SOME EFFECTS OF TWO-AND THREE-DIMENSIONAL STRUCTURE ON MAGNETOTELLURIC DATA

A. S. Orange
Emerald Exploration Consultants
Austin, TX 78759

and

S. Park
Earth Sciences Department
Massachusetts Institute of Technology
Cambridge, MA 02139

and

D. Chambers
Woodward-Clyde Consultants
San Francisco, CA 94111

Introduction

Magnetotellurics (MT) has found widespread application in the evaluation of geothermal resources. Taking advantage of the potential ability both to determine deep crustal properties and to identify and map shallow hot aquifers and fluid-filled fault systems, MT has been used for both regional and prospect-specific exploration.

Data acquisition instrumentation and processing software have steadily increased in sophistication and reliability. As these aspects of MT mature, more emphasis is being placed on interpretation, in particular on the complicating effects of geologic structure as explorationists consider cases that depart from the simple, plane-layered "Cagniard" earth. Since most, if not virtually all, practical geothermal exploration problems involve a geologic setting that is at least two-dimensional, the concern to workers in the field can be easily understood.

This paper is an interim report, a "progress review" of one informal group actively working on various aspects of MT interpretation in complex areas. The authors, representing an academic institution, a geophysical contractor and an exploration group, bring to the study a wealth of varied experience in both theoretical and applied research.

The objectives of the paper are three-fold. First, the authors wish to share selected preliminary observations with colleagues equally concerned with the subject at hand, since it has become obvious that there are subtle pitfalls in MT interpretation awaiting the unwary. Second, it is desired to suggest approaches to MT survey planning that take into account potential interpretive problems. Lastly, it is hoped that awareness of interpretive problems will lead to increased encouragement and support for researchers in the field.

MT Interpretation, An Overview

Standard MT processing results in the calculation of two orthogonal apparent resistivity-vs-frequency curves at each recording location. If the earth is not plane layered, then the two curves will in general be different, and be aligned (at least in the two-dimensional case) parallel and perpendicular to strike. The goal of an MT interpretation is to correctly identify the subsurface configuration that led to the observed data. This is accomplished through the comparison of field data with that obtained from model calculations, and/or the direct inversion of the field data. The latter technique has become increasingly popular, with the recognition that simple relationships exist whereby each of the apparent resistivity-vs-frequency curves can be inverted to a continuous "intrinsic" resistivity-vs-depth form. These single-curve inversions, however, assume for each curve that the earth is one-dimensional, thus two different resistivity-depth curves may be computed at each location. The interpreter's job at this point is one of determining how, from the two available resistivity-depth curves, to best approximate the actual resistivity-depth relationship.

For geothermal applications, the principal implications of the above are as follows: First, for regional studies investigating the lower crust, the location of the deep conductor (the presumably hot lower crust) is the desired target, and the interpretation of the lower frequencies, and a correct inversion of the low frequency data, is critical. Second, when looking for shallow, hot aquifers an accurate interpretation of the location and geometry of conductive anomalies is the desired result. In both cases, in a non-one-dimensional setting interpretive decisions must be made which, as will be shown, may have a critical effect on the outcome.

Two-Dimensional Considerations

In a one-dimensional setting with resulting isotropic MT data the continuous inversion is an excellent interpretive tool. In particular, if crustal parameters are slowly varying laterally then the interpretation of relative depths can be accurate. In a two-dimensional setting, however, the two inversions (of each of the two orthogonal apparent resistivity curves) will differ. Study of a large number of two-dimensional model calculations and comparison with field results in well-understood geologic settings leads to the following observations:

1. The one "correct" apparent resistivity curve and the resulting inversion, i.e., the data that would be observed and calculated if the stratigraphy directly beneath the site in question extended indefinitely in all directions, in general lies somewhere between the extremes of the two observed curves. It is important to note that this is not necessarily a good assumption in the three-dimensional case.
2. In some cases, such as the common geologic setting of shallow, lateral resistivity variations in otherwise plane-layered stratigraphy, one of the observed resistivity curves may be an excellent approximation to the "correct" curve.
3. In some cases, such as large-scale basin and range faulting, the observed data may be extremely anisotropic and neither curve may approximate the "correct" curve to within as much as an order of magnitude, especially at the lower frequencies.
4. In geologic settings resulting in anisotropic data, low-frequency characteristics of one or both of the resistivity curves may be much more reflective of lateral variations than vertical stratigraphy. Stated more strongly, low frequencies do not necessarily equate totally to deep penetration.
5. When thin, highly conductive strata are present, especially if these terminate, then an accurate determination of depth and extent of the conductor may be difficult, especially if the data are noisy.
6. A <u>qualitative</u> interpretation of widely spaced MT sites is almost always possible even if the data are anisotropic, given a knowledge of the regional geologic framework, the topography and surface geology in the vicinity of the site. The <u>quantitative</u> interpretation of anisotropic MT data becomes credible as data becomes available from multiple sites, and improves as sites are spaced more closely, especially in the vicinity of lateral resistivity variations.

Three-Dimensional Considerations

The study of the effect of three-dimensional structural complexity on MT data has been difficult due to the limited availability of applicable modeling programs and the computation expense involved. Recent advances have improved this picture, and model computations have become available, which have provided interpreters with considerable insight. In addition to model studies, the analysis of field data obtained in the vicinity of well-documented, strongly three-dimensional structures has led to a start towards the understanding of what kinds of data to expect under such circumstances.

The model studies have been directed specifically at problems of interest to regional geothermal exploration. The results indicate that for many simple, geologically common settings with structure involving only the shallow upper crust, MT data can be affected such that both orthogonal resistivity curves yield an anomalously shallow lower crust. Thus, by utilizing standard interpretation techniques, a "crustal upwelling" could be identified in cases where none in fact exists. Of particular concern is the case of a broad, conductive sediment-filled valley, which represents a typical location where a regional MT site might be placed. What is most insidious about this class of problems is that the data at an affected site may appear isotropic; the interpreter received no warning from the MT data itself.

Once the possibility of the effect is recognized, then a regional survey can be designed with a grid of sites. With a knowledge of the topography and the geological framework, even a limited number of sites should be able to yield a credible interpretation.

The field data studies have concentrated on an investigation of the "out-of-limits phase" phenomenon, whereby the phase as well as the amplitude of one of the orthogonal apparent resistivity components appears to behave anomalously. If one- or two-dimensional inversion techniques are used under such circumstances, erroneous resistivity-vs-depth values will almost certainly result. The effect appears to be the result of utilizing data analysis techniques that involve assumptions that are invalid in some three-dimensional situations. It is normally assumed, for example, that the maximum and the minimum resistivity components are orthogonal. If in fact they are not, then the minimum resistivity component may be "contaminated" by a contribution from the maximum component, giving rise to the observed errors. While in most cases the existence of a problem site is self-evident, examination of polar plots of the diagonal as well as off-diagonal apparent resistivities should become part of the interpreter's routine in complex areas.

Concluding Remarks

Magnetotelluric interpretation data is a complex art, even in many cases where the data appear straightforward. The recognition of this complexity is a major step towards the realization of the method's capabilities. The study of two- and three-dimensional models will provide the interpreter with invaluable if not critical insight. Finally and most important, a survey should be planned utilizing this insight, and taking into account all available regional and site-specific information.