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CONTROLLED SOURCE ELECTROMAGNETIC METHODS IN GEOTHERMAL EXPLORATION

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CONTROLLED SOURCE ELECTROMAGNETIC METHODS
IN GEOTHERMAL EXPLORATION

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ABSTRACT

The objective of this manuscript is to sketch the problems inherent in application of controlled source electromagnetic methods (CSEM) to geothermal exploration. Measurements have been made in both the time and frequency domains with time domain measurements currently enjoying an advantage over frequency domain measurements for shallow applications.

Application of CSEM methods is impeded by natural field, electrification, geological, cultural, and topographic noise. Lateral resolution of parameters of adjacent steeply dipping bodies and vertical resolution of parameters of adjacent beds in a flatly dipping sequence are concerns with any CSEM method. Current channeling into a localized good conductor from a surrounding, overlying, or underlying conductor poses problems for the interpreter.

In selecting a transmitter-receiver configuration for CSEM in a particular application, a compromise is usually achieved between such factors as domain of data acquisition, rejection of noise, resolution, current channeling, and depth of exploration. Not surprisingly there is only marginal agreement on the optimum selection of each of these variables. However, one of the more promising techniques for application in geothermal exploration is the controlled source audiomagnetotelluric method (CSAMT).

1.0 INTRODUCTION

Keller (1970) reviewed the applications of active and passive electromagnetic methods in geothermal exploration. His article constituted, particularly, a baseline for reference to controlled source electromagnetic methods (CSEM) in the geothermal environments. Subsequent to Keller's review, a number of articles have appeared which illustrate the success and failure of these methods in geothermal exploration. Included in this number are the articles by Lumb and Macdonald (1970), Jackson and Keller (1972), Keller and Rapolla (1974), Jacobson and Pritchard (1975), Ward et al. (1975), Morrison et al. (1978), Tripp et al. (1978), Kauahikaua (1981), Wilt et al. (1981), Goldstein et al. (1982), Keller et al. (1982), and others.

A special version of CSEM which seems to hold considerable promise in terms of resolution and economy in delineating two- and three-dimensional resistivity distributions to 1 km depth is the controlled source audiomagnetotelluric method first described by Goldstein and Strangway (1975). Otten and Musmann (1982) and Sandberg and Hohmann (1982) and others have recently given illustrations of its successful use in geothermal exploration.

Controlled source electrical methods (CSEM) are applied in mining, geothermal, sedimentary basin, and deep crust/upper mantle exploration. In this manuscript the problems inherent in controlled source electromagnetic methods are described with particular reference to geothermal exploration. The problems include lateral and vertical resolution, current channeling, and natural field, electrification, geological, cultural, and topographic noise for all CSEM techniques. Where pertinent, the implication of each of these problems for geothermal exploration is discussed.

Whenever CSEM are to be used, whatever the scale of the problem, care must be exercised in selecting the optimum transmitter-receiver configuration. Factors to be considered include domain of data acquisition, rejection of noise, resolution, current channeling, and depth of exploration. Means for evaluating all of these factors objectively is not always at our disposal and hence, not surprisingly, there is only marginal agreement on the optimum system for any given application. One of the relatively new techniques for application in geothermal exploration is the controlled source audiomagnetotelluric method (CSAMT).

After treating the problems of CSEM, and discussing the basis for selecting an optimum system for a given application, some recent results using CSEM in geothermal exploration are summarized. When one attempts to apply CSEM to unravel geological problems in terranes where heterogeneous conductive geological materials exist near surface, deep crustal exploration by CSEM becomes problematical. Even then, two- and three-dimensional earths must be used in interpretation.

In the references given above, the targets for CSEM were a) shallow brine-saturated and altered fracture zones of convective hydrothermal systems, b) shallow layered structures in which brine and alteration are confined to one layer, c) shallow molten magma, and d) the deep crust beneath geothermal systems.

2.0 PROBLEMS WITH INDUCTIVE CSEM SYSTEMS

2.1 *Overview*

Figure 1 illustrates a generalized model of a convective hydrothermal system. We wish to explore the various features of this system by the electromagnetic array depicted in Figure 2. As depicted, a primary voltage (E) at the receiver is due solely to direct induction of the primary or transmitted alternating magnetic field. Superimposed on this primary voltage is a secondary voltage (ΔE) due to alternating magnetic fields arising in induced currents flowing in the assemblage of conductive media in the subsurface geoelectric section. From ΔE, or from $\frac{\Delta E}{E}$, the intention is to extract information about one or more of the media in the subsurface, i.e., their depth, depth extent, dip, strike, strike length, and conductivity-thickness product. Some times this intent is satisfied, but in some instances it cannot be because the induction numbers θ_i for each member of the geoelectric section are too similar. As an illustration, one would hope that the following inequality holds:

$$\theta_1 = \sigma_1 \mu_1 \omega t_1 L \ll \theta_2 = \sigma_2 \mu_2 \omega t_2 L \quad . \tag{1}$$

In equation (1) σ, μ, ω, and t are the conductivity, magnetic permeability, angular frequency, and thickness for the overburden (subscript 1) and the target of interest (subscript 2). The parameter L is the separation between transmitting and receiving coils. If this inequality holds, then the contribution of the target of interest can be clearly distinguished from the contribution of the overburden, in ΔE, provided all other induction numbers are much less than θ_1. As might be expected, the various θ_i are not always far apart with the result that separation of the contributions of the various elements of the geoelectric section to ΔE is not clear-cut. In addition,

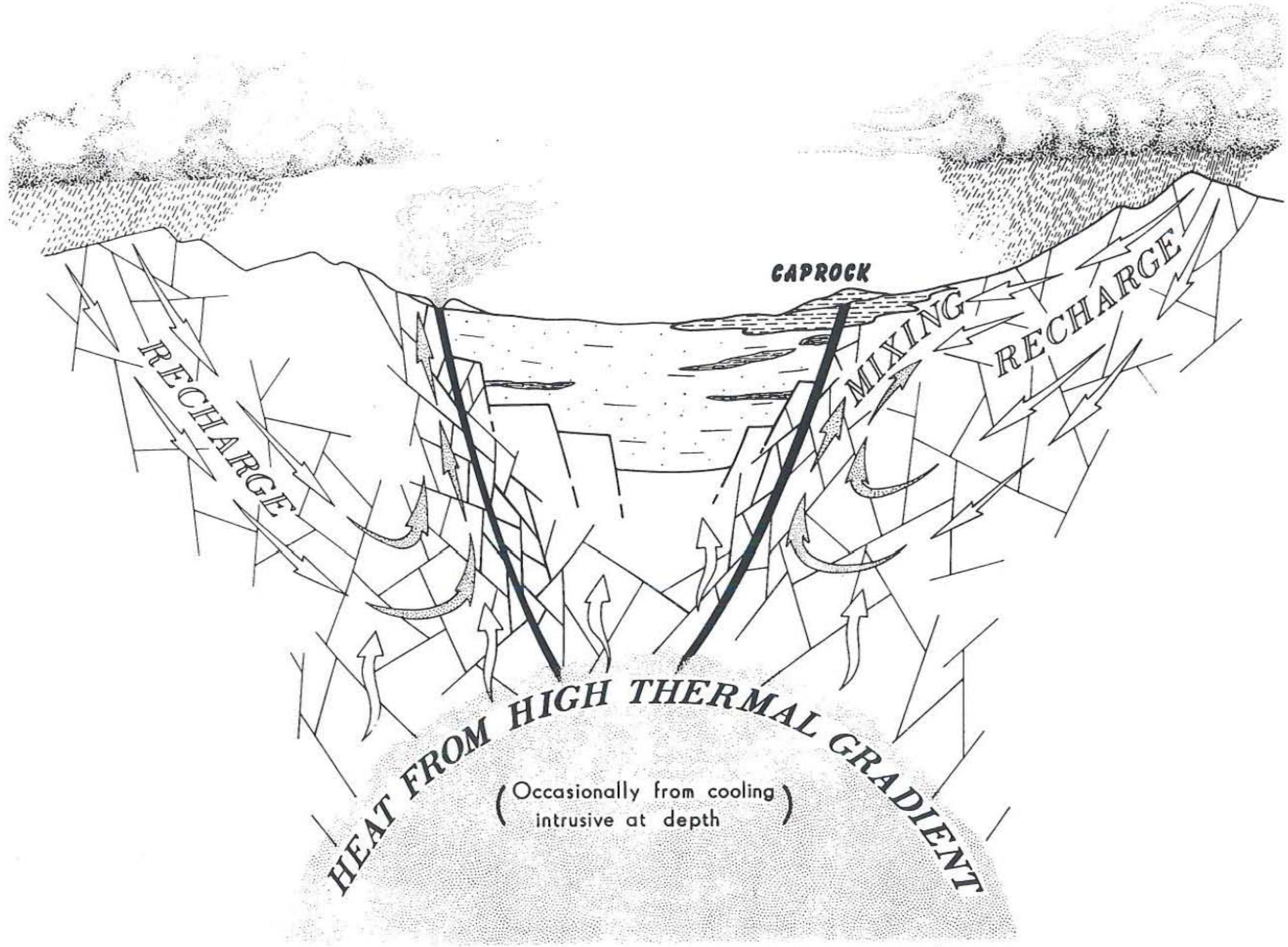


Figure 1. Generalized model of convective hydrothermal system.

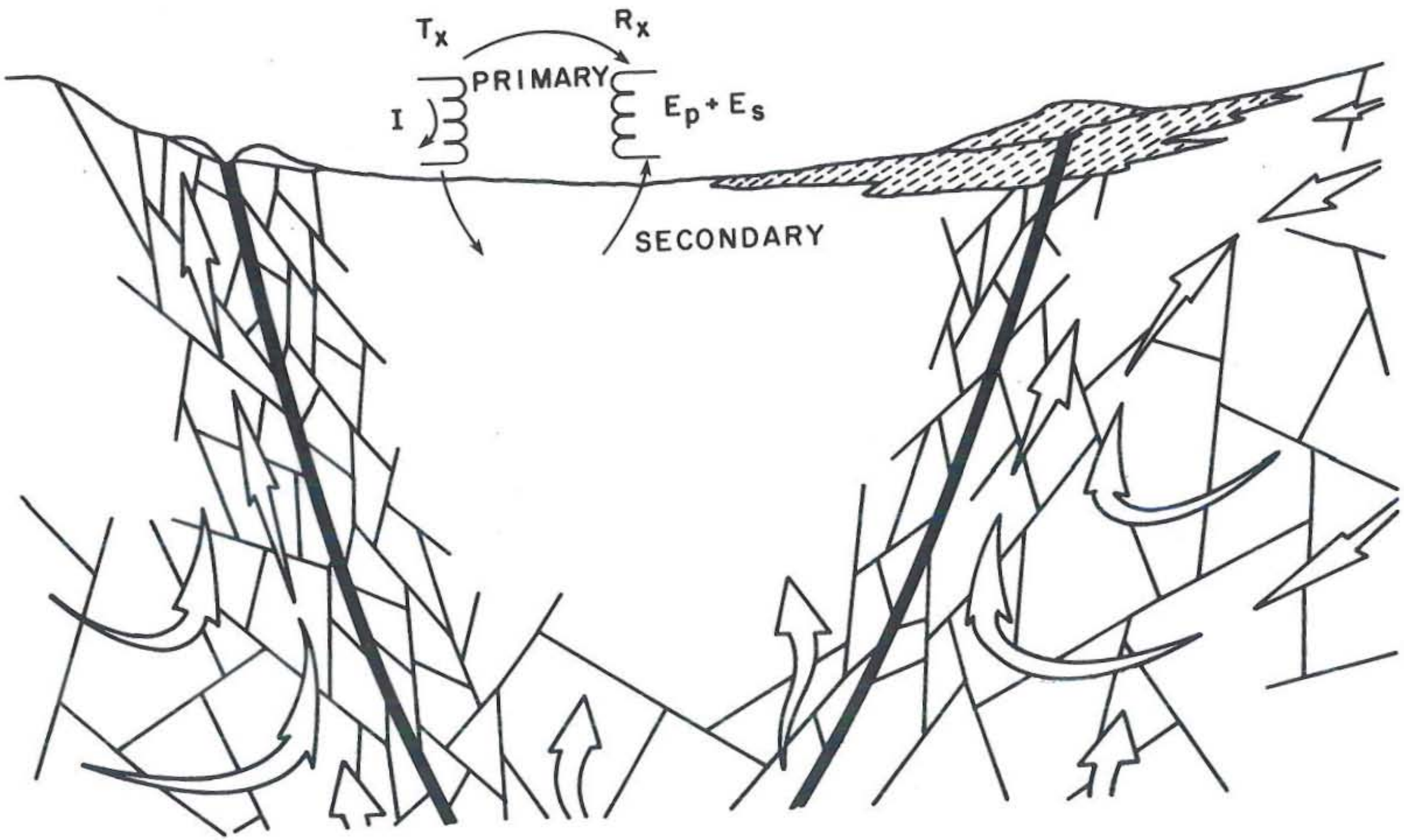


Figure 2. Schematic layout of transmitter (T_x) and receiver (R_x) coils on or above the earth showing sources of primary voltage E_p and secondary voltage E_s.

interactions between the elements of the geoelectric section can and do take place, e.g., current channeling into a highly conductive medium from a less conductive medium. Nevertheless, the ultimate objective posed for any purely inductive electromagnetic method is to diagnose the parameters of each member of the geoelectric section from ΔE observed at surface.

Unfortunately, a number of problems with all CSEM methods hinders the realization of the ultimate objective. In the ensuing, we shall address each of these problems in turn and make our suggestions for their minimization.

2.2 *Natural field noise*

Figure 3 illustrates a typical natural magnetic field spectrum. It exhibits field strength characteristics as follows: a low near 3 Hz, a rapid increase with decrease in frequency below 3 Hz, an interim peak just below 100 Hz, and a trough near 2000 Hz followed by a rise at higher frequencies. Shallow CSEM for mining, geothermal, and sedimentary basin studies, utilizes the frequency range from 1 Hz to 10^5 Hz.

In the 1 Hz to 10^5 Hz range, natural field noise arises in atmospheric discharges, especially those associated with lightning. The major worldwide centers for lightning storms are in Indonesia, Central America and northern South America, and in northcentral Africa. These thunderstorm centers shift north in northern hemisphere summer and south in southern hemisphere summer. The energy from these major lightning discharge centers propagates in a waveguide bounded by the ionosphere and the earth's surface. At any point on the earth's surface the measured noise includes this waveguide propagated energy plus atmospheric discharges from nearby sources. The resulting spectrum of noise exhibits a wide dynamic range and a very transient type of individual peak. Schemes to deal with such a difficult noise source include

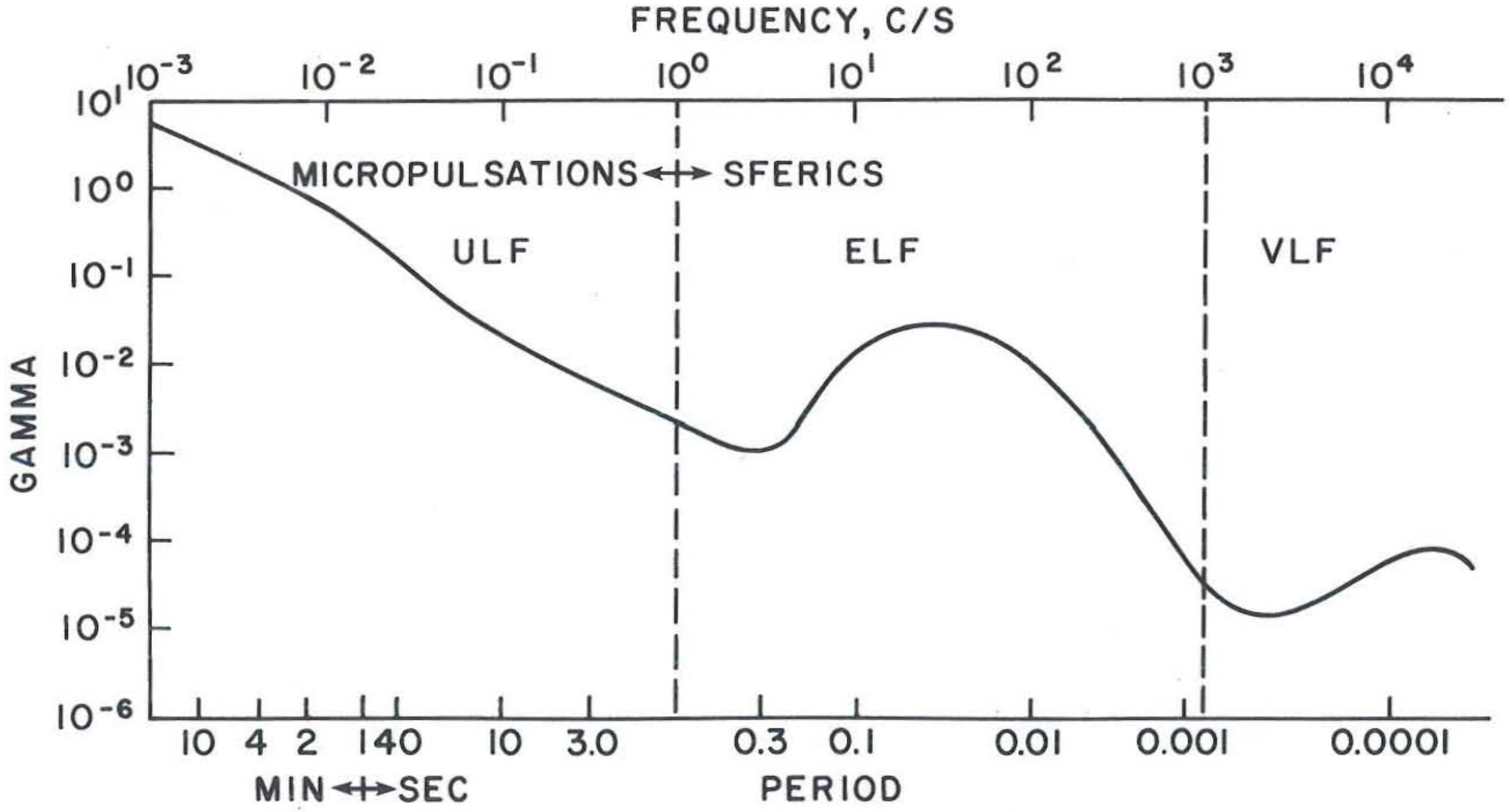


Figure 3. Generalized spectrum of natural magnetic fields. (After Bleil, 1964).

limiters which truncate the highest peaks, and data point removal in digital systems designed to accept data points only within a prescribed range of amplitudes. Narrow band CSEM systems effect signal to noise enhancement and these are used for frequency domain CSEM systems. Broad band CSEM systems can only use stacking and data point removal.

2.3 *Cultural noise*

One finds, as Table 1 indicates, that cultural developments create active and passive noise. Circuits completed through fences, pipelines, power lines, telephone lines, rails, and other conductive cultural structures produce anomalies largely unrelated to subsurface geology. These sources of noise can, in rare instances, be reduced by removing the offensive structure, but, by and large, they can only be avoided by placing transmitters and receivers well away from them. This is not always possible in areas of concentrated industrialization, and hence important geological problems simply cannot be attacked in such areas.

Some of these cultural developments also serve as sources for narrow or broad-band electric and magnetic field noise, especially power lines, telephone lines, and electrified rails as Table 1 indicates. Further compounding the problem is the fact that these active sources of cultural noise induce eddy current in the passive cultural noise sources such as fences and pipelines. Notch filters centered at 60 Hz (50 Hz) and 180 Hz (150 Hz) are characteristically used in CSEM systems to eliminate power line noise.

2.4 *Geological noise due to overburden*

Overburden can be described variously as unconsolidated sediments, weathered rock, or both. The overburden may be resistive or conductive. Weathered rock is invariably conductive because the geological process of

CULTURAL NOISE

⇨ PASSIVE

- FENCES
- PIPELINES
- POWER LINES
- TELEPHONE LINES
- RAILS

⇨ ACTIVE

- POWER LINES
- TELEPHONE LINES
- ELECTRIFIED RAILS

Table 1.

weathering leads to a) increased porosity, b) increased presence of clay minerals with their attendant surficial electrical conduction, and c) increased concentrations of ions in the pore waters of the weathered rocks. In dry climatic environments, evaporation strongly increases the concentration of ions in the pore waters, on average. Dilution of these ions takes place during the rainy season in dry or wet environments. A worldwide study of these factors points out that the shallow resistivity profile is closely related to local climatology, to glaciation, and to tectonic style. The depth of overburden related to weathering seldom exceeds 100 m but can easily reach 2 km for valley fill in the Great Basin of the U.S.A.

Sedimentary rocks in such areas as the Gulf Coast oil-producing region of Texas and Louisiana in the U.S.A. commonly exhibit resistivities as low as 1 to 10 Ω m due to interstitial brines (Pirson, 1963). This also is true of some geothermal areas such as the Imperial Valley in California, U.S.A. (Meidav and Furgerson, 1972) and of deep valley fill containing evaporites in Nevada and Utah, U.S.A. (Ward and Sill, 1976). Values as low as 0.1 Ω m have been recorded in some of these areas. In a broader context than used herein so far, these conductive sediments also can be treated as overburden if one is attempting to study the electrical properties of the deep crust. If a surficial conductive horizon, i.e., overburden of any sort, overlies a substratum to be studied with CSEM, the percent of current entering the substratum becomes of utmost importance. Figure 4 illustrates the fraction of current $f(\alpha)$ confined to the overburden as a function of $\alpha = \frac{2S\rho}{L}$, where S is the conductivity-thickness product of the overburden, ρ is the resistivity of the basement, and L is the distance between the current electrodes (Edwards and Howell, 1976). In order to assure that, say, 80% of the current persists below the overburden, then α must be about 0.3. If the

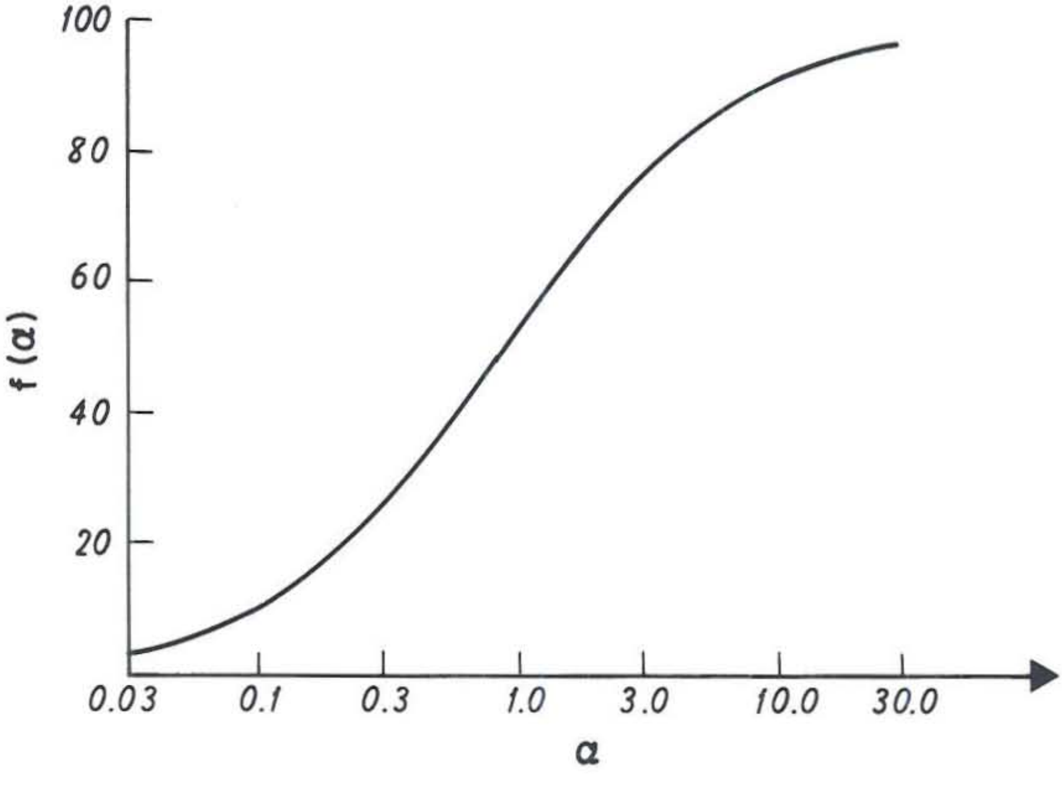


Figure 4. The function f(α) which determines the percentage of current remaining in a conductive, thin surface layer above a resistive half-space. (After Edwards and Howell, 1976).

overburden is 1 km thick of resistivity 10 Ω m and the resistivity of the bedrock is 10^3 Ω m, not unreasonable numbers in areas of thick conductive overburden, then the distance between current electrodes needs to be 1000 km to assure that 80% of the current flows in the bedrock. This is an incredible requirement which clearly demonstrates the difficulty of electrically detecting geological structure beneath conductive overburden when using bipolar electric sources. The analysis has been made for D.C., and may not apply strictly for A.C.

When horizontal coil sources are used, induction in the overburden is strictly controlled by θ_1 , the induction number of the overburden. This induction number can be decreased by lowering the angular frequency. For example, given an overburden of 1 km thickness and 10 Ω m resistivity excited by an inductive coil source with measurements made at 3 x 10^{-2} Hz at a distance of 10 km from the source, the value of θ_1 is 0.2, well below values resulting in significant overburden response (Wait, 1955). For MT, the situation is probably better because the skin depth for the same earth model given by

$$\delta = 500 \sqrt{\rho/f} \quad , \tag{2}$$

is 15 km and thus implies that the 1 km thick overburden of resistivity 10 Ω m is virtually transparent to plane electromagnetic waves of frequency 3 x 10^{-2} Hz.

From the above we might conclude that the order of preference for sources to be used in regions of high surficial conductivity is a) plane waves, b) inductive coils, and c) grounded bipoles. This is, of course, only a partial analysis of the problem, but it does present the nature of the difficulties of probing the crust in regions of thick conductive overburden or sediments. Geometrical decay of fields from the three source types, and the attenuation of electromagnetic waves from each of the source types are other factors to consider (Hohmann and Ward, 1981).

2.5 *Resolution and the effect of geological noise*

To facilitate vertical resolution, i.e., resolution of the resistivities and thicknesses of horizontally layered media, an inductive electromagnetic system would need to sample at three or four frequencies per decade. At least four decades of spectrum are required if one wishes to explore both shallow and deep layers. If lateral inhomogeneities are superimposed on the layering, then an adequate spatial density of receiving stations must also be assured over a distance sufficiently large to permit delineation of all inhomogeneities of interest. A broad spectrum is necessary if the θ_i of the inhomogeneities cannot be predicted in advance. Data is then best plotted as contours of field quantities in frequency-distance space. We shall illustrate this in discussion of the CSAMT method below.

Roving two-loop sources, to be described subsequently, provide the best lateral resolution. However, for deep crustal electromagnetic exploration we are obliged to use a fixed transmitter, either a loop, or a grounded bipole and so we are also obliged to accept the lateral resolution that is achievable with these sources.

It is well known (Madden, 1971) that inductive techniques, passive or active, usually provide information on conductivity-thickness products of conductive layers, whereas they usually provide only thickness information on resistive layers. On the contrary, resistivity techniques usually provide information on resistivity-thickness products for resistive layers and conductivity-thickness products for conductive layers. Vertical resolution of resistive and conductive layers is well illustrated via inversion (e.g. Fullagar and Oldenburg, 1982). Joint inversion of inductive and resistive data sets can markedly improve the resolution (Petrick et al., 1977).

2.6 *Topography*

Table 2 lists three effects of topography on measurements made with an inductive electromagnetic method. Variations in elevation of the receiver relative to the transmitter will produce elevation errors in electric or magnetic fields along a traverse, relative to the fields that would be observed over a flat surface. These can be severe for short separations between transmitter and receiver as might arise in shallow geothermal exploration.

If topographic relief is large, one seeks to assure that a square coil or bipole source is horizontal and that measurements are made of horizontal and vertical magnetic and horizontal electric fields. Alternatively, the plane of the transmitting coil must contain the axis or the plane of the receiving coil and orthogonal magnetic field components are measured relative to this axis or plane. If either one of these alternatives is ignored, *alignment* errors will result.

If, for example, a transmitter is located below and adjacent to a ridge, *induced currents* will occur in the ridge at the higher frequencies and will contribute a source of noise which may obscure subsurface features.

2.7 *Current channeling*

Current channeling occurs due to discontinuity in electric field and a consequent charge accumulation at a boundary between media of different

EFFECTS OF TOPOGRAPHY

- ELEVATION ERRORS
- ALIGNMENT ERRORS
- CURRENT CHANNELING IN RIDGES

Table 2.

resistivities. The normal component of current density J_n is continuous across an interface while, by definition, the resistivity ρ is discontinuous. Hence at an interface between media 1 and 2 we find

$$J_{n1} = \frac{E_{n1}}{\rho_1} = \frac{E_{n2}}{\rho_2} = J_{n2} \quad , \tag{3}$$

forcing E_n to be discontinuous at the interface. If $\rho_1 > \rho_2$ then $E_{n1} > E_{n2}$ in order to satisfy this relation; normal electric fields are larger in the medium of highest resistivity adjacent to the boundary. Therefore, at an interface, dielectric displacement $\vec{D} = \varepsilon\vec{E}$ must be discontinous and the fourth Maxwell equation must be written as $\nabla \cdot \vec{D} = \rho_s$ where ρ_s is a surface charge accumulation. Thus, since two interfaces bound the sides of a two- or three-dimensional body in a homogeneous exterior, a dipolar charge distribution occurs across the body. When the electric field of this body is added to the inducing electric field, the net result is an electric field distribution that causes the current flow in the external medium to be channeled, or "short-circuited" into the body.

Current channeling is most pronounced for MT where plane waves are involved. It becomes of increasing importance at lower frequencies (Wannamaker et al, 1982). The phenomenon becomes less as the size of the transmitting source decreases. If the receiver is restricted to regions close to the transmitter, the θ_i referred to earlier may be so small that the system may not observe the current channeling. For a one-, two-, or three-dimensional source, current channeling may occur along one or all axes of the body, depending upon the direction of propagation of the plane wavelets associated with the source. Finally, currents can be channeled from regions exceptionally remote from the body, especially for plane wave excitation.

2.8 *Depth of exploration*

A rule of thumb employed by most geophysicists is that the depth of exploration is from 0.3 to 1.0 times the separation between transmitting and receiving coils.

Depth of exploration is mostly controlled by target response, geological noise, and separation between transmitter and receiver (Hohmann and Ward, 1981).

2.9 *Lack of interpretational aids*

Undoubtedly the greatest hinderance to application of CSEM is the lack of interpretational aids. One cannot stress too much the need for cost-effective analytic or numerical solutions and catalogs to problems involving plane waves over two-dimensional structures (2D) and three-dimensional structures (3D), three-dimensional sources over two-dimensional structures (2D-3D), and three-dimensional sources over three-dimensional structures (3D-3D). I shall not dwell on this matter here.

3.0 BASIS FOR SELECTING INDUCTIVE ELECTROMAGNETIC SYSTEMS

3.1 *Time domain, frequency domain, and decades of spectrum*

Table 3 itemizes factors to consider in selecting controlled source electromagnetic systems. Figures 5 and 6 illustrate the wave forms most commonly used with frequency domain (FEM) and time domain (TEM) electromagnetic systems. Time domain (TEM) systems are much in vogue today in shallow crustal exploration, especially mining and sedimentary basin exploration, because measurements over a broad spectrum may be made in a short period of time whereas FEM systems require much more field time. Further, there is at present an inherently higher sensitivity in TEM than in FEM because TEM measurements are made in the absence of the primary field. On the other hand, power is concentrated in a narrow bandwidth with FEM while it is spread over a broad bandwidth with TEM. Higher ratio of signal to noise results with FEM. This can be countered in TEM if a square wave of low duty cycle is used; it provides short on time and long off time with high instantaneous power. Finally, most commercial state-of-the-art TEM systems operate over two decades of spectrum whereas the few state-of-the-art FEM systems operate over four decades of spectrum. The importance of the use of a large number of decades of spectrum is illustrated in our previous discussions of resolution and geologic noise. If exploration to great depths is desired, then measurements must be made at long times after cutoff of the transmitter current. The noise problems of the FEM methods described earlier apply equally to TEM if one simply replaces "low frequencies" by "long times after current cutoff."

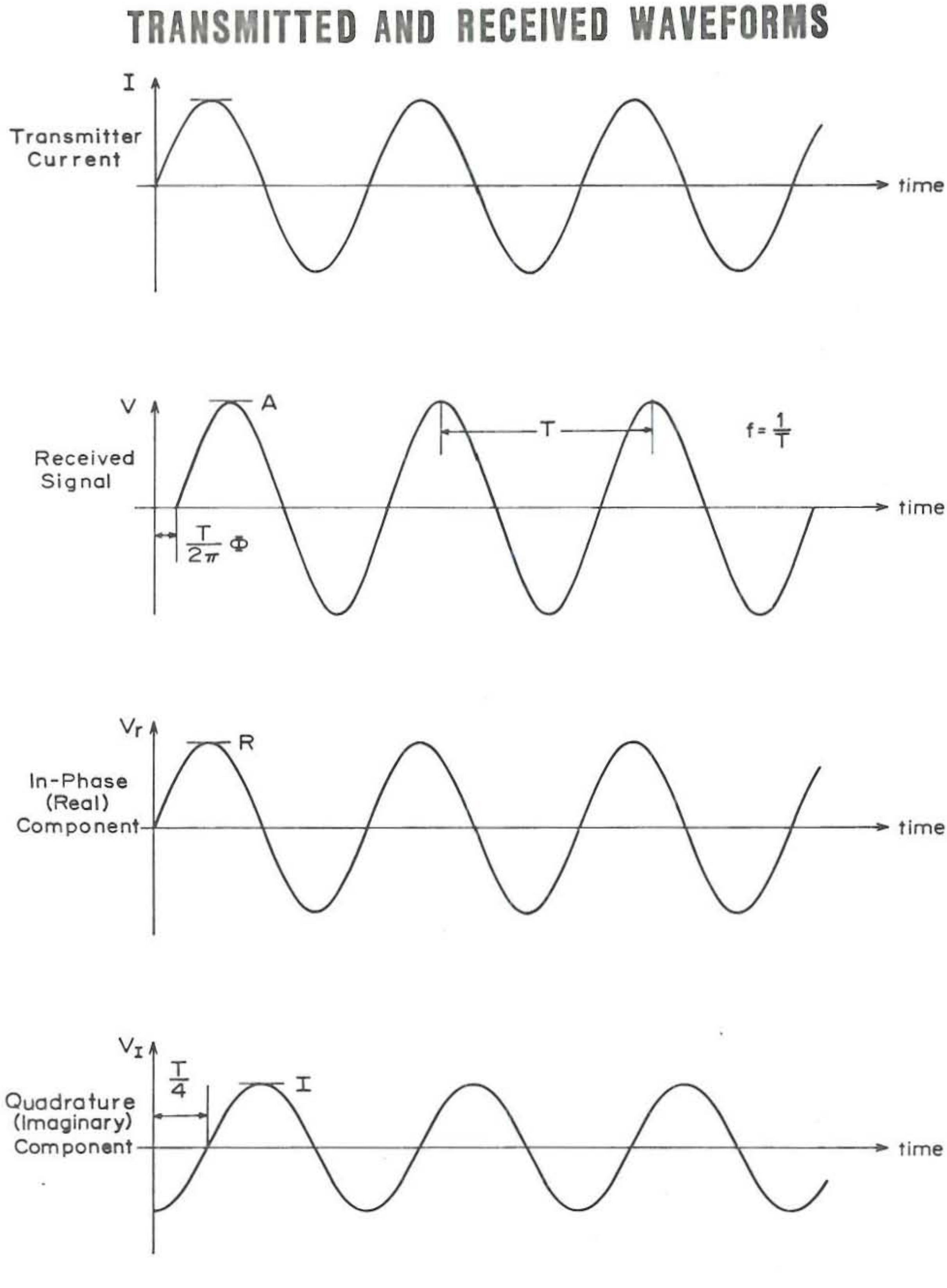
For deep crustal exploration, one might expect that FEM would be favored over TEM because of higher ratio of signal to noise expected with narrow band

BASIS FOR SELECTING CSEM SYSTEMS

- TEM OR FEM
- DECADES OF SPECTRUM
- S/N RATIO
- LATERAL & VERTICAL RESOLUTION
- SOURCE CONFIGURATION
- Tx COIL SIZE
- DEPTH OF EXPLORATION
- CURRENT CHANNELING
- EFFECTS OF TOPOGRAPHY

Table 3.

Figure 5. Frequency domain transmitted and received waveforms. Sine wave decomposed into in-phase and quadrature components. Amplitude is designated by A, phase by ϕ, period by T, and frequency by f.



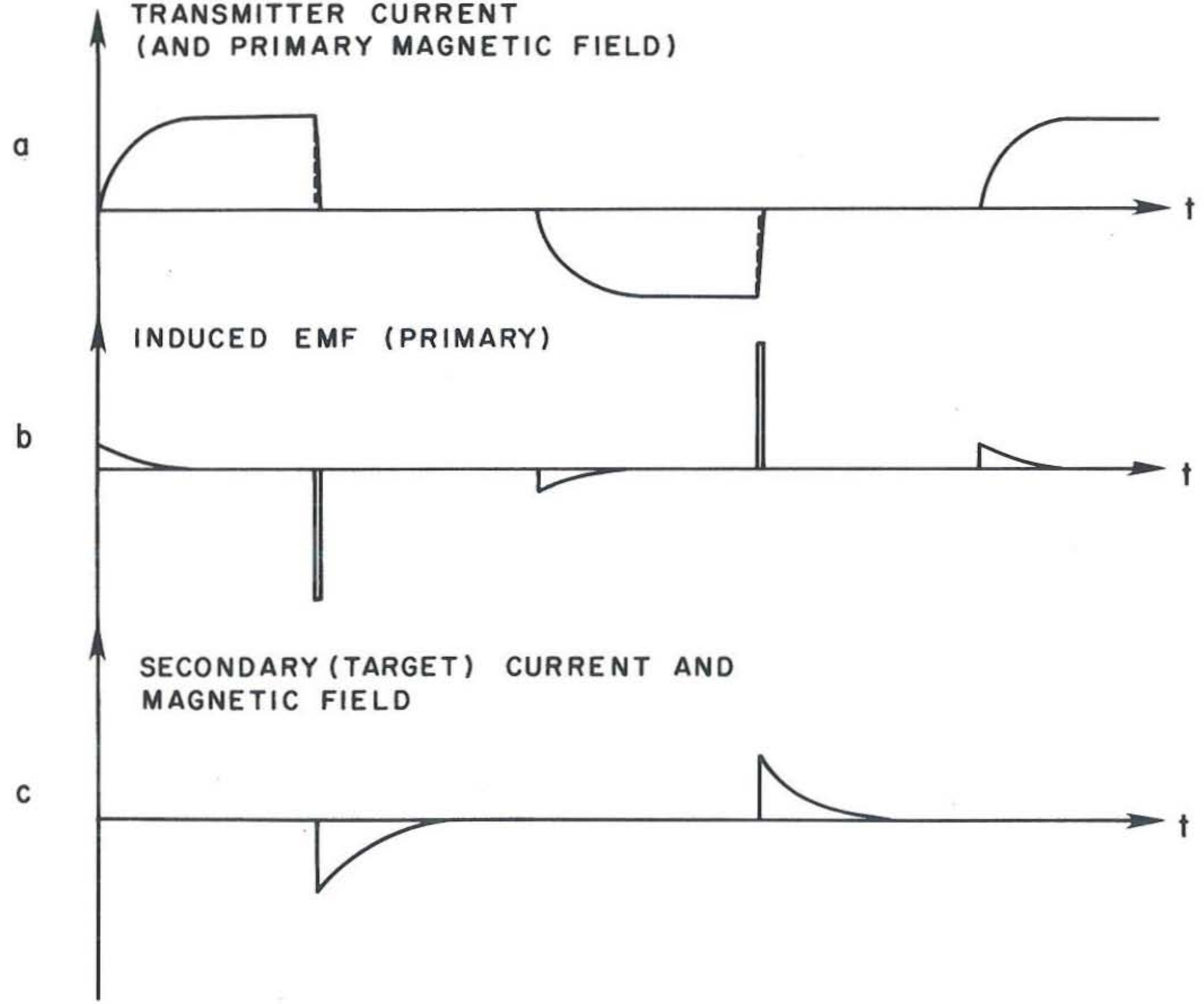


Figure 6. Typical time domain transmitted and received waveforms. (After McNeill, 1980).

(FEM) than with broadband (TEM) systems. While SanFilipo and Hohmann (1982) confirm this notion, further study of the problem is necessary, especially since the signals received from the subsurface targets are model-specific.

Table 4 summarizes the known relative advantages of FEM versus TEM. Apart from these, one should note that a single coil can be used as both transmitter and receiver in TEM. This fact has not yet been exploited in geothermal exploration, but it is a feature of SIROTEM which has been used in mining and sedimentary basin exploration. Further, alignment errors between transmitter (T_x) and receiver (R_x) are unimportant in TEM because measurement is made only of secondary (scattered) fields whereas in FEM measurements are always made of primary (source) and secondary fields combined.

One can depart from the basic waveforms of Figures 5 and 6 to achieve specific objectives. Duncan et al. (1980) and others report on use of a pseudorandom binary sequence (PRBS) but have yet to demonstrate that this modestly broadband system enjoys advantages over FEM narrow-band systems which also employ cross-correlation to extract signal from noise. Several other waveforms have been used in mining exploration (e.g., Barringer, 1962; Lamontagne, 1975; Won, 1980).

3.2 *Ratio of signal to noise*

Reference to this problem has been made several times above and is noted in Table 3. Insofar as the signal is model-specific and a comprehensive study of model responses remains to be completed, few comments can be made concerning inductive electromagnetic systems. Large transmitter moments, adequate signal processing, and transmitter-receiver configurations which couple best with the target of interest must be considered. A major deficiency in our knowledge clearly is evident here.

FEM VS TEM				
	SPECTRUM	BANDWIDTH	Tx - Rx SEPARATIONS	ALIGNMENT ERRORS
F.D.	4 Decades	Narrow	Large	Problem
T.D.	2 Decades	Broad	Small	No Problem

	TIME/READING	SIGNAL	NOISE	INSTANTANEOUS POWER
F.D.	Large	Model Specific	Low	Low
T.D.	Small	Model Specific	High	High

Table 4.

3.3 *Lateral and vertical resolution*

We have earlier drawn attention to lateral and vertical resolution. This sort of an approach has not been documented in CSEM applied to geothermal exploration but has been documented in AMT/MT applied to the same problem (e.g., Wannamaker et al., 1980). Lateral resolution is important for exploration to depths up to 5 km whereafter vertical resolution is apt to become more important.

3.4 *Source configurations*

Figure 7 portrays four basic transmitting source configurations used in mining exploration. For detailed discussions of the many variants on these basic source types, see Grant and West (1965), Ward (1967), and Telford et al. (1976).

The two-loop array (Figure 7) is moved in-line or broadside across the expected strike of the structure. In the frequency domain, real and imaginary parts of secondary magnetic fields are recorded as a percentage of primary field. The phase reference is hard-wired from the transmitter to the receiver by which means the primary field is also bucked out. In the time domain, the secondary transient is simply recorded and stacked at the receiver. Measurements are made every 25 or 50 m along traverse with the transmitter and receiver separated by 100 to 200 m.

The large source loop portrayed in Figure 7 ranges in dimensions from 200 m x 400 m to 500 m x 1000 m. Measurements in the frequency domain are made of field strength and phase of one to three magnetic field components or of field strength ratio and phase difference with a pair of horizontal coplanar or vertical coaxial coils. For the former, synchronized crystal clocks at the receiver and transmitter provide a phase reference for coherent detection.

BASIC GROUND EM METHODS

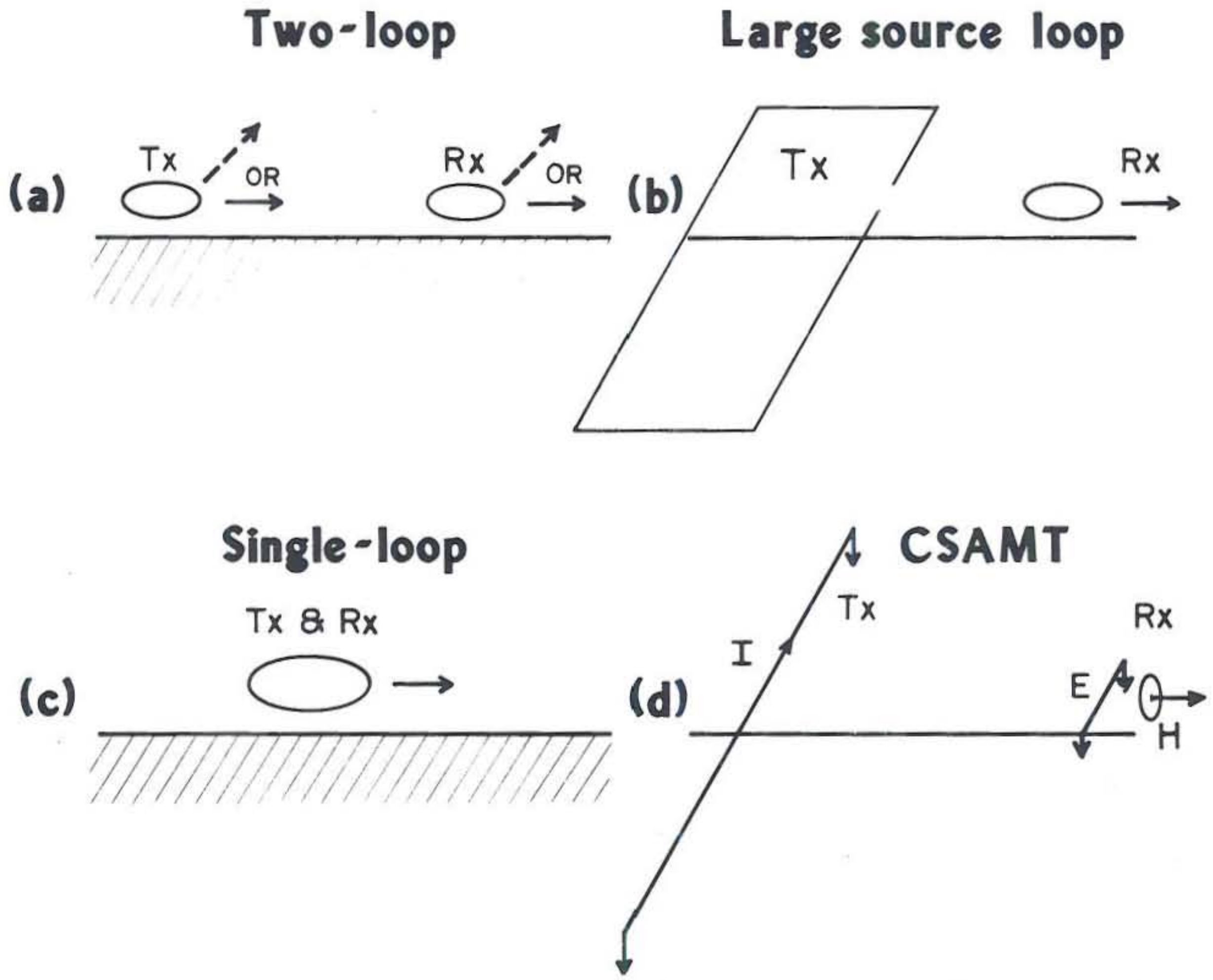


Figure 7. The four basic source types used in electromagnetic exploration: (a) coplanar horizontal, coplanar vertical, or coaxial loop pairs; (b) a large rectangular source loop to which a single horizontal or vertical receiving coil is referenced; (c) a single loop which is used sequentially as transmitter and as receiver in the time domain or whose impedance is measured in the frequency domain; and (d) a grounded wire source to which electric and magnetic field components are referenced.

Measurements of one to three components are also made in the time domain for which crystal clocks provide time reference for stacking. Traverses of the receiving coils are made outside the loop on lines perpendicular to a long side of the loop, and hence nominally perpendicular to geologic strike. In the time domain, measurements are also made inside the loop when one wishes to minimize current channeling (pers. comm. B. Spies, 1982). Typical reading intervals are 25 m to 50 m. If two receiving coils are used, they are separated by about 50 m. A scaled-up version of this system suitable for deep crustal studies is represented by the experiments reported by Connerney et al. (1980).

In the time domain it is possible to use a single loop, first as a transmitter and then as a receiver (Figure 7). Fast switching of the loop from the transmitter to the receiver facilitates this approach. The loop is moved along traverse normal to geologic strike, between measurements, with receiving stations being occupied every 50 or 100 m. The loop typically ranges from 50 m to 100 m to the side. The method is also used in shallow sedimentary basin applications.

The fourth transmitting source shown in Figure 7 is a grounded bipole. As used in the controlled source audiomagnetotelluric method (CSAMT) the bipole is typically 1 to 2 km in length. Readings are made over the frequency range 10 Hz to 10 kHz of components of electric and magnetic fields parallel and perpendicular to the bipole and also of the vertical magnetic field. If measurements are made 3 to 5 skin depths away from the source, plane wave formulation can be used in interpretation (skin depths are calculated for the most resistive medium). The bipole is oriented parallel to strike to excite the TE mode whereas it is oriented perpendicular to strike to excite the TM mode. The method is showing recent increased use with applications in mining, geothermal, and sedimentary basins; the measurement station intervals depend upon the scale of the problem (Goldstein and Strangway, 1975; Sandberg and Hohmann, 1980; Bartel and Wayland, 1981). The grounded bipole studies of Sternberg (1979) and of Duncan et al. (1980) can be considered related to CSAMT, but their measurements were made closer to the grounded bipole than is typical of CSAMT.

One of the least studied matters with inductive CSEM is systematic and objective comparison of the wide range of transmitting and receiving coil pairs which may be used in exploration for various targets. The reasons for this are the incredible size of the task and the lack of availability of all of the computational methods required to make the comparisons.

For deep crustal exploration the selection of systems becomes considerably simplified relative to the options for mining exploration, for example. To start with, the source most likely will be either a grounded bipole or a square coil. Once one has gone to the considerable logistical trouble of laying out the source, it makes most sense to collect all three orthogonal components of magnetic field and the two horizontal orthogonal components of electric field. However costs, logistics, and objectives may dictate otherwise. A large single loop, serving first as transmitter and sequentially as receiver, has not been used for such studies as noted earlier. An objective comparative analysis of the advantages and limitations of each of these sources and of MT/AMT in various one-, two-, and three-dimensional terranes is a highly desirable objective for future analysis.

3.5 *Transmitter source size*

Lajoie and West (1976) have demonstrated that the size of the source can be matched to the size of the target in order to achieve optimum response. They conclude that the source dimensions ought to be of the order of the target dimensions if the target is a three-dimensional body.

3.6 *Other factors*

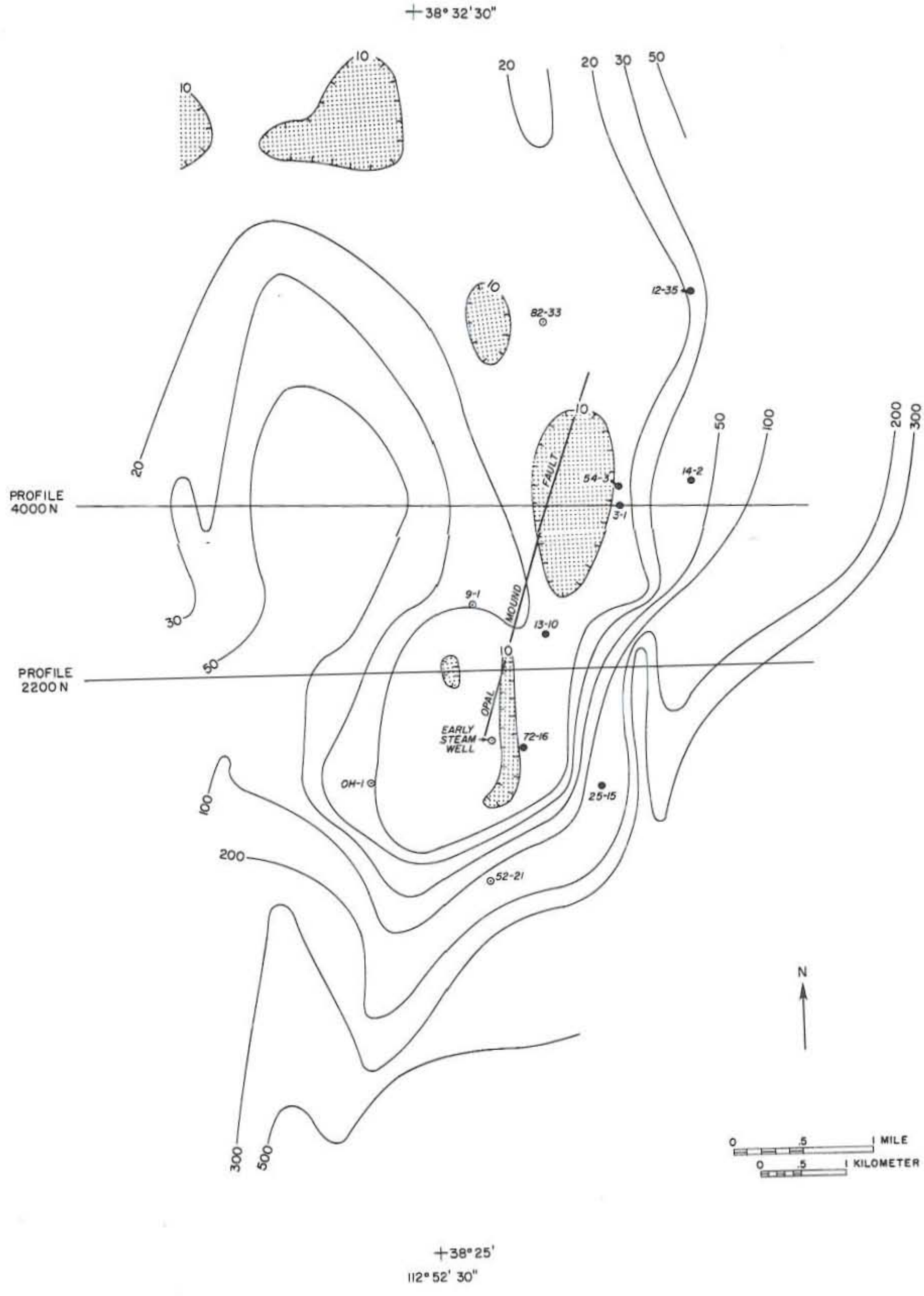
The importance of depth of exploration, current channeling, and effects of topography have been adequately treated under "Problems with inductive CSEM systems" above.

4.0 ROOSEVELT HOT SPRINGS CASE HISTORY

Figure 8 contains a plan map of contoured resistivity obtained with the dipole-dipole array at Roosevelt Hot Springs, Utah, U.S.A. The dipole length was 300 m and the data plotted pertains to the first separation (n = 1). Figures 9 and 10 are CSAMT data at 98 Hz and 977 Hz taken at the same site. A comparison of Figure 8 with either of Figures 9 or 10 reveals the CSAMT is equally capable of mapping the low resistivity zone of the geothermal system adjacent to the Opal Mound Fault. Each method also detects the brine leakage plume to the northwest and the low resistivity sediments of the Milford Valley to the west.

Figures 11 and 12 show, respectively, TM mode field data and TM mode modeled data in section. Figure 13 contains a) the model that fits the CSAMT TM mode field data, and b) the model that fits a dipole-dipole resistivity survey over the same area. The CSAMT field and model data are from Sandberg and Hohmann (1980) whereas the model derived from the dipole-dipole data is from Ward and Sill (1976). While the earth models derived from the two surveys are somewhat dissimilar, their main features are in consonance. Of importance to detailed deep crustal studies is the fact that the high density of sampling of both spatial and frequency variables does permit an exceptionally high degree of forward fitting of field data. One should not be lulled into believing that all of the parameters of all of the two-dimensional models of Figure 13 have been resolved. Rather these are, while detailed, reasonably permissive models.

Figure 8. First separation dipole-dipole resistivity map of the Roosevelt Hot Springs KGRA (a = 300 m). Areas less than 10 Ω-m are shaded. Solid circles denote producing geothermal wells, open circles indicate non-producing wells. (After Ward and Sill, 1976).



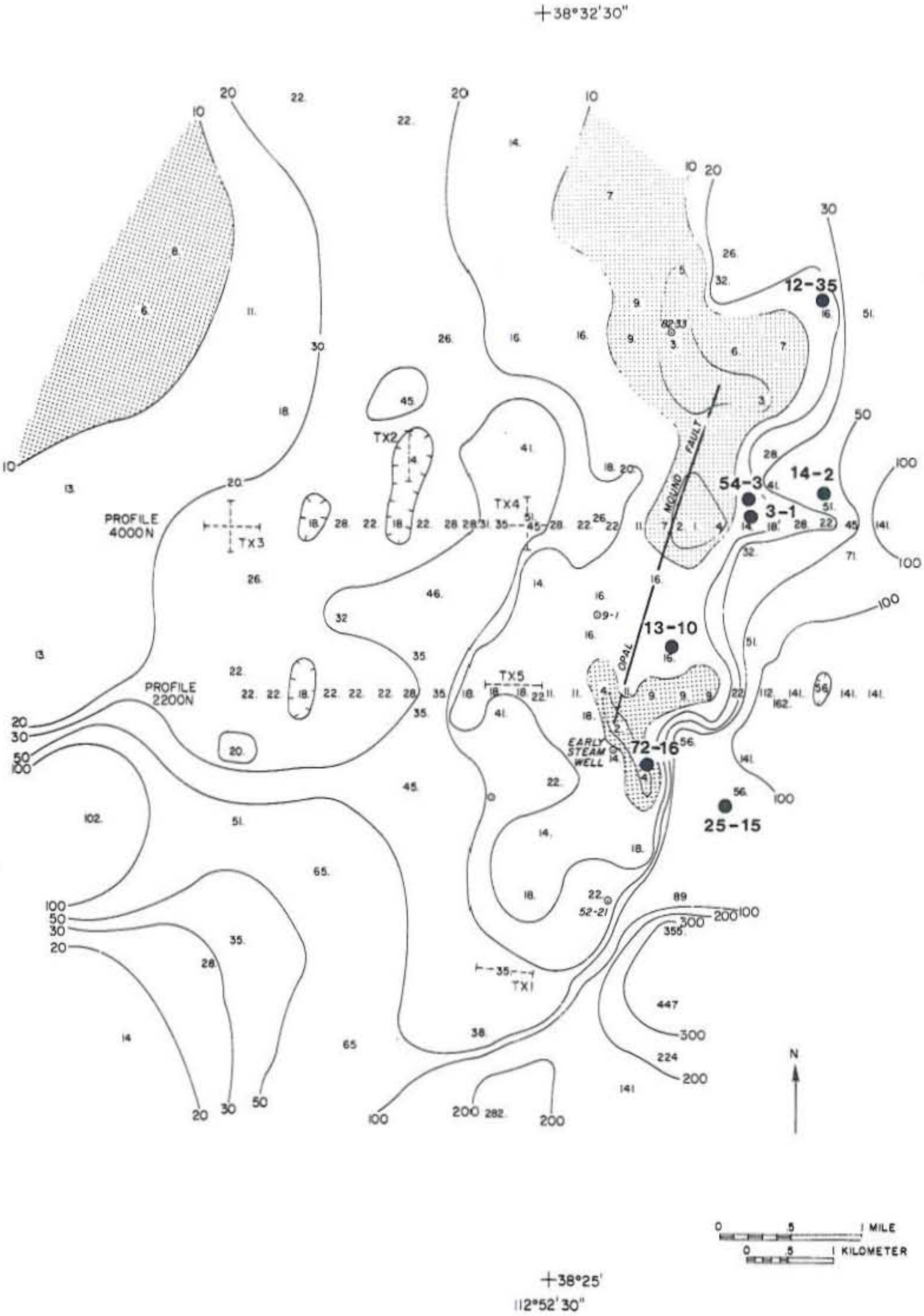


Figure 9. CSAMT apparent resistivity map of Roosevelt Hot Springs KGRA. Frequency = 98 Hz. Areas less than 10 Ω-m are shaded. (After Sandberg and Hohmann, 1980).

Figure 10. CSAMT apparent resistivity map of Roosevelt Hot Springs KGRA. Frequency = 977 Hz. Areas less than 10 Ω-m are shaded. (After Sandberg and Hohmann, 1980).

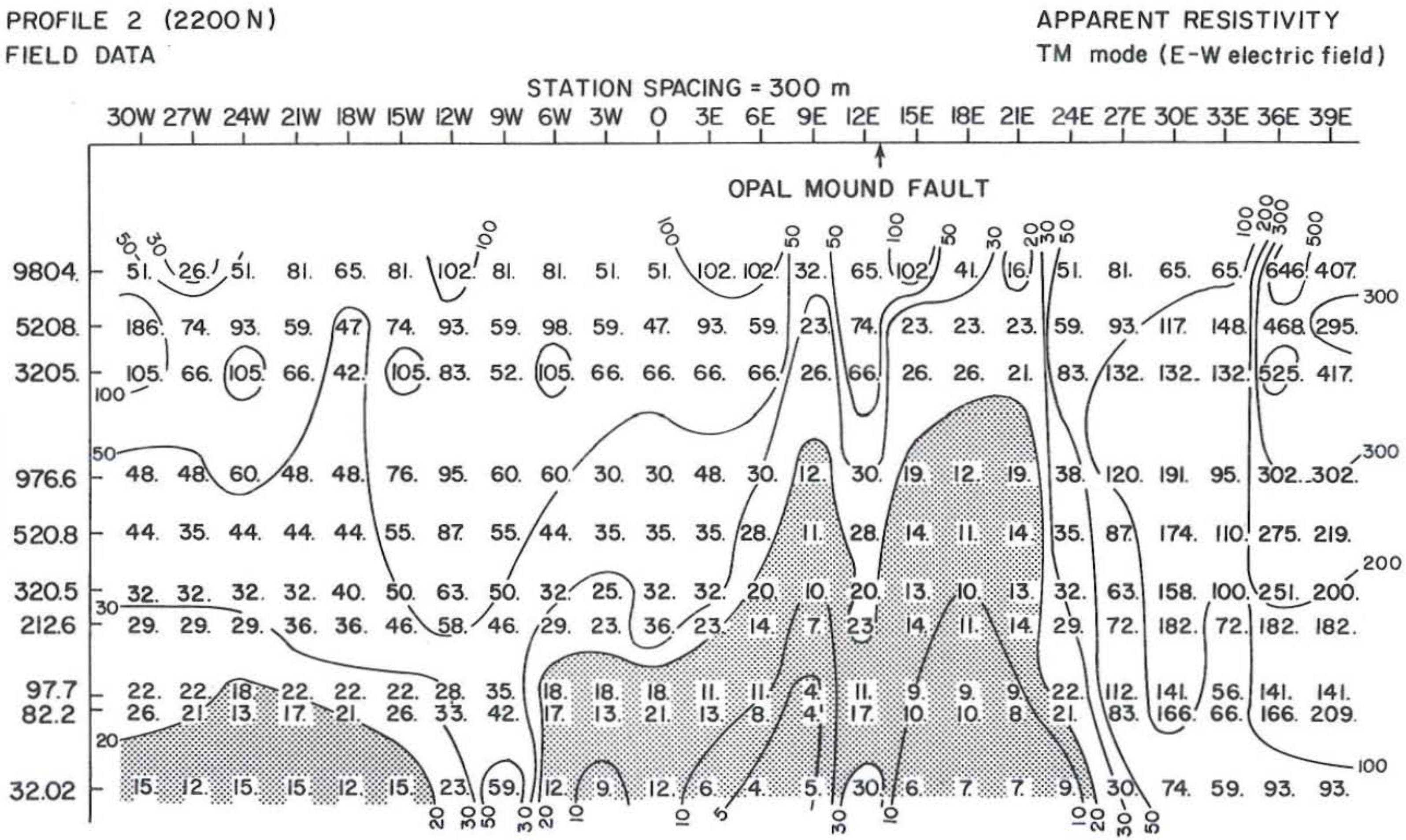


Figure 11. TM mode CSAMT field data, Roosevelt Hot Springs, Utah, U.S.A. (After Sandberg and Hohmann, 1980).

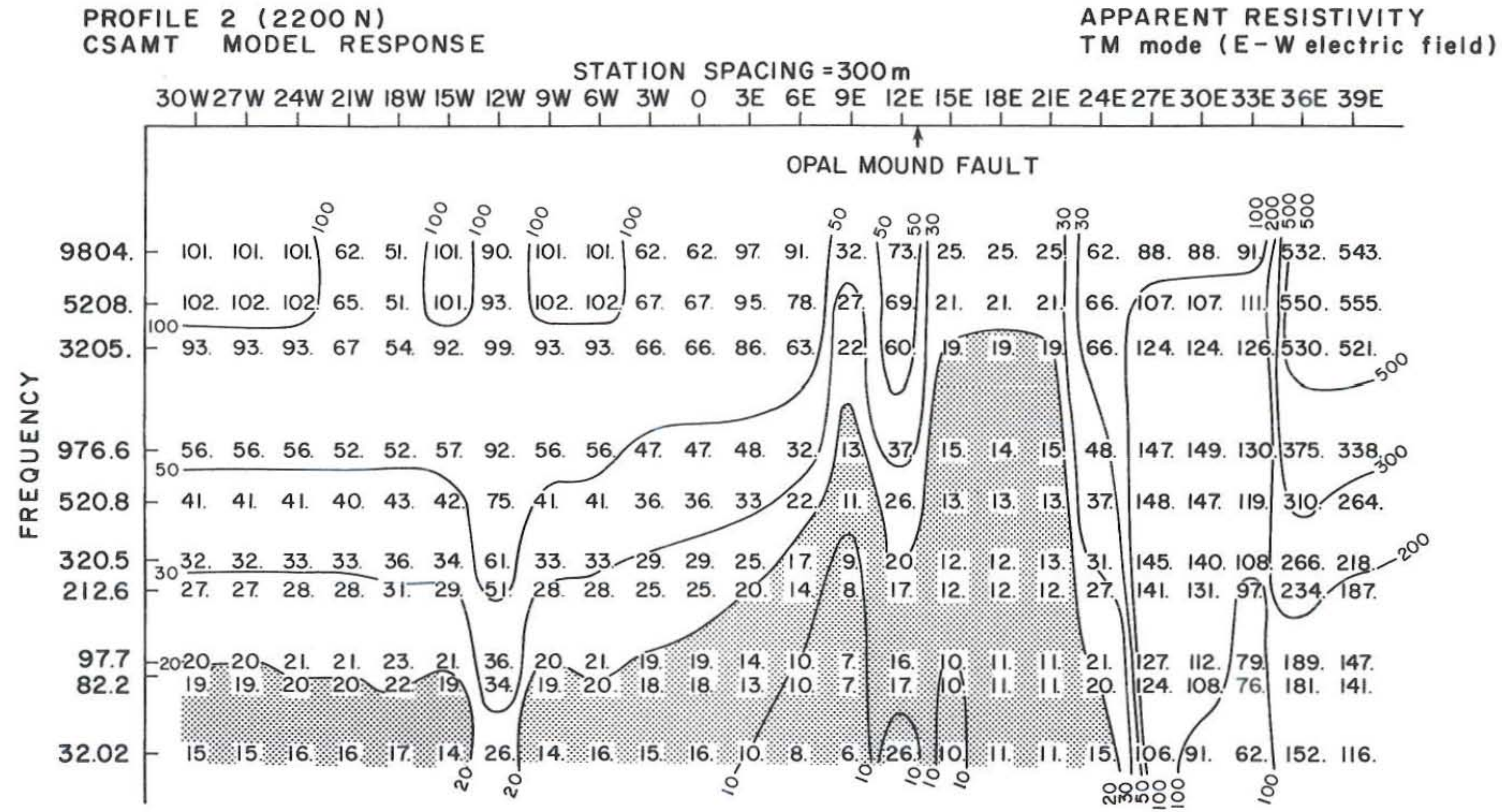


Figure 12. TM mode CSAMT modeled data, Roosevelt Hot Springs, Utah, U.S.A. (After Sandberg and Hohmann, 1980).

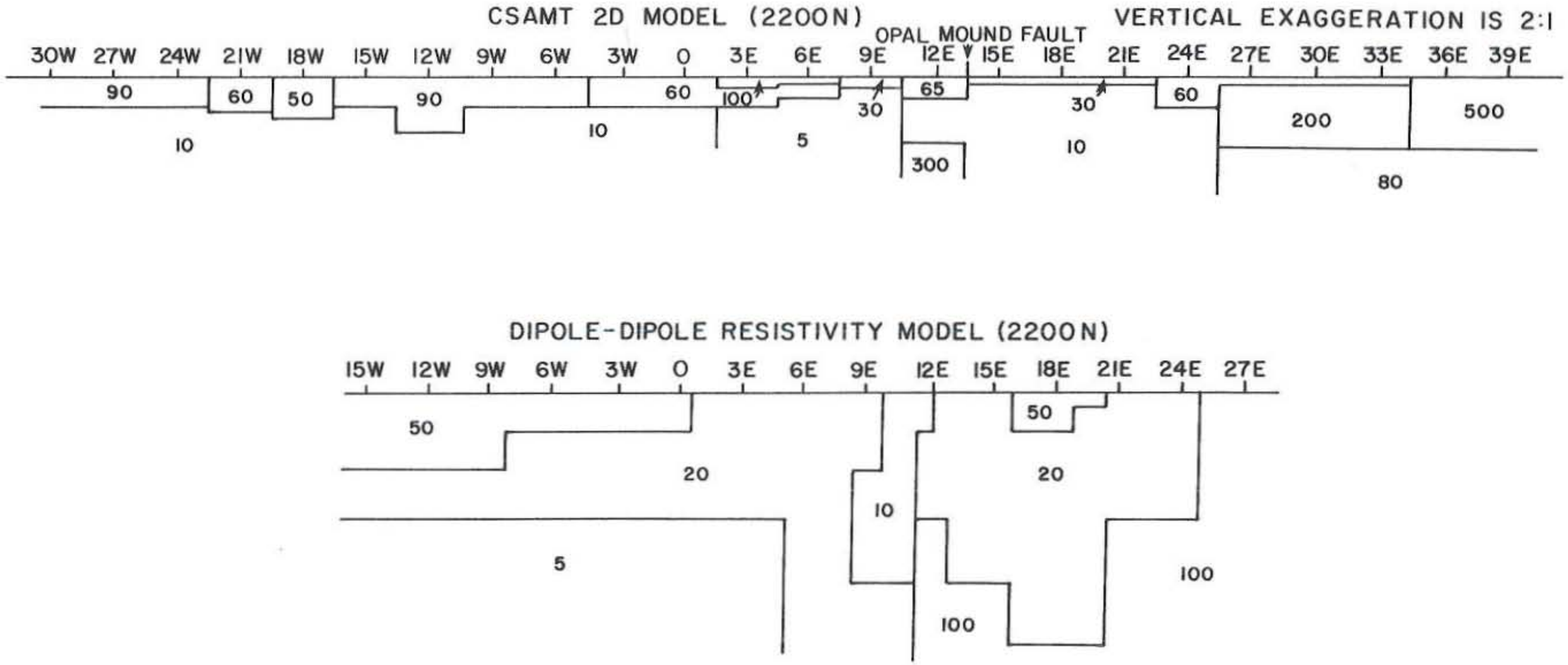


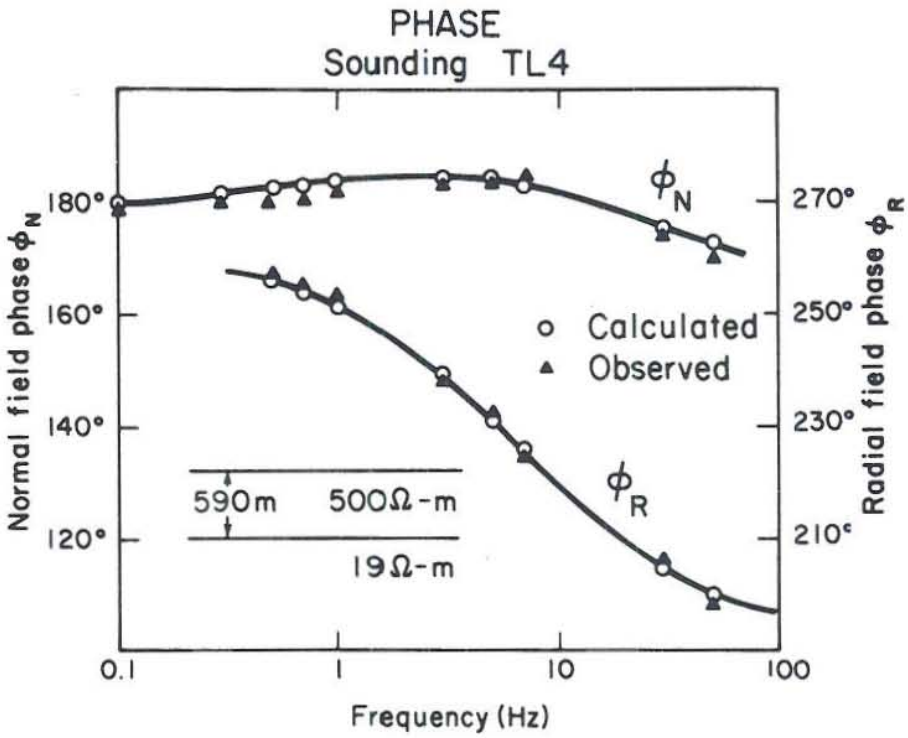
Figure 13. Two-dimensional model from which the modeled data of Figure 12 were calculated (top) and two-dimensional model derived from dipole-dipole resistivity survey (bottom). (After Sandberg and Hohmann, 1980).

5.0 OTHER CSEM FIELD EXAMPLES

Figure 14 portrays the phase and amplitude spectra for sounding TL4 performed at Mt. Hood, Oregon, U.S.A. by Goldstein et al. (1982). A layered earth interpretation is given for each data set. Similarly, Figure 15 portrays tilt angle and ellipticity for a CSEM sounding plus apparent resistivity for a Schlumberger sounding at Roosevelt Hot Springs, Utah, U.S.A. Tripp et al., 1978, inverted the three data sets simultaneously to yield the four layer model illustrated. Figure 16 illustrates the geoelectric section interpreted by Keller (1970) from time domain soundings in the vicinity of the Broadlands thermal field in New Zealand.

A number of experiments has been performed, in recent years, which were designed to allow electrical investigation of the deep crust. Table 5 summarizes the conditions of the experiments and the results obtained. Clearly, one can explore deeply in the crust using grounded bipole or loop sources, but the task is not an easy one. It is yet to be established whether or not such deep crustal CSEM soundings bear on geothermal resource development.

Figure 14. Phase (ϕ_N and ϕ_R) and amplitude (H_N and H_R) of tangential and radial magnetic fields for EM 60 loop source at Mount Hood, Oregon, U.S.A. Earth model shown was derived by inversion. (After Goldstein et al., 1982).



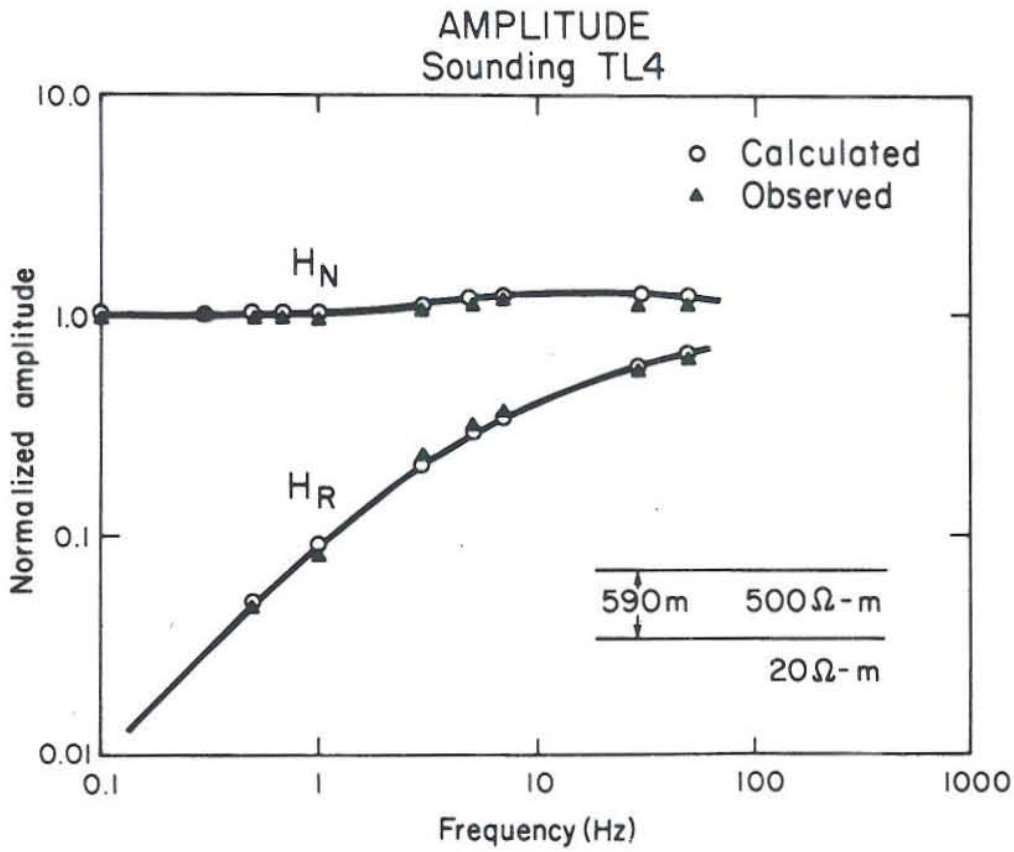
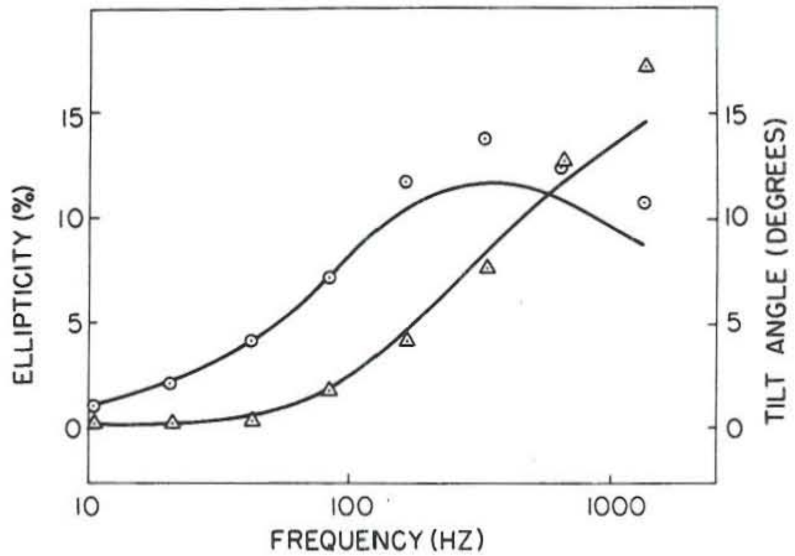
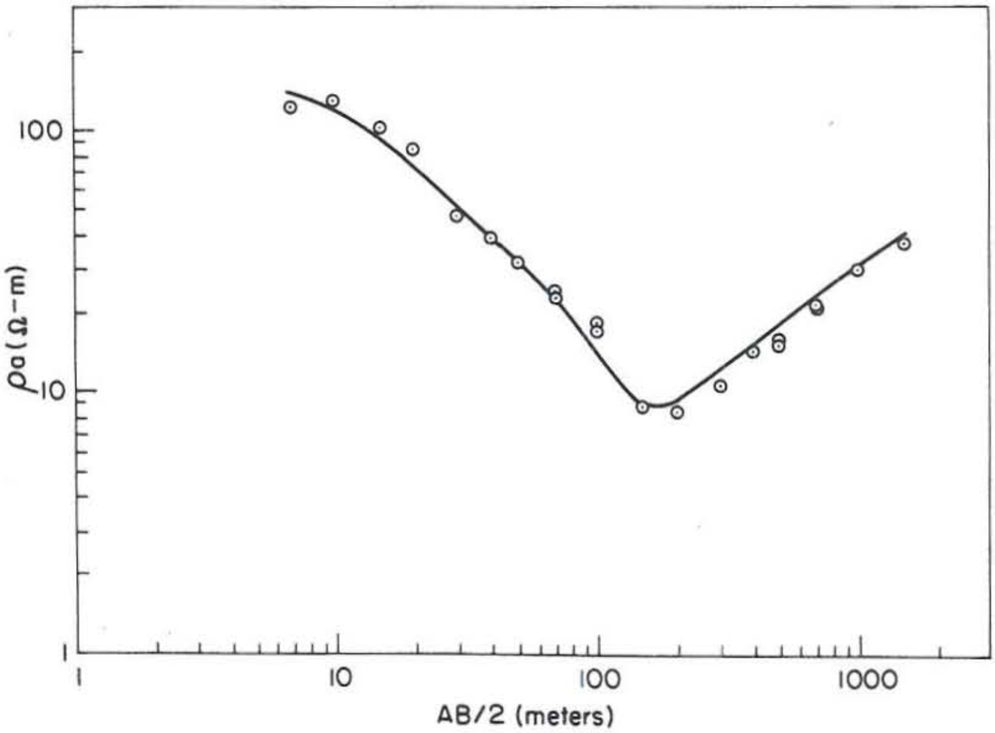


Figure 15. Ellipticity and tilt angle of CSEM sounding and apparent resistivity Schlumberger sounding curve at Roosevelt Hot Springs. Earth model shown was derived by joint inversion of all three data sets. (After Tripp et al., 1978).

ρ_1 = 151 Ω-m(128,178)	t_1 = 7.4 m(5.8,9.4)
ρ_2 = 39 Ω-m(32,47)	t_2 = 36 m (32,41)
ρ_3 = 2.4Ω-m(1.8,3.2)	t_3 = 46 m (35,61)
ρ_4 = 73 Ω-m(52,103)	





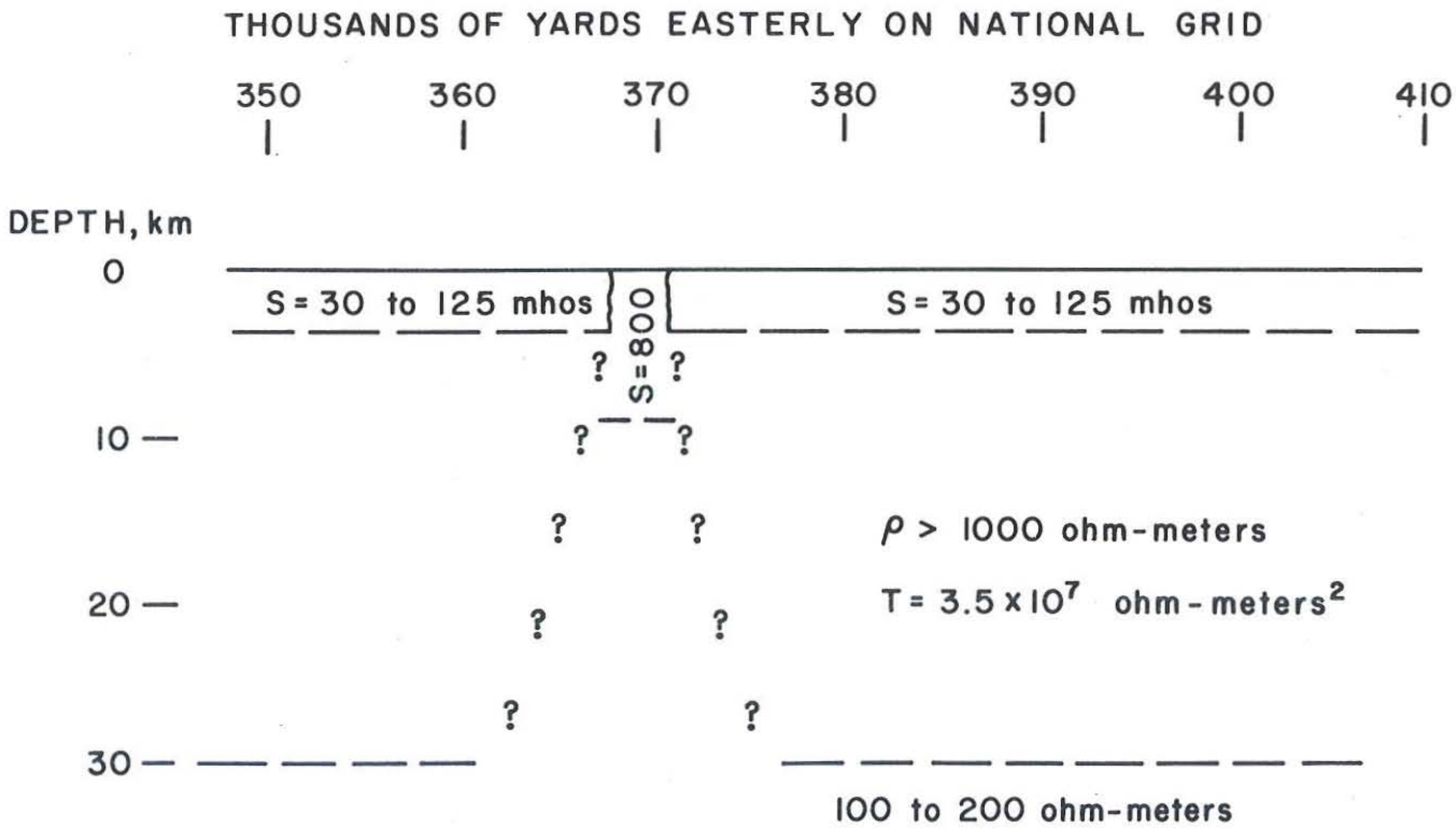


Figure 16. Electrical cross section along a profile crossing the thermal area of the North Island of New Zealand in the vicinity of Broadlands. S is the product of conductivity and thickness in the surface layer, and T is the product of resistivity and thickness in the second layer. (After Keller, 1970).

RECENT EXPERIMENTS USING CSEM FOR DEEP CRUSTAL STUDIES							
INVESTIGATORS	**SOURCE TYPE**	**SOURCE CURRENT**	**BANDWIDTH**	**Tx-Rx SEPARATION**	**WAVEFORM**	**STACKING TIME**	**CRUSTAL MODEL**
LIENERT & BENNETT, 1977	1400 km GROUNDED POWER LINE	300A	0.001-0.01 Hz	5-55 km	SQUARE	20 STACKS	0 20 — 10^2-10^3 Ωm 35-45 — 1-10 Ωm km — 100 Ωm
STERNBERG, 1979	22-24 km GROUNDED BIPOLE	70A	0.5-10 Hz	5-40 km	SQUARE	100 STACKS	0 10 — 10^3 Ωm 14-22 — 10^5 Ωm km — 50-1200 Ωm
CONNERNEY, ET. AL; 1980	4.5 km DIA. LOOP	65A	0.05-400 Hz	20-65 km	SQUARE	TO DAYS	0 10 — 10^4 Ωm 20 — 10^3 Ωm 30 — 10-25 Ωm km — 10^4 Ωm
DUNCAN ET AL; 1980	20.5 km GROUNDED BIPOLE	5A	1.0-50 Hz	35-85 km	PRBS	TO 10 HRS	0 17-29 — 1.5×10^4 Ωm km — 270 Ωm
VAN ZIJL, 1977	SCHLUMBERGER	72A	D.C.	AB TO 1000 km	SQUARE	174 STACKS	0 28-30 — 2-10×10^3 Ωm 30-40 — 10-60 Ωm km — HIGHLY RESISTIVE

Table 5.

6.0 CONCLUSIONS

Controlled source electromagnetic methods can be used effectively in geothermal exploration. Depths of exploration ranging from tens of meters to tens of kilometers can be achieved. Where resistive rocks occur at surface, CSEM may enjoy an advantage over resistivity methods which may suffer from difficulties encountered in injecting large currents into the ground. CSEM will allow estimates of the conductivity-thickness product of a thin conductive bed, but only the thickness of a thin resistive bed. On the other hand, resistivity methods will yield the conductivity-thickness product of a thin conductive bed, and the resistivity-thickness product of a thin resistive bed. Where both techniques can be avoided, joint inversion of both data sets will lead to much improved earth models.

The CSAMT method offers considerable promise for geothermal exploration since it appears to be less expensive than resistivity and yet yields much the same information.

For loop-loop CSEM surveys, the loop separation is much smaller than the current electrode separation in Schlumberger soundings. This results in less effects from geological features off to the side of the array.

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