A NOVEL APPROACH FOR COMPENSATING NEUTRON POROSITY LOGS FOR BOREHOLE EFFECTS

Michael Evans, David Best and Kyel Hodenfield

Schlumberger

ABSTRACT

Neutron porosity logging techniques have been used for many years to measure the porosity of a formation surrounding a borehole. It is well known that the measurement is adversely affected by changes in measurement geometry such as borehole size, shape and tool position within the borehole (tool standoff).

Compensation techniques attempt to overcome these perturbing effects by using two detectors — one located far from the source to measure formation porosity and a second located near the source to measure the effects of changing measurement geometry. Taking the simple ratio of near-to-far (N/F) counting rates reduces the effects of changing geometry. However, this procedure does not provide complete compensation and the resulting porosity values must still be corrected for borehole size, shape, and tool position within the borehole.

Much improved compensation for borehole geometry effects is achieved by modifying the simple near-to-far ratio. A function of the far-detector count rate can be determined that results in the two detectors having nearly identical radial responses in the proximity of the tool. The ratio of the near-detector count rate to this function of the far-detector count rate yields a modified ratio that is insensitive to geometric perturbations that occur near the tool. This modified ratio results in a porosity measurement that is borehole invariant — a measurement that virtually needs no correction for washouts, rugosity, borehole shape or tool standoff. The technique is applicable to both wireline and logging-while-drilling (LWD) neutron porosity measurements.

The benefits of this new compensation technique will be described and illustrated with laboratory data and Monte Carlo simulation results. The ability of the technique to implicitly account for changing borehole geometry will be demonstrated with several well log examples.

INTRODUCTION

Neutron porosity logs are essential in evaluating the economic potential of prospective formations when drilling wells for the production of hydrocarbons. Combined with a density log, they are used for gas identification and lithology determination. Modern neutron porosity tools have two neutron detectors spaced at different distances from the source. The source is typically an isotopic source of fast neutrons. Neutrons emitted by the source exit the tool and travel through the surrounding borehole and formation. A portion of the neutrons returns to the tool where they are detected. The neutrons interact primarily with hydrogen nuclei in the fluids of the borehole and the pore spaces of the formation. This results in a measurement that is related to the porosity of the formation.

The tool is typically calibrated in well-characterized formations having a fixed borehole size, fluid and tool position. The response of the tool in these "standard or calibration conditions" is used as a reference. During logging, variations in measurement geometry such as washouts, borehole rugosity and standoff occur that significantly perturb the response of the tool compared with the calibration conditions. To be useful, the resulting log must be corrected for these effects.

Dual detector compensation techniques attempt to overcome these perturbing geometry effects by using two detectors — one located far from the source to measure formation porosity and a second located near the source to measure the effects of changing measurement geometry. Compensation is achieved by taking the simple ratio of near-to-far counting rates. However, this procedure does not provide complete compensation. The resulting porosity values must still be corrected for significant errors caused by variations in borehole size, shape and tool position within the borehole.

The magnitude of these effects can be large, especially for logging-while-drilling (LWD) tools, which are typically run centered in the borehole as a result of stabilizers in the bottom hole assembly. This is illustrated in Fig. 1, which shows the effects of borehole size (hole enlargement or washout) for the 4.75-in. VISION* Density Neutron (VDN*) tool. The borehole size correction for the 4.75-in. VDN tool at 30 p.u. is seen to be about 8 p.u. for a washout that is 8-in. in diameter. Without accurate caliper information regarding borehole size (and to a lesser extent, borehole shape and tool position), these errors are very difficult to correct. Even when caliper data are available, the accuracy of the resulting correction can be seriously compromised by heavy mud weight, unconsolidated formations and a small amount of gas in the mud.

Borehole invariant porosity (BIP) processing addresses many types of variations in measurement geometry. Specifically, the technique will correct for radial geometric effects such as borehole size, eccentricity/standoff, washouts, breakouts and rugosity. Some of these measurement geometries are illustrated schematically in Fig 2. The technique makes these corrections by creating a radial zone around the tool in which the compensation is virtually complete and the measurement shows no response to changes in borehole geometry — a borehole invariant porosity. As long as the borehole perturbation lies within the zone of compensation, the borehole invariant porosity processing will yield the true formation neutron porosity.

METHODOLOGY

The zone of compensation can be appreciated by referring to Fig. 3, which illustrates radial responses for a neutron porosity measurement. Traditional near-to-far ratio algorithms have a radial response that is clearly not ideal, having significant sensitivity to radial borehole changes near the tool. This sensitivity is demonstrated by the Monte Carlo data points shown in Fig. 3 for the 4.75-in. VDN tool. In contrast, an ideal tool response would be zero for the first several inches out from the tool and then increase monotonically to the saturation value. The actual shape of the ideal response is not critical, as long as a zone of full compensation exists near the tool.

The borehole invariant porosity technique achieves compensation by forcing the near-tool radial response of the far neutron detector to approximate that of the near neutron detector. This is done by choosing a function of the far count rate that results in the same percentage change in count rate for radial effects as the near detector. Taking the ratio of the near count to this function of the far count rate cancels the response of the measurement to near-tool radial variations seen by the detectors.

The far radial response is matched to that of the near by determining a function of the far count rate such that the BIP ratio, near/*f*(far), is constant as borehole size changes for constant porosity. Experimental and Monte Carlo data are used to define the parameters of the response matching function. It has been determined that the matching function is virtually identical for all porosities for a given tool design.

This process is illustrated in Fig. 4 for a single porosity — a 17.5 p.u. fresh-water limestone. The data shown are from an LWD tool, the 4.75-in. VDN tool centered in fresh water boreholes with diameters of 6, 7, 8, 9, 10,11 and 12 in. The three curves shown have been arbitrarily normalized at 1000 cps for a 6-in. borehole to facilitate comparison of their shapes with increasing borehole diameter. Actual BIP processing involves no such normalization. The three curves represent near count rate, far count rate and the function of the far count rate used in the BIP technique.

As shown in Fig. 4, all three count rates decrease with increasing borehole size but at different rates. What's important to notice is that the function of the far count rate decreases at the same rate as the near count rate curve up to a diameter of about 8 in., then decreases at a slightly faster rate. This is the radial response matching of the near- and far-detector responses mentioned earlier. The result of this matching is to make the BIP ratio invariant to changes

* Mark of Schlumberger

in borehole diameter within the zone of full compensation. For the 4.75-in. VDN tool, the zone of full compensation extends to about 8 in. For the larger 6.75-in. VDN tool, the zone of full compensation extends to about 10 in. Since this procedure matches radial responses, the BIP ratio is also invariant to radial variations in the measurement geometry such as eccentering/standoff, borehole shape and rugosity. This superior compensation is achieved without the use of caliper information.

The effect of the matching on the radial response is shown in Fig. 5. The BIP data were computed using Monte Carlo modeling for the 4.75-in. VDN tool. The response of the BIP ratio exhibits a response much closer to the ideal response for a neutron porosity measurement. That is, it has very little response for the first 1.5 in. from the tool surface and then increases monotonically to saturation. Thus, the measurement does not respond to borehole perturbations within a 1.5 in. zone around the tool. It should also be noted that the BIP ratio does not respond to formation porosity within the zone of full compensation, effectively making the measurement "see" only the deeper formation porosity variations. This is beneficial in measuring true formation porosity in the presence of formation alteration, filtrate invasion and borehole breakout.

The effectiveness of the BIP compensation is compared with traditional near-to-far compensation in Fig. 6 for the 4.75-in. VDN tool. The figure displays the apparent porosity of a 17.5-p.u. fresh-water limestone as a function of borehole diameter for several porosity algorithms assuming standard conditions (i.e., a 6-in. borehole). In addition to BIP and N/F processing, the curve labeled "Near" in the figure represents the apparent porosity measured by only the near detector. Likewise, the curve labeled "Far" represents the apparent porosity measured by only the far detector.

Borehole enlargement has the greatest effect on the near-detector apparent porosity, while the effect on the far-detector apparent porosity is about half that of the near, as expected from the greater depth of investigation. Traditional near-to-far ratio processing provides only partial compensation for borehole enlargement. A residual error of 7 p.u. remains for an 8-in. borehole. BIP processing, however, yields the correct porosity from 6 in. up to about 8 in. Beyond 8 in., BIP processing yields porosity values that slowly deteriorate with increasing borehole size. However, the effect is much less severe than for the near-to-far ratio method. Even for a 10-in. borehole, which is well outside the zone of full compensation, BIP processing results in only a 5-p.u. error, whereas near-to-far processing results in a much larger 17-p.u. error.

Since BIP processing provides radial compensation, the technique will also minimize errors resulting from eccentering or standoff of the tool within the borehole. This is confirmed by the data shown in Fig. 7. The porosity error incurred by fully eccentering the tool in boreholes of 6, 8 and 10 in. is shown for BIP and N/F algorithms for two formation porosities: 17 and 43 p.u.. As expected, the BIP algorithm compensates very well (average porosity error ~0.35 p.u.) for eccentering effects in boreholes smaller than 8 in. — the zone of full compensation. Traditional N/F processing results in errors as large as 3 p.u.. Well outside the zone of full compensation, the BIP algorithm results in errors that are about a third as large as those from N/F processing. This application will benefit LWD tools in vertical wells that are run slick or with an undergauge stabilizer where tool position in the borehole is undetermined.

BIP processing also provides compensation for other borehole conditions. In particular, BIP processing is quite effective in removing the effects of mud hydrogen index in the borehole. One of the more dramatic effects is for aerated muds, as shown in Fig. 8. The porosity error resulting from aerated mud is shown for BIP and N/F algorithms as a function of mud weight. The N/F algorithm requires a correction of about 8 p.u. for a 30-p.u. sandstone formation and a 6-in. borehole filled with 0.6-g/cm^3 (5-lbm/gal) aerated mud. However, the BIP algorithm requires only about a 1-p.u. correction under the same conditions. Clearly, the change in hydrogen concentration in the mud affects the BIP ratio in a manner similar to that of a change in borehole/formation geometry. Downhole mud density (and therefore hydrogen index) is usually quite variable with aerated mud, and input for corrections to neutron porosity may not be reliable. Additionally, aerated mud precludes the use of ultrasonic caliper data for borehole size correction.

LOG EXAMPLES

The characteristics of borehole invariant porosity processing described in the previous sections are illustrated by the following log examples.

1. Example of borehole washout compensation

The log shown in Fig. 9 presents an interesting example of borehole washout. The well was drilled with an 8.5-in. bit and is deviated at 50 degrees. A 6.75-in. VDN tool with an 8.5-in. stabilizer was used to log the well during drilling and the well was subsequently logged by wireline. Wireline gamma ray, neutron porosity and caliper are shown with LWD curves for BIP and traditional N/F neutron porosity (labeled TNPH). The TNPH response was computed assuming a bit-sized borehole, while the wireline TNPH has been caliper corrected.

The wireline caliper shows the borehole is in gauge for most of the well below about X820 ft. Above this, the borehole is significantly washed out, increasing nearly monotonically in size from about 9.5 in. at the top of the log to about 12.5 in. at X800 ft. This provides a nearly perfect test case for BIP washout compensation over a wide range of washout diameters.

As shown in the figure, traditional N/F processing is significantly affected by washout above about X820 ft., overestimating the porosity by an average of about 8 p.u. from X700 to X740 ft. (Zone A), by about 20 p.u. from X760 to X770 ft. (Zone B) and by about 12 p.u. from X780 to X820 ft. (Zone C). In comparison, BIP processing matches wireline porosity very well in Zone A, where the caliper log does not exceed 10 in. This is the depth of the compensation zone for the 6.75-in. VDN tool. In Zones B and C, the very large washouts are not completely compensated for by BIP processing because the caliper indicates washouts with diameters greater than 10 in. However, even in these zones BIP processing offers much better compensation that that available from traditional N/F processing. Below X820 ft., where there is little washout, the BIP, traditional N/F and wireline porosities agree nicely.

2. Gas invasion compensation example

BIP processing was intended primarily to overcome perturbations in measurement geometry caused by formation washout or tool positioning. However, the radial compensation scheme also minimizes errors resulting from other perturbations occurring near the tool, as shown in Fig. 10A. This log shows an example of invasion drape that has been discussed in a previous paper (Holenka et al., 1995). This is a 8.5-in. horizontal wellbore that was logged while drilling with a 6.75-in VDN and a 8.5-in. stabilizer. The TNPH response was computed assuming a bit-sized borehole. The shaded black bands at the bottom of the caliper track indicate when the tool is sliding instead of rotating. The sliding indicator is useful in flagging those portions of the caliper and density logs that potentially represent invalid data. Invalid data results from having the density and caliper sensors oriented away from the bottom of the borehole while sliding. An orienting sub is now available to ensure proper orientation of the sensors while sliding.

The difference between bottom and top quadrant density measurements indicate significant invasion in the gas sand from about X340 to X390 ft. (Zone A). The BIP and traditional N/F (labeled TNPH) porosities agree quite well in the shale near the top of the log (Zone B) where the calipers indicate minimal washout but disagree in the invaded gas sand, especially from X340 to X380 ft. In this zone, BIP indicates about 3 p.u. less porosity than the traditional N/F processing.

This behavior can be explained by referring to the schematic drawing of Fig. 10B, which presents a simple model describing filtrate drape or gravity segregation of the invasion fluid to the bottom of this horizontal wellbore in a gas sand. Shown in the model, along with the invasion drape, is the zone of full compensation for BIP processing. It is clear from the drape invasion profile that traditional N/F processing will respond much more to the invaded zone than will the BIP processing. This is due, of course, to the fact that BIP does not respond to the invaded gas zone within the first 1.5-2 in. of the formation, resulting in a lower porosity value that is closer to the true gas sand porosity reading. This effect has been confirmed by Monte Carlo calculations simulating these logging conditions. It should be noted that the difference between BIP and N/F porosities would be even greater if the invasion were uniform around the wellbore instead of gravity segregated.

It is interesting to note the shale just above this gas. The ultrasonic caliper indicates that the shale from X300 to X310 ft. (Zone B) is nearly in gauge, while the shale from X310 to X340 ft. (Zone C) is significantly washed out. The BIP processing agrees well with the traditional N/F processing for the in-gauge zone but indicates about 5 p.u. less porosity in the washed-out zone. This is another example of the implicit BIP washout compensation.

3. Example of compensation for aerated mud effects

An additional compensation provided by BIP processing is shown in the log of Fig. 11. This deviated well was drilled with a 6 1/8-in. bit and logged while drilling with the 4.75-in. VDN tool without a stabilizer in aerated mud (5-lbm/gal density). Fig. 11 compares the neutron porosity logs resulting from three different computations: traditional N/F processing with no mud weight correction labeled TNPH; traditional N/F processing with a mud weight correction for the aerated mud labeled TNPH-CORRECTED; and BIP processing with no mud weight correction. The traditional N/F processing should result in low-porosity readings, which is clearly the case judging by the apparently clean, wet sand near X060 ft. (Zone A), where the density and traditional neutron porosity curves should coincide but do not because of the aerated mud. However, the BIP-processed curve matches the density porosity reading in this sand, indicating that BIP greatly minimizes the effects of aerated mud on the neutron porosity log without knowledge of the mud weight. This is confirmed by the good agreement throughout the log between the mud weight-corrected traditional porosity and the uncorrected borehole invariant porosity.

CONCLUSIONS

Traditional near-to-far ratio processing does not provide adequate compensation for the many perturbations in measurement geometry that can occur with a neutron porosity log. The porosity values must still be corrected for borehole size, washouts, shape and tool position within the borehole. Much improved compensation for borehole geometry effects can be attained by modifying the simple near-to-far count rate ratio to yield a porosity measurement that virtually needs no correction for these effects. Laboratory, Monte Carlo and log data confirm the ability of the BIP method to compensate for perturbations in measurement geometry. This is especially important when accurate caliper information regarding borehole size, borehole shape and tool position are lacking or are incomplete. And even when caliper information is available, the accuracy of the data can be seriously compromised by heavy mud weight, unconsolidated formations and a small amount of gas in the mud. In these circumstances, the efficacy of a self-correcting neutron porosity measurement like BIP cannot be over-emphasized.

REFERENCES

Holenka, J., Best, D., Evans, M., Kurkoski, P., Sloan, W.:Azimuthal Porosity While Drilling, paper BB, Transactions of the 36th SPWLA Annual Logging Symposium, Paris, 1995.

AUTHORS

MIKE EVANS is an engineering specialist in the Nuclear Tools group for Schlumberger in Sugar Land, Texas. He worked as a staff member at Los Alamos National Laboratory after graduating from Texas A&M University in 1976 with a PhD in physics. He joined Schlumberger in 1981 at the Houston engineering center, where he worked on several wireline nuclear logging tools. In 1986 he joined the Logging While Drilling project and is involved in the design and interpretation of nuclear tools.

DAVID BEST is working on interpretation for Schlumberger in Sugar Land, Texas. After graduating from Rice University with a BA in chemical engineering, he joined Schlumberger in 1962 working as a field engineer in Texas and the Middle East. Since 1971, he has been involved with computerized log analysis and interpretation development in a number of positions with Schlumberger. He has worked on LWD projects since 1987.

KYEL HODENFIELD is the LWD New Technology product manager responsible for interpretation, answer products, applications and training. He joined Schlumberger in 1985 and worked in various locations throughout the western United States in field assignments and in sales, marketing and management positions. He received a BS degree in geological and petroleum engineering from the University of North Dakota and is a member of SPWLA and SPE.

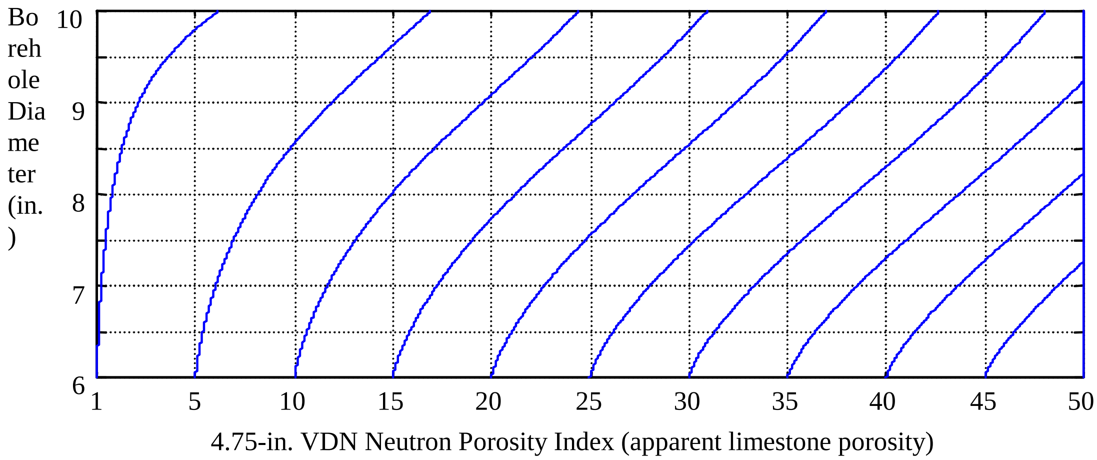

Fig. 1. Magnitude of borehole size effects on the 4.75-in. VDN log.

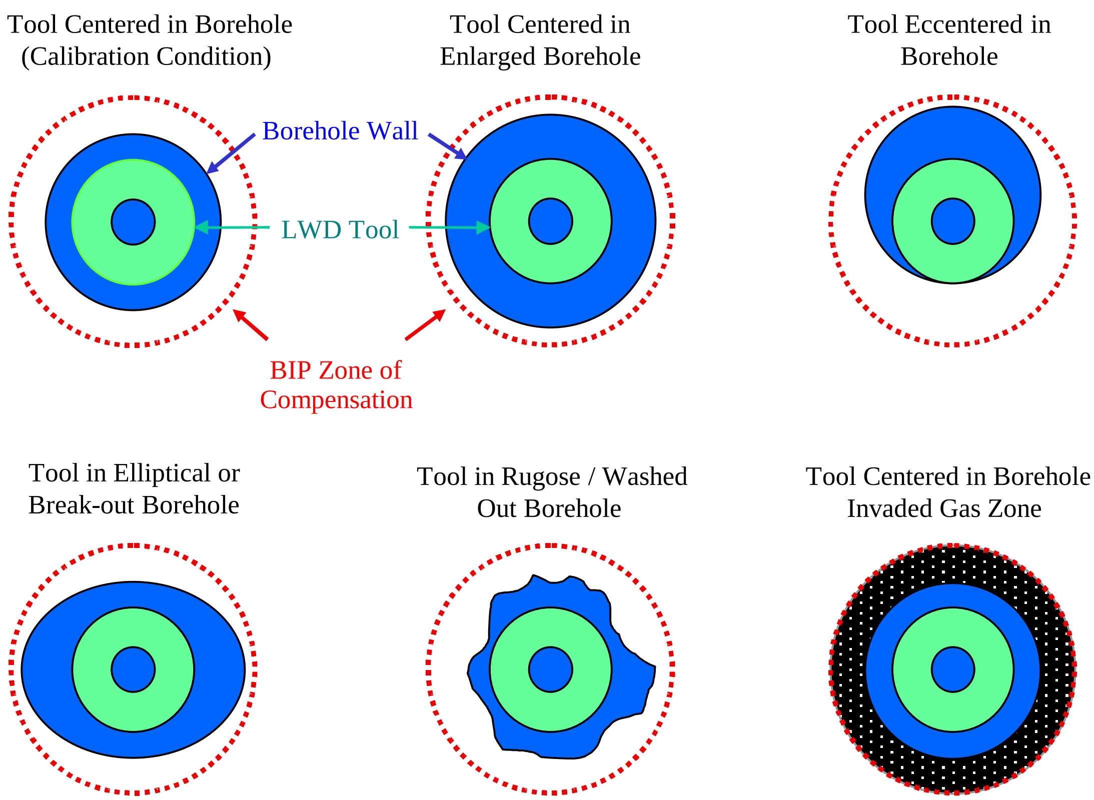

Fig. 2. Zone of full compensation for several measurement geometries.

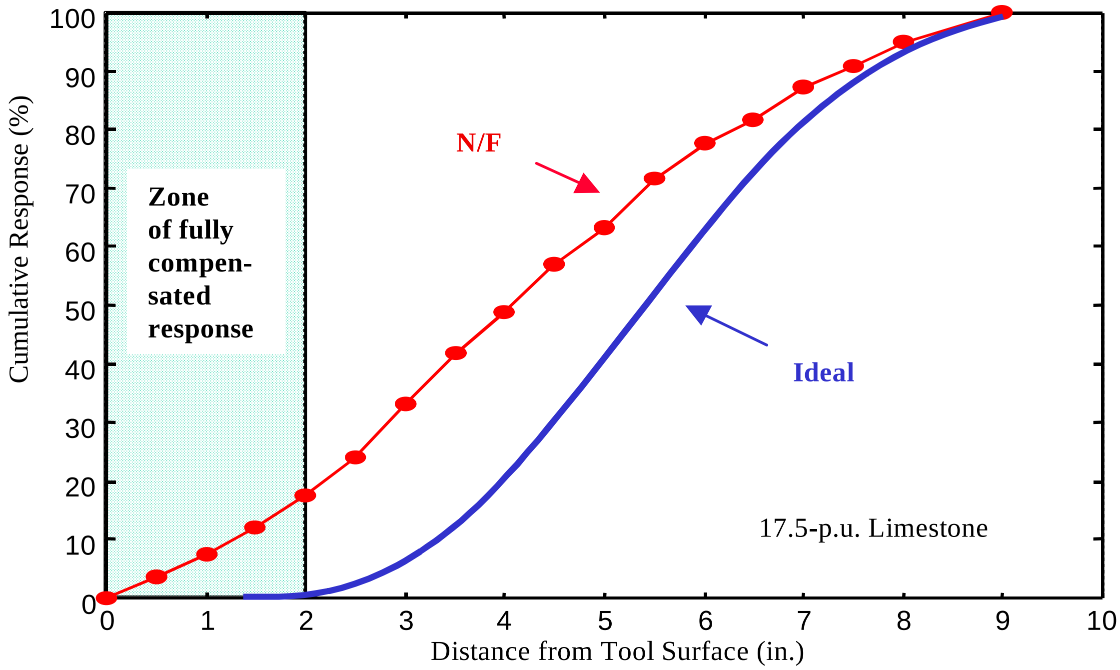

Fig. 3. Radial response curves for a neutron porosity tool.

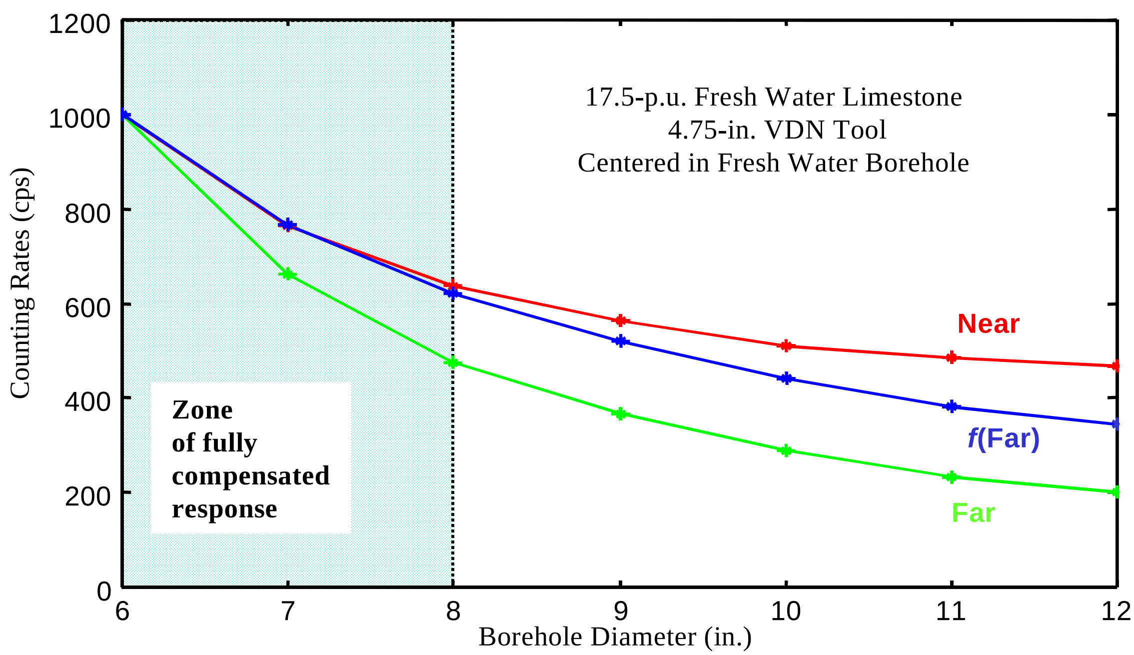

Fig. 4. BIP radial response matching.

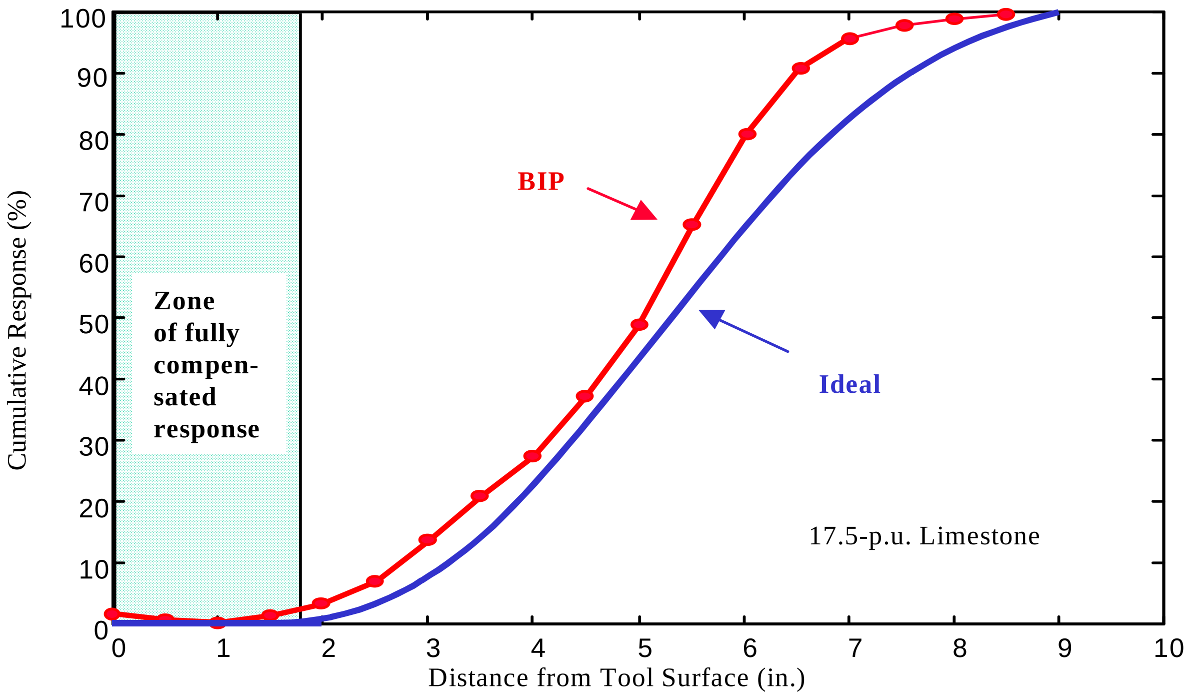

Fig. 5. BIP radial response for the 4.75-in. VDN tool.

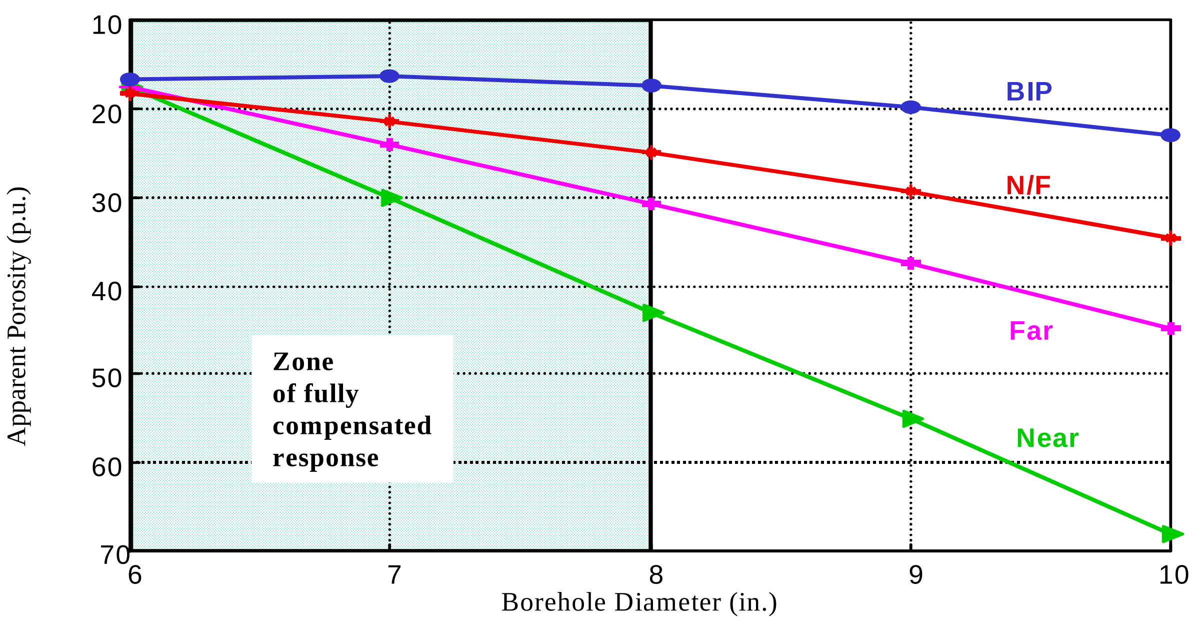

Fig. 6. Effectiveness of washout compensation for several 4.75-in. VDN porosity algorithms. Data are for a 17.5-p.u. fresh water limestone. The standard condition is a 6-in. borehole.

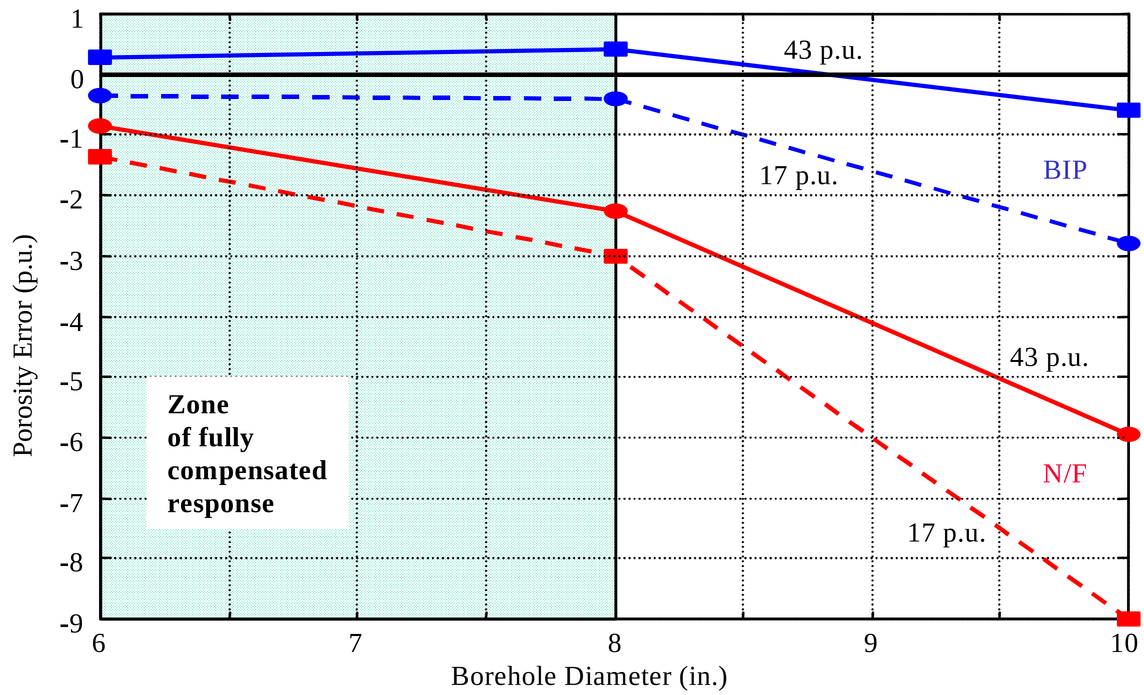

Fig. 7. Comparison of BIP vs. N/F eccentering effects for the 4.75-in. VDN tool.

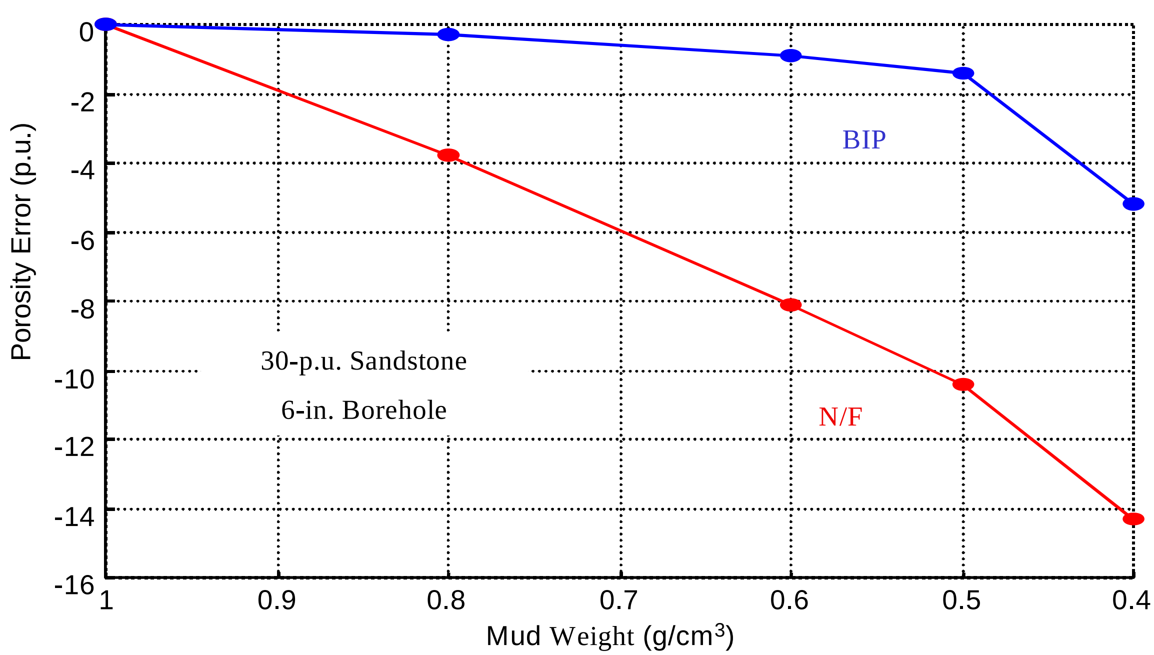

Fig. 8. Comparison of BIP vs. N/F aerated mud effects for the 4.75-in. VDN tool.

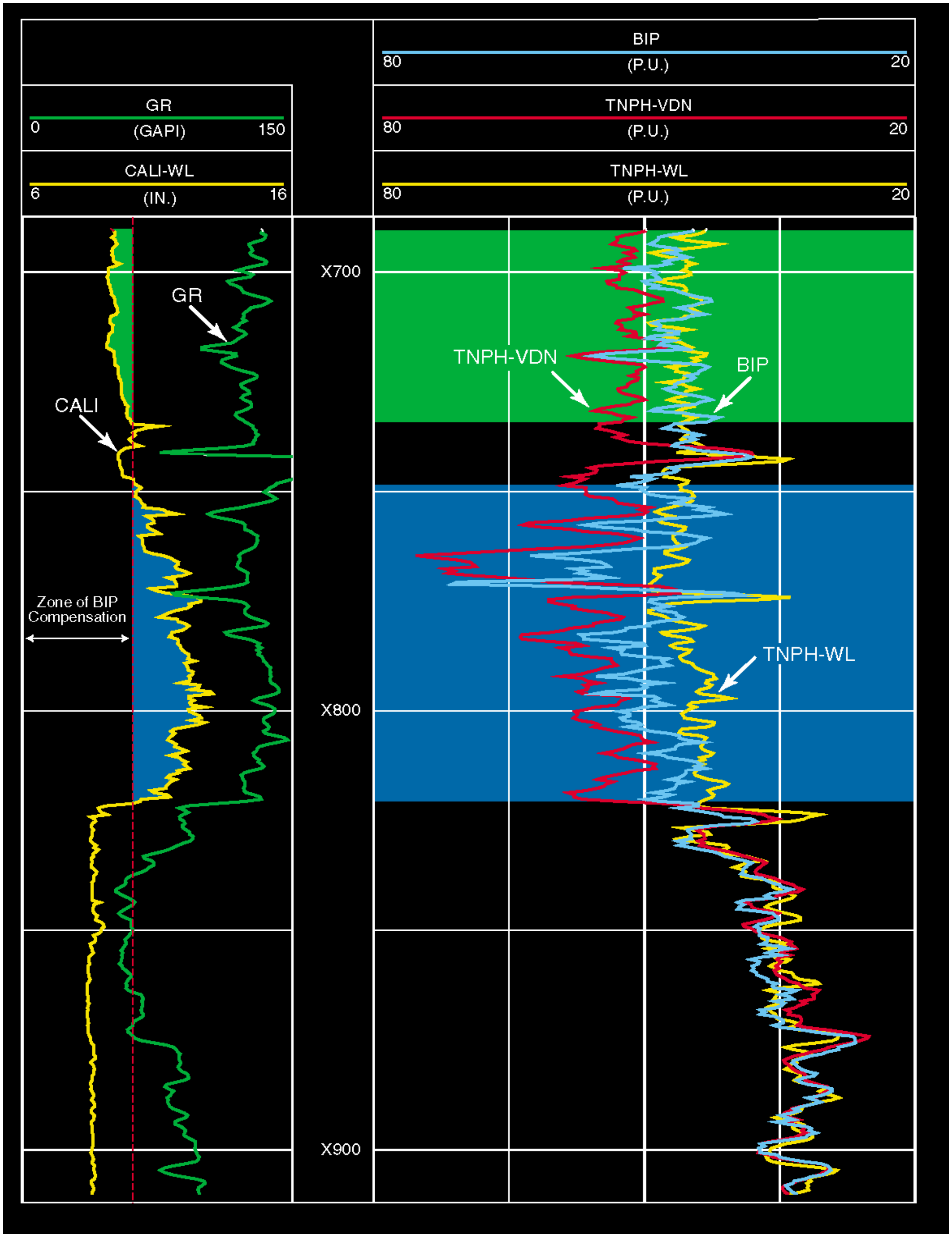

Fig. 9. Example of borehole washout compensation.

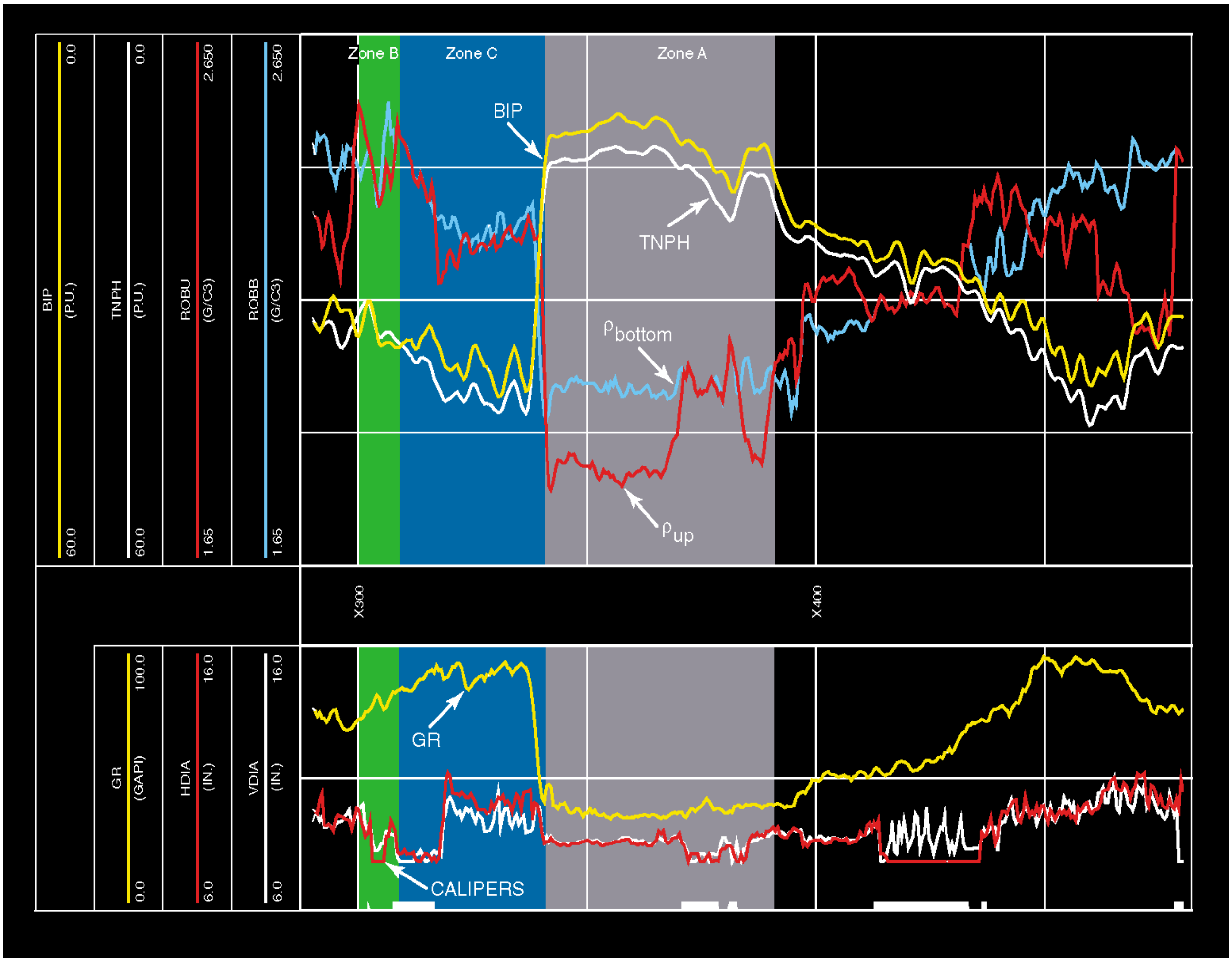

Fig. 10A. Example of filtrate drape compensation. In Zone A, the difference in neutron porosity is due to invasion, in Zone C it is due to washout.

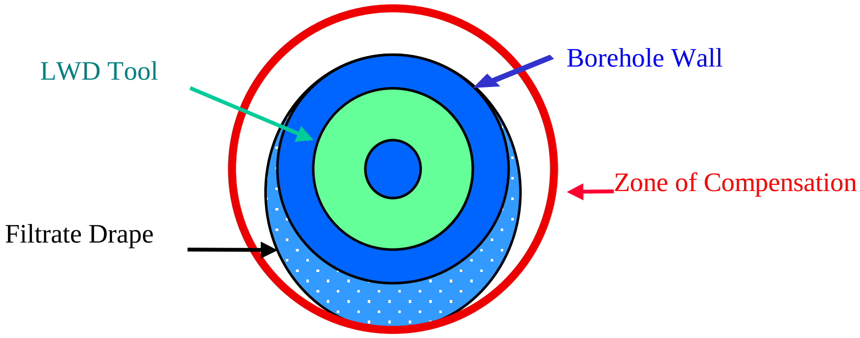

Fig. 10B. Filtrate drape model.

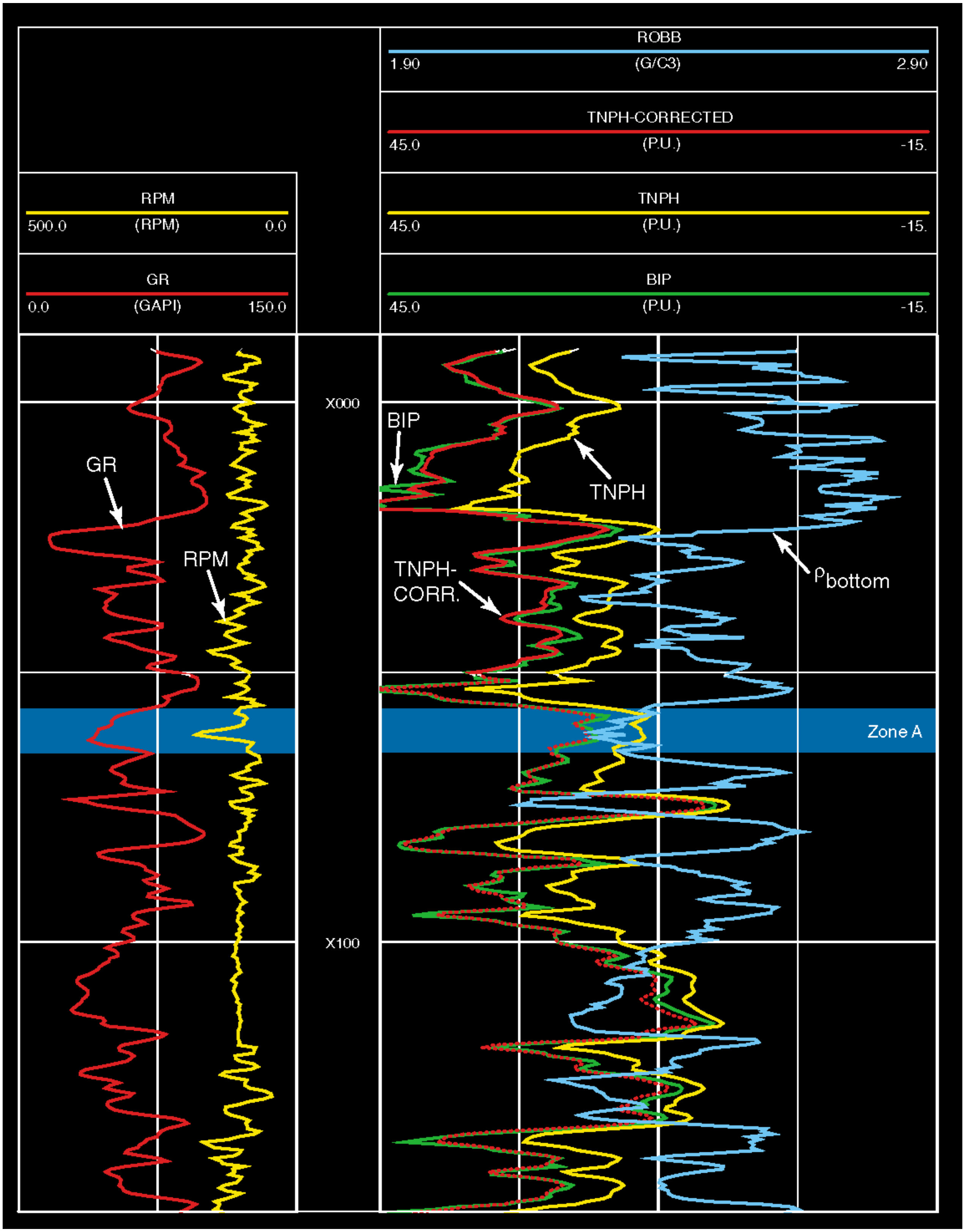

Fig. 11. Example of compensation for aerated mud effects.