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資　　料

Finding remaining & by-passed hydrocarbon through saturation monitoring behind casing*

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Abstract : Over the last three years, more than 400 cased-hole reservoir monitoring logs were acquired in Indonesia. These were acquired utilizing mainly cased-hole resistivity technology, but also some pulsed neutron and cased-hole density / neutron logs as well. The results were very encouraging in terms of identifying, and quantifying, by-passed hydrocarbon.

This paper describes four case histories where the hydrocarbon would have been missed, and not produced, without cased-hole reservoir monitoring information.

These case histories demonstrate how cased-hole reservoir monitoring can be used to evaluate bypassed zones which were missed for various reasons during open-hole log evaluation, identify un-depleted areas, waterflood evaluation and cost effectively maximize the life of a mature hydrocarbon field.

Key words : formation resistivity, cased-hole, by-passed hydrocarbon

1. Introduction

In this paper we define "reservoir monitoring" as running logs in existing wells to monitor changes in fluid saturation in the reservoir over time. In this case the logs used were pulsed neutron logs, and cased-hole resistivity logs. A brief description of these logging services can be found in the appendix. Fig. 1 and Fig. 2 show examples of uniformly depleted reservoirs logged with a pulsed neutron log and a cased-hole resistivity log. Several other techniques for reservoir monitoring with logs also exist.

This paper tries to introduce an expanded way of thinking about reservoir monitoring through a series of case studies. Common practice is to think about the known reservoirs in the field, and to monitor depletion or water movement within those reservoirs only. With the advent of more sophisticated reservoir monitoring technology, we have noticed that many relatively old wells pass through small or low quality productive zones that were previously not identified or documented as reservoirs due to the vintage of log technology available at the time, hole conditions, deep invasion, or simply the economics of the time where only large oil bearing zones were produced, and smaller, or gas bearing zones were ignored for example. We have also noticed a lot of unproduced zones which were commingled during production with more permeable zones.

As mature fields start to approach the end of their economic life, it is often beneficial to re-log zones in the field not previously considered to be of reservoir quality. With modern logging techniques, it is often possible to identify by-passed hydrocarbon-bearing zones which can extend the life of the field.

Water injection in complex channel sands is also notoriously difficult since the injected water will

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follow the easiest path between injector and producer, bypassing lower permeability reservoir sections. Reservoir monitoring can also be used to identify bypassed areas of a field and to help choose optimal infill drilling locations to best drain the remaining oil, or improve water sweep efficiency.

In the following pages we present four case studies from Indonesia where monitoring operations were able to increase the productivity of mature fields.

1.1 Case-1

This case study involves field-wide resistivity mapping of a large mature oil field in Indonesia. The original oil in place was 8.7 billion barrels, and over 1450 wells have been drilled in the field (Fig. 3). The field has been under water flood for decades. The water cut of the field prior to the monitoring work was 98.7 % and the decline rate was 20% (Fig. 4).

Two hundred seventy wells were logged using cased-hole resistivity tool within two years. These wells were carefully selected to give a representative saturation map of the field and highlight areas of higher saturation where remaining oil was likely to be located. The infill-drilling program was focused on these areas of higher probability of locating remaining oil. The decline rate of the field improved to 6%, adding several years to the economic life of the field.

Valuable information about the movement of the injected water derived from the resistivity response also helped make the water flood more efficient (Fig. 5)

The deep reading cased-hole resistivity logs were selected for this work, to minimize the uncertainty associated with the near-wellbore environment due to reinvasion of borehole fluid. This advantage outweighed the uncertainty caused by changes in formation water salinity due to the water flood.

1.2 Case-2

This case study involves a previously bypassed, low resistivity, silty pay zone known as the Telisa formation in a mature field in Sumatra, Indonesia (Fig. 6). The main zone was a carbonate layer below the Telisa, and was the main objective of logging the wells. The cased-hole resistivity log was extended above the carbonate into the Telisa and it was observed that the cased-hole resistivity was significantly higher than the open-hole resistivity. This was repeated in several different wells and the results were the same (Fig. 7). One likely reason the resistivity was higher in cased-hole is that deep filtrate invasion during drilling affected the resistivity readings of the vintage logging tools used to log the open-hole. The low performance mud systems of the era when the wells were drilled often invaded deeply into low porosity zones. On re-evaluating the well using the new resistivity log, the Telisa appeared to be oil bearing, and on testing the zone in several wells, oil was produced after stimulation (Fig. 8). Fig. 8 also shows the gas chromatograph reading recorded by mud loggers during the drilling of the wells. The gas readings, which are often used to identify oil zones, do not correlate with the final production results, since the low permeability reservoir required stimulation to produce, and the production rates partly depend on the effectiveness of the stimulation. The Telisa was also perforated in other parts of the field, and some wells produced more than 500 bopd, which is significant production for this area.

1.3 Case-3

This case study involves low contrast gas pay where it was very difficult to identify gas from the open-hole logs due to clay laminations. The relatively high clay content suppressed the traditional density-neutron crossover and the low resistivity on the order of a few Ohm-m made even identifying reservoir quality rock difficult, much less hydrocarbon content (Fig. 9).

A Pulsed Neutron Sigma log and a Cased Hole Formation Resistivity log were run in casing. The sigma-GR overlay in track 5 of Fig. 10 showed a possible gas effect. An increased resistivity reading in casing, compared to open-hole, supported this (Fig. 11). The top five meters of the zone were tested, and produced 2 MMSCF of gas. This zone had not previously been identified as hydrocarbon-bearing.

1.4 Case-4

This case study involves uneven depletion in a reservoir helping to identify reservoir compartmentalization. Fig.12 shows the open-hole logs recorded in two offshore wells; well-A close to the crest of the structure, and well-B further down the flank. The correlation between the three zones in the wells was so good that the sands were assumed to be continuous. The purpose of the development was to provide gas for a gas lift project on the platform. Six

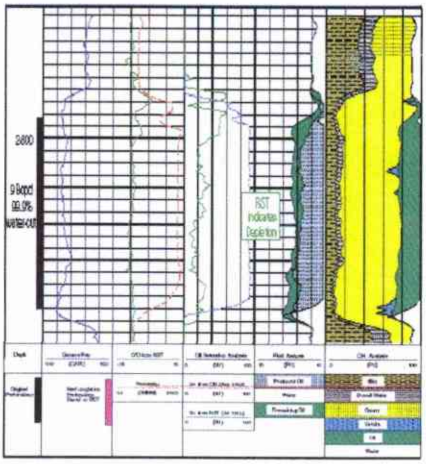

Fig. 1 Pulsed Neutron Log in an evenly depleted massive zone.

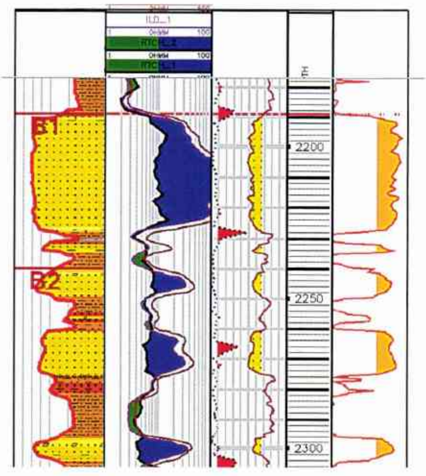

Fig. 2 Cased Hole Formation Resistivity log run over 3 evenly depleted commingled zones. Cased hole resistivity is significantly lower than open hole resistivity.

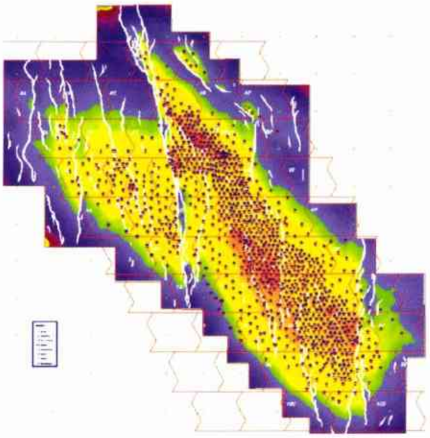

Fig. 3 Case 1 Field map of a large field in Indonesia. 250 wells were logged with cased hole resistivity throughout the field to derive a current resistivity map, and identify pockets of remaining oil.

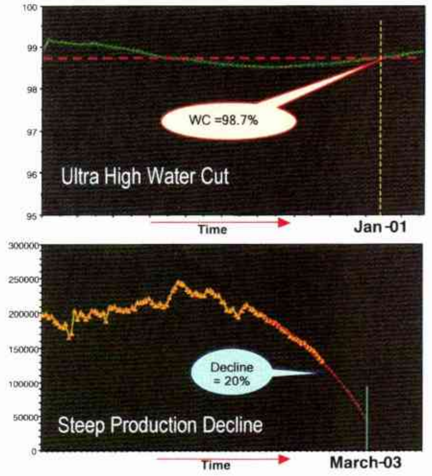

Fig. 4 Case 1 Water cut and decline curve for the field in Fig. 3.

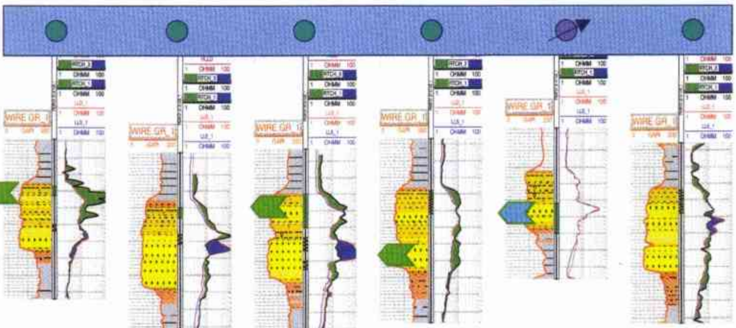

Fig. 5 Case 1 Tracking the movement of injection water using cased-hole resistivity logs.

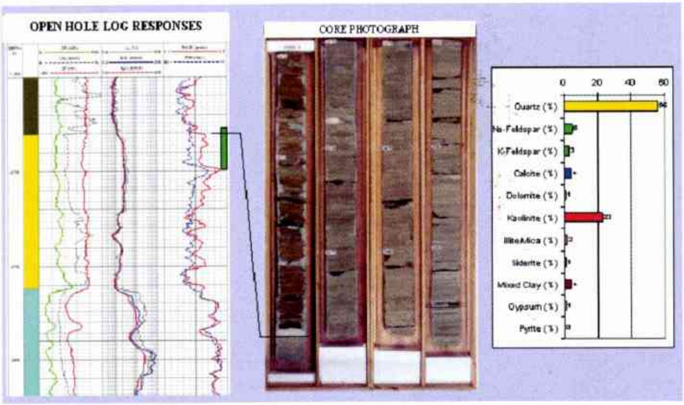

Fig. 6 Case 2 Telisa formation. Low resistivity, silty, formation found to be oil bearing when logged with the cased-hole resistivity log as part of the monitoring project in the carbonate formation below.

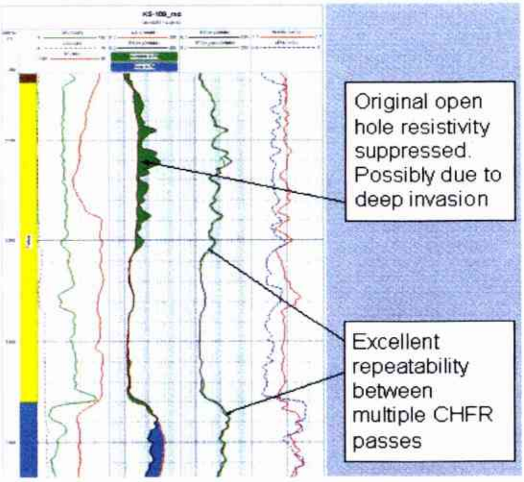

Fig. 7 Case 2 Cased-hole resistivity log reading higher than the open-hole log. The log was repeated to confirm the surprising readings, then the zone was perforated and tested.

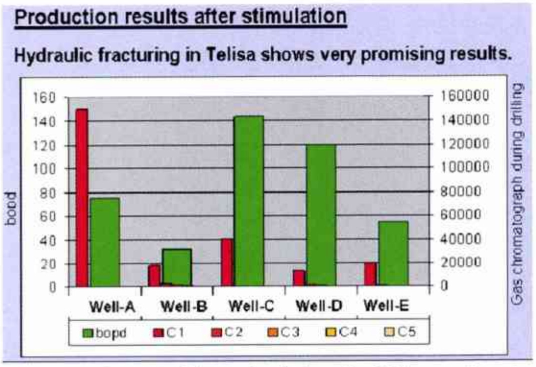

Fig. 8 Case 2 After stimulation the Telisa produced oil from all of the wells tested.

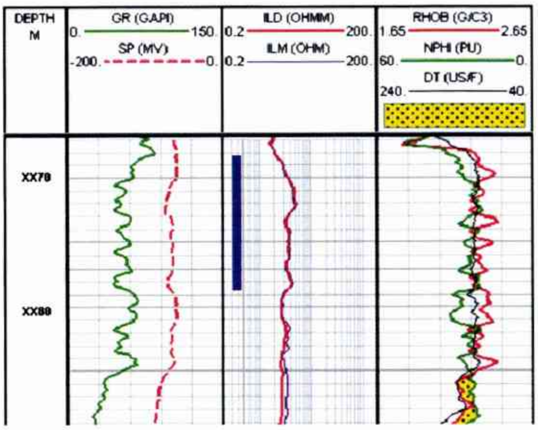

Fig. 9 Case 3 Low resistivity silty formation found to be gas bearing after cased-hole resistivity and pulsed neutron logs were run.

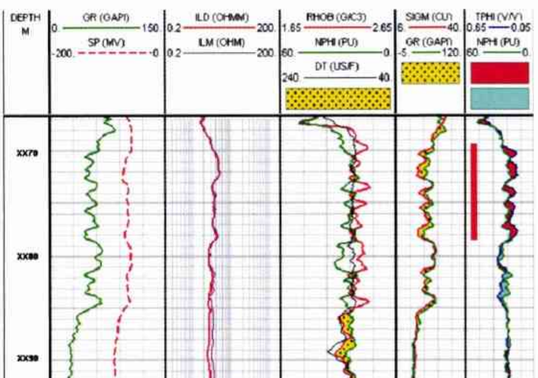

Fig. 10 Case 3 Pulsed neutron sigma log shows a high probability of gas (red shading in track 6).

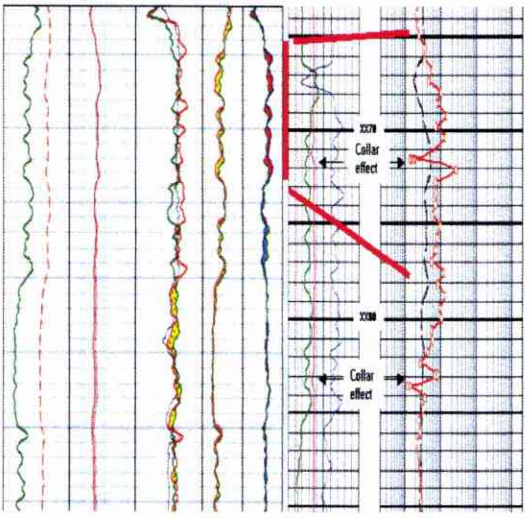

Fig. 11 Case 3 Cased hole resistivity log confirms the gas shows from the pulsed neutron log, with higher resistivity than the open-hole log over this zone.

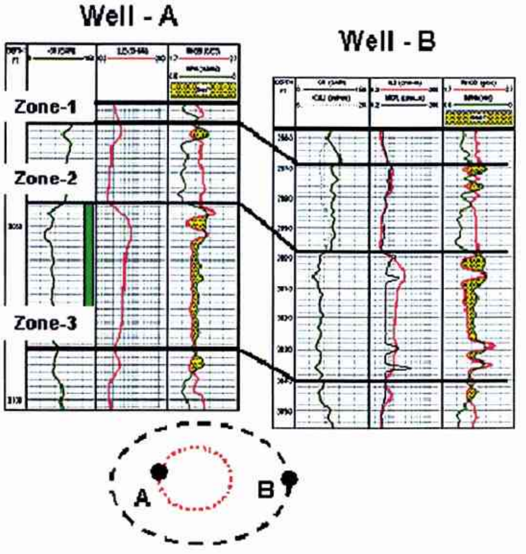

Fig. 12 Case 4 Good correlation between sands in well-A and well-B. Reservoir assumed continuous between wells.

years into the project, well-A started producing water earlier than expected. A pulsed neutron sigma log was run to identify the source of the water. It was found that zone-2 in well-A was depleted, while zones 1 and 3 remained at original gas saturation (Fig. 13). The question arose as to whether it was worth logging well-B also, to see water movement up the flank of the structure. Well-B was logged. Zone-3 was found to be depleted, and zones 1 and 2 were at original saturation (Fig. 14). This surprising result showed that zone-2 was not continuous between the two wells, and that reservoir compartmentalization was the cause of the early depletion of zone-2 in well-A.

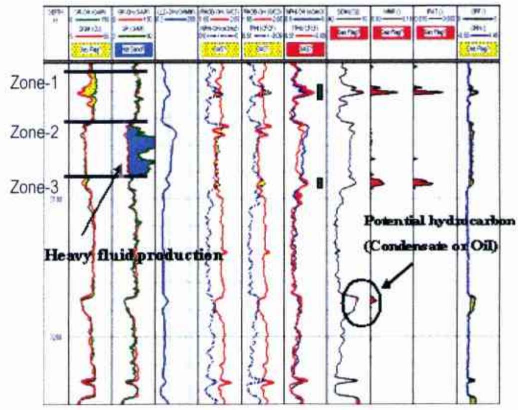

Fig. 13 Case 4 Well-A: Zone 2 found to be depleted from the pulsed neutron log. Zones 1 and 3 still gas bearing.

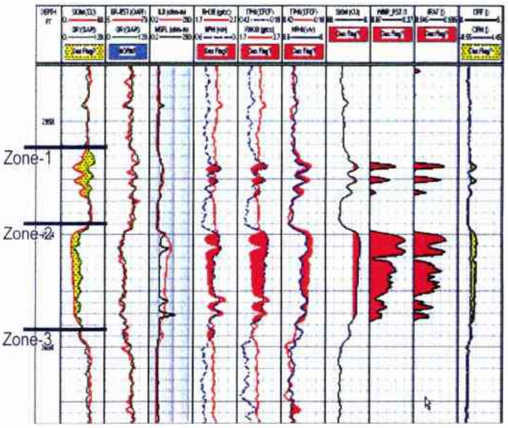

Fig. 14 Case 4 Well-B: Surprisingly zone 2 remains at original gas saturation, implying lack of communication within the reservoir between wells A.

2. Conclusions

These examples highlight the importance of reservoir monitoring in mature fields, to identify both uneven depletion and water flood performance. Monitoring programs should also be extended to include possible bypassed zones for re-evaluation. It is likely that zones considered uneconomic when the field was discovered, could be worth producing with newer cheaper technology. On a field scale, selection of wells for monitoring should be made to test for possible compartmentalization.

3. Appendix

Cased Hole Formation Resistivity (CHFR*)

The CHFR is a cased hole, laterolog type, resistivity measurement. The principle of the measurement is to inject a large amount of electrical current into the casing, and measure the small leakage current that returns to an electrode on surface. This leakage current is proportional to the resistivity of the formation at the position of the CHFR, and the casing resistivity. The casing resistivity is also measured at the same point, so the formation resistivity can be calculated. Current versions of the CHFR must be logged as stationary measurements. The log is recorded by making stationary measurements every 2 ft in the well. The vertical resolution of the current version is 4 ft. The depth of investigation into the formation is several feet depending on the resistivity. This is the main advantage of the CHFR logging services over nuclear logging services, which measure only a few inches into the formation. The CHFR is currently available in 3-3/8" and 2-1/8" diameters.

3.1 Pulsed Neutron Logging Tools (RST*, TDT*)

The TDT and the later generation RST logging tools measure the sigma and neutron porosity of the formation. Sigma can be used to differentiate between saline water, oil and gas. The RST can also measure the ratio of Carbon to Oxygen (C/O) which is proportional to oil saturation, porosity and carbon/oxygen content of the formation. If the porosity and lithology is known, then the oil saturation can be computed. The C/O log can be used to differentiate between fresh water and oil, which have similar sigma responses. Through processing the RST log a detailed estimate of lithology components can be made in siliciclastic environments.

The main advantage of the RST is that it can provide a measure of water saturation in areas where the parameters for resistivity based saturation equations are unknown. The RST is currently available in 2-1/8" and 1-11/16" diameters.

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要　　旨

管内水飽和率検層を活用した残留およびバイパス炭化水素の発見

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ベニャミン・T. サントサ

過去3年以上にわたり、400以上のケースドホール水飽和率モニタリングログがインドネシアにて取得された。これらのログは主としてケースドホール比抵抗テクノロジー（CHFR）を活用して取得されたものであるが、同時にパルスドニュートロンログおよびケースドホール密度（中性子ログ）も活用されている。これはバイパス炭化水素を認識および数値化する上で非常に有用な結果をもたらした。

本稿では、管内水飽和率検層ログで取得された情報がなければ炭化水素の発見および生産が見過ごされていたであろう事例について解説する。

これらの4つの事例で、裸坑検層の評価の過程でさまざまな理由によって見過ごされたバイパスゾーンの評価、枯渇していない領域の認識、水攻法の評価、成熟したフィールドの延命などに、管内水飽和率検層をいかに活用することができるかを解説する。