

Electrotelluric Geophysical Exploration

Ali A. Yazdi, MS in Geophysics, consultant to Geophysics International, Dallas, Texas, and Jack G. Elam, Ph.D. in Geology, Independent Producer, Midland, Texas.

While electrotelluric surveying has long been known to be capable of delivering a unique blend of geophysical information (reservoir presence, fluid content, fluid type, relative porosity, depth, and thickness) in three dimensions, it does have its limitations. These limitations must be adequately addressed to achieve a successful survey.

To date, the Petro-Sonde, a patented electrotelluric instrument that measures changes in the earth's electric field (marketed by Geophysics International of Dallas, Texas) is by far the most advanced telluric surveying tool on the market. It offers an impressive level of resolution and information. The Petro-Sonde has been used in thousands of surveys over the last decade and it has undergone many changes and improvements. As a result, the Petro-Sonde logs are now being digitally recorded and presented in a format similar to that of a detailed electrical conductivity log (without the need of a bore hole!). The structural and stratigraphic features of most reservoirs can be identified using the electrotelluric method by correlating the distinctive electrotelluric response patterns from station to station, after being properly calibrated with existing electric logs. The electrotelluric survey gives accurate and detailed information regarding the reservoir presence, porosity and depth, and works best where electrical logs of nearby oil producers are available for calibration.

Theory

Telluric currents are naturally-occurring electrical currents which flow in large sheets everywhere in the crust of the earth. The current density within these sheets is a function of the resistivity of the formations carrying the currents. The depth of the telluric current depends on its frequency and the resistivity of the overlying stratigraphic column. It is expressed by the equation $h = \frac{1}{2} \sqrt{r/f}$ where h is depth in kilometers, f is frequency in hertz and r is resistivity in ohm-meters (Robinson and Coruh, 1988). The equation reveals that telluric currents with higher frequencies are present closer to the surface, and currents with lower frequencies are found deeper in the earth. Some of the most detailed Petro-Sonde logs are from depths below 20,000'.

The telluric current originates in the ionosphere. The motion of particles ionized by solar radiation creates electric currents within the ionosphere. By electromagnetic induction the ionospheric currents produce diurnal fluctuations in the intensity of the earth's magnetic field, and it is these changes in the intensity of the earth's magnetic field that are the primary inducing mechanisms of telluric currents. Earth currents vary geographically, diurnally, and seasonally. The pattern of earth-telluric currents appears fixed with respect to the sun, shifting along the earth's surface as the earth rotates (Dobrin, 1976).

The electrotelluric instrument, the Petro-Sonde, operates as a receiver and analyzer of the electromagnetic field generated by the flow of the telluric current in the earth's subsurface. Elam, (1986, 1990), describes the instrument and the concept in detail.

The electrical and magnetic properties of a medium through which a current travels affect the current's behavior and the associated magnetic field produced. Since lithologic units have differing electrical and magnetic properties, the flow of the telluric current through each unit generates a distinct magnetic field reflecting that unit's mineral and fluid content. The magnetic field produced by the current flow through each lithologic unit overlaps the magnetic fields produced by other lithologic units. Therefore, the earth's magnetic field at any point is stacked, i.e. it contains overlapped magnetic fields from the different lithologies. To study each distinct magnetic field, hence the lithology and fluid content it represents, each magnetic field has to be

unstacked (sorted out) or deconvoluted.

The previously-mentioned equation, $h = \frac{1}{2} \sqrt{\rho T / f}$ is used to unstack the electromagnetic fields. The equation specifies that the frequency of the telluric current (also the frequency of the electromagnetic field produced) is a function of depth and total resistivity of the overlying stratigraphic column. Since resistivity can be assumed to be constant (and is available by calibration with existing electric logs), frequency and depth are directly related. In processing by the Petro-Sonde instrument, band-pass filters are utilized to admit the signal to be analyzed at a specific frequency range (depth). Within the tool, that specific signal is then converted into an audible sound that the operator listens to with a set of earphones. Distinctive sound patterns or signatures are associated with different lithologic units and fluid contents. Once a distinctive signature for a given depth has been recognized (by calibration with existing downhole logs), the next depth or frequency is admitted for processing. The data is then plotted in a format similar to that of a downhole electrical conductivity log with corresponding fluid and lithologic interpretations.

In simple terms, the instrument operates in a fashion similar to a radio or TV, where each depth can be considered as a distinct broadcasting station. The sound patterns broadcast by each station (depth) are lithology, fluid content, and porosity. By tuning in to a specific station frequency (depth) a specific sound pattern (signature) is heard based on the actual lithology, fluid content, and porosity at that depth.

Survey Parameters, Advantages and Limitations

In spite of the fact that the electrotelluric survey gives an unequalled amount of geologic information regarding a reservoir's presence or absence, depth, thickness, relative porosity and fluid content, the cost is but a small fraction of that of a 3-D seismic survey. Another distinct advantage of the instrument is that most prospects can be easily evaluated in the field with the Petro-Sonde because the instrument is small and portable (the size of a shoe box) and does not require an artificially-generated energy source (such as dynamite in the case of seismic surveying). In the Permian Basin, anyway, it has been found that most prospects are crisscrossed by public access roads and highways, which means that the prospect can be evaluated to a considerable degree from readings within the adjacent bar ditch. It only takes 20 minutes to digitally record the signal at a Petro-Sonde station, which can then be analyzed by a Petro-Sonde operator in the field or sometime later in his office. Thus, the Petro-Sonde can easily be utilized for reconnaissance. It has been found that one of the most important attributes of the tool is that it very frequently displays a structural or paleogeomorphic periodicity that can be of great importance to an explorationist. This is particularly important in prospecting within symmetrical rifted basins, such as the Permian Basin.

To insure the success of an electrotelluric survey, though, the fundamental survey design parameters must be thoroughly understood. The main parameters include environmental conditions, geologic control in the area, the number and quality of available calibration electric logs, length of vertical window, and spacing between stations. It has been found that to get the best out of this tool it is almost essential that the geologist thoroughly cross section and contour with electric logs the prospect area prior to the Petro-Sonde survey. That allows the geologist to repeatedly check his geological insights.

The driving mechanism initiating the telluric currents in the earth is solar. Thus, telluric current surveying should be done in the daytime for optimum signal strength. Telluric currents are also affected by electrical activities in the atmosphere. The tool becomes unreliable during electrical storms (thunder storms and incoming cold fronts). Although an electrotelluric survey is affected by such outside factors that cannot be controlled, they can be monitored. Moderate amounts of ground moisture do not affect the survey but an electrotelluric survey should never be conducted directly above surface water. The vehicle should not be parked in a mud puddle if the recording is being conducted from inside the vehicle. For best results the Petro-Sonde operator sets the receiver on the ground. The signal is more repeatable under these conditions. When a survey is not conducted under optimum environmental conditions, the telluric signal may not be as reliable. The survey may have to be repeated if the logs are not correlatable. This often happens when a cold front is passing through the area, or when lightning and thunder become a factor. When there is a question about signal quality, a proposed drill site should be surveyed a second time to insure optimum environmental

conditions.

As previously mentioned, to gain full value from using the Petro-Sonde, the Petro-Sonde survey should be preceded by a well-documented geologic survey outlining the geologist's projected structural relationships and his feel for the variations in the depositional environments involved. Only in that format does the geologist have any way of checking on the validity of his geological logic! Dipmeter data is extremely valuable. The geologist should be knowledgeable of any steeply-dipping stratigraphic intervals suggesting drape over vertical faults. That is because the Petro-Sonde can also be used to solve 3-point problems in that interval. In reality, the Petro-Sonde tool can be used in the same manner that a field geologist utilizes a Brunton Compass.

In some areas, improved capillarity of oil-bearing sands and siltstones may represent a major challenge to the geologist relying on the Petro-Sonde. This improved capillarity within the reservoir may well log as being oil productive with the Petro-Sonde, but the reservoir may still be limited. This is particularly true when one is mapping pods of porosity within delta systems, such as in crevasse splays, point bars, barrier beaches and meander belts. Although greater porosity may be accompanied by an improved permeability, that is not always the case. Siltstones often have good porosity but little permeability, and thus they may well be too tight to produce commercially, even if oil bearing. That is why it really is best if a Petro-Sonde operator is able to calibrate with both an actual producer and a dry hole during the survey.

Oil source rocks with nominal porosity, such as the lower Mississippian Woodford shale, often log as being oil productive on a Petro-Sonde log, but they seldom produce. In addition, silty beach-sand bodies saturated with hydrocarbons may also log as being oil productive on a Petro-Sonde log, but still lack sufficient permeability to produce commercially. The most dependable oil-filled porosity readings come from caverns formed in karsted carbonate reservoirs. There, the Petro-Sonde will be logging 100% oil-filled porosity. Indications of gas-filled reservoirs are less compelling. Where thick oil columns are encountered, the lower permeability rocks in the section will often log as being wet. It also has been noted that caverns in the karsted Ellenburger dolomite often log as being oil productive, even after the Ellenburger oil has already been watered out. In some instances there may well be some critical data that may be worthwhile having a second survey validate.

The company geologist should expect to be responsible for the correlating of the Petro-Sonde-- logs with the electrical logs. This is why it is recommended for him to layout linear cross sections ahead of time. On the larger multi-pay structures, one usually ends up with several horizontal oilwater contacts. As with any field, an "experienced" user will normally be able to obtain a much more satisfactory picture of the subsurface conditions.

The quantity and quality of calibration well logs are very important parameters for a successful electrotelluric survey. While an electrotelluric log can be generated anywhere and for any depth, a single electrotelluric log may well be meaningless without the proper calibration with existing electric logs. Each lithologic signature should be properly correlated and identified with a known lithology. On inferior prospects, one may commonly find oil zones and water zones sitting at the same subsea levels, which may be reflecting variable reservoir capillarity. One should be very chary about drilling those kinds of prospects. It is best to obtain and properly identify electrotelluric signatures of the target formation from several producers and dry holes, if that is at all possible. This allows the signature range to be modulated. Without applying any depth corrections, depth errors up to 50' are to be expected with this tool, as a result of the diurnal fluctuations and changes in the earth's resistivity from one location to the other. As a consequence, very low relief features (e.g. 20' closure) are risky to justify searching for with the Petro-Sonde. A greater number of stations are recommended for those kinds of low-relief prospects.

Certainly, it is also important that calibration wells be re-logged several times during the day in order to permit the proper diurnal variation depth corrections to be made. One has to accept that the Petro-Sonde is very much an averaging tool, and experienced users are hesitant to recommend drilling a proposed drillsite where the Petro-Sonde data was gathered only one time within a single day. The cost of double checking a proposed drillsite location with additional confirmation stations only amounts to a few dollars as compared to the cost of actually drilling a well. By being very cautious, one may well reduce the risk of a dry hole by half.

The length of the vertical window is another critical parameter. Most users tend to log too small an

interval in an attempt to minimize the tool charge, but that may compromise the survey. The vertical window should include the formation of interest and enough other section to help identify the relative position of the potential pay zone within the window, and also to allow some room for dip and possible depth shifts as a result of the diurnal variation. In most cases the window size will be from 250 to 750 vertical feet. It works best when the window contains both oil-filled and water-filled porosity. This permits better differentiation of the oil saturations. This is no time to be penny wise and pound foolish!

Finally, the spacing between the stations will establish the lateral resolution of the survey. Closer spacing will not only help in monitoring small changes within the lithology, but will greatly reduce the chance of incorrect correlation. It is important to note that whenever correlation problems occur in an electrotelluric survey, they can usually be traced to spacing stations too far apart. As the spacing distance increases, it becomes more difficult to be certain of the correct correlation. In a way, it is like spacing seismic geophones. A shallow seismic survey would have little significance if the distance between geophone traces were 1,000 feet! Correct station spacing is a most critical factor for the success of the telluric survey, and its importance increases if the field geologist has not fully researched the prospect. Spacing will vary based on geologic conditions. However, proper spacing usually ranges from 100 to 660 feet. It is recommended that the company geologist first solve some 3-point problems in the area of his control wells, in order to check the authenticity of his structural grain to start with. It is always gratifying when the dip and strike conforms to your contours.

While telluric surveys are capable of offering an unparalleled amount of information regarding the subsurface (reservoir presence, fluid type, relative porosity, depth, lithology thickness, etc.) they are sometimes compromised due to their reliance on an uncontrollable energy source, which is compounded by the effects of adverse environmental factors. In achieving the true capabilities of an electro telluric survey, understanding the parameters affecting the survey and proper applications are important for the survey's success, and this comes mainly from experience in the field. The Petro-Sonde is capable of supplying the geologist with both an abundance and accuracy of information that often no other geophysical tool is able to offer.

Dr. Elam specializes in the search for fields below 20,000'. In the recent past, several of what were the deepest wells in the world at the time they were drilled were his prospects. After about 35 of these deep wildcats were drilled, many of which had both seismic and Petro-Sonde control, it became very apparent that at these super depths the Petro-Sonde structure was validated more frequently than the seismic structure. The major oil companies are just now starting to institute 3-D seismic programs to compensate for seismic's poor record at these extreme depths. At the same time, it is suggested here that when wells cost many millions of dollars each, using both tools in tandem may well save millions of dollars.

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