Comparison of lateral and multi array induction logs in highly inclined wells drilled in a multi layered carbonate reservoir

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Abstract

Reviving production from declining fields has become a major objective for oil and gas companies. New technology has made it easier to drill and log horizontal wells. All the wireline logging tools have been modeled in the past for vertical wells, where the reservoirs cut across the borehole horizontally. However, when the relative dip is higher, this is not the case any more, as log response becomes complicated. This is particularly true for the induction resistivity tool.

The multi array family of induction tools is carefully focused to limit the contributions outside a relatively thin layer of response. Thus, at high relative dip the focused response cuts across several beds and gives a cumulative resistivity reading of all the layers cut by the well. The focusing developed for the vertical well is no longer valid.

Numerous modeling codes are available where the responses can be modeled and corrected for. The laterolog resistivity log requires a 3-D modeling code and is difficult to model. For this reason, more often than not the operator takes the deep measurement as the true resistivity. This implicitly implies that the dipping effect on the logs has been ignored. In extreme cases this may lead to unrealistic saturation estimation.

In this study, raw multi array induction logs and modeled induction logs have been compared in highly inclined and horizontal wells. The results were then analyzed together with the electrode resistivity logs. The raw induction logs are affected due to the relative dip and bed boundary effects that cause a reduction in the resistivity even across the hydrocarbon bearing zones. The modeled induction logs show an improvement by accounting for the bed boundary effect and also explain better the response of the nuclear logs.

Introduction

The array induction tool (AIT) was logged in some of the wells in the Bombay High South field. It was observed that the two foot deep AIT measurement, i.e., the AIT 90 inch (90 inch referring to the depth of investigation) log was not reading as high as expected in such hydrocarbon bearing formations. Subsequently, the DLT, dual laterolog tool was logged in the same section to determine the laterolog response and compare it to that of the AIT. Array induction tools of the AIT family are designed for vertical wells and are focused to a relatively thin layer of response (Barber et al, 1995). At high relative dip, such as, in the current studied wells, the focused response cuts across several layers and are not isolated to a single layer as is the case of vertical wells (Fig.1). Thus, the raw / field array induction log, as it is, may not be suitable to evaluate the pay zones. These logs need to be modeled in order to get formation response. AIT log modeling by maximum entropy inversion method (MERLIN) corrects for the relative dip effect in such highly deviated wells. This paper presents the results of the AIT modeling in three wells and compares it to the DLL log; it also discusses the processing required for correcting AIT logs in highly inclined wells. The AIT log from the field

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was first corrected for borehole effects; the environmentally corrected AIT conductivity was then used as input into MERLIN Application (Maximum Entropy Resistivity Log INversion) to correct for low resistivity contrast between adjacent beds, which is coupled with high relative dip (Barber et al, 1989).

The following sections first describe the Bombay High Stratigraphy; then the Induction measurement principles and response in deviated wells is explained along with the MERLIN methodology; finally the results from the studied wells are presented, followed by summary and conclusions.

**Bombay High Stratigraphy**

The Bombay high field (Sharma et al, 1998; Tewari *et al.*, 2000), where the study wells are located (Figure 2), is situated W-NW 160 Km offshore Mumbai. The Bombay high field is a giant offshore oil field in India that comprises a highly heterogeneous carbonate reservoir with the main reservoir unit in L-III. The L-III reservoir contains 90% of the field’s reserves; it is essentially a multi-layered reservoir with 10 limestone layers separated by shale (Tewari *et al.*, 2000). Figure 3 shows the stratigraphy with a closer focus on the L-III sub zonation. The figure clearly shows several layers that the studied wells cut across.

**Principles of AIT Induction Tools**

AIT Array Induction Imager family of tools abandon the concept of fixed-focus sensors and are constructed of eight independent arrays with main coil spacings ranging from 6 in. to 6 ft. The two basic AIT tools presently in the field include the AIT-B* (standard AIT tool) and the shorter AIT-H* (PLATFORM EXPRESS* AIT tool). The AIT-B tool operates simultaneously at three frequencies; in-phase and quadrature signals are acquired from each array at one or two frequencies suitable for that array length. The AIT-H tool operates at a single frequency and measures the R- and X-signals for each array. All these measurements, each with its unique spatial response, are simultaneously acquired every 3 in. of depth. Nonlinear processing methods have been developed that use each of the array measurements, combining them in such a way, so as to focus the log response at a desired region in the formation that does not change as formation conductivity changes. Several output logs can be presented, each focused to a different distance into the formation. Each of the new logs is a combination of several array measurements, and all are interpretable as induction logs with full environmental corrections. The logs are virtually free of cave effect and can be used to provide Rt estimates with no built-in assumptions about the invasion profile (Figure 4). In AIT logs, full borehole corrections are derived from external measurements over a wide range of Rt/Rm contrasts. Short-array information can be used to solve for effective borehole parameters in extremely difficult situations. The five AIT logs have median depths of investigation of 10, 20, 30, 60 and 90 in, respectively. Median responses are constant both vertically and radially over a wide range of formation conductivities. The vertical resolution of each log is closely matched to that of the others. Three resolution widths are available: 1, 2 and 4 ft. The description of invasion is improved in both oil- and water-base mud systems. This includes an accurate Rt estimate and a quantitative description of the transition zone. Resistivity and saturation images of the formation can be produced. The signal measured by an induction sonde eccentered in a borehole can be shown as a function of four parameters: the borehole radius r, the mud conductivity σm, the formation conductivity σf and the tool position x with respect to the borehole wall, which is commonly referred to as the "standoff."

Traditionally, induction tools have been limited to fresh mud in which Rxo > Rt invasion characteristics are expected.

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However, this is not always so, as revealed by many AIT field examples. The radial processing algorithm for the AIT family of tools, unlike earlier tools, works as well for $R_x < R_t$ as for $R_x > R_t$ within limits. The main limitation to using AIT tools in salty muds remains the ability to do accurate borehole corrections. Obviously, if the mud is salty and the borehole in bad shape, the laterolog tool remains the resistivity tool of choice. In addition, the deep laterolog is affected less by deep invasion than the conductivity-reading induction tool. Most applications where $R_t/R_m > 500$, the laterolog tool will provide a closer estimate of $R_t$. The AIT tools contribute important invasion information even in these extreme cases. For salty mud, array induction-laterolog combinations always produce a better answer than either tool alone. Table 1 lists the specific effects on the AIT for different operation for the array induction tool.

**AIT log response in wells with high relative dip**

When there is an angle between the formation with respect to the induction sonde like in a deviated well or the situation of dipping beds in a vertical well, the scenario of focused response of the array induction to a single layer breaks down and the response cuts across several layers. This condition is well documented in literature (Barber *et al*., 1989; Hardman *et al*., 1986). The effect of introduction of a relative dip is a fuzzy formation resistivity (lazy bed boundary definitions), generation of horns at bed boundaries and also invasion type artifacts on the induction log. The resulting array induction log, if not corrected for the effect of relative dip, can make pay zone identification difficult at the well-site and also lead to mis-interpretation of the invasion artifacts. In such cases, the induction log requires correction for relative dip effects, which are performed at the data processing centre, resulting in a usable log with clear bed definition, more accurate invasion profiles devoid of polarization horns. Such a log is obtained by forward modeling inversion technique based on maximum entropy (MERLIN).

**MERLIN (Maximum Entropy Resistivity Log Inversion) Technique**

MERLIN is a processing algorithm that isolates the response of the array induction log into thin layers at any relative dip. This fast 1D forward model is based on maximum entropy (Freedman *et al*., 1991; Dyos, 1987). The term “entropy” refers to the measure of the order (or discreetness) in a system (or group). For example, considering a formation that consists of a series of thin bed layers of high and low conductivity, that series of thin layers is highly “ordered”; each layer is clearly distinct from the next. Yet, the vertical resolution of the raw measurements of an induction logging tool may be too broad to resolve each discreet layer, and only provide us with average values of conductivity of the layers; this can be thought of as a low entropy solution. The MERLIN (maximum entropy) solution provides the maximum order possible to define and distinguish the conductivity of discreet beds. The algorithm is restrained (by the entropy term), however, so as not to allow a solution that shows beds thinner than is inherently achievable with the AIT logs.

The results from this 1D forward model compare well with the results of the 3D induction forward model for a wide range of invasion profiles, even in cases of high relative dip (Barber *et al*., 1998). This method of correction of the array induction for effects of relative dip is found to be sensitive to borehole noise and the relative dip value is required to be known to the accuracy of +/- 5 degrees.

MERLIN requires the set-up of a sequence of thin beds, all with the same thickness. The inputs to MERLIN include borehole corrected conductivity arrays.

**Case study in 3 wells**

Well A is a highly deviated well (~83
degrees) where the AIT resistivity logs show the effects of high relative dip. At some intervals, especially at around X80 m and also around X30 m (Fig.6, 7), the field AIT logs did not read as was expected in such hydrocarbon bearing formations. The AIT logs were first borehole corrected; the borehole corrected data was run through a 1D inversion using MERLIN, as shown in figures 8 to 12. The parameters for Merlin have been optimized to obtain the best possible results in the studied wells. The processing was fine tuned by changing the dip angles and zoning them. Snapshots of important intervals are presented in figures. The Merlin AIT results from wells A, B and C are shown in figures 8 to 14. The results clearly show a better bed definition as compared to the field processed AIT log. This is observed by the good correlation between Merlin AIT logs with respect to GR, density and neutron log responses. Merlin processing has improved the resistivity profile by removing artifacts, as shown in figure 11. The invasion artifacts against shale zones are removed and the AM10 log (Merlin induction log with 10 inch of investigation) is in better agreement with the other resistivity curves (Figure 10).

Summary and Conclusions

Array induction logs (AIT) were acquired in three horizontal wells in the Bombay High South field. These logs were affected due to the high relative dip, which masked the bed definition and also resulted in anomalous resistivity profiles. Thus, the field AIT logs had to be corrected for this effect by using MERLIN resistivity inversion modeling. The MERLIN modeled AIT logs in this study show clear bed definition, more accurate invasion profiles devoid of polarization horns and closer to the laterolog resistivity response.

The MERLIN AIT logs are in good agreement with GR, density and neutron log responses in the three studied wells.

Therefore, the MERLIN modeled AIT logs assisted in correctly identifying pay zones and were subsequently used for computation of more accurate water saturation and completion optimization.

References


Dyos, C.J.; 1987; Inversion of the induction log by the method of maximum entropy, SPWLA 28th Annual Logging Symposium, Paper T

Freedman, R., and Minerbo, G.; 1991; Maximum entropy inversion of the induction log, SPE 19608, presented at the 64th SPE Annual Technical Conference and Exhibition


Tewari R. D., Rao M., and Raju A. V., 2000, Development Strategy and Reservoir Management of a Multilayered Giant
Fig 1 Induction response at relative dip. Adapted from T.D Barber et al., 1998.

Fig. 2 The location of the study wells in Bombay High South field.
Fig. 3 LIII reservoir sub-zonation in Bombay High field

Fig. 4 AIT field log processing in different scenarios for arriving at invasion parameters.
<table>
<thead>
<tr>
<th>Condition</th>
<th>Effect</th>
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<tbody>
<tr>
<td>High R&lt;sub&gt;t&lt;/sub&gt; / R&lt;sub&gt;m&lt;/sub&gt; contrast</td>
<td>Borehole signal &gt;&gt; formation signal</td>
</tr>
<tr>
<td>Bad hole</td>
<td>Can produce unexpected very large borehole signals that are difficult to correct</td>
</tr>
<tr>
<td>Corkscrew hole</td>
<td>Produces periodic large borehole signal as tool standoff approaches zero</td>
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<tr>
<td>High dip or deviation</td>
<td>Adjacent-bed effect can grossly distort the log readings</td>
</tr>
<tr>
<td>High R&lt;sub&gt;t&lt;/sub&gt; / R shoulder</td>
<td>Violates Born approximation-used to form filters for signal processing (AIT, Phasor)</td>
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<tr>
<td>Unexpected salt water</td>
<td>Produces high R&lt;sub&gt;t&lt;/sub&gt; / R&lt;sub&gt;m&lt;/sub&gt; inflow contrast and large borehole signal</td>
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<tr>
<td>Magnetic mud weighting</td>
<td>Can produce offsets in the material data with short arrays being more affected</td>
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*Table 1. Table showing the effect of specific logging conditions on the recorded AIT field log*

![Fig.5 MEM model for 1D inversion forward model using MERLIN](image)
Fig. 6 Array induction field log (AIT90:AE90) presented in comparison with the dual laterolog (DLL:LLD) in well A. In the zones highlighted the AE90 field log reads lower than expected in such formations.
Fig. 7 The figure above shows problems evident on the field AIT log (well A). The deepest AIT log (AT90) was not reading as high as as compared to the laterolog measurements. The formation beds (based on other logs like the GR) could not be clearly distinguished. The invasion profile not representative of the formation.
The above figure shows AIT field logs in the zone around 2122-2138 m wherein the resistivity profile seems anomalous and also the resistivity AHT90 reads slightly lower than the DLL log.

The above figure shows on the right most track the environmentally corrected AIT logs in the zone around 2122-2138 m.

AIT log after Merlin has an improved profile and reads close to that of the DLL log/corrected AHT20 log.

Fig.8 The above figure shows the step by step approach towards Merlin results (well A)
Fig. 9 Composite presentation with raw logs (well A), environmentally corrected logs and Merlin AIT logs over the interval X58-X38 m in well A.
Fig 10 The figure above shows the MERLIN AIT logs (well A) compared with other logs such as the GR, density (RHOZ) and neutron (TNPH). The deepest MERLIN AIT log (AM90) reads resistivity values close to those expected in these hydrocarbon bearing formations with clear bed definitions and invasion profile representative of the formation.
Invasion artifacts removed after Merlin processing.

Clearer bed definition in relation to GR log.

**Fig. 11** Zoomed Merlin results over a section in well A.
Field AIT log shows an anomalous resistivity profile. Merlin processed AIT log improves the resistivity profile. Also to note is higher resistivity values after Merlin which are close to that of the environmentally corrected AHT20 log.

Fig. 12 Merlin results over a section in well A
Fig. 13 Merlin results over a section in well B
Fig. 14 Merlin results over a section in well C