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Surface-Measured Resistivity May Be Key to Successful Stratigraphic Trap Exploration - A Recent Discovery Using Electromagnetic Imaging

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ABSTRACT

New technology is needed for effective stratigraphic trap exploration. Surface-measured resistivity (Electromagnetic Imaging) appears to be the solution. Commonly used exploration methods such as seismic, gravity, and magnetics have not always been successful in stratigraphic trap exploration. Geochemical methods are used for reconnaissance purposes and are inferred to depth. There is a large gap between the resolution capabilities of 2-D and 3-D seismic and potential fields methods such as gravity and magnetics. The resolution capability of the Electromagnetic Imaging (EMI) method falls between the two groups. The EMI method is a low-frequency, time-domain electromagnetic sounding technique utilizing a grounded-wire transmitter and an induction-loop receiver. It is the best of all the electrical methods because of its high degree of resolution, large depth of penetration, portability, and cost-effectiveness.

When hydrocarbons accumulate in reservoirs as a result of suitable trapping conditions, the reservoir rocks and a large volume of rock closely associated with and generally above the reservoirs undergo resistivity changes creating a large exploration target. Under these conditions, using a surface-based electrical method such as EMI to map stratigraphic traps becomes possible. Using the EMI method, we have found that stratigraphic traps, in almost all cases, manifest themselves as areas of deep-seated, high-resistivity anomalies which correlate closely with the hydrocarbon reservoirs.

The East Kinsler oil and gas field located in Morton County, Kansas produces from Morrow sandstones. An EMI line run across this field produced a robust resistivity anomaly delineating the field. Using this field as a model, a multi-line EMI survey was carried out in southwestern Kansas. A test hole drilled on one of the resulting EMI anomalies discovered gas in the lower Morrow sandstones and oil in the Mississippian St. Louis Formation.

INTRODUCTION

In 1946, Canada produced only one tenth of its oil needs and had gone 10 years without a significant oil discovery. Some companies, including Imperial Oil Limited (Exxon) were on the verge of calling it quits. Imperial's explorers pleaded for one last chance and in the spring of 1946 they got it.

Vern Hunter was chosen to supervise the drilling of Leduc No. 1. Despite the comments by Hunter such as "They'll never find oil there, it's too close to the city," geologist George McClintock felt that "favorable evidence was accumulating constantly." Hunter observed, "All the way down from the first 2,000 feet or so, we started to pick up a little gas and signs of oil in the Cretaceous. The whole thing was alive... with oil shows" (Thomas, 1996).

In February 1947, Leduc No. 1 discovered oil in Upper Devonian Nisku carbonates and was completed with an initial production of 1,000 bbls/day. The Nisku Formation is a porous dolomite containing abundant corals and Bryozoa in a biostromal reef about 600 feet thick located at a depth of 5,000 feet (Landes, 1975). The Leduc field turned out to be 21,900 acres in areal extent with total reserves of 340 million barrels of oil.

Even after numerous dry holes, everyone felt very positive about Leduc No. 1. Geologist George McClintock recalled "all of us were convinced that we were dealing with no ordinary posthole" (Thomas, 1996). We can't think of any other reason for the optimism during drilling but the fact that a large percentage of the section, 60% to be exact, was alive with hydrocarbon shows.

Today's oil and gas industry, with all the conventional methods at its disposal, does not have the technology to map deep-seated areas of high gas concentrations, yet the delineation of these anomalous areas has the potential to dramatically improve the success rate in stratigraphic trap exploration. Our objective is to demonstrate that these targets can be located indirectly by mapping one of the physical parameters of the rocks, namely

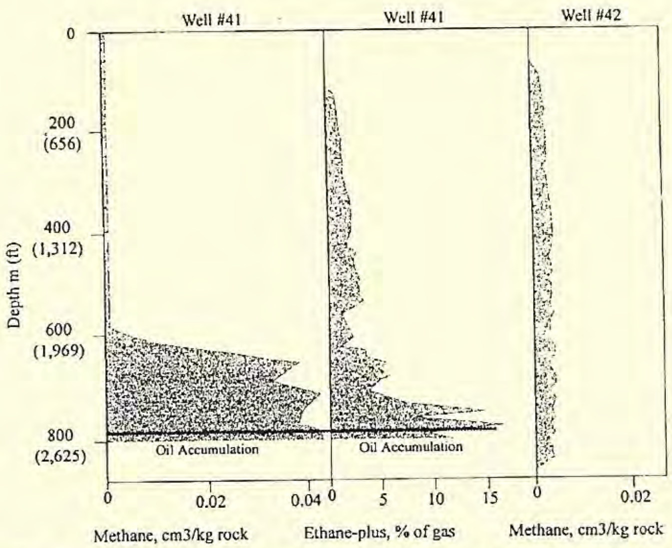

Figure 1. Gas logs (mud logs) of two wells in the Kum-Dag region of the former Soviet Union (after Hunt, 1996). Well no. 41 is productive, well no. 42 is a dry hole.

resistivity, using Electromagnetic Imaging (EMI). Since 1985, our efforts have been directed at stratigraphic trap exploration, specifically channel sand reservoirs and reefs, using the EMI method. In almost all cases, stratigraphic traps manifest themselves as areas of deep-seated, high-resistivity anomalies which correlate closely with the reservoirs. Since 1993, this method has contributed to five stratigraphic-trap discoveries.

Origins of Shallow Gas

According to Siegel (1974), in all cases the concentrations of hydrocarbon gases in rock cores taken in areas of oil and gas fields are much greater than those from outside the limits of influence of the hydrocarbon fields. In the late 1950's, V.A. Sokolov and B.P. Yasenev noted that in sedimentary rocks immediately above productive oil or gas fields there was commonly more gas than in rocks from dry hole areas (Hunt, 1996). They recorded both continuous mud logs and intermittent core samples of both reservoir and non-reservoir rock. Hermetically sealed cores were heated to 70 °C (158 °F) to expel the gas. Figure 1 shows gas logs for two wells; one a producer, one a dry hole. Well no. 41 is alive with hydrocarbons, whereas well no. 42, drilled 3900 ft, away is essentially dead. Hunt (1996) also states that mud logs from the Paradox Basin have higher shale gas yields near production than in the surrounding barren areas.

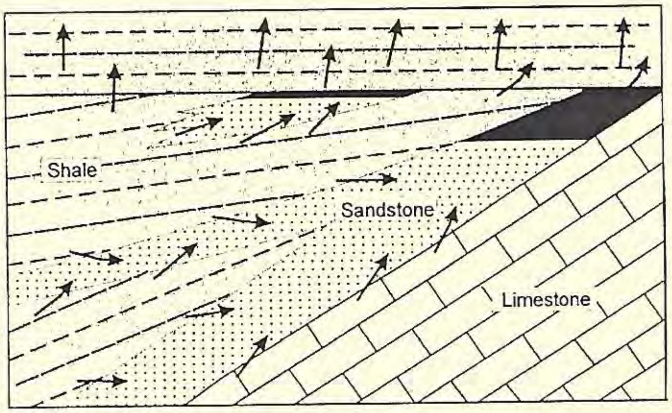

Figure 2. Fluid flow in and around a stratigraphic trap (after Hunt, 1996). Hydrocarbons are retained by the stratigraphic trap.

Horvitz (1980) writes that data obtained from cuttings collected from a large number of wells have disclosed the existence of definite relationships between the hydrocarbons found in well cuttings and petroleum accumulations. For example, mud logs of producing wells show relatively low gas values in the upper part of the well but, at some distance above the accumulation, a definite increase in gas concentration is encountered. From this point on, the gas values gradually increase until the deposit is reached where maximum values are obtained. Mud logs of nonproductive wells show relatively small gas values throughout. The distance above the deposit where significantly higher gas values first appear is dependent upon the nature of the accumulation; the lower the gravity of the deposit, the shorter the distance.

As a general rule, the non-reservoir rocks overlying hydrocarbon accumulations contain relatively large amounts of gas. In gas-prone areas, both the coarse- and fine-grained rock will contain primarily methane. In oil-prone areas, the ethane-plus fraction comprises a substantial percentage of the gas (Hunt, 1996).

The increase in the hydrocarbon content of the non-reservoir rocks overlying the reservoirs starts during the secondary migration phase. (The secondary migration phase is the movement of fluids within reservoir rocks leading to oil and gas segregation). The majority of the shallow gas is the result of the vertical seepage during tertiary migration (tertiary migration is the movement of oil and gas after formation of a recognizable accumulation). The gas yields die out both vertically and horizontally away from petroleum accumulations. Also, no direct relationship between shallow gas yields and the organic matter of the host rock is found. Most hydrocarbon gas in the subsurface exists either in the free form, dissolved in oil, dissolved in formation water, or adsorbed on sediment particles. The concentrations and partial pressures of methane and heavier gases increase toward the accumulations of hydrocarbons (Zorkin, 1969). The hydrocarbon content in subsurface brines associated with petroleum accumulations decreases with increas-

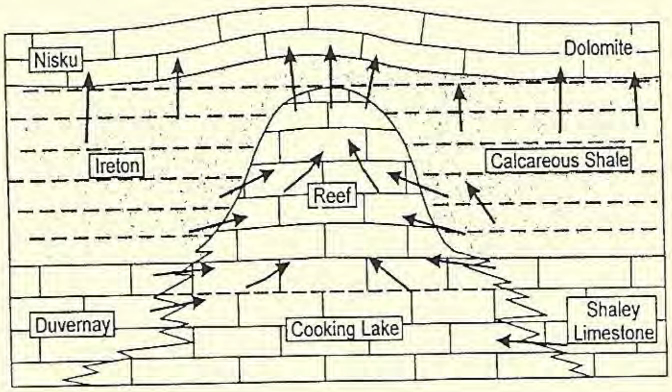

Figure 3. Fluid flow into a pinnacle reef. This would be typical of the reefs in the Leduc area, Western Canada (after Hunt, 1996).

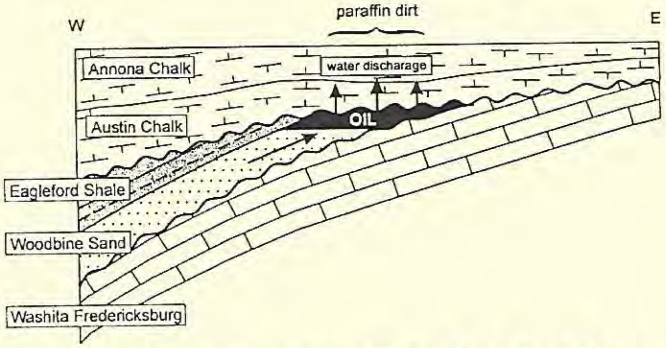

Figure 4. Schematic profile of the East Texas field showing local contact of the Woodbine aquifer with overlying chalks to allow escape of waters and genesis of paraffin-rich soils (after Roberts, 1980).

ing distance from the oil occurrence (Zarella et. al, 1967). From an exploration standpoint, the source of the gas in the non-reservoir rocks above the reservoirs is less important than the fact that it is there in large quantities.

Roberts (1980) writes that traps are not just passive receivers or containers. They can be focal points for the discharge waters from deeper parts of the basin. They function as both active focal mechanisms to gather and to process feedstock waters carrying hydrocarbons and other organic derivatives. The most important function of a trap is to leak water while retaining hydrocarbons. The hydrocarbons and other organics are separated from the waters as they pass through the trap. The separation is caused by abrupt changes in pressure, temperature, and probably salinity which in turn are jointly related to the basic change in direction of water movement from lateral to upward (Figures 2 & 3). Traps are imperfect and hydrochemically noisy systems. Reports of paraffin dirt in the soils overlying the East Texas field suggest the leakage of some hydrocarbons with the water (Figure 4).

Application to Exploration

In general, oil and gas exploration is a high risk business. Needless to say, exploration for stratigraphic traps holds even more risks because seismic methods, potential methods, and subsurface mapping are less definitive than for structural traps. We believe that anomalously high petrogenic gas concentrations above hydrocarbon reservoirs is a phenomenon which can be used to improve the odds of success in stratigraphic trap exploration. Overlying non-reservoir rocks with high gas concentrations appear to be closely associated with the hydrocarbon reservoirs. Therefore, if areas with anomalously high gas concentrations can be mapped, a new, powerful parameter for exploration for stratigraphic traps would be created. However, delimiting these anomalously high gas area with traditional drilling methods (i.e, drilling of wells down to several thousand feet in a prospective area to run mud logs, taking core samples for gas analysis at intermittent intervals, etc.) would not be cost effective. Geochemistry may be of limited effectiveness because, in many instances, migration does not reach the surface in concentrations high enough to offset the interfering effect of hydrocarbons generated from organic matter in shallow, near-surface sediments. Also, vertical hydrocarbon migration can follow erratic pathways to the surface that do not outline subsurface accumulations. Surface geochemical prospecting can be useful as a regional tool to show the general area of oil or gas accumulations, provided information is available on the geology, the effect of near-surface diagenetic hydrocarbons, and the local and regional fluid flow systems in the sediments (Hunt, 1996). Further, surface prospecting cannot outline a subsurface pool in a way that will enable a drilling location to be made, except in very rare cases (Hunt, 1996).

GAS SEEPAGE AND SHALLOW RESISTIVITY ANOMALIES

When pore fluids in the rocks are replaced by oil or gas, these rocks become much more resistive than surrounding rocks, especially if the surrounding rocks are saturated with saline water because electrical resistivity depends directly on porosity, pore fluid resistivity, and saturation (Archie, 1942). Stratigraphic traps are formed from lithologic changes due to primary deposition or secondary diagenesis. Resistivity is a function of primary lithology. Resistivity is also affected by diagenesis because diagenetic changes modify rock porosity and permeability,

Oil and gas traps are continuously active systems. They are hydrocarbon separators or, in a sense, filters. They are imperfect seals and they must leak to function as a trap. Traps can also be focal points of deep water discharge. The basic change in the sense of movement, from lateral to vertical, causes separation of organic components from the water (Roberts, 1980). The migration of large volumes of reduced fluids with their pressures, thermal energies, hydrocarbons, organic compounds, and dissolved salts can initiate a number of diagenetic reactions in the rocks overlying hydrocarbon accumulations. These chemical reactions cause mobilization or precipitation of minerals in the stratigraphic column above the leaking reservoir, thus, modifying or reducing its porosity and permeability. Sealing cements include silica minerals, clays, zeolites, carbonates, sulphates, chlorides and other minor mineral groups (Schmidt et al., 1983).

The contribution of lithologic changes around stratigraphic traps to the resistivity anomalies is small compared to the effect of anomalous hydrocarbon concentrations and the diagenetic changes. However, in the case of reefs, the lithologic contribution can be significant. Reefs with several hundred feet or more of build-up, such as pinnacle reefs, represent a substantial lithologic variation in a normally monotonous sedimentary section (Figure 3). Build-ups alone are not the only lithologic factors adding to the deep resistivity variations associated with reefs. In general, reefs tend to develop over structurally or topographically high areas, and the highs normally have deep-seated causes. The presence of a build-up causes drape and thinning of overlying stratigraphic units due to non-deposition and differential compaction. Structure caused by the drape can lead to hydrocarbon accumulations. For example, in the Leduc Field, the Nisku formation is productive due to the structural drape over the bioherm (Figure 3). The overlying formations also reflect this structure, but to a lessening degree (Landes, 1975). The presence of a reef build-up influences the depositional environment resulting in winnowing of sediments and deposition of larger grains above the build-ups, and in some cases, resulting in the deposition of reservoir quality sands above the reefs. Non-deposition, differential compaction, and porosity-modifying diagenetic changes also take place over reef build-ups and sea bottom highs.

Reservoirs are an important and yet a small part of oil and gas traps. If we look beyond the reservoir and evaluate the sedimentary section associated with the traps, we realize that a large percentage of the section undergoes resistivity modifying processes. The resistivity of the sedimentary rocks is affected by increased hydrocarbon saturation, porosity and permeability modifications due to diagenetic changes, and lithologic variations. No electrical method has the resolution capability to delineate a reservoir tens of feet thick at depths of thousands of feet; however, because hydrocarbon traps manifest themselves as much larger resistivity targets than the reservoirs alone, mapping the deep-seated resistivity anomalies caused by oil and gas traps using a surface electrical method is a possibility. The method to be used must have, in addition to having a high degree of resolution, the capacity for deep penetration to evaluate the resistivity profile of the sedimentary column down to crystalline basement. Resistivity is rarely used in exploration, except in well-logging to determine the water saturation of reservoirs. Therefore, information on the overall resistivity of oil and gas traps from an exploration standpoint is essentially nonexistent.

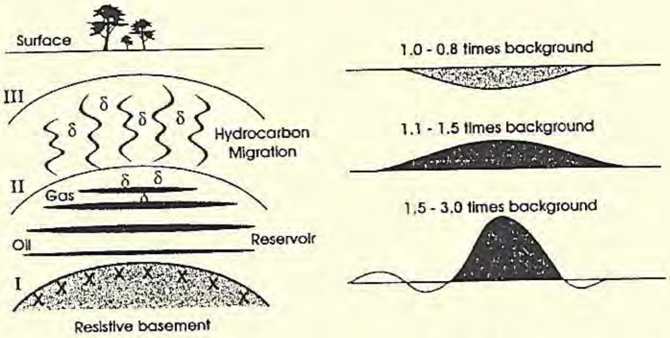

Figure 5. Geoelectric model and resistivity profile summarized in three-layer model of oil and gas fields (after Spies, 1983).

Previous Studies Using Surface-Measured Resistivity

The most comprehensive, published study to date on the geoelectric characteristics of oil and gas fields was carried out by Kirichek and others (Spies, 1983). In order to evaluate electrical methods in oil and gas exploration, statistical data were compiled over a ten year period on the in-situ geoelectric characteristics of oil and gas fields in the former Soviet Union. The electrical logs for more than 950 wells from various size oil fields located in generally clastic environments were used for the study. The resistivity data were summarized in a three-layer model above basement. Figure 5 represents a resistivity summary for very large fields with a total effective thickness of hydrocarbon saturated rock of over 350 ft. The vertical wavy lines represent emanations of hydrocarbon leakage. The resistivity of the layer which contains the reservoir (I) can increase by a factor of 3. The overlying layers (II) also exhibit increased resistivity, whereas near-surface layers (III) generally show a small decrease in resistivity. For large fields with a total reservoir thickness between 150 and 300 ft, the resistivity of the productive stratum (I) usually increases by a factor of up to 1.5, but can increase as much as 4.5 times (in the case of the Gazli gas field by a factor of 10). For smaller fields, resistivity contrasts are generally more pronounced over gas fields than over oil fields; the resistivity increase of the productive stratum (I) can be up to 1.3 times the background. The resistivity of near-surface layers appears to be partially dependent upon climatic conditions. In non-productive areas the resistivity of the potentially productive stratum is usually unchanged or decreased (Spies, 1983).

SURFACE ELECTRICAL METHODS

In the search for an electrical geophysical method to detect resistivity variations *associated with* hydrocarbon traps, the following parameters need to be considered: depth of penetration and resolution capability, cost effectiveness, ease of data acquisition and interpretation, susceptibility to distortions, and ability to penetrate near-surface, high-velocity, high-resistivity rocks such as carbonates and volcanics. In order to detect a hydrocarbon *reservoir* directly, ideal lithologic conditions are required. We have not yet encountered an area with such suitable conditions.

The effective use of surface electrical methods in stratigraphic trap exploration requires a clear understanding of the limitations of the method and a good understanding of the geoelectrical structure of the traps being explored. A lack of understanding of these two subjects is the main cause of prior failures using electrical methods. Almost all of the methods previously used had a shallow depth of penetration; therefore, the resistivity anomalies measured were near-surface variations, most of which had no correlation with hydrocarbon accumulations at depth. Near-surface resistivity measurements are susceptible to distortions due to climatic and shallow lithologic changes in addition to sources of cultural contamination such as pipelines, power lines, railroad tracks and even metal fences.

Electrical methods can be divided into two groups: 1) Direct current (DC) methods, and 2) Electromagnetic (EM) methods. Electromagnetic methods can be divided into two categories: a) Natural field methods b) Controlled source methods.

There are numerous ways in which electromagnetic fields can be generated and measured. For example, we can distinguish between methods which operate at a single frequency with source-receiver spacing being used to control penetration, methods in which a wide spectrum of frequencies is used to control penetration, and those that operate in the time-domain. A further distinction among electromagnetic methods can be made on the basis of transmitter type. An electromagnetic field can be generated by passing a current through a grounded length of wire or an ungrounded loop of wire. Finding the optimum surface electrical method is not an easy task.

Time Domain Electromagnetic Method (TDEM)

Based on our experience with various electrical methods since the early 1970's, we believe that the time-domain electromagnetic sounding system (TDEM) with a grounded-wire source at intermediate offsets (2-5 miles) is the most effective system for exploring for reservoirs at depths up to 12,000 feet, even in the presence of high-resistivity screens in the section. Being able to penetrate high-resistivity, near-surface layers is very important because these layers are normally carbonates, basalts and granites that tend to have high velocities and make the acquisition of interpretable seismic data difficult.

The TDEM sounding method, a low-frequency, controlled-source sounding method, was chosen for our field studies. The TDEM method was developed at the Colorado School of Mines (Keller, et al., 1984). When this deep, electromagnetic sounding tool is employed in a basin, the resistivity profile of the sedimentary section well into the basement can be measured with a high degree of resolution. The TDEM method possesses the highest sensitivity to resistivity changes among all the electrical methods (Kaufman, 1978).

In the TDEM method, an electromagnetic field is generated by passing a square-wave electrical current through a grounded length of wire which is one to two miles long. The square-waves normally have a half-period of 5 to 20 seconds and amplitudes of 100 to 300 amperes. In the upper half-space (air), a magnetic field establishes itself almost instantly over the surface of the earth, while in the lower half-space (earth), the magnetic field develops much more slowly with high-frequency components attenuated in the conductive earth. At the surface of the earth, energy refracts downward into the ground by induction. This energy induces secondary eddy currents in the earth which in turn generate their own magnetic field which travels back to the surface. This returned magnetic field is measured at a site where we wish to know the subsurface resistivity variations. The deeper the excitation field penetrates into the earth, the longer it takes for the field to return to the surface. At the receiver site, the returned vertical magnetic field is recorded as a function of time (Zhdanov and Keller, 1994).

In order to measure the vertical magnetic field variations as a function of time, an induction-loop receiver is placed on the surface of the ground at intermediate distances (2-5 miles) from the transmitter dipole. In traditional structural studies, soundings are recorded in a loose grid which depends on the accessibility of the sounding sites using a portable receiver system. For detailed studies, soundings are recorded about 300 to 500 ft apart along profile lines generally parallel to the transmitter dipole. At every sounding site, the vertical magnetic field changes are recorded as time-varying voltages. These curves which start at zero time (surface) and continue from several hundred milliseconds to over 15 seconds, depending on the conductivity of the sedimentary section,

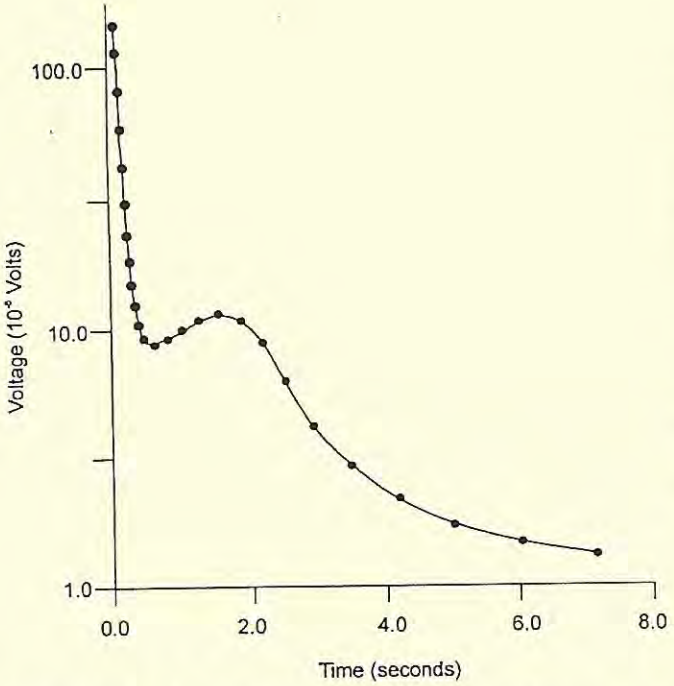

Figure 6. A typical voltage transient as a function of time.

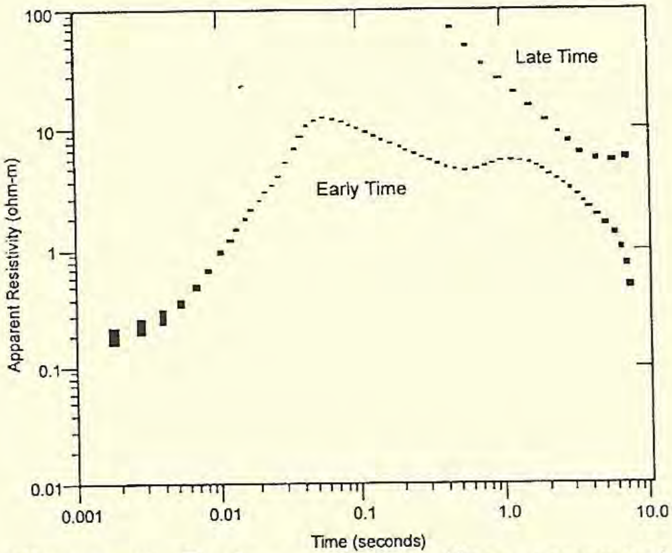

Figure 7. Early- and late-time apparent resistivity curves.

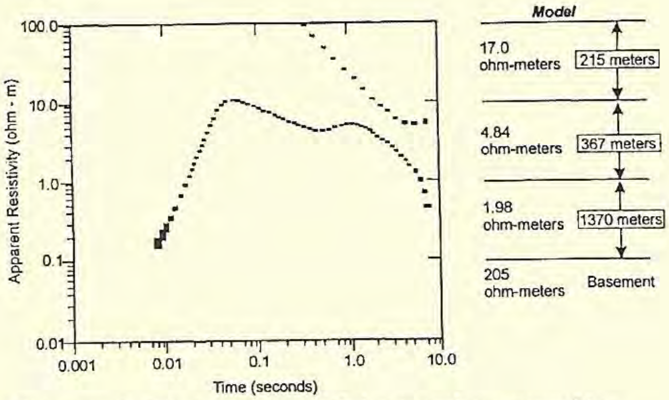

Figure 8. Multi-layered inversion results.

are called transients (Figure 6). The amplitude and shape of the transients are used to determine the resistivity distribution of the sedimentary section, generally to basement, directly below the receiver loop. Bulk changes in earth resistivity with depth cause voltage changes in the recorded curves. At every sounding site, 60 to 120 individual transients are recorded and selectively stacked in order to improve the signal to noise ratio; then, resistivity formulas derived from Maxwell's equations are used to calculate apparent resistivity curves as a function of time (depth) at each sounding site (Kaufman and Keller, 1983). Two different apparent resistivity curves are calculated using the same voltage transient and two separate equations. These two curves called early-time and late-time apparent resistivity, define apparent resistivity through all times (Figure 7). After the resistivity soundings are interpreted in the form of a layered earth model at each sounding site, a conductance value (thickness/resistivity) for each layer is calculated and then these values are summed to determine a total conductance value which reflects the bulk resistivity of the sedimentary column (Figure 8). Conductance is the equivalent of travel-time in reflection seismology. Our experience indicates that conductance values are the most robust parameters derived from multi-layered inversion which in itself is a non-unique solution. When the data quality is good, conductance values provide reliable, quantitative information on the bulk resistivity of the complete sedimentary section. Conductance plots are used to delineate areas of anomalous resistivity.

Distortion of TDEM Signal

Acquiring noise- and distortion-free data is not always possible. In most cases, distortions caused by cultural sources at the surface make it difficult to obtain reliable, multi-layered inversions. The most common causes of distortions are metallic objects such as pipelines, railroad tracks, power lines, and near-surface expressions of faults. A practical solution to this problem was found in apparent resistivity cross-sections. We observed that in many cases, with soundings recorded over existing oil fields, where metallic objects are abundant, the apparent resistivity curves are affected by near-surface distortions. However, these high-frequency, early-time distortions are attenuated in the conductive medium and apparent resistivities at later times delineated with good correlation the anomalous resistivity patterns associated with the oil and gas traps. The use of apparent resistivity cross-sections to map resistivity images caused by hydrocarbon traps

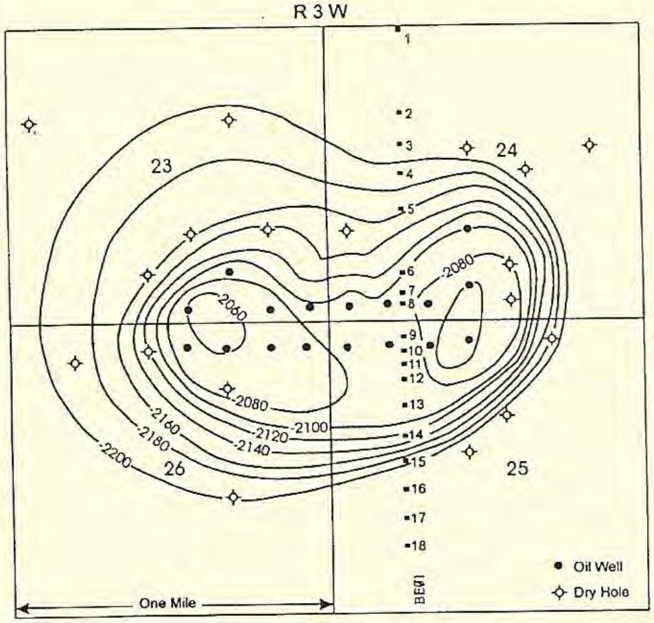

Figure 9. Sounding location map for line BE01 and structure map (contour interval = 20 ft) of the Bartelso East field on the top of the Hunton Megagroup (after Bristol, 1974).

has been named the electromagnetic imaging (EMI) method (Tasci and Zordan, 1996). Apparent resistivities are not true rock resistivities but they do represent real changes in resistivity with time (depth); mathematical inversion is used to calculate true bulk resistivities for the section (Figure 8). All of the apparent resistivity cross-sections presented in this paper are derived from early-time apparent resistivity curves.

Resistivity cross-sections are "unique" for a particular recording geometry. The values are repeatable and the only variable is the noise level such as wind noise, spherics, and power line noise during the time of recording. The cross-sections show the result of the transients recorded in the field which have all been treated equally; therefore, the values presented do not include any interpretation. Interpretation of the resistivity cross-sections consists of determining whether a deep-seated resistivity anomaly exists which is independent of near-surface changes and distortions, and whether this anomaly presents a recognizable pattern that has been observed over oil and gas fields in a similar geological setting. Therefore, it is always recommended to first acquire data over an existing field located near the prospect being evaluated.

FIELD STUDIES

Bartelo East Oil Field, Clinton County, Illinois

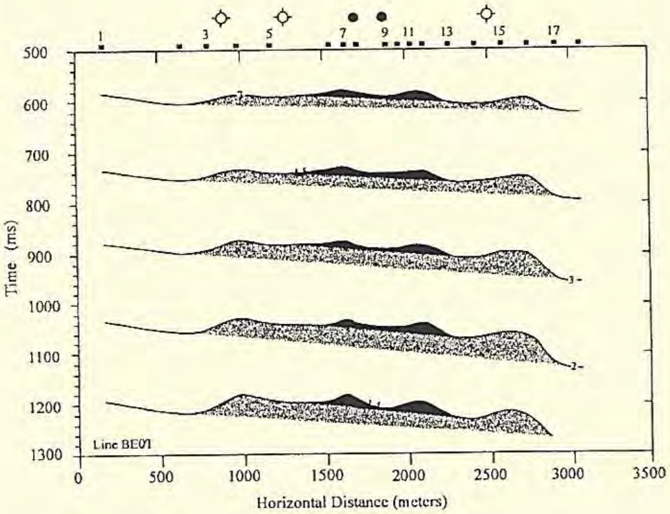

Figure 10. Apparent resistivity cross-section for line BE01, Bartelso East field.

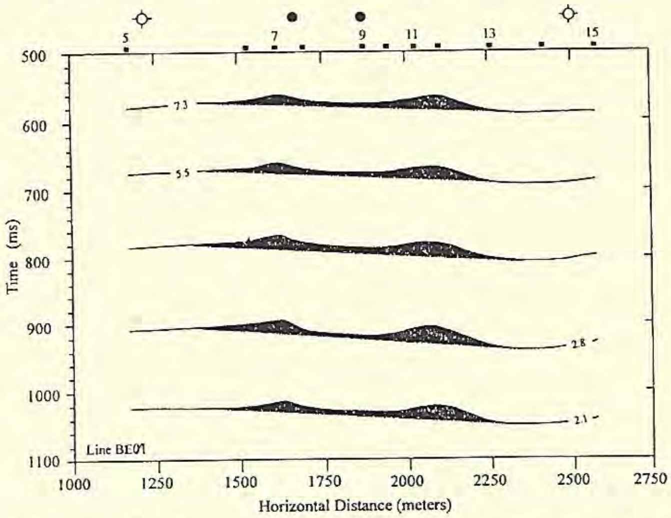

Figure 11. Apparent resistivity cross-section focused on area of production for line BE01, Bartelso East field.

The Bartelso East Field in Clinton County, Illinois produces oil from a Silurian age pinnacle reef and from overlying Devonian carbonates at a depth of about 2550 ft. The field had 17 producing oil wells in an area of 280 acres. Between 1950, the discovery date, and 1972 the field produced about 900,000 bbls of oil; some of the wells are still producing today (Bristol, 1974).

In September 1994, a two-mile-long, north-south EMI line (BE01) was run across the field (Figure 9). The soundings delineated two resistivity anomalies superimposed on one another (Figure 10). The broad anomaly located between soundings 4 and 16 correlates well with the closure caused by the reef buildup shown on the structural map of the top of the Hunton Megagroup (Figure 9). The narrow anomaly between soundings 7 and 12 is superimposed and centered on the broad anomaly. Figure 11 focuses on the narrow anomaly and illustrates it in greater detail;

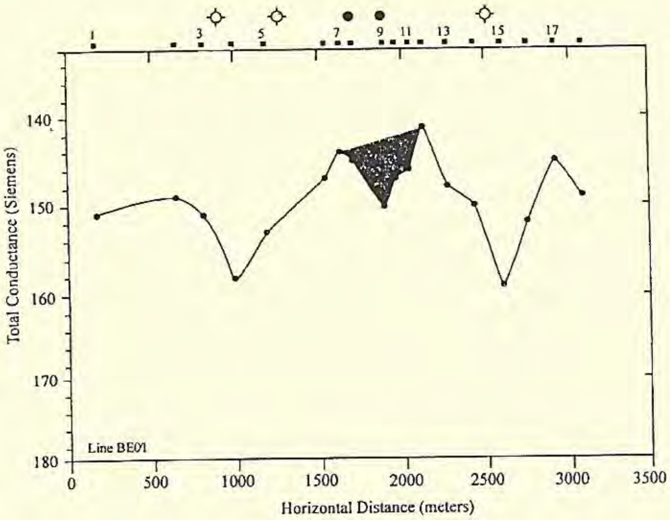

Figure 12. Total conductance profile from three-layer inversions for line BE01, Bartelso East field.

this anomaly correlates well with the limits of oil production.

The total conductance profile from three-layer inversions confirms the boundaries observed on the resistivity cross-section (Figure 12). The oil reservoir is located between the two lowest conductance edges, namely, soundings 7 and 12. Note that the resistivity anomalies delineate both the area of the reef buildup and the productive part of the reef.

East Kinsler Field, Morton County, Kansas and Cavner #A1 Discovery Well, Stevens County, Kansas

The Hugoton gas field, the largest gas field in the USA, is located mainly in southwestern Kansas and extends south into Oklahoma. With an areal extent of hundreds of square miles the field produces gas from shallow depths of about 2000 ft and 3000 ft. Within the boundaries of the Hugoton gas field, there are a number of Pennsylvanian age Morrow channel sandstone fields. The Morrow channel fields, in general, are one square mile or less in size and are located at depths just under 6000 ft.

The East Kinsler oil and gas field is located in Morton County, Kansas within the Hugoton gas field. Production is from Morrow channel sandstone at a depth of about 5500 ft. In March 1994, a three-mile-long north-south EMI line (EK01) was run across the East Kinsler field (Figure 13). The objective was to determine if the Morrow channel field could be delineated below the shallower gas-bearing formations.

The shallow, apparent resistivity cross-section (less than 300 ms) was distorted due to pipelines and power lines (Figure 14). A 12 inch pipeline crosses the line between soundings 13 and 14 creating the largest distortion. Although the sounding locations were kept at least 300 ft away from any metal objects, distortions were unavoidable; as a result we were not able to invert the soundings with a layered earth model and prepare a total conductance profile.

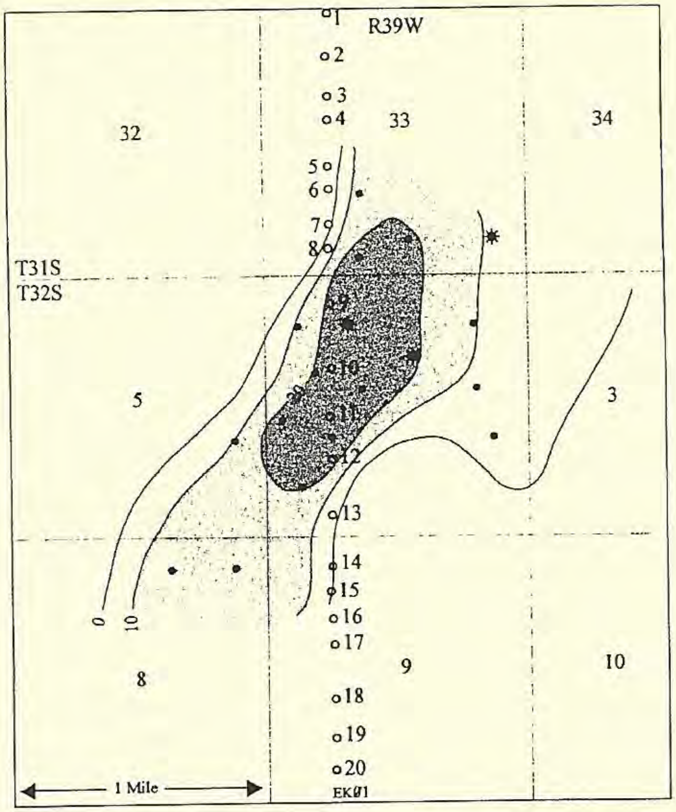

Figure 13. Total Morrow sandstone thickness (contour interval = 10 ft) and sounding location map for line EK01, East Kinsler field.

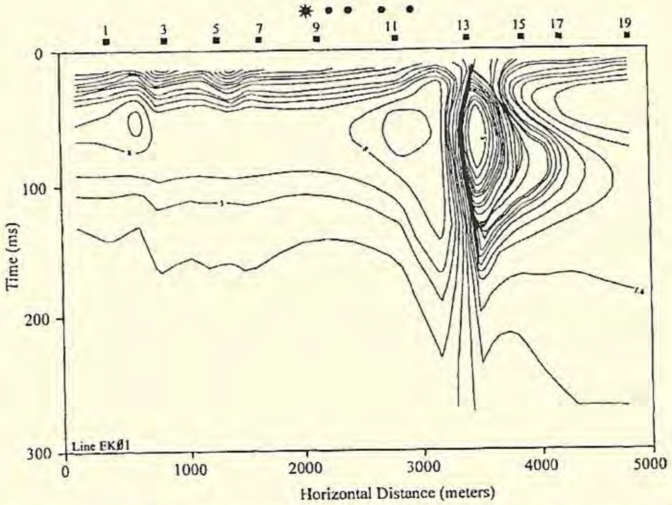

Figure 14. Apparent resistivity cross-section showing near-surface distortions along line EK01, East Kinsler field.

The apparent resistivity section down to 1500

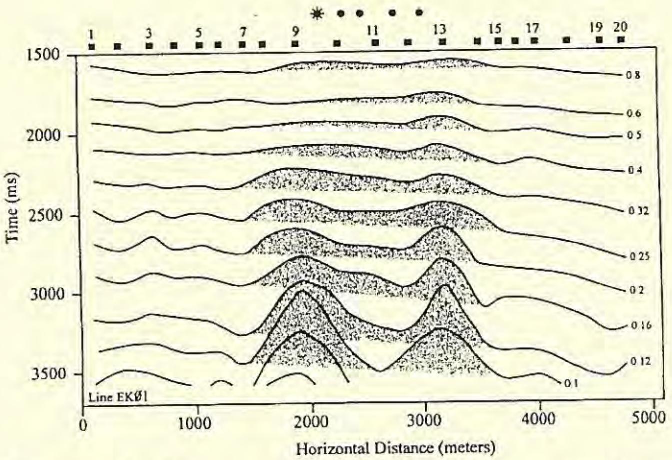

Figure 15. Apparent resistivity cross-section for later time for line EK01, East Kinsler field.

ms did not display a coherent image that correlated with the field. On the other hand, below the 1500 ms level, a resistivity anomaly emerged and is better defined with increasing time (Figure 15). Because the method is inherently robust, the shallow distortions are attenuated in the conductive earth and the apparent resistivities at later times delineated the field with excellent correlation. The shallow gas of the Hugoton gas field acts like a uniform layer, blending into the somewhat monotonous background and not affecting the deeper resistivity data.

As a result of the encouraging test over the East Kinsler field, an extensive, multi-line survey was carried out in southwestern Kansas in 1994. A number of well-defined, deep-seated, high-resistivity anomalies were delineated. The apparent resistivity cross-section of line EK03 from this survey (Figure 16) has a well-defined anomaly located between soundings 7 and 14, which is 0.75 mi wide in the north-south direction. In order to prepare a total conductance profile, the soundings were inverted using a four-layer model. The total conductance profile (Figure 17) shows anomalously low conductances between soundings 7 and 14. The conductance values for soundings 8 and 9 appear to be slightly distorted possibly due to a small pipeline. The Cavner #A1 well, one of the discoveries resulting from the extensive survey, was drilled on this line between soundings 10 and 11. No seismic data was available and geologic information alone was insufficient to justify drilling a well. The well site was chosen solely on the basis of the EMI data (personal communication with operator).

The Cavner #A1 well, located in the northwest corner of Section 31, T31S, R38W, Stevens County, Kansas discovered commercial quantities of gas in the lower Morrow sandstone at a depth of 5,800 ft and commercial quantities of oil in the Mississippian St. Louis formation at a depth of 6,050 ft. The well was completed in August 1995 by OXY USA. This as-yet unnamed field is also located within the Hugoton gas field.

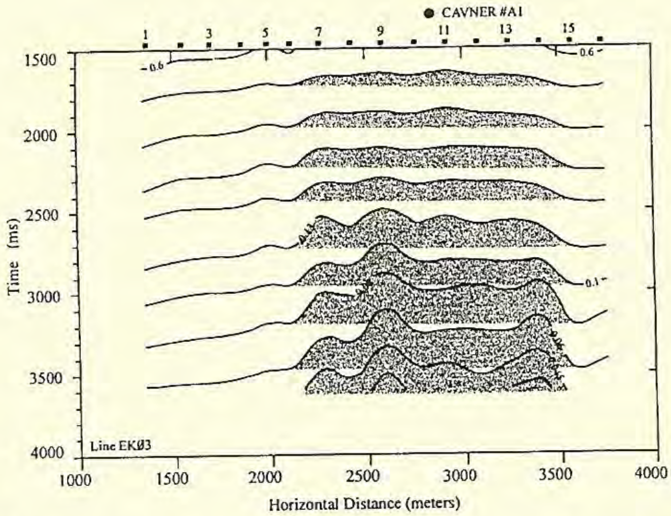

Figure 16. Apparent resistivity cross-section for line EK03, Cavner #A1 discovery.

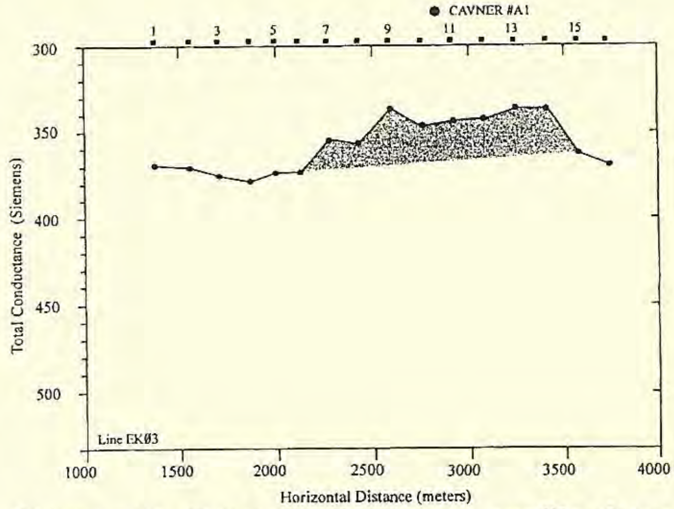

Figure 17. Total conductance profile from four-layer inversions for line EK03, Cavner #A1 discovery.

CONCLUSIONS

Stratigraphic traps have also been subtle or obscure traps because they are difficult to find with existing exploration methods. In the USA and in many other countries, most of the relatively easy-to-find structural traps have already been discovered. The future of onshore exploration in many basins lies mainly with stratigraphic traps.

As a general rule for both stratigraphic and structural hydrocarbon accumulations the overlying non-reservoir rocks contain relatively large amounts of petrogenic gases. Because of increased hydrocarbon concentrations in rocks directly above oil and gas reservoirs (and associated diagenetic and lithologic changes), a large volume of rock closely associated with the hydrocarbon accumulations undergoes resistivity changes resulting in a much larger resistivity target than the resistivity within the reservoir alone. Electromagnetic sounding methods, except in very rare geological conditions, do not have the resolution to map thin hydrocarbon reservoirs at large depths. However, the TDEM method allows for mapping the overall resistivity anomalies caused by entrapped hydrocarbons. This method has a high degree of resolution and a large depth of penetration.

Stratigraphic traps have been mapped to great depths using the TDEM/EMI method. The method has been used in carbonate and basalt-covered basins, and even in areas of very rugged terrain. All of the oil and gas fields that we have investigated have measurable resistivity anomalies. The method has contributed to six field discoveries, five of which were stratigraphic traps and one was a combination trap. In a prospective area, a deep-seated resistivity anomaly provides a powerful indication of a hydrocarbon accumulation; however, it does not guarantee commercial hydrocarbon production. The resistivity information needs to be integrated with other geophysical, geological, and geochemical data.

Surface electrical methods have been misunderstood and misused. As a result, the oil and gas industry routinely conducts resistivity logging only for reservoir evaluations and rarely uses resistivity in exploration. Surface-measured resistivity is the only principal physical parameter of rocks that has not historically been utilized effectively in oil and gas exploration. We strongly believe that TDEM has the potential to greatly improve the odds of discovery in stratigraphic trap exploration.

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