INVERSION-BASED WORKFLOW FOR QUANTITATIVE INTERPRETATION OF THE NEW-GENERATION OIL-BASED MUD RESISTIVITY IMAGER

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ABSTRACT

The new high-definition oil-based mud (OBM) imager is a pad-based microelectrical imager operating at high frequency to establish capacitive contact with the formation in wellbores filled with nonconductive mud. From multiple modes of operation, formation resistivity-like images are generated using an efficient composite data-processing scheme that approximates formation resistivity either by filtering or applying a correction to minimize the contribution of the OBM to the measured signal. Data from the different modes are “blended” based on estimated formation parameters to generate an optimized image. This approach requires some knowledge of mud electrical properties.

In addition to the composite processing scheme, we also developed a model-based parametric inversion for quantitative interpretation. The Gauss-Newton algorithm matches the measurements to an accurate computationally efficient approximate forward model built by multidimensional fitting of the data generated using a finite-element simulation. The workflow overcomes the underdetermined inversion problem and calibration limitations of the measurements. The inversion allows flexible model definition and parameterization, including refinement of the calibration, and can process intervals of logging data and measurements from multiple buttons simultaneously. The workflow stabilizes the inversion and improves the consistency of the processed results. To overcome the underdetermined nature of the problem and speed up the inversion, we use a sequence of inversion runs to first iteratively estimate the mud properties for a small depth section of the log; this estimate is then used to invert for the button standoff and the formation resistivity and permittivity for longer data sections.

Besides its ability to produce more accurate formation resistivity, the inversion may improve image quality in highly resistive and fractured formations, improve consistency between the different pads, and help eliminate eventual “blending” artifacts. In addition to formation resistivity, the inversion generates a tool standoff that provides the borehole shape and facilitates standoff-corrected formation properties. Moreover, inversion-derived formation dielectric permittivity images can be valuable for standalone formation evaluation or joint interpretation with array dielectric measurements.

The inversion algorithm is validated using synthetic data generated by a finite-element simulator that accurately models the detailed tool and surrounding borehole and formation. We present examples of inversion sensitivity and error propagation for a synthetic model with wide range of all parameters. The inversion is able to quantify error propagation through a sensitivity analysis and provides error bars and uncertainties for inverted parameters.

The inversion is applied to field data acquired in different conditions, for a wide range of formation resistivity, dielectric permittivity, mud properties, and borehole conditions, illustrating the potential of the inversion-based workflow to further enhance interpretation of the new OBM imager. The field data examples include various complex cases with potential blending artifacts and with large standoff. The processed resistivities compare well with standard array induction responses. The inverted standoff image also compares well with the ultrasonic caliper as do the computed dielectric permittivities with those derived from an array dielectric tool.
INTRODUCTION

The application of the micro-electrical imager (Luthi, 2001) has been limited to the conductive water-base fluids (WBM), conditions favorable for use of the low-frequency galvanic measurement physics. The WBM imager is able to produce high-definition images of 0.2-in. resolution and 80% circumferential coverage in an 8-in. borehole, using 192 buttons distributed over 8 pads. Conventional interpretation of the micro-electrical images covers determination of structure, identification of thin beds, classification of heterogeneities, facies classification, identification of the depositional environments, fracture analysis, and use in constraining the reservoir model (Hansen and Fett, 2000; Slatt, 2010).

Since the 1990s, most deepwater wells have been drilled with nonconductive oil-base mud (OBM), and the conventional high-resolution WBM imager could not be used. The first generation of microresistivity imager for OBM, introduced more than a decade ago (Cheung et al., 2001) represented a major industry breakthrough and quickly became a standard part of the formation evaluation program for most deepwater wells. However, the OBM sensor design and measurement physics determine the reduced resolution (0.4-in.) and coverage (20 sensors) compared to WBM technology. The measurement physics also causes reduced sensitivity to features parallel to the wellbore, strong shoulder-bed effect, response complexity in heterogeneous formations, and high sensitivity to clay dehydration cracks.

The recently introduced OBM imager (Bloemenkamp et al., 2014) overcomes limitations of the first-generation sensors. The new physical principle and the tool layout provide superior performance, reducing the possible ambiguities in interpretation due to significantly improved sensitivity to bedding and more natural response to formation texture. The tool provides 98% circumferential coverage in an 8-in borehole via 192 microelectrodes, capable of producing images of similar quality and high specification as those acquired in WBM. The prototype of the new tool was successfully field tested in a few dozen wells in a wide range of geologic environments (Laronga et al., 2013), demonstrating the ability to reliably resolve the sedimentary and structural details of the formation.

The images are used for quantitative interpretation of boundaries and structure. So far, wireline microelectrical imagers have not been used for quantitative interpretation of formation resistivity as have their lower-resolution logging-while-drilling (LWD) azimuthal resistivity counterpart (Bonner et al., 1994). Complete removal of standoff effect and other artifacts requires calibrated measurements, not common for wireline microelectrical imagers, and a model-based approach, commonly applied to formation evaluation logs (Ellis and Singer, 2007). A related inversion-based method for standoff and shoulder-bed correction from LWD density images was recently proposed (Shetty et al., 2013).

In this paper, we present a novel, inversion-based methodology for quantitative interpretation of microelectrical imagers for OBM. The inversion complements the images based on conventional processing. It outputs resistivity, dielectric permittivity, and standoff images that can be used for formation evaluation, structural interpretation and evaluation of borehole shape and for QC of standard images. The new workflow was applied to a dozen field data sets, which demonstrated the tool’s ability to produce resistivity images with improved consistency and reduction of artifacts due to standoff and multifrequency response blending.

OIL-BASED MUD IMAGING TOOL AND STANDARD INTERPRETATION

The new high-definition OBM-adapted imager is an electrode tool similar to the industry-standard microelectrical imager for WBM (Ekstrom et al., 1986), with comparable resolution and image quality. The tool operates at the megahertz frequency range in order to establish a capacitive contact with the formation (Chen and Habashy, 2006; Bloemenkamp et al., 2014). The tool measures the impedances as seen by the electrode buttons at two separate frequencies. The measurements are affected by both the formation to be measured and the mud/mud cake layer which often exists between the electrodes and the formations, and are not directly proportional to the formation resistivity as in the case of microelectrical imagers for WBM. The simplified tool layout is shown in Figure 1.

An efficient composite processing scheme has been proposed to obtain the formation impedance images (Bloemenkamp et al., 2014). In low to intermediate impedance range the method corrects for the mud and standoff effect by projecting the measured impedance in a direction perpendicular to the mud impedance vector to approximate the formation impedance (ZB90-processing mode). This processing obtains approximate
mud impedance angles and is most effective for formations where the contribution of the permittivity to the formation impedivity is limited. For higher formation impedivity, the mud impedance is estimated and subtracted from the measured impedance amplitude (mud corrected amplitude processing mode). The composite processing (ZTBC image) selects the most appropriate processing mode based on an estimation of the formation impedivity. The produced impedivity image is a function of the formation resistivity and dielectric permittivity and is not linearly dependent on resistivity.

Fig. 1 Simplified tool model (left) and measurement phasor diagram explaining the OBM imager measurement principles. \( Z \) represents measured button impedance, having contribution from mud and formation, \( Z_m \)– mud impedance, \( Z_f \)– formation impedance. The ZB90 processing projects the formation impedance \( Z_f \) to direction orthogonal to mud impedance.

**INVERSION-BASED INTERPRETATION WORKFLOW**

The standard measurement processing requires a higher level of calibration of microelectrical imager measurements compared to the WBM formation microimager, although not at the level of formation evaluation resistivity and dielectric measurements. The “raw” measurements are still not directly usable for quantitative interpretation of formation resistivity.

Because of the measurement physics, the OBM imager has increased sensitivity to large standoff, and response nonlinearity and composite processing involving multiple measurements may also cause some “blending” artifacts. For complete removal of these environmental effects, we apply model-based inversion, using the parameterization shown in Figure 1. The inversion is used to determine model parameters: formation and mud resistivities and dielectric permittivities and standoff. The approach also requires calibrated measurements. The good quality of the imager raw measurements allows application of approximate calibration through the inversion.

The inversion algorithm. The inversion algorithm is based on the Gauss-Newton optimization approach with box parameter constraints and a line search scheme (Habashy and Abubakar, 2004). The cost function has the data misfit and the multiplicative regularization terms, defined as

\[
C(\bar{m}) = \frac{1}{2} \left[ \frac{\| W d \cdot (S(\bar{m}) - \bar{d}) \|_2^2}{\| W d \cdot \bar{d} \|_2^2} + \lambda_k \frac{\| W m \cdot (\bar{m} - \bar{m}_p) \|_2^2}{\| W m \cdot \bar{m}_p \|_2^2} \right],
\]

where \( \bar{m} \) is the vector of unknown model parameters. It contains formation properties such as the conductivity \( \sigma \) and the permittivity at two frequencies \( (\varepsilon_F1, \varepsilon_F2) \), the sensor standoff \( s \), and mud permittivity \( \varepsilon_m \), and conductivity \( \sigma_m \), or phase angle of the mud impedance \( \varphi_m \) (referred to as “mud angle”) at two frequencies.

The vector \( S(\bar{m}) \) is the simulated data for the model \( \bar{m} \), and \( d \) is the measured data vector, which consists of the in-phase and out-phase impedances at the two frequencies. The elements of the diagonal weight
matrix $\mathbf{W}_d$ are the inverse of the measured amplitudes of the in-phase and out-phase impedance, which prevents over-weighting of single-frequency data.

The vector $\mathbf{m}_p$ represents the reference (prescribed) parameter values. The diagonal weight matrix $\mathbf{W}_m$ controls the contribution of each individual model parameter to the total cost function. Larger weighting is needed if a particular model parameter is not very sensitive to the measurements. The scale variable $\lambda_k$ is the multiplicative regularization coefficient at the $k$-th Gauss-Newton iteration. It is defined as a function of the data misfit at the $k$-th iteration:

$$\lambda_k = \alpha \left( \frac{\| \mathbf{W}_d \cdot (\mathbf{S}(\mathbf{m}_k) - \mathbf{d}) \|^2}{\| \mathbf{W}_d \cdot \mathbf{d} \|^2} \right)^\beta,$$

where $\alpha$ is a constant determined by numerical trials for fast and stable convergence. The expression within the large bracket is the data misfit at the $k$-th Gauss-Newton iteration. The exponent $\beta$ is used to control the changing rate of the regularization term and is typically larger than 1. Since the data misfit itself is mostly less than 1, $\beta (>1)$ makes the regularization term vanish faster as the inversion converges. We find it necessary to set an upper limit for scale variable $\lambda_k$ to avoid the inversion slow down during the early iterations. Additional regularization to reduce ambiguity between the mud permittivity and standoff are also included in the cost function.

**Forward modeling and analytic Jacobian calculation.**

An efficient forward modeling technique is very important in inversion since the models must accurately represent the tool responses and be able to be run fast enough to be tested in the inversion loop in the minimization process. Given the huge amount of data acquired by an imaging tool, it is not practical to employ a full-scale numerical modeling to calculate the impedance $Z$. An accurate fast forward model was developed by polynomial fitting of the finite-element generated responses. We constructed the fourth-order polynomial in terms of the formation impedance $\xi_f = 1/(j\omega \varepsilon_0 \sigma_f)$, mud impedance, $\xi_m = 1/(j\omega \varepsilon_0 \sigma_m + \sigma_m)$ and the mud standoff, resulting in 70 polynomial coefficients. The residuals of the fitting range from 0.086% to 2.08%. The sensitivities for the model parameters (elements of the Jacobian matrix) are easily derived by polynomial differentiation.

**Multipoint and multistep inversion strategy.**

The resulting problem is underdetermined since the number of available measurements (total of four) is well below the number of model parameters (up to eight) at each log point. To overcome the problem, we apply the inversion to multiple log points, taking advantage of the fact that the mud properties are slowly changing and are nearly constant locally. While each individual log point has its own formation properties and standoff, the mud properties are shared for all the log points in each inversion. We also look for the less-sensitive model parameters and use approximate values for them.

Since the mud properties may change with the depth, they need to be inverted periodically, after initial segmentation. We first invert the mud properties for a short interval, typically 5- to 10-ft long, selected after visual inspection of raw data, and then use these mud properties to invert the sensor standoff and the formation properties for longer log sections, typically about 300-ft long. The inversion is run in multiple passes, iteratively refining the mud properties.

To meet the quantitative interpretation requirements, the calibration needs to be fine-tuned through the algorithm. The inverted mud properties also serve to compensate for imperfect measurement calibration. That is the reason why different mud properties are assumed for each button. The inversion allows inversion of multiple buttons simultaneously, using the common mud properties for a pad or group of pads. In that case the true calibration amplitude and phase are solved explicitly. After mud properties are calibrated in the short reference section, the more accurate mud angle can be used in conventional processing scheme. Furthermore, it is possible to take into account the mud angle variation based on changes observed in the conventional mud angle logs.

The inversion also supports a user-guided model, allowing expert-level use and manual fine-tuning of inversion parameters. Furthermore, mud angle from the inversion can be used in conventional composite processing, often improving the quality of images.

**INVERSION VALIDATION**

The inversion algorithm and the workflow were validated on synthetic data sets generated using a finite-element simulator. The test cases are designed to assess the inversion performance for a wide range of formation, mud, and standoff parameters. They also serve to evaluate the measurement sensitivity and can
explain the performance and some artifacts that may be seen on field data sets. The simulated data are used to generate logs, while the inversion uses the approximate forward model. The mismatch between the two forward models is better than 5%. The formation resistivity-permittivity profile and the standoffs are completely random and uncorrelated, with resistivities varying from 0.2 \( \Omega \cdot m \) to 20,000 \( \Omega \cdot m \); permittivities taking discrete values with 0.5, 1 and 2 times the nominal value for the given formation resistivity at the two frequencies, and standoffs between 0.1 mm and 9 mm. Dozens of cases with different mud properties were tested.

Figure 2 illustrates an example of a formation resistivity–standoff profile and inverted values. The modeled mud properties are \( \varepsilon_{m1} = 10, \varepsilon_{m2} = 10, \varphi_{m1} = -81^\circ, \varphi_{m2} = -81^\circ \). The entire data set was treated as the mud evaluation interval, and inverted values of mud properties are \( \varepsilon_{m1} = 10.41, \varepsilon_{m2} = 10.49, \varphi_{m1} = -81.12^\circ, \varphi_{m2} = -80.38^\circ \), converging in four steps. There are only four points at which the residual was above 10%, and they all correspond to maximal formation resistivity of 20,000 \( \Omega \cdot m \), where sensitivity is very low. The same results are presented in Figure 3, but for visual clarity, the profile was changed. We reordered the resistivity from low to high to demonstrate that reconstruction of resistivities is very good and consistent. Similarly, to evaluate the quality of inverted standoff, the profile is changed to create a staircase standoff profile, as shown in Figure 4. High values of residual are for highest resistivities and very low standoff (below 0.5 mm). Reconstructed standoff matches well the true values, typically within 1 mm. Inverted formation permittivities at two frequencies are shown in Figure 5. The high frequency permittivity is better resolved, since measurements are more sensitive to it, especially for higher resistivities.

![Fig. 2](image-url)
Fig. 3 Results from Figure 2 reformatted to evaluate inverted resistivities (top). The residual is the highest for maximum resistivity of 20,000 Ω·m, but resistivities are recovered very well by the inversion for random resistivity-permittivity and standoff variation.

Fig. 4 Results from Figure 2 reformatted to evaluate inverted standoff (top). High values of residual are for highest resistivities and very low standoff (below 0.5 mm).
FIELD DATA EXAMPLES

We present some of the major inversion benefits through the field test examples and compare the inverted resistivity images with the conventional composite images and logs. The composite processing itself is a very efficient and is a proven method to visualize the measured image for geological interpretation, as is typically done with other resistivity images. On the other hand, the inversion provides quantitative resistivity and permittivity and their images. In addition, the inverted standoff can be a very useful quality indicator of the composite image, providing information about the borehole shape, drilling marks, and fractures, and whether they are opened or closed.

Quantitative formation resistivity and improved image consistency. Figure 6, from a job performed at the Catoosa test facility, Oklahoma, USA, shows the inversion-derived resistivity (trek 1) and standoff (trek 2) images compared to the standard composite image (trek 3). The inverted resistivity image has improved consistency among different pads and can better delineate thin layers. The standoff image shows the drilling marks that cannot be seen in the original composite image. The inverted resistivity agrees quite well with the array induction 10-in. resistivity curve. In a typical quantitative interpretation workflow, the ZTBC curve (impedivity from composite processing) would be calibrated against the shallow resistivity from array induction (AE10), while inversion-derived resistivities are independently evaluated. The composite image shows some blending artifacts due to combining of responses at different frequencies. These blending artifacts are not present in the inverted resistivity image since the inversion provides a single formation resistivity output that is continuous and monotonic over the full range of commonly encountered resistivities by jointly inverting responses at two frequencies.

Figure 7 shows an example of the inverted resistivity image enhancing thin conductive stylolites in a 15-ft. long calcareous section from an Eagle Ford well. The resistivity varies between 10 Ω·m and 500 Ω·m. The inversion enhancement of the thin conductive stylolites is noticeable around xx09 ft, xx14 ft, and between xx01 ft and xx 02ft. In general the inversion is shown to improve the consistency among the eight imaging pads.

Figures 8 to 10 display examples from a well drilled in a Northeastern US shale formation in an interval of
highly contrasting clay and calcareous laminations. Again the inverted resistivity image significantly improves consistency, and enhances both resistive and conductive layers. This is a difficult case for conventional processing due to the rollover effect, since the resistivites vary from several $\Omega \cdot m$ to close to 1000 $\Omega \cdot m$. The rollover effect in ZTBC processing is due to nonlinear dependence of measured button impedance on formation impedivity. It causes very resistive formation to be mistakenly shown as conductive, as can be seen in the fourth trek in Figures 8 and 9 where the ZTBC curve and the inverted resistivity swing in the opposite direction. In both cases the inverted resistivity logs are consistent with array induction 10-in. curves. Near the top and the bottom of Figure 10, around xx85 ft and xx91 ft, two sidewall core holes are clearly identified on pad 5 (seventh from left) in both the inverted resistivity and standoff images as white circular spots. The white color suggests high resistivity and a large standoff, which indicates that the tool is correctly sensing the OBM mud. The ZTBC, however, shows conductive spots due to aforementioned rollover effect. Notice the image noise occurred around the core holes is due to the image “harmonization” algorithm imperfection in displaying events with very high resistivity contrast. Figure 11 presents a 35-ft. long section from another shale play in the Northeastern USA where inverted resistivity images improve consistency.

The accurate and quantitative images of formation resistivity provided by the inversion are a key enabler for improved thin-bed evaluation using the new high-definition OBM-adapted imager. This new tool has great advantages over the previous generation OBM-adapted imager for this application, owing to its higher resolution and lack of significant shoulder-bed effects, but it is important that petrophysicists performing this interpretation be able to define cutoff parameters in terms of meaningful units (ohmm) that can be applied equally to all wells in a field. Quantitative high-resolution $R_{xo}$ in OBM is also useful for flushed zone evaluation to determine bound water volume. The quantitative resistivity images can also be used in a porosity transform, such as the one proposed by Newberry (1996), though considering that the images are acquired in an OBM environment, care must be taken with interpreting the significance of the results.

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**Fig. 6** Inverted resistivity image improves consistency compared to standard image. From left to right: Composite image; inverted resistivity image; inverted standoff image; resistivity logs (AE10-induction 10-in. curve; inverted resistivity, RHO, inversion; ZTBC composite processing projected impedivity).
Fig. 7 Inverted resistivity image enhances thin conductive layers from another Eagle Ford well. From left to right: Composite image; inverted resistivity image; inverted standoff image; resistivity logs (AE10-induction 10-in. curve, RHO-inversion, ZTBC composite processing projected impedivity).

Fig. 8 Inverted resistivity image improves consistency among pads and enhances resistive and conductive layers in a marly section of a Northeastern US shale formation. From left to right: Composite image; inverted resistivity image; inverted standoff image; resistivity logs (AE10-induction 10-in. curve, RHO-inversion, ZTBC composite processing).
Fig. 9 Inverted resistivity image improves consistency among pads (shale formation, Northeastern US). From left to right: Composite image; inverted resistivity image; inverted standoff image; resistivity logs (AE10-induction 10-in. curve, RHO-inversion, ZTBC composite processing).

Fig. 10 Inverted resistivity image improves consistency among pads and enhances resistive and conductive layers in a Northeastern US shale. Two sidewall core holes are identified on pad 5 near the top and the bottom. From left to right: Composite image; inverted resistivity image; inverted standoff image; resistivity logs (AE10-induction 10-in. curve, RHO-inversion, ZTBC composite processing projected impedivity).
Inverted standoff as an indication of borehole condition. In addition to the formation resistivity, the button standoff is always inverted for all button positions, producing the mud standoff images. Such inverted standoff values are good indications of the borehole conditions and can be used to diagnose the ZTBC processing and the inversion results. Besides the borehole breakouts, drilling marks, spiraling, cored zones, and pad touching the formation (zero standoff), the inverted standoff image may also indicate events such as open or closed fractures. We have shown through synthetic data tests that the inverted standoff is generally more accurate for less-resistive formations for given mud properties. When the formation is very resistive, the contrast between the mud and the formation becomes small. As a result, the measurements will be less sensitive to the standoff, which defines the place of separation between the mud and the formations.

Figure 12 shows a bad hole section with large maximum standoff around 13 mm at xx78ft in and around 15 mm at xx82ft in a well drilled in the Eagle Ford formation. Use of inverted mud angles improves the composite-processing-derived image but does not remove the ‘resistivity ambiguity.’ The spalled sections of the borehole wall in this case present as conductive patches in the composite impedivity image due to the aforementioned ZTBC rollover effect. The inverted resistivity and standoff images clearly show white (resistive) spots, indicating that the tool is effectively reading the mud in these spots, thus conveying important information about the borehole condition.

In Figure 13, we present inverted resistivity and standoff images along with the composite processing-derived image from a well drilled in a shallow-marine clastic environment in Texas, USA. The inverted standoff explains the inconsistency in the original image is due to the borehole spiraling effect and occasional instances of direct electrode contact with the formation. The resulting inverted resistivity image shows consistent layering, with the exception of intervals where the middle buttons of pad one (marked by the green line) are occasionally touching the formation. A similar example from the other section of the same well is shown in Figure 14, with clearly observable spiraling effects. Significant button touching is observed around xx12.5ft and at the figure bottom.

In Figures 15 and 16 we show images of a zone with breakouts in a well drilled in a shallow-marine clastic
environment in Texas, USA. The raw measured data, the measured impedance amplitude (ZBAM) and impedance phase (ZBPH) at two frequencies for the middle button of pad one, indicate spikes created most likely by electrodes touching the formation. In both examples conventional processing often shows conductive patches due to rollover effect, while inverted resistivity images consistently show resistive zones corresponding to breakouts and indicating that the tool is reading primarily mud. Notice in Figures 15 and 16 we did not harmonize the inverted resistivity images due to the huge resistivity contrast. As a result, the images contain many vertical lines.

In Figure 17, we show another example from an Eagle Ford well, demonstrating that the inconsistency on the ZTBC images mostly due to sensor standoff effect. We observe a one-to-one correspondence between the large standoff spots shown on the standoff map in white and the inconsistent bright spots shown on the ZTBC image. Those versed in the interpretation of borehole images will immediately note that in the inverted resistivity image, these breakouts are much more easily recognized as such, not only because the resistivity contrast is more intuitive, but also because their boundaries are much better defined such that the features appear more ‘natural.’ A glance at the standoff image erases any lingering doubt as to the interpretation of these features; note that the highest values of standoff are seen at the edges; in fact the real standoff at the center of the breakout is much larger and probably lies outside the range for which we can presently invert. With the inverted standoff image from the new high-definition OBM imager, interpretation of wellbore geomechanics in wells drilled with OBM is taken beyond even what was possible with microresistivity images in WBM. A further benefit to the inversion in this example is that the space between the breakouts is more clearly imaged.

Fig.12 Inverted standoff from a rough hole section in the Eagle Ford formation. From left to right: Original composite processing image; composite processing image using inverted mud angle; inverted resistivity image; inverted standoff image; and inverted resistivity log (RHO).
**Fig. 13** Inverted standoff from a rough borehole drilled in the Eagle Ford formation. From left to right: Original composite processing image; inverted resistivity image; inverted standoff image; and resistivity logs (RHO-inversion, ZTBC composite processing).

**Fig. 14** Inverted standoff from a rough borehole drilled in the Eagle Ford formation. From left to right: Original composite processing image; inverted resistivity image; inverted standoff image; and resistivity logs (RHO-inversion, ZTBC composite processing).
Fig. 15 Inverted standoff and formation resistivity indicate breakouts, (shallow-marine clastic environment, Texas, USA). From left to right: Original composite processing image; inverted resistivity image; inverted standoff image; raw measured button impedance amplitude and phase at two frequencies, indicating pad touching.

Fig. 16 Inverted standoff and formation resistivity indicate breakouts, (shallow-marine clastic environment, Texas, USA). From left to right: Original composite processing image; inverted resistivity image; inverted standoff image; raw measured button impedance amplitude and phase at two frequencies, indicating pad touching.
Fracture evaluation. The synthetic data tests indicated that the inverted formation resistivities follow the true values and have much larger dynamic range than the standard composite processing. As a result, the inversion may enhance imaging of resistive fractures and thus help better-characterize fractured reservoirs. Additionally, we may hypothesize that the inverted sensor standoff may potentially provide information as to whether the fracture is open or closed. It is important to note that the inverted standoff is used only as an indication of the fracture property, assuming that very resistive fractures with large standoff are filled with OBM, therefore “open”. It should be noted that a typical fracture will occupy just a small fraction of the measurement aperture of any given button electrode, but within the relatively small aperture of the fracture itself, depending on its angle of incidence with the borehole its standoff may be viewed as very large. Ostensibly some averaging takes place during the measurement and thus the new high-definition OBM-adapted imager measurements would not be expected to directly sense the actual depth or aperture of open fractures.

Figure 17 shows the composite image compared to inverted resistivity and standoff images acquired over a fracture swarm associated with normal faulting in an Eagle Ford well. We observe slightly enhanced fracture signatures on the inverted resistivity image, especially for the first fracture near the top of the figure. The inverted resistivity image has also improved the consistency of layering where previously standoff had slightly affected the composite image. Along with images we show the logs of inverted resistivity of pad one, middle button, the corresponding ZTBC impedivities from composite processing, and the shallow 10-in array induction reading.

We observe relatively small standoff for most fractures seen in resistivity image. However the large fractures seen below xx04 ft exhibit a clear large standoff, suggesting that they are most likely mud-filled. The relatively high array induction measurement (AE10) appears to confirm the open dipping fractures. Fractures and minor faults in the upper part of the image are interpreted as most likely closed. The minor normal fault between xx01 and xx02 ft is a special case. The increased standoff bounding this fault on either side of the borehole demonstrates that the fault has actually slipped approximately 7 mm since the well was drilled due to reactivation by hydrostatic pressure. From this single event, it can be inferred that the present-day minimum horizontal stress remains closely aligned to the fault dip direction, approximately East-West. This
highlights once again the strength of the inverted standoff image for wellbore geomechanics; in the past this interpretation could only have been achieved by running an acoustic imager.

Examples from two other fractured and faulted borehole sections in the same data set are presented in Figures 19 and 20, showing enhanced fracture signatures in the inverted resistivity images compared to the composite-processed images. The fractures are typically seen clearly and consistently across all pads in the inverted resistivity images, while the inverted standoff is not necessarily always consistent, due to the fracture orientation and possibly non-uniform fracture aperture. An example of inversion-enhanced fracture signature in high-definition OBM-adapted images acquired in one of the Northeastern US shale datasets is shown in Figure 21. The standoff image clearly shows chipping of the borehole wall at the upper and lower tips of the fracture trace. The increased standoff combined with relatively high array induction reading also suggests that these two fractures are either open or filled with some type of very resistive materials such as calcite or OBM.

The ability to tell the difference between an open fracture and a closed fracture from a microresistivity image alone has long been regarded as a ‘holy grail.’ This is particularly true in environments where high mud weights and mud solids hamper running an acoustic (ultrasonic) imager. The results presented above look very promising toward solving this problem, and we look forward to having a well with conventional core so that we can further validate this fracture indicator.

Fig. 18 An example of a fracture swarms from an Eagle Ford dataset. The inversion is able to differentiate between the actual fracture and the standoff. From left to right: Standard composite processing image; inverted resistivity image; inverted standoff image; and logs of inverted resistivity (RHO), array induction 10-in. curve (AE10), and ZTBC impedivity reading.
Fig. 19 Example of enhanced fracture signature in inverted resistivity images from an Eagle Ford dataset. From left to right: Standard composite processing image; inverted resistivity image; inverted standoff image; and logs of inverted resistivity (RHO), array induction 10-in. curve (AE10), and ZTBC impedivity reading.

Fig. 20 Example of enhanced fracture signature in inverted resistivity images from the same Eagle Ford dataset as the previous figure. Some fractures are clearly suggested as open by white traces in the standoff image. From left to right: Standard composite processing image; inverted resistivity image; inverted standoff image; and logs of inverted resistivity (RHO), array induction 10-in. curve (AE10), and ZTBC impedivity reading.
Fig. 21 Example of enhanced fracture signature in inverted resistivity images from a shale well in the Northeastern US. The two fractures shown are interpreted as essentially open or filled with resistive material, as larger standoff is shown at the fracture locations accompanied with increased induction reading; increased standoff near the upper and lower tips is interpreted as chipping of the borehole wall. From left to right: Standard composite processing image; inverted resistivity image; inverted standoff image; and logs of inverted resistivity (RHO), array induction 10-in. curve (AE10), and ZTBC impedivity reading.

Quantitative formation dielectric permittivity. The measurement sensitivity to formation dielectric permittivity depends on the relative strength of the displacement currents versus that of the conducting currents. Since high frequencies are used, the measurements have substantial sensitivity to formation permittivity over a broad resistivity range. The potential applications of permittivity images are an area for future development. Among other applications one might envision that the inverted formation permittivity in combination with the inverted formation resistivity could be valuable for determination of water saturation. This combination can also be powerfully complementary to the interpretation of array dielectric measurements in OBM, extending the frequency range and adding an intermediate frequency, with potential to better characterize the dispersion for petrophysical interpretation.

Figures 22 to 24 show the ZTBC result, inverted formation resistivity, and permittivity images for two data sections acquired in the Catoosa test well. In addition to the inversion-generated images, we show inverted logs of the formation resistivity and permittivity (both plotted in red), compared to the resistivity and permittivity at the two lowest frequencies (F0 and F1) of the array dielectric measurements (in green and blue) and the 10-in resistivity curve of the array induction tool (in black). We observe very good consistency between the measured resistivities for all three tools as well as for the corresponding permittivity values. The inversion-derived permittivity and resistivity from the new imaging tool agree well with the dielectric tool, and show more details due to much higher resolution. Figure 22 shows the images and logs from a 10-ft section including a resistive zone where the dielectric effect is strong and composite processing has some lateral inconsistencies between pads primarily due to blending and partly due to coupling of formation dielectric and standoff effect. The inverted resistivity and high frequency dielectric permittivity images are more consistent. In Figure 23, we show the results from a 20-ft section including a less resistive zone. Inverted permittivity images are consistent over a wide range of resistivity, even for values as low as 4 Ω·m. Figure 24 shows another section from the same well. In this case,
we identify fractures and they are seen more clearly in the permittivity image than in the resistivity.

New high-definition OBM-adapted microresitivity images acquired by the new tool in a well drilled in the Bakken formation, where the array dielectric tool was also run are processed using the new algorithm. Similar consistency is observed as in the first data set, as shown in Figures 25 and 26. As expected, the high-frequency dielectric permittivity from the new OBM-adapted imager is mostly between the dielectric measurements at frequencies $F_0$ and $F_1$. The inverted resistivities are again consistent with those obtained by processing of dielectric tool measurements and the high-resolution array induction logs (AE10).

While dielectric permittivity images of the formation are certainly not the first thing geologists are typically looking for, the potential significance of their realization should not be lightly dismissed. This is the first time ever that a high-definition wireline-conveyed imager has imaged a quantitative formation parameter other than resistivity or acoustic impedance. Moreover, since resistivity and dielectric permittivity derive from the same sensor array, the two images are matched in depth and in volume of investigation—and therefore perfect for joint interpretation. Knowing the broad range of applications of dielectric logging tools, one can envision a future range of image-based quantitative interpretation methods. The potential for innovation is high.

![Fig.22](image-url) Short high-resistivity section comparison of inverted resistivity and permittivity for the Catoosa test well dataset. From left to right: inverted high frequency dielectric permittivity ($\varepsilon_{F2}$); inverted resistivity image; standard composite resistivity image; inverted standoff; resistivity logs; dielectric permittivity logs (new OBM-adapted imager, array dielectric measurements), AE10 – high resolution array induction response.
Fig. 23 Short section comparison of inverted resistivity and permittivity from the Catoosa test well dataset. From left to right: inverted high-frequency dielectric permittivity ($\varepsilon_{F2}$); inverted resistivity image; inverted standoff; resistivity logs; dielectric permittivity logs (formation resistivity and permittivity from the new OBM-adapted imager in red, ADT dielectric measurements in blue, AE10 high-resolution induction response in black).

Fig. 24 Fracture identification on dielectric image. Comparison of inverted resistivity and permittivity for the Catoosa test well dataset. From left to right: standard composite processing image; inverted resistivity image; inverted high-frequency dielectric permittivity ($\varepsilon_{F2}$); resistivity logs; dielectric permittivity logs (formation resistivity and permittivity from the OBM-adapted imager in red, dielectric measurements in blue, AE10 high-resolution induction response in black).
Fig. 25 Consistency of inverted resistivity and permittivity for the Bakken formation dataset. From left to right: standard composite processing image; inverted resistivity image; inverted high frequency dielectric permittivity ($\varepsilon_{F2}$); resistivity logs; dielectric permittivity logs (formation resistivity and permittivity from the OBM-adapted imager in red, dielectric measurements in blue, AE10 high-resolution induction response in black).

Fig. 26 Consistency of inverted resistivity and permittivity for the Bakken formation data set. From left to right: standard composite processing image; inverted resistivity image; inverted high-frequency dielectric permittivity ($\varepsilon_{F2}$); inverted standoff; resistivity logs; dielectric permittivity logs (formation resistivity and permittivity from the OBM-adapted imager in red, dielectric measurements in blue, AE10 high-resolution induction response in black).
SUMMARY AND CONCLUSIONS

We developed a model-based parametric inversion algorithm using the Gauss-Newton minimization approach to process the new oil-based mud imager data. The workflow is designed to address and overcome two major challenges related to the fact that the inversion problem is underdetermined and the imaging measurements are not fully calibrated. The inversion allows a flexible model definition and parameterization that can also include measurement calibration coefficients, and can process intervals of data and measurements from multiple buttons simultaneously. The multi-step workflow stabilizes the inversion and improves the consistency of the processed results. To overcome the under-determined system and to speed up the inversion, we use a sequence of inversion steps to first iteratively determine the mud properties for a small depth section of logs. These mud properties are then used to invert for the button standoff and the formation resistivity and permittivity for much longer data section.

The inversion algorithm is validated using finite-element generated synthetic data demonstrating that the approach can be used for quantitative interpretation of the oil-based mud imager data. The inversion has been applied to several data sets from different part of the world, covering different formation resistivity ranges.

The new inversion corrects for the mud-standoff and formation dielectric effects to produce an accurate and singular resistivity image that is monotonic and continuously spans the entire range of commonly encountered formation resistivity. It gracefully avoids the potential pitfall of ‘rollover’ or contrast-inversion that may occur with composite processing in situations where the blending logic does not work perfectly. Resistivity response of small and strongly contrasting features such as fractures, vugs, core holes, or clasts is therefore truer, and the pad-to-pad consistency of the images greatly improved. Having images scaled quantitatively in resistivity and accurate to within a few percent is a strongly desirable prerequisite, and a key enabler to quantitative interpretation methods such as sand counting.

In addition, the mud properties obtained through the inversion can be used to refine the standard composite processing and the resulting impedivity image.

The inversion-generated standoff image, as expected, has a proven valuable complement for the quality control of both the inverted resistivity images and the composite impedivity images. Moreover, we have found that it contains a wealth of unique and interpretable geologic and geomechanical information, clearly delineating breakouts, helping to determine whether fractures are open or closed, and even detecting fault slips, where previously such applications were the exclusive domain of ultrasonic acoustic imaging tools.

Finally, the dielectric images of the formation permittivity are a unique and exciting industry ‘first’ as a wireline imaging tool is now able to produce an image of something other than the resistivity or the acoustic impedance. We are only now beginning to learn what we may interpret from such images. Considering the added dimension that the array dielectric measurements have recently been shown to add to the petrophysical interpretation, we may envision the start of a new era in quantitative image interpretation.

ACKNOWLEDGMENTS

The authors thank the oil companies for permission to use their data in this paper. The authors are also thankful to Fabinne Legendre for processing the array dielectric tool measurements, to Aria Abubakar for many helpful technical discussions, and to Laetitia Comparon for performing log calibration.

REFERENCES


Cheung, P., Pittman, D., Hayman, A., Laronga, R., Vassereau, P., Ounadjela, A., Desport, O., Hansen, S.,
Lamb, M.; Schlumberger, Borbas, T., and Wendt, B., 2001, Field test results of a new oil-base mud formation imager tool: Transactions of the SPWLA 42nd Annual Logging Symposium, Houston, Texas, USA, June 17–20, paper XX.


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