PART 2- Theory

New method helps to refine subsurface interpretations

Geologist/producer finds passive electrotelluric surveying a worthwhile complement to other predrilling investigations

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PASSIVE ELECTROTELLURIC SURVEYING (accomplished by a tool called the Petro-Sonde) is a major new addition to the oil industry's array of exploration techniques. These surveys can determine true vertical depth of a given formation, help to discriminate diffractions from reflections on nonmigrated seismic sections, and identify potential pay zones. However, they are *not* a cure-all; they *cannot* create prospects that fail to meet basic geological and geophysical criteria. As applied by the author, such surveys are best used as a validating tool, accompanying seismic and other noninvasive exploration techniques to help enhance the success of each well drilled, for the least amount of investment.

This article addresses the theory behind passive electrotelluric surveying as applied by the Petro-Sonde, as a detailed description of the tool and its appropriate application can be found in Part I, October 1986, *World Oil.* The author is an independent geologist and producer in West Texas who has no direct ties to the company offering the Petro-Sonde service. However, he has had access to the tool at a discounted cost in order to check its effectiveness. Results of his application of the technique are reflected herein.

THE TECHNIQUE

The passive electrotelluric surveying technique applied by the Petro-Sonde service is based on known physical principles. Briefly, the electrical fields detected and recorded by the portable surveying instrument are generated by the interaction of solar radiation with the Earth's ionosphere. (These naturally occurring sheets of telluric currents have long been known to flow along the Earth's surface.[1]) The Earth's ionosphere, or plasma envelope, causes the electromagnetic pulses to pass into the Earth, and travel downward until they reach a change in conductivity caused by a change in lithological composition, porosity or mineral content. At that contact, a secondary electromagnetic pulse is generated that radiates to the surface, where it rejoins the ground wave and is detected by the survey unit's horizontal antenna. Hence, electrotelluric surveying is passive, unlike other forms of electromagnetic prospecting that require artificially induced currents.

The antenna relays the characteristics of the detected current to a digital recorder and to a survey unit, which converts the current to an audio signal. The audio signal is interpreted and recorded by the unit's operator (a geologist, typically conversant on local geology, and henceforth called the surveyor) as a conductivity log. Given the ability to record the electrical signal obtained at multiple stations per job, playback is facilitated, which increases the reliability of each log.

The frequency of reradiated currents is a function of the depth of the originating subsurface plane. Hence, the survey unit can be calibrated with an existing log for a given frequency or depth. Correlating frequency changes from station to station allows true vertical depth readings on a given formation top-long a problem with seismic surveys. In fact, a majority of the geophysics research conducted during the past decade concentrated on overcoming this handicap. Modern three-dimensional seismic surveys have made a major step forward in solving this problem, but remain an incomplete and expensive solution.

True vertical depth (TVD) readings are but one piece of the information obtained by passive electrotelluric surveys. They also identify lateral/vertical lithological variations, small-scale structures and structural displacements. Resulting data can be used for stratigraphic correlation, porosity geometries, and reserve estimation. But using the technique for detecting hydrocarbons and estimating their type and volume should be done with caution though its main strength is in measuring TVD.

THEORY

Originally offered to the exploration community in the mid-1980s, the passive electrotelluric technique and the specific physics behind the Petro-Sonde tool could not be explained in detail then due to patents pending. Its subsequent success at the time depended solely upon geologists who were willing to test its validity in the field, and experiment with its possible applications. This author was one of the primary explorationists willing to do so.

A patent has since been obtained (Kober, et al., 1987, Patent Number 4,686,475). Accordingly, the following text is the author's explanation of the theory behind passive electrotelluric surveying, as condensed from the detailed report given by Petro-Sonde developers Carl L. Kober and H. David Proctor-Gregg of Littleton, Colorado.

Physical properties sensed. Nonstatic and time-variable pulsating telluric currents create their own electrical field, $E(t)$, and a corresponding magnetic field $H(t)$, wherein:

$$E(t) = ZH(t) \qquad (1)$$

The complex impedance of the Earth, Z, depends on its magnetic, dielectric and conductive properties. The electrical field components are almost vertical, and the magnetic components are almost horizontal.

It is recognized that a low frequency window (LFW) exists for telluric currents to pass through the Earth's substrate, with

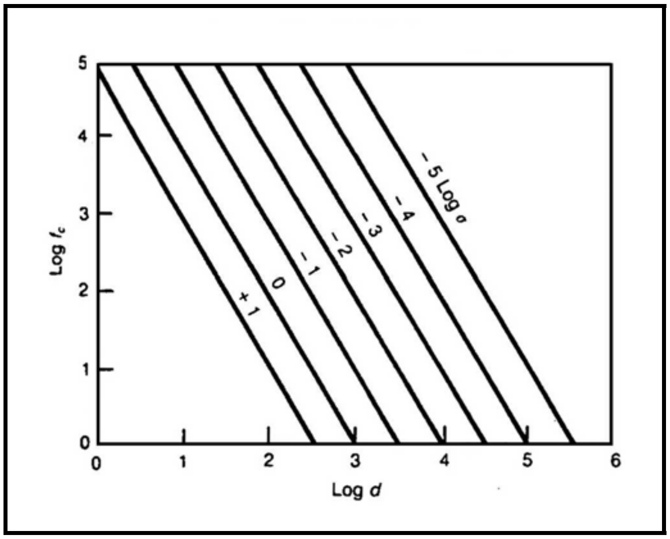

Fig. 1—The relationship between the log of the cutoff frequency (f_c) and the log of the depth (d) is shown for different values of conductivity. The distinctions between depth (d) and conductivity (σ) are used as indicators of depth and formation characteristics.

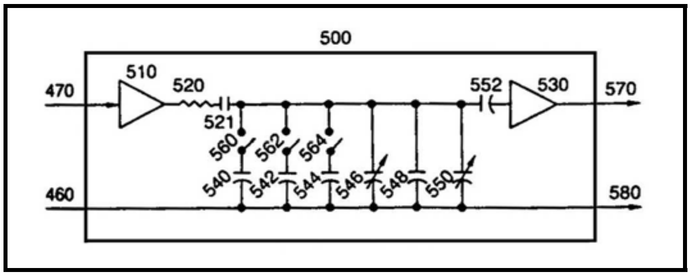

Fig. 2—The tunable filter circuitry of the Petro-Sonde is illustrated. This circuitry can be set to a desired depth as indicated by nearby electrical logs. Capacitor and frequency adjustments are made during electrotelluric surveying as a means to refine the audible signals received by the surveyor.

its various layers acting as conductors.[2] In this LFW, the amplitude of *electrical* field waves coming from below the surface approximately doubles upon impacting the interface between earth and air because the voltage reflection coefficient is positive. Whereas, the amplitude of the *magnetic* field is reduced to zero because of the negative reflection coefficient.

Thus, antennae on the surface pick up *electrical* field signals alone.

The LFW has been recognized to exist from zero up to a cutoff frequency, f_c, as follows:

$$f_c = 3.76 \times 10^6/(2d)2 \qquad (2)$$

where: $2d$ = distance to the point of observation (in meters)
σ = conductivity of the medium in mhos/m
f_c = frequency at which the electric amplitude is 3dB less than the value at zero frequency.[2]

Generally, the LFW is in the audio range and extends from zero Hz to several kHz, depending on the Earth's conductivity and the depth of the signal's origin. The tool determines f_c at the surface through a single observation of the electrical field, *E(t),* of the telluric current.

By definition, *d* is a continuous variable, strongly influencing (by the square) the cutoff frequency, f_c; whereas, the conductivity, σ, is a piece-wise constant variable altering the frequency with a change in lithology, but by an order of magnitude. The tool records, at the surface, these two subsurface frequency changes.

In Fig. I, the relationship between the log of the cutoff frequency and the log of the depth is shown for different values of conductivity. For example, for a conductivity of 10-2mhos/m, as the depth increases the cutoff frequency drops correspondingly. Therefore, if different strata have different values of conductivity, the cutoff frequency is affected in a piece-wise constant manner.

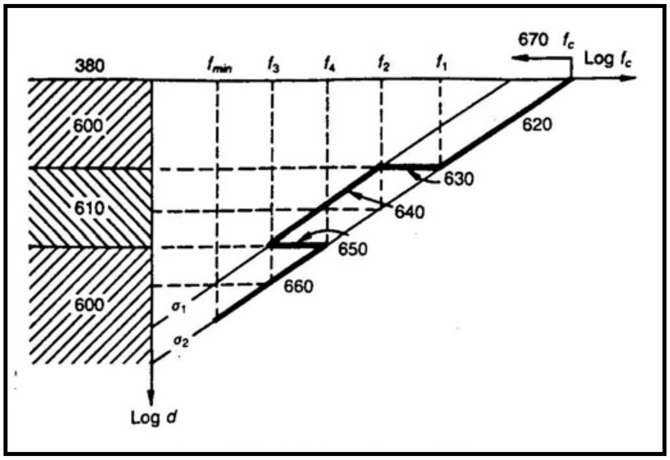

Fig. 3—Illustrated is a plot of the log of depth (d) versus the log of the cutoff frequency (f_c) for a limestone zone (600) and a shale zone (610), at two different conductivities (σ and σ). Note the step change that occurs in line 620 at each of the limestone/shale interfaces. Conductivity influences the cutoff frequency only in step functions!

The tool utilizes these distinctions between depth *(d,* affecting the cutoff frequency by the square) and conductivity *(σ,* affecting the cutoff frequency in a piece-wise or step function) to provide an indication of both the depth and nature of various strata.

The tool also takes advantage of another characteristic of telluric currents. That is, the field pulsations originating in the plasma envelope induce a secondary telluric current in hydrocarbon or mineral deposits. This secondary *current, I(t),* flows at the boundaries of the volume, *V,* of the deposit in the form of a dipole moment, *I(t)L,* given by the following equation:

$$I(t)L = (\sigma_1 - \sigma_2)E(t)V \qquad (3)$$

where: *E(t)* = primary electric field strength penetrating the Earth through the LFW (low frequency window).[3]

The dipole moment, *I(t)L,* consists of a dipole distribution at the borders of the deposit, which produces a secondary pulsating electromagnetic field. These secondary field pulsations are propagated toward the surface in the form of audio pulses, also band limited by the LFW at the surface. These audio pulses moderate the horizontal ground wave at the surface.

Hence, the electrotelluric surveying tool senses both the primary telluric currents as indicators of depth and the nature of the substrate, and the secondary telluric currents as indicators of the presence of hydrocarbons, minerals and other inhomogeneities in a particular section of strata.

Tool mechanics. The Petro-Sonde matches the impedance of the sensor to the impedance of the ground to enhance coupling with the telluric current. The antenna is oriented in the horizontal position for maximum coupling. The indicator utilizes a low ohmic resistance to discharge the capacitive buildup in the sensor in synchronization with the electromag-

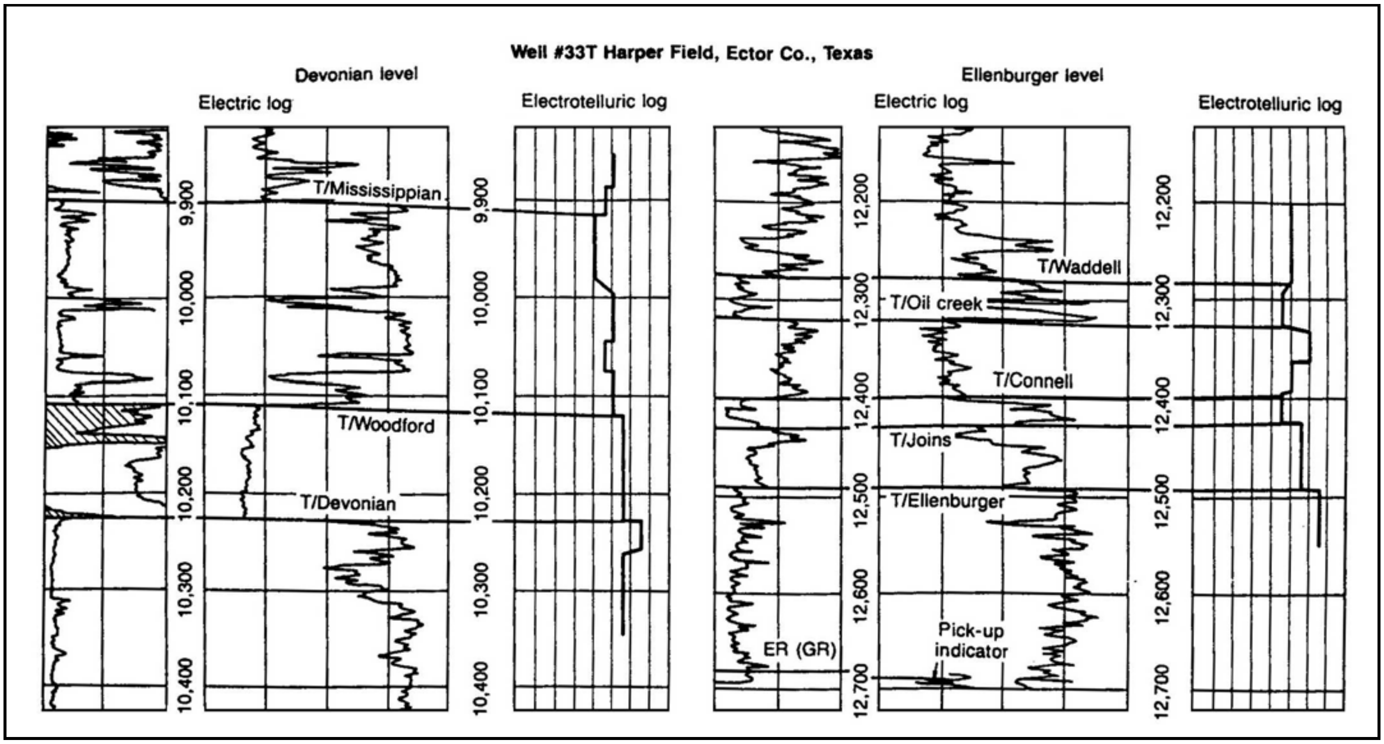

Fig. 4-Electrotelluric logs taken from Harper field, Ector County, Texas, correlated nicely with electric logs from nearby boreholes. The electrotelluric logs were blind readings at the Devonian and Ellenburger levels, as selected from the electrical logs. The electrical logs were taken from a 12-ft KB, 80 the electrotelluric logs actually read lower than shown. Normally, ± 50 ft is considered an acceptable calibration because of the minute changes within the Earth's plasma envelope overtime. In this calibration, the surveyor wanted to determine which formation would be easiest to correlate. The Ellenburger was chosen because it's Waddell and Connell sands were so distinctive, despite the fact that the Ellenburger is sometimes porous, and sometimes tight.

netic field.

The surveyor uses a state variable filter as a deconvolution technique for arriving at a solution to Eq. 2. By utilizing a *stereo* audio output, compensated for the surveyor's ear sensitivity and background noise, the signal interpretation produced by the indicator is significantly enhanced.

Since the purpose of passive electro telluric surveying is to arrive at a depth for a given formation(s) and determine the characteristics of subsurface strata (including the presence of hydrocarbons) a deconvolution of the acquired data is necessary. This is accomplished by using the spectrum or Fourier transform of $Q(t)$ or $I(t)$:

$$I(t) = d\,Q(t)/dt \qquad (4)$$

The depth of the substratum is determined by solving Eq. 2 for $2d$. By decreasing the cut-off frequency, f_{co}, greater depth can be obtained for signal analysis. Recent changes in instrumentation have made it possible for the tool to sense currents reflected from as deep as 40,000 ft. The previous depth cut off was 20,000 ft.

According to the tunable filter circuitry shown in the patent, and displayed in Fig. 2, the output occurring on the lines to the earphones (570 and 580) is essentially white noise corresponding to the transform of $Q(t)$ or $I(t)$, ranging from zero Hz to the cutoff frequency, f_c. Since Eq. 2 is nonlinear, a direct reading of the depth scale is required. The bias capacitor (548) is bigger than capacitors 540, 542 and 544. Thus, depth $2d$ relates linearly to the change f_{co}:

$$2d = (3.76 \times 10^6/f_{co}\,\sigma)1(1.5\Delta f_c/f_{co}) \qquad (5)$$

The bias capacitor provides a direct reading of the depth scale for the Petro-Sonde. To analyze depths down to thousands of feet, the decade capacitors (540, 542 and 544 in Fig. 2) are selectively switched in.

At this point, it is important to return to the mathematical problem of Eq. 2. Two unknowns exist, so the formula cannot be solved mathematically with one reading of the electrical field of the telluric currents. However, the tool provides an indication of the solution. That is, by setting the tunable filter (Fig. 2) to a depth of $2d$ and determining the cutoff frequency, f_c, then only a small error is present in the reading due to the steepness of the straight conductivity constant lines set forth in Fig. 1.

Fig. 3 sets forth a plot of the log of depth versus the log of the cutoff frequency in an example where the lithologies are limestone (600 in Fig. 2) and shale (610 in Fig. 2). Plotted on the graph of log d versus log f_c are two different conductivities, which are constant for a given substratum.

The conductivities for the two lithologies are σ_2 and σ_1.

Note how the cutoff frequency lowers as the depth increases linearly along line 620. However, when the cutoff frequency reaches the limestone-shale interface, it makes a step change along line 630. That step change is recorded by the tool.

As the depth is increased, the cutoff frequency is linearly decreased along line 640, corresponding to the conductivity line σ_1, shale. At the shale-limestone interface, the cutoff frequency again makes a step jump, increasing the value of the cutoff frequency to the conductivity curve for limestone. That change also is noted by the tool.

Clearly, depth is a continuous variable that strongly influences the cutoff frequency by its square. Whereas, conductivity influences the cutoff frequency only in step functions.

As shown in Eq. 5, the surveying tool indicates a solution to this problem by continuously adjusting the tunable filter to depth $2d$ and determining the cutoff frequency, or vice versa.

The error is minimized due to the steepness and linearity of the conductivity curves in Fig. 1. The error amounts to about 25 ft to 50 ft and is defined by:

$$\Delta d = [(2d^3 \sigma/(7.34)(10^6)][\Delta f_c] - 0 \qquad (6)$$

The tunable filter is first set to a certain depth, based on comparison with a well log in the area being surveyed. The remaining deconvolution of the information consists of audibly (and subjectively) determining the lithologic nature of the underground formation. Each formation tends to have its characteristic audio signature.

For a fixed depth, the cutoff frequency changes strongly as a function of the conductivity of the strata. Capacitors 540, 542, 544 and 546 (Fig. 2) can be selectively added to the tunable RC filter to reduce the bandwidth of the circuit from f_c to f_{min} in the direction of arrow 670 (Fig. 3). When capacitor 546 is adjusted to increase capacitance, and frequency f_1 is reached, there is an immediate change in cutoff frequency f_2, which is not due to the tunable circuit but rather to a conductivity change at the limestone-shale interface. This is because there is a step function discontinuity between σ_2 and σ_1, along line 630. This change can be audibly detected.

Each lithologic formation has its own characteristic white noise. Therefore, electrotelluric surveying can not only determine the depth of each formation, but also help with identifying various formations after its data are correlated to the logs of nearby wells.

In sum, the Petro-Sonde deconvolves the charge $Q(t)$ by indicating the solution of Eq. 2. The surveyor tunes the filter to decrease the cutoff frequency, thereby increasing the depth of investigation. Because of the soft roll-off characteristics of the tunable filter, the transient is enhanced and deconvolution is obtained.

Presently, passive electrotelluric surveying can generate analog information indicative of both formation lithology and depth, as well as the presence of any inhomogeneities (such as porosity variations) therein. 'This output, while not actually solving Eq. 2, does provide an audible indication of its solution. The answer is an approximation with an accuracy of ± 50 ft.

Audio system. The human ear is an ergonomic (biotechnology based) recognition system. Further, the human mind can localize sound sources in space. In fact, the localization of stereo sound sources in space by the human mind represents the best "field portable" recognition system.

Recognizing this long ago, the U.S. Navy trained sonar operators to detect minute Doppler frequency shifts related to the relative movement of target submarines. Computers still cannot equal the human ear for such purposes, so a human surveyor must plot a log from the electrotelluric data heard over earphones. Putting a human in the system, of course, results in minor logging variations from surveyor to surveyor. But not until computers are capable of matching the combined sensitivity of the human ear and brain will comparable electrotelluric logs be generated by a computer.

There is a crossover circuit in the tool that enhances a human ear's bandwidth recognition by using a high-low, crossover, band-pass filter to generate *stereo* sound in the surveyor's ears. Hence, f_c two separate outputs are provided to each ear. The left earphone receives the low band-pass response, and the right earphone the high response. The crossover point is between 1,200 and 1,600 Hz.

Essentially, a stereo sensation is created in the surveyor's ears. Changes in the band width localize the sound impression as a wandering from the right ear to the left, and vice versa. This permits the surveyor to subjectively plot conductivity changes that look much like a borehole electric log presentation. In fact, the two logs can be compared easily.

What the surveyor hears is generally white noise. Three signatures are detected. The first is any change of frequency suddenly occurring in the white noise; the second is the characteristic of the white noise itself. The third is the detection of any pulsating signals present in the white noise. The latter is associated with the presence of fluids, particularly oil. Gas does not have much of a signature and normally cannot be detected directly with the Petro-Sonde. However, the thickness of a gas column has been measured by noting the level of the first water reading in a zone of continuous porosity.

Hydrocarbon readings from passive electrotelluric surveys should be used with considerable reservation. This is mainly because the ability to detect hydrocarbons varies widely between surveyors, and even with the same surveyor throughout the course of a day. The ability to obtain oil readings tends to decrease sharply late in the day.

It is important to recognize that the telluric current environment is extremely noisy overall. Yet, an electrotelluric survey conducted with a Petro-Sonde can provide an analog output in stereo mode that is extremely sensitive to the specific current differences of interest to explorationists. Further, as might be expected, thunderstorms in a survey area will terminate field work, because the logs become nonrepeatable as a result of these spurious influences.

Digital recording. The basic ground wave recorded by the surveying unit's antenna is preserved with a digital recorder.

This provides multiple playback opportunities, as all frequencies from 0 to 20,000 ft or 0 to 40,000 ft are recorded. The tapes can be played many times through the filter, which helps to overcome human error in the logging process.

Digital recording has not always been a part of the Petro-Sonde service. Having used it for several recent applications, the author has found digital recording to have caused a quantum leap in his ability to use the electrotelluric logs. It permits different surveyors to log the same recorded signals. Prior to digital recording, it was necessary to use different surveyors to log the same stations in the field on different days in order to check for repeatability. In doing so, sometimes there is just enough difference in the Earth's plasma envelope at a station from day to day to cause unexplainable variations in the resulting electrotelluric logs. With the ground wave now recorded for playback, there is no excuse for nonrepeatability of logs.

Used properly, the technique described herein has given the author 85 % accuracy on depths and lithologies, but hydrocarbon readings still are seldom more than 50% accurate. Hydrocarbon readings also require a greater expertise by the surveyor. The technique works best on prospects that do not rely too heavily on oil readings for proof of closure. Oil source rocks often show up on these logs as potential pay zones. For example, in the Permian basin, the Woodford shale is often logged as Siluro-Devonian pay, particularly when the underlying Siluro-Devonian objective happens to be tight, and this caused some early dry holes.

Field checking and correlating. Field checking the accuracy of electrotelluric surveying is an easy process. Simply have selected readings taken at well sites for which electric logs are available. Normally, electric logs of a selected interval can be replicated by an electrotelluric log, but results are best when looking for well-defined lithologic breaks (Fig. 4). In areas such as deltas, where there are many variations in stratigraphy, miscorrelations are easily made. However, this can be overcome by taking many close readings. In areas where electric logs are difficult to correlate, electro tell uric correlations are even less reliable.

Experience is needed to correlate electrotelluric logs. They are crude conductivity logs, measuring physical properties somewhat different than those read by electrical logs. Typically, the geologist that accompanies the electrotelluric surveyor out to the field does the correlating. It is best to rely on final correlations only after data are laid out in cross section.

Poor depth correlation between electrotelluric logs and electrical logs can occur because the boreholes in which the electric logs are taken are seldom truly vertical, which means that the bottom of the hole is seldom directly below the surface location. This is especially true in deep basins. Whereas, repeated field checking of electrotelluric surveys substantiates that the Petro-Sonde records data from directly below a given station (receiver). Obviously, some discrepancy between the two logs will occur in these circumstances, but it is seldom more than a few tens of feet.

CONCLUSION

Passive electrotelluric surveying is not a cure-all, but it is an important new exploration technique. When properly used, as a supplement to other technologies, it provides fast, accurate and cost-effective data concerning subsurface conditions. For example, it is a good complement to seismic, as it can help discriminate diffractions from reflections in nonmigrated seismic sections, or in migrated sections that cross the structure obliquely. It also can help to determine true formation depth at a given location and identify potential pay zones.

While good exploration geologists continue to be needed to locate prospects worthy of surveying, the passive electrotelluric technique enables more accurate validation or elimination of such prospects prior to cost-intensive drilling. Now given the physics behind this technique, geologists should no longer be reluctant to try it out for themselves. After all, it has helped this author to cost-effectively complete overlooked West Texas production.

The author

Jack G. Elam is currently a consulting geologist and independent producer in Midland, Texas. He received bachelor's and master's degrees from UCLA in 1943 and 1948, respectively. A PhD was received from Rensselaer Polytechnic Institute in 1960. He has served in teaching or lecturing positions from 1946 to the present at UCLA, University of California Ext. Div., Rensselaer Polytechnic Institute, University of Texas of the Permian Basin, University of Texas at Arlington and the Permian Basin Graduate Center. In addition to consulting geology work, his career has included employment with Stanley and Stolz, Richfield 011 Corp., Cameron 01/ Co., Exploration Ltd. (general partner), Nor-Am Petroleum Corp. (vice president), and Keba 011 and Gas Co. (director). He presently Is president of 2501 Corp., Jack G. Elam Inc., and Naja International S.A He Is a member 01 AAPG, GSA, SIPES, Permian Basin Section of SEPM, West Texas Geological Society and Sigma Xi. Also, he is founder, past president and past chairman of the board of Permian Basin Graduate Center.

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