AUDIO-FREQUENCY MAGNETOTELLURIC MEASUREMENTS IN THE BROADLANDS GEOTHERMAL FIELD USING 50Hz MAINS POWER AS THE SIGNAL SOURCE

P.C. Whiteford

Geophysics Division, D.S.I.R.
Wellington, N.Z.

ABSTRACT

Audio-frequency magnetotelluric (AMT) measurements using 50Hz mains power as the signal source were made at sites along three traverses crossing the resistivity boundary of the Broadlands Geothermal field. The traverses were in the same positions as those used previously for d.c. resistivity measurements which were made to locate the resistivity boundary of the geothermal field, and the results from the AMT measurements have been compared with the results from the d.c. measurements. The increase in apparent resistivity (ρ_{gm}) from low values to higher values (of up to $1\frac{1}{2}$ orders of magnitude) occurred at nearly the same locations as obtained from the d.c. measurements. The actual values of apparent resistivities (ρ_{gm}) were similar to those obtained from d.c. measurements, usually differing by a factor of less than 2, but at 4 of the 19 sites the apparent resistivities differed by factors of 3, 3, 4, and 10. Reproducibility was evaluated by making measurements at different times and with different array orientations at two sites. Good reproducibility (the apparent resistivities varied by up to 12% of the mean) was obtained except when the AMT measuring array was oriented close to a null in the 50Hz electromagnetic field.

INTRODUCTION

The audio-frequency magnetotelluric (AMT) method is a quick method for measuring ground resistivity which uses light portable equipment (Hoover 1975, Whiteford 1975). The method is based on the same theory as the magnetotelluric method which uses lower frequencies (Vozoff 1972).

The apparent resistivity (ρ_a) is calculated using the formula defined by Cagniard (1953).

$$\rho_a = \frac{\mu_o}{2\pi f} \left(\frac{E}{B}\right)^2 \quad \text{.....................} \quad (1)$$

where μ_o is the permeability of free space, E (V/m) is the amplitude of a component of the horizontal electric field, B (Tesla) is the amplitude of the component of the horizontal magnetic field at right angles to E, and f (Hz) is the frequency of the electro-magnetic field. These signals are measured at the surface of the earth. Cagniard (1953) stated that (1) should be used only when the ground is isotropic or when it consists of isotropic horizontal layers, and that it is assumed that the electromagnetic waves are planar and vertically incident on the earth's surface.

The depth of ground which influences the apparent resistivity varies between tens of metres and several kilometres, depending on the frequency of the wave and the resistivity of the ground (Strangway et al (1972)).

When the ground is anisotropic or inhomogeneous the ratio E/B in (1) varies with the orientation of the measuring array, and with different polarisations of the electromagnetic signals. These effects are explained theoretically by Rankin and Reddy (1969) and have been observed in AMT measurements repeated at the same sites (Strangway et al 1972, Whiteford 1975). These measurements showed that the apparent resistivities (as computed from (1)) varied by a factor of up to four when using natural signals as a signal source.

The natural signals are the electromagnetic waves at frequencies of 8 to several thousand hertz which are generated mostly by thunderstorms occurring throughout the world. The polarisation of the signals is not constant and this leads to the poor reproducibility when the ground is anisotropic.

Artificial signal sources may be used for AMT measurements and in the work described here, artificial signals emitted from the 50Hz mains power lines have been measured. The 50Hz mains signals, coming from a virtually constant source, have little change in polarisation which should result in good reproducibility in anisotropic ground. The 50Hz signals are several orders of magnitude larger than the natural signals and so are very much easier to measure than the natural ones.

When using artificial signal sources it is necessary to have a spacing between the receiver and signal source of at least three skin depths for equation (1) to be valid (Goldstein and Strangway, 1975). In ground with apparent resistivity of 2 Ωm this spacing is 300m and in ground with apparent resistivity of 20 Ωm this spacing is 1km.

The aim of the work was to compare the results of the 50Hz **AMT** measurements with **d.c.** measurements that had already been made in the Broadlands geothermal field. The AMT measurements were located along three traverse lines used previously for d.c. resistivity measurements which were made to locate the resistivity boundary of the geothermal field. The reproducibility of the **AMT** method was also checked.

INSTRUMENTS

The sensors of the instruments, which are electrodes and induction coils, detect signals that are proportional to the four components of the horizontal electromagnetic field (E_1, E_2, B_1, B_2). The four signals are amplified and integrated simultaneously for a fixed period. The magnitudes of the integrated signals are measured, and orthogonal pairs E_1, B_2 and E_2, B_1 are used in equation (1) to calculate the apparent resistivity. The orthogonal pairs of signals can be measured in succession, but it is quicker to measure them simultaneously.

The output signal V_c (volts) of an induction coil is

$$V_c = -k \frac{dB_i}{dt}$$

where k is a constant and B_i the component of the magnetic field in the direction of the axis of the coil, and t is time. The coils were calibrated to determine the value of k for each coil by placing them in turn at the centre of a 2-turn 30m diameter coil where the strength of the magnetic field could be calculated.

The electric field was detected with two pairs of iron-spike electrodes driven about 0.3m into the ground. The signal detected by the electrodes V_e (volts) is

$$V_e = E_i l$$

where l (m) is the spacing between electrodes, and E_i is the component of the electric field in the direction of the electrodes.

The electronic unit consisted of four channels, each with a pre-amplifier, filter, rectifier, and integrator. All four integrators were controlled simultaneously from a timer.

FIELD PROCEDURE

The measuring array, consisting of two pairs of electrodes and two coils, was aligned in the same azimuth at most sites. The two electrode pairs were aligned N-S true (E_1) and E-W (E_2) with a spacing between the two electrodes in a pair of 15m. The two horizontal coils were aligned N-S (B_1) and E-W (B_2). When the sensors were aligned in this manner the measuring array was said to have an azimuth of 0° true.

The wires from the electrodes and coil were connected to the electronic unit and the attenuation adjusted to give suitable signal amplitudes. The signals (either E_1 and B_2, or E_2 and B_1) were monitored on two of the instrument's meters and the presence of spikes or signal fluctuations observed. The 50Hz signals were usually of constant amplitude. Between 3 and 6 observations were made at each site.

Field measurements were made in the Broadlands Geothermal Field along three traverse lines previously used for d.c. measurements (Risk et al 1977) and at two sites for reproducibility tests, one inside and one outside the geothermal field (Fig. 1). At both sites where reproducibility tests were made, **AMT** measurements were made at different times, and at one of these sites measurements were made with two array orientations.

The traverse lines are labelled C, G, and K in Fig. 1. The AMT sites were spaced 100m apart along the traverse lines. There were 7 sites along traverse C, 7 along G, and 6 along K. The AMT sites for traverse line C were adjacent to the d.c. traverse line for C as Fig. 1 shows. Inside the geothermal field the **d.c.** and AMT traverse lines were about 180m apart but outside the geothermal field the ends of the traverse lines coincided.

Site B and traverse line C were about 900m from the nearest power lines, site A was about 200m, traverse line K about 500m to 900m, and traverse G about 2500m from the nearest power lines.

At each site two apparent resistivities were calculated using equation (1), one using E_1 and B_2, and the other using E_2 and B_1. These were combined as a geometric mean to give a mean apparent resistivity ρ_{gm} for the site.

RESULTS AND DISCUSSION

<u>Traverses</u>

The apparent resistivity ρ_{gm} was calculated for each site and plotted in Fig. 2 for traverse C, in Fig. 3 for traverse G, and in Fig. 4 for traverse K. Also in these figures are plotted the values of d.c. apparent resistivity measured for 2 or 3 separate runs on each traverse, each run having a different d.c. signal source (Risk <u>et al</u> 1977). The boundary of the geothermal field defined by Risk <u>et al</u> (1977) is shaded. It is defined as the zone where the d.c. apparent resistivities lie between 1.2 and 2.5 times the ambient apparent resistivity value on the inside of the boundary. In Fig. 4 (traverse K) the boundary zone was defined by d.c. traverse lines adjacent to K but not including K (Risk <u>et al</u> 1977) and would be placed in a different position using d.c. traverse line K alone.

The AMT apparent resistivities (ρ_{gm}) inside the field vary between 0.7 Ω.m and 4 Ω.m and increase to between 13.7 Ω.m and 52 Ω.m on the outside, an increase of between ½ and 1½ orders of magnitude. When AMT and d.c. sites were not the same the d.c. apparent resistivities were interpolated. The ratio of the larger to the smaller value of AMT and d.c. apparent resistivity at each site was calculated. All but four are less than 2, and these have ratios of 3, 3, 4, and 10.

The results show that the AMT apparent resistivities agree well with the d.c. values. Along the traverse lines the AMT apparent resistivities show clearly the increase from low values inside the field to higher values outside, following the d.c. increases very closely. If the AMT apparent resistivities are used to define the boundary of the geothermal field, it would be very close to the d.c. one.

All the traverse sites are at least three skin depths from the 50Hz power lines except for the three sites outside the geothermal field on traverse line C. These sites have apparent resistivities ρ_{gm} of 35, 52, and 39 Ω m. The distance to the nearest power lines is about 900m, the distance in skin depths being 2.1, 1.75, and 2 respectively. The effect on the apparent resistivity of being closer to the source than three skin depths is to increase the measured apparent resistivity above its true value (Goldstein and Strangway, 1975). For spacings between the source and receiver of 2.0 and 1.75 skin depths the apparent resistivity is increased by about 35% and 70% respectively (Goldstein and Strangway, 1975). Although these correction factors apply to isotropic ground they can be expected to give reasonable results when applied to the measurements. Hence the apparent resistivities for these three sites are too high and correct values would be about 30 8.m.

The depth of penetration (or probing depth) would be considerably less for the AMT apparent resistivity than for d.c. measurements. For the AMT apparent resistivity the probing depth in ground of apparent resistivity 2 Ω.m (e.g. inside the field) is about 50m, and in ground of apparent resistivity 20 Ωm (e.g. outside the field) is about 160m. The probing depth for the d.c. measurements is between 1.5km and 3km but the top lkm was thought to have the most influence (Risk et al 1977).

In traverses G and K the AMT and d.c. apparent resistivity profiles are very similar although the probing depths are different. This would indicate that the resistivity must be fairly constant with depth. Inside the field on traverse G the AMT apparent resistivity is 0.7 Q.m while the d.c. value is about 6 Ω.m, suggesting that the resistivities are lower near the surface.

Outside the field on traverse C the AMT apparent resistivity is higher than the d.c., indicating lower resistivities with increasing depth, whereas inside the field on this traverse both AMT and d.c. apparent resistivities are of similar value.

Reproducibility Tests

Measurements were repeated at different times at two sites (site A and B, Fig. 1). The periods between repeat measurements were several hours to several days. At site B the measurements were made with two array orientations which were 45° different. Between 3 and 4 sets of readings were made at each observation time and the values of apparent resistivities (ρ_{gm}) calculated from each of these together with their means (called observation means). A site mean was calculated for each site. For site B, where measurements were made in two different array orientations, an array mean for each array orientation was also calculated from the observation means.

At site A and site B with the array azimuth of 80° the observation means differ from the site and array means by up to 12%, which is good reproducibility. At site B with array orientation 125° the observation means differ from the array mean by up to 68%, which is considered to be poor reproducibility.

When the field measurements were examined it was noticed that, for the measurements with good reproducibility, the magnitude of the component E_2 was 0.5 to 0.8 of the magnitude of E_1 in all cases. The ratios of the magnitudes of B_1 and B_2 were similar. In contrast, for the measurements with poor reproducibility (site B array orientation 125°), the magnitude of the component E_1 was 0.1 to 0.2 of the magnitude of E_2, and the magnitude B_2 was 0.1 to 0.3 of B_1. Hence most of the 50Hz electromagnetic signal was in the direction of E2 and B_1, and little in the direction of E_1 and B_2 (i.e. E_1 and B_2 lie close to a null in the 50Hz electromagnetic field). Apparent resistivities (ρ_a) were calculated using equation (1) for the larger components E_2 and B_1 (measured at site B, array orientation 125°) and they had a small variability of up to 10% of the mean value. This is good reproducibility. However apparent resistivities (ρ_a) calculated from the components near the null direction (E_1 and B_2) had a large variability of up to 500% of the mean. These results show that virtually all of the variations in ρ_{gm} for site B with array orientation 125° come from the variations in the components E_1 and B2. To obtain good reproducibility at sites such as this, only the larger components should be used to calculate the apparent resistivities.

At site B with array orientation 125° small changes occurring in the 50Hz mains signals (due to current changes in the network of local power lines) would affect the components E_1 and B_2 significantly but have little effect on the components E_2 and B_1. Differences in the orientation of the induction coil for component B_2, which may have occurred from one repeat measurement to the other, would also cause changes in the amplitude of component B_2.

Hence when making AMT measurements using 50Hz as a signal source the apparent resistivity ρ_{gm} should have good reproducibility if the components of E_1, E2 or B_1, B_2 are roughly the same size. If the components are different by more than a factor of about 3, then the larger components should be chosen and used in equation (1) to obtain an apparent resistivity. This should have good reproducibility.

At all of the traverse sites except three, the ratios of the magnitudes of the components were greater than 0.5 and accurate results could therefore be expected from them. At the three sites the ratios of the magnitudes of the components were greater than 0.3 and results of reasonable accuracy could be expected.

CONCLUSIONS

Measurement of AMT apparent resistivities using 50Hz mains as the signal source gives results that agree very closely with d.c. measurements made at the same sites. The boundary of the geothermal field can therefore be located with AMT measurements in the same manner to that used with d.c. measurements.

Reproducibility of the AMT apparent resistivities is good except when the AMT measuring array is oriented close to a null in the electromagnetic field and noise becomes significant. This reproducibility is very much better than that obtained from AMT measurements using natural signals.

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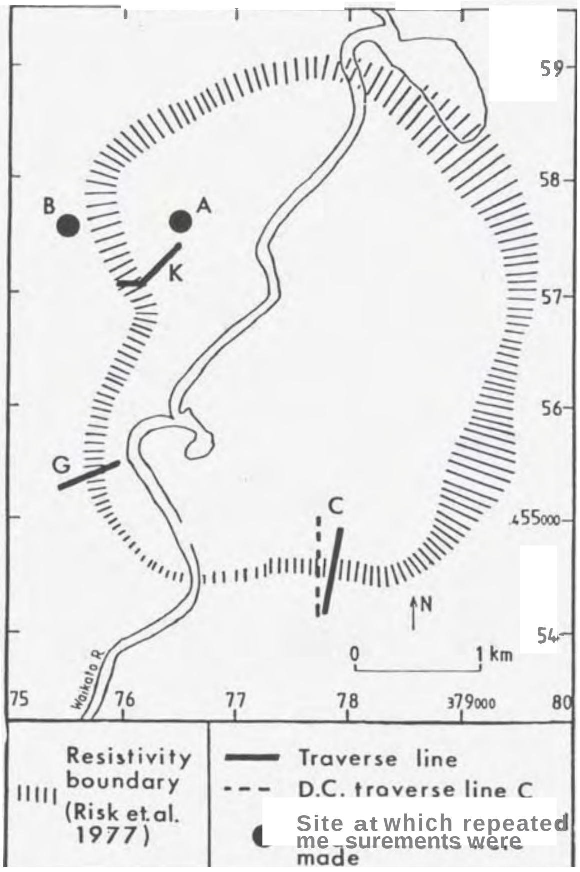

Fig. 1 Location of the traverse lines and sites at which repeated measurements were made at the Broadlands Geothermal Field.

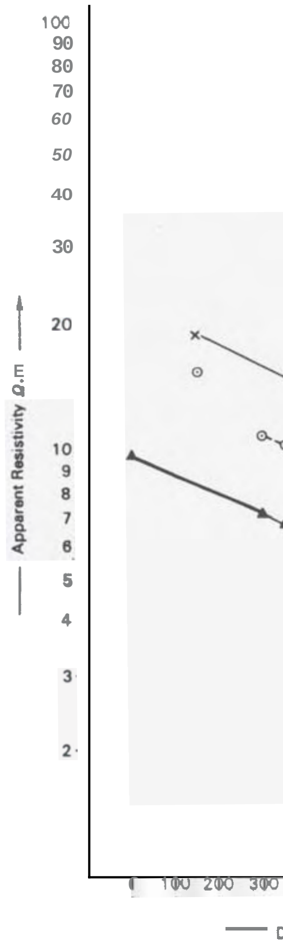

Fig 2 50Hz AMT appare

measure

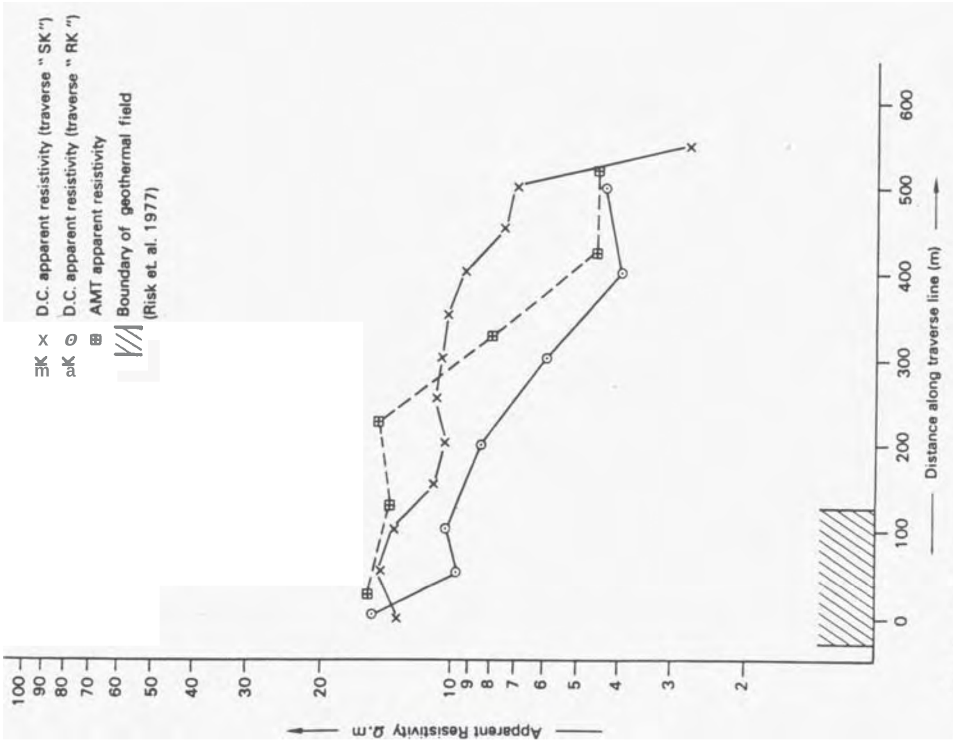

Fig 4 50Hz AMT apparent resistivity (ρ_{gm}) and d.c. apparent resistivities measured at sites located along traverse line K.

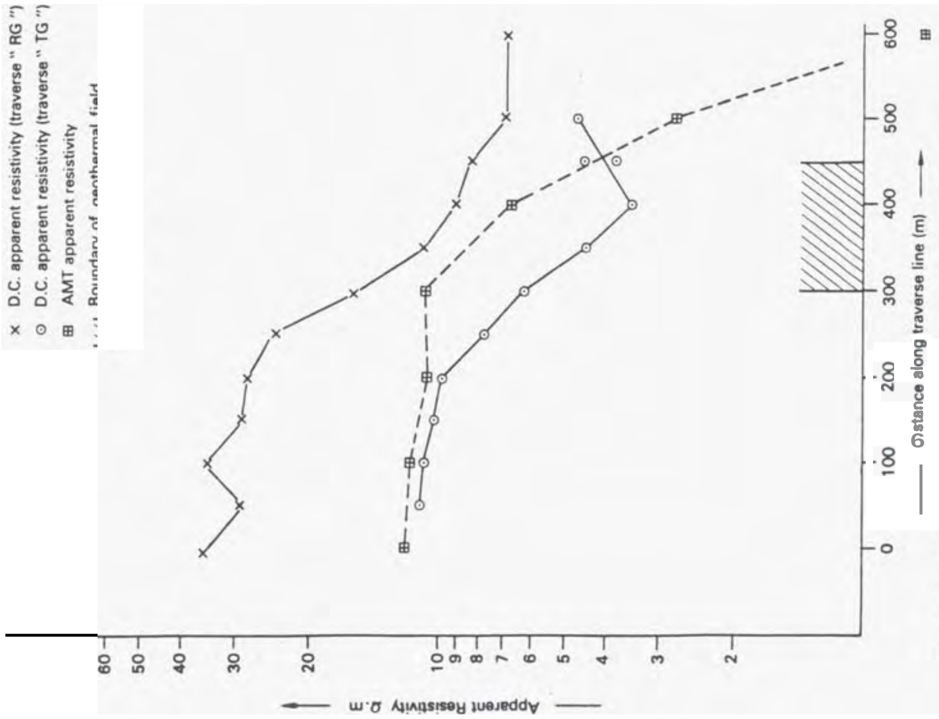

Fig 3 50Hz AMT apparent resistivity (ρ_{gm}) and d.c. apparent resistivities measured at sites located along traverse line G.