AC EFFECTS IN RESISTIVITY DATA FROM GEOTHERMAL PROSPECTS

Grant Caldwell

Geothermal Institute
University of Auckland

M.P. Hochstein

Geothermal Institute
University of Auckland

Befekadu Oluma

Ministry of Mines, Energy
& Water Resources, Ethiopia

ABSTRACT

Electromagnetic coupling effects have not previously been considered important in the interpretation of Schlumberger resistivity measurements, Calculations presented here suggest that these effects can be of major significance in areas with low resistivities typical of geothermal systems.

Data from the Langano-Aluto geothermal prospect (Ethiopia) are successfully explained in the light of the results presented here. Although not as definitive as the Ethiopian data, data from a number of other geothermal prospects seem to show similar effects.

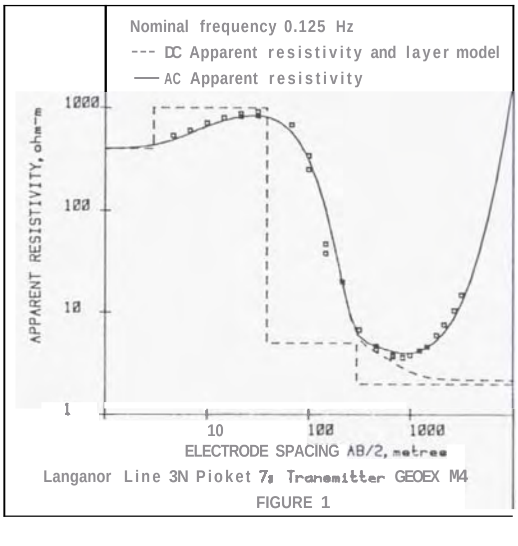
Introduction

Although the importance of electromagnetic (E.M.) coupling effects on induced polarization (I.P.) measurements has been recognised for some time (Madden, T.R. and Cantwell, T. (1967)), and detailed calculations for the dipole-dipole array have been published e.g. Millet, F.B. (1967) and Hohman, G.W. (1973), the effect of E.M. coupling on Schlumberger soundings has not been considered in detail.

As the results presented will show, the effect of E.M. coupling for the Schlumberger array using standard (i.e. long switching period) current sources is negligible if the current electrode spacing AB is not large (AB/2 $\lesssim$ 800 m) and all the resistivities in the ground are $\gtrsim$ 10 Ω-m. Since it is rare in other than a geothermal exploration survey for both of these conditions to be satisfied, the effect of E.M. coupling on Schlumberger resistivity soundings is not widely appreciated.

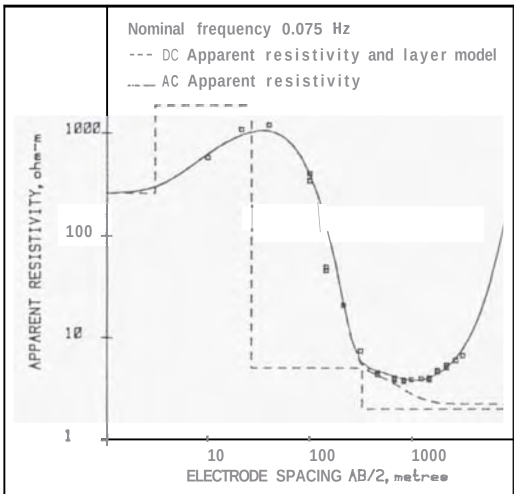
These effects, usually appearing as steeply-rising (>45°) sections on Schlumberger sounding curves, were recognised by Hochstein (pers. comm.) during a 1969 survey of the El Tatio geothermal field (Chile) when using a 0.3 Hz AC current source, and attributed to "skin" (electromagnetic) effects. Similar results were noted by H.M. Bibby (pers. comm.) in results from the Chinameca geothermal field (El Salvador).

However, it was results from a 1981 survey of the Langano-Aluto geothermal prospect, conducted by the Ethiopian Ministry of Mines, that motivated this paper. In this survey more than 20 large, maximum AB/2 = 3160 m, Schlumberger resistivity soundings were measured using a high-powered, controlled period, current sources*. All 20 curves show rapidly (>45°) increasing apparent resistivities for AB/2>1000 m., e.g. see Fig. 1.



Langanor Line 3N Pioket 7; Transmitter GEOEX M4

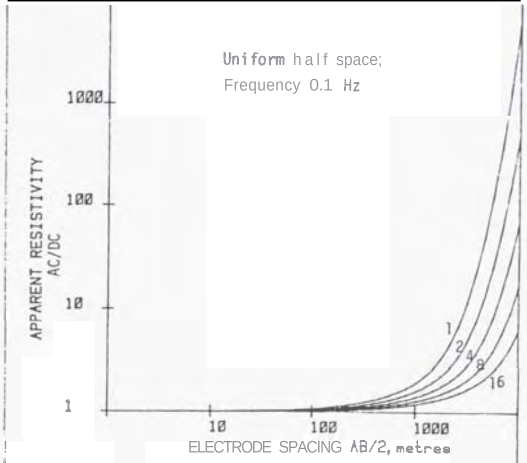
FIGURE 1



Langano Line 3N Picket 7; SINTREX IPR-10.

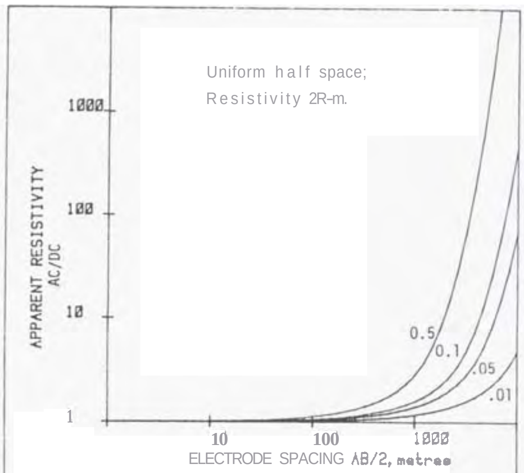
FIGURE 2

* *Heinrichs Geo-exploration Company I.P. and Resistivity Sender, Tucson, Arizona; and Scintrex IPC-7 15 kW I.P. transmitter, Concord, Ontario.*



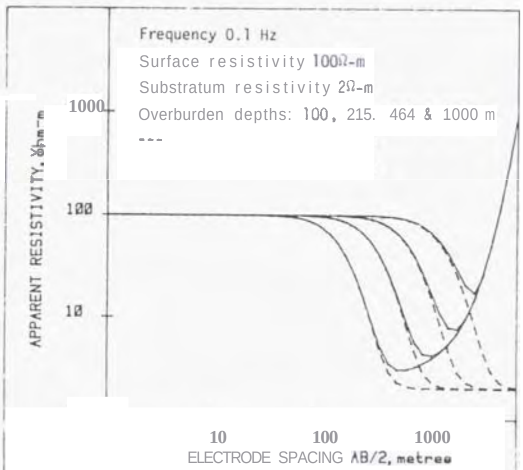
AC/DC app. reeie. for 1; 2; 4; 8 and 16 ohm-m.

FIGURE 3



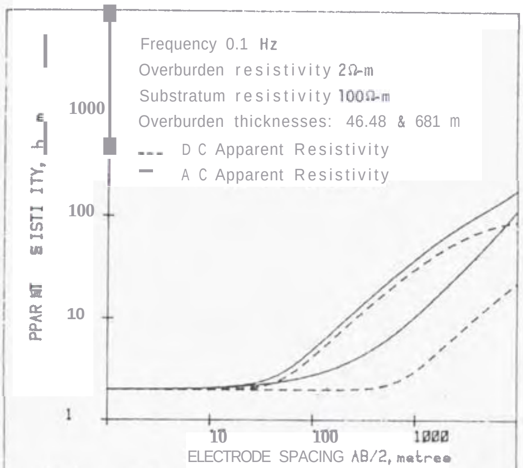
AC/DC app. resie. for .01; .05; 0.18 0.5 Hz

FIGURE 4



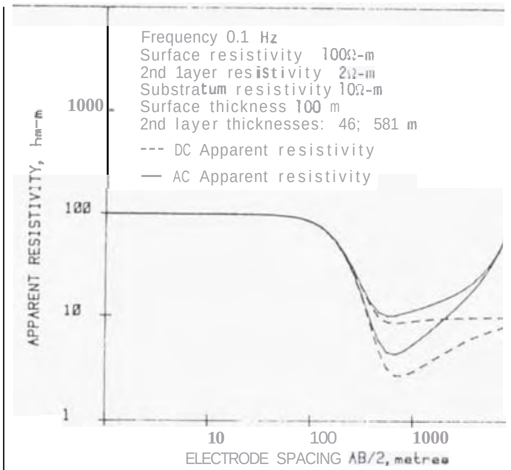
AC Appararent resistivity; reeietive overburden.

FIGURE 5



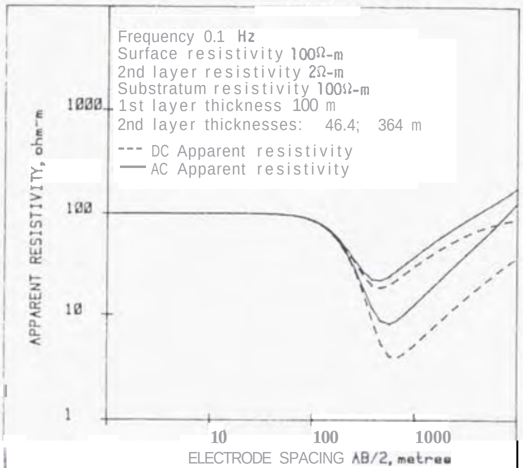
AC Apparent Reeietivityi oonduotive overburden.

FIGURE 6



AC Apparent Resistivity; three layer oaee.

FIGURE 7(a)



AC Apparent Reeietivityi three layer oaee.

FIGURE 7(b)

For $AB/2 \lesssim 800$ m the form of the curves is that of a normal descending type of sounding curve. Standard layer model interpretation of the initial part of the curves implies that resistivities of less than 10Ω-m occur throughout the survey area.

Non-layered structures and topographic effects can also produce steeply (>45°) rising branches of Schlumberger curves, Jackson, D.B. and O'Donnell, J.E. (1980) interpreted a sounding curve of similar form measured in the Coso geothermal area (U.S.A.) in terms of a conductive overburden overlying a highly resistive basement dipping parallel to the direction of array expansion. Such an explanation of the Ethiopian data is untenable for a number of reasons:

Even though the measurements were made over a wide area, all the soundings upturn at approximately the same electrode spacing. Also, soundings measured at the same position and azimuth using different source waveforms and receiver characteristics gave different results only for $AB/2 \gtrsim 1000$m, i.e. the steeply ascending section (Figures 1 and 2).

<u>Theory</u>:

The mutual impedance between two co-linear current elements dx and dx' lying on the surface of a homogeneous non-permeable earth of resistivity ρ is given by Ward, S.H. (1967) as

$$\frac{dv}{I} = dx\, dx' \left[\frac{i\mu\omega}{2\pi r}\left(\frac{1 - (1 - ikr)e^{ikr}}{-(kr)^2}\right) - \frac{\rho}{2\pi r}\right] \quad \text{(Eqn. 1)}$$

where: r is the distance between the elements

ω is the angular frequency

μ ($=\mu_0$) the magnetic permeability of the ground (free space)

and k the propagation constant.

For low frequencies displacement currents may be neglected and the propagation constant is given by

$$k^2 = +\frac{i\omega\mu}{\rho}.$$

For a Schlumberger array, potential electrode spacing MN << AB the current electrode spacing, equation 1, may be integrated along AB and rewritten in terms of apparent resistivities ρ_a to give

$$\rho_a^{AC} = \frac{\pi a^2}{MN}\frac{dv}{I} = \frac{\mu_0\omega}{2}\left[\frac{\sin ka + ika\cos ka}{k^2} - a^2\left\{ka - \frac{(ka)^3}{3.3!} + \frac{(ka)^5}{5.5!} - \ldots\right\}\right] + \rho$$

where a = AB/2.

These expressions may be generalised for an n-layered earth by substituting ρ_a^{DC} for ρ and k_a for k where k_a is given approximately by the plane wave propagation constant of a layered earth, i.e.

$$k_a = +k_1\left[\frac{z_1 + \hat{z}_2\tanh(ik_1h_1)}{\hat{z}_2 + z_1\tanh(ik_1h_1)}\right]$$

where k_1, h_1 and $Z_1 = \frac{\omega\mu}{k_1}$ are, respectively, the propagation constant, thickness, and intrinsic impedance of the first layer, and $\hat{Z}_2$ is given by the recussive formula

$$\hat{Z}_{j-1} = Z_{j-1}\left[\frac{\hat{Z}_j + Z_{j-1}\tanh(ik_{j-1}h_{j-1})}{Z_{j-1} + \hat{Z}_j\tanh(ik_{j-1}h_{j-1})}\right]$$

with

$$\hat{Z}_{n-1} = Z_{n-1}\left[\frac{Z_{n-1} + Z_n\tanh(ik_{n-1}h_{n-1})}{Z_{n-1} + Z_n\tanh(ik_{n-1}h_{n-1})}\right]$$

<u>Results</u>:

In general the amplitude and the phase of the sinusoidal signal are changed with respect to the source waveform. For non-sinusoidal waveforms the Laplace Transform of the waveform must be used to compute the received waveform. This, together with the detailed response of the voltage measuring circuitry, would enable the apparent resistivity for any particular waveform to be calculated.

However, the results presented here, in the form of sounding curves, are plots of the amplitude of the AC apparent resistivity at a single frequency.

Figures 3 and 4 show for a homogeneous medium the behaviour of $|\rho_a^{AC}|/|\rho_a^{DC}|$ as a function of frequency for ρ = 2Ω-m, and as a function of resistivity for f = 0.1 Hz.

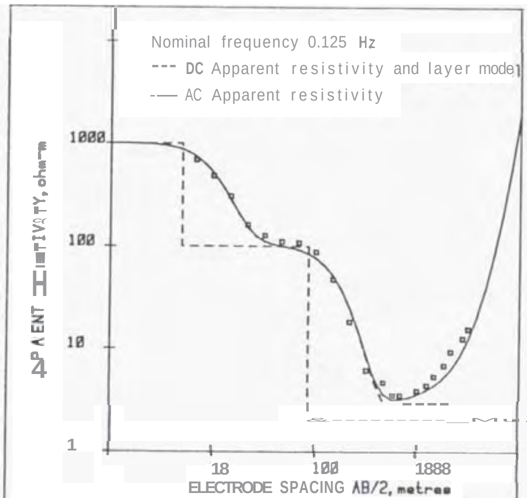
For a two-layer medium there are two possibilities, a conductive substratum or a conductive overburden:

For the conductive substratum case shown in Figure 5, the most interesting point to note is that if the overburden is thick then the apparent resistivities do not approach the substratum resistivity.

For a conductive overburden underlain by a very resistive substratum, the results (Figure 6) suggest that incorrect estimates of the depth below surface of the resistive layer will be made if the effects of electromagnetic coupling are ignored.

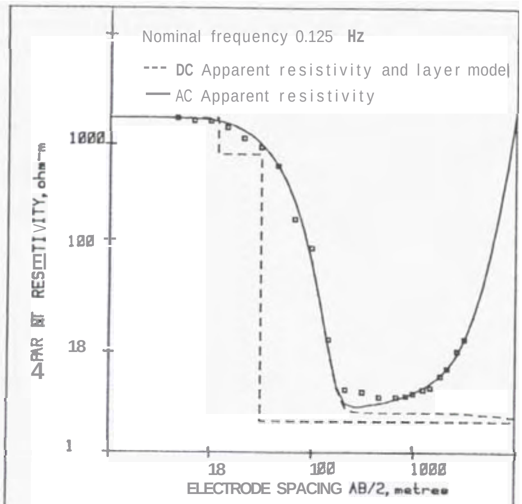
The three layered cases shown in Figure 7(a) suggest that a similar misinterpretation of the sounding curves will occur. In Figure 7(b) the presence of a thin conductive layer is relatively insignificant for AB/2 < 1000 m, as expected.

Figure 8 shows layer interpretations for two more of the curves from Langano based on the data for $AB/2 \lesssim 1000$ m. The interpretations suggest that low resistivities are present at about 100 m below the surface. If the AC effects are included then the complete curve can be reproduced without the need



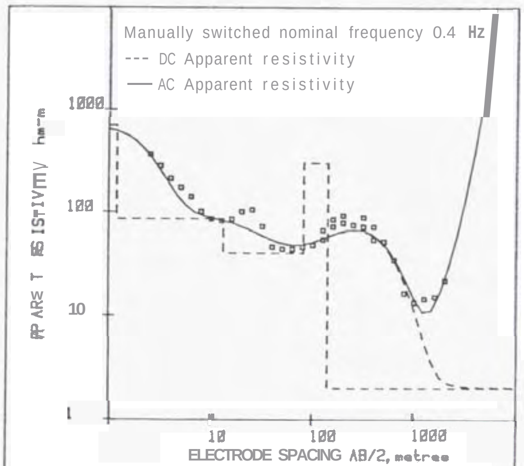
Langano: Line 14 Piokct 2W; Source GEOEX H4.

FIGURE 8(a)



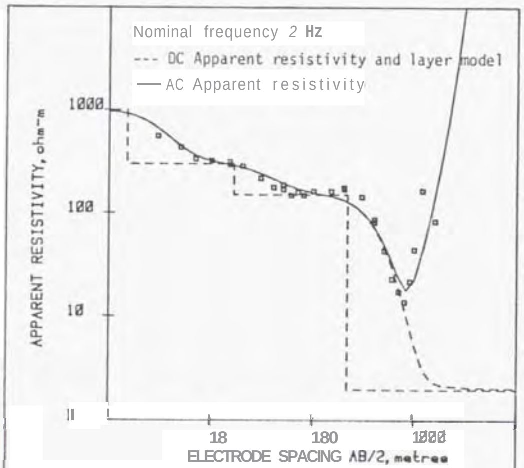
Langano: Line 14 Pioket 17; Source GEMX M4.

FIGURE 8(b)



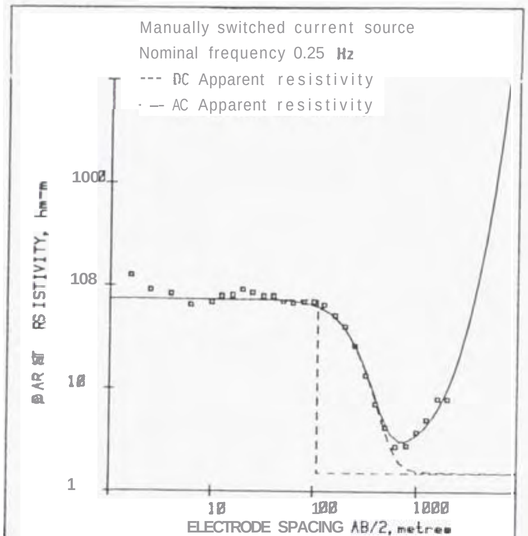
Bratan geothermal prosprot Bali from Mulyadi 1982.

FIGURE 9



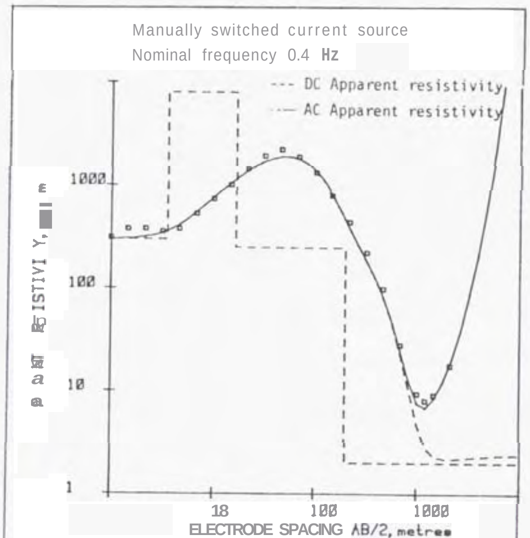
Kamojang geothermal firld Sudaraan S. in prep.

FIGURE 10



North Sulawesi (Indonesia) from Andan A. 1982

FIGURE 11



I. Teroerioa the Azores; Anderson E. et al. 1982

FIGURE 12

postulate a resistive substratum. It must be stressed that the interpretation here is approximate since a sinusoidal input current has been assumed. The current wave form used in this survey was the standard positive square pulse, off, negative pulse, off, I.P. wave form. The pulse duration was 8 or 10 seconds and with voltage being sampled near the end of the positive and negative pulses.

Discussion and Conclusions

The results presented here suggest that serious misinterpretations of larger array Schlumberger resistivity data will occur in areas of low resistivity unless the electromagnetic effects are taken into account. Areas with a thick layer of high resistivity overlying a conductive substratum will be most severely affected. In these cases the apparent resistivities measured will not suggest the presence of low resistivities at all.

In New Zealand and Indonesia it has been common to use manually switched current sources in conjunction with chart recorders to measure the voltage signal. Although every effort is made to measure the voltage change significantly after the switch, when the signal is small (large AB/2's and low resistivities), the tendency is to measure the high frequency edge of the wave form and also to increase the switching rate, especially in the presence of noise. These effects may explain the resistivity upturns seen in sounding data from Bali (Figure 9), Kamojang (Figure 10), and North Sulawesi (Figure 11).

In data from a geophysical survey of the Azores both these tendencies were noted in the chart records for the curves that showed a steep upturn (Figure 12); Tearney, K. (GENZL), (pers. corn.).

E.M. effects may also provide an alternative interpretation for the Coso data.

These results do not necessarily suggest that resistive material does not underlie these areas (indeed, the presence of a deep resistive basement may increase the electromagnetic coupling) but that the evidence from large array Schlumerger measurements cannot be used alone to infer this unless the electromagnetic effects have been considered. This does not seem to have been the case in any of the Schlumberger surveys of geothermal fields known to the authors.

The main conclusion of this study is that the electromagnetic effects on Schlumberger surveys in low resistivity areas are far more important than is generally realised. Unless the electromagnetic effects are considered, the interpreted results of such surveys could be very misleading.

ACKNOWLEDGEMENTS

The authors acknowledge the help and co-operation of the geophysical personnel at Geothermal Energy New Zealand Ltd. (GENZL) for facilitating communication with Ethiopia, and for many interesting and helpful discussions.

REFERENCES

ANDAN, A. (1982), Scientific Study of the Kotamobagu Geothermal Prospect, North Sulawesi, Indonesia. Geothermal Institute Report 82.01, University of Auckland (unpublished).

ANDERSON, E., TEARNEY, K., and USSHER, G. (1982), Geophysical Survey ,of the Pico-Alto Geothermal Prospect, Terceira Island, Azores. In Proc. of the N.Z. Geothermal Workshop, 1982.

BEFEKADU, O. (1982), Interpretation of resistivity and gravity of Aluto (Langano) geothermal prospect, Rift Valley, Ethiopia. Geothermal Institute Report 82.03, University of Auckland (unpublished).

HOHMAN, G.W. (1973), Electromagnetic coupling between wires at the surface of a two layer earth. In Geophysics, Vol. 38, No. 5, pp 854-863.

JACKSON, D.B. and O'DONNELL, J.E. (1980), Reconnaissance Electrical Surveys in the Coso Range, California. In J. Geophysical Research, Vol. 85, No. B5, pp 2502-2516.

MADDEN, T.R. and CANTWELL, T. (1967), Induced polarization: a Review. In Mining Geophysics, Vol. II, Tulsa SEG.

MILLET, F.B. (1967), Electromagnetic coupling of co-linear dipoles on a uniform half space. In Mining Geophysics, Vol. 11, Tulsa SEG.

MULYADI (1982), Exploration of the Bratan Geothermal Prospect, Bali. M.Sc. thesis, University of Auckland (unpublished).

SUDARMAN, S. (1982). M.Sc. thesis, University of Auckland (in prep.).

WARD, S.H. (1967), Electromagnetic Theory for Geophysical Applications. In Mining Geophysics, Vol. 11, Tulsa SEG.