WELL LOGGING REQUIREMENTS FOR MISCIBLE FLOOD PROJECTS IN THE PERMIAN BASIN

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ABSTRACT

New wireline logging services and procedures are supplying much needed answers to modeling CO_2 floods in the Permian Basin. The new measurements of photoelectric absorption cross section, gamma ray spectrometry and dielectric permitivity from LDT[TM], NGT[TM], and EPT[TM] are combined with CNL[TM], BHC[TM] and resistivity measurements in a Synergetic[TM] log called VOLAN[TM]. Volan supplies the all important lithology, porosity, permeability and residual oil saturations needed for reservoir description. Cased reservoir description is now obtaining lithology, porosity, vertical permeability distribution, and oil saturations through casing. The GST[TM], CNL, NGT, and BHC are incorporated into a VOLAN PS. Determining hydraulic isolation and pipe integrity has become crucial because of the high cost of CO_2. New monitor techniques using CNL, TDT[TM], and NGT show how CO_2 flood can be accurately monitored to determine both vertical and areal sweep efficiency.

INTRODUCTION

There are 100,000 producing wells and 1,000 waterfloods in the Permian Basin. If CO_2 flooding were to recover an additional 10% of the oil in place, the nation's reserves would be increased by 20 percent. Therefore an extremely large investment is being placed into CO_2 flooding several West Texas oil fields; some fields exceeding 1200 wells. An operator of a 650 well field plans to inject 250 billion cf of CO_2 at a present value of $1.2 per mcf ($310 M). Since CO_2 so dramatically affects the cost to produce a barrel of oil (usually around $10 per barrel) new care must be taken to control flooding.

This paper discusses the wireline evaluation of CO_2 floods. Economic considerations are presented for increased information gathering. The logging measurements that can meet these requirements are considered.

ECONOMIC CONSIDERATIONS

More information about the reservoir is needed at the time tertiary production is being considered. The conventional logs, cores and production data will not be sufficient when considering the financial commitments involved with miscible flooding. Some operators have started injecting CO_2 with just the information previously stated. These projects conducted with this "waterflood mentality" often turn sour. Proper information gathering and completion techniques may be impossible to obtain after CO_2 flooding begins. Good data can prevent an unprofitable project from being started or being done in a profitable manner. It is extremely important to understand the costs involved in flooding with CO_2. To acquaint the reader with the "waterflood mentality" consider the following statements often expressed:

> " We are just going to pump some CO_2 into the ground and see what happens."
>
> " This CO_2 flood is marginal so we can't afford to spend a lot of money on fancy logs and such."
>
> " I don't know how much this CO_2 is going to cost per barrel of oil, but I know it will help with the Windfall Profits Tax. That's why we're doing it I think."
>
> " When we modelled our CO_2 flood we didn't worry about the loss of water under waterflood. Mechanical problems like cement and casing are up to the field to solve."

These comments contrast the engineered floods, with operators who are aware of the problems:

> " Our estimate for the cost of CO_2 per barrel of oil is $11."
>
> " If we lose 15% of our CO_2 to the wrong zone whether its due to cementing problems or not selecting the correct perforations, that is more than the cost of drilling the well."
>
> " 20% of the expense in our CO_2 flood is due to drilling and completing the wells, 80% is CO_2 related."

Projects that lost water during waterflooding and are applying the same completion techniques to CO_2 – such as insufficient reservoir description, not examining and repairing cement and casing, not monitoring the flood closely – can forget about that marginal profit and can get set for a real financial disaster!

DESCRIBING THE RESERVOIR

New technology has enabled the accurate determination of lithology in complex reservoirs using well log data. Incorporating the Litho-Density (LDT), Compensated Neutron (CNL), Natural Gamma-Ray Spectrometry (NGT), and Borehole Compensated Sonic (BHC) measurements in the advanced computer software of VOLAN (Volumetric Analysis of the Resevoir) the different elements making up the lithology are described. Knowing the lithology increases the accuracy of the calculation of porosity. Lithology and porosity are necessary for the calculation of water saturation and producibility. From porosity and water saturation, a log derived permeability can be calculated. See Figures 1, 2, and 3.

In waterflooded reservoirs, there is often a problem in knowing what the water resistivity (Rw) of a zone is due to the injection of waters of varying salinities. The calculation of oil from the deep resistivity becomes only qualitative. To evaluate such zones for tertiary production we measure the water saturation of the flushed zone (Sxo) which is mostly influenced by the salinity of the drilling fluid (Rmf) which is known. There are 2 tools for determining Sxo: the Electomagnetic Propagation Tool (EPT) and the Micro-Sperically Focused Log (MSFL). The EPT has significant advantages over the MSFL. The EPT has a shallower depth of investigation (1 to 3 inches) and is independent of "M" and "N". In moderately saline muds, the EPT also calculates Sxo independent of Rmf. However, when the mud is salt saturated, the EPT Sxo is dependent upon Rmf. In this environment the MSFL also works well. Furthermore by running both tools it is possible to calculate a continuous "M" to improve the Sw calculation from Archie equations.

It is extremely important to know the Sxo when drilling overbalanced. This number best represents the minimum amount of oil that will be left after waterflooding. The pressure at the drill bit will push oil back more effectively than waterflooding. In conventional log analysis determination of the oil-water contact indicates the lowest point in a zone where oil is to be recovered. This is no longer true when considering zones for tertiary recovery. Though the zone may contain no primary or secondary oil which can be displaced by drill bit pressure, high residual oil may make zones below the oil-water contact commercial. This measure of the amount of residual oil below the oil water contact allows operators to add zones as they become commercial. Though these zones will produce with a high water content, they often extend over long intervals and may represent important future reserves.

In some fields a reasonable value of Rw can be estimated from the logs. Using the EPT to determine residual oil saturation, and deep resitivity to determine the water saturation of the zone, it is then possible to determine the amount of primary and secondary oil remaining. This allows the operator to pick perforations that limit early water production by producing the free oil first and then adding perforations at a time when it is most advantageous to recover the tertiary oil objectives.

Cased Reservoir Evaluation

The Gamma Spectrometry Tool (GST) has made reservoir description through casing possible. The GST measures the gamma ray energy levels given off by the elements of the formation when bombarded with high energy neutrons. The relative contribution of sulphur, silcon, calcium, iron and chlorine are measured to determine lithology. Knowing lithology the porosity measurement can be corrected. A reading of 15 PU on limestone matrix from a CNL indicates the porosity is 15 PU limestone or 7.5 PU dolomite or 19 PU sandstone. Though the CNL is our best cased hole porosity measurement we need to measure the lithology continuously through the zones to determine the porosity. Water saturation is calculated two ways. The first, based on "Dual Water Model Cased Reservoir Analysis" (Schlumberger, 1980), is water salinity dependent and calculates water saturations by measuring the macroscopic capture cross-section (Σ). The second is independent of water salinity which is very important for waterflooded reservoirs. The GST measures the ratio of carbon-oxygen. By measuring the porosity and lithology, the amount of carbon from the hydrocarbons and the rock can be compared with the oxygen from H_2O and lithology to determine the oil saturation. (Gilchrist, 1983). Both methods are dependent upon measuring the lithology but with the second it is critical. As most CO_2 floods are conducted with cased injectors and producers, being able to determine oil saturation through casing is extremely important. To evaluate the effectiveness of the flood it is necessary to determine what percent of the oil is being removed from what zone and at what time. This is the key to flooding effectively. See Figures 4 and 5.

CASING AND CEMENT EVALUATION

Cement Evaluation

To determine if there is a need for cement evaluation look at the track record for the field: How much water was lost during waterflooding? Is it going to be more difficult to keep CO_2 within zone? Was the cement used (or being used) subject to attack by CO_2? Should the cement be monitored over time? Guessing whether wells are isolated is not economically sound.

The CET is an answer to an EOR prayer. It gives a circumferential evaluation of the cement distribution around the pipe to spot channelling. With the combination of the CBL-CET it is possible to evaluate the distribution of cement, gasified cement, water and gas in the casing annulus (Catala, 1984).

Casing Evaluation

Knowing the condition of the pipe and the rate at which it is corroding is imperative. If holes exist they must be repaired or CO_2 losses will remove any chance of profit. The use of inhibitors is expensive but necessary. However, monitoring metal loss in casing can prevent their over use and determine an optimum rate of inhibitor injection. The Pipe Analysis Tool (PAT) and Electromagnetic Thickness Tool (ETT) can evaluate the condition of the pipe and monitor corrosion with time.

MONITOR LOGGING

The expense of CO_2 has required that accurate monitoring be done to prevent its waste. Monitor logging is a method to evaluate changes with time. A log is run before changes are expected. A monitor log is run to measure what changes have taken place. This time lapse logging may be the only method to measure small changes accurately.

Several different tools and combinations of methods can be used to monitor a flood. These methods use the following tools: NGT, CNL, TDT and PLT[TM].

No matter which method is chosen, repeatability is extremely important. Multiple passes at low logging speeds are recommended. These should be depth shifted and merged to improve statistical accuaracy and prove repeatability.

Natural Gamma Ray Spectrometry Monitor

Radioactive tracers are used to determine which zone is being flooded. The method consists of dumping a slug of radioactive material into an injector and running gamma ray logs on a monitor well drilled between the injector and the producer (Albright, 1984). This well could be cased with steel or fiberglass. The results from monitoring show (see Figure 6):

Compensated Neutron Monitor

The CNL responds to CO_2 or N_2 by showing a decrease in the hydrogen index. CO_2 has no hydrogen while H_2O and hydrocarbons do. The porosity calculated by the CNL is therefore reduced as the saturation of CO_2 or N_2 increases. The following equation is used to calculate CO_2 saturation (Powell, 1980) see Figure 7:

$$S_{CO_2} = \frac{\phi_{CNLbaselog} - \phi_{CNLmonitorlog}}{\phi_{CNLbaselog}}$$

The excavation effect has been shown to be negligible for porosities over 10 PU and is believed negligible for lower porosities.

When the CNL is run with IES resistivity monitor the difference in response is used to show the oil bank being pushed in front of the CO_2.

The BHC-CNL overlay is a good detector of gas and CO_2. The sonic porosity will be increased slightly if CO_2 is in gas phase, otherwise will show no change in porosity. The BHC-CNL overlay shows the typical cross-over expected with gas. This is very helpful when there are no base logs available and CO_2 injection has already taken place. To get a good overlay the CNL must be lithology corrected and the BHC porosity should be calculated using Hunt-Raymer (not Wyllie) sonic transit time to porosity transform (Raymer, 1980). See Figure 8.

Thermal Neutron Decay Time Monitor

Most CO_2 monitoring must be done through tubing. The CNL provides a good measure of CO_2 saturation, however its smallest tool size is 2.75 inches in diameter. The TDT is therefore a good alternative to the CNL.

The TDT provides a pseudo resistivity and neutron porosity through casing. The TDT measures the rate of absorption of thermal neutrons by the formation. The decay rate (τ) is related to the thermal neutron capture cross-section (Σ) by the equation:

$$\Sigma = \frac{4550}{\tau}$$

For San Andres formation in the Permian Basin typical values of Σ are:

$$\Sigma_{water} = 70$$

$$\Sigma_{oil} = 20$$

$$\Sigma_{CO_2} = 0$$

The Σ_{water} will vary as Rw varies. If the Rw remains relatively constant an increase in water will be reflected by an increase in Σ, a decrease in Σ will indicate an increase in oil or more likely an increase in CO_2 saturation. See figure 9.

The ratio of the counts at the near and far detectors is crossplotted with Σ to determine porosity. Similar to the CNL, the TDT measured porosity decreases with increases in CO_2 saturation since it also responds to changes in the hydrogen index. Under favorable conditions, three phase saturations can be determined from ratio and Σ measurements (Svor, 1982). See figure 10 and 11.

The TDT is often used to determine residual oil saturations by using the log-inject-log technique.

CONCLUSION

1. New technology allows for calculation of lithology in open and cased hole. Determining tertiary oil above and below oil-water contact is possible even after waterflooding.

2. Reservoir description is necessary before starting a CO_2 flood to determine what zones should be flooded and to quantify how each zone should respond.

3. Base logs are necessary if monitor logs are to see early response to flood.

4. CNL responds well to changes in CO_2 and is ideal for monitoring except for thru-tubing applications.

5. The TDT appears to be an adequate CO_2 monitoring method for thru-tubing applications.

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ACKNOWLEDGMENTS

I wish to thank Amoco Production Company, Cities Service Oil and Gas Corporation, Conoco Inc., Exxon Company, U.S.A., Shell Western Exploration and Production Inc., Texaco Inc., and Union Texas Petroleum Corporation, for their advice and assistance on this paper.

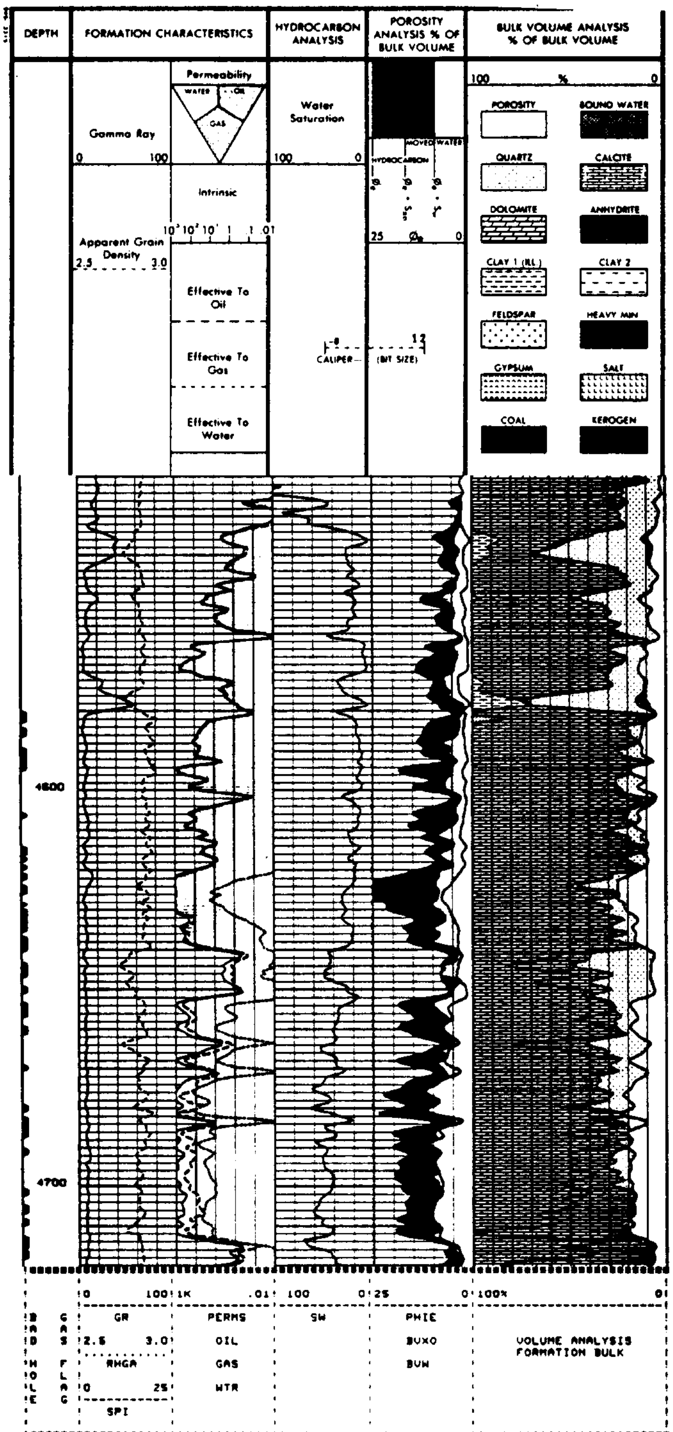

Figure 1 - In this Volan the lithology is calculated from the LDT-CNL. The black shading is the difference in the porosity measured by the LDT-CNL crossplot and the water-filled porosity measured by the EPT in the flushed zone, Bulk Volume Water in Flush Zone (BVXO). The grey shading between the BVXO and the Bulk Volume Water (BVW) is the oil moveable under waterflooding. The BVW is dependent on R_w.

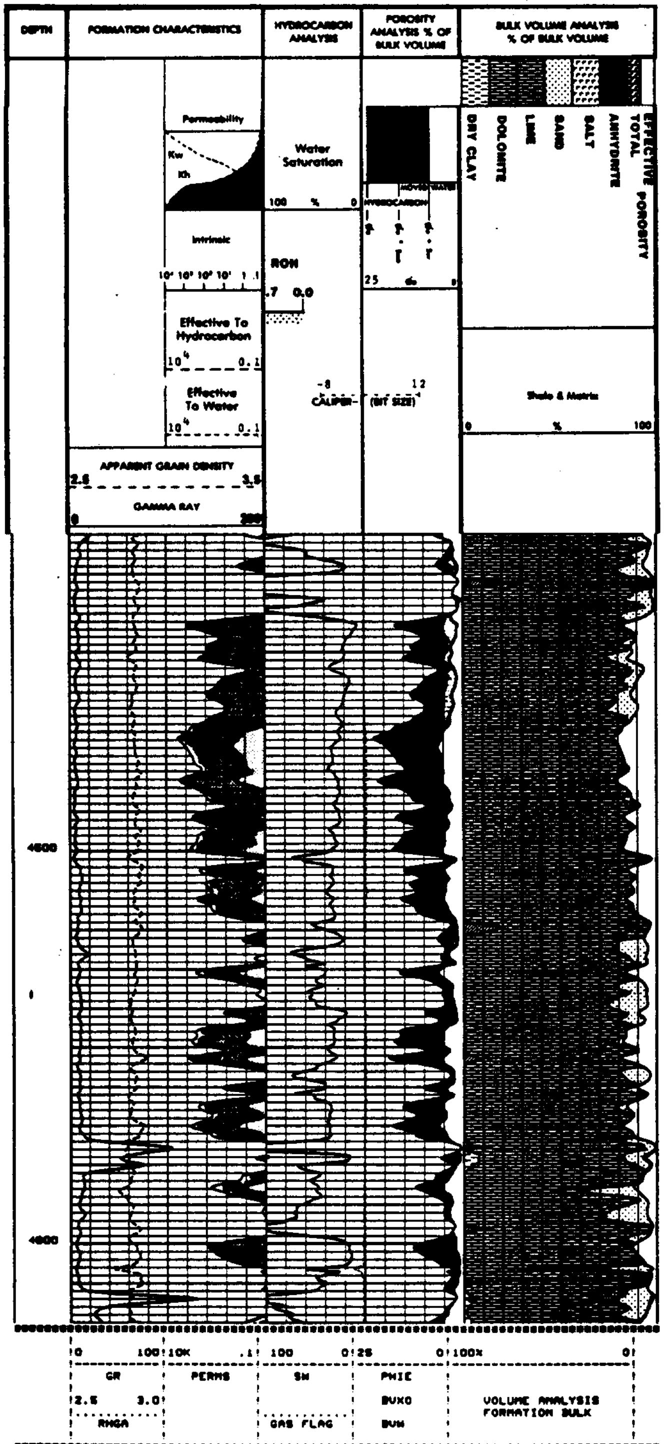

Figure 2 - This Volan is interpreted as showing very little oil that would be moveable to waterflooding. This well would be a good tertiary oil candidate.

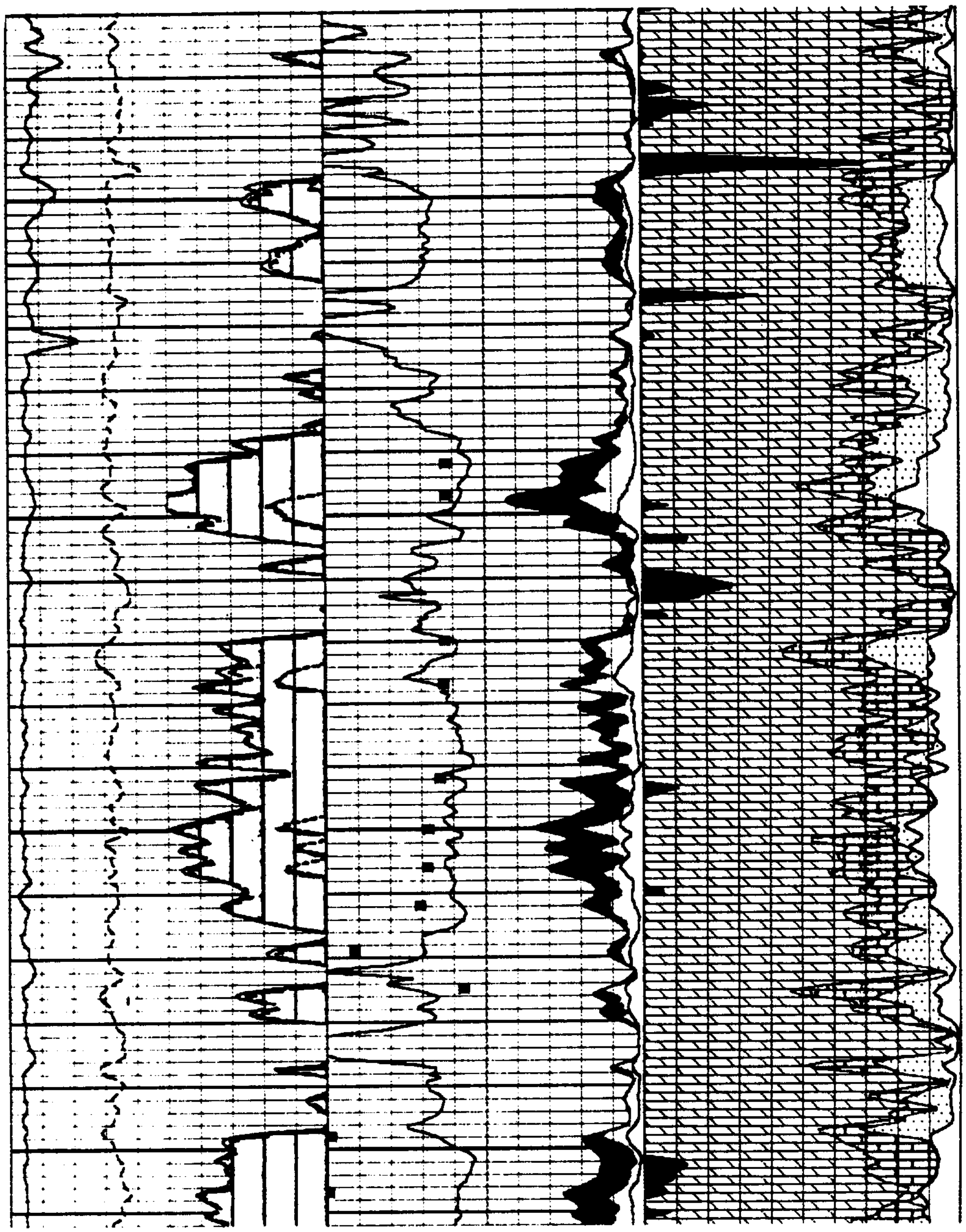

Figure 3 - RFT pressures were taken on this well and represented as the square dots. The pressure increases from right to left. Note the higher pressure readings in the bottom zone. The lower zone was also assumed to be below the oil-contact, but this log indicates that oil-water contact is deeper as shown by low BVW.

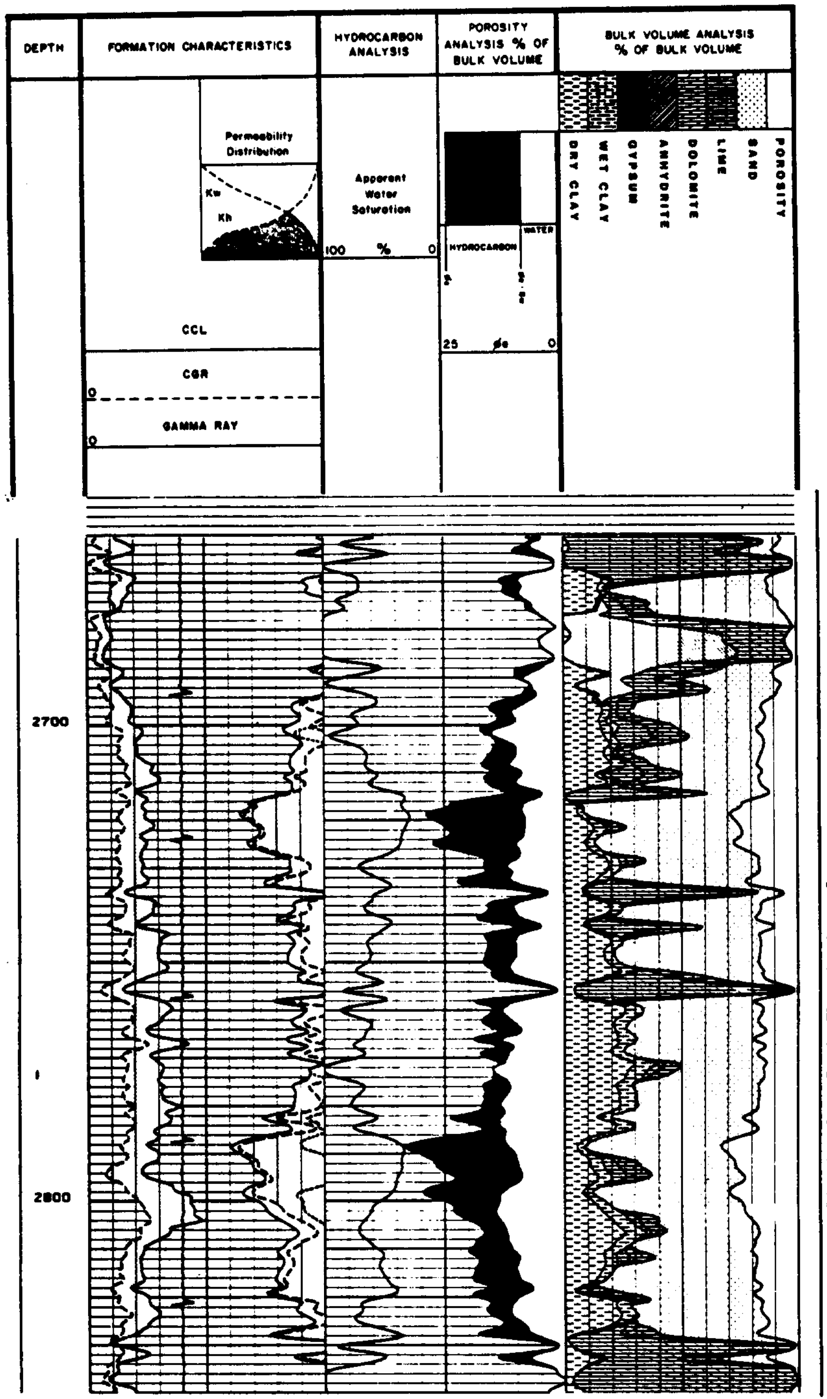

Figure 4 - Volan PS Level 1. Note that the upper zone at 2720 feet and the lower zone at 2790 feet look quite similar.

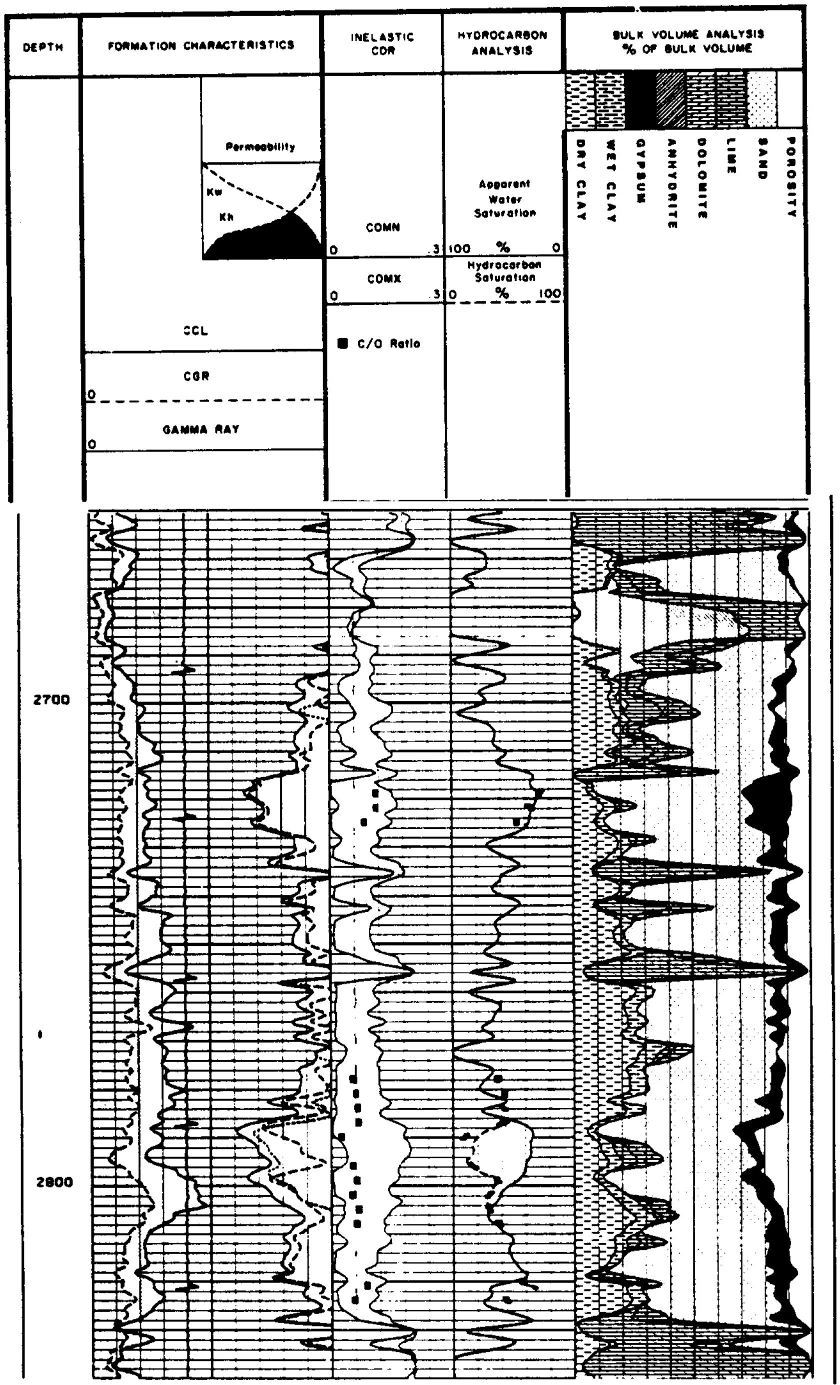

Figure 5 - Volan PS Level 2 uses the information determined in Volan PS Level 1 and also uses the measured carbon/oxygen ratio to determine oil saturation and compares this to the water saturation calculated from sigma. Note that only the bottom zone is being affected by the fresh waterflood.

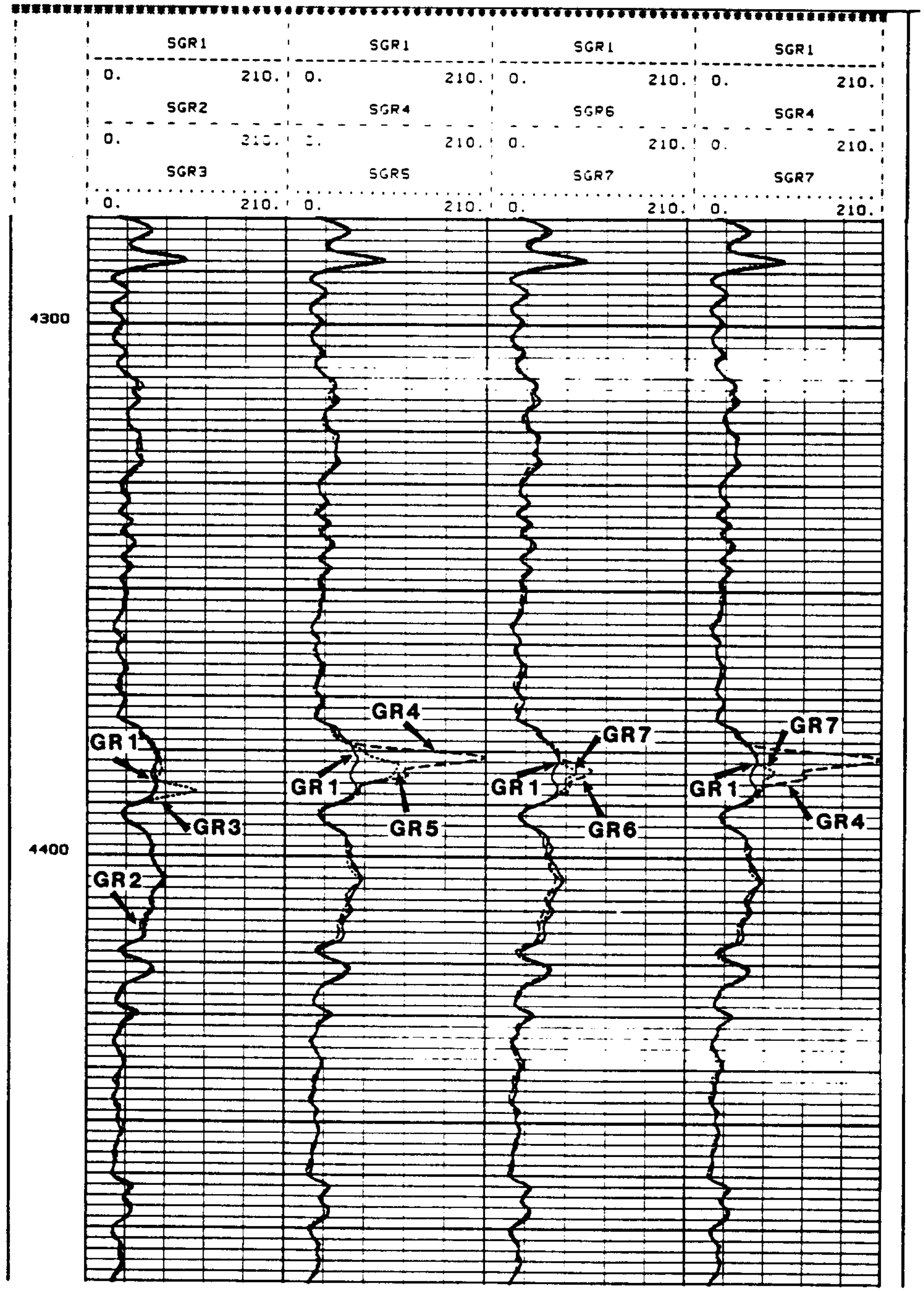

Figure 6 - Multiple time-lapse runs of gamma ray are overlayed to show where a radioactive tracer is going through formation. Note that run 4 had the largest response and by run 7 the response had all but died away.

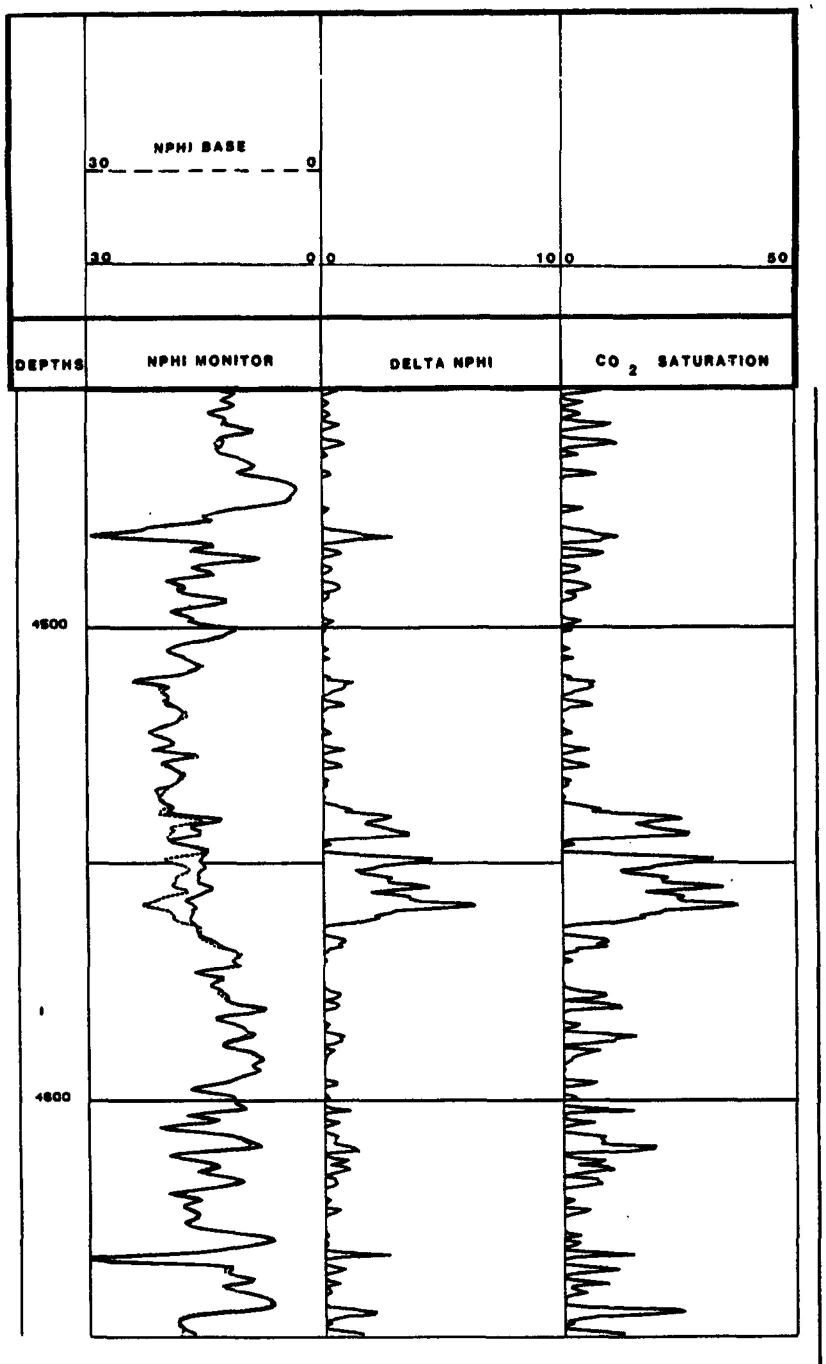

Figure 7 - CNL base and monitor runs are compared. The decrease in the measured porosity is displayed as a delta neutron porosity curve. This apparent decrease in the hydrogen index is used to calculate the CO_2 saturation curve. Note that only about one third of the zone from 4470 to 4570 feet is being flooded by CO_2.

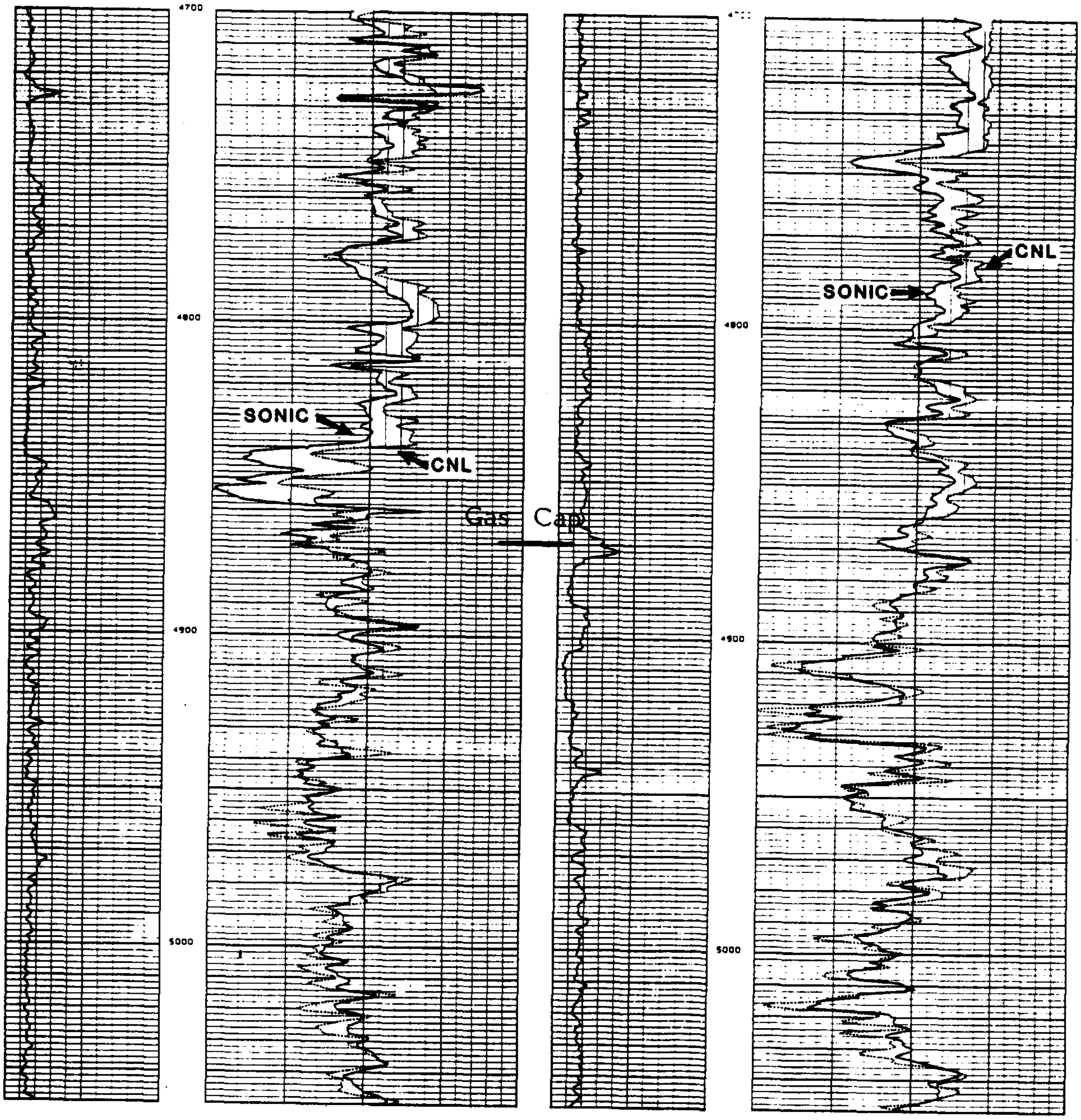

Figure 8 - The BHC-CNL overlays on two wells in a CO_2 flood are used to determine the gas cap depth across the field. The good agreement between the BHC and CNL porosities suggests the CNL can be used as a base run for calculations of CO_2 saturation.

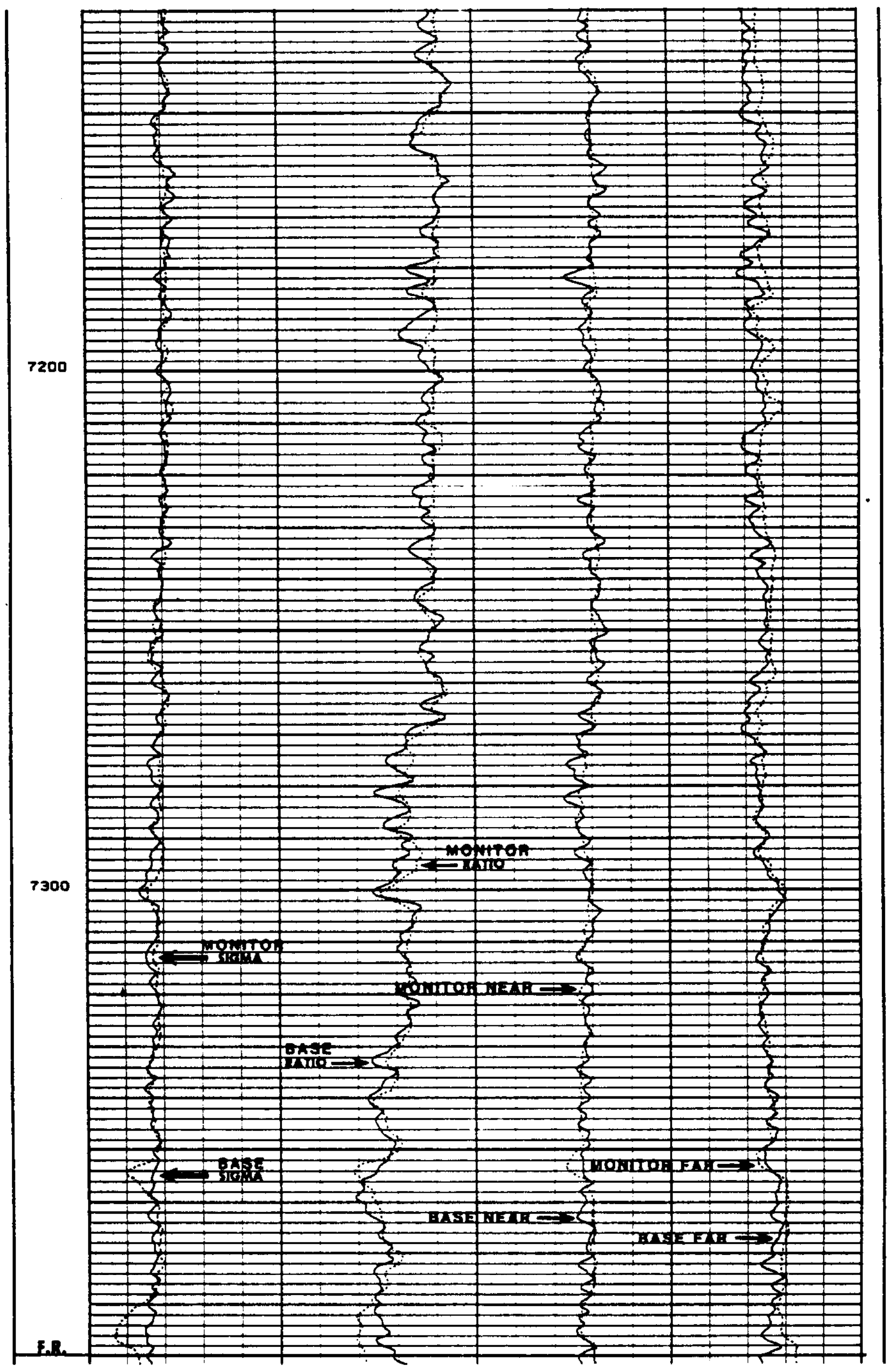

Figure 9 - The base and monitor TDT runs are overlayed. Nitrogen had been injected into the top of the reservoir between runs. Water injection is taking place at the edge of the field. From this log, the original gas cap was predicted to be at 7190 feet. The gas cap is now interpreted to be at 7235 feet with some gas fingering below as interpreted from the decrease in ratio. The increase in sigma at 7355 feet is interpreted as encroachment of water. This agreed with testing.

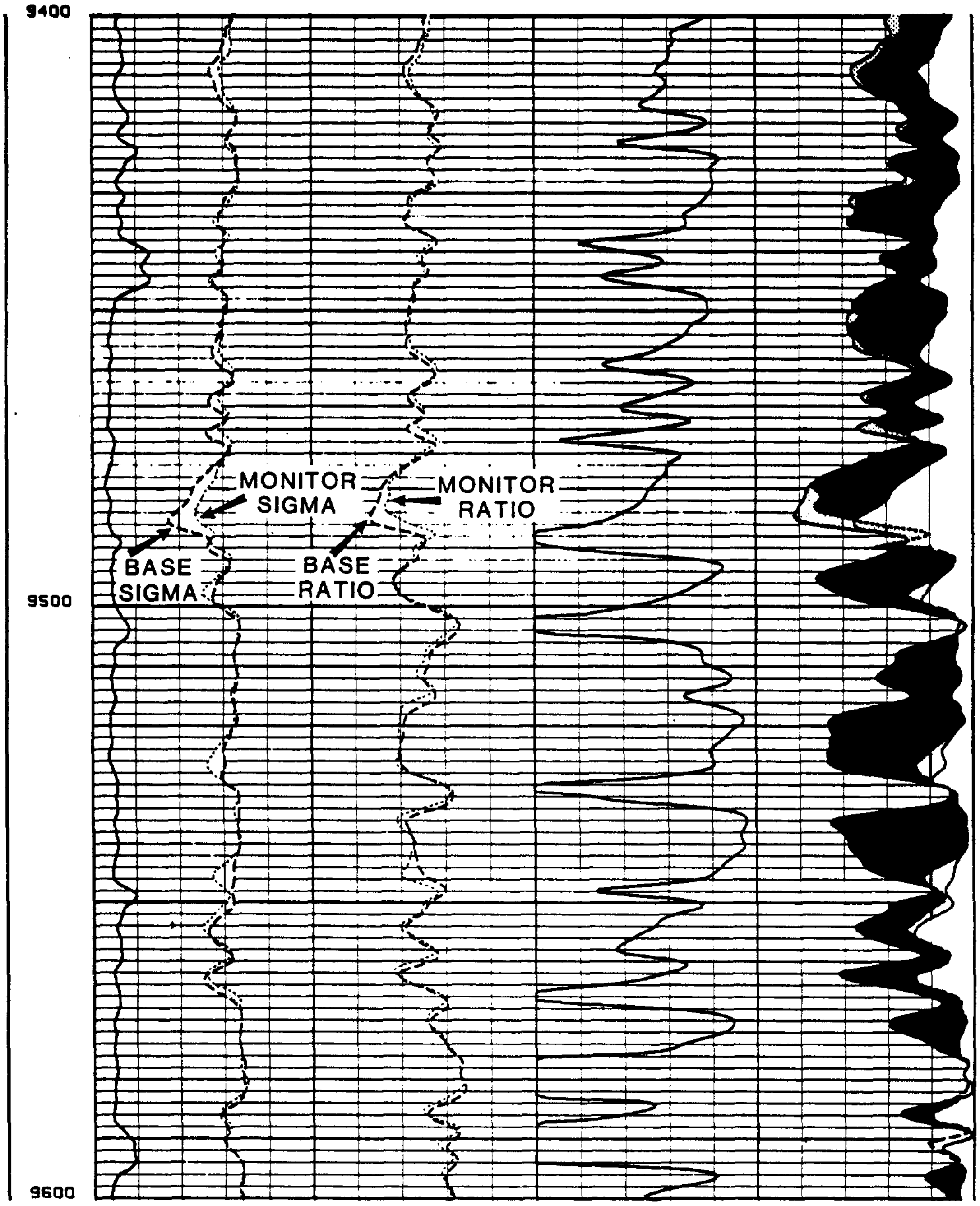

Figure 10 - This is the data from two Cased Reservoir Analysis (CRA) which were overlayed to indicate changes in CO_2 saturation and water saturation. At 9485 feet note the decrease in the measured porosity, sigma and ratio indicating a decrease in hydrogen index and an increase in CO_2 saturation. The increase in sigma and BVW at 9526 feet indicates an increase in the water saturation.

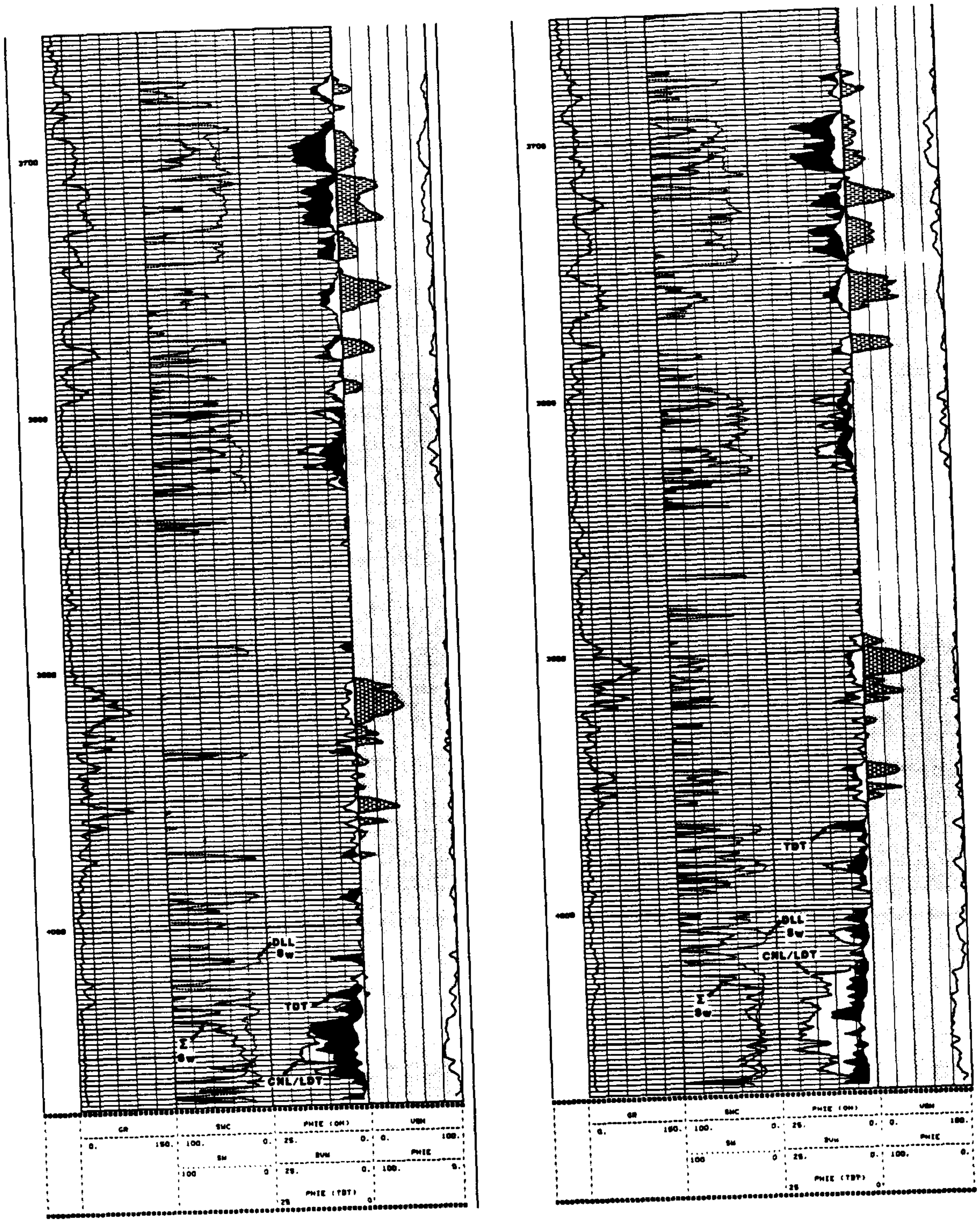

Figure 11 - No base TDT logs had been run on these two wells before CO_2 injection had been started. The open hole logs were used to establish what the porosity and water saturation was before injection was started. The TDT porosity is affected by CO_2 as seen by a drop in the calculated porosity. The TDT was interpreted as showing the bottom zone on the right hand well had high CO_2 breakthrough. This agrees with production results.