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SURFACE-TO-BOREHOLE ELECTROMAGNETIC EXPERIMENT AT ROOSEVELT HOT SPRINGS

A FEASIBILITY STUDY

by

A. C. Tripp, H. P. Ross, J. A. Stodt, and P. M. Wright

University of Utah Research Institute
Earth Science Laboratory
391 Chipeta Way, Suite C
Salt Lake City, UT 84108-1295

ABSTRACT

The electrical resistivity structure of a geothermal reservoir is a function of many reservoir properties, such as temperature, water salinity, the presence of steam, hydrothermal alteration mineralogy, porosity, and fracture density and orientation. Thus, determining the resistivity structure of a particular reservoir can be of great use in planning optimal exploitation of the resource.

There are many conceivable ways of estimating the resistivity structure of a reservoir from geophysical measurements. In this paper, we describe one method in which a coil receiver is situated in a borehole and the transmitter is a current line grounded on the earth's surface. This particular method is easy to use in the field and can give good resolution of conductive features at depth. We illustrate the applicability of the technique to detect fracture zones at depth in the vicinity of Well 9-1 at Roosevelt Hot Springs.

INTRODUCTION

Effective exploitation of a geothermal reservoir requires a detailed knowledge of the physical state of the reservoir. Since many reservoir parameters influence the rock electrical resistivity, determination of the spatial or temporal distribution of the electrical resistivity of the reservoir may be useful in determining important reservoir parameters.

If reservoir parameters are to be estimated from rock resistivities, two goals must be met. First, functional relationships between reservoir parameters and rock resistivity must be established. Second, effective means of estimating reservoir-scale resistivity variations must be found. Achieving each of these goals for a particular reservoir is a formidable task. Much more research needs to be done to facilitate these electrical investigations of reservoirs.

Our purpose in this paper is to discuss one possible means for estimating reservoir-scale resistivity variations in the vicinity of Well 9-1 at Roosevelt Hot Springs (Figure 1). Although we discuss a particular example, the generalization of our approach to other cases is obvious.

GEOLOGIC SETTING

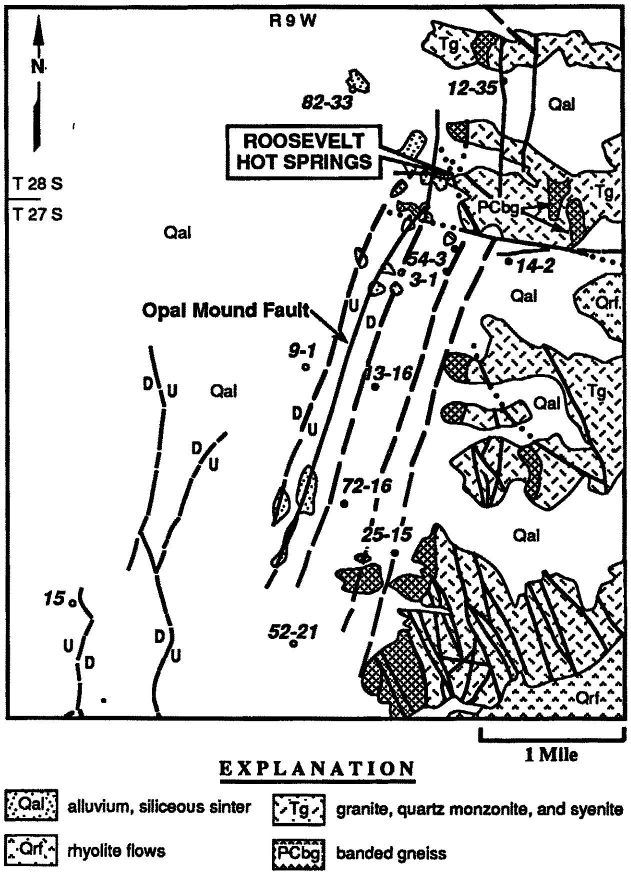

Figure 1. Geologic map of Roosevelt Hot Springs KGRA and vicinity (after Sibbett and Nielson, 1980).

The Roosevelt Hot Springs geothermal system occurs on the west side of the Mineral Mountains near the town of Milford, in southwestern Utah. The bedrock geology of the area is dominated by metamorphic rocks of Precambrian age and felsic plutonic phases of the Tertiary Mineral Mountains intrusive complex (Nielson et al., 1978). Igneous activity between 0.8 and 0.5 m.y. produced rhyolite flows, domes and pyroclastic deposits. North to north-northeast-trending normal faults form the western margin of the range and cut Quaternary alluvium adjacent to the range. The permeability within the geothermal system is controlled by these structures and the intersections with other fracture sets.

Utah State Geothermal Well 9-1, sited approximately 480 m west of the Opal Mound fault, penetrated 205 m of alluvium before entering Precambrian gneisses and mafic

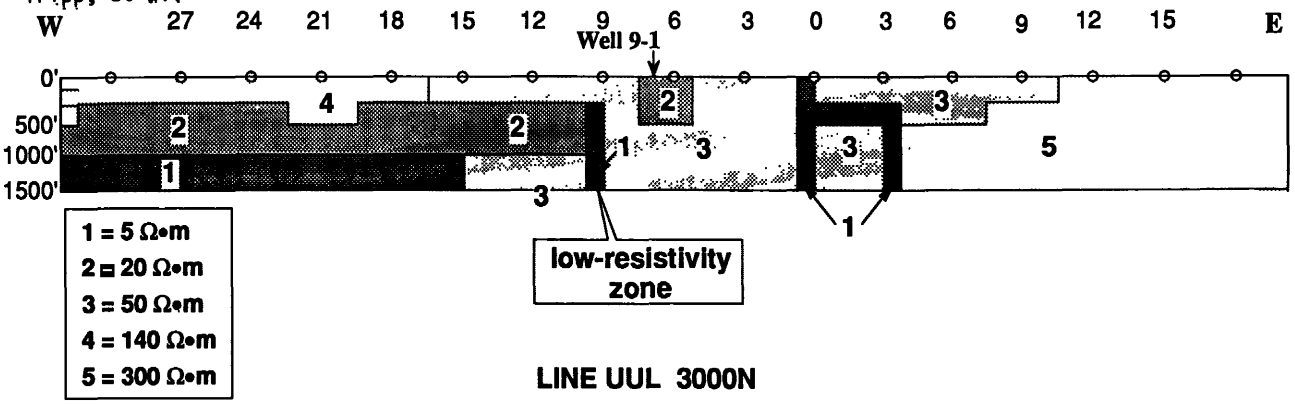

Figure 2. Theoretical model for 300 meter dipole-dipole data along line UUL 3000 N.

diorites, and then Tertiary granite and microdiorite which continued to total depth of 2099 m. Although the hole is hot (227°C), no significant thermal fluid production was recorded (Glenn et al., 1981).

Dipole-dipole electrical resistivity data is part of an extensive geophysical data base for the Roosevelt Hot Springs geothermal area. Profile UUL 3000 N trends east across the Opal Mound Fault near Well 9-1 and was completed for both 100 m and 300 m dipoles. When interpreted by numerical modeling (Figure 2; Ross et al., 1982) these data indicate the presence of a narrow, low-resistivity zone which is near vertical and suggests alteration products and/or conductive fluids along a fracture zone. Since the original data set only included apparent resistivities to N=4, the depth extent of the zone is not known. In fact, determining the depth extent of this thin zone by any surface electrical technique might be difficult. This is because the very methods used to increase the depth of investigation of electrical techniques lead to decreased resolution of features at depth. One way of ameliorating the decrease in resolution with depth is to place either transmitter or receiver or both in a borehole. In this paper we will examine one such method, which is an adaptation of a technique suggested by Nabighian et al. (1984).

ELECTROMAGNETIC MODELLING

Figure 3 shows a transmitter - receiver array which is useful in investigating the depth extent of the low-resistivity zone. The transmitter is a 1000-meter wire which runs parallel to strike and is grounded above the low-resistivity zone. With this arrangement, there is a maximal amount of current channeling into the zone. The receiver is a vertical coil which is lowered down the borehole. With this receiver arrangement, there is maximal coupling between the magnetic fields caused by electric current flow in the low-resistivity zone and the vertical coil. Since the measured magnetic field is parallel to the borehole, the field should propagate through the steel casing given a frequency which is sufficiently low. As this example shows, surface-to-borehole and borehole-to-borehole electromagnetics permit a great variety of source and receiver geometries and hence electromagnetic field configurations. This is unlike the case of surface geophysics, in which sources and receivers are confined to the earth's surface, which limits electromagnetic field configurations.

For our feasibility study, we assume that the low-resistivity zone extends either 300 or 600 meters, with a constant resistivity of 5 Ω·m (Figure 3). The resistivity

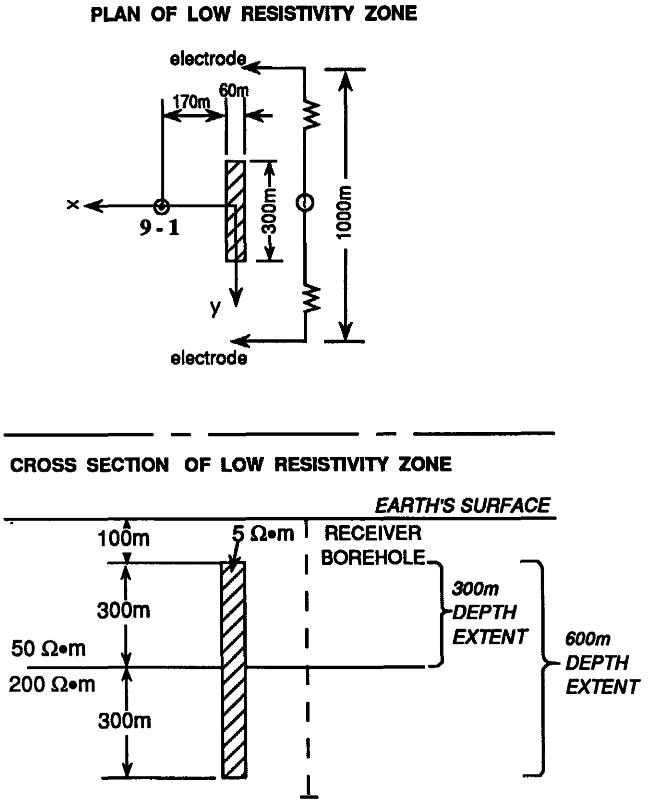

Figure 3. Plan and cross section of the modelled low-resistivity zone, showing array geometry.

and thickness of the upper part of the zone is based on dipole-dipole resistivity (Figure 2). Since the integral-equations algorithm which we use calculates the electromagnetic response of a three-dimensional body (Hohmann, 1987), the fault zone model must be of limited strike extent. For modelling convenience we have set the strike extent at 300 meters. The casing has not been explicitly considered in these calculations. The inclusion of a layer of 200 Ω•m resistivity is based on a resistivity log of 9-1 (Glenn et al., 1981).

We will now determine whether the conductive zone can be detected using the particular source-receiver geometry espoused. Figure 4 shows the primary, secondary, and total in-phase vertical magnetic fields in nanoteslas per transmitter ampere (nT/Amp) at 0.1 Hz. The primary field is the response of the layering alone, the secondary field is the response of scattering currents in the low-resistivity zone, and the total field is the sum of the primary and secondary fields. Also shown in this figure and subsequent similar figures is an estimate of the vertical geomagnetic field and an estimate of noise of realizable coil systems, as compiled from the literature (Stanley and Tinkler, 1983).

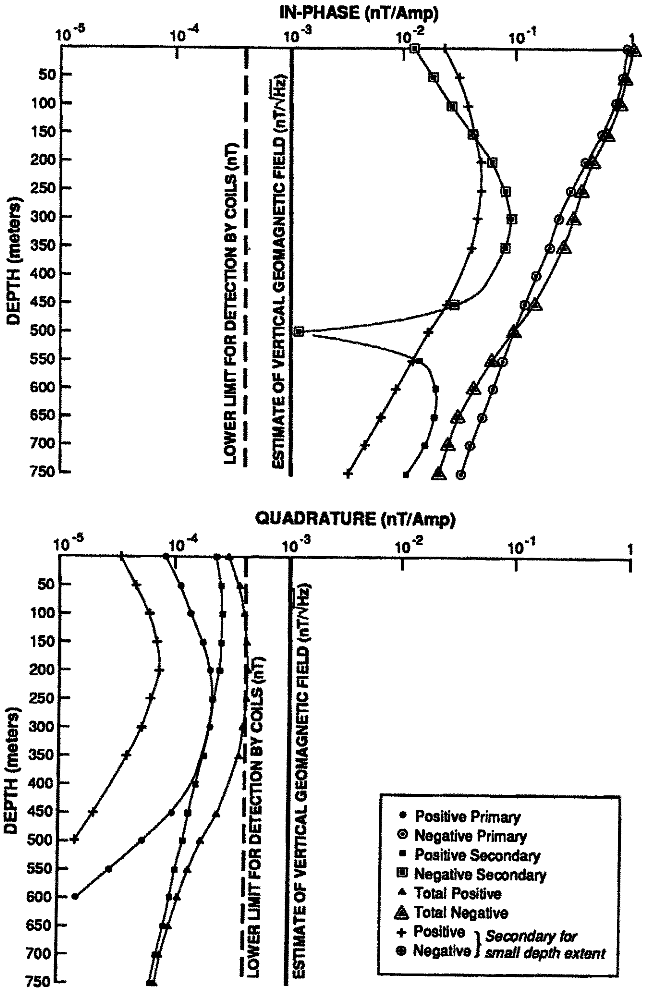

Figure 4. In-phase and quadrature components of the vertical magnetic field plotted against well depth for .1 Hz.

As the figure shows, the in-phase secondary fields for a transmitter current of one ampere are clearly measurable over the range of the borehole and the character of the total fields would be determined in a field survey. The in-phase secondary field for the zone of limited depth extent has a magnitude comparable to that of the extended zone, but the two fields have opposite signs over much of the hole. Thus the extended zone and the truncated zone could be distinguished from their responses. The quadrature field components, also shown in Figure 4, are less pronounced. Even with a transmitter current of 20 amperes, the secondary fields would not exceed the estimate of the vertical geometric field by a significant amount over much of the borehole.

Figure 5 shows the in-phase fields at 10 Hz. These fields are almost identical to their counterparts at 0.1 Hz.

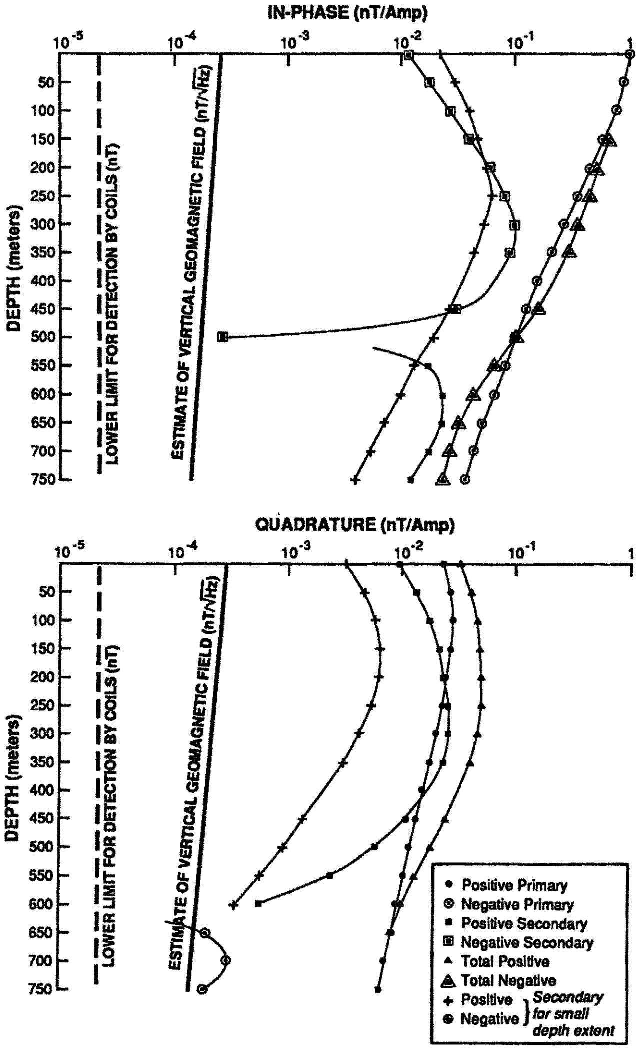

Figure 5. In-phase and quadrature components of the vertical magnetic field plotted against well depth for 10 Hz.

In contrast, the quadrature fields at 10 Hz are much larger than their counterparts at 0.1 Hz and are easily measurable in an uncased well.

Figure 6 shows the in-phase and quadrature components for an excitation frequency of 1000 Hz. As for the case at 10 Hz, the fields would be easily measurable in an uncased well.

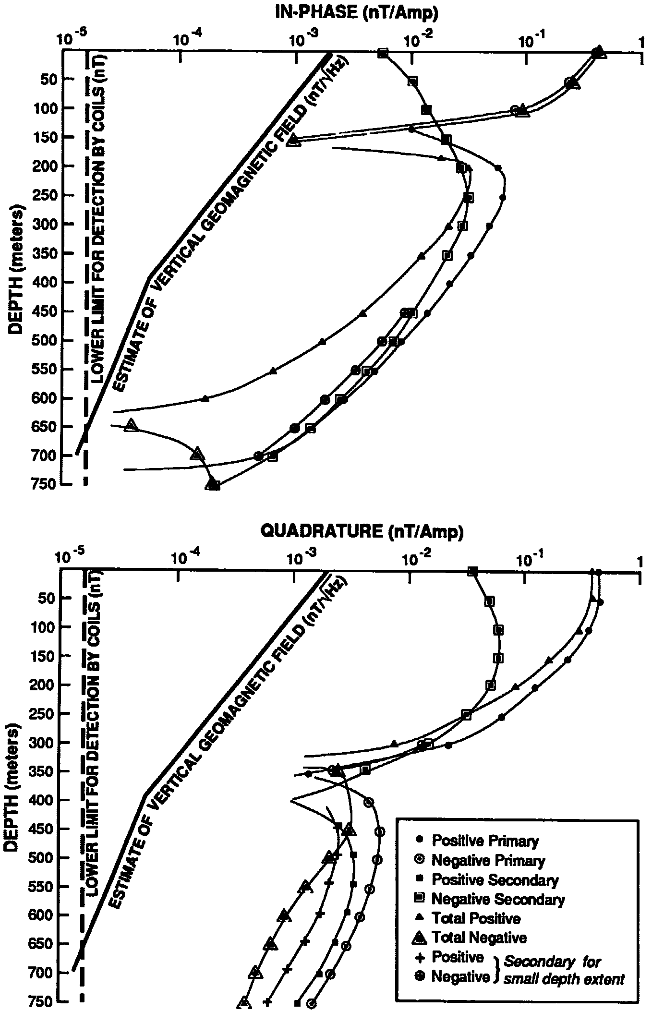

Figure 6. In-phase and quadrature components of the vertical magnetic field plotted against well-depth for 1000 Hz.

Comparison of the in-phase and quadrature components for the three frequencies is instructive. The corresponding in-phase secondary components at 0.1 Hz and 10 Hz are nearly identical and represent the D.C. response of the body. Electromagnetic effects are apparent in the quadrature fields, however, where the 10 Hz fields are approximately two orders of magnitude larger than the 0.1 Hz fields. The shapes of corresponding quadrature field curves at the two frequencies are almost identical, which suggests that the quadrature current patterns in the earth at the two frequencies are similar, although of different magnitude.

At 1000 Hz, strong electromagnetic effects are apparent in both in-phase and quadrature fields. The shapes of both the in-phase and quadrature fields are dissimilar to their respective counterparts at 0.1 Hz and 10 Hz, which suggests a dissimilarity in current systems. Hopefully, this means there is model information in the 1000 Hz which is orthogonal to the information in the 0.1 Hz and 10 Hz data. At this frequency, the responses for the zone of limited depth extent and the extended zone are nearly the same. This suggests that the skin-effect of each zone limits current penetration to the upper regions of the zones.

Complete analysis of the response of the conductive zone at the three frequencies would require an extensive model study coupled with examination of the current patterns in the earth for each of the models. This analysis is beyond the scope of the present work. What we have shown is that the responses are readily measurable in an uncased well, that software is available for an interpretation of the data and for model perturbation studies, and that information about the depth extent of a low-resistivity zone is contained in the data.

EFFECTS OF CASING

Our integral-equation computations have not included the effect of the steel well casing in Well 9-1 on the electromagnetic fields. A completely rigorous analysis of these effects for our geometry is possible, but is beyond the scope of the present paper. For our present purpose a short semi-quantitative discussion of these effects should suffice.

The transmission of magnetic fields through well casing is a function of the electrical resistivity and the low-field magnetic permeability of the casing. Attenuation of both axial and normal magnetic fields due to the casing resistivity is dependent on frequency and will go to zero as frequency decreases (Jaeger, 1940; Rikitake, 1987). Although the magnetic permeability of the casing has an inductive expression at non-zero frequencies, it causes attenuation of the magnetic field component normal to the casing even at zero frequency (Jaeger, 1940; Jackson, 1962; Rikitake, 1987). However, casing permeability effects on the axial magnetic field are negligible for frequencies which are sufficiently low. Although the precise estimation of the degree of distortion of the axial magnetic field at a particular frequency requires an extensive mathematical analysis (Jaeger, 1940; Rikitake, 1987), a semi-quantitative estimate of the degree of distortion can be gained by a simple skin depth calculation. We assume that the well casing for Well 9-1 has a resistivity of 10^{-6} Ω·m and a relative permeability of 500, which agrees with well casing physical properties given by Wait and Williams (1985). Then, the skin depth in this casing material at 0.1 Hz is 2.8 inches. Since the casing wall is approximately 0.304 inches thick, the magnitude of the internal axial field will be approximately 90% of the external field. In contrast, the skin depth in the casing material for 10 Hz is 0.28 inches.and for 1000 Hz is 0.028 inches. Consequently the magnitudes of the internal axial fields are only 34% and 0.002% respectively of the external field. We conclude from this analysis that electromagnetic responses at 0.1 Hz could be readily measured through casing although higher frequency fields would be highly attenuated.

DISCUSSION

Our modelling has shown that a low-resistivity unit such as that shown in Figure 2 would be readily detectable at depth in the vicinity of Well 9-1 at Roosevelt Hot Springs using our surface-to-borehole technique. Since the computed signal was so strong, we believe that features having smaller resistivity contrasts could also be detected. Although the low-frequency axial magnetic field will be unaffected by casing, high-frequency fields are strongly attenuated. This is unfortunate because the higher-frequency fields should offer information about the earth not contained in the low-frequency fields. The strong signal computed for 1000 Hz suggests that in the absence of casing even higher frequencies might be used, with subsequent increases in model resolution at shallow depths.

ACKNOWLEDGEMENTS

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