Thin bed resolution and the determination of flushed zone resistivity in oil based mud

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Abstract: In the detailed description of reservoirs, thin bed resolution by wireline techniques is a vital factor. While common microresistivity devices may suffice in water based muds, special techniques must be devised for oil based drilling fluids. Rather than running an exclusively designed tool, a cost saving could be effected if the desired information could be derived from a logging tool routinely run for other purposes. The Six Arm Dipmeter has been extraordinarily successful in producing dips in oil based muds. The raw data can also be used for discrimination of sand-shale laminae down to thicknesses as little as one inch. A reliable measurement of net sand thickness is thus provided as well as the volume fraction of shale in laminated form, V_{lam}, for input into laminated shaly sand saturation equations.

In addition, the same measurement provides data for the value of the flushed zone resistivity, R_{xo}, in oil based muds, information which can be used to further refine saturation computation. This is possible because the Six Arm Dipmeter generates resistivity curves absolutely calibrated in ohm.m. Furthermore, there is scope to study the depth of invasion of specific oil based muds, and because measurements are made on six sides of the hole, to recognize and bypass pad contact problems.

These applications of the Six Arm Dipmeter are approached from both the computer modeling and field examples.

INTRODUCTION

The primary reason for the use of oil based mud is its ability to produce stable borehole conditions in the presence of clays which tend to hydrate and disintegrate in contact with water. This stabilizing effect results in a considerable saving in rig time as the need for wiper trips and circulation time is markedly reduced. Although penetration rate itself is not increased, the overall drilling efficiency is improve to the point that the majority of North Sea wells are currently being drilled with oil based mud.

On the other hand, the use of oil based mud introduces difficulties in the evaluation of cuttings, geochemical analysis, fluid sample analysis and in most wireline logging techniques. The unknowns surrounding the depth of invasion and the nature of the invaded fluid are complicating factors. For example, thin bed resolution in water based mud is accomplished by pad-type microresistivity devices which read essentially in the flushed zone. No equivalent device exists for oil based mud. Rather than building specialized tools, it would seem economically advantageous to use a multi-purpose device for thin bed resolution.

The Six Arm Dipmeter enjoys good success in defining dip in wells drilled with oil based mud. (Boyelidien *et al.,* 1984; Chemali & Goetz, 1989; Goetz, 1988). Since it has a vertical resolution of better than one inch, why not use it for thin bed discrimination? In this way, the volume of shale in laminated form, V_{lam}, could be determined. The same device should be able to measure R_{xo} in invaded formations and to provide valuable insights into the characteristics of the invasion.

Dipmeter Hardware

In dipmeter work, the crucial ingredient is similarity of the correlation curves. In turn, the single most important factor for curve similarity is the quality and uniformity of pad contact. The Six Arm Dipmeter design effectively isolates arm motion from tool body motion by means of independent arm articulation in which each arm is completely free to move in and out by itself. In addition, each pad is mounted on a vertical swivel of limited travel. This doubly mechanically articulated design allows each pad to seat itself against the borehole wall. This is particularly critical in oil based mud in which intimate electrode contact is a stringent requirement.

The oil based mud version of the Six Arm Dipmeter is based on dual contact electrodes arranged side-by-side. This arrangement provides a somewhat deeper depth of investigation than monoelectrodes and is relatively insensitive to electrode penetration into the formations. The zone of investigation of the dual contact electrode arrangement is probably more closely controlled than in the case of focused current or induction designs. Of major importance is the fact that the dynamic range of the circuitry is wide enough to cover the resistivities of most sedimentary rock sequences without range switching. This allows calibration of the recorded curves directly in terms of ohm-m.

· Since it is unlikely that a contact electrode system will ever exhibit the tolerance microrugosity of a focused electrode (water based mud) system, redundancy of data is an important factor in dip determination. The 6-arm design provides 20 combinations of 3 elevations or 5 times the redundancy of a 4-arm tool. SHIVA, a global mapping dip computation program, makes optimum use of the available redundancy through a weighted least squares optimization approach. the use of this redundancy plus the generally smoother borehole conditions usually found in oil based mud holes result in dip data quality which rivals that produced in water based mud in many cases.

AIR vs WATER BASED MUD COMPARISONS

Adequate test fixtures to compare oil based and water based mud conditions are difficult to find. Opportunities for meaningful back-to-back comparisons on the same well are rare. A well drilled with water based mud and then changed

to oil based mud will be too rugose for a comparison of micro-devices. The inverse case is unlikely to be found and if it were, the borehole wall might be untypically altered by exposure to the oil followed by water. Probably the best test case is found in a well drilled with air. logged, then converted to water based mud and relogged. Such a case is shown in Figure 1 which compares raw curves from opposite sides of the hole run in air on the left and in conductive mud on the right. Because of different tool orientations on the two runs, curve #1 in air follows roughly (within 15°) the path seen by electrode #5 on the water based log (the solid curves correspond to each other). The layering sequence is shales and low permeability sandstones. Typically, the log in air demonstrates the noisiness of a contact electrode device. However, some of the resistivity differences between air and mud are due to variable depths of invasion by totally different fluids. In the depth track of both logs is displayed the unfiltered output of the Z axis accelerometer. This suggests a somewhat rougher ride for the tool in the airfilled hole even though rugosity was worse during the logging run in mud as evidenced by pad standoff at X117 feet. These tool speed variations account for apparent thickness differences of some beds.

A bottom line test of any dipmeter data is repeatability of the computed results. Such a comparison is seen in the arrow plots of Figure 2 which compare results from air and water based mud runs. Although repeatability is not perfect, 74% of the points repeat within 2° of solid angle on a level-by-level basis. In an overall global sense of average dip, repeatability is much better. This is considered quite acceptable given the degree of rugosity shown by the calipers.

THIN BED RESPONSE

The description of thinly laminated sand-shale sequences has been an elusive goal in oil based mud. To evaluate the performance of the Six Arm Dipmeter in this application computer modeling was undertaken to simulate the tool response in 2 inch and 4 inch laminations. Some results are shown in Figure 3, which depicts the tool response in laminations alternating between one and ten ohm.m. Also shown are an average (in conductivity) over 2 feet of the dipmeter response and a standard deep induction response. It will be noted that the induction curve tends to sketch an envelope along the conductive end of the dipmeter response end of the dipmeter response excursions.

Figure 4 shows the shoulder bed effect on the response of the Six Arm Dipmeter side-by-side electrode arrangement. These departure curves, generated by computer modeling, indicate that although beds as thin as 1 inch are detected, shoulder effects become large under 2 inches. On the other hand, with this contact electrode system, layering resistivity contrast has a minimal effect on bed resolution.
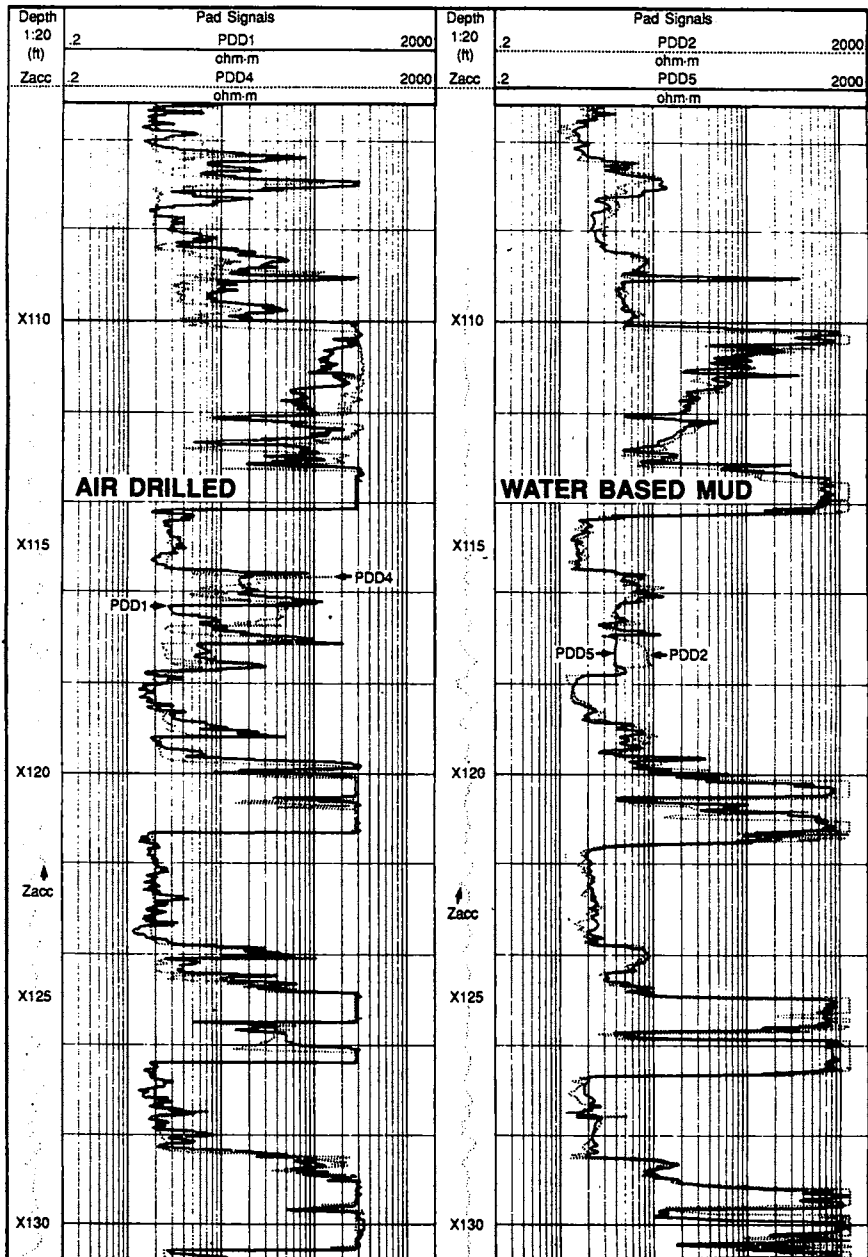
SIX ARM DIPMETER

Figure 1: Comparison of raw dipmeter curves run in air on the left and in water based mud on the right. The trace coding indicates data origin from approximately the same side of the hole.
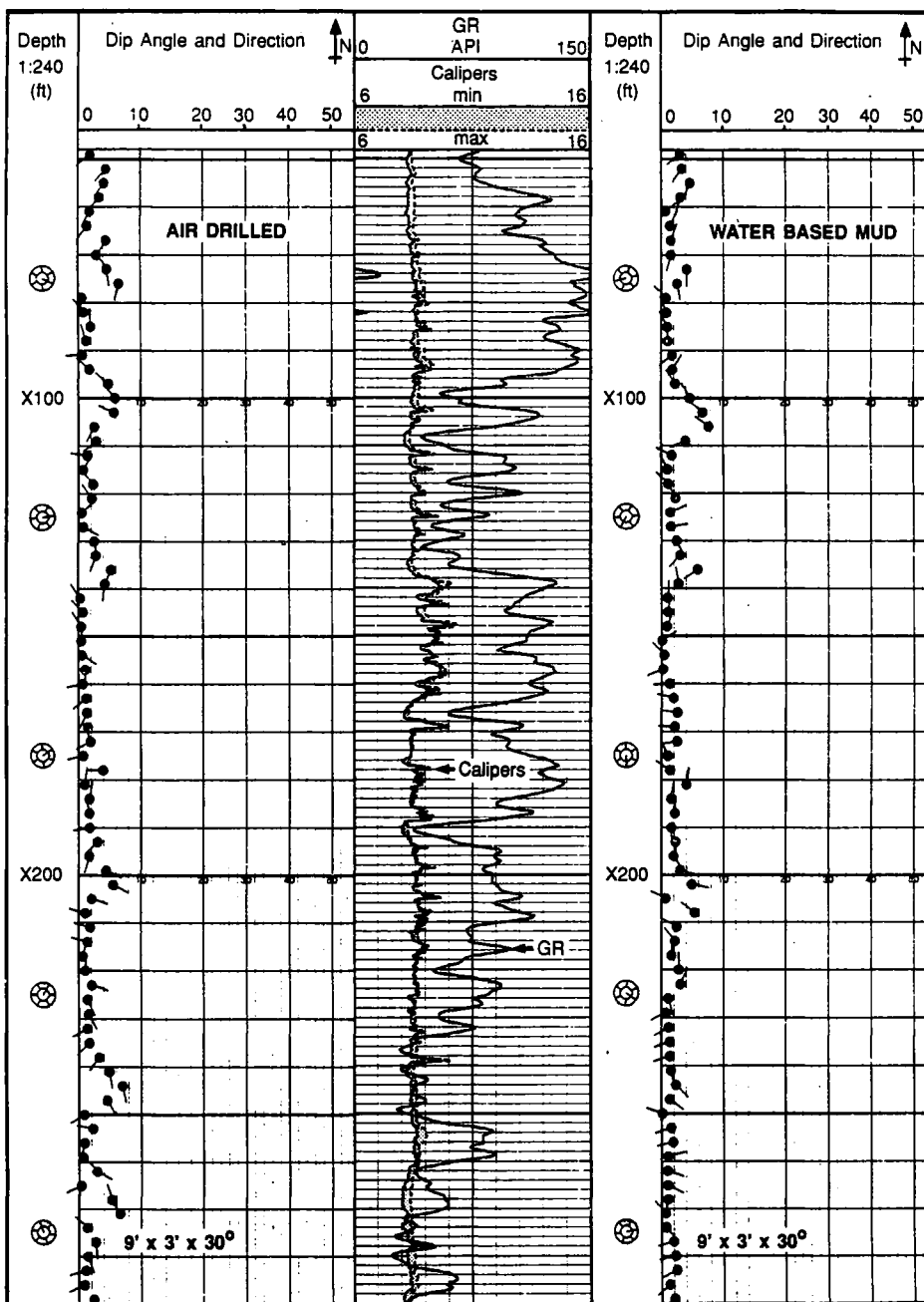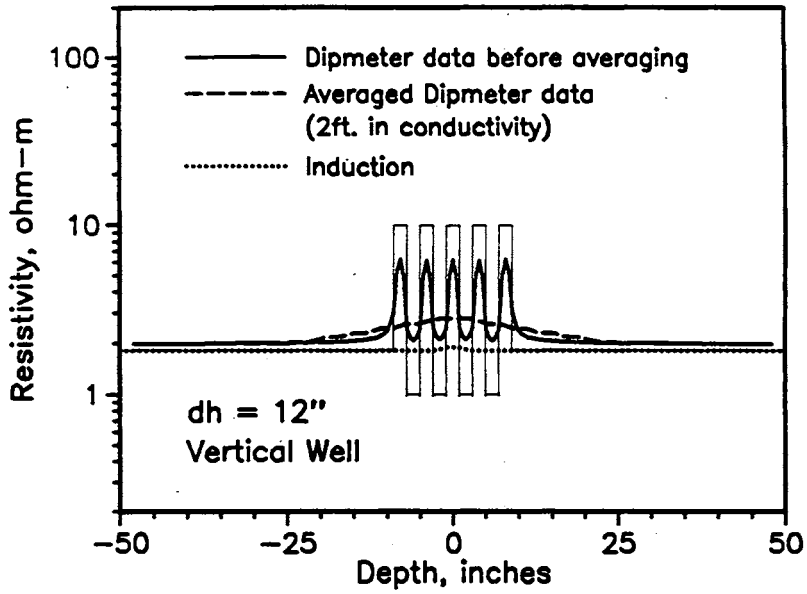
SIX ARM DIPMETER

Figure 2: Computed dipmeter results in air on the left compared to those in water based mud on the right.
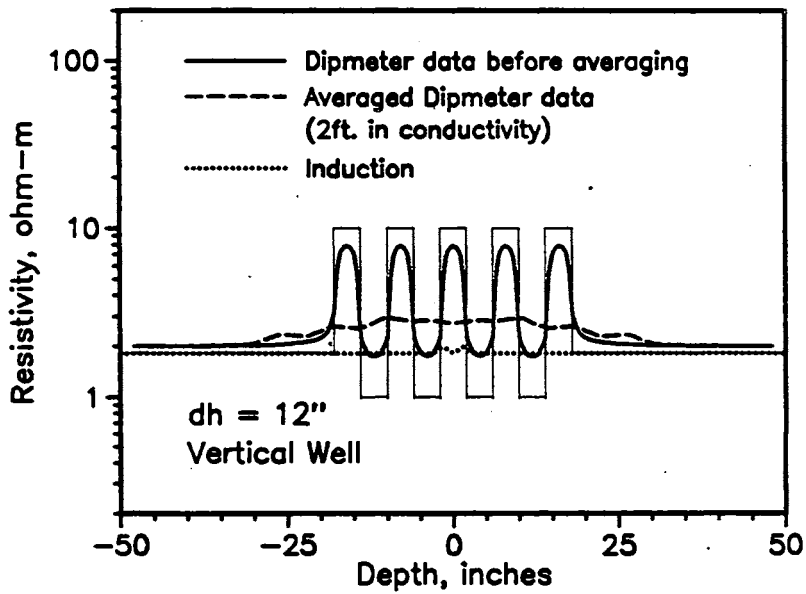
2" Laminations

4" Laminations

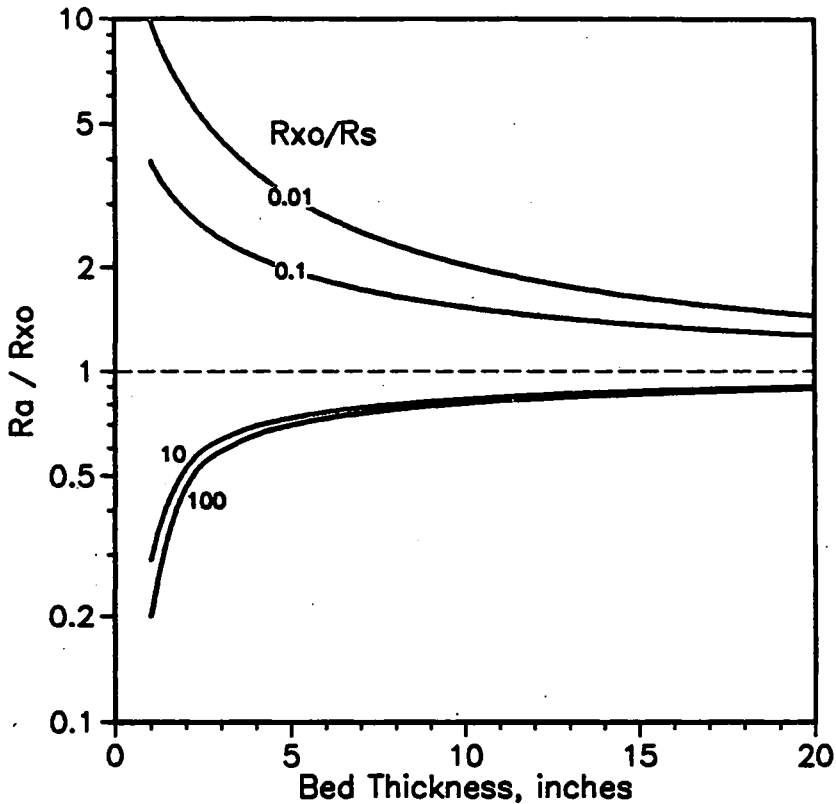**Figure 3:** Modelling results showing oil based mud dipmeter microresistivity response to thin beds.

Figure 4: Shoulder bed effect of the Six Arm Dipmeter oil based mud measurement, showing effect
of bed thickness and contrast.

Figure 5 is a field example of a low porosity laminated sandstone. The Dual
Induction-Guard log run in water based mud shows little evidence of lamina-
tions. (In this instance the Short Guard log is averaged over 1-$\frac{3}{4}$ feet). In
contrast the Six Arm Dipmeter recording previously run in air indicates a clearly
laminated condition. This is clarified in the expanded view of the dipmeter curve
which defines distinct shale and sandstone layers. Choosing a resistivity cutoff
line differentiates between shale on the left and sandstone on the right. The bulk
volume fraction of shale in laminated distribution mode, V_{lam}, is found from the
summation of thicknesses in which the curve is to the left of the cutoff relative
to the total zone thickness. In this example Vlam = 0.53.

INVASION AND R_{xo} OBSERVATIONS IN OIL BASED MUD

Emulsifiers are a key ingredient in the makeup of oil based muds. Emulsi-
fiers are essentially directional molecular complexes with one end exhibiting
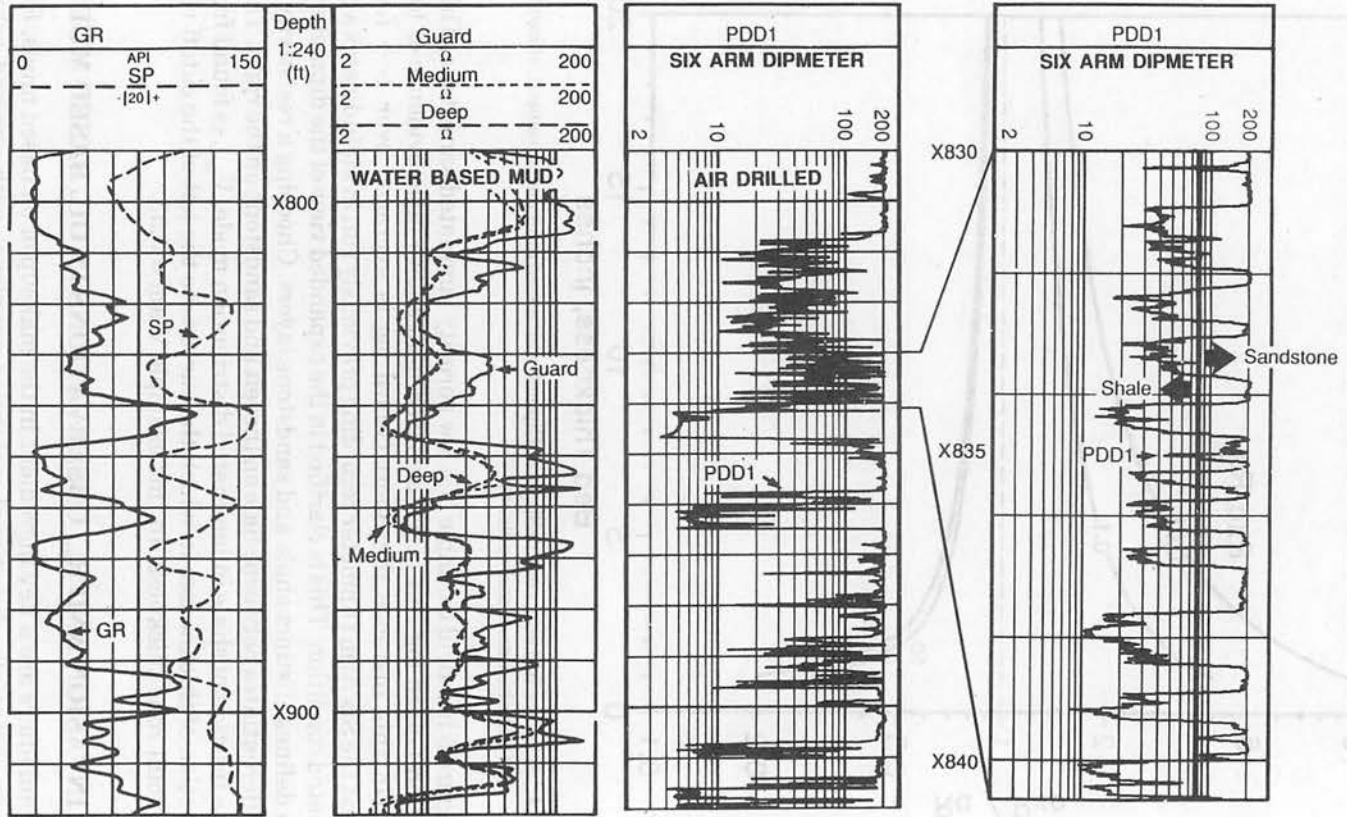water affinity and the other oil affinity. The water affinity ends embed them-

Figure 5: Example of thin bed laminated sandstone-shale resolution in an air-filled hole by means of the Six Arm Dipmeter.

selves in water droplets such that the water droplets become coated by the emulsifying agent. The water droplets thus become isolated and the composite unit exposes a coating that has oil affinity, rendering oil the continuous phase. Accordingly, resistivity should be infinite. Nevertheless, there may be residual water which can result in some conductivity.

The emulsifier coatings themselves may not be perfect, so that it is possible for water to leak out under pressure. Oil based mud usually produces an oil filtrate, but under high pressure water filtrate can be produced. The residual water content of the mud cake will probably vary inversely with the ratio of oil to water filtrate production so that a conductive mud cake is a possibility. The percentages of oil and water in the mud are quite variable,... from perhaps 90:10 to 50:50. These relative fractions and the efficiency of the emulsifier under temperature and pressure will determine the properties of the oil based mud and thus its invasion characteristics, both in terms of fluid type, i.e., oil, water, or both, and how much. Formation properties such as porosity, intrinsic permeability, relative permeability, and pressure overbalance as well as time will of course play major roles. Taken together, these characteristics can have a major impact on the response of logging measurements, especially shallow reading microdevices.

For many years, common wisdom indicated that oil based muds did not invade at all. More recent papers show evidence of very deep invasion of oil,... as deep or deeper than in the case of water based mud. It appears that the logging industry is only now learning that oil based mud is extremely variable. In fact, oil based mud properties have changed over the years in terms of oil type (diesel vs. low toxicity oils) emulsifier efficiency, and oil/water mix. The bottom line is that oil based mud properties are widely variable and the combination of those properties and formation plus borehole conditions will dictate invasion characteristics (fluid type and depth) and result in these being much more variable that in the case of water based muds.

Figure 6 is a schematic of the Six Arm dipmeter and its relationship to the borehole and the invaded zone. Figure 7 shows the pseudo geometrical factor computed for the Six Arm Dipmeter short normal system for various R_{xo}/R_t ratios. Note that the modeling indicates practically no difference between R_t/R_{xo} = 0.1 and 0.01

A complex gas-bearing sand drilled with oil based mud is seen in Figure 8. Core permeability, shown on the right, indicates wide variability. Superimposition of deep and medium induction curves suggests that invasion, if any, is at least not very deep. The resistivity curves from the Six Arm Dipmeter show an astonishing variation of resistivity values. Moreover, this variation is quite correlatable to the core permeability. In high permeability zones, dipmeter resistivity is almost the same as induction resistivity, 3 to 4 ohm.m. In low
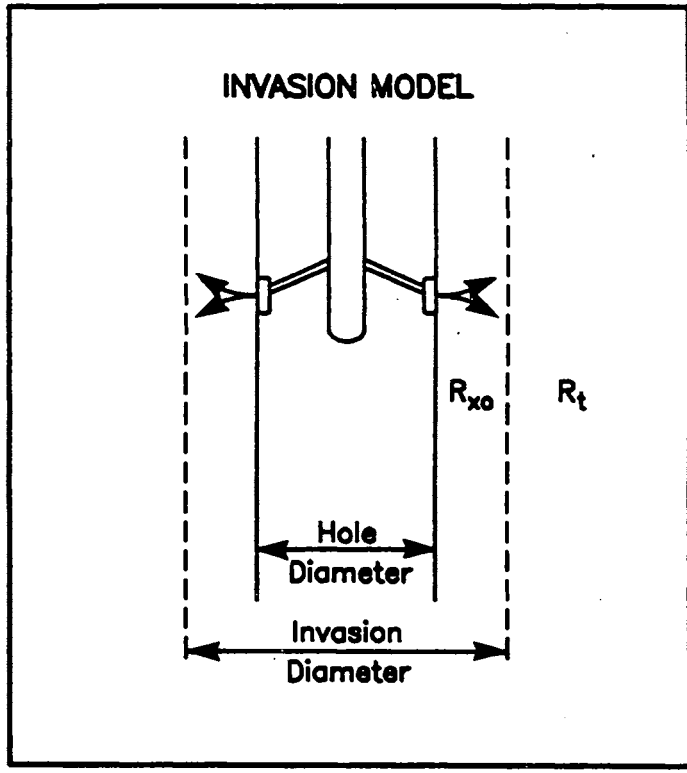
Figure 6: Physical model of the Six Arm Dipmeter opposite an invaded formation.
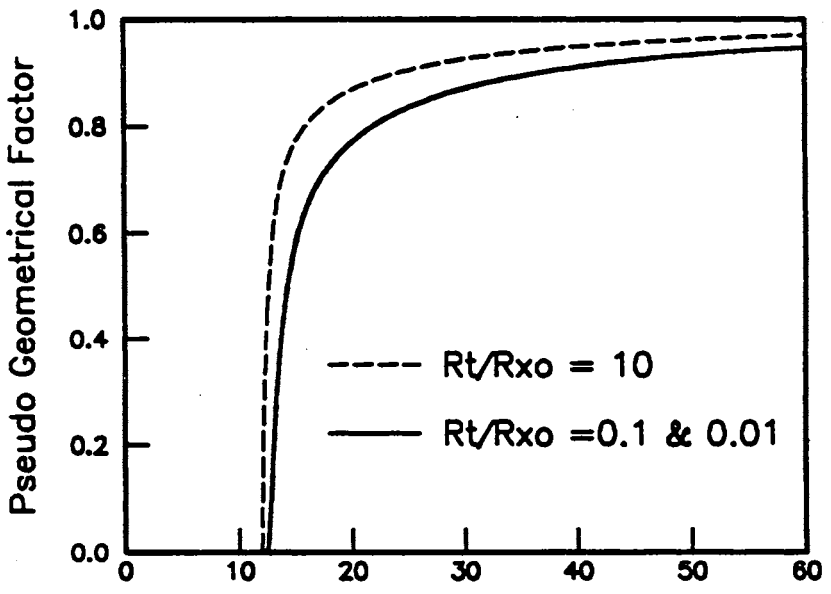

Figure 7: Pseudo geometrical factor of the Six Arm Dipmeter oil based mud microresistivity measurement.
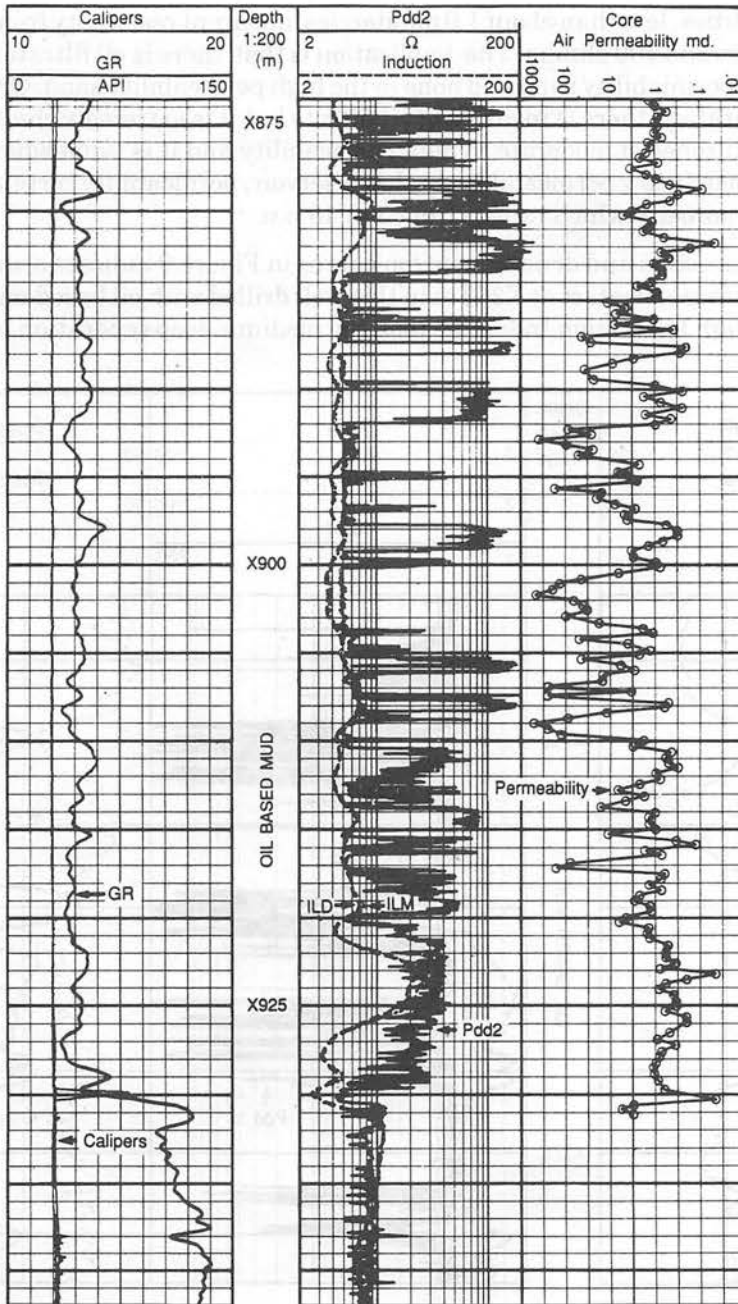
Figure 8: Example of a complex gas-bearing sand in which dipmeter resistivity appears to be related to permeability while induction resistivity remains essentially constant. The implication is that oil filtrate invasion depth is inversely related to permeability.

permeabilities, less than about 1.0 milidarcies, apparent resistivity from the dip-meter is around 100 ohm.m. The implication is that there is oil filtrate invasion in the low permiability sand and none in the high permeability sand. Or perhaps more accurately, there is invasion of oil filtrate but it is extremely shallow (<0.2 inches?) in zones of moderate to high permeability and it is somewhat deeper, say >1.0 inch in low permeability. In this reservoir, permeability correlates very well with porosity which ranges from 3 to 18 p.u.

The induction and density-neutron curves in Figure 9 indicate a shaly sand with a gas/water contact at X263 m in this well drilled with oil based mud. Since this is a High Resolution Induction tool, the medium-deep separation is not due
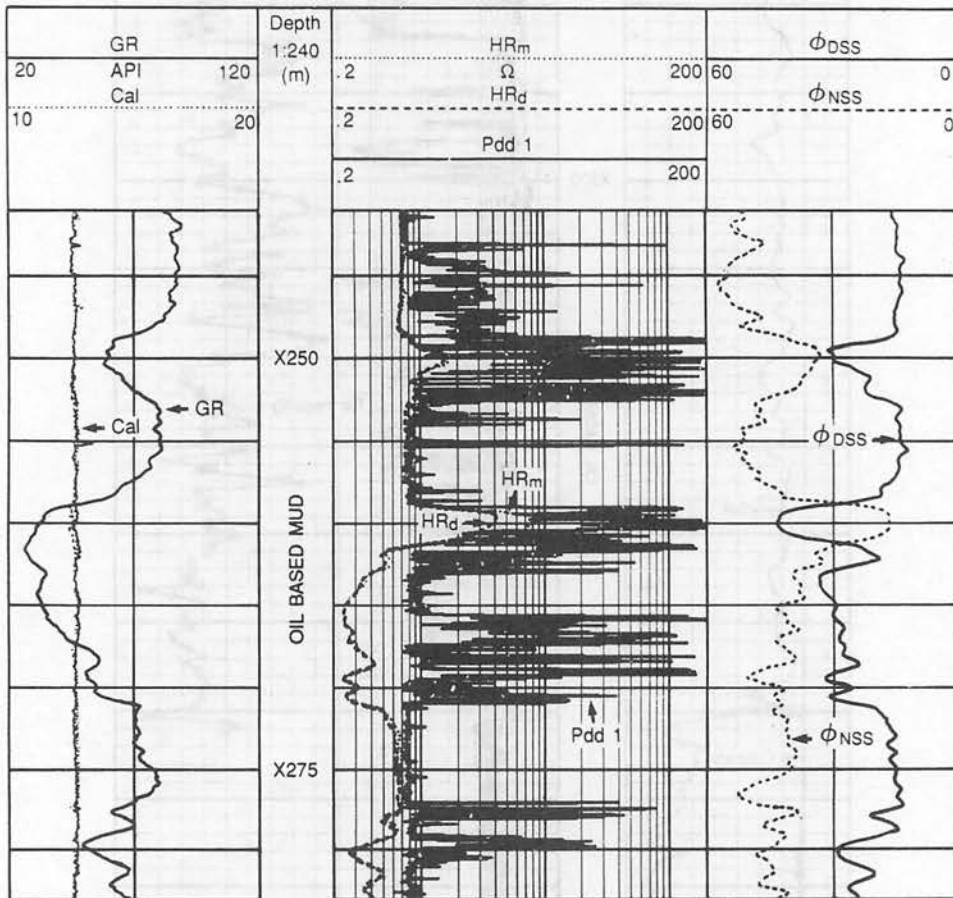

Figure 9: Example of a shaly sand with water and gas. Dipmeter resistivity detects the gas/water contact and implies that oil filtrate invasion is deeper in the shailer low permeability zone at the bottom of the reservoir.

to bed thickness effects, but rather suggests deep invasion of oil filtrate. The dipmeter resistivity curve registers a few ohm.m higher than the induction in the water zone and recognizes the gas/water contact. This suggests rather shallow (~0.5 inches?) invasion throughout or preferential invasion of oil filtrate in the low water saturation zone only. Curiously, below X265.5 m, high dipmeter resistivity is seen again. This is in the very shaly and presumably low permeability part of the reservoir. If the logic of the previous example is applicable, deeper (>0.5 inches) invasion of oil filtrate is suggested in the lower permiability. A word of caution: in this example as in all contact electrode situations, it must be borne in mind that electrode lift-off will cause a similar effect. However it would be difficult to imagine why all six electrodes would lift simultaneously as in this case (other curves not shown).

CONCLUSIONS

The Six Arm Dipmeter is a viable and economical alternative for the resolution of thin beds in oil based muds. In smooth hole conditions, the same tool can provide estimates of the resistivity of the zone immediately behind the borehole wall. However, these authors make no pretense of understanding the complexities of oil based mud invasion nor whether the concept of a flushed zone in the classical sense, really applies in the case of oil based mud.

ACKNOWLEDGEMENTS

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