American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-6, Issue-6, pp-192-203
www.ajer.org
Research Paper Open Access

TDT and CHFR Logs Monitoring of Water Production and Bypassed Oil Layers and Water Production Management in Matured Sandstone Reservoirs

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ABSTRACT: *Monitoring of sandstone reservoir saturation performance through cased wells, usually is the main key factor for proper reservoir management and recovery optimization in the cases of developed and mature oil fields. Thermal decay time tool (TDT) has been the main technique used for monitoring the inter wells water saturations in developed reservoir. One of the main problems that encountered while using TDT log is the reservoirs with low formation water salinity, this problem may also appear in reservoirs that are supported by water injection projects, in which the formation water is diluted by the injected water. This problem has been solved by combining TDT technique and cased hole formation resistivity tool (CHFR). It is important to detect and evaluate bypassed hydrocarbon and monitor fluid movement in sandstone reservoir. It is difficult to interpret the TDT data in reservoirs with low-salinity sandstone formation water. This problem cannot be solved because TDT measurements depend on the salt content in formation brine. Instead the cased hole formation resistivity tool (CHFR) is proposed to overcome the limitations associated with pulsed-neutron tools. This paper presents case studies of pay zones-saturation monitoring obtained from TDT and CHFR logs recorded in wells in an oil field in the Sinai Peninsula, Egypt. The results are referenced to open-hole resistivity logs. Interpretation of CHFR log is easier than that of TDT log because, while interpretation of CHFR log, two factors which come from the same origin, are compared with each other's. it is not easy to compare them and detect any differences between them. It was found that water saturations calculated from CHFR logs are more accurate than TDT log in most cases. Water shut-off remedial action to manage water production from producing sections in the studied wells has been much more successful based on CHFR / TDT logs than the proposed remedial action based only on TDT data interpretation.*

Keywords: *Cased hole formation resistivity, (CHFR), Thermal decay time (TDT), Water saturation monitoring, Pay zones*

I. INTRODUCTION

Continuous reservoir saturation monitoring , through cased wells, usually is the main key for proper reservoir management and recovery optimization especially for huge and mature oil fields. The main technique, which has been used for monitoring reservoir saturations, is TDT tool. One of the main problems that encountered while using TDT log is the reservoirs with low formation water salinity. This problem was very obvious in some wells in studied oil fields located in Sinai and producing from sandstone formations. These formations have naturally low salinity formation water (about 20,000 – 30,000 ppm). Also this problem could be appeared in reservoirs that are supported by water injection projects, in which the formation water is diluted by the injected water. This is because the injected water, used in water injection project in this field, is the Red Sea water. The average salinity of this water is about 40,000 ppm, which is greatly less than average salinity of formation water for other zones (about 150,000 ppm). The problem concerning the low formation water salinity is actually related to the theory of TDT itself. This is of its measurements that depend upon the chlorine (NaCl) content in the formation water, which is highly dependent on the salinity of formation water. Therefore, TDT in such cases can not distinguish between the low salinity water (salinity below 60,000 ppm.) and oil. Therefore, wells drilled in reservoirs of low-salinity water could not be evaluated by TDT log at all. This problem has been solved by the Carbon-Oxygen (C/O) technique, which was combined with TDT technique into another tool called RST tool [Morris et al, 2005, Hamada and Heikal, 1998; Aldred, 1993;; Al-Mufaerrej et al 2017].

Some other problems were being faced while using TDT log: the wells with high pressures or wells which need to be killed before work over. Also wells that completed with Electrical Submersible Pump (ESP) artificial lift strings (about 88 % of wells in the selected field are completed with (ESP). TDT tool can not be run through this production string to record against producing formation because the string is close ended by the ESP. therefore, in order to record the TDT log, production string must be pulled out of hole first, which needs killing the well by a killing fluid. The actual problem, encountered in the above mentioned cases, is that the killing fluids may invade the producing zone and this invaded zone will affect greatly the results of TDT logs. This problem may also be encountered in wells which are producing with high water cut and shut-off for long time. The segregated water will invade the hydrocarbon perforated zones. Actually, the origin of this problem is the short depth of investigation of the TDT tool (about one foot). So, any near-wellbore-effects may greatly influence the TDT log measurements. This problem was not solved by the new RST tool (C/O mode) because it provides a very short depth of investigation (6-8 inches), even shorter than that of the TDT. For these reasons, there was a necessary need to find another cased-hole log, which can overcome the limitations and restrictions of the Pulsed Neutrons technique. From field experience, it was found that both the used techniques (TDT, CHFR) have their own advantages and limitations and that each technique of them can be suitable for certain wells with certain conditions.
The main objectives of the present work are to evaluate the new technique (CHFR) through actual field examples of sandstone reservoirs and to compare applications of CHFR and TDT techniques.

THERMAL DECAY TIME (TDT)

Time-Lapse Technique

The most useful and most practical approach to TDT interpretation is based on the so-called time-lapse technique. To apply this technique, a reference log must be run soon after well completion in normal producing conditions. The computation of water saturation change can be done using the following relationship [Rinehart and Weber, 1975; Morris et al, 2005; Moyner et al 2015]:

$$\Delta Sw = \Delta \Sigma \log / \Phi (\Sigma w - \Sigma h) \qquad (1)$$

The main disadvantage of this technique is that the reference logs or base TDT runs are not always available in many wells because the recording of a base log requires the well to be re-entered some weeks or months after completion. In case of wells that are developed by sub-sea completion, recording of TDT base runs few weeks after completion is not practical.

Quantitative Interpretation (Stand-Alone Technique)

Generally, the reliability of TDT quantitative evaluation increases with formation porosity and water salinity. This technique is based on the fact that capture cross- section of a material is the summation of the cross-section of all its elements multiplied by their respective volume proportions.
In general case of shaly porous formation containing water and hydrocarbons, water saturation, Sw from TDT is [Hamada and Heikal, 1998; Rinehart and Weber, 1975; Iglesias et al 2016]:

$$Sw = (\Sigma \log - \Sigma ma) - \Phi (\Sigma h - \Sigma ma) - Vsh (\Sigma sh - \Sigma ma) / \Phi (\Sigma w - \Sigma h) \qquad (2)$$

CASED HOLE FORMATION RESISTIVITY (CHFR)

The CHFR resistivity tool provides saturation measurements from depth of investigation significantly beyond that of nuclear logging tools used for through casing evaluation. The dynamic range of CHFR measurement in such evaluation is also possible for low porosity and low formation salinity [Dubourg et al, 2001, Hunka et al, 1990, Singer et al, 1995, Maurer and Henniker, 2000; Beguine et al, 2000; Fouda et al 2015].
Because CHFR log provides cased hole resistivity values very resemble to the open hole resistivity values, therefore the quantitative interpretation of CHFR logs will be very similar to open hole logs quantitative interpretation, using the traditional Archie equation. The Archie equation is used to determine the water saturation (Sw) from true formation resistivity logs for clean formation, as follows [Dubourg et al, 2001]:

$$Sw_{(CHFR)} = (FR_w / R_{CHFR})^{0.5} \qquad (3)$$

Depletion-Indicator, DI is the ratio of the reference open-hole to new cased-hole Archie water saturation values. It is given by

$$DI = (Rt / R_{CHFR})^{0.5} \qquad (4)$$

This depletion Indicator (DI) can be plotted versus depth for formation of interest, taking the value 1 as a base line, below which the formation can be considered as it is depleted: R_{CHFR} less than R_{OH} [Dubourg et al, 2001, Ferguson et al, 2001,[Hupp et al, 2002, Starcher et al, 2002, Ma et al, 2004 and Murty et al, 2005].

FIELDS EXAMPLES OF TDT AND CHFR
CHFR Field Examples
Field Example 1

This is the first well logged with CHFR. CHFR logging was recorded directly after recording open-hole resistivity log and setting the casing. Fig. 1 shows CHFR and LLD data for well A. From Fig. 1, it was clear there is a good match between CHFR log and open-hole LLD log. This logging data comparison is an important step for testing and evaluating CHFR data to monitor subsurface inter-wells water saturation changes. Next example will show the impact of the use CHFR logging technique based on the matching degree between CHFR resistivity and open-hole resistivity.

Field Example 2

This is a producing well for a period of 10 years with a gross rate of production 2700 bpd from about 90 meter shaly sand layers, as shown by the old perforation set in Figure 2. This well started suffering from high water cut, 49.5 %. This well was drilled in a reservoir where the formation water is mixed water salinity (90, 0000 ppm) of the water aquifer salinity 150, 000 ppm and inection water salinity 40, 000 ppm. This current formation water salinity complicated the use of open-hole resistivity logs restricted the use of TDT to monitor change in reservoir water saturation to solve high water cut problem. It was recommended to use CHFR technique. CHFR was recorded against the interval (2495 – 2523m.) instead of TDT to determine the actual water saturation of producing zones for well B, Fig. 2.

The comparison of Open-hole LLD and CHFR logs in Fig., 2 showed that CHFR resistivity is generally lower than open-hole resistibity in R2A and R2B. This resistivity difference indicated that these are depleted and flooded zones. The reduction of water cut value was managed by squeezing the interval (2513 – 2543) m) and re-perforate selectively the total intervals avoiding the flooded zones. Fig. 2 shows the new perforation sets based on CHFR data. As result of this job that based on CHFR data interpretation, the total production has been reduced to 1500 bpd while the water cut has went down to only 0.80 %.

Field Example 3

This is the case of well C has gross production rate 820 bpd and completed with ESP pump from sandstone reservoirs and with very low water cut 0.80 %. After certain time water cut started to increase and reached 72.3 %. It was required to know the reasons of this high water cut. Also this well was suffering from low water salinity; formation water salinity was in the range of 22, 000 ppm. TDT can not give results for this salinity range, so, it was decided to use another logging technique to monitor the change in water level to identify where this water coming from. It became a classical case for the use of CHFR log to solve the problem. Fig. 3 shows CHFR resistivity and open-hole resistivity, for well C. It was obvious from the logging data that water is coming from the middle of the perforation interval (2589 – 2615 m). The decision was to squeeze the interval (2595 – 2611 m), water flooded section, as shown in Fig. 3. After squeezing job, water cut started to decrease to about 35 %.

TDT Field Examples
Field Example 1

This well D was drilled and completed as oil producing well with ESP pump. Well gross rate was 1260 bpd and water cut was 1.6 %. Fig. 4 shows open-hole logging data against producing sand and shaly sand intervals (2804 – 2812, 2816.5 – 2832 and 2832.5–2848 m.). After two years of production water cut reached 62.3%. Formation water salinity was in the range of 178,000 ppm, so, it was decided to run TDT for detecting water flooded zone. Fig. 5 shows the TDT data for the same intervals. From TDT interpretation, it was found that the intervals (2816.5 – 2832 and 2832.5 – 2848m) were water flooded. Based on TDT data, the lower intervals were isolated, but it did not change the water cut and decreased the oil production.

Field Example 2

This is lower section of well D in the field example 4.2.1, it produces 600 bpd. Producing intervals were mainly sand and shaly sand (2933- 2941 and 2946- 2951). Fig. 5a shows the open- hole data, neutron-density logs shows clearly the producing sections. Fig. 5 illustrates the TDT for the same intervals, it is clear from TDT sigma curve that the producing intervals were water flooded. It is believed that the water is coming from zone IVA according to the interpretation of TDT.

COMPARTIVE STUDY OF TDT and CHFR LOGS

From previous section, CHFR may replace TDT where reservoir conditions or well completion are not suitable for running TDT log. Also CHFR can clear out confusions on TDT interpretation. One of the major problems with TDT is the difference between quick look interpretation of TDT log and quantitative interpretation with TDT water saturation model. In this section technical comparison between CHFR interpretation and TDT interpretation is presented. Fig. 6a composes TDT and CHFR for zone IV, well D and Fig. 6b depicts TDT and CHFR for zone IVA, well D. From quick look interpretation of TDT, lower sections of zone IV and IVA is water flooded. From CHFR only upper section of IV and lIVA are water flooded.

Fig. 7a shows quantitative interpretation of open–hole data, TDT and CHFR for zone IV. TDT interpretation has shown that the whole section is flooded which disagree with the TDT quick look interpretation. CHFR interpretation showed that only top section is water flooded which agree with the CHFR quick interpretation. Figure 7b contains quantitative interpretation of open-hole, TDT and CHFR for zone IVA. Both TDT and CHFR indicated that this is a flooded zone. It is worth to note that TDT has shown more water saturation difference with reference to open-hole water saturation which indicates that TDT shows more flooding than CHFR.

The difference between open- hole saturation profile and CHFR or TDT saturation profiles indicates that zone IVA and the top section of zone IV were producing zones. But they have been swept and flooded because of bad water movement monitoring program and interpretation.

Based on TDT data interpretation it was decided to isolate zone IVA. The results of the TDT job was that the water cut did not change as it was planned. On the other hand and based on CHFR data interpretation it was recommended to isolate zone IVA and upper section of zone IV; thereupon, water cut has been reduced from 62.3 % to 38 % and kept decreasing to about 2% in well D.

II. CONCLUSIONS

1. Water saturations derived from CHFR log were more accurate than those from TDT log. Also, CHFR results were very representative to reservoirs of low formation water salinity, low porosity
2. TDT log gives water saturations greater than that given by CHFR log against same intervals. Therefore, decisions of water shut-off operations based on TDT log, will loose this difference of oil saturation, which means that large volumes of oil may be lost.
3. Interpretation of CHFR log is easier than that of TDT log because, while interpretation of CHFR log, two factors which come from the same origin, are compared with each others. These two factors are open and cased-hole resistivities, so, it is easy to compare them and detect any differences between them. In the case of TDT log, two different factors are compared with each others; these factors are TDT sigma and open-hole resistivity that makes the comparison difficult and not realistic.

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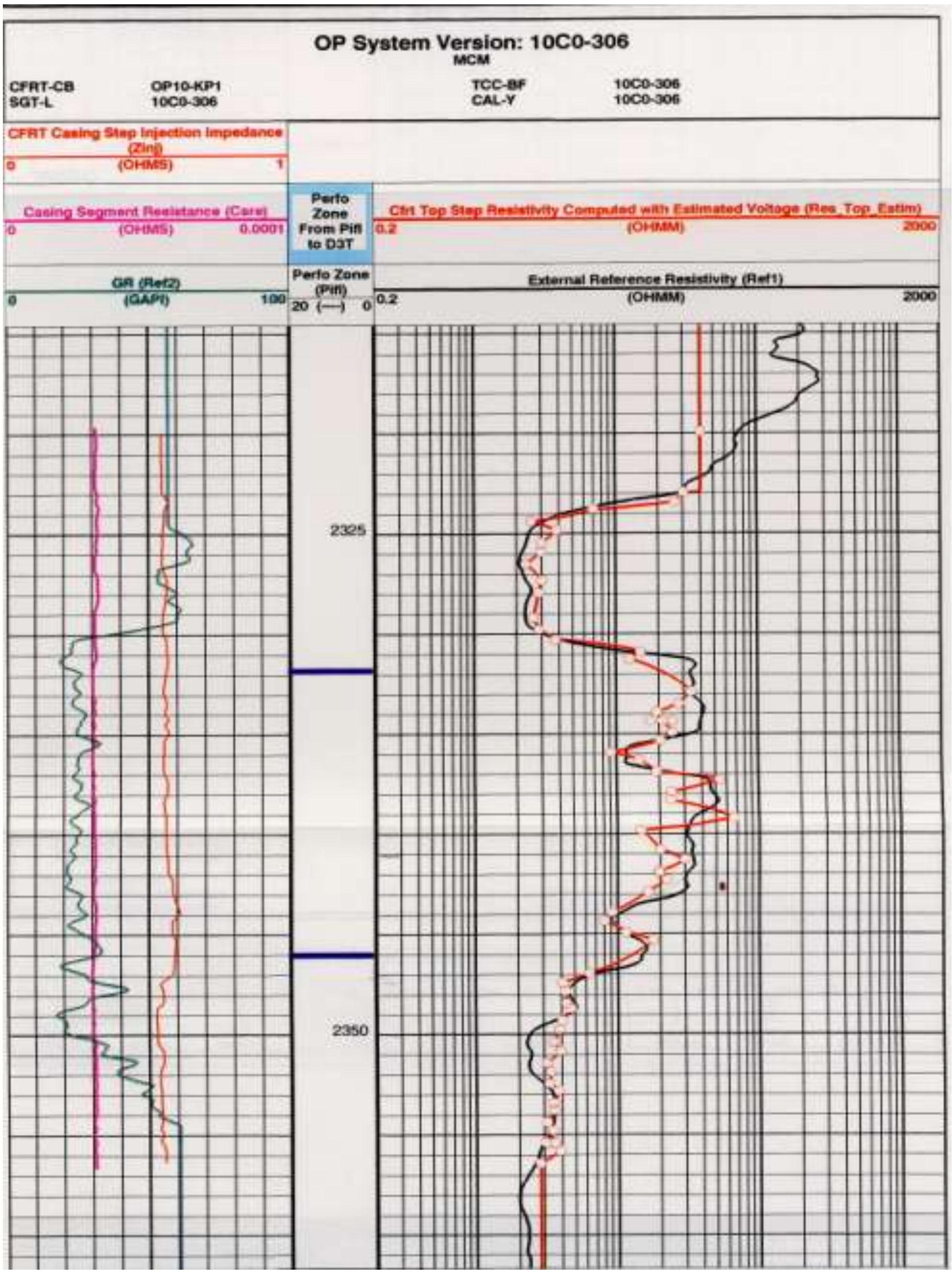

Fig. 1 CHFR logging with open-hole LLD in well A

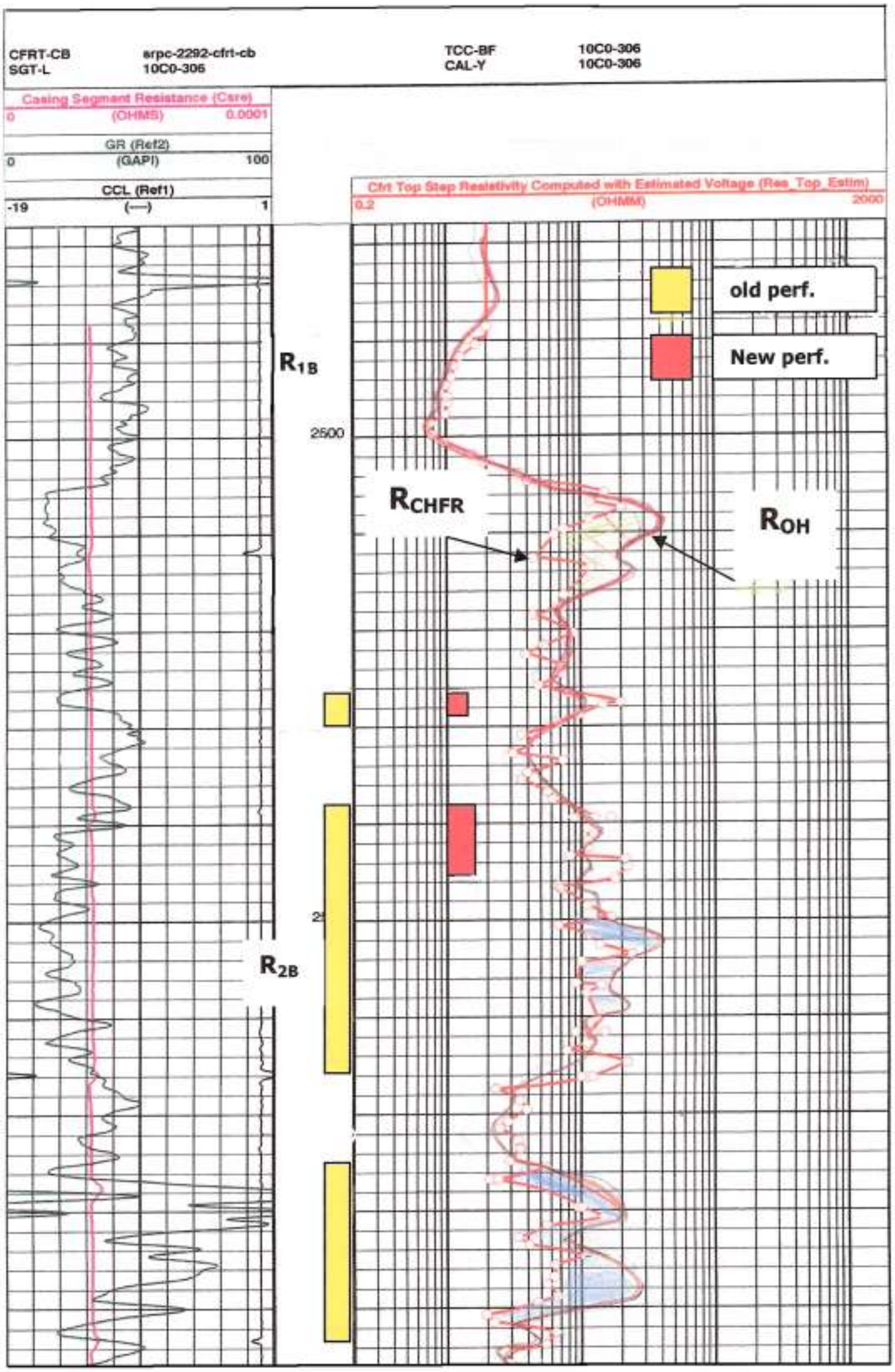

Fig. 2 CHFR and LLD logs for well B

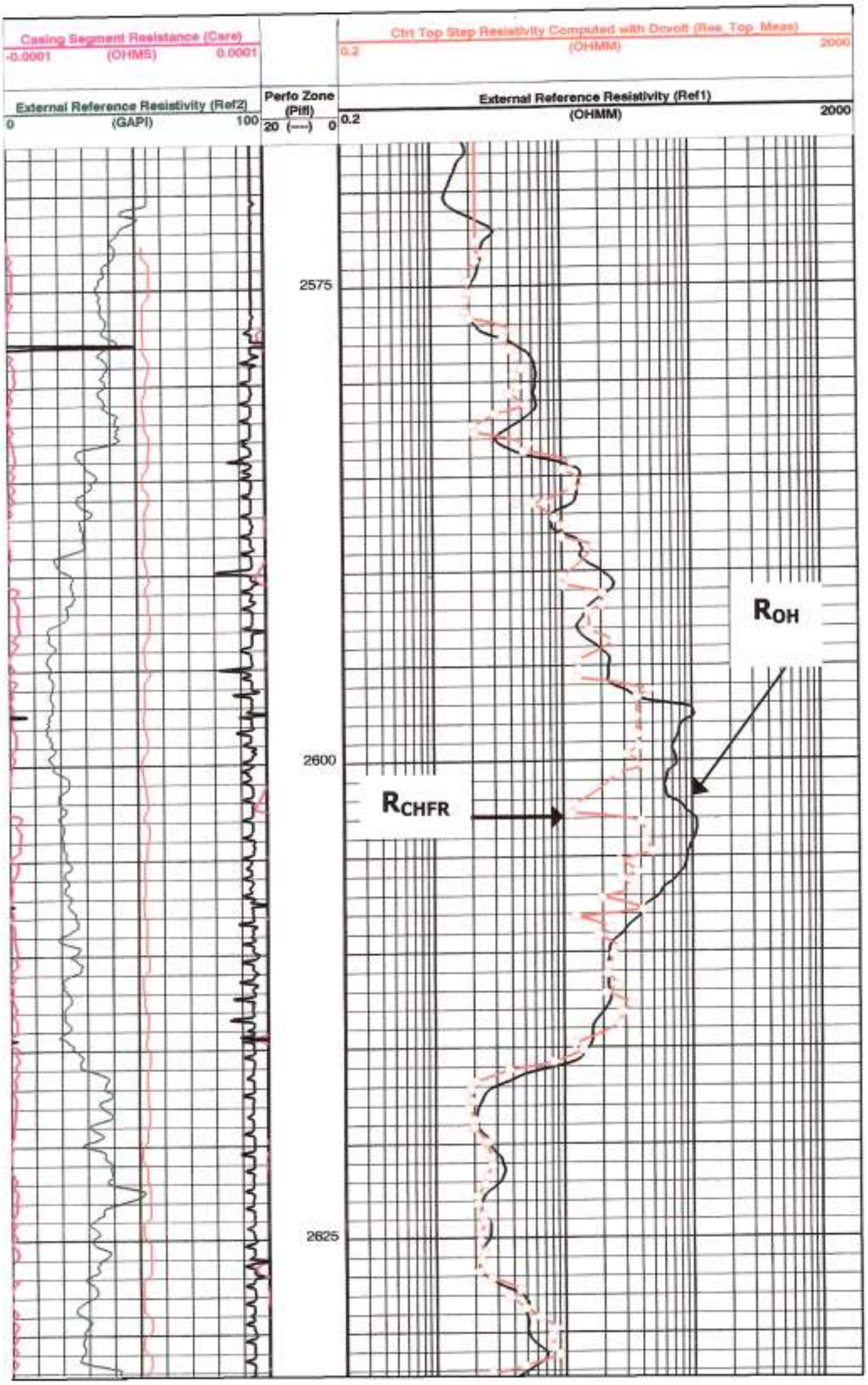

Fig. 3 CHFR and LLD for well C

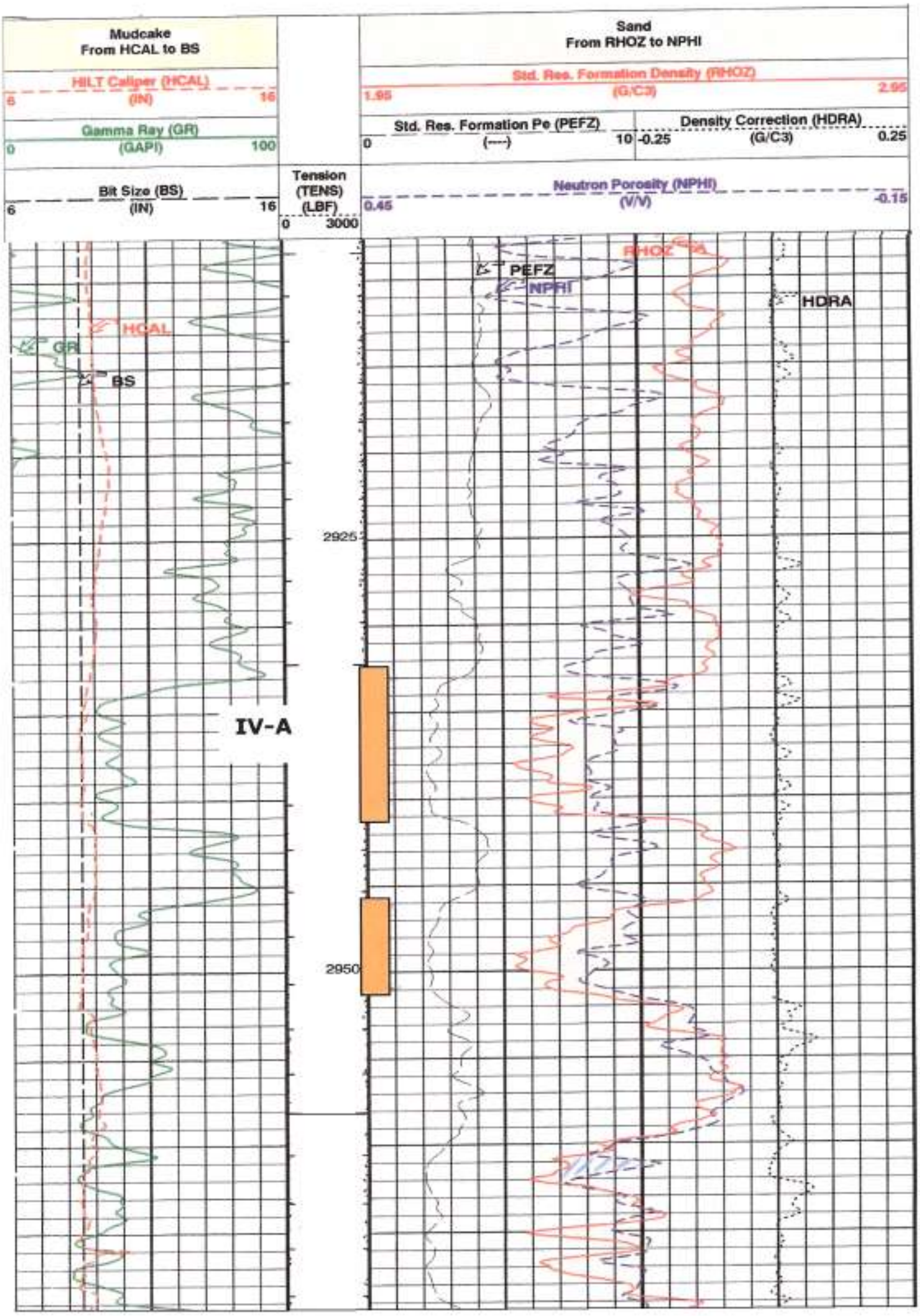

Fig. 4 Open-Hole log for well D

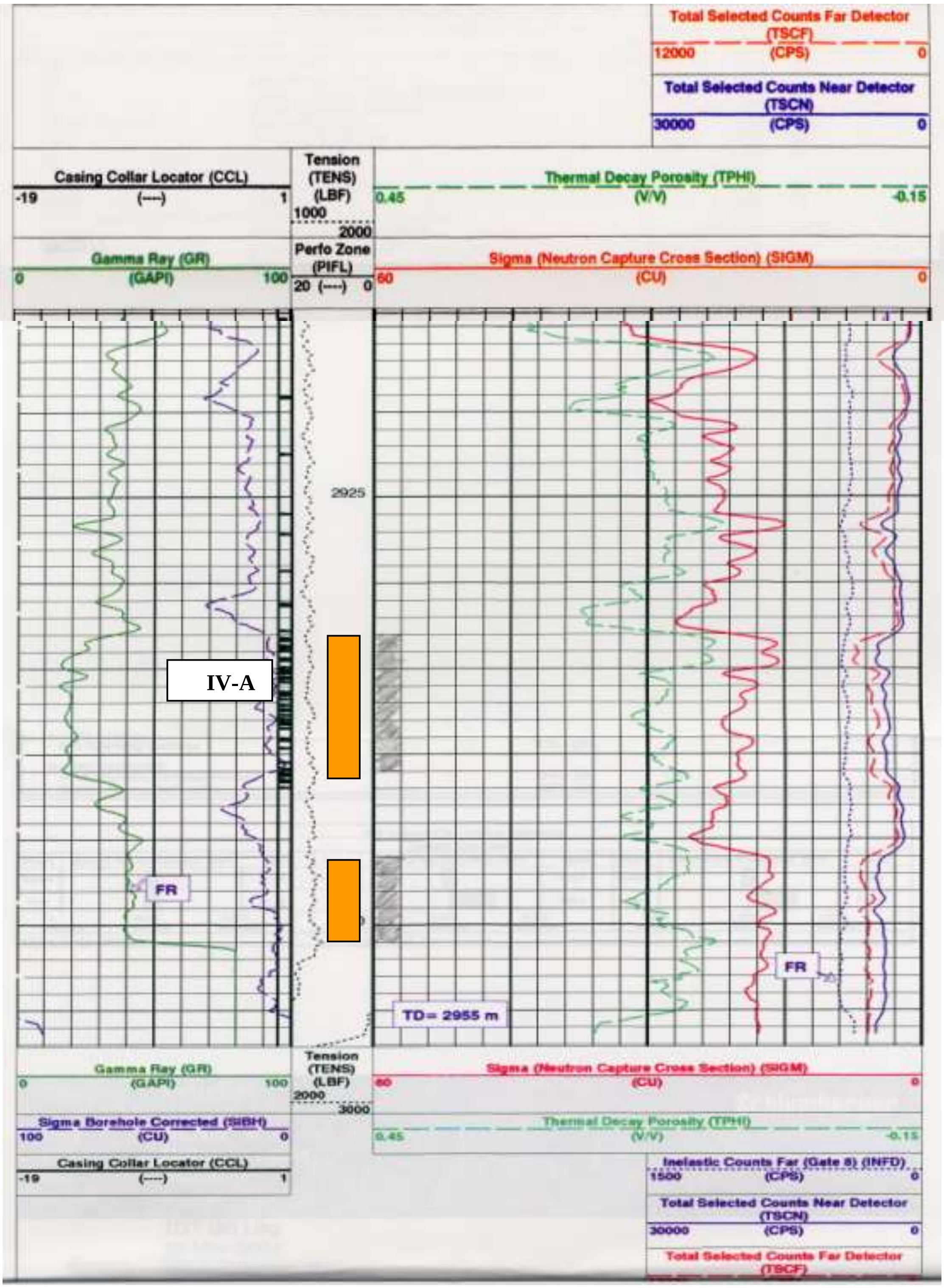

Fig. 5 TDT Log for Well D

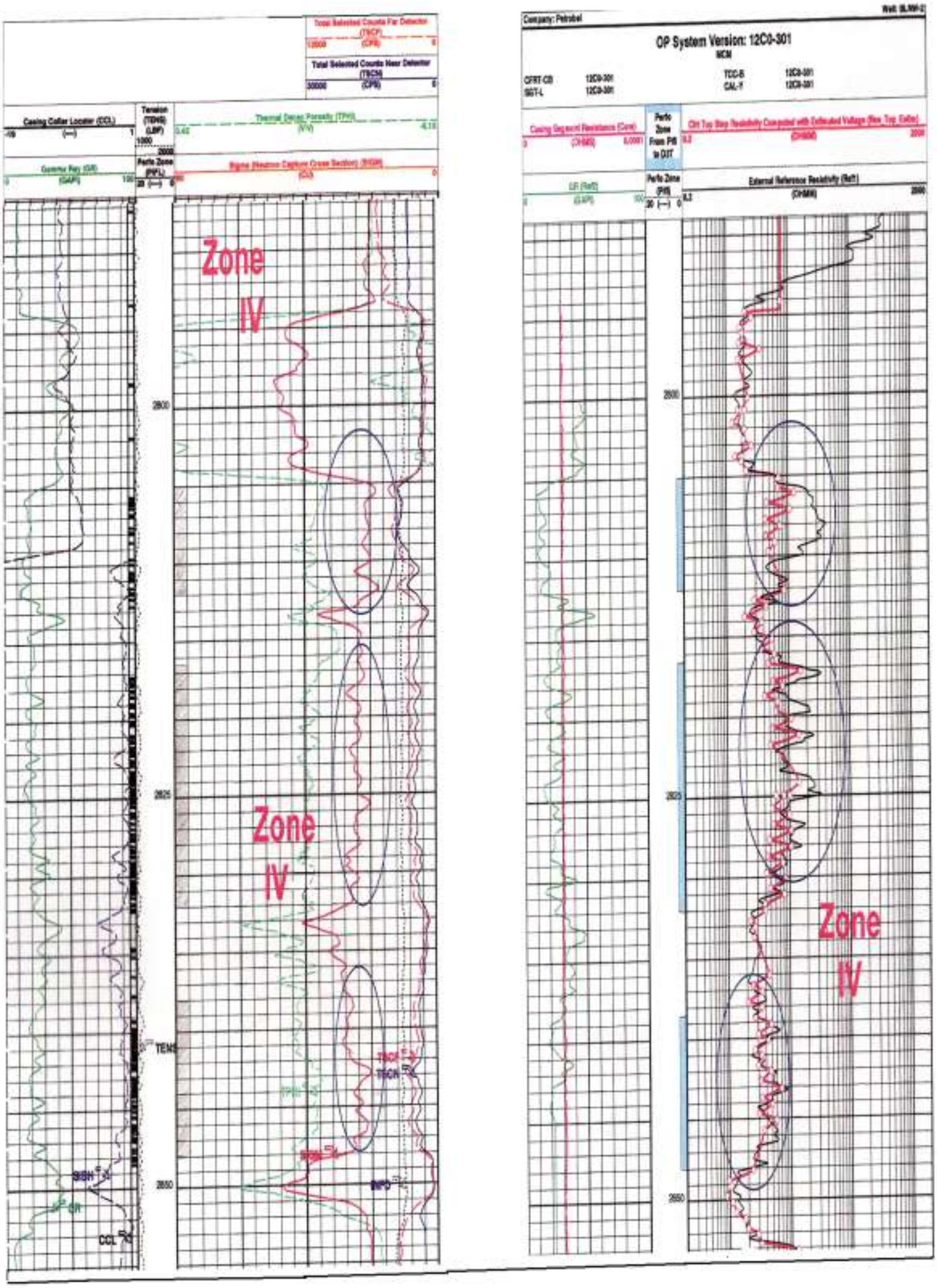

Fig. 6a TDT and CHFR logs Zone IV, Well D

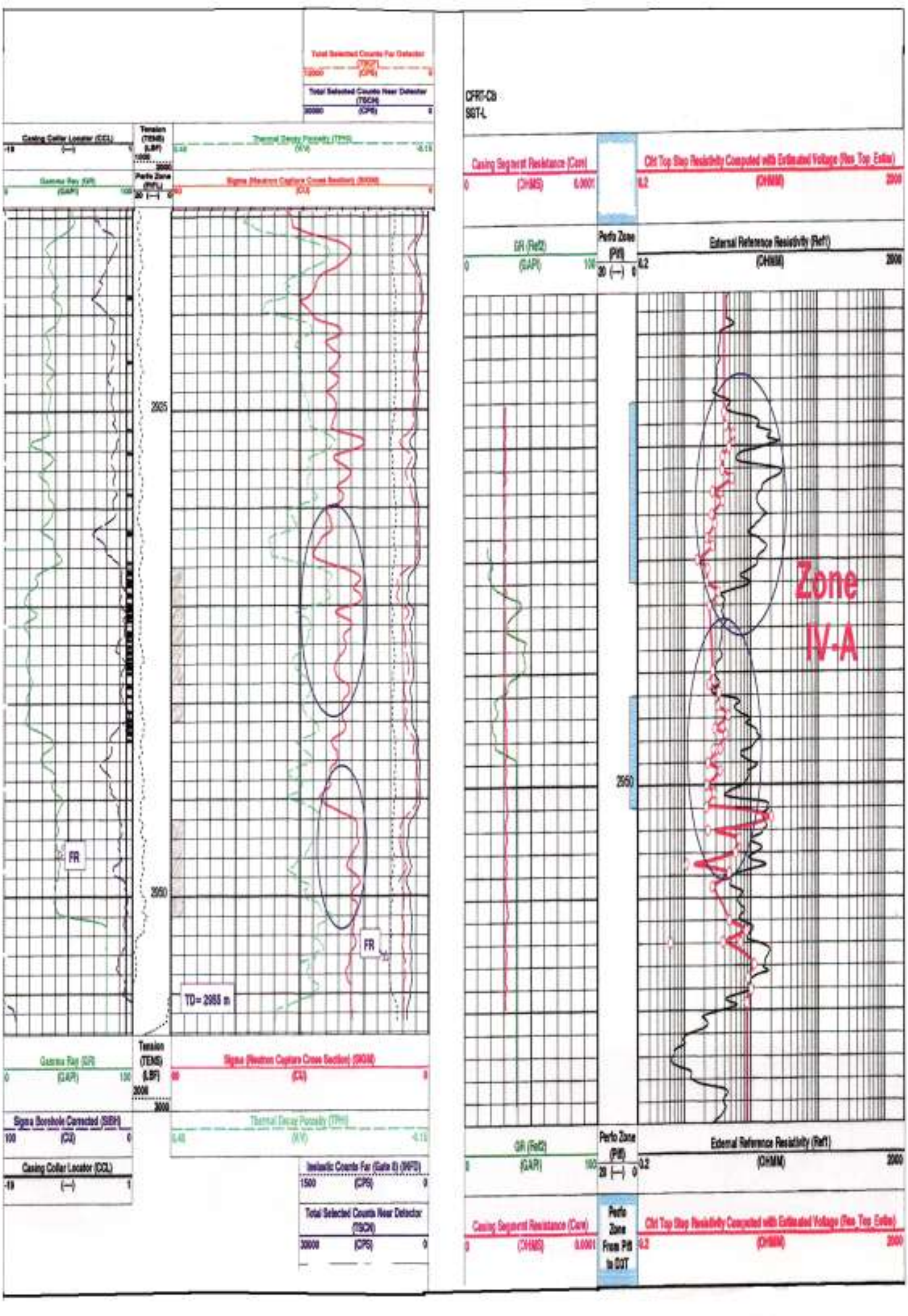

Fig. 6b TDT and CHFR for Zone IVA, Well D

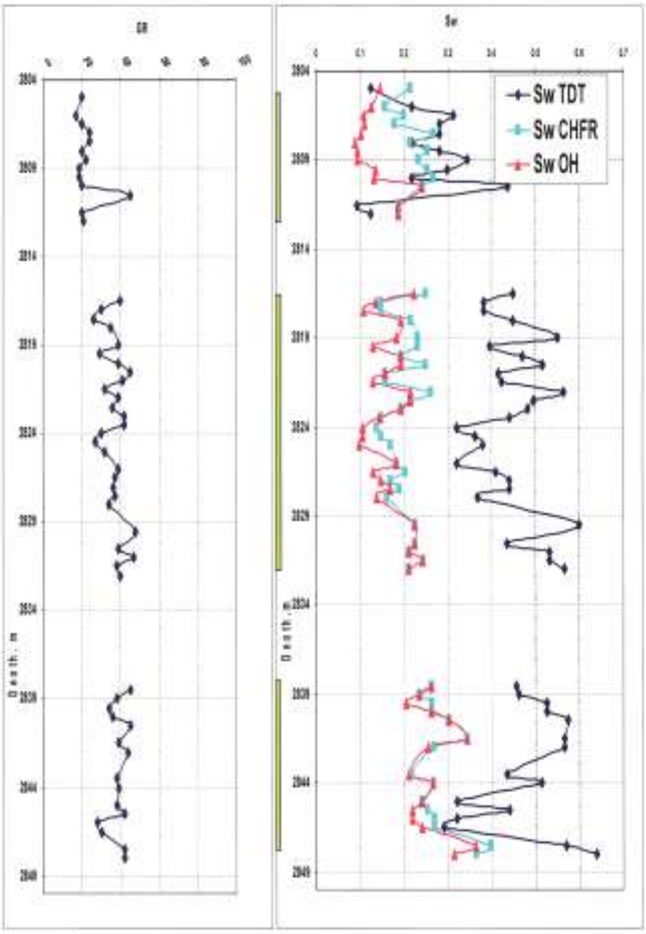

Fig.7a Water Saturation Profiles Derived from LLD, TDT and CHFR Logs for Zone IV, Well D

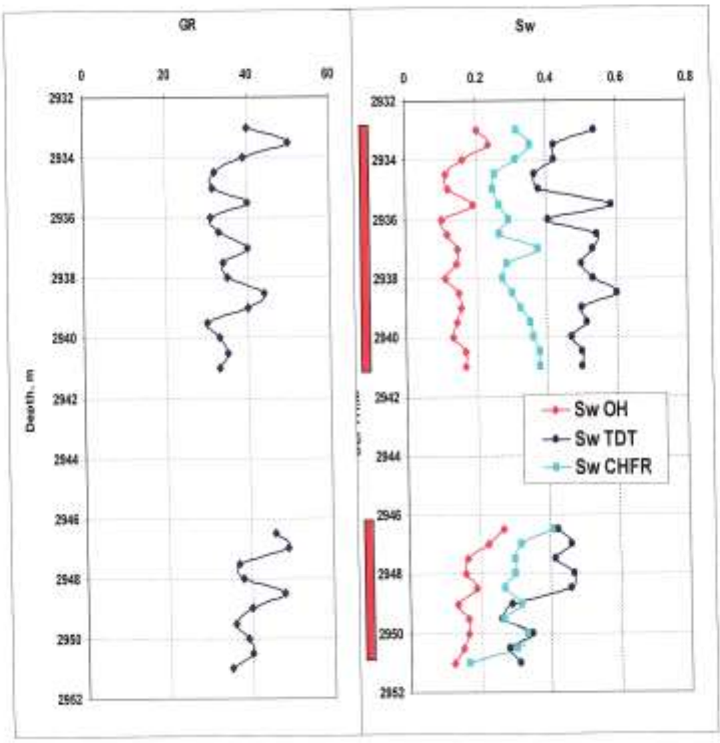

Fig.7b Water Saturation Profiles Derived from LLD, TDT and CHFR Logs for Zone IVA, Well D