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A Model-Based Method to Supply Missing Log Information

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Abstract

Joint interpretation of well logging data requires that all logs involved in the interpretation process be mutually consistent. We have developed a model-based method that achieves raw data quality and consistency improvement by means of log data depth matching, recalibration of abnormal logs, and reconstruction of missing logs.

To perform model-based log depth matching, we select a log to serve as a depth reference. Using this log, we generate a reference earth model and calculate all the synthetic logs that must be depth-matched. Depth matching is accomplished by shifting each log to the appropriate depth level of the synthetic log in order to match the main features of both curves. In many practical cases, a single depth shift is not enough. A more general approach is based on the application of our method to a sequence of depth windows.

To perform the model-based log calibrations, we apply the following two-step procedure. At the first step, we execute the raw data inversion by using the undisturbed (normal) measurements. At the second step, to reconstruct abnormal or missing logs, we calculate all the synthetic logs by using the inversion results. These reconstructed synthetic logs can then be used in the petrophysical interpretation process.

Practical applications of the method to the raw data are presented. In the first example, we perform depth matching and recalibration for a suite of old electrical logs (data from Western Siberia). In the second example, we perform a correction of abnormal absolute voltage measurements made with the array lateral log tool (data from Western Australia).

Introduction

The evaluation process for oil and gas reservoirs includes the accurate estimation of underground formation resistivities. The use of array logging data such as old lateral logs (e.g., suite of Russian BKZ logs)[1-5] or of modern array logging measurements (e.g., array induction and array lateral log)[6-8] allows the interpreter to accurately determine the near-wellbore formation resistivity distribution under different environmental conditions. However, the full benefit of array technology can only be achieved if multi-dimensional, joint inversion processing is applied to a consistent suite of logs.[5, 8]

In practice, however, especially when we are dealing with the suite of old electrical logs, the latter are often not properly calibrated and depth matched (due to multiple runs of the logging instruments in the same well). Some important logs (e.g., mud resistivity) may not be available for an interpretation process. Some logs could exhibit measurement offsets. Such a problem could appear, for example, on normal galvanic logs, when the absolute voltages in low-resistive formations exhibit an offset (level shift) due to the physical nature of this type of measurement.[8]

Special correcting procedures must be applied to prepare the raw data for joint, inversion-based interpretation. Once the logs pass through these procedures, they can be used to accurately determine formation resistivity, and then to perform more reliable petrophysical analysis of the reservoir properties.

A Model-Based Log Data Correction and Restoration Method

In this section, we describe a model-based method to supply missing and to correct abnormal logs. The method consists of a set of preprocessing procedures, designed to perform log depth matching, recalibration, offset elimination, and recalculation of missing logs.

Generally, each preprocessing procedure involves three steps. First, we generate a reference earth model using the accurate log readings or executing the raw data inversion on a set of measurements assumed to be valid. Then, we calculate the synthetic logs based on the generated earth model. Finally, we perform depth matching, missing log reconstruction, and abnormal log correction. The reconstructed and corrected logs can be used in the further petrophysical interpretation.

It should be noted that, for the preprocessing procedures we describe below to be feasible, we must make certain assumptions regarding data quality and availability.

Depth matching procedure. Let us assume that the mud resistivity log (R_m) and the caliper log are known, and select one log (preferably one more explicit to the depth features, e.g., focused-type resistivity log LL3) as the depth reference. To perform depth matching in a simple and fast manner, we first calculate all the synthetic logs by doing forward modeling based on a simple, non-invaded earth model. The earth model parameters are defined directly from the borehole and shoulder-bed corrected reference log.

Depth matching is accomplished by shifting each log to the appropriate level of the synthetic log to match the main features of the two curves. This could be achieved with log cross-correlation. In practice, such a depth matching procedure should be executed sequentially, using a set of overlapping and sliding windows along the borehole.[5]

Recalibration procedure. Let us assume that the R_m and the caliper logs are known and that they are depth-matched. To define the earth model structure, we apply radial, one-dimensional (1-D), or point-by-point inversion to a set of logs, including the poorly calibrated ones. We apply this inversion over a short interval within a relatively thick and uninvaded formation.[5]

The log scaling (calibration) factors determined by the above inversion procedure can then be used to recalibrate the logs. This procedure provides the most reliable and stable results when only two logs with similar resolution are used in the correcting process.

Offset correction procedure. This procedure is similar to the previous one. The difference is that we apply inversion to logs that do not exhibit measurement offset. To determine an offset value, it is sufficient to run the inversion algorithm over a short interval. Then, one calculates all the synthetic logs using the generated formation model. The log offset is calculated as the difference between the raw and the synthetic logs.

Missing log reconstruction procedure. This procedure is quite similar to the offset correction approach. As an example, we show here how to restore the mud resistivity log (R_m). Let us assume that the caliper log is known. We select resistivity logs that are depth-matched and properly calibrated. Applying the 1-D inversion to a shallow-reading log in a relatively thick uninvaded interval, we recover the true R_m value. Finally, using the temperature log, we can reconstruct the entire R_m log.

Case Studies

In this section, we present two case studies for vertical exploration wells from Western Siberia and the North-West shelf region of offshore Western Australia. All depths are relative and given in meters. These case studies will demonstrate practical applications of the logging data correction and reconstruction procedures we have developed.

Case Study 1 – Russian BKZ Data from Western Siberia. A suite of BKZ logs (L045, L105, L225, L425, and L850)[3-5] from a vertical well, WS-1, logged in Western Siberia was available for an inversion-based interpretation. The data was logged at a rate of 6 samples per meter. The caliper and the SP logs were provided. The goal of interpretation was to evaluate the interval below the Bazhenov shale in the Jurassic sands.

Analysis of the raw data indicated that the logs were not properly depth-matched, and that estimation of mud resistivity was required. Application of the preprocessing procedures described in this paper allowed us to perform depth matching of the BKZ logs and estimate accurately the mud resistivity value, $R_m = 0.7\ \Omega\cdot m$, for the interval of interest.

The 2-D inversion was next used to determine a picture of the formation resistivity around the borehole over a selected 100-meter interval. The SP log was used for both detecting layer boundary positions and estimating intervals of high shale content. These layers were assumed to be impermeable while constructing an initial resistivity model. Initial resistivity values were determined from the 1-D inversion results. The 2-D resistivity interpretation results are shown in Fig. 1. We can see a good match between the raw and theoretical responses (tracks 3 and 4) calculated using the final inverted model. This good data match indicates reliability of the preprocessing results and could also be used for QC of the inversion results.

Case Study 2 – Array Lateral Log Data from Australia. This section covers the array lateral log (HDLL) data interpretation for the E-1 exploration well from offshore Western Australia. The well contained two hydrocarbon columns. In this paper, we present resistivity interpretation results only for the top column, the Lower Barrow group sand, located at 478.5 — 490.0 m with a gas/oil contact at 484.5 m.[8]

At a well site, the resistivity image of the formation around the wellbore derived from the so-called software-focused resistivity (SFR) curves, provides information necessary to delineate permeable zones and supports immediate operational decisions. At a geoscience center, a more detailed image of the formation resistivity around the wellbore can subsequently be derived with a more rigorous 2-D (in case of a vertical well) or 3-D (in case of a deviated well) inversion.[7]

The SFR resistivity curves indicated an anomalous response over the water-bearing section of the Lower Barrow Formation below 480 m. The shallow SFR curves overlay each other, between 0.6 and 0.7 Ω·m, while the 20″, 30″, and 40″ SFR curves overlay each other at about 1.0 Ω·m, with the 50″ SFR reading around 1.2 Ω·m (Fig. 2, track 7). There does not seem to be any explanation for this response, as invasion should have produced a more gradual increase in resistivity. It was suspected, however, that a voltage discrepancy caused by offset measurements was the reason for these unexpected SFR results.

The 2-D inversion performed with the first differences only is immune to offsets in the absolute voltages. The inversion results, L_{xo}, R_{xo}, and R_t curves (depth of invasion, resistivity of invaded zone, and resistivity of uncontaminated zone, respectively), are displayed in Fig. 2 (tracks 3-4). Evident in the hydrocarbon zone is the minor amount of separation between the R_{xo} and R_t curves. This indicates a low degree of invasion, probably due to a strong mud cake.

It was then possible to simulate all the theoretical curves, including the first differences and voltages, using the final earth model derived by inversion. The excellent match of the array lateral log first differences (track 5) indicates the reliability of the inversion results. It is evident that the match of the absolute voltage V4 (track 6) is far from satisfactory.

To investigate this problem, let us consider a 3-layer synthetic formation model presented in Fig. 3. It will allow us to illustrate the effect of the reference electrode V4 offset on the SFR curves. This model was generated using a simplified formation model from well E-1.

Track 1 shows V4 accurately calculated for this model and V4S shifted by a constant 25% of its value calculated far away from the central layer. This means the actual V4 offset at the central part of the model is much less than at the shoulders, and is about 4%. Track 2 shows the SFR curves calculated using the offset voltage V4S. They exhibit the same abnormal behavior as the field SFR curves shown on Fig. 2 (track 7).

In the model case, the accurate SFR curves calculated using the accurate voltage V4, provide a correct radial resistivity profile (Fig. 3, track 3). In the field case, the SFR curves recalculated using the synthetic V4 log, more closely support the results of the rigorous 2-D inversion (Fig. 2, track 8).

Conclusions

A model-based method that allows for fast logging data consistency improvement by means of log data depth matching, recalibrating abnormal logs, and supplying missing log information has been developed and tested. The field tests were performed with the old electrical logs from Siberia and with modern array lateral logs from Australia.

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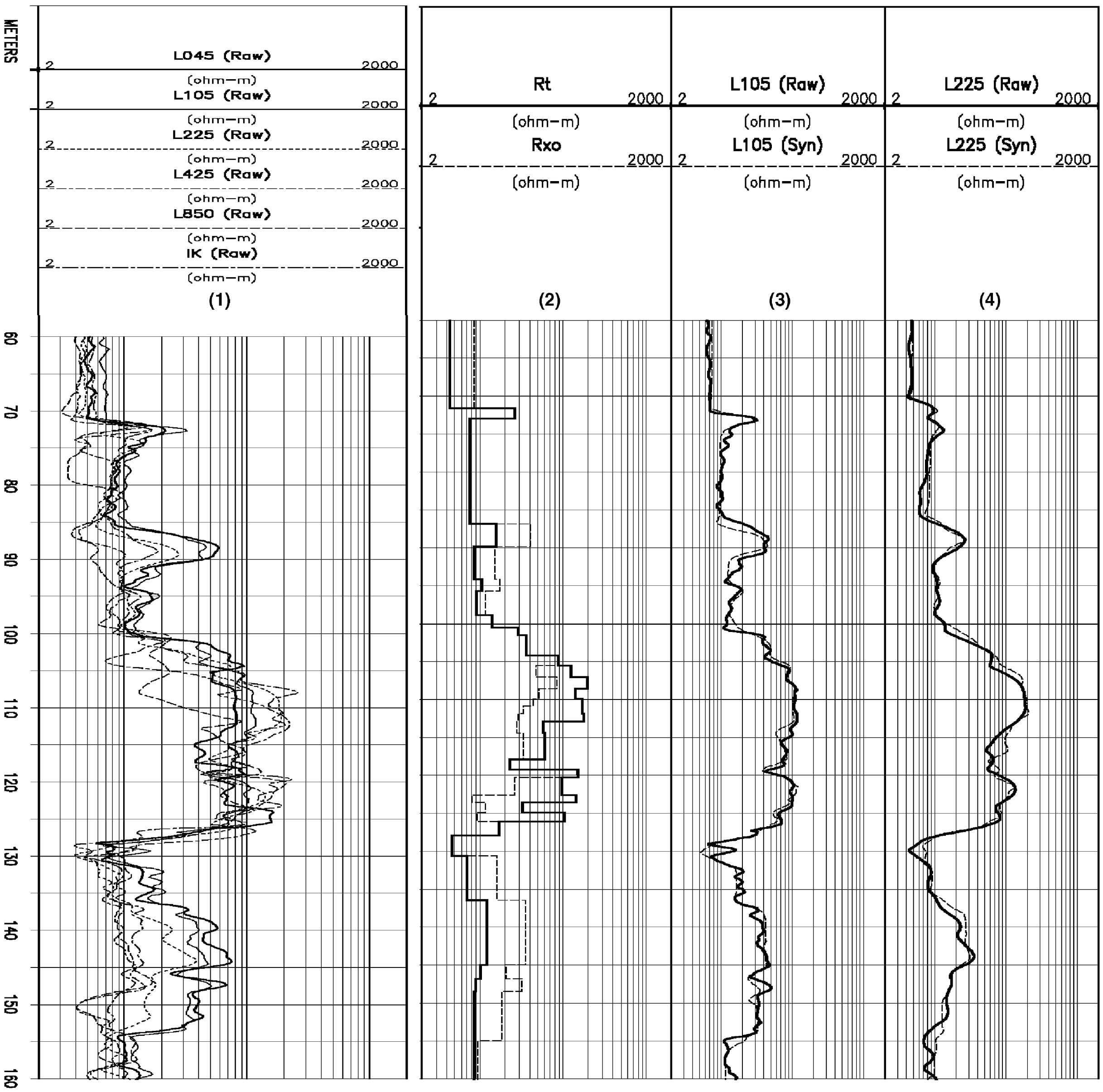

Fig. 1: Interpretation results of the BKZ resistivity logs for well WS-1. The raw data is presented in track 1; the 2-D inversion results are in track 2 (dashed curve is resistivity of invaded zone, R_{xo}; solid curve is resistivity of uncontaminated zone, R_t). Data match between the raw and synthetic L105 and L225 BKZ lateral logs is shown in tracks 3 and 4, respectively.

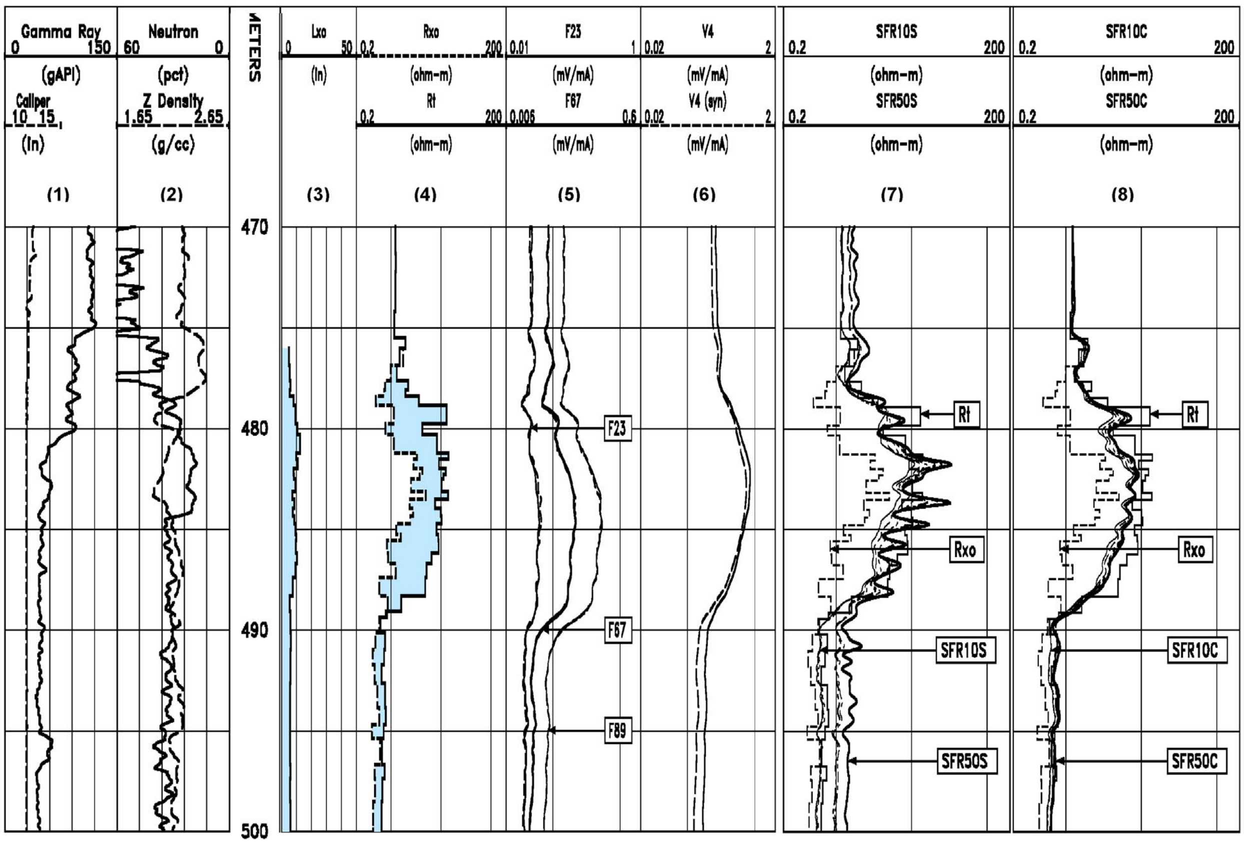

Fig. 2: Raw logs and inversion results for the interval, 470-500 m, Well E-1 from Australia. Results of 2-D inversion are shown in tracks 3 and 4. The data fit between measured and synthetic HDLL first differences and the absolute voltage V4 are shown in tracks 5 and 6, respectively. The 2-D inversion results and field SFR curves calculated using recorded (offset) voltage V4S are presented in track 7. The corrected SFR curves calculated with application of the synthetic V4 log are shown in track 8.

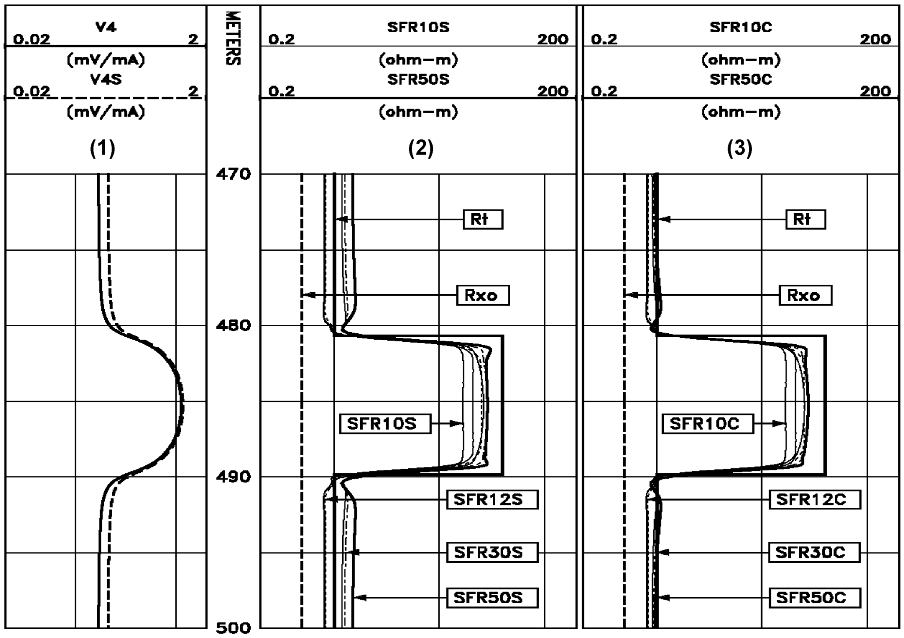

Figure 3: Effect of the reference voltage V4 offset on the SFR curves. Model parameters: R_m=0.06 Ω·m, Bhd = 12.25", R_{xo} = 0.5 Ω·m, L_{xo} = 6", R_t = 1-40-1 Ω·m. Nomenclature: V4 and V4S are accurate and shifted (offset) reference voltages, respectively (track 1). The SFR curves calculated using shifted voltage V4S and accurate voltage V4 are shown in tracks 2 and 3, respectively.