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Induction, resistivity and MWD tools in horizontal wells

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Abstract: Conventional induction and focused resistivity tools ar designed to measure resistivity from a vertical borehole surrounded by a cylindrically invaded zone while minimizing the signal contribution from adjacent horizontal beds. In recent years our understanding of these devices was extended to include beds exhibiting a large dip relative to the borehole as in the case of a highly deviated well. We shall investigate the applicability of induction and resistivity devices to horizontal wells, where the borehole runs parallel to the bed boundaries.

The presence of the borehole may be simply ignored for induction sondes and the tool response in computed via an analytic solution. Because of the relative simplicity of the induction solution, the log response is computed for entire trajectories for the more common radii of curvature used in the drilling process.

On the other hand, for focused resistivity devices such as the dual laterolog or the MWD toroid sonde the borehole is an essential part of the problem. The tool response is evaluated using a numerical solution to simulate accurately the complex physical situation.

The modeling results for the resistivity devices indicate that the measurement is more sensitive to conductive than to resistive shoulder beds. Typically, for the MWD sonde fifty percent of the resistivity signal comes from the adjacent conductive bed when it is half a foot away from the approaching borehole wall. A similar sensitivity to a resistive adjacent bed is not attained until the borehole has actually penetrated the bed. The reverse physical situation is evidenced with induction devices; resistive adjacent beds are more readily detected than conductive adjacent beds.

INTRODUCTION

Horizontal wells for exploration and development of oil fields are rapidly gaining acceptance in many types of reservoirs. Principally because of the enhanced recovery, increased penetration of vertical fractures and controlled coning, production is generally more favorable from a single horizontal well than from several vertical wells in a given area [Mahony, 1988]. Horizontal wells even help gather data more effectively to study the geology and the petrophysics in complex fields [De Montigny, 1988]. Furthermore, horizontal drilling is apparently trouble free.

This new technology calls naturally for new formation evaluation methods. Since all existing instruments were primarily designed for the traditional geometry of a borehole normal to the bedding, their response in a situation wherein bed boundaries are more nearly parallel to the borehole axis is of essential importance. This is particularly true for resistivity sondes such as induction, laterolog and measurement while drilling because of their large range

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of investigation into the formation. In many situations the measurement while drilling sonde or the open hole sondes are strongly influenced by the resistivity of a neighboring shoulder bed. This is a desirable feature if the sonde is used precisely to signal the approaching upper boundary, but is an unwanted source of error if the sonde is run to measure the resistivity of the formation traversed by the borehole. In any case, mathematical modeling will be applied below to predict the response of standard resistivity devices in the more commonplace situations.

Two configurations will be modeled specifically, first the case of an approaching single bed boundary, then, the situation where the sonde is in the center of a bed surrounded by an upper and a lower shoulders of similar resistivities. For completeness, the case of highly deviated wells will be addressed using recently published modeling techniques.

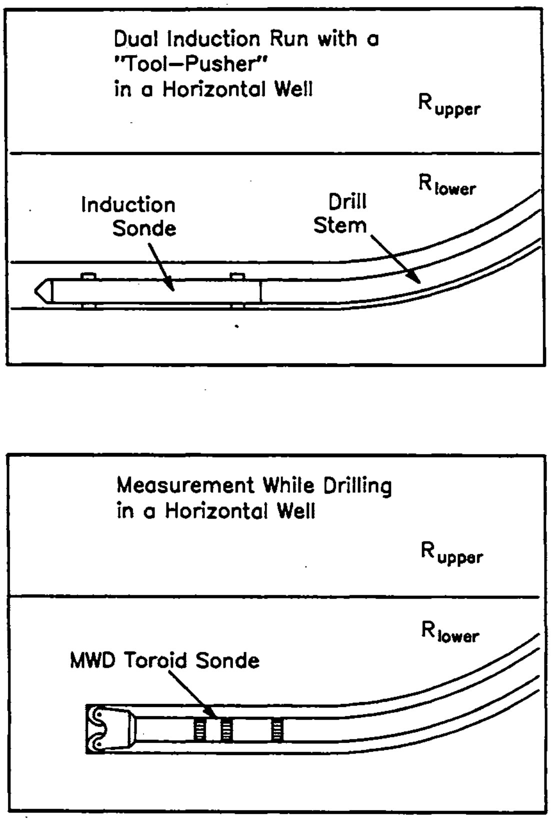

Figure 1: Logging horizontal wells with wireline and MWD resistivity tools.

SIMULATED LOGS IN A HORIZONTAL WELL NEAR A BED BOUNDARY

When drilling horizontally in a reservoir it is generally desirable to stay near the top of the oil or gas zone, immediately below the impervious cap rock. The boundaries between the various media tend to be parallel to each other and parallel to the borehole. If one of the boundaries is close to the wellbore, then its effect is likely to be dominant. Therefore a natural first step towards understanding the response of induction, laterolog and the measurement while drilling toroid sondes in horizontal wells is to simulate their behavior near a single horizontal bed boundary.

Dual Induction

The borehole has been omitted in the physical model shown in figure 2. Indeed, past experience has shown that the response of an induction tool calculated in such complex geometries does not depend significantly on the inclusion of the borehole in the model. Analytic solutions developed for more general physical situations [Gianzero, 1989], [Anderson, 1986], [Shen, 1986] are then directly applicable to this simplified configuration.

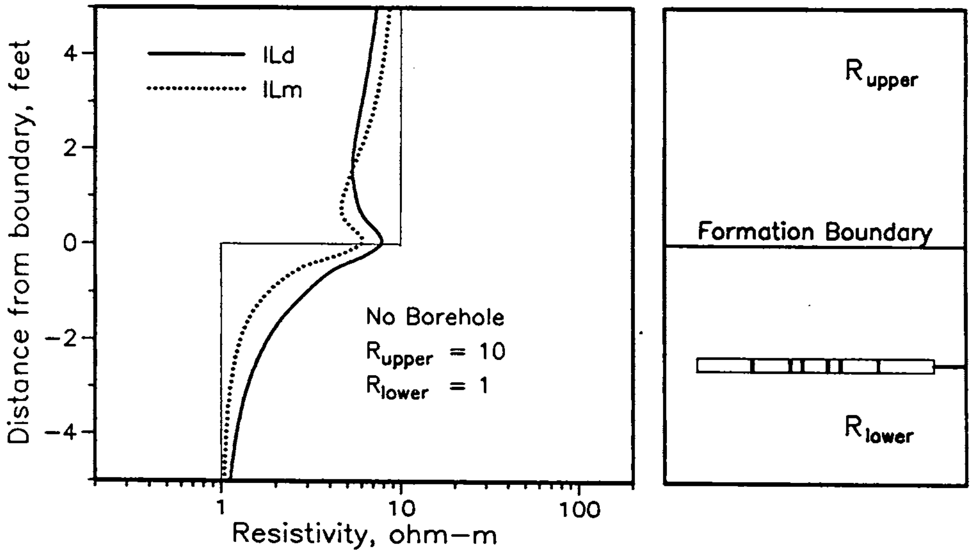

Figure 2: Computed response of the dual induction in a horizontal well near a bed boundary

The results of the modeling are plotted in figure 2 as a function of the distance separating the axis of the borehole from the horizontal bed boundary. When the dual induction is in the lower formation, far below the boundary, it naturally reads R_{lower}. As the sonde approaches the upper resistive formation, both the medium and the deep measurements sense this medium long before it is reached. After several feet above the interface, both induction devices read only R_{upper}.

The distance at which the sonde senses the resistive formation cannot be quantified exactly because the progressive transition between the two resistivity values also includes an overshoot. There are two conflicting requirements illustrated with figure 2 which present themselves to the log analyst. If the principal concern is the error in the resistivity reading introduced by the adjacent bed, then, the error in the ILd is excess of 10% when the borehole is within five feet of the resistive shoulder and 25% when the nearby shoulder is conductive. Obviously, this latter situation is obtained by reversing the perspective in the figure. Clearly, these effects are less severe for the ILm.

On the other hand, if the principal concern is to detect an approaching bed, only a significant change in the measured resistivity is considered a positive indication of the presence of a neighboring bed. For that specific application an approximate *distance of investigation* may be selected visually from the computed logs. From the conductive formation it appears that the deep induction sees the resistive shoulder from a distance of one foot. The medium induction with its shallower investigation identifies the approaching resistive shoulder at only half a foot away. In the reverse situation when the sonde is in the resistive bed approaching a conductive shoulder the log trend toward lower resistivity values is not clear for the deep measurement until the sonde is one foot inside the conductive formation. Similarly the medium induction needs to be one half foot inside the conductive bed to be significantly affected by it. These trends are further complicated by the presence of a horn on the curve precisely at the bed boundary.

Dual Laterolog

Because the borehole usually has a significant impact on the response of the dual laterolog, it has included in the model [Chemali, 1983].

The physical model of a dual laterolog in a horizontal well approaching a bed boundary is depicted in figure 3. Since no simple analytical solution is available for that complex configuration, the simulation of the tool response is carried via a three dimensional finite element program. Consequently, the amount of computation required is several orders of magnitude larger than for the induction model.

It is apparent from the results in figure 3 that the behavior of the dual laterolog is complementary to that of the dual induction. More specifically, the dual laterolog is more sensitive to a nearby conductive bed than a resistive bed. An approaching conductive bed is positively identified at approximately one half foot by the shallow laterolog and one foot by the deep laterolog, whereas, a resistive bed is not seen by the dual laterolog until the sonde has actually penetrated the bed.

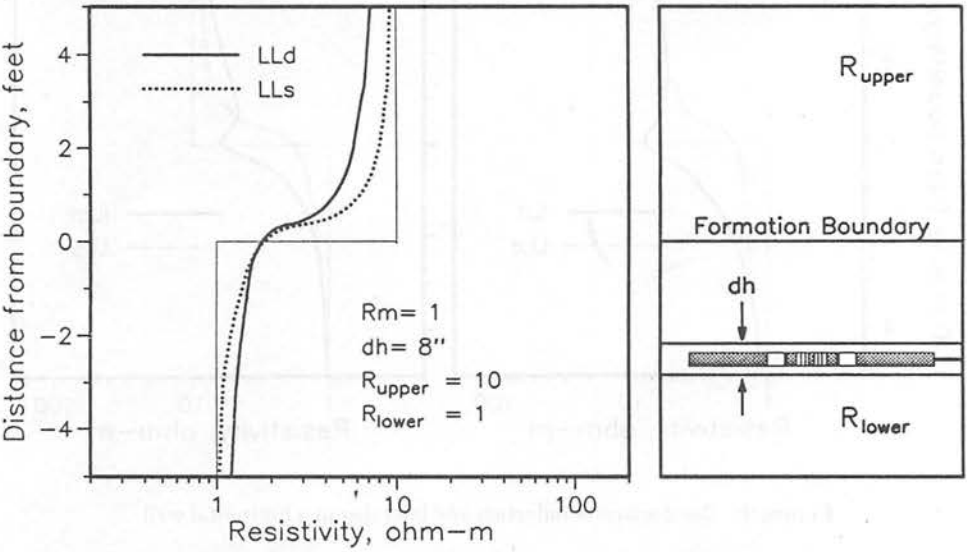

Figure 3: Computed response of the dual laterolog in a horizontal well near a bed boundary.

As in the case of the deep induction, the perturbing effect of a shoulder bed on the response of the deep laterolog is measurable from several feet away. For example, in the configuration of figures 2 and 3 the errors observed at 5 feet away are nearly identical for the dual induction and the dual laterolog.

Overlaying the deep induction and deep laterolog in one chart, and the medium induction and shallow laterolog on another (figure 4) helps to visualize their relative behavior.

MWD Toroid Sonde

The same study was carried out for the toroid dual resistivity sonde which is implemented on a drill collar for a measurement while drilling application. This tool consists of two measurements, one called the Lateral and the other called the Bit. The lateral measurement is similar to the shallow laterolog and the bit measurement measures the formation characteristics near the drill bit assembly. A detailed description of this tool is given in various publications [e.g. Gianzero, 1985].

The computed response of the tool near a horizontal bed boundary is shown in figure 5, As expected the lateral has nearly the same characteristics as the shallow laterolog.

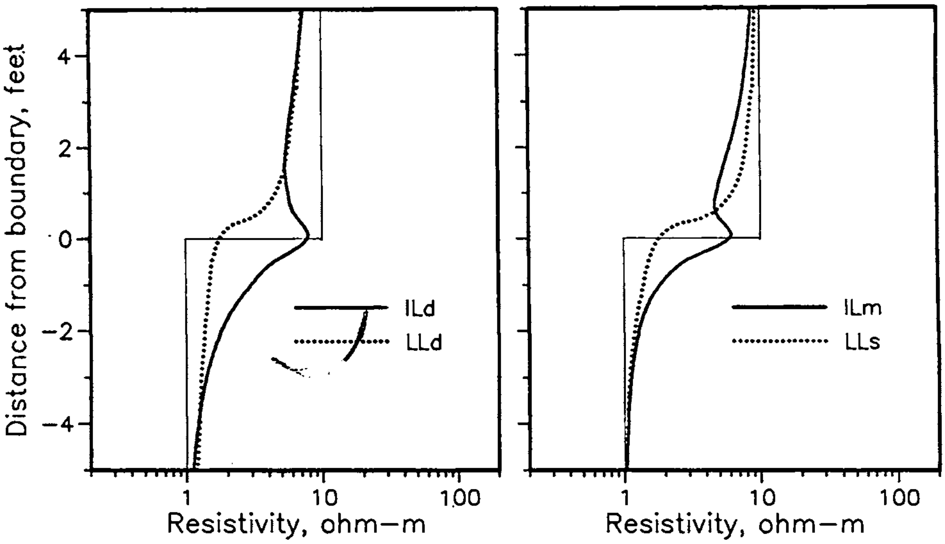

Figure 4: Comparison of induction and laterolog in a horizontal well

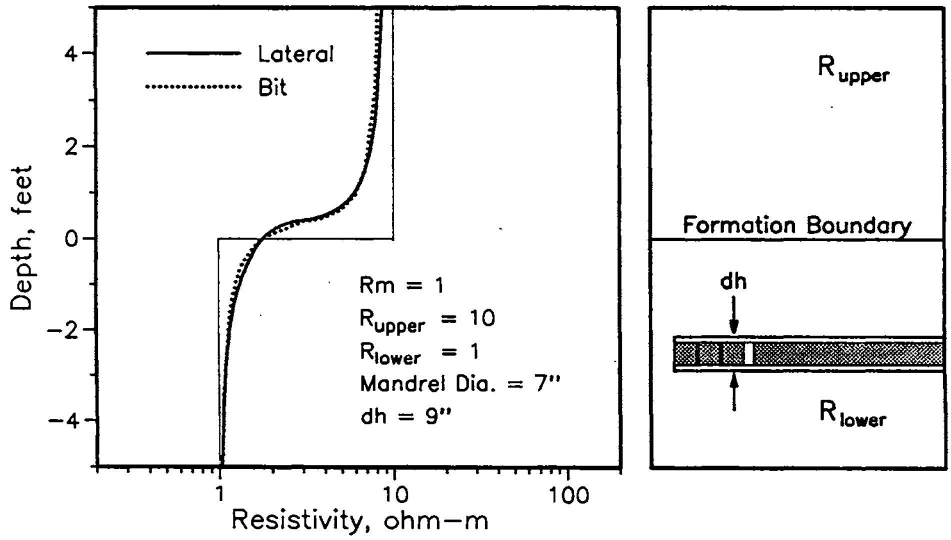

Figure 5: Computed response of the MWD resistivity tool in a horizontal well near a bed boundary.

CORRECTION FOR SHOULDER BED EFFECT IN HORIZONTAL WELLS

In the case of vertical wells, the shoulder bed effect of adjacent formations has been extensively modeled both for induction [Schlumberger, 1972] and laterolog tools [Chemali, 1983]. The study has been recently extended to the case of dipping beds or deviated wells [Shen, 1986], [Chemali, 1988]. Naturally the question arises as to the magnitude of that effect in the case of horizontal wells parallel to the upper and lower bed boundaries.

The evaluation of the shoulder bed effect is conducted for the model shown in figure 6. The sonde is in a formation of resistivity R_t parallel to the upper and lower boundaries with shoulder beds. A borehole fulled with a fluid of resistivity R_m is also included in the model of the dual laterolog. The calculations are limited to the situation where upper and lower shoulder beds have the same resistivity R_s, and the sonde is exactly at the formation. We have omitted the computation for the measurement while drilling lateral sonde because its response is so similar to the shallow laterolog.

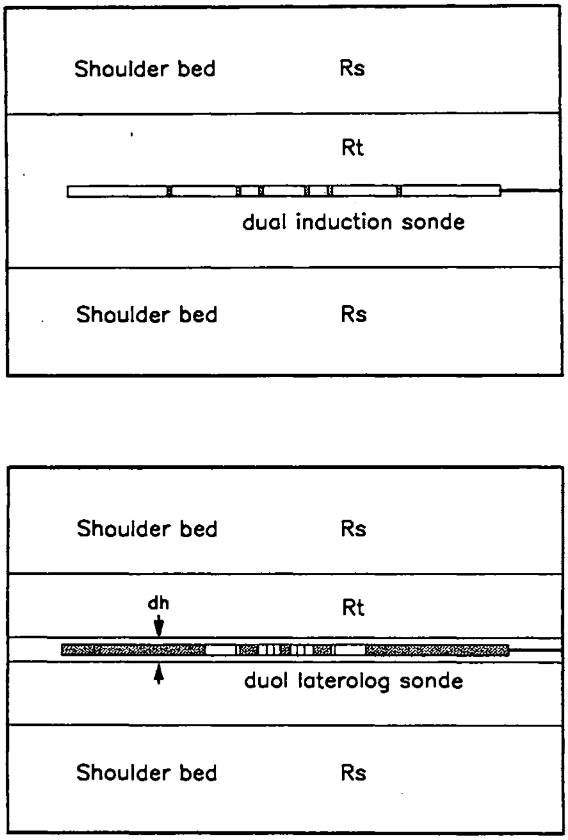

Figure 6: Physical configuration of a dual induction or a dual laterolog in a thin bed.

Dual Induction

A set of correction charts for the shoulder bed effect is reproduced in figure 7 for the ILd and figure 8 for the ILm. As in the case of wells perpendicular to the bedding, the variable parameter from one correction chart to the next is the value of the shoulder bed resistivity R_s.

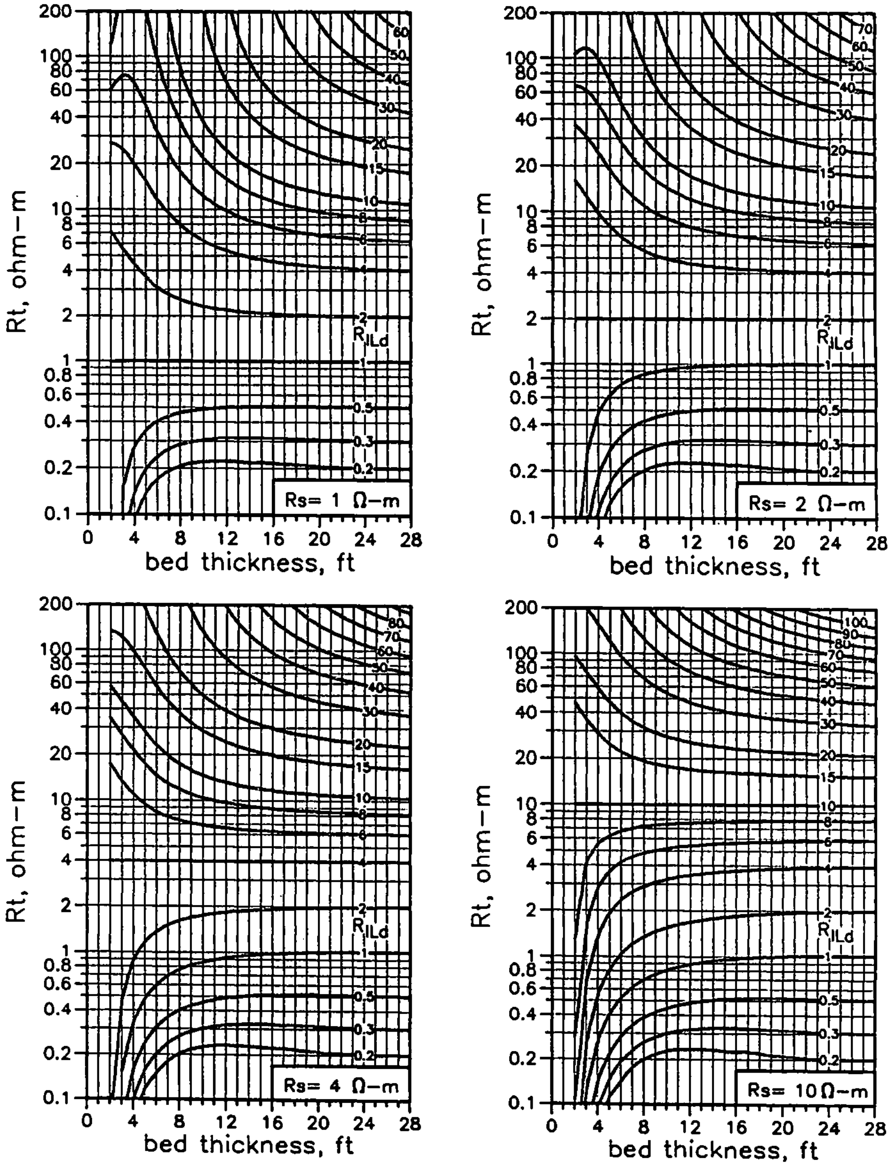

Figure 7: Shoulder bed correction for the deep induction in a horizontal well.

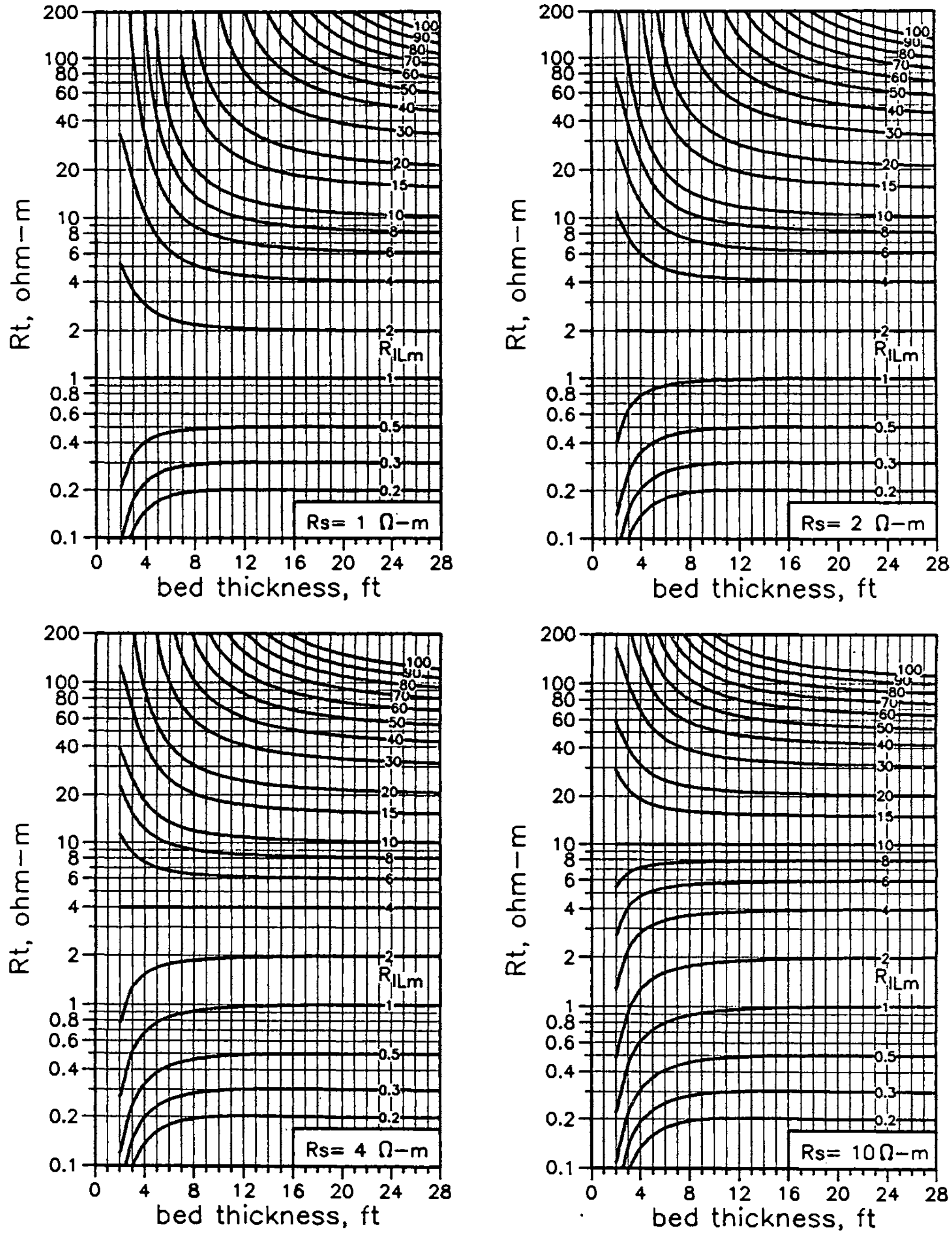

Figure 8: Shoulder bed correction for the medium induction in a horizontal well.

A cursory examination of these charts indicates that the correction for shoulder bed in horizontal wells is a monotonic function of bed thickness as long as the latter exceeds 4 feet.

Dual Laterolog

Correction charts for the shoulder bed effect are shown in figure 9 for the LLd and figure 10 for the LLs. In this case the variable parameter from one chart to the next is the resistivity ratio between the mud and the shoulder bed. From the limited number of cases evaluated in this study it appears that the resistivity of the borehole fluid is less critical in horizontal wells than in vertical wells [Chemali, 1983].

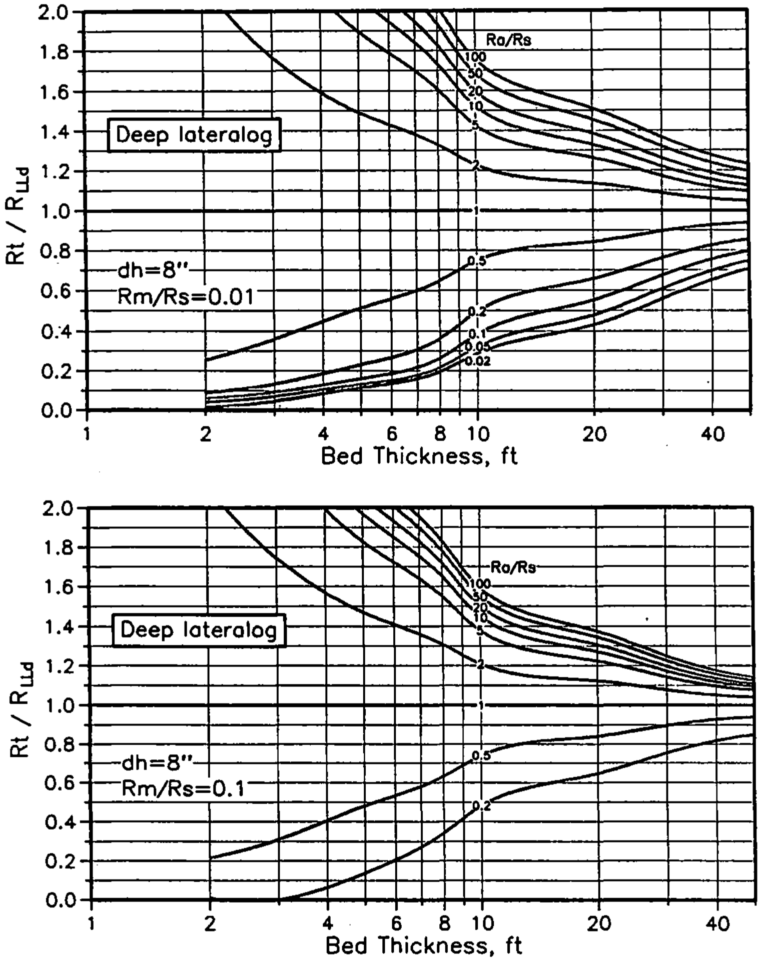

Figure 9: Shoulder bed correction for the deep laterolog in a horizontal well.

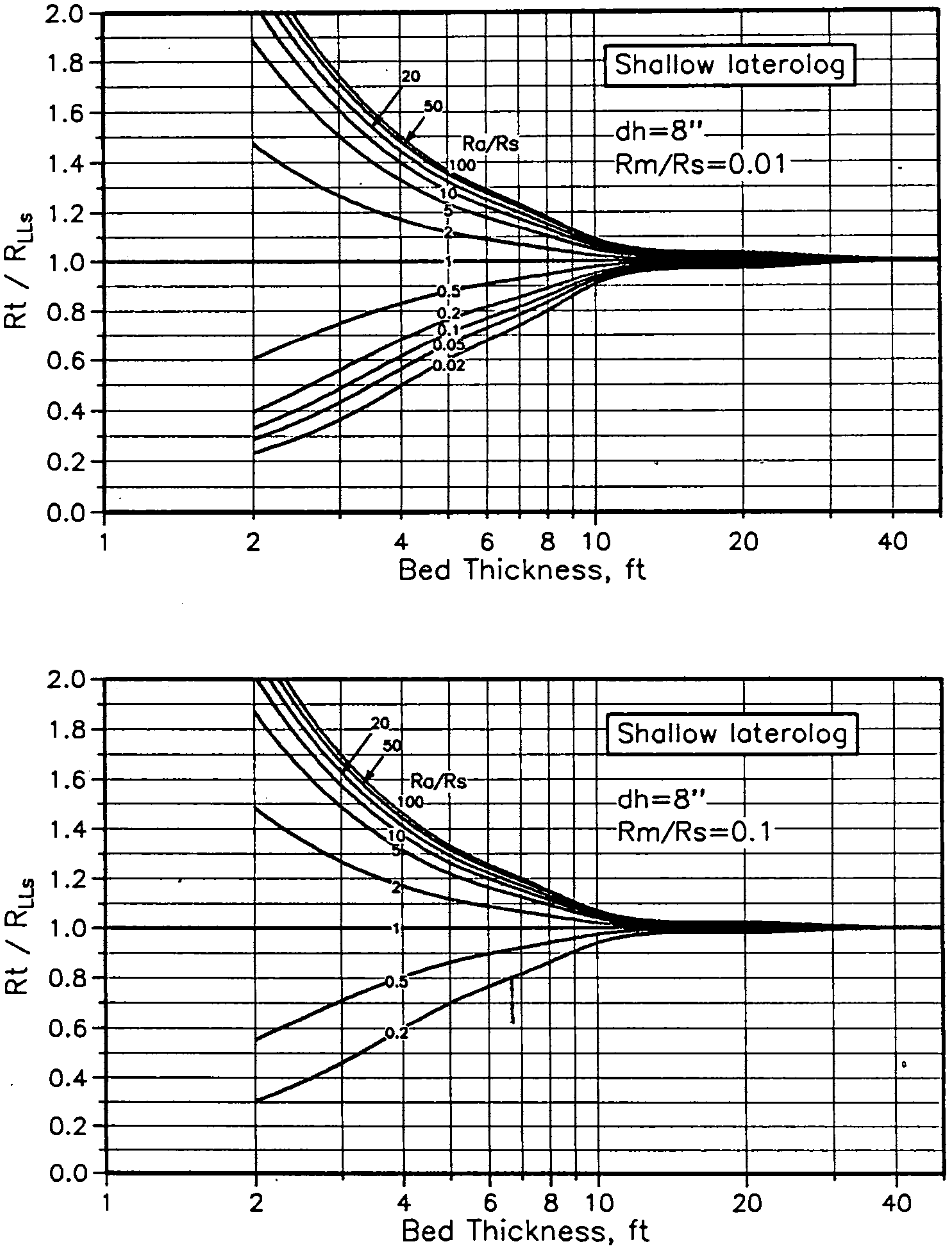

Figure 10: Shoulder bed correction for the shallow laterolog in a horizontal well.

As observed with the dual induction, for a given R_a/R_s, the correction for shoulder bed effect exhibits a monotonic variation with bed thickness. Furthermore the shallow laterolog has very little shoulder effect when the formation thickness is ten feet or more.

As mentioned previously, the shoulder bed effect of the lateral measurement while drilling sonde is so similar to that of the shallow laterolog that the results are omitted.

SIMULATED LOGS IN HIGH RELATIVE DIP

The common practice for drilling horizontal wells consists of starting out with a nearly vertical borehole and deviating progressively along a specified curved trajectory until reaching the desired depth and direction. Along such trajectories the resistivity sondes encounter the various formations at progressively increasing relative dip angles.

Typical trajectories for reaching a horizontal direction are shown in the diagram of figure 11(a). They are generated by turning the drill bit assembly at rates of 6°/100', 20°/100' or 191°/100'. Along such trajectories the relative dip angle varies continuously from 0° to 90°. By entering the relative dip angle at each point into analytic response equations for induction sondes, simulated logs are computed for the given trajectories. They are plotted in figures 11(b) and 11(c) for the ILd and ILm respectively. Observe that the simulated logs are plotted vs. true depth, measured normally to the bedding. For reference, the resistivity profile and the ILd and ILm logs computed for a vertical well are also shown on the plots. In the sections of the hole where the relative dip is high, the deep induction exhibits horns and increased shoulder bed effect as indicated in previous publications. By comparison, because of the inherently smaller shoulder effect, the ILm is not as severely affected as the ILd.

Computation times for the same profile for the dual laterolog are prohibitive and were omitted. However, the simulation of the dual laterolog in a bed with a high relative dip is shown for the specific case of a 5 feet resistive bed with a relative dip of 75° (figure 12). The computed log is plotted vs. apparent depth along the wellbore and vs. depth measured normally to the bedding. As pointed out in a previous publication [Chemali, 1988], the response of the dual laterolog in this case does not exhibit any unexpected feature, except for a generally increased sensitivity to the shoulder bed effect.

CONCLUSION

Induction, resistivity and MWD tools were modeled mathematically in horizontal wells. The response characteristics to single bed boundary revealed that the induction and resistivity tools reverse their roles from the normal vertical wells situation. Specifically, induction tools are more sensitive to resistive shoulder beds whereas, resistivity tools are more sensitive to conductive beds.

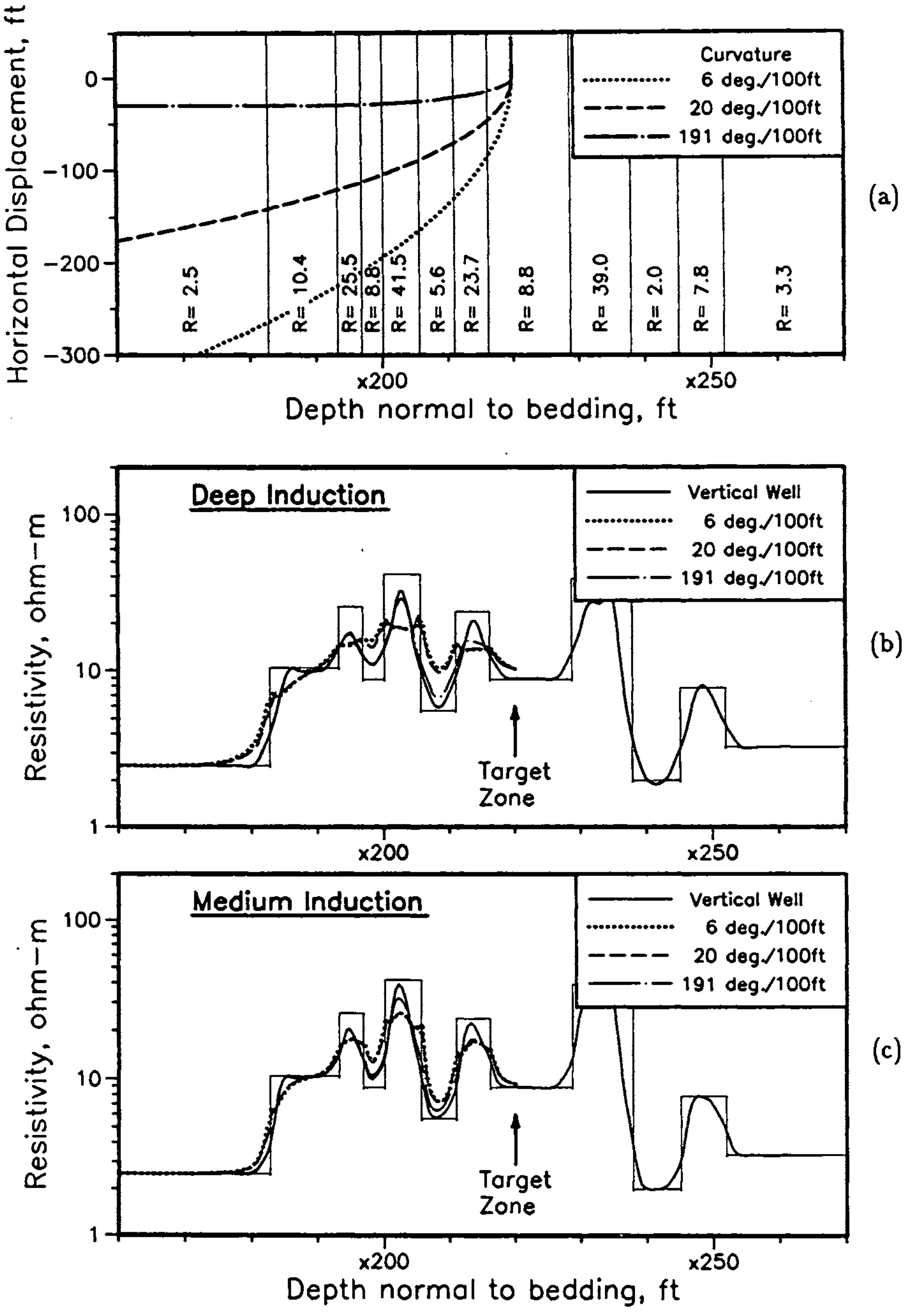

Figure 11: Computed dual induction logs for typical well trajectories.

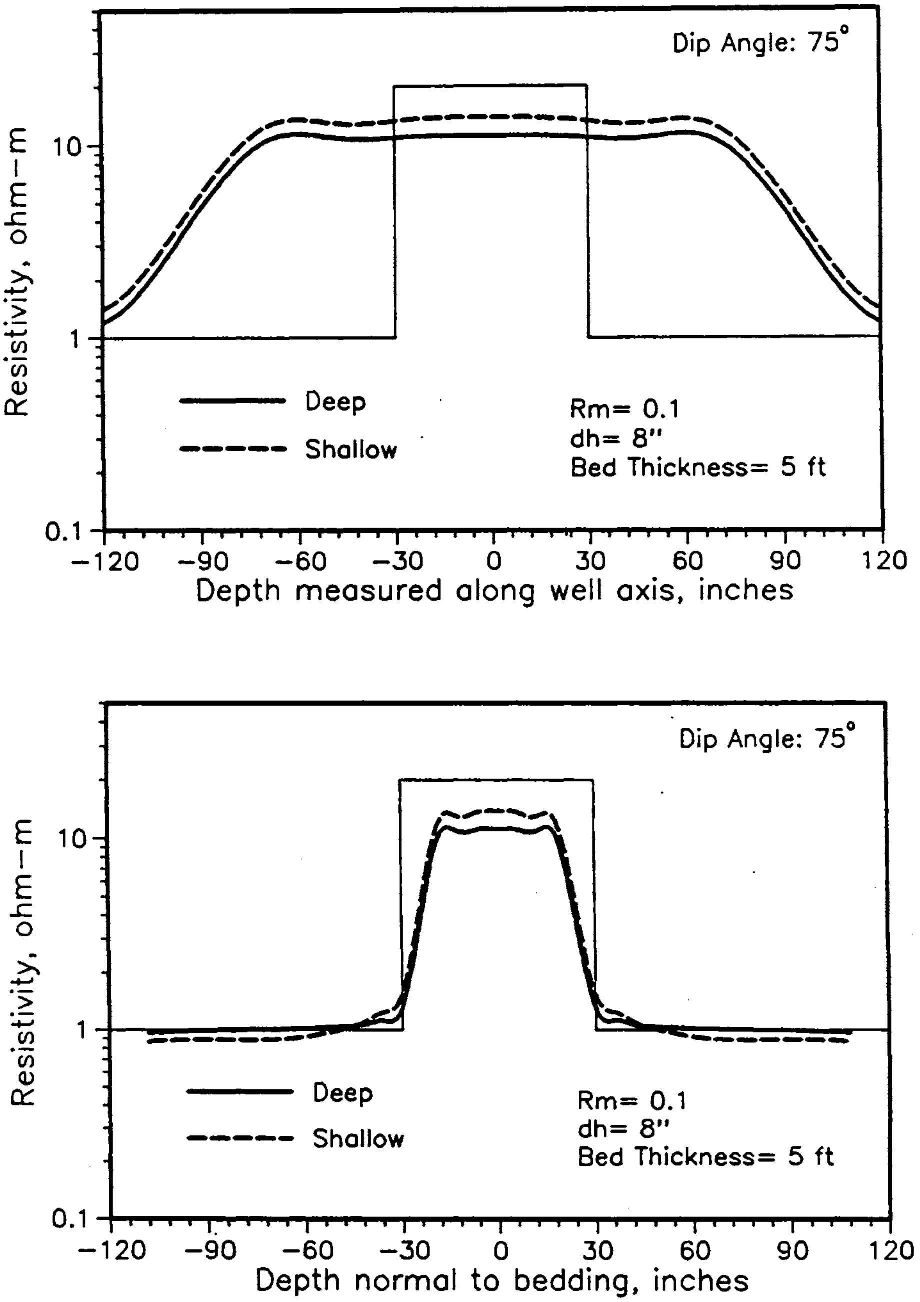

Figure 12: Compputed dual laterolog response in a highly deviated well.

A series of shoulder bed correction charts for either a centered induction or resistivity device are provided for use to the log analyst. The results for the resistivity device indicated a reduced sensitivity to borehole conditions for horizontal wells than for vertical wells.

Finally, complete trajectories for the more common drilling conditions have been provided for the standard dual induction. Additionally, a log profile of the dual laterolog response is provided for the extreme case of 75° deviation angle for purpose of comparison.

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