PREDICTION OF FORMATION WATER SATURATION FROM ROUTINE CORE DATA POPULATIONS

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Abstract

A new empirical water saturation model is presented which facilitates the derivation of reservoir hydrocarbon saturation from core capillary pressure data or directly determined core saturation data.

The new model outperforms existing models and is shown to be applicable to a wide range of lithotypes from tight gas sands to carbonates. The only inputs the model requires are permeability and either directly determined water saturation or drainage capillary pressure data.

The model has been shown to predict core water saturation to a higher standard than actual directly extracted core saturations for populations where both types of input data exist. The model has also been used to detect and rectify errors in laboratory data determinations used to populate the model.

The number of inputs required to populate the model are fewer than those required to generate water saturation from wireline logs and thus have much reduced scope for experimental error. In addition, when applied to conventional core data or probe permeability data, the model can predict reservoir saturations with far higher resolution than logging tools which inevitably suffer from bed boundary effects. Case studies have demonstrated systematic underestimation of hydrocarbon in thin bedded formations by logs when compared with saturation data from the model.

Another application of the model is in prediction of the free water level. This has been implemented in situations where direct water saturation of core plugs was determined and it was desired to avoid penetration of the water zone by the well. In another example, the model prediction of free water level agreed to within a fraction of a metre of the value being carried for the field, which had been derived from pressure test data for a plurality of wells.

Introduction

It has long been recognised that permeability influences the primary drainage capillary pressure characteristics of reservoir rocks. One of the earlier and most enduring proponents of this was M.C.Leverett [1], whose famous “J Function” involved the square root of permeability as part of a capillary pressure normalisation term. In more recent times, a number of researchers have observed near-linearity variously between water saturation, drainage capillary pressure and permeability in bi-logarithmic space. This led the authors of this paper to the conclusion that water saturation might reasonably be treated as a planar function of permeability and capillary pressure in tri-logarithmic space. This may be expressed mathematically thus:

$$S_w = a \quad Pc^b \quad K^c \tag{1}$$

In the course of our investigations, the authors encountered work by Johnson [2], who arrived at a somewhat more complex functional form which may be described thus:

$$S_w = a \quad 10^{(b\ Pc^c)} \quad K^d \tag{2}$$

Søndenå [3] developed a similar model and was able to match the quality of the Johnson analysis of his data, albeit at the cost of introducing extra parameters. Søndenå curiously misquotes the Johnson functional form in his paper as equivalent to the simpler form favoured by the authors of this paper (Equation (1)).

The functional forms arrived at for their models by both authors seem to be a consequence of the staged approach taken.

A significant drawback of these methods as published is that this staged approach is rather tedious and also requires data at a series of fixed capillary pressures, which renders some types of data (such as direct core water saturations) inadmissible. However, with the desktop computing power now available it is trivial to regress multivariate data and complex functional forms directly.

The simpler conception by the current authors of a planar relationship in tri-logarithmic space quoted in Equation (1) nonetheless outperforms that of Equation (2) for the data populations studied and presented in this paper.

For many years, it has been the objective of some researchers to use capillary pressure data to attempt to predict formation permeability. It is clear from the relationships shown here that a given change in water saturation is associated in general with a much higher percentage change in permeability. Permeability should therefore be a much more accurate predictor of water saturation than vice-versa.

The chief purpose of this paper is to demonstrate that routine core data typically has much underused potential in formation evaluation and has the power to predict formation water saturation to unequalled accuracy in many circumstances.

Treatment of Capillary Pressure Data

It is clearly a prerequisite for modelling data with the functional form of Equation (1) that each capillary pressure curve be essentially linear when plotted in bilogarithmic space. It is the experience of the authors that the vast majority of curves honour this boundary condition, although rarely over the whole saturation range covered.

The example in Figure 1 which shows both air/brine capillary pressure and mercury intrusion data converted to an equivalent system is typical. The air/brine data becomes linear below some critical wetting phase saturation, and agrees well with the scaled mercury data in the mid saturation range. The departure of the two curves at higher drainage pressure is expected for fundamental reasons. Since vacuum takes the place of a true wetting phase during mercury tests, there is no retention either of wetting films or trapping of occluded porosity lacking a drainage path. Non-linear behaviour seems to be a good measure of these phenomena and thus forms a reasonable exclusion criteria when filtering data to be fitted.

Direct core saturation data clearly cannot be treated in this way, however this has not been deleterious to the quality of fit in the authors' experience as the examples discussed later in this paper demonstrate. Nevertheless, with these types of data, care should be taken at high wetting phase saturations to avoid including data which might cause diminution of the quality of the model.

Applications of the Model

Screening of Experimental Data

The model is generally capable of describing capillary pressure datasets to sufficient precision that the mean difference between model and measured saturations is of the same order or lower than random errors. In principle, therefore, the model may be used to detect excessive error in particular data points with a view to possible correction.

The example shown in Figure 2 is a set of air/brine data for a small group of sandstones featuring significant quantities of microporosity. Sample 1 was initially an outlier and was excluded from the fit. Upon correction of a typographical error in pore volume amounting to some 15% which caused systematic error in all of the saturation data for the sample, the corrected data closely matched the estimate derived from the model of the remainder of the population as shown in Figure 3.

Modelling of Direct Water Saturation Data

The model is well suited to this type of data since each datum possesses an independent permeability and consequently provides more degrees of freedom than an equivalent population size of capillary pressure data.

Example 1

The suite of data shown in Figure 4 represents a small population of directly extracted core saturations from a single core (and thus over a small depth range) from a UK Central North Sea Palaeocene play. In this instance, the range in water saturation is largely a reflection of permeability variation, since there is little change in depth across the suite of data. The mean difference between measured and model water saturation is 0.019.

The permeability exponent converged on a value of -.266. This in fact demonstrates relative insensitivity of saturation to permeability change. Cursory examination of Table 1 reveals that a permeability range of over three orders of magnitude is required to cause the observed range in water saturation. The corollary of this is that permeability information is a much more powerful predictor of water saturation than saturation is of permeability, especially at low water saturations. This is the key to the predictive use of routine permeability. The dissemination of the potential for the use of routine permeability data in this way is the ultimate goal of this publication.

Example 2

In this case, two sets of direct S_w from core data from two different wells from the same field in the UK West of Shetland province were used to generate the model.

Height above Free Water Level was substituted for capillary pressure thus:

$$S_w = a \quad H^b \quad K^c \tag{3}$$

The results are presented in Figure 5, with the model parameters quoted on the plot. Well 1 (plotted solid red) is a crestal well remote from the Free Water Level and with the single exception of a low permeability siltstone sample exhibits generally low water saturations. The model nonetheless describes this particular sample (existing some 230 m above the Free Water Level) almost perfectly. Well 2 (plotted solid blue) is transitional and consequently exhibits a range in S_w arising chiefly from regression between water saturation and increasing height above Free Water Level.

The mean difference between observed and model saturation is 0.012 for this dataset. It is clear that the model can precisely describe water saturation over a wide range of both permeability and height above Free Water Level.

Prediction of Free Water Level

The high standard of agreement between observed data and the model above would not be achieved if significant uncertainty existed in the depth of the Free Water Level because the resulting error for each sample would be strongly influenced by its depth. Data pertaining to depths more remote from the Free Water Level would suffer relatively less error than transition zone points.

These data were used as an exercise to estimate the true vertical depth of the Free Water Level, already well defined by pressure data from a plurality of wells drilled through to the water zone.

This was accomplished by making a trivial alteration to the model substituting for height:

$$S_w = a \quad \left(D_{fwl} - D\right)^b \quad K^c \tag{4}$$

Where

D = Sample True Vertical Depth, mtvdss
D_{fwl} = Depth of the Free Water Level, mtvdss

The parameter D_{fwl} was allowed to converge to a best fit value, which matched the value being carried for the field to within 7 centimetres. The potential for using data of this type in circumstances where the Free Water Level is less certain is obvious.

Prediction of Formation Water Saturation from Routine Core Data

The equation developed to describe core water saturation in the West of Shetland field was then compared with the wireline log data through the cored interval for Well 2. The result is displayed in Figure 6. This interval is relatively massive, so the comparison is generally good. It is clear however that the core derived values offer superior resolution and occasionally pick out both good and poor thin beds missed by the logs.

The same relationship was then used to transform the routine permeability data for another well (Well 3) in the same field to water saturation. This well had been considered for some time to suffer log resolution problems related to thin beds. The model-derived data was compared with the log data as before.

The comparison shown in Figure 7 is quite revealing and illustrates the limitations of the log data. As can be seen in this plot, the relatively thick beds show very good agreement. However, the logs are clearly incapable of adequately resolving water saturation in sandy beds due to the ubiquitous influence of shale in the thin sand / shale sequences through the interval.

The existence of thin beds below the resolution of deep resistivity tools generally causes underestimation of formation resistivity, which in turn leads to underestimation of hydrocarbon-in-place. The effect here is very large over much of the cored interval.

Probe permeametry data was acquired over the cored interval and was processed by the model in the same way as the routine core for the well. Figure 8 compares all three water saturation functions at the top of the cored interval to permit scrutiny of the data. The probe permeametry data naturally defines water saturation to a markedly higher resolution than the other curves, and it is clear that the log data has been badly affected by bed boundary effects. The extent of underestimation of hydrocarbon saturation by the logs throughout this interval is clear.

Conclusions

A simple model utilising core capillary or water saturation data in conjunction with routine or probe permeability populations has been demonstrated which defines continuous formation water saturation to a greatly superior resolution than wireline log data. The potential of conventional core data in formation evaluation is currently much under-utilised.

Nomenclature

S_w	Water Saturation
P_c	Capillary Pressure
K	Permeability
K_L	Klinkenberg Corrected Permeability
H	Height above Free Water Level
D	True Vertical Depth, mtvdss
D_{fwl}	Depth of the Free Water Level, mtvdss
mtvdss	Metres, true vertical depth sub sea

Acknowledgements

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References

[1] Leverett, M C (1941). Capillary Behaviour in Porous Solids, *Transactions, AIME* 142, 151-69

[2] Johnson, A (1987). Permeability Averaged Capillary Data: A Supplement to Log Analysis in Field Studies. *Proceedings of the SPWLA 28th Annual Logging Symposium*, Paper EE

[3] S∅ndenå, E (1992). An Empirical Method for Evaluation of Capillary Pressure Data. *Proceedings of the Society of Core Analysts Third European Core Analysis Symposium*, p129.

Table 1: UK Central North Sea Well - Basic Sample Properties

Sample	Water Saturation fraction	Klinkenberg Permeability mD
1	0.753	0.077
2	0.208	41
3	0.093	217
4	0.204	10.1
5	0.142	112
6	0.194	40
7	0.242	46
8	0.196	112
9	0.228	62
10	0.388	12
11	0.221	84

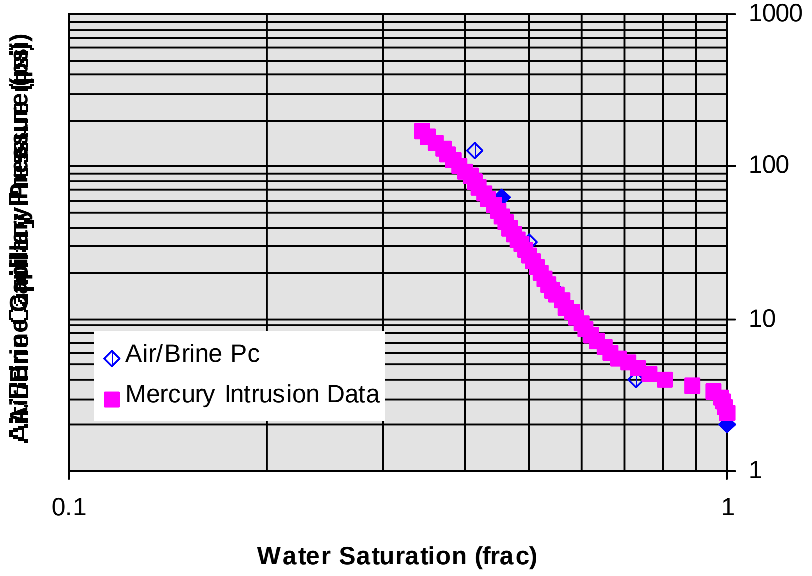

Figure 1: Bi-Logarithmic Plot of Capillary Pressure v Water Saturation

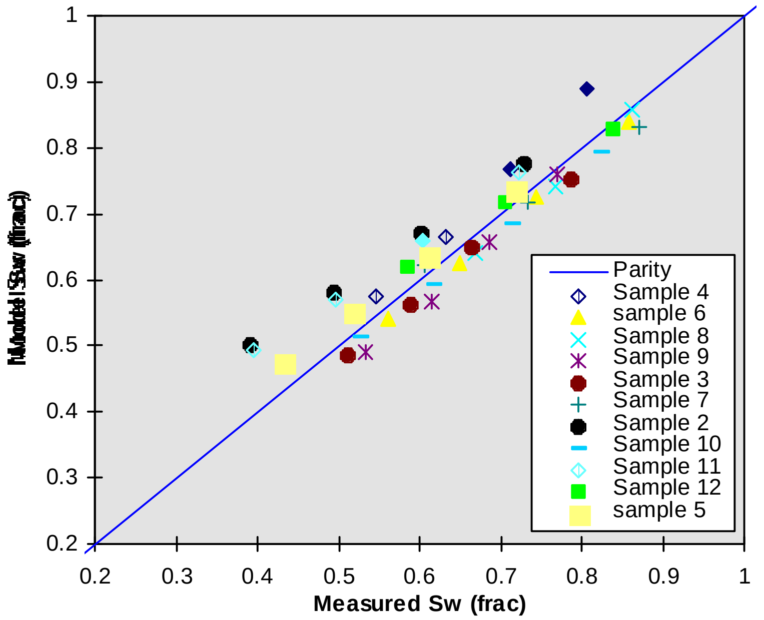

Figure 2: Model Versus Measured Drainage Capillary Pressure

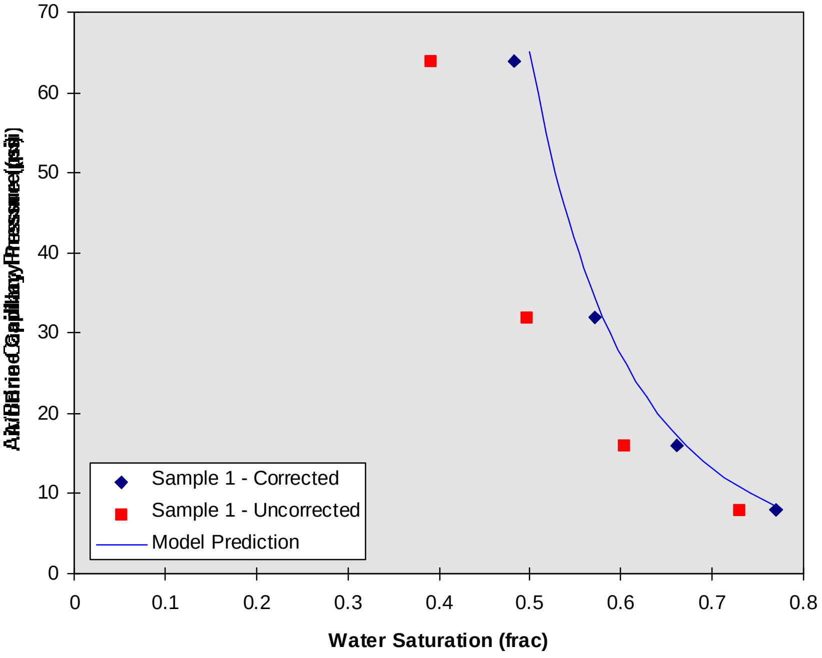

Figure 3: Model Prediction of Capillary Pressure Curve

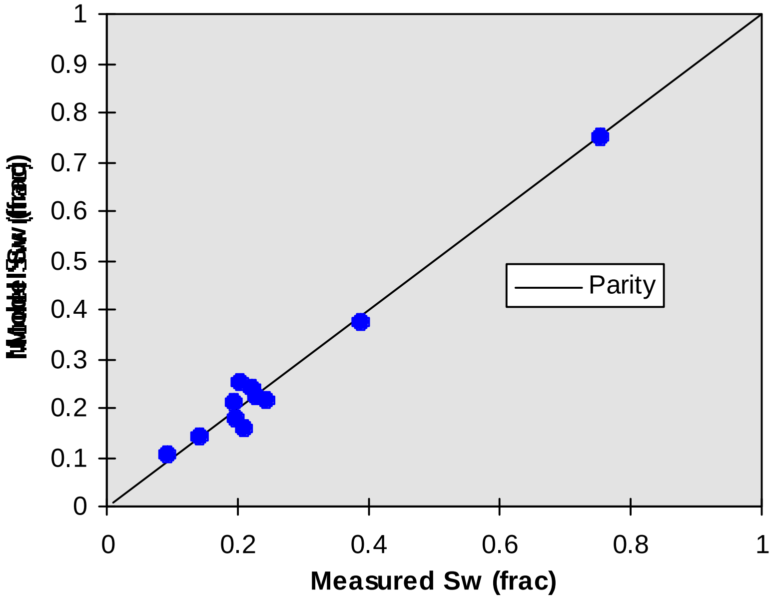

Figure 4: Measured Versus Model S_w- UK Central North Sea

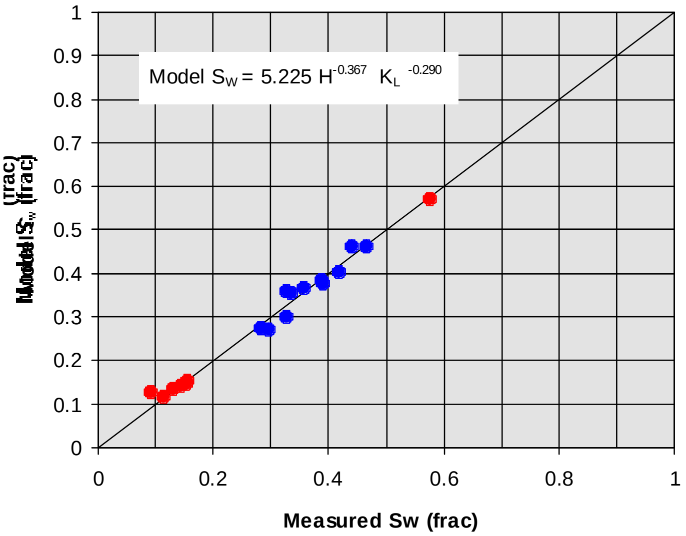

Figure 5: Measured Versus Model S_w- UK West of Shetland

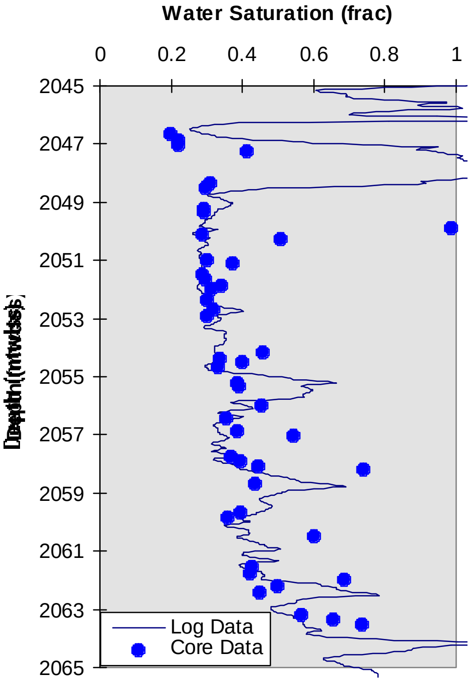

Figure 6: Log Versus Model Prediction of S_w- UK West of Shetland Well 2

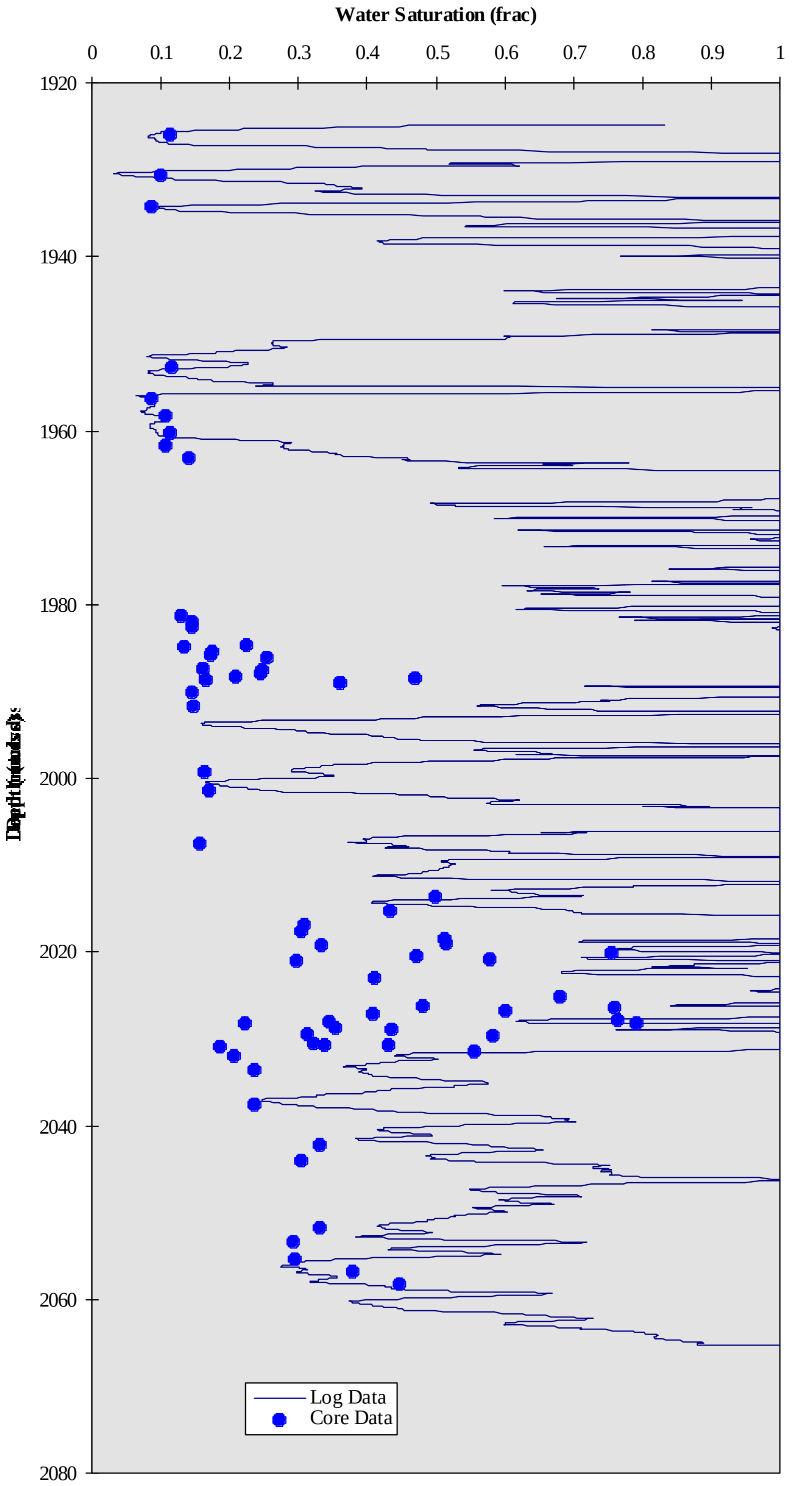

Figure 7: Log Versus Model Prediction of S_w- UK West of Shetland Well 3

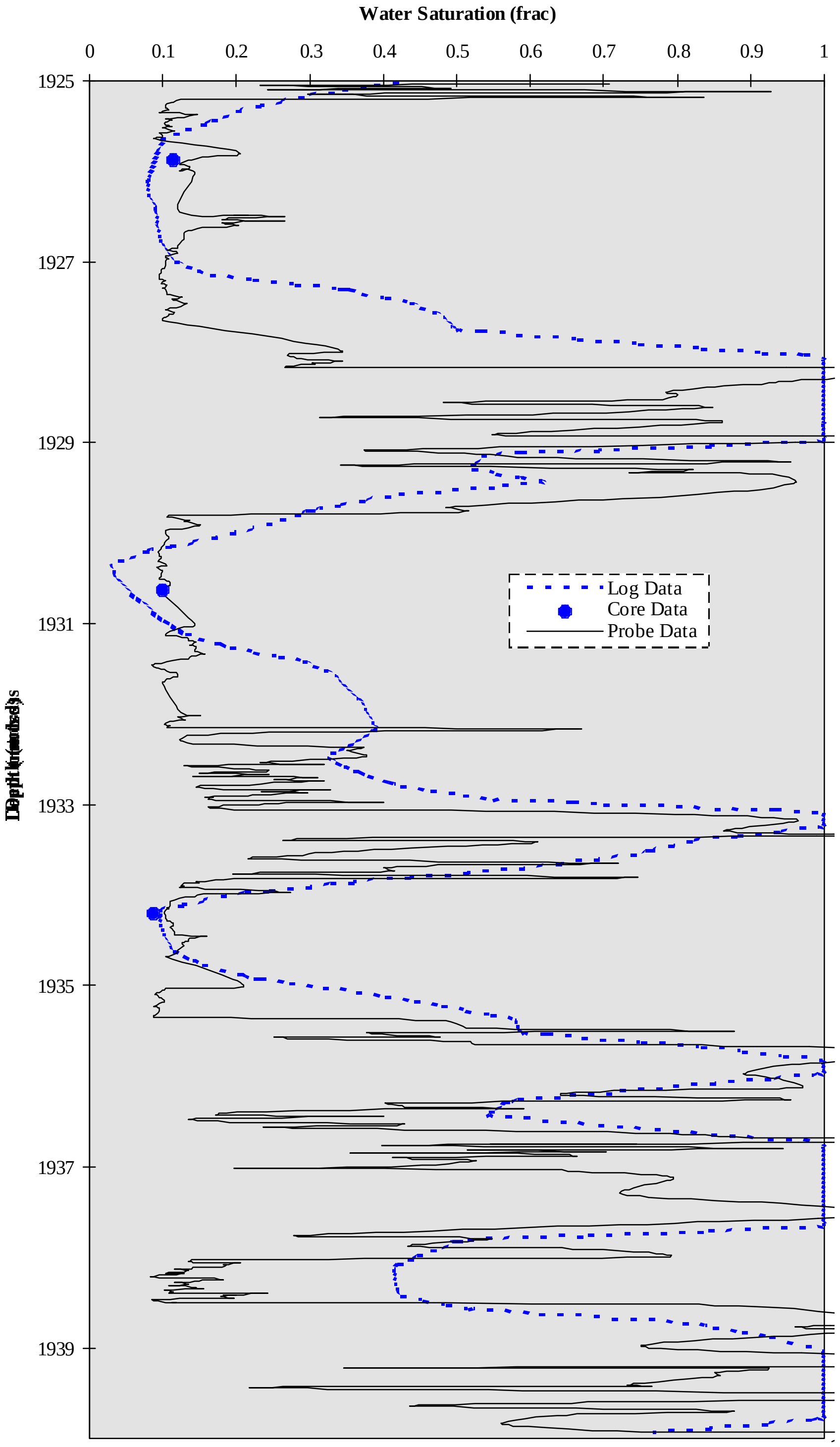

Figure 8: Log Versus Model Prediction of S_w- UK West of Shetland Well 3