Log analysis of heavy oil reservoirs may be hampered by difficulties in distinguishing heavy oil from freshwater. A wellsite quicklook evaluation process that incorporates a multifrequency dielectric measurement is helping operators overcome this challenge.

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Movability Quicklook for Heavy Oils

Vast reserves of heavy oil have been discovered in more than 30 countries around the world. These resources, estimated at 890 billion m$^3$ [5.6 trillion bbl] of heavy oil and bitumen, make up a dominant share of the world's petroleum inventory. Though challenging to produce, heavy oils will become increasingly important as reserves of lighter oil inevitably decline.

Most heavy oil deposits originated as light- to medium-gravity oils formed at depth. These oils migrated upward and became trapped in shallower formations, where they were later degraded, chiefly through microbial action. Much of this degradation occurs near the oil/water contact; bacteria live within the aqueous region but do not thrive in oil. The bacteria metabolize paraffinic, naphthenic and aromatic hydrocarbons into heavier molecules. Chemical or physical processes may also be involved. These processes strip away lower molecular-weight hydrocarbons through preferential migration of lighter components, devolatilization and evaporation beneath leaky seals and washing by formation waters. As the lighter fractions are removed, only complex hydrocarbon compounds are retained, and heavy oil is formed.

Heavy oil has been defined variously as oil whose gas-free viscosity is between 100 cP and 10,000 cP [100 mPa.s and 10,000 mPa.s] at reservoir temperature or oil that is slightly less dense than water whose gravity ranges between 10 and 22.3 degrees API. Heavy oils are characterized by long, complex hydrocarbon molecules and are low in hydrogen; they are often high in carbon, nitrogen, sulfur or heavy metals.

The long hydrocarbon molecules impart high internal friction that results in increased viscosity. Because of its inherent resistance to flow, heavy oil requires specialized methods to produce it. These methods include waterflooding and steam injection to mobilize the oil or chemical treatments that alter wettability, lower viscosity and reduce interfacial tension. Central to developing an optimal recovery strategy is an assessment of the reservoir rock and the fluids contained within.

These assessments usually begin with a suite of logs, which the operator uses first to identify oil-bearing formations and then to ascertain which intervals are producible. The conventional approach to formation evaluation is based on computing water saturation from resistivity and porosity logs. The presence of hydrocarbons is generally indicated by high resistivity measurements in porous zones. By measuring the porosity of the rock and determining the percentage of pore volume saturated by water, geoscientists can then infer the remaining percentage of pore space that is saturated by hydrocarbons.

However, this technique is ineffective for determining hydrocarbon saturation in reservoirs containing formation waters of low or unknown salinity; heavy oil reservoirs, typically found at shallow depths, tend to contain relatively freshwater. Freshwater, like oil, is a poor conductor of electricity. Conventional resistivity tools exhibit high resistivity through oil zones and through low-salinity water zones, causing oil-bearing intervals to be indistinguishable...
from those containing freshwater. Assessment of heavy oil reservoirs may be further complicated by difficulty in distinguishing producible oil from oil that is not movable. Conventional resistivity and porosity logging suites do not measure the movability of heavy oil within a formation. This article describes how operators in California, USA, use Dielectric Scanner measurements in a wellsite quicklook evaluation to identify intervals containing movable heavy oil.

A Different Approach

Heavy oil reservoirs often require operators to look beyond conventional logging suites for determining oil saturations and movability. Dielectric permittivity, the ability of an electromagnetic field to permeate a formation, has been measured by various logging devices since the 1970s. A dielectric measurement can distinguish between oil and water of low or indeterminate salinity using the contrasting dielectric properties of oil and water. Dielectric tools have a shallow depth of investigation and thus analyze the flushed zone surrounding a wellbore—that part of the formation invaded by drilling fluid filtrates, which have partially or completely displaced the original formation fluids. Because the movable fluids have been flushed, the dielectric measurement evaluates the filtrate plus any residual fluids that have not been flushed by the invading filtrate. In wellbore intervals that experience very little invasion, the oil saturations of the flushed zone and deeper uninvaded zones are nearly equal, thus making the shallow dielectric measurement useful for inferring saturation values of the uncontaminated zone within heavy oil reservoirs.

The Dielectric Scanner multifrequency dielectric dispersion service uses multiple frequencies, polarizations and transmitter-receiver spacings to acquire dielectric permittivity and conductivity measurements at four depths of investigation. This logging technology isn’t new—it has been used extensively since its introduction in 2010 as an improvement over the EPT electromagnetic propagation tool. However, the development of a versatile quicklook analysis process takes advantage of multiple depths of investigation to help operators evaluate heavy oil reservoirs.

Through rapid analysis of logging data at the wellsite, operators obtain information needed to determine whether to complete an interval, condemn it or investigate further using sidewall coring or other techniques. In some instances, this quicklook analysis has identified where to shoot sidewall cores that later confirmed the presence of producible oil.

Sensors and Measurements

Dielectric measurement technology has evolved substantially since the introduction of the EPT electromagnetic propagation tool, which has only a single depth of investigation and single frequency. The Dielectric Scanner tool makes nine separate autocalibrated, borehole-compensated measurements. These measurements include phase shift and attenuation. Unlike some dielectric tools, the Dielectric Scanner tool can be run in both water-base and oil-base mud systems.

The tool uses an articulated pad that can move freely in three dimensions, which enhances borehole contact for measurements in rugose hole conditions (Figure 1). Two electromagnetic
transmitters in the middle of the pad are bracketed by two arrays of four receivers in a symmetrical configuration. Each transmitter and receiver consists of orthogonal crossed dipole antennae. The transmitters broadcast along two axial orientations at four frequencies ranging from 20 MHz to 1 GHz; the lower frequencies propagate deeper into the formation. The receiver arrays take advantage of four transmitter-to-receiver (T-R) spacings to record dielectric permittivity measurements. In some cases, vertical resolution of 2.5 cm [1.0 in.] can be achieved for evaluating thin formation laminations.

**Quicklook Evaluation**

In most wells, the first suite of logs run in the hole helps operators assess the formation and determine whether further evaluations are warranted. In addition to gamma ray, resistivity, spontaneous potential and caliper tools, this suite often includes neutron porosity and bulk density tools. The neutron porosity and bulk density measurements are useful in determining total porosity. In heavy oil wells, this initial suite is sometimes run in conjunction with the Dielectric Scanner tool, which measures the water-filled porosity of reservoir rocks. By comparing the total porosity measurements with water-filled porosity measurements, the operator can calculate water saturation in the flushed zone of the formation.

Figure 2. Oil crossover response. In the presence of oil, the water-filled porosity curve of the dielectric measurement (Track 3, blue) will read lower than the total porosity curve derived from the density-neutron measurements (black). This separation creates a readily identifiable crossover response for distinguishing oil from water. (Adapted from Hizem et al, reference 3.)

Figure 3. Porosity track of the quicklook presentation. Variations in the saturation profile are generated by comparing total porosity from the density measurement with water-filled porosity measurements from the Dielectric Scanner tool. Separation between density porosity and four dielectric measurements (T-R1 to T-R4) obtained at depth of investigations (DOIs) of approximately 2.5 cm, 5 cm, 7.5 cm and 10 cm characterize the depth of invasion and, by extension, the movable oil saturation in the formation (top). Dielectric curve separations indicate depth of invasion and show how oil saturation varies within the 10-cm maximum DOI region of the tool (bottom). If the T-R3 and T-R4 curves read the same but are separated from T-R1 and T-R2 curves (yellow oval), the invasion depth is less than 10 cm. Where the T-R3 and T-R4 curves separate, invasion has flushed oil within the 10-cm DOI and possibly farther. If all four dielectric curves are separated from each other (green oval), the mud filtrate has swept deeper than 7.5 cm and probably deeper than 10 cm. In the event that all four curves overlie, the oil saturation is unvarying within the 10-cm DOI. An alternate interpretation when the four curves overlie is of an oil-bearing zone that has been fully flushed and is at residual oil saturation. (Adapted from Grayson and Hemingway, reference 4.)
A wellsite quicklook application uses this porosity comparison to differentiate between intervals containing water or heavy oil. At its foundation is an analysis process originally used in conjunction with the EPT tool, which also compared total porosity with water-filled porosity. Across water-filled intervals, the neutron-density total porosity curve will overlie the dielectric water-filled porosity curve; conversely, in intervals containing oil, these curves will diverge. The dielectric tool measurement is insensitive to oil, so as the curves separate, the water-filled porosity curve will read lower than the total porosity curve. This response produces an “oil crossover” indicator, allowing for easy identification of pay at the wellsite, regardless of formation water salinity (Figure 2). The amount of separation is proportional to the oil saturation in the flushed zone of the near-wellbore region.

In heavy oil and low-permeability reservoirs, if oil is not flushed by mud filtrate while drilling, the porosity comparison provides a quantification of water saturation ($S_w$) deeper within the formation in the undisturbed zone surrounding the wellbore. When oil movement has occurred, however, the operator must be able to assess the depth and extent of flushing. This capability was not provided by tools that had only a single depth of investigation.

By measuring across four depths of investigation, the Dielectric Scanner tool is able to create a saturation profile across the flushed zone. The resulting quicklook presentation shows a total porosity curve derived from the bulk density measurement along with four dielectric measurements of water-filled porosity taken at 1-in. [2.5-cm] intervals spanning approximately 1 to 4 in. [2.5 to 10 cm] into the formation.

The oil saturation profile reflects oil movement resulting from the invasion process. By examining the relative change of oil saturation in the flushed zone, analysts can evaluate oil movability (Figure 3). In zones characterized by low oil movability, the saturation profile curves will overlie one another. Conversely, if oil is seen to move within the flushed zone, the curves will separate.

Movability in a formation is influenced by a variety of factors that affect the capability of an invading fluid to displace oil within a formation. The differential between the formation pressure and the pressure exerted by the mud column drives the mud filtrate into the formation. Formation porosity and permeability impact the quantity of filtrate and the maximum flow rate that can be achieved through the rock. Mud properties affect the development of mudcake, which eventually forms a barrier to prevent further filtrate invasion. Formation characteristics, such as pore size, the wettability of the rock face and the viscosity of the oil, influence how easily the oil will be displaced by the filtrate. The quicklook shows the effects of these factors.

**Field Applications**

Diatoms, microscopic algae that have silica-rich cell walls, have existed since the Cretaceous Period. In some basins, the remains of ancient diatoms form a sedimentary rock called diatomite, which can make an excellent reservoir rock. In California, cyclic steam injection is being used to produce 13 degree API gravity heavy oil from a diatomite reservoir. At one lease, a well was drilled prior to initiation of steam injection in this portion of the field. However, because the well is situated close to a lease line, the operator wanted to determine whether the well would be affected by thermal stimulation carried out by a neighboring operator in an adjacent section of the field. Given that the salinity of injected water usually differs from that of native waters in the reservoir, the operator had concerns about how injection water might affect the resistivity response in the usual triple-combo logging suite. Therefore, the operator also obtained a Dielectric Scanner log to supplement the formation evaluation program (Figure 4).

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The separation between the dielectric curves illustrates a drastic change in oil movement over a very short interval at Y15 ft. Where significant flushing of the oil is seen, data from the temperature sensor in the tool pad show that the maximum temperature coincides with the zone of enhanced oil movability. This coincidence supports the idea that the steam stimulation by the offset operator has contributed significantly to enhanced production. Other wells drilled in the field, located farther from the lease line, do not show these responses.

Sidewall core analysis, a routine part of many well evaluations, may also serve to emphasize the impact that heavy oil movability has on oil saturation measurements. Oil movability will affect the capability of filtrates to flush oil from the pore space of rock in the near-wellbore region and can create a measurable effect on the saturation of the rock. In low-movability zones, oil saturation in sidewall cores (SWCs) is relatively unaffected by flushing. In high-movability zones, flushing reduces the oil saturation measured in SWC samples.

Percussion sidewall cores are typically acquired in heavy oil reservoirs and used by geologists to estimate porosity, oil saturation and oil gravity. Depending on rock strength and bullet design, most SWC bullets will penetrate the formation to a depth of about 2.5 cm [1 in.]. After the core bullets are retrieved to the surface, they are sent to a laboratory for analysis. These analyses may provide input for calculating field reserves.

Because the dielectric oil-movability quicklook provides a wellsite indication of oil flushing, it can be a valuable tool for selecting depths from which to obtain SWC samples that are more representative of actual saturations. Where oil movability is low and no flushing is seen on the dielectric quicklook log, SWC saturations should accurately reflect the oil saturation in the zone (Figure 5).

By contrast, in zones of higher movability, the oil will be flushed away from the near-wellbore region, where an SWC bullet acquires the rock sample. In this case, the oil saturation derived from the SWC analysis will be lower than the actual oil saturation of the zone and the 2.5-cm and 10-cm dielectric curves of the quicklook presentation will be separated. The oil saturation obtained from the 2.5-cm dielectric curve should reflect the saturation seen in the core; however, the saturation from the 10-cm curve will reflect the actual oil saturation of that interval if the invasion has not extended to 10 cm into the formation (Figure 6).

Using the oil saturation invasion profile through the 10-cm depth of investigation, the operator can place sidewall cores in optimal locations where minimal flushing has occurred. But where cores have already been obtained, the core-derived oil saturations may be complemented or sometimes replaced by oil saturation values derived from the combination of dielectric and triple-combo log measurements. Log-derived oil saturations, measured continuously over the entire zone of interest, have an advantage over...
those obtained at discrete sample points by sidewall cores. The quicklook log has been used to identify zones affected by flushing, where core-derived oil saturations are suspect (Figure 7). One operator’s pessimistic core evaluations, previously used in reserve calculations, were later discounted after the quicklook log showed the effects of flushing, resulting in an increase in booked reserves. This experience demonstrated the importance of using the deepest-reading measurement for fluid saturation when flushing is identified, especially when calculating reserves. It also shows the value of identifying flushing before shooting sidewall cores to ensure that representative samples are acquired.

The Dielectric Scanner multifrequency dielectric dispersion service helps operators readily distinguish hydrocarbon zones from freshwater zones. The oil-movability quicklook analysis gives geoscientists broader insight into variations of permeability, oil saturation and viscosity in heavy oil reservoirs. The ability to identify flushing can help operators improve petrophysical evaluations, especially when calculating reserves. The quicklook oil saturation profile provides a straightforward observation of oil movability variations and can help operators optimize completion strategies by providing information at the wellsite to show zones of higher movability within a formation.

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Figure 7. High productibility potential contrary to sidewall core (SWC) analysis. The Dielectric Scanner measurement results (Track 3) indicate a potentially productive zone that SWC analysis failed to identify. Points A, B and C were sampled with SWCs, which were then analyzed. Laboratory analysis of SWC oil saturation yielded 39% at Point A, 35% at Point B and 34% at Point C. The quicklook log through this diatomite heavy oil reservoir showed oil flushing at Point B but no flushing at Points A and C. Oil-saturation curves derived from the T-R1 and T-R4 dielectric measurements are identified in Track 1. When flushing takes place, as at Point B, higher oil saturations are indicated by the deepest-reading (T-R4) dielectric curve. Where no flushing is observed, saturations from the T-R1 and T-R4 curves read the same. The movability of oil observed at Point B indicates a zone having either higher permeability or having oil of lower viscosity than the adjacent zones. Although SWC oil saturation at Point B was 35%, the T-R1 measurement shows 42% oil saturation and the T-R4 measurement shows 69%. (Adapted from Grayson and Hemingway, reference 4.)