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Some Applications of the Combined Use of Cure Analysis and Electric Log Data

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Abstract: Values of critical water saturation determined from core analysis may be used in combination with electric log data to assess whether or not hydrocarbon bearing zones will produce water-free or at an uneconomically high water-cut. Theoretical examples as well as case histories are included.

INTRODUCTION

Even though accurate assessments of water saturation, and thereby hydrocarbons-in-place, may be derived from electric logs, it does not necessarily follow that a reliable assessment of pay zones can be made on the basis of log data alone. For example, zones showing an apparent water saturation of greater than 50 percent traditionally often receive no further consideration for testing or production. However, water-free oil production has been recorded in sands where the apparent water saturation is as much as 70 percent (Vajnar *et al.,* 1977).

One way to assess whether or not hydrocarbon bearing zones are potentially productive is to determine values for critical water saturation which can be defined as the formation water saturation that must not be exceeded if hydrocarbons are to be produced water-free or at a low water-cut.

Critical water saturations may be derived from core analysis data. By integrating these values with laboratory-derived electrical properties of the formation rock it is possible to produce a curve for critical resistivity or minimum productive resistivity, Rmp. The true formation resistivity (Rt) must not fall below the Rmp if hydrocarbons are to be produced water-free or at a low water-cut.

With transparent film, a calculated Rmp curve can be used to overlay the deep resistivity log to quickly identify potential pay-zones. The Rmp curve can be put to best use as part of a full CoRes Log (Granberry & Tucker 1973) whose construction and use is discussed below.

USE OF CORE DATA TO CONSTRUCT CoRes LOG

Figure 1 illustrates one method (Keelan, 1972) of deriving critical water saturations for calculation of Rmp. An oil-bearing formation is assumed. To facilitate description of the procedure, fewer samples are shown than are normally required to determine definitive critical water saturations for a given formation.

Initially, plug-size samples are drilled at regular intervals (every 1 ft or 0.25 metres, for example) from the conventional core taken from the formation of interest. After sample preparation, routine measurements of permeability to air and porosity are made and the values plotted (Figure 1A). Representaative samples are chosen for further testing (sample A, B and C).

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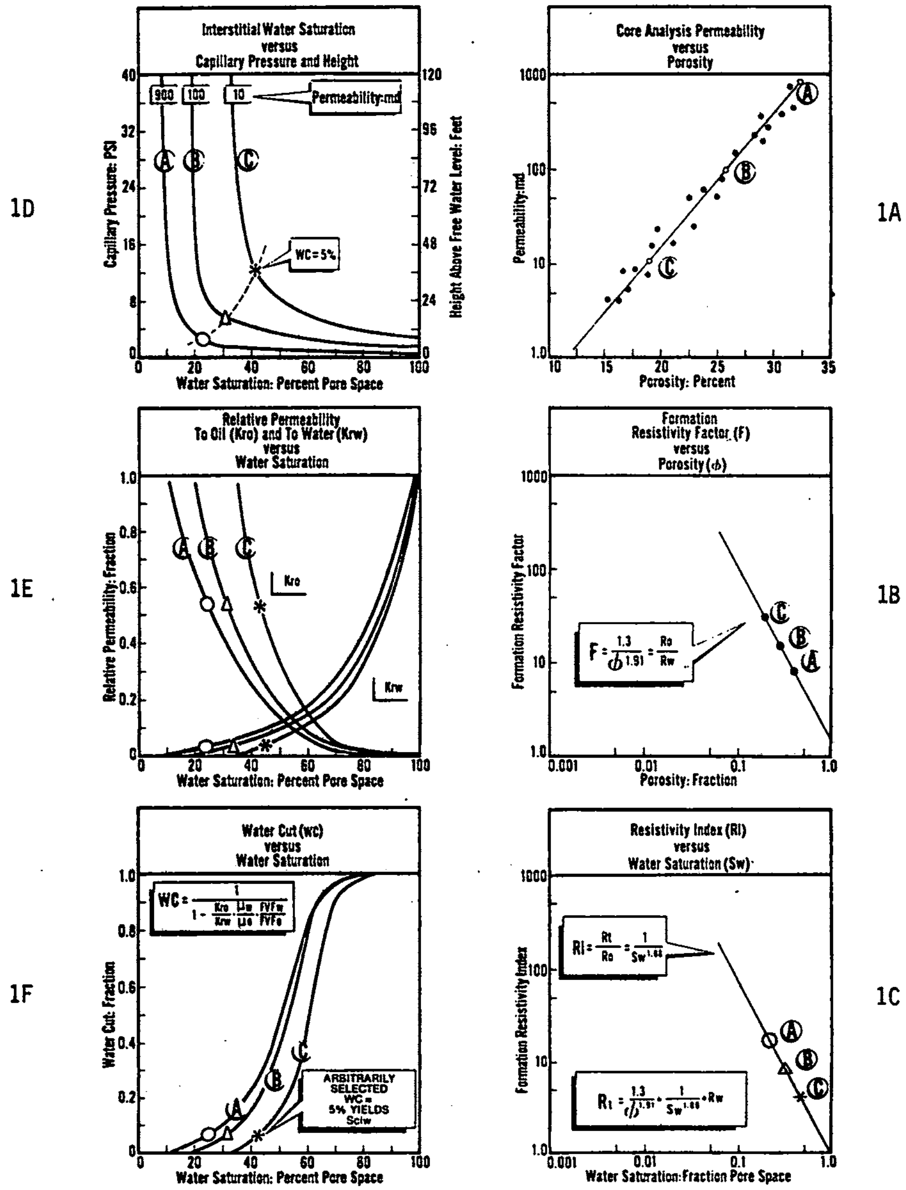

Reference: SPE 4160
Keelan, Dare: "Core Analysis Techniques and Application", Paper Presented at Columbus, Ohio SPE Meeting (Nov. 8-9, 1972)

Figure 1: Relationship of core analysis and special core analysis data.

The representative samples are next saturated with simulated brine and electrical resistivity measurements made to determine values of "a" and "m" (1.3 and 1.91 respectively in Figure 1B).

Each sample is then desaturated at incrementally increasing pressures in a porous-plate cell and electrical resistivity measurements made on the partially saturated cores to derive a value of "n" (1.88 in Figure 1C).

At each incremental pressure, water saturations in the cores are calculated and plotted (Figure 1D) and capillary pressure values converted to height above free-water level. For example, if rock sample C of 10 md permeability occurred at 24 ft above the free-water level, a 52 percent water saturation would be expected.

Upon completion of capillary pressure tests, the samples are subjected to oil-water drainage relative permeability tests (Figure 1E) and the data plotted as water-cut curves using fractional flow equations (Figure 1F). An arbitrary cut-off of 5 percent water-cut has been selected and plotted on the fractional flow curves to yield critical water saturations for the three representative plugs as follows:

SAMPLE NO	PERMEABILITY MILLIDARCIES	CRITICAL WATER SATURATION, PERCENT
A	900	23
B	100	32
C	10	42

As would be expected, the higher the permeability, the lower the critical water saturation. Therefore, whenever rock-type C, for example, occurs in the reservoir, it should produce at 5 percent water-cut or less when the water saturation is 42 percent or lower.

Extension of these critical water saturation values to Figure 1D show that, for example, rock of 10 md permeability would exhibit water saturation values at or below critical when occurring 36 ft or higher above the free-water level. Thus, if 10 md rock were perforated at less than 36 ft above the free-water level, oil would be produced at a water-cut higher than the previously imposed economic limit of 5 percent.

Once critical water,saturations have been correlated as a function of permeability and/or porosity, values can be assigned to each and every core plug initially taken for routine analysis (Figure 1A). If core material is not available throughout the zone of interest, a correlation could be made between the downhole porosity logs and the available core data so that critical water saturations could be assigned on a point-basis throughout the formation under investigation.

Now consider the re-arranged Archie equation shown in Figure 1C. If values of Sciw (critical water saturation) are used, values of Rmp can be, generated:

$$\mathrm{Rmp} = \frac{1.3}{\text{Ø}^{1.19}} \cdot \frac{1}{\mathrm{Sciw}^{1.88}} \cdot \mathrm{Rw} \qquad (1)$$

In a more general form, the equation can be written as follows:

$$Rmp = \frac{a}{\text{Ø}^{m}} \cdot \frac{1}{Sciw^{n}} \cdot Rw \qquad (2)$$

Calculation of Rmp is not limited to the fundamental Archie equation. Shaly sand equations can also be used. For example the Waxman-Smits-Thomas (Waxman & Smits, 1968; Waxman & Thomas, 1974).

$$Rmp = \frac{a^{*}}{\text{Ø}^{m^{*}}} \cdot \frac{1}{Sciw^{n^{*}} \, (1 + Rw \cdot B \cdot Qv / Sciw)} \cdot Rw \qquad (3)$$

Thus, a critical resistivity (or minimum productive resistivity) curve can be generated. The example CoRes Log shown in Figure 2 includes not only an Rmp curve but also a calculated Ro curve that is, the anticipated log response from the formation if it were 100 percent water-saturated throughout. When these curves are used to overlay the downhole deep resistivity log, the Ro curve will then be used to identify oil (or gas) bearing zones and the Rmp be curve will indicate if these zones can be produced at little or no watercut.

Permeability data are included for more extensive interpretation as described below.

THEORETICAL EXAMPLE (Core Laboratories, 1977)

Figure 3 shows a construction of a dual induction laterolog with various zones of interest (4-8). Figure 4 shows this same log with a CoRes Log overlay constructed with the assumption Rw equals 0.01 ohm-meters. Points illustrated are:-

1. Ro From Core Data: the curve representing 100 percent water saturation.

2. Rmp From Core Data: this curve reflects changes in lithology and permeability and yields the minimum log resistivity required for hydrocarbon production at little or no water cut. The overlay of these two curves permits correlation of core depths with log depths by vertical alignment of characteristic resistivity changes. An 11 ft depth discrepancy is illustrated..

3. CoRes Log Reference Line: the one ohm-meter reference line provides an easy way to adjust the overlay to actual reservoir Rw. The reservoir Rw value is multiplied by 100 and the one-ohm meter reference line shifted to this value. Here Rw is 0.04 ohm-meter, and so the reference line is placed at 4.0 ohm-meter on the log.

4. Productive Zone Identification: A decrease in resistivity in the two core analysis calculated curves and a similar decrease in the deep recorded log resistivity curve between 14236' and 14246' reveals an increase in porosity, but no increase in formation water saturation. Since the formation resistivity far exceeds the calculated Rmp, this zone should be water-free to the base.

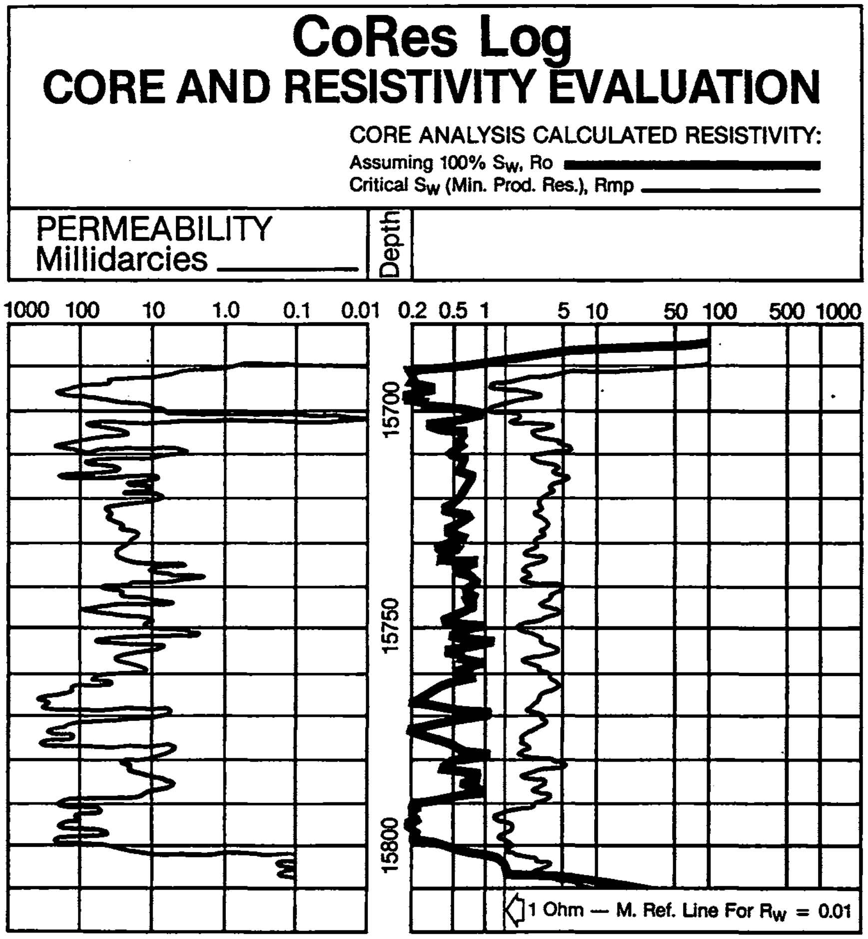

Figure 2: Typical CoRes Log.

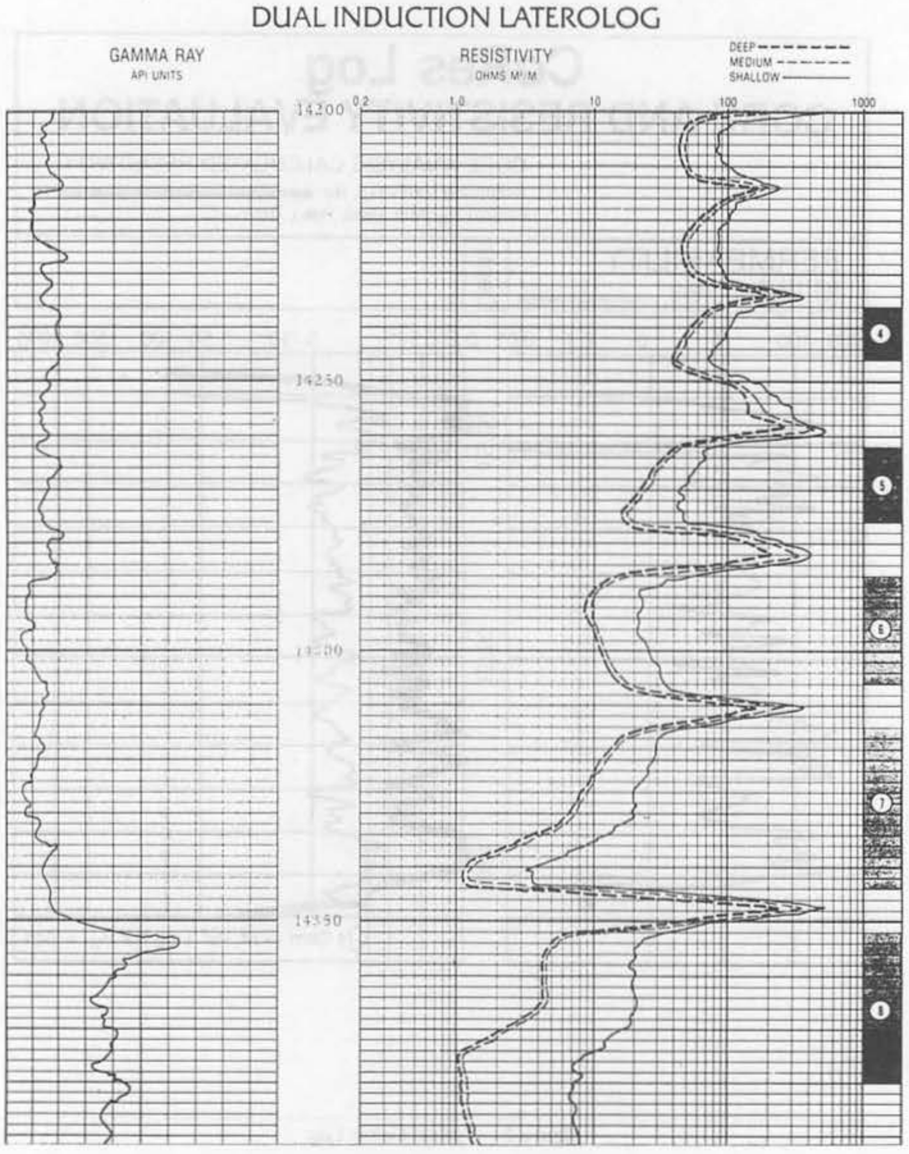

Figure 3: Downhole resistivity log – theoretical.

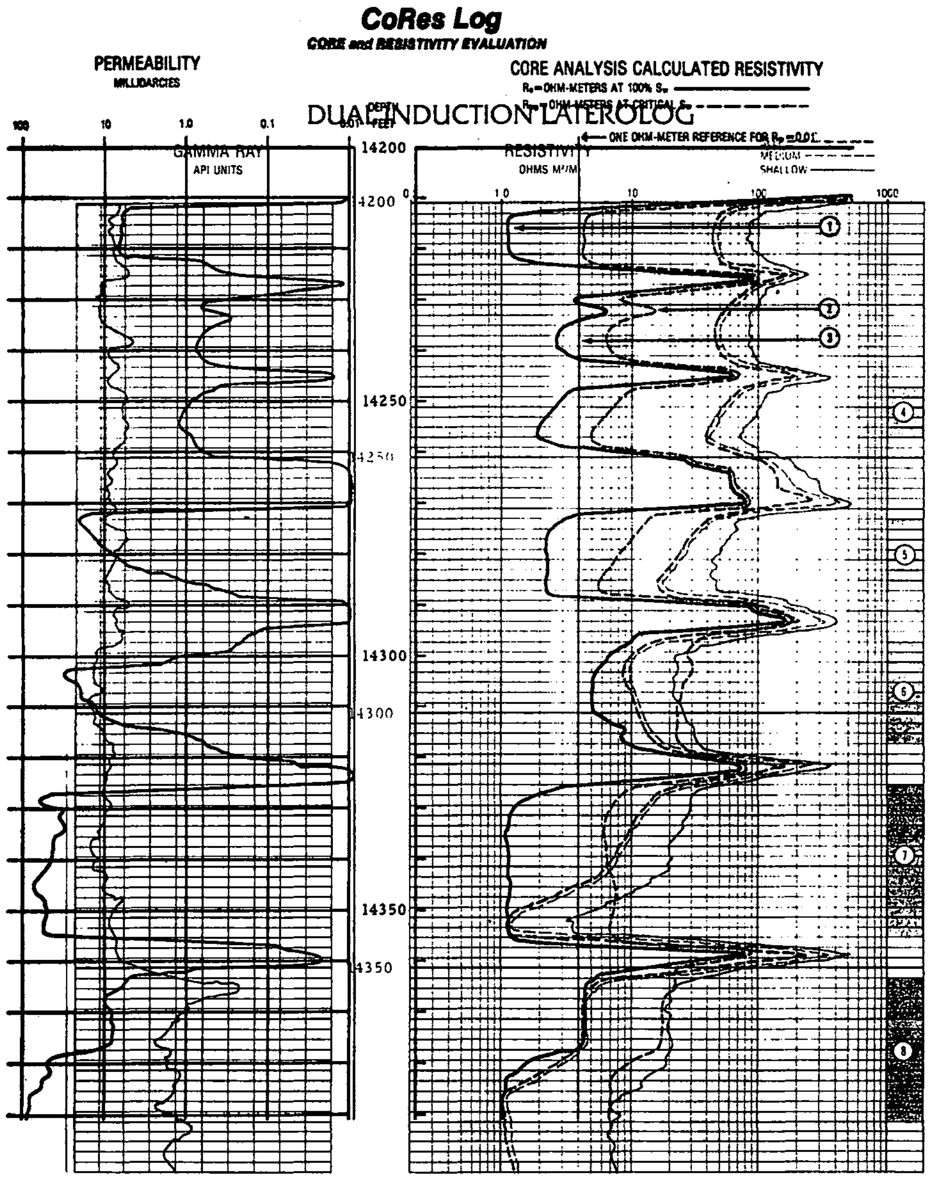

Figure 4: CoRes Log overlay – theoretical.

5. False Transition Zone Identification: The constant Ro calculated from core analysis reveals constant porosity. The decrease in both Rmp and formation measured resistivity reveals a significant increase in formation water saturation. The indicated higher water is not due to approach to a water level, but is a capillary phenomenon related to permeability. This results in an increased irreducible (immobile) water saturation as the measured permeability decrseases. This higher water will not flow.

6. Watered-Out Hydrocarbon Zone Identification: The formation resistivity is greater than calculated Ro, but significantly less than Rmp. If this occurs in a zone having good shows by core analysis, it is indicative of residual shows or a zone flushed by water encroachment.

7. Transition Zone and Water-Hydrocarbon Contact Identification: Both the core analysis calculated Ro and Rmp are constant, but the log formation resistivity is decreasing. The constant Rmp curve reveals uniform capillary properties with no lithological reason for an increase in water saturation. In this instance, the higher formation water saturation indicated by reduced resistivity on the deep resistivity curve must be attributed to transition zone as the water level is approached. Completion in this zone above a log depth of 14,330 feet should result in no more than 5 percent water-cut.

8. False Hydrocarbon Production Indication: The formation resistivity in the top half of this zone is four times the resistivity in the lower half and "looks" favourable in contrast, but definite water is indicated by the close agreement with the calculated Ro curve. The higher resistivity is simply a result of lower porosity in the top. Throughout the zone the formation resistivity is significantly lower than the Rmp required for hydrocarbon production.

Note that the formation water resistivity (Rw) can be determined by overlaying the CoRes computed Ro curve on the downhole log Rt found in a known water zone. Rw is found by reading the down-hole log resistivity value lying under the one ohm-meter reference line, and then dividing this value by 100.

FIELD EXAMPLE ONE (Core Laboratories, 1973)

Without further information, the resistivity logs in Figure 5 might be interpreted as showing a productive hydrocarbon zone down to 13,506 ft, a transition zone from 13,506 - 13,556 ft and a water zone from 13,556 ft down past 13,608 ft. Indeed, the well was successfully produced down to 13,500 ft for many years.

Sidewall cores taken later in the deeper part of the well demonstrated a gradual loss of permeability with depth which correlated with the slight increase in shaliness as shown by the SP log. Lower permeability samples would naturally tend to have higher Sciw. Calculated Rmp points show that log resistivity is above minimum productive resistivity throughout the apparent transition zone and water zone. Production testing at the lowest point of resistivity yielded minimal water production. Results are given on the log.

FIELD EXAMPLE TWO (CORE LABORATORIES, 1973)

Possible condensate production was predicted from residual fluid saturations determined by routine core analysis on cores taken from 13,722 to 13,750 ft (see Figure 6).

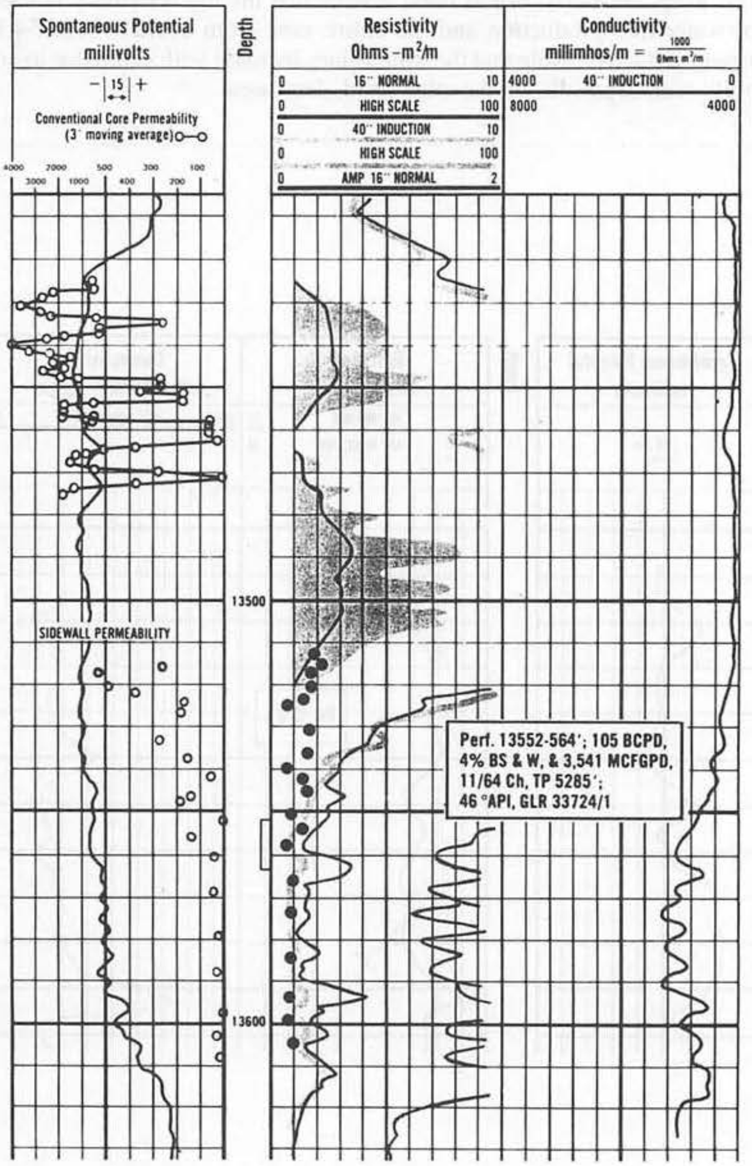

Figure 5: Identifying transition zone – Rmp-Rt comparison for Frio Sand, So. Louisiana.

A low log resisivity of 0.6 ohm-maters is noted at the bottom of the sand as compared to 1.9 ohm-maters at 13,728 ft. This threefold increase in resistivity would normally indicate production the top of the sand. The zone was production from 13,720 to 13,730 ft and it flowed 500 B/D water plus 400 mcf gas through 1/4 inch choke.

A plot of Rmp values (shown as dots) reveals that the log resistivity is less than the required for water-free production and the entire sand from 13,725 - 13,754 ft is now primarily water productive. Note that the Rmp values increase with depth due to an increase of permeability with depth. Rt, on the other hand, decreases.

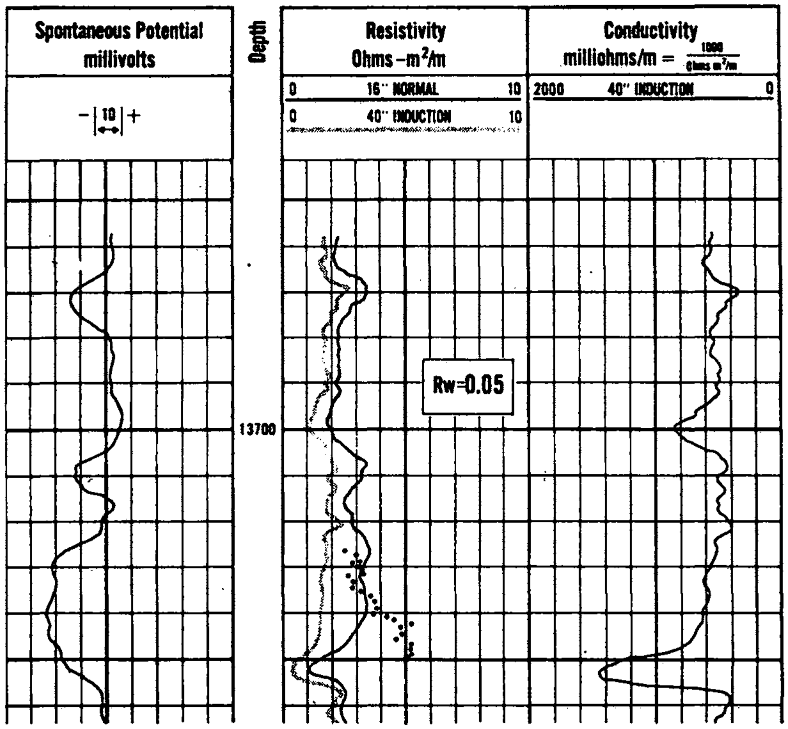

Figure 6: Identifying depleted gas zone – Rmp-Rt comparison for Miocene Sand, So. Louisiana

CONCLUSIONS

By combining specialised core techniques with electric log data, potential zones can be identified with more certainty.

This may have particular relevance to wells which have been shut-in without testing, or "poorer" zones in producing wells where apparent water saturations have been considered too high for economic production.

NOMENCLATURE

a : intercept
a* : idealised intercept
B : specific counterion activity $\frac{1}{\text{ohm-m}} \Big/ \frac{\text{eqviv}}{\text{liter}}$
B/D : barrels/day
mcF : thousand cubic feet
m : cementation exponent
m* : idealised cementation exponent
n : saturation exponent
n* : idealised saturation exponent
Qv : cation exchange capacity, meq/ml of pore space
Sciw: critical water saturation
Rmp: minimum productive resistivity, ohm-meters
Ro : resistivity of 100% water-saturated formation rock, ohm-meters
Rt : true resistivity of formation, ohm-meters
Rw : resistivity of formation water
Ø : porosity

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