New Logging Technology
Brings New Perspective
To Mature Oil Fields

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BAKERSFIELD, CA.—A new petrophysical measurement is casting new light on residual oil, especially in heavy crude deposits in such areas as the San Joaquin Basin in California. One might reasonably conclude that the San Joaquin Basin was reaching the end of its productive life, and few would have argued the point, because while the basin is California’s most prolific oil producer, it was discovered more than a century ago and heavy crude deposits have largely been off the industry’s radar screen for much of the past decade.

However, with strong crude oil prices relative to natural gas on a Btu equivalent basis, operators are taking a fresh look at mature oil provinces from the San Joaquin to the Permian Basin. It is a new day for these mature assets, and thanks to the ability to precisely measure the dielectric permittivity parameter, the industry is getting a whole new perspective on mature and heavy oil fields.
Defined as the ability of an electromagnetic field to penetrate geological formations, dielectric permittivity has been measured by various logging devices for 30 years. The measurement’s big advantage was its ability to discriminate hydrocarbons in the presence of fresh water, and that single factor made the measurement ideal for San Joaquin Basin sands, many of which had low-gravity crude interspersed with waters of less than 20,000 parts per million total dissolved solids.

Early-generation dielectric tools had limitations. The principle problem was that the tools were unable to produce accurate information in washed-out or rugose bore holes.

Many California reservoirs consist of unconsolidated sandstones that have a tendency to wash out when they are drilled. In addition, many of the heavy oil fields in the region have been produced using steam flood techniques. This has created a double problem: The steam condensate had a different salinity than the native formation waters, and the steam injection caused nonlinear geothermal gradients. The early mandrel tools had difficulty in providing sufficient accuracy to produce quantifiable interpretations.

A second, more perplexing, problem was a parameter known as dispersion. This refers to the nonlinear relationship of resistivity measurements depending on the frequency of the emitted measurement signal. Legacy electromagnetic permittivity devices such as the electromagnetic propagation tool emitted a single frequency of 1.1 gigahertz, which made it impossible to accurately characterize dielectric dispersion. And since the radial depth of investigation of the tool is frequency-dependent as well, it could not be determined how deep the measured signal was looking if resistivity was unknown.

Notwithstanding these limitations, the dielectric permittivity tool became a standard part of the logging suite used by most San Joaquin operators for many years.

New Measurement

A completely new petrophysical measurement has been introduced that is able to acquire high-resolution measurements that accurately determine oil saturation irrespective of clay content, water salinity, oil viscosity and marginal bore hole conditions. At the heart of the tool is an articulated bore hole-compensated transmitter/sensor pad that can negotiate rugose hole profiles.

As shown in Figure 1, the new tool makes nine multifrequency, bore hole-compensated measurements of phase shift and attenuation from an articulated skid that hugs the bore hole wall. Located in the pad are two electromagnetic transmitters capable of broadcasting at four frequencies, ranging from 20 megahertz to 1 gigahertz, and at two axial orientations. Two arrays of four receivers bracket the transmitters and allow radial formation fluid profiling at four spacings. In some cases, vertical resolution of 1.0 inches can be achieved for evaluating extremely thin formation laminations. The tool is able to perform in both water-based and oil-based mud systems.

A close look at the pad architecture reveals that each transmitter and receiver consists of orthogonal crossed dipole antennae. In addition, two electric dipoles are oriented perpendicular to the pad surface just outside the transmitters. These are used in propagation mode in conjunction with the transverse magnetic dipole transmitters. One measures the properties of the mud cake immediately in front of the pad. Both are used for quality control when the logging data are interpreted.

Transmitter and receiver dipole orientation is longitudinal, parallel to the tool’s axis, or transverse, at right angles to the tool’s axis. The antenna array makes nine separate auto-calibrated, bore hole-compensated measurements. They are symmetric, and the measurements include both phase shift and attenuation. A complete measurement is defined as the amplitude ratio and phase shift measured at a specific receiver with respect to the signal from transmitter A versus the same properties measured with respect to the signal emitted from transmitter B.

Rich Data Set

A rich data set is generated because of the four frequencies emitted from the transmitters plus the four radial depths of investigation afforded by the combination of different transmitter/receiver spacings and transmission frequencies, with the lower frequencies propagating deeper into the formation. Bore hole compensation is achieved by the symmetric combination of the array measurements.

**FIGURE 1**

Multifrequency Dielectric Dispersion Tool Configuration
In the petrophysical world, there exist four classic “zones about the bore hole:” the mud cake, the flushed zone, the transition zone and the virgin formation. One advantage of varying radial depths of investigation is the ability to develop a radial resistivity profile that can be related to fluid mobility. In heavy oil, the depth of invasion is frequently shallow and the measurement easily reaches the virgin zone. On the other hand, in water zones, mud filtrate can invade more deeply because of the higher mobility of the water compared with that of the heavy oil. As a result, the electromagnetic and geometric parameters can be related, allowing invasion profiles to be derived irrespective of fluid salinity (resistivity).

Since the multifrequency dielectric dispersion tool makes its measurements at four frequencies, the dispersion pattern can be characterized using a curve-fitting technique. In carbonates, the shape of dispersion is a function of two key factors: the cementation factor and the saturation exponent. These factors are unknowns in the Archie saturation relationship, and for more than half a century, have affected the accuracy of saturation determinations. These characteristics are referred to as rock textural parameters, and heretofore have not been possible to measure except in a laboratory. Similarly, in shaly sand, the dispersion measured is a function of the shale volume, which is a key input in shaly sand saturation equations.

### Lots Of Remaining Oil

In the heavy oil sands of the San Joaquin Basin, typical recovery ranges from 20 to 40 percent. This means that despite years of aggressive steamflooding, over half of the original oil in place remains to be produced. The problem is that the oil zones are concealed by freshwater zones. A standard triple combo log had been used, and because of the extremely low contrast between the resistivity of oil-filled pores and those saturated with fresh water, it was difficult to differentiate between pay zones and wet zones, and consequently, to decide which zones to complete.

Typically, Kern River sands are unconsolidated fluvial deposits interrupted by silts and clays. Production has been found as shallow as 50 feet and as deep as 1,600 feet. Average porosity is 31 percent and permeability ranges from 500 to 10,000 milliDarcies. Oil with an API gravity of 12-13 degrees occurs in a saturation range of 20 to 50 percent. Steamflooding commenced in the 1960s to enhance production of the heavy crude. Today, about 9,600 Kern River wells produce a total of 77,000 barrels of oil a day. Kern River cumulative production reached the 2 billion barrel mark in 2007.

In the Kern River oil field, Chevron has been challenged primarily to differentiate oil sands from freshwater sands, and secondarily to find bypassed oil in steamflooded zones. Original formation water salinity was less than 2,000 parts per million, but because of a half century of steamflooding, it is now considerably fresher. As a result, techniques for determining water saturation using resistivity are unreliable.

The company acquired conventional cores as well as sidewall cores, and attempted to resolve the issue of fluid contacts and mobility using laboratory core analysis. Although accurate, this technique was both costly and time consuming. Carbon-oxygen (CO) logging performed after casing was set did a reasonable job of determining oil saturation, but was limited to beds more than 18 inches thick at best.

When the new Dielectric Scanner™ multifrequency dielectric dispersion logging tool was added, the hydrocarbon-bearing zones were clearly indicated, making it easy to select interval perforations. As shown in Figure 2, the multifrequency dielectric dispersion measurement clearly enables interpretation of the hydrocarbon zones from X,260-X,280 feet and X,410-X,440 feet in Track 5. The standard triple-combo log was overly optimistic, showing freshwater zones as potentially productive.

### Cymric Field

The Cymric Field lies to the west of the Kern River Field in the foothills of the coastal range. It is also a heavy oil producer enhanced by steamflooding. The new dielectric tool was run to evaluate the Tulare formation, which is a poorly consolidated fluvio-deltaic sandstone bounded by shale. Reservoir depths range from 700 to 1,200 feet. Porosity averages 34 percent, and permeability ranges between 2,000 and 3,000 milliDarcies. Oil saturations run from 55 to 65 percent and API oil gravities are between nine and 14 degrees.

The challenge was to profile the heavy oil response in spite of the presence of fresh formation water and steamflood condensate. The basic logging suite included a triple combo. In addition, the legacy electromagnetic propagation tool had been run to determine water saturation and to compare with the new multifrequency dielectric dispersion tool. At the Cymric Field, Chevron had acquired several sidewall cores (indicated by black dots on the log tracks in Figure 3).

The saturation profiling in the Cymric Field illustrates the
limitations of resistivity and electromagnetic propagation logs in washed-out sections. Standard resistivity curves are in Track 1 of Figure 3, while hydrocarbon-filled porosity is shown in green in all tracks. The EPT log (Track 5) missed considerable pay between X,690 and X,710 feet and X,740-X,755 feet because of washouts.

In this case, bore hole rugosity played a role in the results. Wherever the caliper showed the bore hole to be washed out, only the new articulated sonde was able to maintain pad contact and render an accurate profile. The four frequency curves show the radial profile of invasion even in the washed-out zones, but the shallow resistivity log reads mud resistivity. Residual oil saturation, coded green on the logs, was underestimated in the washed-out zones, but was confirmed by core analysis to coincide with the new measurement results.

The new measurement correlates well with laboratory core analysis and CO logs, (although with 18 times better thin-bed resolution). When compared with standard triple combo logs, the dielectric tool correctly differentiates hydrocarbon-bearing zones from freshwater zones. When compared with legacy dielectric tools, the improved transmitter receiver array and bore hole compensation of the new dielectric tool design do a better job of successfully navigating significant rugosity and mud cake, which results in a much improved answer.

Finally, the application of dispersion corrections to the multifrequency data of the new dielectric tool results in several significant advantages over single-frequency electromagnetic propagation measurements; namely, the delivery of two measurements of water-filled porosity at different depths of investigation, enabling a much more definitive invasion analysis and the delivery of stable, reliable conductivity measurements that can be used for more advanced applications, such as rock textural analysis.

**FIGURE 3**

**Cymric Field Saturation Profiling**

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<th>Depth, ft</th>
<th>Caliper</th>
<th>2 MHz Resistivity</th>
<th>Residual Hydrocarbon</th>
<th>Oil</th>
<th>Core Water Saturation</th>
<th>Carbonate</th>
<th>Dielectric Scanner</th>
<th>Water-Filled Porosity</th>
<th>Total Porosity</th>
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