VARIATIONS IN THE ELECTRICAL BEHAVIOR OF THE EKOFISK FIELD IN THE NORTH SEA.

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ABSTRACT

Laboratory measurements on a limited number of core plugs often present an incomplete and possibly inaccurate description of the electrical properties used for the interpretation of open-hole well logs. This paper presents the methods and results of an extensive field-wide study for the highly fractured Ekofisk field to better understand the variation in the resistivity properties throughout the chalk reservoirs. Core plug preparation and accurate determination of the resistivity and fluid saturation utilized conventional laboratory methods. The use of extracted core plugs, refined oil, and synthetic brine to simplify the testing was supported by the direct comparison of resistivities from laboratory measurements with conventional well log resistivities. The laboratory results also showed that the formation factor varied with the mineralogical content of the chalk. Non-Archie electrical behavior was observed in the chalk after imbibition. The water saturation exponent after an imbibition waterflood diverged significantly from that at initial water. A comparison of the histogram of after imbibition laboratory measurements with an independent well log determination of the water saturation exponent for a water flooded zone supported the laboratory measurements. This study developed a data base of measurements on 200 plus core plugs from which correlations and techniques can be further developed to improve conventional well-log interpretation for the field.

INTRODUCTION

The hydrocarbon saturation state in most reservoirs has historically been determined via well logs using an Archie [1] calculation of the form

$$Sw = \left(\frac{1}{Ir}\right)^{\frac{1}{N}} = \left(\frac{Ro}{Rt}\right)^{\frac{1}{N}} , \qquad (1)$$

where **Sw** is the water saturation, **Ir** is the resistivity index, and **N** is the saturation exponent. The resistivity index is the ratio of **Rt**, the resistivity of the reservoir rock containing brine and hydrocarbons, to **Ro**, the resistivity of the reservoir rock containing only brine. The saturation exponent, **N,** and the relationship for **Ro** to well log porosity (ϕ) is normally determined from electrical measurements in the laboratory. The ratio of **Ro** to **Rw** (formation brine resistivity) is defined as the formation factor **(F)** and is determined by the Archie equation,

$$\frac{Ro}{Rw} = F = \frac{a}{\phi^m} . \qquad (2)$$

The tortuosity factor and the cementation exponent, **a** and **m** respectively, are obtainable in the laboratory from measurements on core plugs of known porosity containing a brine of known resistivity.

Determination of the correct values for saturation exponent, tortuosity factor and cementation exponent in the laboratory allows for the calculation of water saturation in the reservoir via the equations above from conventional well logs. The determination of correct parameters is, however, subject to a number of difficulties and limitations. Primary among these are the reliability of laboratory measurements and the degree to which the laboratory measured values match the reservoir. The reliability of laboratory measurements was improved by using independent measuring techniques and by making a large number of measurements. This provides for a more robust data set and improves the chance of identifying system parameters. The measured laboratory behavior was also evaluated against reservoir production behavior and reservoir well logs.

EXPERIMENTAL

Core Selection and Preparation: Plugs for this study were selected from 14 wells from the Ekofisk field in a manner to obtain good areal and vertical distributions (Figures 1 and 2). Although core material was not equally available from all selected wells, the core plugs were chosen to represent the available chalk core material from each well. The frequency histogram of the plug selection versus depth (Figure 2), is consistent with the dome shape of the field with less reservoir (and less core material) at the upper crest and lower flanks. The productive chalk zones identified in this field are described from the top as the upper Ekofisk, the lower Ekofisk, the tight zone (not very productive), and the Tor. The selection of plugs from these zones numbered 92, 53, 6, and 70, respectively.

The plugs were extracted by alternating multiple cycles of toluene and methanol in a soxhlet extraction unit until the toluene cycle produced no hydrocarbon discoloration. We used cleaned samples because paraffin deposition from the paraffinic Ekofisk crude oil and possible oxidation of crude components had contaminated the core material. The extraction procedure which may be specific to this field, was designed to remove the bulk hydrocarbons but retain the organic films which are believed to determine the wetting characteristics that affect the electrical behavior of the chalk.

The core plugs were studied using 1.2 molar NaCl brine and n-decane. Stock tank field crude oil was not used to avoid paraffin deposition. The NaCl brine concentration was selected to be similar in resistivity to the formation brine and to facilitate the use of the empirical Arp's equation [2] for adjusting the resistivity of NaCl brines from one temperature to another. Dry plugs were saturated using vacuum evacuation. Desaturation of the brine saturated core with n-decane to an initial water saturation (**Swi**) was accomplished by centrifuging. To achieve a uniform distribution of brine and oil, core plugs were sand packed under n-decane and centrifuged with the samples rotated and flipped end-to-end multiple times using an angled centrifuge head. MRI images validated the centrifuge procedure by showing a uniform fluid saturation distribution (Figure 3). Imbibition of 1.2 molar brine was performed on the bench-top using glass imbibition cells to measure the volume of oil produced.

Electrical Measurement: Laboratory resistivities were measured on 100 percent brine saturated core plugs, on plugs at Swi, and on plugs after imbibition (**Swf**) using a 2-electrode method with silvered electrodes at a frequency of 10 kilohertz. All measurements were made with the core plugs in a Hassler sleeve under a hydrostatic pressure of 1580 psig to approximate the net stress state experienced by the chalk under initial reservoir conditions. Electrical measurements were continued until a stabilized reading was reached.

Saturation Determination and Measurement: Laboratory determination of the saturation state in the core plugs at the measured resistivity consisted of gravimetric and volumetric measurements as appropriate. Corrections for compaction by the simulated net overburden stress were also made. Nuclear Magnetic Resonance (NMR) provided an independent confirmation of the saturation state.

Porous Disc: The porous disc desaturation method was used to desaturate selected core plugs using n-decane replacing brine with simultaneous electrical measurements. The 100% brine saturated sample was first mounted inside a Hassler cell with a water wet 15 bar porous disc butted against the outlet end. Decane pressure was applied to the inlet end, and produced brine exiting the porous disc was measured by volume. Hydrostatic overburden stress maintained good capillary contact between the disc and the core sample.

Chalk Composition: Chalk composition was determined by mass spectroscopy. The quartz content of the chalk was calculated from the silicon fraction.

RESULTS AND DISCUSSION

Formation Factor: An examination of the formation factor data showed a distinct variation with the quartz content of the chalk. It is possible to identify two major trends separately plotted as Figures 4 and 5. One trend exists for the low quartz containing chalk (generally less than 5%) of the Tor and lower Ekofisk formations and another one exists for the higher quartz containing chalk of the upper Ekofisk formation and the tight zone. Outlier points above the trend in Figure 5 were confirmed through repeated tests. These outliers contained a higher quartz content than the samples that comprised the trend. A regression fit of the data determined "a" equal to 0.72 and "m" equal to 2.14 of equation 2 for the lower Ekofisk and the Tor formations which is similar in form to the Humble equation [3] often used for softer rock. The traditional Archie equation with "a" equal to 1 and "m" equal to 2 for formation factor appeared to fit the upper Ekofisk and the tight zone.

The effect of quartz on the formation factor was probably related to the change in the structure of the chalk brought about by the presence of quartz. The permeability of quartz containing chalk was observed to be generally less than the permeability of purer forms of chalk.

Saturation Exponent at Initial Water Saturation: Electrical measurements during porous disc desaturation were used as an independent measurement to validate centrifuge desaturation followed by electrical measurements. Both methods yielded comparable saturation exponents at similar initial water saturations (Figure 6). The porous disc technique provided detailed resistivity information with varying saturation, but it can take an exceedingly long time (months) to complete a set of measurements per core plug. The centrifuge technique combined with conventional electrical measurement procedures allowed for the rapid evaluation of the saturation exponent at a single saturation state (Swi or Swf).

The laboratory measured resistivity indices for a typical Ekofisk field well are shown in Figure 7. There were no apparent trends observed by formation, except for the segregation by permeability and porosity. Initial water saturations were higher for samples with lower porosity and permeability as reflected in the higher initial water saturations for the upper Ekofisk (Table 1 summarizes the range of chalk properties in this study). Some decrease in the slope of the data may be occurring at very low water saturations (this was observed for 1 to 2 data points per well from a number of wells) suggesting non-Archie type behavior. (Archie type behavior requires a constant slope to this data on a log-log plot which passes through Ir equal to 1 at 100% water saturation.) It was not unexpected that the empirical Archie relationships may fail at low water saturations as they were originally formulated for drainage in various porous media at water saturations 15% and above [1]. Givens [4] reported that apparent non-Archie behavior can occur in reservoir rocks and that the existence of a decreasing slope at low water saturations could indicate a parallel conductive path independent of the rock/fluid electrical properties predicted by the Archie relationships. In viewing individual wells or the bulk of the data (Figure 8), it was concluded that there was insufficient justification for the use of a non-Archie method to calculate initial connate water saturation for the Ekofisk reservoirs. Any error would be insignificant when compared to other potential errors in log interpretation.

To evaluate laboratory behavior, laboratory determined resistivity indices at initial water saturation were compared with the well log determined deep resistivity indices versus depth and versus porosity. To make the comparison, laboratory resistivity indices were calculated from measured Rt and Ro values. Well log resistivity indices were calculated from environmentally corrected well log measured deep resistivities for Rt and from well log porosities using formation water resistivities (originally determined by sampling) for Ro. Both indices were adjusted to a common temperature (77 degrees Fahrenheit). A typical comparison (Figures 9 and 10) showed good agreement. However, apparent good agreement between the lab and field electrical data can not by itself ensure that the reservoir and the laboratory behave consistently. Four variables determine electrical behavior. They are: (1) the structure of the chalk, (2) the brine saturation in the chalk, (3) the resistivity of the brine in the chalk, and (4) the distribution of the brine in the chalk pore spaces. To compare electrical behavior with well logs, an appropriate accounting must be made for each of the four variables. The structural properties of the reservoir chalk were assumed to be matched by using core plugs from the reservoir with porosities which agreed with the log determined porosities (over the same cored interval) and by operating under reservoir like stress conditions. The resistivity of the brine was reconciled by measurements of the laboratory and reservoir brine resistivities and by the Arp's equation to correct between reservoir temperatures and laboratory temperatures. The appropriate wettability and brine saturation were established by considering field production behavior and well log observations. If the field reservoirs were oil-wet or near neutral, much of the connate water would be in the center of pores and fractures and therefore would have been mobilized during primary depletion. The wells in this field produced little water during primary production. The absence of appreciable water production coupled with low clay content in the chalk indicated that the initial brine saturation was low. Electrical logs such as the laterolog were used on occasion in this field. Since these logs required continuous current brine paths through the chalk formation to work, connate water must be located as films along the pore walls with the oil located in the center of the pores (water-wet distribution of fluids). The cleaned Ekofisk core plugs were water-wet and had initial water saturations that were appropriately low. The resultant laboratory state of the cleaned core plugs was therefore considered consistent with the initial connate water state of the Ekofisk field reservoir.

Saturation Exponent after Imbibition: It was observed that the laboratory resistivity indices measured after imbibition resulted in saturation exponents that were greater (Figure 11) than the saturation exponents determined at initial water saturation. The higher imbibition resistivity indices showed an increase in the slope of the data from the expected Archie behavior. Unlike the possible decrease in the slope observed at low initial water saturations, this change was due to the oil/water/chalk system becoming less conductive (more resistive) than the Archie relationship. The saturation exponents after imbibition also appeared to have a dependancy on the final water saturation (see Figure 12). Since higher final water saturations after imbibition are primarily a reflection of more strongly water-wet core plugs, it is possible that this non-Archie behavior is related to the wettability of the chalk. The literature [5] has normally reported that only less water-wet rock have higher electrical resistivities. The observed behavior for the chalk after imbibition showed the opposite. The authors did not know of any published non-Archie relationships to describe this electrical behavior for well-log interpretation. The development of such relationships was beyond the scope of this study.

The measured saturation exponents after imbibition were observed to vary with depth as seen in Figure 13. The shallower sections of the field trended towards a lower saturation exponent while the deeper sections trended towards a higher saturation exponent.

As previously, to evaluate the laboratory behavior, laboratory determined resistivity indices after spontaneous water imbibition were compared with the well log determined near well bore resistivity indices versus depth and porosity (Figures 9 and 14). The resistivity indices were determined similarly to that previously described at initial water saturation with the exception that a near wellbore log resistivity replaced the deep well log resistivity. The coring process in this well was done with a water based mud, and as a result, the near well bore region has undergone a waterflood. Initial displacement of oil near the well bore may have resulted from spurt loss followed by a long period of filtrate seepage through the mud filter cake. The ultimate displacement of oil near the well bore appeared to be equivalent to the laboratory spontaneous imbibition values. The similarity in the resistivity indices after spontaneous imbibition in the laboratory to that of the well logs also indicated that the state of the core plugs was electrically consistent with the reservoir.

An independent determination of the saturation exponent after waterflood was available from the field where a water flooded zone in the Tor formation was logged with a suite of Schlumberger tools. The near well resistivity from the Micro Spherically Focused Log and the deep resistivity from the Dual Induction Log closely overlaid when adjusted for differences in formation water resistivity and mud filtrate resistivity (Figure 15). This indicated similar water saturations near and far from the well bore. A Reservoir Saturation Tool (continuous carbon/oxygen log) was used to determine a non-Archie near-well water saturation. With measurements from this combination of well logs, water resistivities, and porosity from a Formation Density Compensated log, it was possible to directly calculate the saturation exponent for the water flooded zone from rearrangement of equations 1 and 2. The resultant saturation exponent frequency histogram from the well logs compared favorably with that measured in the laboratory for the Tor formation (Figure 16). This is perhaps the strongest evidence supporting the core selection, laboratory preparation and measurement techniques utilized in this study of the Ekofisk field chalk.

CONCLUSIONS

1) Well logs and reservoir behavior indicated the correct electrical behavior for laboratory measurements and the appropriate core preparation methods. Extracted plugs, refined oil, and synthetic brine were suitable for reservoir electrical studies in the Ekofisk field.
2) The trends in the formation factor was observed to vary with the quartz content of the chalk. The quartz content of the chalk may have affected the structure of the chalk and hence the electrical behavior.
3) The saturation exponents after imbibition at high water saturations exhibited non-Archie behavior with a dependency on water saturation. The limitations of the Archie methods were recognized under these circumstances.
4) The saturation exponent in the chalk after imbibition was significantly greater than that before imbibition. The use of a saturation exponent determined for drainage would have introduced a substantial error in water saturation for water flooded zones.
5) The large data base provided data sufficient to see relationships between variables. The verification of the data via different laboratory measurement techniques helped avoid laboratory artifacts which could have rendered such a data base unreliable.

Acknowledgments

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Table 1
Average Core Plug Properties

Formation	Porosity	Permeability	Swi	Swf
Upper Ekofisk	32.3%	4.28 md	14%	61%
Lower Ekofisk	34.0%	6.11 md	7%	68%
Tight Zone	20.0%	0.49 md	33%	64%
Tor	30.3%	6.63 md	8%	68%

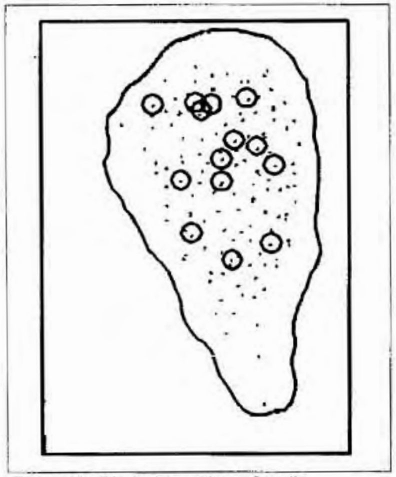

Figure 1: Circled location of wells providing core material for this study.

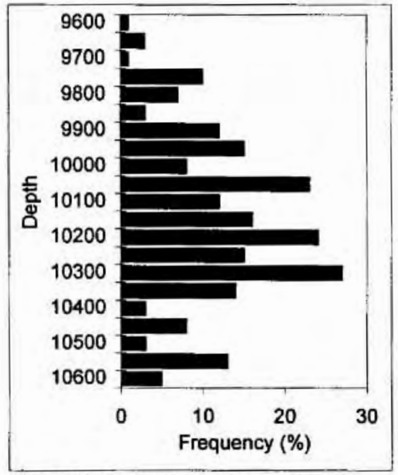

Figure 2: Frequency of core plugs by depth.

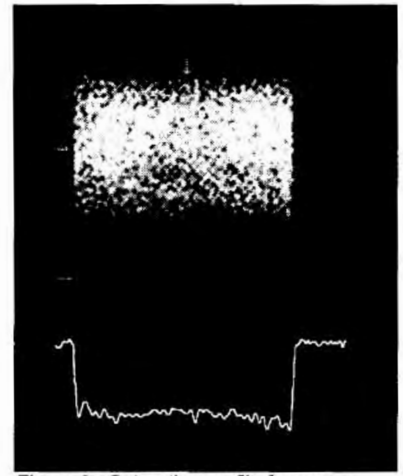

Figure 3: Saturation profile for a core plug prepared by centrifuge.

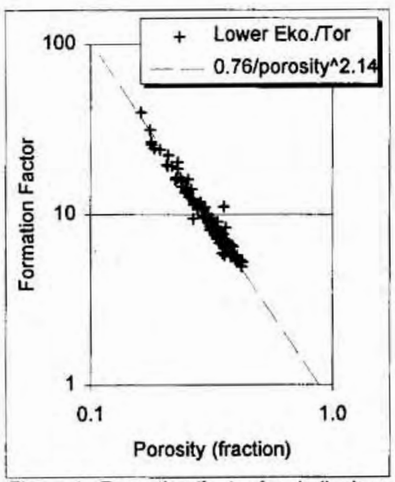

Figure 4: Formation Factor for chalk plugs with low quartz content.

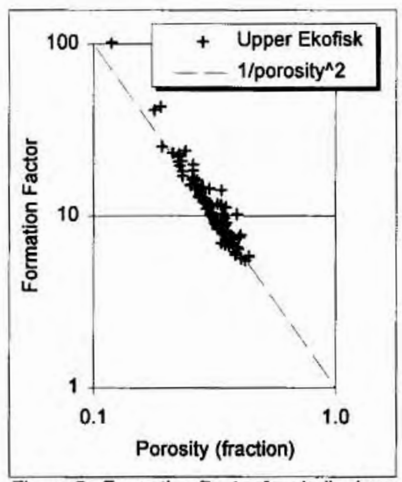

Figure 5: Formation Factor for chalk plugs with high quartz content.

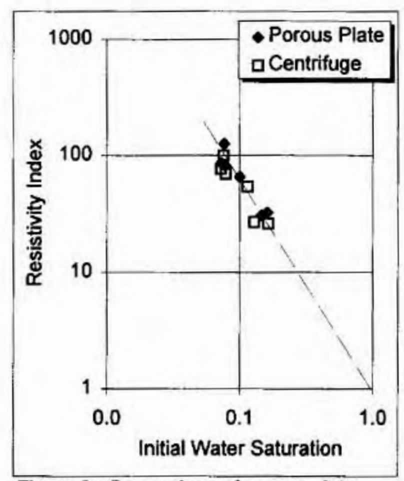

Figure 6: Comparison of porous plate results with centrifuge results.

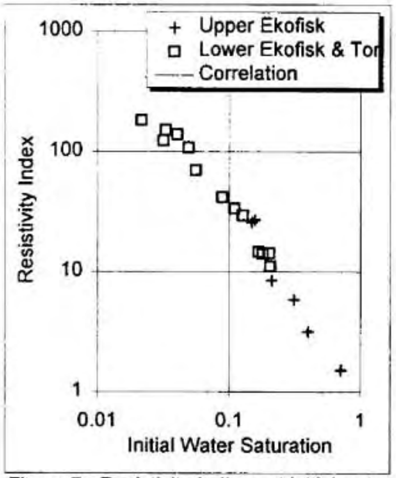

Figure 7: Resistivity Indices at initial water saturations for core plugs from a single well.

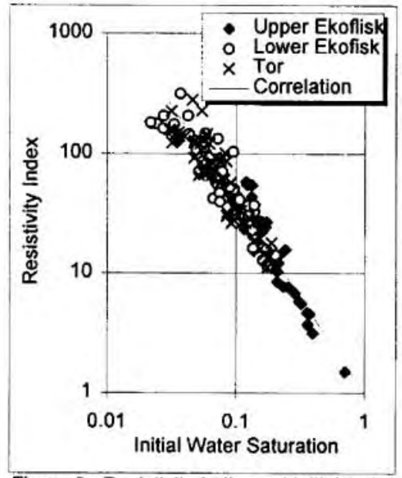

Figure 8: Resistivity Indices at initial water saturations for all core plugs.

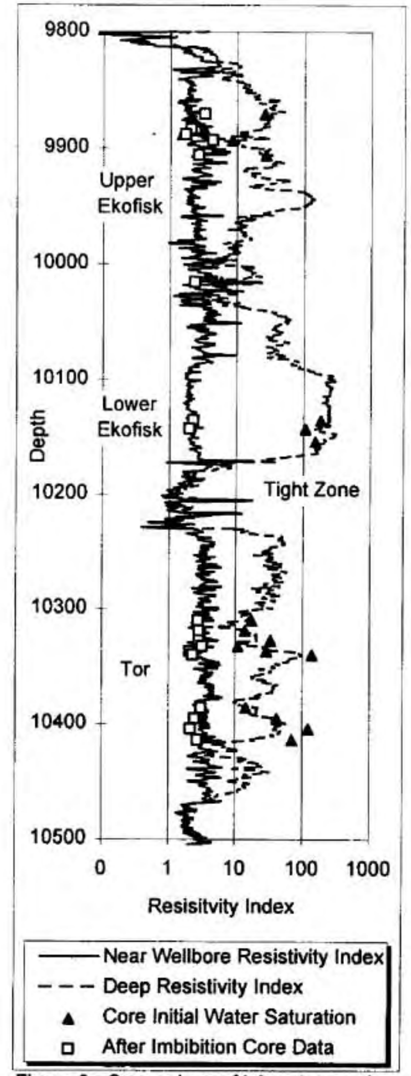

Figure 9: Comparison of laboratory and well log measured resistivity indices.

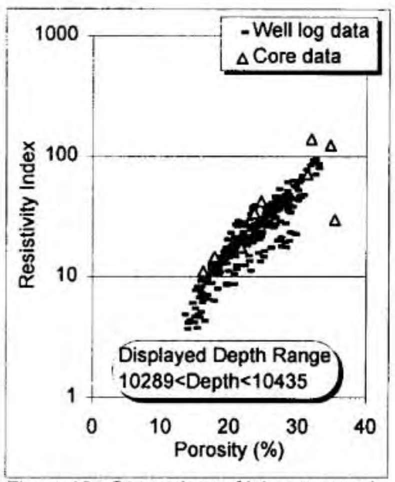

Figure 10: Comparison of laboratory and well log resitivity indices at initial water saturations with porosity.

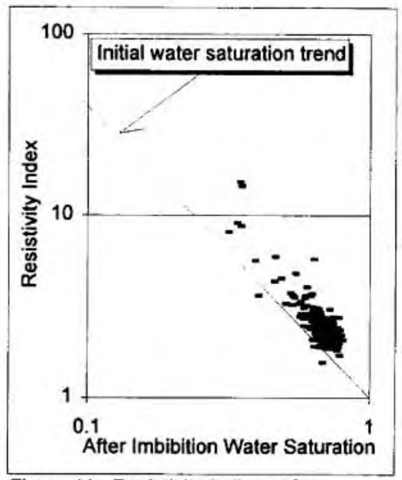

Figure 11: Resistivity Indices after imbibition compared with the resistivity index trend at initial water saturation.

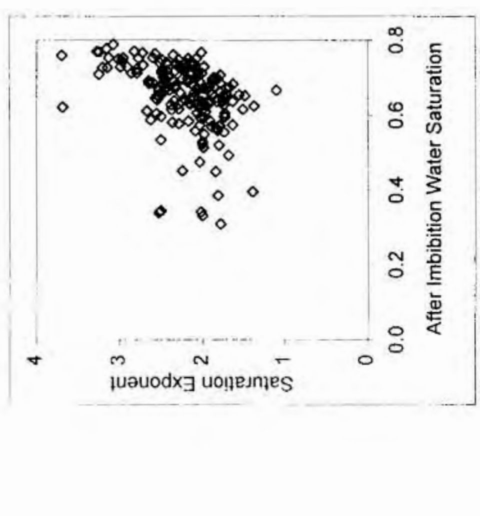

Figure 12: Illustrates the variation of the saturation exponent after imbibition with water saturation.

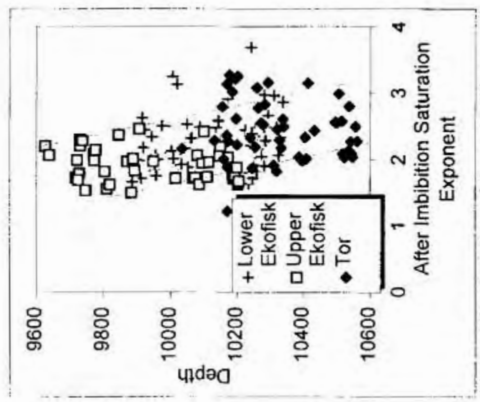

Figure 13: Variation of the saturation exponent after imbibition with depth.

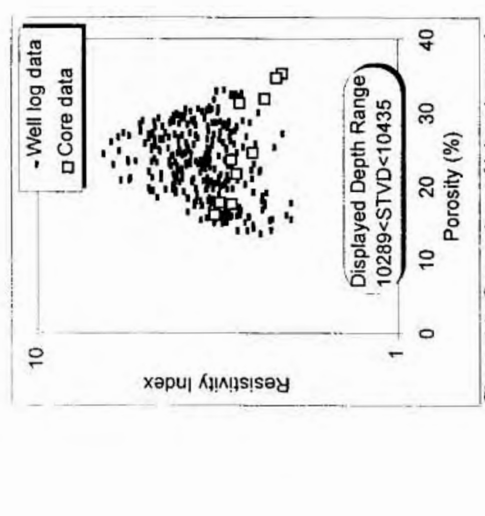

Figure 14: Comparison of laboratory and well log resitivity indices after imbibition with porosity.

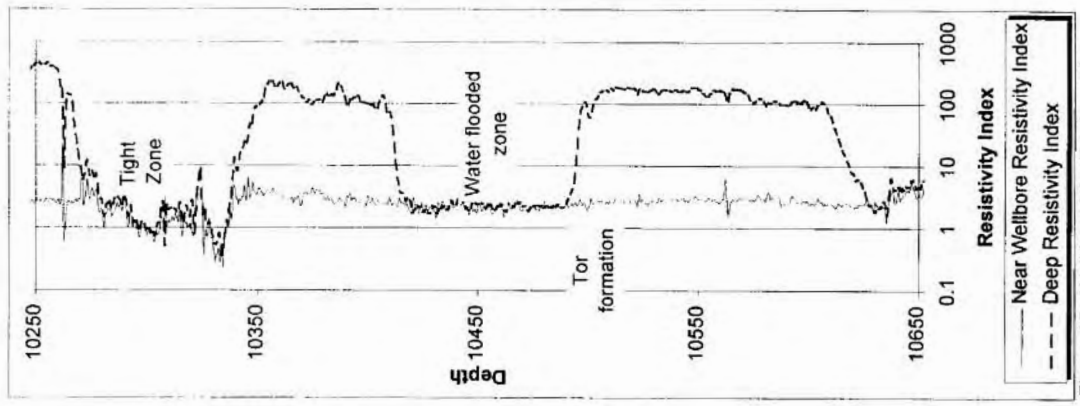

Figure 15: Well log of the Tor formation showing matching of the resistivity indices in a waterflooded zone.

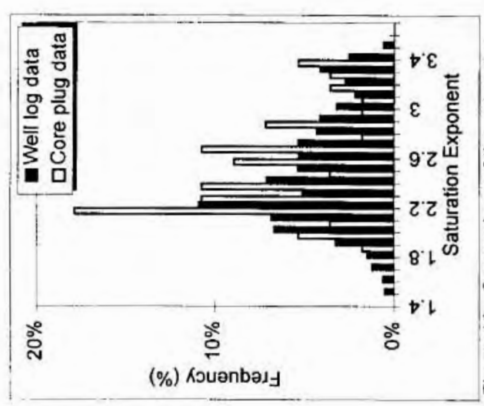

Figure 16: Comparison of the saturation exponents calculated from well logs with those determined in the laboratory.