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Resistivity Modeling of Array Laterolog Tools: An Application in an Offshore Norway Clastic Reservoir

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Abstract

Resistivity logs, as directly used for the determination of Water Saturation profiles, have always been of focal interest for the oil industry; it's clear that the quality of these measurements, currently used in the net pay and hydrocarbon-in-place determination, must be very high. As a consequence, more accurate and flexible resistivity tools have been developed in recent years. We are addressing here the family of array tools, and especially the HRLA[1], which makes available a set of 5 galvanic resistivity measurements at different depths of investigation.

Unfortunately, the most common types of environmental noise (borehole effects, shoulder bed resistivity contrasts, invasion, the presence of dips, anisotropy), still alter the measured resistivity, thus affecting the estimation of the true resistivity in hydrocarbon bearing levels.

In order to remove these alterations, Schlumberger, in cooperation with ENI-AGIP, has developed a 2D resistivity modeling & inversion technique that can simultaneously correct a number of environmental effects.

This paper presents the results obtained in two wells of a reservoir in the offshore Norway area where the sandstone bodies are interbedded with deltaic shales. The values of porosity and permeability are generally very high and a complete set of data (conventional & special core analysis, conventional wireline logs, microresistivity imaging logs, NMR, sedimentological analysis from core and images) is available.

The 2D modeling provided a better definition of the water saturation in the thinner sandstone bodies of the sequence and in the presence of anomalous invasion profiles.

When comparing the resistivity modeling results with those obtained by standard interpretation techniques, we can see the effectiveness of the developed methodologies (both hardware and software) in improving the reservoir characterization and in maximizing the return of the investments in logging and well data measurements.

Introduction

The aim of this paper is twofold: the authors want to show how complex reservoir studies can benefit from the correct integration of heterogeneous geological data, and to address at the same time the added value of applying a 2D modeling & inversion numerical technique to resistivity measurements in order to compute accurate Water Saturation profiles.

One of the most important issues of the formation evaluation process is the correct estimation of all the petrophysical parameters necessary to determine the hydrocarbon content of the reservoir. This implies the need to compute a saturation profile as correct as possible. Since S_w (and consequently S_h) strongly depends on resistivity, porosity and shale volume, it is of the utmost importance that the uncertainty on these measurements be kept very low. In recent years the accuracy of resistivity tools has been greatly improved by the introduction of array measurements [1,2]; unfortunately, the utter complexity of real formations can often lessen the intrinsic advantages of the available logs. The most common environmental noise sources, as listed in many well-known works [3,4,5], are:

- thin beds and/or dips;
- deep and/or exotic invasion profiles;
- high resistivity contrasts between mineralised (porous) and tight layers (shoulder effects);
- electrical anisotropy (usually related to laminations and grain size variations).

In most cases their combined effects cannot be removed separately, but must be treated as a unique, non-linear problem. In previous work [6,7,8,9] it has been shown how resistivity modeling & inversion techniques can solve these kinds of problems, provided that an appropriate and fast

[1] Mark of Schlumberger

forward model (2D or 3D) is available for all the acquired tools, and that a robust and efficient inversion algorithm can be implemented.

The code used in the present application was a resistivity interpretation software platform, INVASION 2.1, developed by Schlumberger S-RPC; INVASION 2.1, which includes an older inversion program developed in collaboration with AGIP, implements a methodology for 2D and 2D+dip resistivity modeling, based on three main steps:

- describe the formation properties (geometry & petrophysics);
- compute the corresponding synthetic resistivity logs by way of proprietary numerical forward models of Schlumberger tools;
- optimise the values of the formation parameters by minimising the quadratic distance between the synthetic logs and the actual measurements.

The program can be run in automatic or expert mode; the output is a better estimation of R_t, together with other user-selected parameters of interest, such as radius of invasion, R_i and layer thickness, Z_i.

Interesting results have been obtained in operational environments [10,11], which can assess the state of the art of the technology, at least for 2D applications, while new developments towards 3D are due in a short time.

In the following paragraphs we will show how the integration of different types of data (geological studies, wireline logs, NMR measurements, core data) together with the most advanced numerical interpretation techniques, can produce accurate and robust results for many formation evaluation problems, thus reducing the uncertainty of the estimation of the petrophysical parameters which are relevant in reservoir studies. The importance of geological and petrophysical information in defining a correct formation model has also been addressed in a recent paper [12], which shows how this information is also useful in constraining the inversion process.

For this reason, we will first describe the geological setting of the reservoir and the available data, highlighting the interpretation process and the problems encountered; we will then focus on the methodology used for the evaluation of the correct Water Saturation profile from resistivity measurements, demonstrating how this methodology, based on modeling & inversion techniques, can enhance the robustness of the results, as confirmed by different sources of information. Since the field study has not been yet completed, from the reservoir point of view, the conclusions will not be definitive, and the paper will end with a work-in-progress description of the next activities. We will, however, be able to state the advantages of the proposed numerical modeling & inversion technique applied to laterolog array measurements, especially when in presence of data of different quality.

Geological setting and petrophysical description of the reservoir

The reservoir under investigation is characterized by sandstone bodies interbedded with deltaic shales.

The sandstone bodies are characterized by high values of porosity and permeability; the reservoir is oil-bearing and a water/oil contact is evident from log interpretation and is confirmed by pressure analysis.

The data from MDT indicate the probable presence of a single hydrocarbon column. Three main sedimentological environments have been recognized by the sedimentological facies analysis:

Vegetated, water saturated flood plain (fig. 1)

It consists of mottled massive to thinly laminated silty-shales and very-fine grained sandstones.

Sandstones occur as thin or very thin-bedded alternances or, more commonly, as amalgamated packages in which the bioturbation can be very intensive. The internal structures and the original thin-bedded stratification suggest a deposition from small-volume sand-laden waning currents, probably produced by fluvial overbank floods or crevasse splays.

All these flood plain deposits are expected to be characterized by a remarkable lateral continuity.

Porosity: the effective porosity varies between 5 and 8 p.u. in the shaly intervals and up to 30 p.u. in the thin sand layers. In these bodies, the log-measured porosity is always less than that determined on core plugs because of the inadequate vertical resolution of the downhole tool in relation to the thickness of the porous layers.

Pore system: the shaly intervals are dominated by the finest elements and fully saturated with irreducible water, whereas the thin sand bodies are characterized by a poorly sorted pore system with predominating fine elements.

***Permeability*:** the shaly layers may be considered impermeable. The sand layers have permeability values lower than 1 Darcy.

***Mineralisation*:** S_w values vary between 20% and 40%, although the calculated S_w values are overestimated because of the incorrect value of R_t recorded by the resistivity device.

The value of the S_{wi} calculated from NMR analysis is about 20%. It is possible to assume that this value is realistic for the thin sandstone bodies.

Fluvial distributary channel (fig. 2)

It mainly consists of coarse-grained sandstones. The cross-beddings are of large and medium-scale (up to 60 cm a single foreset) with the individual laminae outlined by grain-size segregations or, more rarely, by coal/plant debris. According to the literature, this type of channel should be characterized by a low sinuosity. Very coarse to microconglomerate sandstone levels are locally present.

Porosity: varies between 20 and 32 p.u.

Pore system: homogeneous and well sorted with very low values of irreducible water saturation (always lower than 5%).

Permeability: very good estimated permeability, especially in association with higher values of effective porosity (2-4 Darcy, with peaks at 5 Darcy).

Mineralisation: S_w values calculated for this system generally match the value of S_{wirr} derived from the NMR device in the oil bearing levels. The values of S_{wirr} are generally very low (from 5% to 10%).

Tidal influenced fluid interdistributary or tidal channel (fig. 3)
It consists of medium and fine-grained sandstones and silty-shales. The sandy levels show internal cross-bedding (medium and small-scale) characterized by occasional bidirectionality. This tidal sandstone package should be characterized by a considerably greater lateral extent than the underlying fluvial distributary.
Porosity: varies between 22 and 32 p.u.
Pore system: the pore system is poorly sorted with irreducible water volumes related to the grain size of the sediment. ***Permeability:*** very good estimated permeability, especially in association with higher values of effective porosity (always less than 2 Darcy)
Mineralisation: the S_{wi} values of this system can vary from 5%, in the best sorted levels, to 20% with an average value of 12%.

Operational information

The data under evaluation were acquired in two vertical wells:

	Well 1	Well 2
Mud type	Formate polymer	K + formate
Mud density	1.31 g/cm^3	1.25 g/cm^3
Mud resistivity @ 15 degc	0.062 ohm.m	0.078 ohm.m
Mud filtrate resistivity @ 15 degc	0.052 ohm.m	0.061 ohm.m
Resistivity devices	HALS[1] –MCFL[1]	HRLA[1]-MCFL
Cores	YES	YES
Hole diameter	8.5”	12.25”

The sequence of data acquisition was the following:
Well 1:
run 1: PEX[1] - HALS
run 2: CMR[1] - GR
run 3: FMI[1] – DSI[1] (monopole-upper dipole-lower dipole) - GR
run 4: MDT[1] Sampling
run 5: MSCT[1]
Well 2:
run1 1: PEX - HRLA
run2: FMI - DSI-(monopole-upper dipole-lower dipole) - GR
run 3: CMRplus[1] – APS[1] – HNGS[1]
run 4: MDT Sampling
run 5: Dual CSAT[1] - GR

All the operations were conducted without operational problems and there were no reports of mud losses during or between the wireline operations. A description of the HALS and HRLA laterolog tools can be found in the following references [13,14].

Resistivity Modeling

The analysis of deep-reading electromagnetic measurements is critical to the evaluation of hydrocarbon reserves. However, in thin bed formations, poor tool vertical resolution and corresponding low sensitivity to hydrocarbon presence make interpretation in the virgin zone difficult. A priori knowledge such as the formation geometry or auxiliary petrophysical information is necessary to overcome these difficulties.

The purpose of the Invasion 2 product [6], developed by Schlumberger S-RPC in cooperation with ENI-AGIP, is to provide a common environment for the interpretation of electrical tools, wireline or LWD, in thinly bedded environments in order to:

- provide tool-interpretation modules with a common interface and inversion-based techniques for better reserve estimations;
- define a standard processing methodology with progressive refinements, as explained below;
- validate each step from the analysis of Quality Control indicators;
- propose different levels of user mode: (i) the automatic mode enables R_t to be derived for the whole interval assuming simple invasion profiles, (ii) the expert mode allows the local analysis of different resistivity data together with possible use of petrophysical knowledge to constrain the formation in complex environments.

Methodology
The processing methodology is usually split into three main phases, applied in sequence:

- 1D+1D corrections & validation;
- 2D automatic modeling & inversion;
- 2D expert mode processing.

Let us describe in brief the purpose and the outputs of each phase.

1D+1D corrections & validation. In many circumstances, environmental effects (such as borehole, shoulder and invasion effects) can be corrected independently, in sequence. This is often referred as the 1D (radial) + 1D (vertical)) sequence of corrections. These so-called 1D environments are characterized by just one noise source, i.e., radial invasion in an infinitely thick layer. This assumption is valid if the corresponding types of environmental noise are independent.
Down to real cases, if the tool-response can be coherently simulated by a 2D forward model, given the resistivity distribution (R_t, R_{xo}, D_i) identified after performing the 1D+1D sequence of corrections, we are surely in the presence of independent effects, and no further processing is required. This quality control is referred to as the “Validation” phase.
2D automatic modeling & inversion. Automatic processing (2D and 2D+dip) is an efficient way to model & invert a complex formation (as described in the introduction); it is

based on the capability of the software to describe the formation as a large number of beds, each of which is then modelled and inverted as a step-profile invasion layer. The simplification of the formation modeling guarantees very fast processing, but may lead to inaccurate results, for instance when very complex invasion profiles are present; in this case, the expert mode inversion is the only solution.

2D expert mode processing. Expert modeling is based on an accurate description of each formation layer, in terms of invasion profile, thickness, dip, and possibly porosity and shale volume. The inversion process optimises some of the petrophysical parameters, like resistivity, radius of invasion and layer thickness, but can lead to wrong answers in presence of badly modelled formations. From this point of view, the term expert is often related to the petrophysicist's capabilities.

The described methodology has been applied to both wells. In some intervals, the 1D+1D corrections were sufficient to recompute the correct value of R_t. In general, the 2D automatic modeling brought little improvement. The 2D expert mode was needed to optimise the most difficult "local" problems (complex invasion profiles, thin beds).

1D+1D processing and Validation

The first step consisted in running a 1D+1D sequence on both Well 1 & Well 2. Environmental corrections were performed according to the following procedure:

- for HALS data (Well 1): borehole corrections, eccentering corrections, Groningen effect corrections (negligible), shoulder correction and finally inversion for invasion to obtain the values of R_t and D_i, R_{xo} being directly given by the MCFL micro-resistivity tool.
- for HRLA data (Well 2): borehole corrections, eccentering corrections (obtained by forcing the 5 readings to overlay in shale areas), and again inversion for invasion to obtain Rt, D_i and R_{xo}. External R_{xo} from the MCFL micro-resistivity tool was used here only as a quality control check.

For both wells, 1D+1D processing provided satisfactory results when the assumption that environmental corrections were independent proved valid. This was confirmed by the small reconstruction errors obtained through the Validation task in the zones where bed thickness was relatively large.

For thin beds, where shoulder bed effects were important, the Validation task, with large reconstruction errors, showed the necessity of further processing.

2D automatic processing

The second phase of the processing, the 2D automatic mode, was applied to the full interval for both wells [1].

This processing first performed a segmentation of the input logs on a relatively fine sampling scale (1-3 ft for the HALS, 0.5-1.5 ft for the HRLA), taking into account the vertical resolution of the tools. Each bed of the formation was then described as a simple step profile, using 1D+1D processing results to initialise the values of R_t, R_{xo} and D_i. For the HALS, because of the limited number of available data at each measured depth, the resistivity of the flushed zone was fixed to the MCFL value. An iterative inversion scheme was then performed to minimise the errors between the measured and simulated logs.

Results in zones where shoulder effects were important have been improved. The 2D automatic processing provided best results, in a fast and robust manner, for large beds and simple formation models (step invasion profile).

2D expert mode processing

The last phase of the processing, the 2D expert mode, was performed only in few selected intervals, extracted from both wells.

The interval extracted from Well 1 presented a very interesting characteristic, that is the presence of a peculiar invasion profile at the bottom of the main sand layers. These layers showed very shallow invasion along most of the bed, and then a very deep invasion ramp at the bottom of the body. These profiles are usually more evident in thick sand beds, and they are mostly due to high values of both vertical and horizontal permeability [15]. Their detection is also related to the time span between drilling and the beginning of logging operations, since such deep invasion needs some time to set.

The second characteristic we want to address is the presence of sequences of thin beds generally related to the overbanks in the flood plain. In these beds, the differences between the calculated S_w from log data and the S_{wi} measured on core plugs are often quite large [16]. The reduced thickness of these layers (definitely below the resolution capability of most of the tools used both for resistivity and porosity measurements) suggests the possibility of an incorrect measurement of R_t and Φ, and consequently the possibility of an overestimation of S_w.

This problem could be observed in Well 2, where sequences of thin layers at different depths induced a general reduction of the measured resistivity value.

Deep invasion. The presence of high vertical permeability driven anomalous invasion profiles has been described in former work [15], and it is known to produce alterations in the induction resistivity measurements. These alterations, which can lead to a misplacement of the oil/water contact, have been observed in the laterolog measurements available for Well 1, and can be summarized as follows (fig. 4):

- linear reduction of the measured R_t at the bottom of the layer;
- undershooting of R_t at the lower boundary of the layer;
- problems in defining fluid contacts.

The automatic 2D modeling provided a reasonable solution for R_t and R_i, but, when looking at the reconstruction errors, it was evident that both petrophysical and geometrical (boundary positions) formation parameters could still have been improved. The expert mode 2D modeling allowed the petrophysicists to correct the misplaced boundary positions, and, moreover, to describe a very accurate invasion profile. The thick sand body (more than 4 m) was thus split into three petrophysical zones:

- a main upper layer, characterized by a constant invasion radius;
- a transition layer (more than 1 m), characterized by a linear increasing of the invasion radius;
- a very thin bottom layer where the invasion radius is again constant.

The expert inversion produced a final result where:

- the value of R_t in the transition layer and in the bottom layer is the same as in the upper one;
- the upper layer is characterized by very shallow invasion, while the slim bottom layer is deeply invaded (more than 40 in.);
- the undershooting effect at the bottom has been removed and the thickness of the bed as a whole has increased;
- the reconstruction errors have been reduced.

These results are summarized in fig. 5, where, in the centre column, the final R_t profile (thick red line) is plotted together with the measured resistivity (thin continuous lines) and the output of the 2D automatic modeling (black dashed line).

The final R_t is more accurate and consistent with the MDT pressure data, which gave evidence of a single oil column with a lower OWC.

Sequences of thin layers. Sequences of alternating sand-shale thin layers are very common in many sedimentological environments, and are present in both Well 1 (fig. 6) and Well 2. The most significant example was taken from Well 2, where a series of hydrocarbon bearing layers, each one less than 0.5 m thick, induces a strong reduction in the measured R_t. The 2D automatic modeling, while computing a good R_t profile in thicker beds, could still not recover the correctly enhanced R_t values in the thinner ones, thus suggesting an expert mode reprocessing of some selected intervals.

Here again, the problem remains the correct evaluation of S_w in thin hydrocarbon bearing levels [6], and finally the best estimation of the hydrocarbon potential of the sequence. The 2D expert mode processing allowed the petrophysicists to compute a more correct R_t for further elaboration.

The initial layering was driven by a complete sedimentological description of the cores and by FMI data interpretation; R_t was constrained to maintain the same value in all the layers belonging to the sequence. This assumption was supported by the evidence of hydraulic continuity confirmed by formation tests, and by the high homogeneity of the textural/sedimentological facies.

The final value of R_t in thin beds was quite enhanced, both with respect to the field acquisition values and to the results of 2D automatic modeling; the reconstruction errors were very low, and the final R_i values as expected.

The final Rt profile, as shown in fig. 7, (centre column, thick red line), is the integration of 2D automatic modeling (in thick beds) and 2D expert mode processing (in thin layers) results; reconstruction errors are below 15% for both solutions.

The last step consisted in recomputing the value of S_w, according to the new R_t profiles.

The computation of S_w was performed by using the Indonesia formula; the necessary exponents and coefficients were calibrated against core analysis data. In fig. 8, a comparison among three different S_w profiles is shown. The first was computed using the field 1D+1D R_t and the density-neutron porosity. The porosity was then modified according to the following criteria:

- the final layering obtained from the resistivity modeling was used to square the porosity curve;
- the porosity was set to 24 p.u. in the levels where R_i>15 in., in order to compensate its underestimation due to the level thinness. The value of 24 p.u is consistent with the routine core analysis.

The second S_w profile was computed using the field 1D+1D R_t and the modified porosity; the third S_w was then evaluated using the final 2D R_t (integrated automatic & expert mode) and again the modified porosity.

This last S_w profile is more consistent with the field data (single hydrocarbon column) and with core analysis data (S_{wi} from NMR and from capillary pressure tests).

Next steps

The study of the reservoir is still in progress, and the satisfactory results obtained from resistivity modeling in Well 1 and in Well 2 will be the start for further analysis which will include:

- the extension of 2D expert-mode processing to all the intervals with thin sand layers, in both wells;
- the comparison between the traditional petrophysical analysis data (mainly in terms of S_w) and the new results computed from the 2D modelled resistivity profiles;
- the evaluation of previously unidentified hydrocarbon bearing zones;
- the evaluation of the differences in the volumes of hydrocarbons in place.

According to the invasion behaviour observed in Well 1, the petrophysical interpretation of future wells in this area will check for the presence of anomalous invasion profiles.

Conclusions

A rather new methodology for 2D resistivity modeling & inversion of laterolog measurements has been applied in operational conditions in order to reduce the uncertainty on the final Water Saturation profile.

The methodology is based on an iterative process split into various phases of increasing complexity, thus allowing the formation evaluation specialists to take into account all the geological and sedimentological data necessary to obtain petrophysically coherent solutions.

The integration of petrophysical information was helpful to constrain the formation model properties in both the examined wells, where very different R_t estimation problems have been faced and solved.

The final results have been judged of good quality and quite important both for the completion of the reservoir study and for future well planning & interpretation.

Nomenclature

k_h = Horizontal Permeability, mD
k_v = Vertical Permeability, mD
D_h = Hole Diameter, in.
D_i = Invasion Diameter, in.
R_i = Invasion Radius, in.
R_m = Mud Resistivity, ohm.m
R_{mf} = Mud Filtrate Resistivity, ohm.m
R_t = Virgin Zone Resistivity, ohm.m
R_w = Formation Water Resistivity, ohm.m
R_{wb} = Bound Water Resistivity, ohm.m
R_{xo} = Invaded Zone Resistivity, ohm.m
S_{xo} = Invaded Zone Water Saturation, %
S_w = Virgin Zone Water Saturation, %
V_{cl} = Shale Volume, %
Φ = Porosity, %

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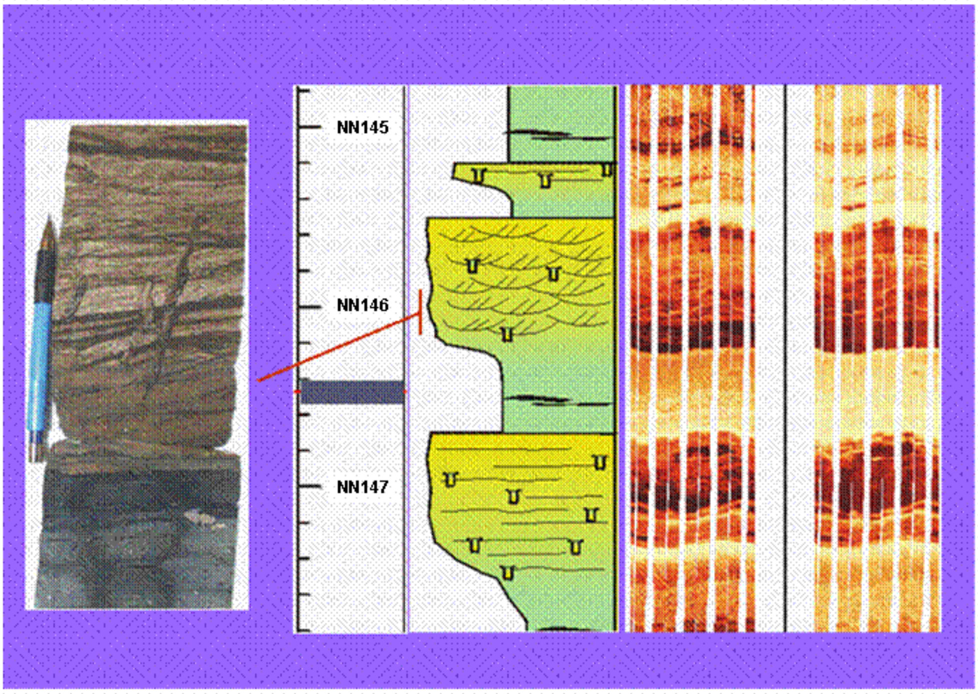

Fig. 1: **Overbanks in flood plain**.

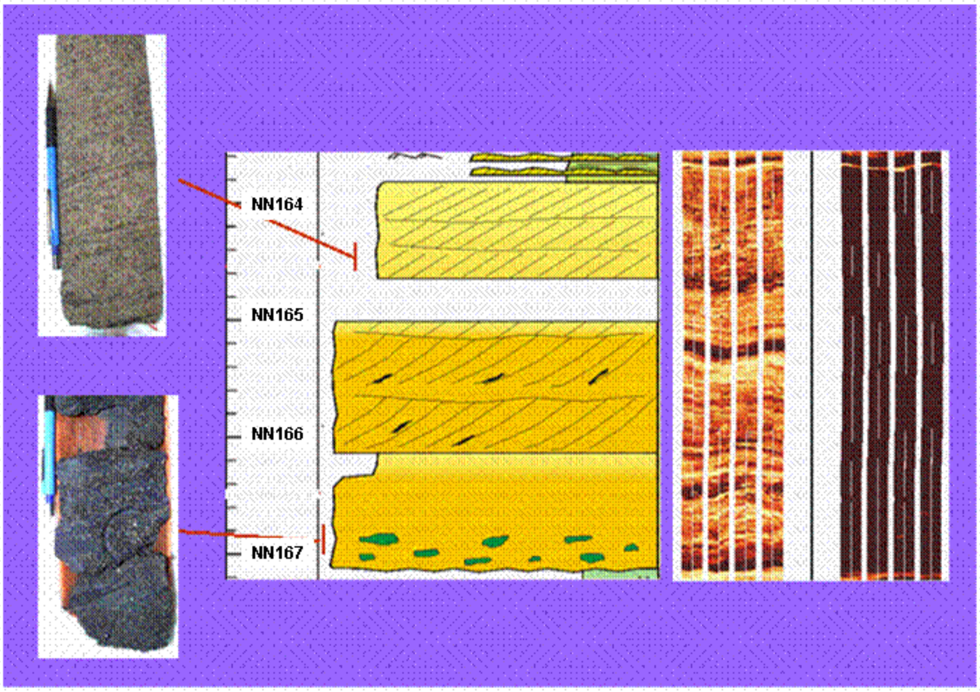

Fig. 2: Fluvial channel.

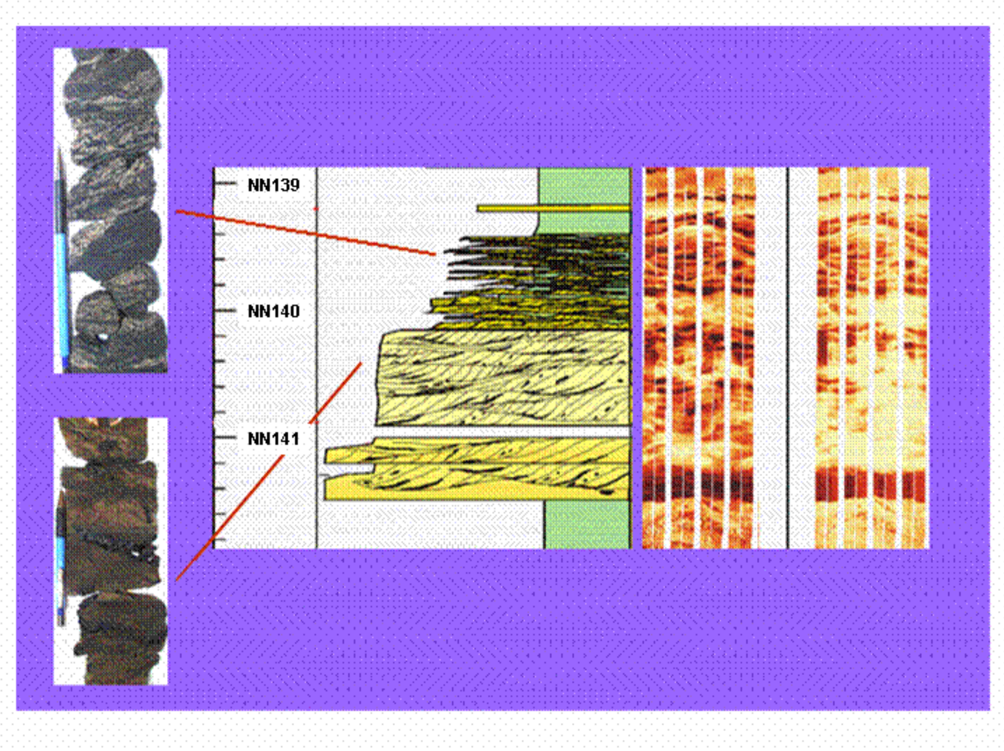

Fig. 3: Tidal influenced channel.

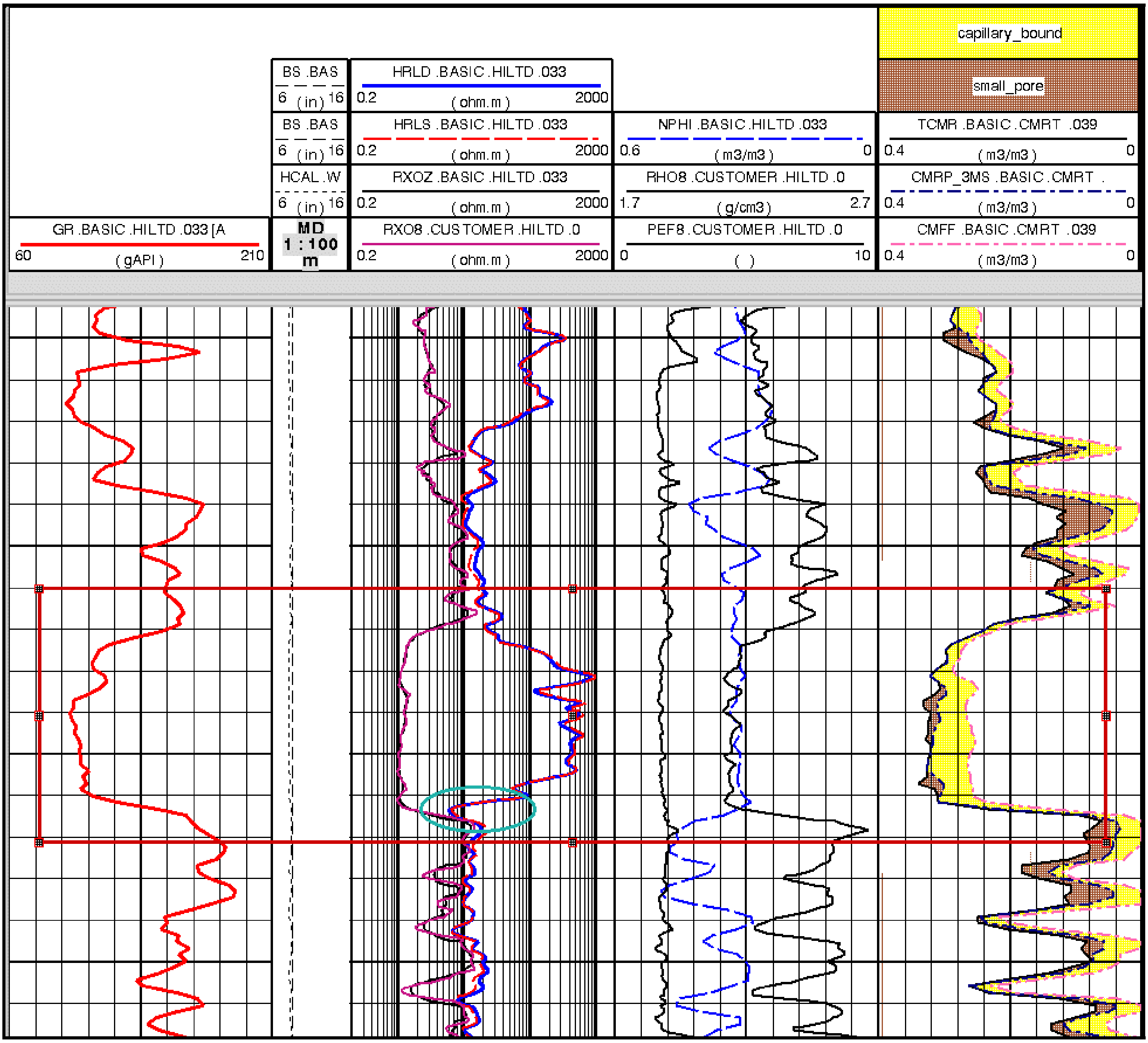

Fig. 4: Well 1. Anomalous invasion or OWC?

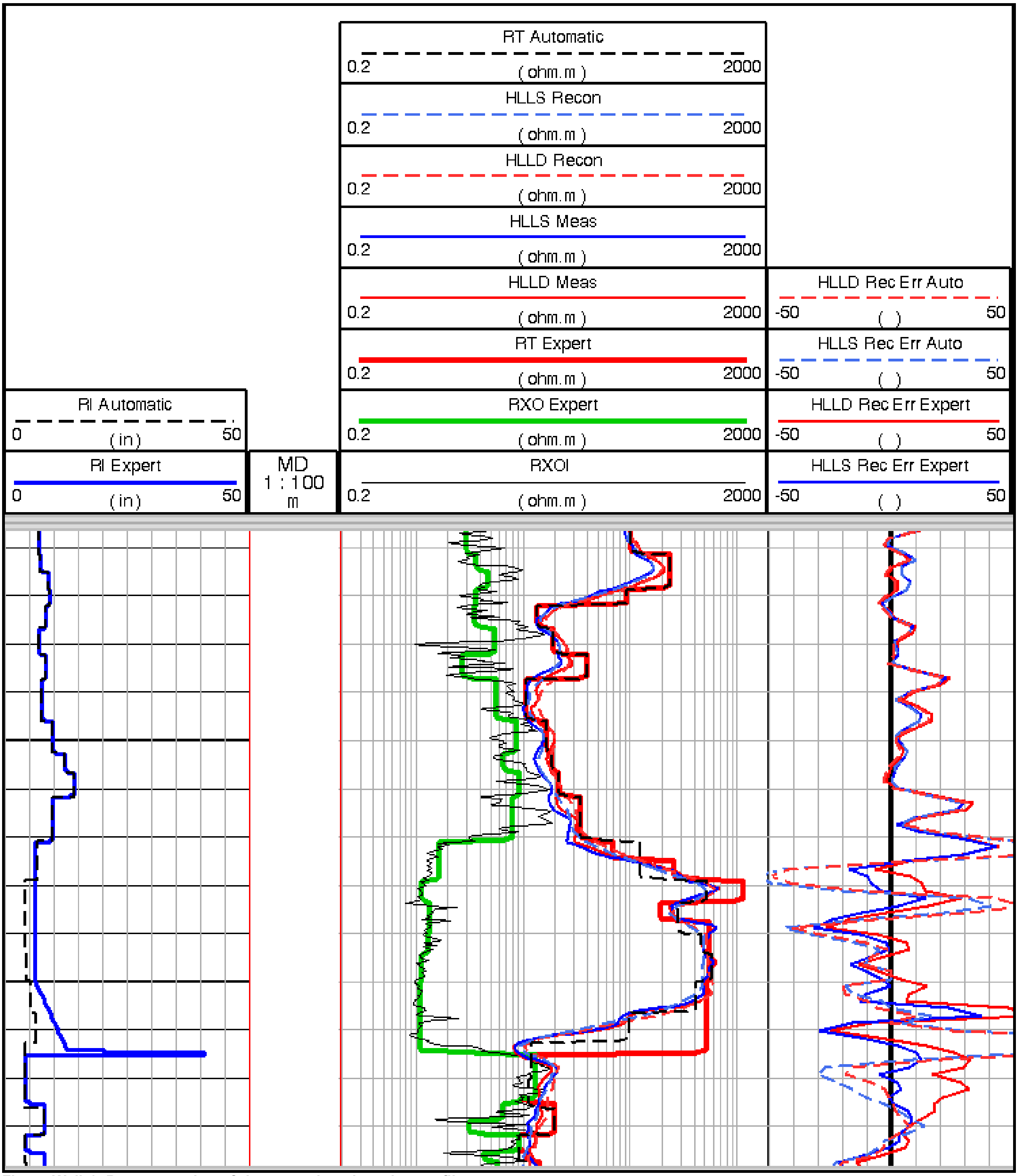

Fig. 5: Well 1. Reconstruction of the anomalous invasion profile. The invasion radius (left column, thick blue line) increases quickly at the bottom of the layer, thus triggering the anomalous Rt profile recorded by the resistivity tool (centre column, thin continuous lines). After the 2D expert-mode processing the final Rt profile (centre column, thick red line) is consistent along the whole layer.

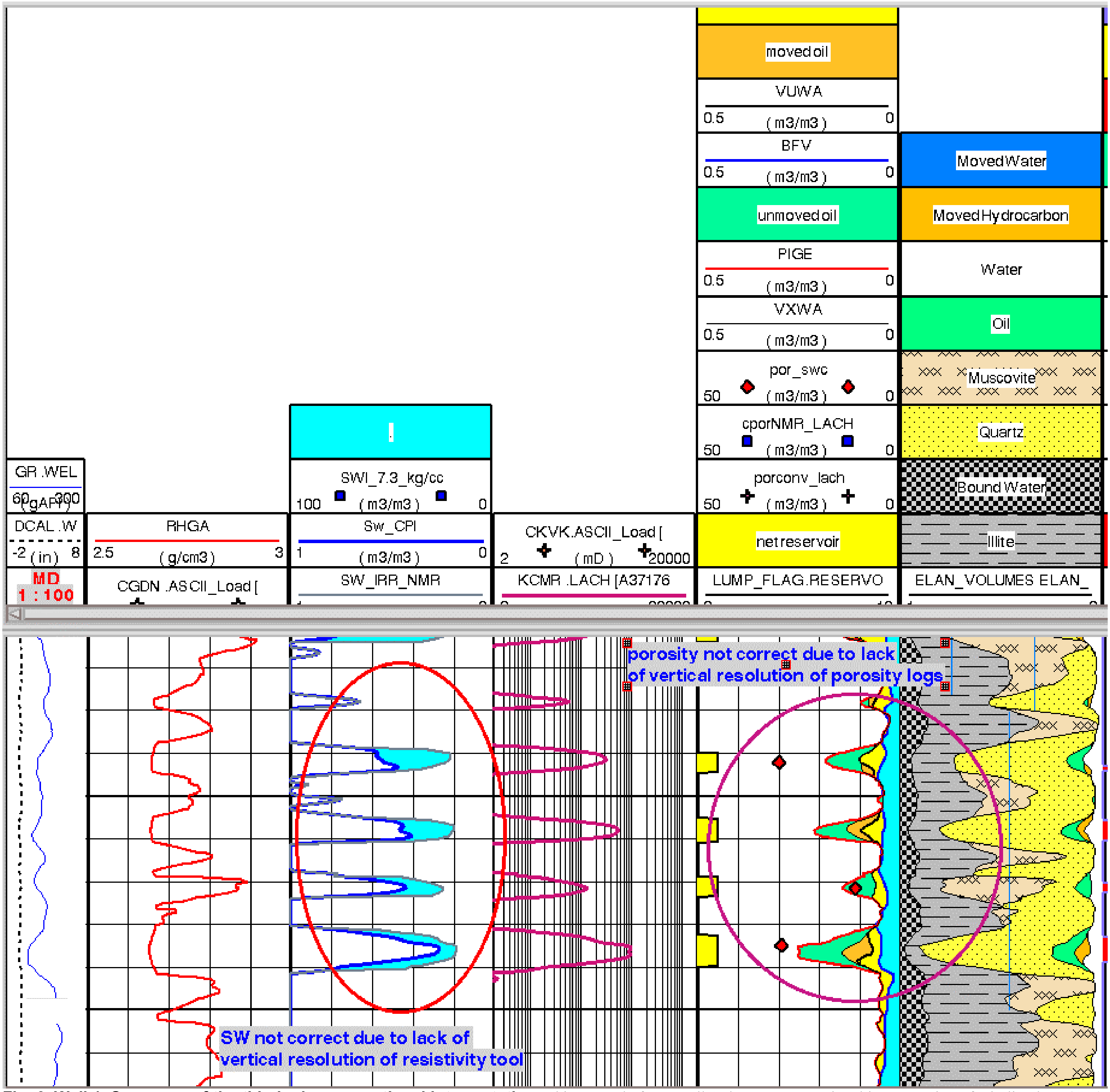

Fig. 6: **Well 1. Sequence of the thin beds: conventional interpretation.** This example from Well 1 shows a conventional interpretation of wireline logs (CPI). We can see that the estimated porosity is lower than core measurements (right dark-red oval) and that SW_CPI is higher than SW_IRR from NMR (left red oval).

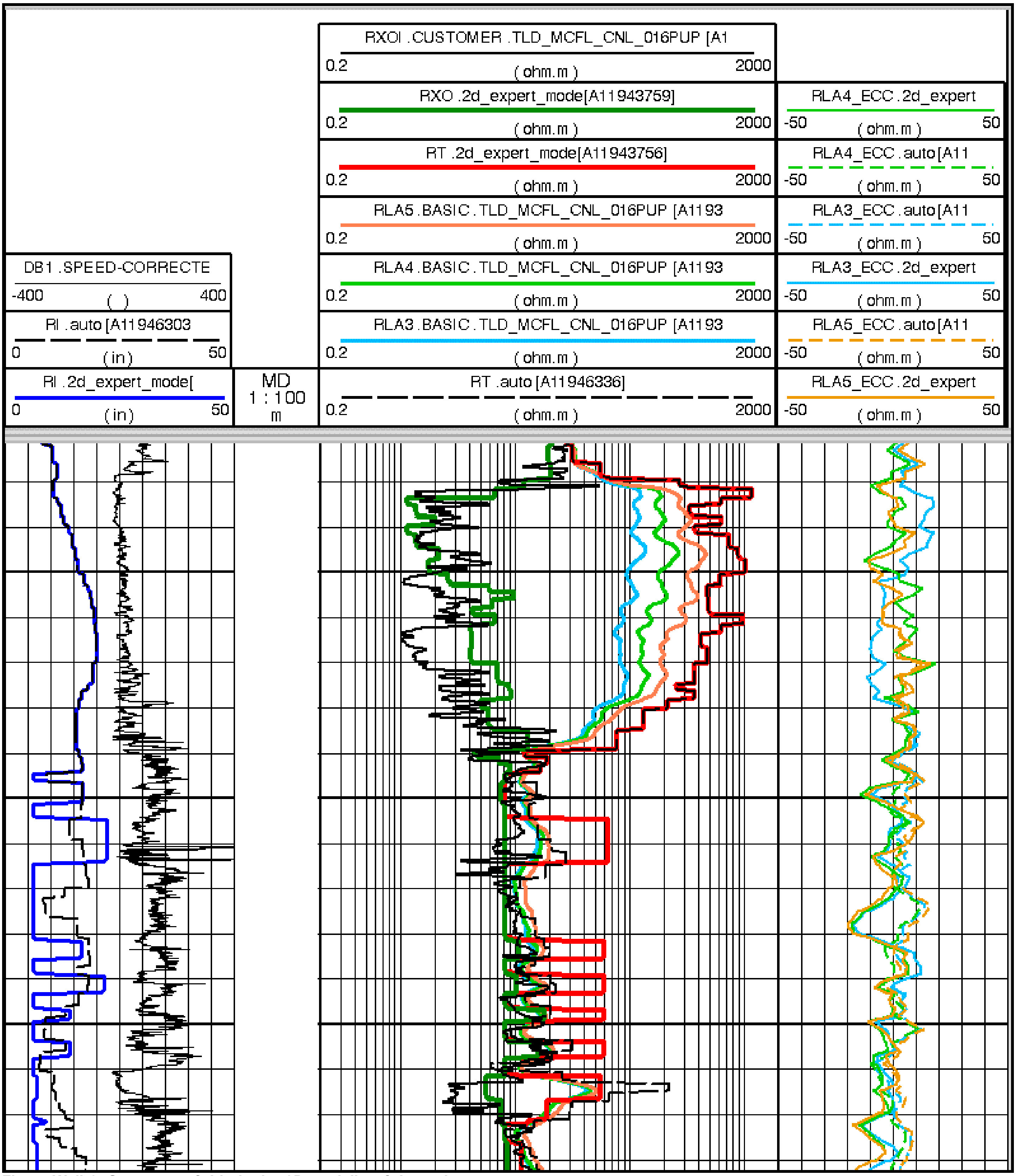

Fig. 7: **Well 2. Sequence of thin beds: 2D modeling & inversion.** The 2D automatic inversion computed a good log reconstruction (right column, dashed lines), but, due to the low sensitivity of the tool, didn't modify the very low resistivities in the thin beds (centre column, black dashed line). The 2D expert-mode processing did succeed in improving the R_t value in the thin layers (centre column, thick red line) while keeping the reconstruction errors very low.

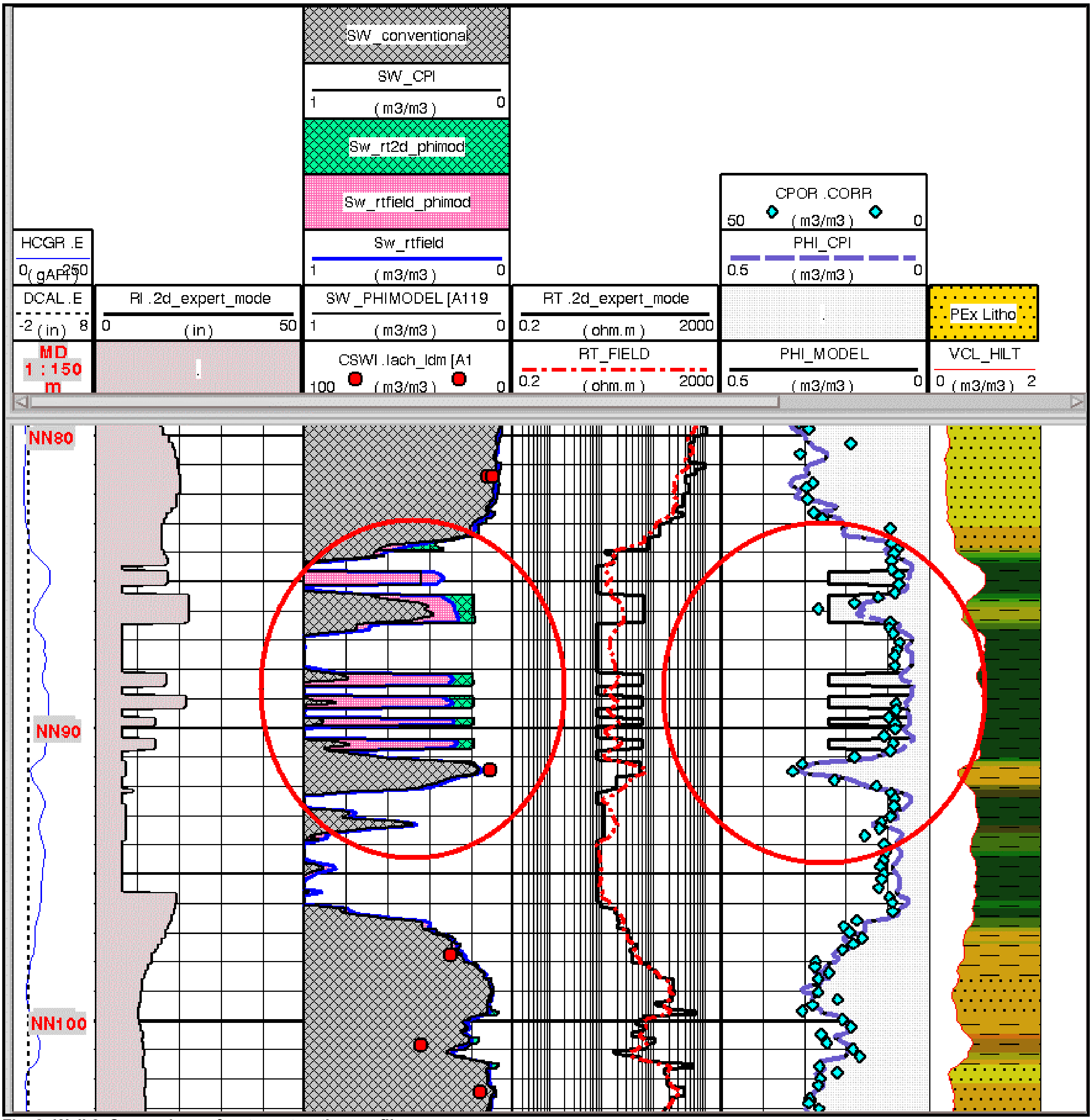

Fig. 8: Well 2. Comparison of water saturation profiles.