Chapter 10
A Short History of Electrical Techniques in Petroleum Exploration

10.1 INTRODUCTION

The utilization of electrical techniques in oil and gas exploration has always been a subject of great interest to geophysicists, largely because of the hope that the application of such techniques would eventually lead to the direct detection of hydrocarbons through their insulating properties. However, 60 years of constant and at times frenzied debate over direct detection has failed to produce clear evidence of success, and wildly unrealistic claims by competitive service companies have done much to discredit the use of all electrical methods in petroleum exploration. Apparently, this was a problem from the very start. Even as early as the 1930s, while the seismic reflection method was evolving from infancy to a dominant role in the oil patch, electrical prospecting was still mired in an abyss of ignorance about the very fundamentals of electromagnetic theory. Peters and Bardeen (1932) commented:

> At the present time electrical methods of prospecting for oil seem to be in disrepute. This is partly due to cost of electrical surveys as compared with other geophysical methods and partly due to the failure of the extravagant claims made for the process to materialize. However, the electrical method of prospecting for oil cannot be forgotten because it is one of the two prominent geophysical methods in which it is possible to control the field being employed. Improvements in methods of interpretation and field techniques should give electrical methods a definite field of usefulness in prospecting for oil.

This statement remains valid today, but the situation is even more complex than it was in 1932. The petroleum industry is bombarded with a large number of exploration proposals, some of which are aggressively marketed by persons with minimal technical understanding of the processes they claim to measure. As a result, most if not all electrical methods have quietly been filed in the bottom drawer of "unconventional methods" by the petroleum industry, despite their widespread acceptance and extensive utilization by the mining industry over the past 30 years.

To understand the origin of this prejudice, it is useful to review the efforts of electrical prospectors since they first applied the techniques to petroleum exploration in the 1920s. This will also provide a perspective for evaluating the recent resurgence of electrical techniques in petroleum exploration.

10.2 THE EARLY YEARS: 1900- 1940

Geophysical Development

The early years of electrical methods of geophysical exploration are reviewed in detail by Heiland (1932) and in summary form by Rust (1938). Rust notes that the first use of electrical methods in geophysics is attributed to R.W. Fox. Working in Cornwall mines in 1830, Fox found that the voltages resulting from induced currents were strongly influenced by the presence of ore bodies. He advocated the use of resistance measurements as an exploration tool, but this method was deemed impractical because of contamination of measured voltages by electrode polarization. In 1880, Barus solved this problem by developing a non-polarizing electrode made of a porous wood or unglazed clay cup filled with a metal sulfate solution. Interestingly enough, this invention was very similar in design to the "porous pots" used for potential measurements today. Barus used his new electrodes to trace the Comstock lode past its previously known position.

Electricity had very much captured the public's fancy at this time. Thomas Edison's invention of the incandescent lamp in 1879 was an unparalleled popular success, and further developments of electricity provided conveniences and opportunities never before imagined. It is not surprising, then, that electrical techniques were enthusiastically applied to geological exploration beginning early in this century.

In 1900, Brown and McClatchey applied for a patent on resistivity measurements in the United States, while Daft and Williams proposed the use of potential differences in resistivity work. However, little quantitative work appeared until 15 years later, when Wenner (1915) suggested the use of the four-electrode array which now bears his name. Other arrays were also in use at the time, and there was no general agreement as to which ones were best for exploration.

After testing the DC resistivity method during the years 1913 - 1920, Conrad Schlumberger began to use resistivity mapping as a tool for oil and gas exploration. The approach was to map salt domes and other structures. Work was done in the Pechelbronn oil region from 1921 to 1926, in Romania from 1923 to 1926, and in Alsace from 1926 to 1927. Schlumberger first worked in the United States for Roxana Petroleum Corporation and Shell Company of California from 1925 to 1929. The mapping work tapered off as Schlumberger became increasingly involved in downhole electric logging, but a number of other contractors were heavily involved in surface measurements, including the Swedish-American Prospecting Corporation, Elbof Company, Geophysical Service, Inc., McCollum Exploration Company, Radiore Company, and International Geophysics, Inc. Several oil companies, including Sun Oil, Pure Oil (which later discovered Lisbon Field), and Midwest Refining, maintained in-house electrical prospecting groups. Unfortunately, very little of their work was ever published; and what was published was generally of poor quality.

Methodology and Equipment

By the 1930s, field logistics and techniques varied widely. Heiland (1932), Rust (1938, 1940), and other contemporary writers describe at least eight commonly used arrays, which used up to five electrodes. Many of the methodological distinctions drawn by these authors are now insignificant in terms of their application, and for the most part, they would be classified today as resistivity profile or sounding methods. Three field approaches were in common use during the 1930s: the "resistivity" method, the "potential-drop-ratio" method, and the "vertical electric drilling" method. The surveys were made at both AC and DC frequencies, and in some cases phase angle measurements were carried out, although there is little evidence that phase information was used to any extent for interpretation.

The so-called "resistivity" method involved the transmission of a signal into a long current dipole. The voltage was measured by potential electrodes located either between the current electrodes or near one of them, and an apparent resistivity map was produced.

A second approach, known as the "potential-drop-ratio" method, investigated potential ratios in the vicinity of one of the current poles. The receiving positions were advanced along a traverse, one dipole at a time, with the rear dipole repeating the position previously occupied by the front dipole. By obtaining a ratio of the voltages measured at each set-up by the two dipoles, and by propagating a series of ratios along a traverse, it was possible to make measurements which were independent of the current source strength.

Potential-drop-ratio surveys were laborious, and were not the preferred method used in oilfield work. Instead, the most common technique was one known as "vertical electric drilling," in which an array of three to four electrodes (usually using the Wenner array) was used as an expander around a point about to be drilled. This approach yielded a vertical apparent resistivity sounding, as opposed to the horizontal profile of the potential-drop-ratio method. Heiland notes that interpretation of these electrical data was based upon potential contour maps drawn for various depths of investigation and upon resistivity curves. Results were checked against in-hole electric logs, rock sample measurements, and modeling tank experiments.

Equipment during the 1930s generally consisted of various modifications of the Gish-Rooney apparatus developed in 1925. The receiver consisted of a milli-ammeter for current measurement, a potentiometer for voltage measurement, and a commutator, which provided a low-frequency AC signal. Power was supplied by a hand-driven DC generator, an electric engine, or batteries.

Early Claims of Direct Detection of Hydrocarbons

Prior to 1930, electrical exploration was used primarily for structure mapping. Specific targets included salt domes, anticlines, faults, fracture zones, lithologic contacts, and the mapping of glacial overburden. However, keen competition among the numerous service companies and encroachment on electrical "turf" by a rapidly developing seismic industry seem to have encouraged some companies to make claims which could not be supported. Elbof Company has the dubious distinction of being the first to claim success in the direct detection of hydrocarbons. Elbof's "current deflections" in electromagnetic data were made in an area of complex geology, at great depths; their work, which seems not to have been published, was widely disputed. Further work with resistivity and potential-drop-ratio methods was published in 1930, but the data are of poor quality and the conclusions are not convincing. Hedstrorn (1930) argued against the possibility of direct detection, claiming that resistivity contrasts greater than 10:1 would not produce responses significantly different from contrasts of 1000:1 or more, which might be expected at a hydrocarbon interface. Thus, he argued, an oil response could not be distinguished from many other responses in the ground which are unrelated to the presence of hydrocarbons. Heiland, in a carefully neutral discussion of direct detection, observes that direct detection might be viable in the future, but notes that he "believes that several authors who were involved in the animated discussion at that time wish now, in view of the recent developments, that they had not voiced their opinions in the [direct detection] matter."

Heiland does quote two examples of work supporting direct detection. The first is by Lee and Swartz (1930), who showed "vertical electric drilling" or resistivity sounding data from an oilfield in Allen County, Kentucky. The oil lies about 250 feet beneath a sequence of limestones, cherts, and shales. At first glance, the data appear to show a resistor at depth, but it is difficult to believe that an insulator barely 25 feet (8 m) thick and 250 feet (75 m) deep was detected with the existing equipment. Nevertheless, Heiland was convinced, and he cites a second body of work by Swartz (1932) in which oil was detected at 500 to 800 feet (150 - 250 m), with predictions confirmed by subsequent drilling. One case presented by Swartz shows an anomaly which he attributes to a bed 4 feet thick (1.3 m) buried some 640 feet (195 m) deep. This, of course, is quite impossible to accept, as is Swartz's claim that ". . . the shielding effect of such low resistivity beds as are encountered in oil and gas fields are negligible as far as the detectability of underlying gas and oil horizons is concerned."

Early Transient Methods

During the mid-1930s, the direct detection movement took a new course, de-emphasizing the search for insulators by DC resistivity soundings. Instead, attention was focused on finding electromagnetic transient reflections (Eltran). The psychological incentive to see reflections from depth was certainly understandable, considering the success of seismic reflection methods and the continued desire for a direct indicator of hydrocarbons.

Transient work can be traced back to 1933, when U.S. Patent 1,911,137 was issued to L.W. Blau, a research geophysicist with Humble Oil and Refining. Karcher and McDermott (1935) were evidently the first to advocate Eltran methods for direct detection of oil, and over the next five years, a number of other authors published their results. Keller (1968) provides a working bibliography of these references. Most of the Eltran publications advocate time-domain waveform transients using the four-electrode Schlumberger, Wenner, or dipole-dipole arrays. The results of these surveys, when reviewed in the context of current knowledge, are rather ambiguous. The detection of electromagnetic reflections with the instrumentation of the 1930s is highly unlikely. The first substantial theoretical arguments to this effect were not advanced until the 1950s, even though electromagnetic theory had been up to the task since work by Foster (1931) and Riordan and Sunde (1933).

10.3 CONTINUED DEVELOPMENT: 1940 – 1960

Later Transient Methods

Although the excitement over Eltran seems to have subsided after 1940, the basic ideas were inherited by the Elflex company. The history of Elflex can be traced back to an interesting patent (U.S. patent 2,190,320) by Gennady Potapenko (1940), a professor at the California Institute of Technology. Potapenko describes laboratory measurements on oil-saturated sands over a frequency range of 0.01 Hz to 100 Hz. The claim was that an oil-saturated sand showed a substantially different voltage decay response than a sand which did not contain oil. Potapenko proposed a measurement system in which a Schlumberger array was used for depth sounding in the field. Haakon M. Evjen, a scientist with Shell Oil Company, evidently had worked with Potapenko for a time, and in 1940 he and Hal Edwards left Shell to apply some of Potapenko's ideas commercially in a company they called Elflex. Patents on electrical prospecting equipment similar to Potapenko's were issued to them in 1944 and 1945. Evjen's first electrical paper, published in 1938 while he was still with Shell, focuses on electrical detection of salt domes and faults. He disclaimed the detection of material at depth. In his second paper (1943), he expresses the hope that sandstone reservoirs could be traced horizontally, and that lateral changes in conductivity caused by the presence of oil might eventually be detected. In subsequent papers, Evjen and his colleague, W. Bradley Lewis, generally discuss structural mapping and technical considerations of their work; they avoid commenting on direct detection except in a few of their less technical papers (e.g., Evjen 1953). Although Evjen's technical papers in general are of fairly good quality, it is doubtful that he was actually measuring electromagnetic reflections, especially considering the primitive ballistic galvanometers in use at the time (see section 2.3).

Radio-Wave Methods

During the late 1940s and the mid-1950s, the radio-wave method was applied enthusiastically to hydrocarbon detection. The method used a fixed current antenna and measured a voltage decay curve along an in-line radial. The signal used was at radio frequencies, typically 1 to 2 MHz. One of the chief proponents of this work was W.M. Barret, who claimed that the method lent itself to direct detection of oil. In one article (Barret, 1949), he states that 80.6 percent of the hydrocarbon prospects drilled proved to be productive, and that all condemned prospects proved to be nonproductive. Mooney (1954) investigated these claims and found them to be unsubstantiated, concluding that the true success ratio of radio-wave methods was no better than that which would be expected of a random drilling program in a petroliferous basin.

The whole radio-frequency episode seems odd in retrospect, because it should be fairly obvious that depth penetration in the 1 to 2 MHz range is very small due to severe skin depth attenuation. This was demonstrated by Yost (1952), Pritchett (1952), and Yost et al. (1952). These articles give theoretical and experimental proof that skin depth at such frequencies is hundreds of feet, not the thousands of feet necessary to sound down to oil reservoirs. For example, Pritchett lowered a 1.6 MHz transmitter into a well and found that the attenuation in shales and limestones was 0.75 to 2.0 db per foot (2.5-6.6 db/m). The diversity of opinions over this matter is well demonstrated by the lengthy debate which follows Pritchett's article. Radio methods fell into disfavor in the 1950s, but occasional "discoveries" of the method occurred even as late as the 1970s (Oilweek, 1974b).

10.4 RECENT ELECTRICAL WORK

Introduction

The past five years have seen a remarkable resurgence of electrical techniques in hydrocarbon exploration. Presentations on the subject have increased greatly at recent conventions of the Society of Exploration Geophysicists, and a review of geophysical activity reports shows a dramatic increase in expenditure on electrical work. The number of competing contractors in the field has increased from just a few in 1975 to several dozen in 1982. However, because much of the on-going work is proprietary or has not been published, it is difficult to document the increased activity very accurately. By necessity, therefore, this discussion is incomplete.

The variety of approaches used in the field is impressive, but most on-going work can be classified as follows:

1. Direct Detection of Hydrocarbons
    - Resistivity methods
    - Transient methods
2. Indirect Detection of Hydrocarbons (electrochemical alteration)
    - Induced polarization / resistivity methods
    - Self-potential methods (oxidation / reduction cells)
3. Structure Delineation
    - Magnetotelluric methods
    - Induced polarization methods

Direct Detection of Hydrocarbons

As discussed in Chapter 2, the direct detection of hydrocarbons is theoretically possible, providing that they are fairly shallow. However, the extreme difficulties in detecting an insulating target at normal depths have discouraged all but a few contractors from attempting such measurements.

RESISTIVITY METHODS

The use of resistivity measurements in direct detection of hydrocarbons has been the subject of several recent investigations. Kinghorn (1967) performed tests with a pole-dipole resistivity system, by which an insulator was detected at shallow depths; he concluded that direct detection was at least a possibility. George Keller, working at the Colorado School of Mines, has also been interested in the subject for some time. His article in the School of Mines Quarterly (1968) provides a sound discussion of general electrical techniques in the oil patch; in a second informative article in World Oil (1969), he expresses the hope, based on his research on Russian efforts, that improved instrumentation will eventually lead to direct detection of hydrocarbons by electromagnetic methods.

TRANSIENT METHODS

The transient methods developed during the 1930s have recently been practiced by two prominent contractors-Elflex and Electraflex. As mentioned earlier, Elflex was founded by Evjen and Edwards in 1940. Evjen fell ill in the early 1950s and Edwards took over as president of the company, moving its main office to Calgary, Alberta. In 1975, Edwards moved the company back to the United States. The Elflex method was being used under license as recently as 1979 (DESCO, 1979), and it is believed that Elflex had at least one or two crews in the field up to the late 1970s.

Until recently, the Elflex technique was used primarily as a direct-detection method and only secondarily as an indirect method. However, a recent paper by James Powell (1981) indicates that the company has undergone a significant change in its perception of the measurements. Powell pursues an enlightened discussion of alteration mechanisms over oil fields, and concludes:

> Anomalously high decay voltages appear over hydrocarbon accumulations. This higher voltage occurs because of induced polarization effects, not because of electromagnetic "reflections." The induced polarization probably results from chemical changes caused by upward migration of hydrocarbons or other compounds from reservoirs. Chemical changes may produce higher induced polarization voltages via metal-electrolyte contact effects, or by means of membrane polarization.

Elflex has recently merged with LaJet Energy Company of Abilene, Texas, and information regarding recent endeavors of the new company is generally unavailable.

Electraflex, a spin-off of EIflex, was formed around 1970. Although the two "flex" companies performed similar services, they were distinct from one another, and the atmosphere between them was not always amicable (Oilweek, 1974a). Electraflex has been propelled to the public spotlight largely through the writings of Jamil Azad, who joined the company as a vice president in 1971. Several of his statements may be of interest to those involved in electrical prospecting: "Electraflex, on the contrary, is 'blind' to conductive material of any kind and reacts only to extremely resistive bodies such as hydrocarbons or the cap rock of a salt dome" (1973) . . . "No effect from the lithologic nature and variability of the surface soil has been documented" (1979a) . . . "In my early writings, I found it impossible to avoid some theoretical discussion of the [Electraflex] subject because many editors pay lip service to the altar of theory, without which, apparently, there can be no respectability . . ." (1981). Such statements tend to cast doubt upon Electraflex's understanding of the phenomena they claim to measure.

The Electraflex method is based exclusively on the theory that oil is an excellent insulator, having a resistivity on the order of $3x10^{11}$ ohm-meters, and as such, produces transient reflections when energized by a source current at the surface. A time-domain squarewave signal at about 1 Hz is used, and about 0.05 second after the pulse is turned off, the decay voltage is measured. This technique assumes that all polarization and electromagnetic coupling effects have decayed to a negligible amount after the 0.05 second interval, leaving a transient reflected by the high impedance oil interface. A Schlumberger array is used on all work. Up to 4 kw of power are transmitted into a 2,640-foot (805 m) current dipole; the return voltage is measured in the time domain by a 50-foot (152 m) receiving dipole.

Based upon a large statistical base of 843 wells drilled on anomalies in Canada between 1971 and 1981, Azad claims that 82% of the wells drilled on anomalies were producers, 9% were dry but had shows, and 9% were dry with no shows. Conversely, of 284 wells drilled in non-anomalous areas, 95% were dry. To support these statistics, Azad has published a number of case histories based primarily on relatively shallow fields, although he claims that oil horizons as deep as 16,000 feet (4,900 m) have been detected. Most of the articles dismiss the disruptive effects of well casings and pipelines (when they are perpendicular to the array), but his most recent writings indicate an increased awareness of their importance (Azad 1979a). He has also taken great pains recently to try to prove that the anomalous data are due to reflections from hydrocarbons and not to electrochemical alteration effects.

Electraflex equipment is manufactured by a separate concern, and only recently has the company converted to digital instrumentation. No substantive details are available on this equipment.

Indirect Detection of Hydrocarbons (Electrochemical Alteration)

INDUCED POLARIZATION / RESISTIVITY METHODS

Indirect detection is a relatively new concept in electrical exploration for hydrocarbons. Most of the indirect methods are variations of the induced polarization method, which has been used extensively by the mining industry since the 1950s. The use of induced polarization in oilfield applications was first suggested by Mueller (1934), and the induced polarization phenomenon was recognized by Potapenko (1940) when he patented his prospecting system. However, the full power of the multi-frequency induced polarization approach was not really utilized in oilfield work until the late 1970s. Since then, a number of contractors have become involved in the technique; there may be as many as two dozen active at this time. Geophysical activity reports, published annually in *Geophysics*, show that oilfield induced polarization expenditures have increased from $179,000 (1979) to $1,260,000 (1980) to $3,895,728 (1981).

One of the first companies to apply induced polarization to oilfield exploration in recent years was Colfax Surveys, Ltd., which is mentioned as early as 1976 in the non-technical literature (Oilweek, 1976, 1978). Colfax Surveys used a Schlumberger array with a 440-foot (134 m) current dipole, a 400-foot (122 m) receiving dipole, and a time-domain signal. The method was based upon the geochemical fuel cell model postulated by Pirson (1971, 1974). The object of the surveys was to measure the polarization effect of reducing materials migrating from hydrocarbons at depth. The company is still in existence today.

Educational Data Consultants, Inc. (EDCON) was one of the first companies to publish a detailed case history of induced polarization work over an existing oilfield (Snyder et al. 1981). EDCON had previously specialized primarily in magnetic and gravity techniques, and had recently expanded to electrical methods largely under the direction of Donald Snyder. In early 1979, EDCON and Diversified Exploration Services, Inc. (DESI) collaborated on a proposal for a speculative survey to investigate the use of induced polarization in oilfield exploration (EDCON-DESI, 1979). The authors of this proposal disputed the "flex" claims of measuring reflection transients, and they proposed that the speculative survey employ multifrequency induced polarization to determine the true source of measured anomalies. The proposal was well thought out, and was offered on a participation basis to the petroleum industry for about $50,000. About a dozen companies participated in the work.

The speculative survey included 13 test sites in Wyoming, Texas, Nevada, Utah, California, and North Dakota. Ten projects were known fields, three were prospects. The fields vary in size from fairly small to the very large Pineview Field. Production depths vary from 4,200 to 13,700 feet (1,300-4,200 m). Some of the data were obtained at four discrete frequencies; other data were acquired in a harmonic complex resistivity mode (Van Voorhis, Nelson, and Drake, 1973; Wynn and Zonge, 1975; Zonge and Wynn, 1975a), using a frequency range of 0.02 to 110 Hz. The dipole-dipole array was employed for most of the work. The digital receiver equipment was designed and manufactured by EDCON (Snyder, 1975; 1976).

The results of the project were somewhat favorable. Six of the known fields showed well-defined polarization responses, while four showed responses which were minimal or uncorrelated with the hydrocarbons. Of the prospects, one anomaly was later drilled; shows of gas were found in the well. Two non-anomalous areas were also drilled, resulting in dry holes. In their summary, Snyder et al. (1981a, 1981b) stated that several surveys were poorly designed; they also pointed out problems in coupling separation in low resistivity ground and the importance of selecting the correct dipole separation in survey work.

EDCON has published three case histories from the speculative survey in promotional literature (Snyder et al., 1981a, 1981b). Work at Lambert Field, in Oldham County, Texas, showed low resistivity and high negative phase angle anomalies which correlated well with the lateral extent of the hydrocarbons. Millis Field, located in the overthrust area of western Wyoming, was surveyed prior to the spudding of the discovery well; neither the resistivity or the phase data showed significant anomalies, possibly because the dipole spacing was too small. Data from Meridian Field, in Loving County, Texas, showed a strong negative phase anomaly, but the resistivity pseudosection was complicated and did not show a clear-cut anomaly.

EDCON's conclusion from this work was that the polarization anomalies measured over the known oil and gas fields were caused by micron-sized pyrite particles in the overlying sediments, and not by electromagnetic reflections. It was proposed that pyrite was formed in the overlying sediments by the reaction of iron with sulfur supplied by the upward migration of hydrocarbons. However, Holladay and West (1982) posed an alternative view that the EDCON anomalies may have been from effects due to well casings rather than from any oil-caused alteration. Their paper presented the results of a three-dimensional modeling program in which the Lambert Field data were matched quite well with the calculated well-casing effects. The paper presents a serious objection to the attempts of EDCON, Zonge Engineering and others to prove the viability of induced polarization in oil exploration by showing anomalies over existing fields. This problem is still not fully resolved, and has been discussed at great length in Chapter 2.

Following the publication of the survey conclusions, Snyder left EDCON for a job with Mount Sopris Instruments Company. EDCON has since faded from the electrical exploration scene, and has concentrated on its expertise in gravity and magnetic methods. By 1981, it employed only one electrical oilfield crew; today, the company no longer advertises electrical work. Whether this is due to a change in company philosophy or Snyder's departure is not known.

Zonge Engineering performed its first contract services in hydrocarbon exploration in late 1977, using the harmonic complex resistivity method (Van Voorhis, Nelson, and Drake, 1973; Wynn and Zonge, 1975; Zonge and Wynn, 1975). The current application of the method was originally developed during the early 1970s by Ken Zonge (1972) for laboratory discrimination of various sulfides, and was patented by him in 1976 (U.S. Patent 3,967,190). The technique has been used in the field for the detection of massive disseminated sulfides, geothermal targets, and uranium prospects, and for structural mapping. Wynn and Zonge (1975) introduced the application of electromagnetic coupling to electrical exploration, using proprietary techniques to separate this information from the induced polarization data. With truck-mounted equipment consisting of a Digital Equipment Corporation PDP-8 computer, cassette drive, teletype, a Zonge-designed two-channel receiver, and a 10 to 20 kw transmitter (Zonge, 1973), field work was carried out with the dipole-dipole array at a frequency range of 0.1 to 110 Hz. Beginning in 1980, data were collected with Zonge's two-channel, microprocessor-controlled receiver (Zonge, 1975; Staley, Clark, and Zonge, 1978). At first, measurements at four to six discrete frequencies were made in the 0.125 to 4 Hz range, using a crew of eight and roll-along style logistics. In 1981, software was finalized for running harmonic complex resistivity with the Zonge equipment, and that system has been used since then. Controlled source audiofrequency magnetotelluric measurements were employed for the first time in hydrocarbon exploration in late 1982, although they had been used in mineral exploration since 1978.

A brief discussion of Zonge's hydrocarbon work was provided in 1979, but the first data were not published until three years later (Carlson, Hughes, and Zonge, 1982). This paper presented data from a line run over Lisbon Field, in San Juan County, Utah. A strong conductive anomaly correlates well with the lateral extent of the hydrocarbons. The phase data show a strong, near-surface anomaly, attributed to the influence of a surface pipeline which crosses the line near an electrode station; no residual phase anomaly was seen. A third set of information (called "REM," for residual electromagnetic data) shows a strong conductive feature which, according to the authors, originates from depth. Whereas EDCON had viewed polarization as the diagnostic parameter to be interpreted, the work of Carlson, Hughes, and Zonge indicates that apparent resistivity is the more reliable parameter, and that polarization results are inconsistent. The authors believe that at least two anomaly mechanisms account for the consistent resistivity results and the inconsistent polarization results (both of which are thought to be related to upward migration processes reported in the geochemical literature). They suggest that the resistivity information is related to salinity concentrations above the hydrocarbon trap, while polarization data are related to pyrite and clay alteration, also above the trap. The authors note that their polarization anomalies appear most commonly in Texas and Oklahoma, where iron occurs abundantly in the overlying formations.

Concurrent with this paper, Holladay and West (1982) announced the results of their well-casing modeling of EDCON's Lambert Field data, prompting the Zonge group to provide an analysis of the effects of well casings on their data (Hughes et al. 1982). This paper specifically compares the relative effects of well casings to those expected from a vertical alteration plume. Results were presented from two intersecting lines run over the Cowboy Field, a small oil producer in San Juan County, Utah. The data at a dipole spacing of 1,250 feet (381 m) were shown to be equally well represented either by well casings or by a conductive plume. However, one of the lines had been run with 2,500-foot (762 m) dipole spacings as well, and the character of the data at depth showed geometric effects which could not be reproduced by the well-casing model, but which could be represented well by the presence of a conductive plume. Cowboy Field also showed a relatively well-defined REM anomaly, but no polarization anomaly.

Zonge Engineering also initiated a sale of some of the data which had been collected in 1979 and 1980; the sale included surveys over eight oil and gas fields in Nevada, Utah, and Wyoming. The package was offered for $20,000. The details of this data sale are contained in this volume, so no further mention will be made of it here.

Diversified Exploration Services, Inc. (DESI), which participated with EDCON in its speculative survey, performs induced polarization surveys using receivers and peripherals manufactured by Zonge Engineering. Field logistics vary, but usually the dipole-dipole array is used. DESI data are examined for polarization responses above hydrocarbons, which are attributed to the precipitation of pyrite. According to an informational flyer (DESI, 1982), the success rate of these surveys is encouraging. Of 19 fields surveyed, 16 showed induced polarization anomalies; of nine wildcat wells drilled on induced polarization anomalies, seven were producers and two were dry or noncommercial; and of seven wildcat wells drilled in non-anomalous areas, six were dry or noncommercial, and one was a producer.

Around 1979, Conoco began an induced polarization program called "IN-DEPTH" which was subsequently patented (Sternberg, Miller, and Bahjat, 1981). The technique has been licensed to interested contractors (e.g., Geosource) since early 1980. Early literature is inexplicably vague, referring to "anomaly indicators 1 and 2," but more recent publications (Oehler and Sternberg, 1982) have contributed much to our understanding of near-surface alteration patterns over oilfields. The INDEPTH system consists of truck-mounted equipment using digital receivers. A Schlumberger array is used. The source signal is frequency domain; 0.1 Hz signals are typical, although the frequency may vary from 0.001 to 100 Hz. Signal strength is 2 to 5 amperes.

INDEPTH interpretation is based on geochemical evidence that light hydrocarbons leak from their reservoirs at depth and rise vertically to the surface. Near the surface, a number of geochemical interactions may occur. As explained by Oehler and Sternberg, hydrocarbons near the surface undergo bacterial alteration by means of sulfate reduction, yielding hydrogen sulfide and bicarbonate ions. Iron in the host rock then combines with the hydrogen sulfide to yield pyrite; the bicarbonate ion combines with calcium to form calcite cementation. The pyrite yields a polarization anomaly, and calcite causes a high resistivity anomaly.

Using data from in-hole induced polarization measurements of the top 250 feet (75 m) over Ashland Field in southeastern Oklahoma, the authors showed that high polarization and high resistivity are highly correlated in the logs. Through core analysis, they also showed a direct correlation of calcite to high resistivity, and a fairly convincing correlation of pyrite to high polarization. They confirmed that high methane concentrations occur over the field, but not off the field. INDEPTH surface induced polarization measurements plotted in plan view are shown to be correlated with the known extent of the hydrocarbons: the center of the field was more resistive and polarizable than the background. The authors also discuss the false induced polarization anomalies encountered over the Salt Draw prospect in western Texas, which does not host hydrocarbons. The authors conclude that accurate interpretation of their work requires a combination of downhole geologic, geochemical, and electrical analyses correlated with surface electrical data.

Phoenix Geophysics brought its experience from the mining industry to oilfield exploration with a speculative survey in 1982, in which they proposed to develop a 100 kw transmitter to match their seven-channel induced polarization receiver. Fourteen oil companies signed on for the equipment development, for field work over about a dozen known fields, and for research projects related to induced polarization measurements. The total cost was about $110,000 per participant.

Details of the Phoenix program are proprietary, but available data seem to be of good quality. A dipole-dipole array and frequency domain signal are used over a frequency range of 0.0625 to 128 Hz. Resistivity and phase data are obtained, and a Cole-Cole dispersion model (Cole and Cole, 1941; Pelton et al., 1978) is used for decoupling the phase data. Data from the David Field in Alberta have been published (Klein, 1983; Petrick, 1983); they show a fairly distinctive phase anomaly and a minor resistivity anomaly. Sill (1983), basing his idea on the results of a well-casing model developed for Phoenix, suggests that phase data may be strongly affected by well casings.

Reeves Exploration is also engaged in near-surface induced polarization investigations. Using Zonge Engineering receivers and peripherals, Reeves works with a modified Schlumberger array consisting of a 2,640-foot (805 m) transmitting dipole, and a 500 foot (150 m) receiving dipole which is offset 250 feet (175 m) from the transmitting line. Both time-domain and frequency-domain data are obtained, and a convolution of frequency-domain phase, time-domain amplitude, and apparent resistivity is used for interpretation. Reeves has encountered low resistivities and high polarization over typical oil and gas fields. Two Reeves brochures (1980, 1982) present brief case histories of several Texas oilfields. Reeves has recently been acquired by a group of California investors; their future development is not known.

Auriga, Inc. performs its induced polarization services with a small, portable, microprocessor-controlled, two-channel receiver manufactured by Aquila Instruments, an Auriga subsidiary. The polarization parameter is used primarily for interpretation; pyrite is believed to be the causative mechanism for the measured anomalies (Auriga, 1982). William Frangos, the President of Auriga, had worked with EDCON and DESI on their speculative survey.

M.J. Exploration of St. Louis, Missouri (M.J. Exploration, 1982a, 1982b) conducts a time-domain induced polarization survey using a Schlumberger array. The squarewave is transmitted on a two-seconds-on, two-seconds-off cycle; measurements are taken 0.4, 0.8, and 1.6 seconds after the signal is turned off. The company claims to measure "electrically chargeable particles" which occur near the surface because of the upward migration of hydrocarbons from traps at depth. This movement is believed to take place through microseeps (hence the survey name, "MEAS," for "Microseep Electrical Analog Surveys"). Informational brochures claim that 81 percent of the MEAS anomalies are associated with hydrocarbons; the rest are due to ore zones and other causes. The two types are distinguished, according to the brochures, by varying the electrode separations. It is claimed that some 96 percent of the wells drilled subsequent to MEAS surveys have been producers.

Transiel, a system developed by Compagnie Générale de Geophysique (CGG 1982), is designed to map changes in polarization caused by the presence of hydrocarbons. A four-seconds-on, four-seconds-off time-domain signal is used in conjunction with a Schlumberger array. Currents of 10 to 50 amperes are used. The truck-mounted system consists of a six-channel digital receiver, magnetic tape recorder, and appropriate electronic gear.

SELF-POTENTIAL METHODS (OXIDATION / REDUCTION CELLS)

Self-potential (SP) and magnetic field measurements have been used for over a decade now in an effort to delineate the "redox fuel cells" popularized by Silvain Pirson. Although the practitioners of this method claim success, the specific details are beyond the scope of this volume. Pirson (1971, 1974, 1976, and 1980) has published some useful references.

Structure Delineation

The ability of seismic methods to map subsurface structure has greatly surpassed that of electrical methods in terms of penetration and resolution capabilities. For the most part, electrical structure methods are used only in certain areas where seismic methods fail. The structural delineation techniques are generally classified as magnetotelluric methods or as induced polarization methods.

MAGNETOTELLURIC METHODS

Electromagnetic techniques have been used in oil exploration since the late 1920s (Sundberg, 1920), and electrotelluric surveys were in use by Schlumberger and by Soviet scientists during the 1930s. The magnetotelluric technique proper was first used in the 1940s, but the method did not become popular until after a pioneering paper by Cagniard (1953). It is beyond the scope of this paper to describe the large body of research in this matter, but useful information of U.S. magnetotelluric work can be obtained from contractors such as Woodward-Clyde Associates and Geotronics. The Soviets have been especially active in magnetotelluric research; some references on this work can be obtained in articles by Keller (1968, 1969) and Caldwell (1969).

INDUCED POLARIZATION METHODS

INDESCO appears to be the only major contractor using induced polarization measurements primarily for structure and lithology detection in the oil patch. The company was founded in 1981 by Howard Renick, Jr., who directed an Elflex speculative survey in 1979 under the company name "DESCO." Renick, James Pritchard (who had worked with George Keller of the Colorado School of Mines), and Jack Jordan are responsible for much of the development of the INDESCO system, which is essentially a hybrid induced polarization sounding system. Sounding curves are configured to resemble downhole electric logs. The data are used to detect lithologic units, changes in porosity or facies, the presence of reefs, and detrital material.

The truck-mounted equipment consists of an eight-channel digital receiver, CRT data display, and floppy disk storage. A 150 kw, 400 Hz, three-phase generator supplies a unipolar time domain signal at currents up to 100 amperes. The arrays used are Schlumberger, modified Schlumberger, or non-collinear dipole-dipole. The literature (INDESCO, 1981; Jordan, Pritchard, and Renick, 1982; Pritchard and Renick, 1982) describes in general terms a complex series of multi-layered models and smoothing routines which are applied to the data. Thickness resolution is claimed to be as good or better than 3 percent. A speculative survey in the Pedrogosa Basin of New Mexico was being advertised at the 1982 SEG convention, but no details are generally available.

10.5 INTO THE FUTURE

If there is any value to the preceding discussion, it is in the form of a warning to those who promote electrical techniques: do not allow the enthusiasm of commercial success to overshadow the need for genuine scientific research. The problem of the past has been that some groups, apparently motivated by economic and personal interests, have made fantastic claims for electrical techniques which could not be substantiated. The result is the current atmosphere of suspicion which sometimes clouds an objective evaluation of these methods by the petroleum industry.

The key to the future seems to be in lowering our expectations of what electrical techniques can provide to an exploration program. They will not provide the answers to all exploration problems by themselves, as some have claimed in the past. As those of us who look at geophysical data on a daily basis know all too well, no geophysical interpretation is totally unique; it must be used sensibly in the context of geologic, geophysical, and other data. If we approach the future in this context, we may well find electrical techniques to be the valuable prospecting tool we have been hoping for.

Two exploration approaches show promise during the next decade: the detection of electrochemical alteration over oilfields and the direct detection of hydrocarbons at depth. The detection of alteration has already been demonstrated to be a viable technique, but a great deal of work remains to be done in distinguishing electrochemical anomalies from structural and cultural anomalies, and in providing more quantitative information to the exploration geologist. It is important to realize that anomalies can often be subtle, and the mechanisms which cause them can be very complex. Hence, a full understanding of these mechanisms must surely be gained in order to utilize the technique fully in oil exploration. The second approach, direct detection, should also be considered, despite its unsavory reputation in the past. Some of the evidence that direct detection of hydrocarbons can be achieved, at least over shallow fields in geologically simple environments, appears to be substantiated. However, a complete revolution in instrumentation sensitivity and data processing techniques will be necessary in order to use direct detection as a viable exploration technique for deep fields. Such a revolution is not imminent, but the incentive for it is certainly there.

REFERENCES

Auriga, 1982, Auriga performs: informational brochure.

Azad, J., 1973, Direct oil prospecting with electrical transient reflections: Canadian Jour. of Geophysics, v. 9, Dec., p. 1 - 11.

—, 1979a, Mapping accumulations of oil and gas with electrical transients: Oil & Gas Jour., Jan. 22, p. 80-84.

—, 1979b, Seismic and electrical transients combine to discover oil and gas fields (unpublished): presented at the 49th Annual International SEG Meeting and Exposition, New Orleans.

—, 1981, Electrical transients – a pragmatic approach to oil and gas discoveries: Oil & Gas Jour., Dec. 21, p. 104-108.

Barret, W.M., 1949, Exploring the earth with radio waves: World Oil, Apr.

Blau, L.W., 1933: U.S. Patent 1,911,137, issued May 23, 1933.

Cagniard, L., 1953, Basic theory of the magnetotelluric method of geophysical prospecting: Geophysics, v. 18, p. 605.

Caldwell, R.L., 1969, Electrical methods of exploration in the Soviet Union, *in* Unconventional methods in exploration for petroleum and natural gas: Dallas, Southern Methodist University, p. 87-104.

Carlson, N.R., Hughes, L.J., and Zonge, K.L., 1982, Hydrocarbon exploration using induced polarization, apparent resistivity, and electromagnetic scattering (abs.): Geophysics, v. 47, p. 451. Full paper available in Technical papers, 51st Annual International Meeting and Exposition, SEG, Los Angeles, v. 3, p. 1339-1358.

CGG, 1982 (?), Transiel, an E.M. method applied to hydrocarbon exploration: information brochure.

Cole, K.S., and Cole, R.H., 1941, Dispersion and absorption in dielectrics: J. Chem. Phys., v. 9, p. 341-351.

Conoco, 1980 (?): INDEPTH informational paper.

DESCO, 1979, Sweep: informational brochure on Elflex speculative survey.

DESI, 1982, Annual cumulative statistical summary, induced polarization surveys for hydrocarbons, December, 1982: informational flyer.

EDCON-DESI, 1979, Proposal – evaluation of electrical techniques for direct detection of hydrocarbons: informational paper.

Evjen, H.M., 1938, Depth factors and resolving power of electrical methods: Geophysics, v. 3, p. 78.

—, 1942, Utility of the electric methods in geophysical exploration: Geophysics, v. 8, p. 146.

—, 1953, Surface method detects oil directly: World Oil, Feb.

Foster, R.M., 1931, Mutual impedance of grounded wires lying on the surface of the earth: Bell System Tech. Jour., v. 10, p. 408-419.

Hedstrom, H., 1930, Geo-electrical exploration methods: The Oil Weekly, v. 58, Jul. 25, p. 34-36.

Heiland, C.A., 1932, Advances in technique and application of resistivity and potential-drop-ratio methods in oil prospecting: reprinted *in* Early papers of the Society of Exploration Geophysicists, 1947, p. 420-496.

Holladay, J.S., and West, G.F., 1982, Effect of well casings on surface electrical surveys (abs.): Geophysics, v. 47, p. 439. Full paper available in Technical papers, 51st Annual International Meeting and Exposition, SEG, Los Angeles, v. 2, p. 815-838.

Hughes, L.J., Nosal, E.A., Carlson, N.R., and Zonge, K.L., 1982, Distinguishing well casing from structural effects in electrical anomalies measured over hydrocarbons: a case history (extended abs.): Technical program abstracts & biographies, 52nd Annual International Meeting and Exposition, SEG, Dallas, p. 443-445.

INDESCO, 1981, INDESCO: Electrical geophysics: informational brochure.

Jordan, J.M., Pritchard, J.I., and Renick, H., Jr., 1982, Advances in surface-based electrical resistivity methodology, data acquisition, and processing (abs.): Geophysics, v. 47, p. 438.

Karcher, J.C., and McDermott, E., 1935, Deep electrical prospecting: AAPG Bull., v. 19, p. 64-77.

Keller, G.V., 1968, Electrical prospecting for oil: Quarterly of the Colorado School of Mines, v. 63, no. 2, p. 267.

—, 1969, Electromagnetics may be the key to direct oil finding: World Oil, Dec., p. 85-88.

Kinghorn, G. F., 1967, Electrical methods for deep subsurface exploration: IEEE Trans. on Geoscience Electronics, v. GE-5, p. 51-62.

Klein, J.D., 1983, Spectral induced polarization survey, David Field, Alberta: presented at the 36th Annual Meeting of the Midwest SEG, Denver.

Lee, F.W., and Swartz, J.H., 1930, Resistivity measurements of oil-bearing beds: U.S. Bur. Mines Tech. Paper 48.

M.J. Exploration, 1982 (?)a, Microseep electrical analog surveys: informational brochure.

—, 1982 (?)b, Minimizing false anomalies: informational brochure.

Mooeny, H.M., 1954, The status of (non-direct-current) electrical exploration with special reference to uranium prospecting: Final report to the U.S. Atomic Energy Commission, Contract AT-(49-1)-900.

Mueller, M., 1934: Gerlands beitrage zur angewandten geophysik, v. 4, p. 302-315.

Oehler, D.Z., and Sternberg, B.K., 1982, Induced polarization for hydrocarbon exploration: geochemical / geological interpretation (extended abs.): Technical program abstracts & biographies, 52nd Annual International Meeting and Exposition, SEG, Dallas, p. 445-448.

Oilweek, 1974a, Electrics 100% accuracy disputed but no 'condemned' well ever came in: Oilweek, Sep. 30.

—, 1974b, From space: radio tool to look for oil and gas: Oilweek, Sep. 30, p. 30-31.

—, 1976, Principle of induced polarization applied to geochemical exploration: Oilweek, Sep. 27, p. 31-32.

—, 1978, Induced polarization explained: Oilweek, May 8, p. 21-23.

Pelton, W.H., Ward, S.H., Hallof, P.G., Sill, W.R., and Nelson, P.H., 1978, Mineral discrimination and removal of inductive coupling with multifrequency induced polarization: Geophysics, v. 43, p. 588-609.

Peters, L.J., and Bardeen, J., 1932, Some aspects of electrical prospecting application: reprinted *in* Early papers of the Society of Exploration Geophysicists, 1947, p. 145.

Petrick, W.R., 1983, Interpretation of induced polarization data, *in* Electrical methods in oil and gas exploration, v. 2: Salt Lake City, Earth Science Laboratory, University of Utah Research Institute.

Pirson, S.J., 1971, New electric technique can locate gas and oil: World Oil, Apr., p. 69-72, May, p. 72-74.

—, 1974, Unified magneto-electrotelluric exploration method: Oil & Gas Jour., Mar. 18, p. 138-140, Mar. 25, p. 142-148.

—, 1976, Prediction of hydrocarbons in place by magneto-electrotelluric exploration: Oil & Gas Jour., May 31, p. 82-86.

—, 1980, Pirson: oil is confined in the earth by redox potential barriers: Oil & Gas Jour., Jul 7, p. 153-158.

Potapenko, G., 1940, Method of determining the presence of oil: U.S. Patent 2,190,320, issued Feb. 14, 1940.

Powell, J.A., 1981, Electric transient surveys for hydrocarbon (abs.): Geophysics, v. 46, p. 432. Full paper available in Technical papers, 50th Annual International Meeting and Exposition, SEG, Houston, v. 3, p. 1773-1794.

Pritchard, J.I., and Renick, H., Jr., 1982, Today's exploration capability of electrical method surveys (abs.): Geophysics, v. 47, p. 450.

Pritchett, W.C., 1952, Attenuation of radio frequency waves through the earth: Geophysics, v. 17, p. 193-217.

Reeves Exploration, 1980(?), Electrosearch: informational brochure.

—, 1982(?), Electrosearch: information brochure.

Riordan, J., and Sunde, E.D., 1933, Mutual impedance of grounded wires for stratified two-layer earth: Bell Sys. Tech. Jour., v. 12, p. 162-177.

Rust, W.M., Jr., 1938, A historical review of electrical prospecting methods: Geophysics, v. 3, p. 1-6.

—, 1940, Typical electrical prospecting methods: Geophysics, v. 5, p. 243-249.

Sill, W.R., 1983, Cultural effects in induced polarization data, *in* Electrical methods in oil and gas exploration, v. 2: Salt Lake City, Earth Science Laboratory, University of Utah Research Institute.

Snyder, D.D., 1975, A programmable digital electrical receiver (unpublished): presented at the 45th Annual International SEG Convention.

—, 1976, Field tests of a microprocessor-controlled electrical receiver (unpublished): presented at the 46th Annual International SEG convention.

Snyder, D.D., Kolvoord, R.W., Frangos, W., Bajwa, Y., Fleming, D.B., and Tasci, M.T., 1981a, Exploration for petroleum using complex resistivity measurements, *in* Advances in induced polarization and complex resistivity: Tucson, Arizona, short course reprints, University of Arizona, p. 209-253.

—, 1981b, Exploration for petroleum using complex resistivity measurements: information brochure (EDCON).

Staley, R.B., Clark, R.B., and Zonge, K.L., 1978, The GDP-12 geophysical data acquisition system: Proceedings of the Digital Equipment Computer Users Society, v. 5, no. 2.

Sternberg, B.K., Miller, D.E., and Bahjat, D.S., 1981, Electrode prospecting method providing calculable electromagnetic coupling for the indirect detection of hydrocarbon reservoirs: U.S. Patent 4,295,096, issued Oct. 13, 1981.

Sundberg, K., 1930, Electrical prospecting for oil structure: AAPG Bull., v. 14, p. 1145-1163.

Swartz, J.H., 1932, Oil prospecting in Kentucky by resistivity methods: U.S. Bur. of Mines Tech. Paper 521.

Van Voorhis, C.D., Nelson, P.H., and Drake, T.L., 1973, Complex resistivity spectra of porphyry copper mineralization: Geophysics, v. 38, p. 44-60.

Wenner, F., 1915, A Method of measuring earth resistivity: U.S. Bur. Standards Ser. Paper 258.

Wynn, J.C., and Zonge, K.L., 1975, EM Coupling, its intrinsic value, its removal and the cultural coupling problem: Geophysics, v. 40, p. 831-850.

Yost, W.J., 1952, The interpretation of electromagnetic reflection data in geophysical exploration: Geophysics, v. 17, p. 89-106.

Yost, W.J., Caldwell, R.L., Beard, C.I., McClure, C.D., and Skomal, E.N., 1952, The interpretation of electromagnetic reflection data in geophysical exploration (Part 2: Metallic model experiments): Geophysics, v. 17, p. 806-882.

Zonge, K.L., 1972, Electrical properties of rocks as applied to geophysical prospecting: PhD Dissertation, University of Arizona.

—, 1973, Minicomputers used in mineral exploration, or backpacking a box full of bits into the bush: 11th Symposium on Computer Applications in the Mineral Industry, University of Arizona, Tucson, Apr. 16-20.

—, 1975, Field application of minicomputers as used in economic mineral exploration (abs.): Geophysics, v. 41, p. 382.

—, 1976, Method using induced polarization for ore discrimination in disseminated earth deposits: U.S. Patent 3,967,190, issued Jun. 29, 1976.

Zonge, K.L., and Hughes, L.J., 1981, The complex resistivity method, *in* Advances in induced polarization and complex resistivity: Tucson, Arizona, short course reprints, University of Arizona, p. 163-208.

Zonge, K.L., and Wynn, J.C., 1975, Recent advances and applications in complex resistivity measurements: Geophysics, v. 40, p. 851.

Notes