HISTORY OF ELECTRICAL METHODS OF EXPLORATION

Early History

The early chronology of applications of electrical methods of exploration has been carefully preserved in the literature (eg, Kelly, 1950; Kunetz, 1966; Van Nostrand and Cook, 1966). From those preservations and others one learns that the first attempt to utilize electrical methods dates back to Robert W. Fox. (1830) when he observed that electrical currents, flowing in Cornish copper mines, were the result of chemical reactions within the vein deposits, i.e. self potentials. According to Kelly, "The first recorded discovery of a sulphide body by electrical methods is to be credited to him, as the result of the investigations which he carried out in 1835, in the Penzance Mine of Cornwall."

As early as 1882, Dr. Carl Barus conducted experiments at the Comstock Lode, Nevada, which convinced him that the method could be used to prospect for hidden sulfide ores. To Barus goes the credit for introducing the non-polarizing electrode. Conrad Schlumberger put the method on a commercial basis in 1912. The first plan map of self potential over a metallic deposit was prepared by Conrad Schlumberger in 1913 and published in 1918; it pertained to the pyrite mines at Sain-Bel, France. Roger C. Wells, of the U.S. Geological Survey, in 1914 contributed the first chemical understanding of the passive self potential phenomena. Kelly (1957) introduced the self potential method to Canada and the United States in 1924.

Fred H. Brown, in the era from 1883 to 1891, and Alfred Williams and Leo Daft in 1897 first attempted to determine differences in earth resistivity associated with ore deposits and were granted patents on their methods. In 1893 James Fisher measured the resistivity of copper bearing lodes in Michigan (Broderick and Hohl, 1928), while in 1900, N. S. Osborne did equipotential work in the same district. The first practical approach to utilizing active electrical methods, wherein the earth is energized via a controlled source and the resulting artificial potentials are measured, was due to Conrad Schlumberger in 1912. At that time he introduced the direct current equipotential line method (Schlumberger, 1920).

The concept of apparent resistivity was introduced about 1915 by both Wenner (1912) of the U. S. Bureau of Standards and by Schlumberger (1920). The field techniques for apparent resistivity were then developed by O. H. Gish and W. J. Rooney of the Carnegie Institution of Washington and by Marcel Schlumberger, E. G. Leonardon, E. P. Poldini, and H. G. Doll of the Schlumberger group. Wenner used the equi-spaced electrode array which today bears his name while the Schlumberger group standarized on an electrode configuration in which the potential electrodes are sufficiently close together that the potential gradient, i.e. the electric field, is measured midway between the current electrodes (the Schlumberger array).

The earliest attempt to understand telluric currents is generally credited to Charles Mateucci (1867) of the Greenwich Observatory. It was not until 1934 that Conrad Schlumberger (1939, p. 272-3) made commercial use of the method.

According to Sumner (1976), "Conrad Schlumberger was the first to describe a *polarization provoquée* i.e. induced polarization, in 1920 although he dropped the concept in favor of the self-potential method."

Harry W. Conklin, an American mining engineer took out basic patents on the electromagnetic method in 1917. The first successful application of the *Sundberg* electromagnetic method, the forerunner of the horizontal loop method, occurred in 1925, (Sundberg, et al., 1925); hence the beginning of the Swedish thrust in electromagnetic prospecting which H. Lundberg and K. Sundberg fostered. The Bieler-Watson (1931) method of measuring the ellipse of magnetic field polarization in the vicinity of a large horizontal transmitting coil next appeared.

These were the foundations of the development of the theory and application for the electrical methods of geophysical exploration. In the next decade or so, numerous books, and treatises appeared which expanded rapidly on the foundations. Most notable among these were Ambronn (1928), Eve and Keys (1929), and Broughton Edge and Laby (1931). The three *Geophysical Prospecting* volumes of the Transactions of the American Institute of Mining and Metallurgical Engineers (AIME), in 1929, 1932, and 1934, provided forums for dissemination of knowledge of this rapidly growing field of electrical geophysical prospecting. These volumes were followed by Geophysics, 1940, Vol. 138 and Geophysics, 1945, Vol. 164 of the Transactions of AIME. The Society of Exploration Geophysicists published six papers on electrical methods in *Early Geophysical Papers*. Most of these papers dealt with oil and gas exploration. The first paper on electrical methods to appear in *Geophysics*

(Vol. 1) was by Statham (1936). From these beginnings, the electrical methods slowly developed, with most of the development taking place after World War II. Highlights of these developments follow.

The Resistivity Method

The theoretical basis for the electrical resistivity method became more firmly grounded with the forward solutions developed for horizontally layered earths by Stefanesco, Schlumberger, and Schlumberger (1930), and others. This work culminated in the publication of an album of curves for the Schlumberger array (C.G.G., 1955) and for the Wenner array by Mooney and Wetzel (1956). Until recently, matching of observed and theoretical curves via such albums was the standard method of intepreting resistivity data over horizontally layered earths. Roy and Apparao (1971) and Madden (1971) demonstrated, respectively, the depth of exploration for various electrode arrays and the resolving power of the resistivity sounding for thin conductive and thin resistive beds.

Langer (1933) and Slichter (1933) were the first to develop formulation of the inverse problem in resistivity sounding of horizontally layered structures. Koefoed (1968) and Ghosh (1971) did much to make inversion practical. Zohdy (1975) developed a method of direct interpretation with which he obtained good results. However, none of the above investigations used the method of the generalized inverse introduced by Backus and Gilbert (1967). Inman et al., (1973) introduced the use of the latter method to resistivity sounding, demonstrating that it was the most powerful technique for estimating parameters of a layered earth and for describing the non-uniqueness of the inverse solutions. Vozoff and Jupp (1975), Petrick et al. (1977), and others used simultaneous inversion of resistivity and other data sets.

Tagg (1930) computed apparent resistivity curves for Wenner array resistivity profiles across a vertical fault. Logn (1954) developed expressions for the apparent resistivity over thin vertical sheets. Lundberg and Zuschlag (1931) computed potential-drop-ratio curves over a vertical fault and a vertical dike. Many other workers pursued these initial leads. The dipping-bed problem in electrical geophysical applications was first solved by Skal'skaya (1948) and her work was extended by many others. Frank and von Mises (1935) gave the exact solution for the potential due to a point current electrode over a horizontal buried cylinder. Van Nostrand and Cook (1966) present an excellent summary of one-, two-, and three-dimensional models available for interpretation of resistivity data to that time.

In recent years, the development of practically realizable numerical methods, such as, the finite-difference, finite element, transmission-line, and integral equation methods, has permitted the computation of sounding-profiling results for any electrode configuration over two-dimensional inhomogeneities of arbitrary shape. Madden (1972) introduced the transmission-line method, Jepsen (1969) the finite-difference method, and Coggon (1971), the finite element method, while Snyder (1976) introduced the integral equation method.

The inversion of two-dimensional resistivity data is in its infancy. Pelton et al. (1978) developed an approach to inversion of two-dimensional dipole-dipole resistivity and induced polarization data, using the transmission surface method, which relied upon storage in a computer of a data bank of forward solutions. Tripp et al (1979), following a suggestion by

Madden (1972), utilized Telegen's theorem and the transmission surface analogy to produce a true ridge regression generalized inverse solution for the dipole-dipole array over a two-dimensional earth structure.

Petrowsky (1928) first studied the potential distribution at the surface of the earth due to a buried electrically polarized sphere. Stefanesco (1950) first presented the very interesting and powerful alpha center approach to three-dimensional modeling of resistivity data. Cook and Van Nostrand (1954) calculated a wide variety of resistivity curves over and near filled sinks, appropriate to the Lee and Wenner arrays. Seigel (1959) presented the response of a polarizable sphere in a half-space. The first three-dimensional numerical solution was presented by Hohmann (1975) in a best paper award winner in Geophysics. Pridmore (1978) used the finite element method to calculate apparent resistivities over a complex three-dimensional earth. Dey and Morrison (1979) used the finite difference method to calculate apparent resistivity distributions for the dipole-dipole array over three-dimensional inhomogeneities.

If in the Schlumberger array the current electrodes are far apart and the potential electrodes are moved in-line between the current electrodes then the *gradient array* is achieved. The pole-dipole and dipole-dipole arrays seem to have been promulgated by Madden and his students but they have their roots in the Eltran array (West, 1940). The vector bipole-dipole array (e.g. Doicin, 1976) has achieved prominence in recent years but it has yet to prove its value. The Lee, potential-drop-ratio, equipotential line, and Wenner arrays have not survived the test of time. Van Nostrand and Cook (1966) provide an extensive coverage of resistivity arrays.

Edwards (1974) provided the basis for the magnetometric method of mapping resistivity. This technique is intended for deeper exploration than convetional resistivity methods because it relies upon measurement of magnetic field rather than electric field.

The Schlumberger and Wenner arrays are frequently referred to as a D.C. resistivity methods. At various early times D.C. and A.C. sources such as batteries and the commutated Megger have been used. In more recent years reliance has been placed on low frequency (10^{-2}hz to 10^{2}hz) generators. In the last decade, these generators have provided synchronized signals at the receiver either by a) wave form recognition, b) hard-wire link, or c) synchronized clock link. Also in the last decade, digital receivers in the field have facilitated various frequency or time domain procedures for data processing such as stacking, noise rejection, and band pass filtering (e.g. Sumner, 1976). Current technology, via in-field microprocessors and a time reference between transmitter and receiver, permits processing, plotting and interpretation of data in the field.

The Induced Polarization Method

Subsequent to Schlumberger's (1920) discovery of the IP method, the next record of its study is attributed to Dakhnov (1941). Seigel (1949) provided the first proof that the method could detect disseminated sulfides. Bleil (1953) was sufficiently encouraged by Seigel's work to publish his own work of about the same vintage. Madden and his students put the method on a sound phenomenological and interpretational basis through a series of publications (e.g. Hallof, 1957; Marshall and Madden, 1959). Angoran and Madden (1977) summarize the history of our understanding of IP phenomenology and make important contributions of their own. Commercial application of the method rapidly developed in the decade 1950 to 1960.

As equipment evolved to provide coherent detection over a broad spectrum, either in the time or frequency domain, routine collection of IP data as a function of frequency or time delay became practical (e.g. Van Voorhis, et al., 1973). Broad band IP measurements permit recognition of the deleterious electromagnetic coupling effect and can aid in its removal. Mineral discrimination by broad band IP surveys is an elusive but much desired current goal of IP surveys. Grounded structures such as fences and pipelines constitute a major source of noise in many IP surveys and can be dealt with by calculation in some instances (Nelson, 1977).

Interpretation of IP survey data in terms of two-dimensional earth structures is now routine (Coggon, 1971; Madden, 1971). Hohmann (1975) has introduced a three-dimensional algorithm. Electromagnetic coupling has been computed over a homogeneous earth by Millet (1967) and over a layered earth by

Hohmann (1973). Magnetic induced polarization (Seigel, 1974) offers a promise of better detection of polarizable bodies beneath very conductive overburden. Research on non-linear IP phenomena was initiated by Shaub (1965) and Ryss et al. (1967), but no commercial application of this method of mineral discrimination is yet evident. The text by Sumner (1976) contains a comprehensive list of references on the induced polarization method.

The Magnetotelluric Method

The magnetotelluric method is generally attributed to Tichonov (1950) and Cagniard (1953), with most of the credit going to Cagniard. However, Fournier et al. (1963) note that the roots of the method actually extend back to the work of Van Bemmelen (1908). Wait (1954) used the transmission line analogy to produce a compact form of the impedance of a layered earth to an incident plane wave. While these early workers treated the earth as a homogeneous or horizontally plane layered isotropic medium, Cantwell (1960) recognized the importance of resistivity anisotropy or two-dimensionality and hence introduced the notion of an impedance tensor which permitted determination of apparent resistivity as a function of angular orientation; he rotated his observed data into directions of maximum and minimum apparent resistivities. There followed many applications of the magnetotelluric method in either scalar (Cagniard) or tensor form (Sims, et al., 1971). Vozoff (1972) gives an excellent summary of the processing of tensor magnetotelluric data and of the earth response functions which can be derived from them. While the tensor MT method recognizes anisotropy and/or two-dimensionality in earth structure, its routine application has been in terms of one-dimensional, i.e. plane horizontally layered earths. That this approach is erroneous in the general application has been clearly demonstrated by Wannamaker (pers. com.); in fact, he establishes that even a two-dimensional model is inadequate and that a three-dimensional model is usually required. This then requires the use of a three-dimensional modeling algorithm such as that of Ting and Hohmann (1980). Where the earth is one- or two-dimensional, available forward and inverse algorithms can be applied (e.g. Petrick, et al., 1977; Jupp and Vozoff, 1977). Improvement of signal-to-noise ratio is made possible by the innovative remote reference method of Gamble et al. (1979).

The Electromagnetic Method

The development of the electromagnetic method was largely dormant in the interval 1930 to 1950, with notable exceptions being some scale model results by Slichter (1932), Bruckshaw (1936), and Hedstrom (1940) and some theoretical and field work described in the former reference. However, a flurry of significant developments occurred in the next thirty years, initiated by the enormous creative theoretical works of J. R. Wait (e.g. 1951, 1953, 1955, 1958) and the equipment development and field applications of the staff of McPhar Engineering Co., (e.g. Ward, 1952; Ward and Harvey, 1954; Ward, 1957; Ward, et al., 1958). It was during the 1950 to 1960 decade that the first broadband ground electromagnetic system, the first airborne electromagnetic system, the first drill hole electromagnetic system, ground AFMAG, and airborne AFMAG were developed by McPhar engineers, G. H. McLaughlin, W. O. Cartier, H. A. Harvey, and W. A. Robinson. McLaughlin later went on to develop the time domain PEM system now manufactured by Crone Geophysics (Crone, 1979) and the EMP time domain system now used by Newmont Mining Co. (Nabighian, 1977). Articles by Tornquist (1958), Paterson (1961), Barringer (1962), Fraser (1972), Seigel and Pitcher (1978), and Becker (1979) trace the evolution of the airborne electromagnetic method to digital recording, automatic-interpretation, and continuous apparent resistivity estimates.

A great many ground electromagnetic systems, both time domain and frequency domain, have evolved in the years between 1950 and 1980 and these have been reviewed by Ward (1979). The trend is toward broadband systems employing coherent detection and microprocessor technology. These systems attempt to solve the problems encountered by the electromagnetic method when faced with a real earth consisting of overburden, host rock, surface topography, buried topography, disseminated and massive sulfides, and graphite.

Attempts to design an optimum waveform have been made by Lamontagne and West (1976). Won (1980) has performed laboratory experiments with a sweep frequency generator.

Over the years, scaled physical modeling has been used to develop interpretation schemes, utilizing metallic sheets to simulate thin ore veins, metallic spheres to simulate equidimensional ore deposits, or slabs of carbon/graphite to represent tabular base metal deposits. The variety of geometries of such models is great. Until about ten years ago, the earth was modeled by placing sheets, spheres or slabs in air and totally ignoring all of the other elements of the real earth. That application of the electromagnetic method was successful when using such crude models for interpretation is surprising.

Analytical solutions for a variety of simple earth models are available. These include: electric or magnetic dipoles over a homogeneous earth (Wait, 1953, 1955); electric or magnetic dipoles over a layered earth (Wait, 1958); a uniform alternating magnetic field incident upon a sphere or cylinder in free space (Wait, 1951); magnetic dipoles near a spherical body in free space (Nabighian, 1971); magnetic dipoles near a sphere in a conductive half-space (Singh, 1973).

In recent years solutions have been found to previously intractable electromagnetic boundary value problems (e.g. Coggon, 1971; Swift, 1971; Hohmann, 1975; Lajoie and West, 1976; Stoyer and Greenfield, 1976; and Pridmore, 1978). The earliest of these articles dealt with two-dimensional inhomogeneities in the fields of line sources; this is a true 2D problem. The article by Stoyer and Greenfield (1976) describes a two-dimensional inhomogeneity in the field of a three-dimensional source (the 2D-3D problem) while the articles by Hohmann (1975), Lajoie and West (1976), and Pridmore (1978) described a three-dimensional inhomogeneity in the field of a three-dimensional source (the full 3D problem). Petrick et al. (1979) have developed a 3D inversion scheme based on Stefanesco's alpha center concept.

While numerous algorithms exist for the inversion of resistivity and magnetotelluric data in terms of a layered earth, such is not the case for active source electromagnetic methods. Glenn et al. (1973) was the first of only five papers published on the subject at the time of writing.

The Self Potential Method

An in-depth understanding of the self-potential method was first presented by Sato and Mooney (1960); Nourbehecht (1963) making the next major contribution in this direction. Corwin and Hoover (1978) demonstrated that very low noise levels could be obtained in self-potential surveys provided care was exercised in preparing electrodes. Some modeling with various souces mechanisms has been done (e.g. Nourbehecht, 1963; Corwin and Hoover, 1978) but this activity is only now emerging. Morgan et al. (1979) have performed laboratory experiments designed to elucidate streaming potentials thought to be the cause of self-potential anomalies observed over geothermal systems.

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