissible in MT work. The mean strike angle was about 41 degrees. Figure 7 is a graph of tensor impedance versus log period.

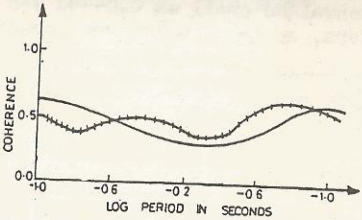

Fig. 5: Coherence versus log period

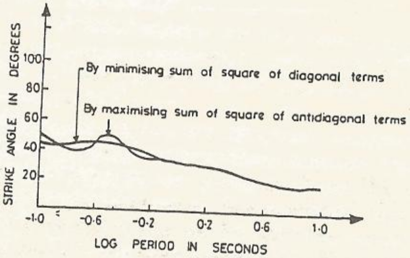

Fig. 6: Strike angle versus log period

The diagonal terms of tensor impedance were low, compared with the anti-diagonal components. This is desirable because the lower the diagonal elements are, in comparison with the anti-diagonal, the closer the structure is to a one-dimensional model, and the easier the interpretation. A proper configuration of the electrodes in the field also ensures the practical achievement of this objective. The structure was two-dimensional, since mean skew was 0.4. Figure 8 is a graph of apparent resistivity versus log period, for electrodes buried in the E-W direction. The minimum apparent resistivity value was about 0.1 ohm-m at a depth of about 38m. This type of low resistivity is typical of wet clay. The graph rises gradually

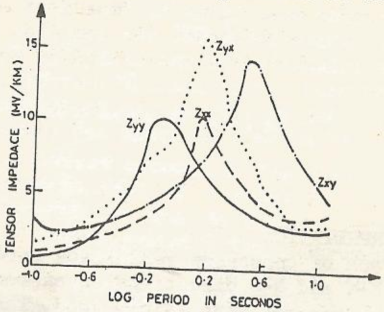

Fig. 7: Tensor impedance versus log period.

from this minimum value as wet, sandy formation was encountered. The thickness of the aquifer was about 5m. This was the only aquifer observed for the entire record length. Identical results were obtained for the N-S orientation of electrodes.

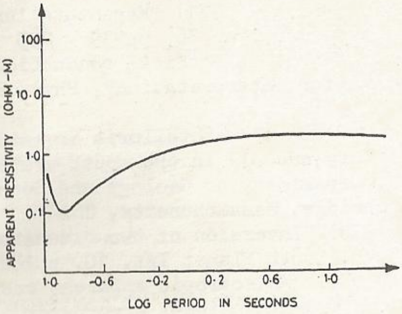

Fig. 8: Apparent resistivity versus log period.

7. CONCLUSIONS

The results of this work show that MT methods can successfully measure aquifer depths. The major drawback in this method is that much computer work is involved in MT interpretation, compared with the more conventional resistivity methods. The reliability of resistivity data decreases rapidly with depth, especially at depths greater than 100m, but results from MT data are reliable for depths of some kilometers. This may be important where, as is the case in many places, aquifer depths are greater than 100m. Besides, depth of investigation for the conventional resistivity survey is about 0.125 of the total cable length spread. As such, a straight path of about 800m would be required to investigate depths as little as 100m. Not many urban centres can provide this space, whereas in the MT method, a cable length of 30m can investigate depths of a few km. In view of its merits over resistivity methods, more research work should be done to improve the MT survey method.

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