REDUCING UNCERTAINTY IN LOG ANALYSIS DUE TO PRESENCE OF HEAVY-CONDUCTIVE MINERALS IN SEDIMENTARY ROCKS

by

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ABSTRACT

Presence of heavy-conductive mineral(s) in formation rocks tends to provide negative influence to some log readings, especially the resistivity log. With regard to its function in log analysis, any distortion in resistivity log readings will certainly lead to potential misinterpretation on petrophysical properties such as water saturation (S_w). Therefore, a method dedicated to minimizing the effect is indeed necessary.

This paper presents results of a study on presence of heavy-conductive minerals, distributed in structural form, on resistivity reading. Based on analogy and expansion of a structural clay distribution model, a correction method plus its application procedure have been proposed. Since the method is developed using an approach that is considered valid in general term it is, therefore, conceptually applicable to any field cases as long as its theoretical conditions are met. In order to make application of the method easier it has also been presented in form of nomographs.

Application of the method on log analysis of two wells in West Java has proved itself well in which corrections on calculated water saturation have yielded values that are more consistent when compared to production test data. The method is also prepared in a manner that it can be easily integrated into standard log analysis practices.

I. INTRODUCTION

In well-log surveys designated to assist formation evaluation, responses detected by log sondes reflect all elements that form formation rocks including minerals and fluids contained in their pore spaces. Apart from approaches and assumptions used in interpretation, differences in characteristics between those elements are used as indicators of both lithological and petrophysical properties.

In many cases in Indonesia, heavy and conductive minerals such as pyrite (FeS_2), siderite ($FeCO_3$), and ferroan calcite ($FeCaCO_3$) are often found in reservoir rocks. Some past investigations report that pyrite contents in reservoir rocks can be as high as 27 % of matrix volume (e.g. Crane, 1990; Widarsono et al, 1997). The presence of these minerals tends to lower rock conductivity, as in the case of shaly sands, that may mislead standard interpretation for hydrocarbon reserves to wrong conclusions (i.e. too pessimistic). In extreme cases, this situation can lead to overlooked/bypassed zones in which potential hydrocarbon-bearing sands are ignored due to low apparent true resistivity.

As in the case of shaly sand, the presence of these metallic minerals has to be anticipated. In order to serve the purpose, a method is needed. Accordingly, several investigators had proposed correction methods. Clavier et al (1976), for instance, discussed extensively over the influence of pyrite on measured resistivity and the way to correct it. They discussed the difference in apparent resistivity values shown by different resistivity tools (i.e. different electric frequency). They also concluded that lower formation water resistivity (R_w) values tend to intensify the distortion by the pyrite's presence. However, they stated that the series relationship presented applies only for pyrite contents of less than 7 %, and the study did not put much attention on the role of other factors such as porosity, tortuosity, and cementation factors on the distortion. Crane (1990) presented a similar approach but using parallel conductivity and subsequently modified the Archie equation. He proposed a method for predicting pyrite-free conductivity through establishing relationship between water saturation and saturation exponent (n) derived from core measurement. Although the study proved better in predicting pyrite-free core conductivity, field application is needed to show the method's validity.

By taking different approach an alternative method has been developed and is then applied in this study.

II. THEORY

A concept that is considered important in quantitative log analysis on electric log is the role of formation factor (F). This factor is defined as a ratio between resistivities of water-saturated rock (R_o) and the water itself (R_w). This concept implies that formation factor of a specific rock is constant regardless of R_w values. This is true if the rock matrix that contains water is totally non-conductive. In this situation only the water provides conductivity to the porous rock.

In reality, minerals that form formation rocks are not always non-conductive. Apart from clay minerals normaly found - type and abundance are dependant on various factors - in sandstones, metalic minerals are also found in many reservoir rocks. In such cases, the metallic conductivity provided by minerals such as pyrite and siderite may be responsible, depending on quantity of presence, for low-resistivity hydrocarbon bearing rocks.

Unlike the commonly acknowledged shale's pattern of distribution, i.e. laminated, dispersed, and structural or combination between the three, presence of heavy-conductive minerals often takes the form of ores or replacement (Schon, 1996). These two forms of presence, in effect, are similar to structural shales. In other words, by using an analogy with distribution of structural shales (Figure 1) it can be assumed that distribution of the heavy-conductive minerals is also of structural form. Starting from this assumption, a method for correction is developed (Widarsono, 1999).

A. *Structural Distribution of Metallic Minerals*

In structural shales, clay crystals are distributed in a manner and size similar to the grains of the rock's basic forming minerals (e.g quartz grains in sandstones). Patnode and Wyllie (1950) proposed a 'slurry model' to describe the influence of structural clay presence in clastic rocks:

$$\frac{1}{R_t} = \frac{\phi^m}{a\,R_f} + \frac{V_{cl}}{R_{cl}}\left(1-\frac{\phi^m}{a}\right) \qquad (1)$$

where R_f, R_{cl}, V_{cl}, and a are pore fluid resistivity, clay resistivity, clay volume fraction in rock matrix, and tortuosity, respectively. In cases of either water-bearing sands or hydrocarbon conductivity is negligible, it can be taken that R_f R_w.

In order to accommodate other minerals present in structural form, Equation 1 can be further expanded into:

$$\frac{1}{R_t} = \frac{\phi^m}{a\,R_f} + \frac{V_1}{R_{met1}}\left(1-\frac{\phi^m}{a}\right) + \ldots + \frac{V_n}{R_{metn}}\left(1-\frac{\phi^m}{a}\right) \qquad (2)$$

where V_1 .... V_n and R_{met1} .... R_{metn} are, respectively, volume fraction and resistivity of all conductive minerals that are present in the form of structural grains.

B. *Approach for Correction*

The very basic approach taken in developing the correction method is to neutralize the influence (i.e contribution) of metallic conductivity in true resistivity (R_t). This is initiated by simplifying the Equation 1 to:

$$\frac{1}{R_t}\,(reading) = C_{fm} + \frac{V_{met}}{R_{met}}\,\left(1-\frac{\phi^m}{a}\right) \qquad (3)$$

where $1/R_t$ (reading) and C_{fm} are, respectively, recorded formation conductivity and hypothetical formation conductivity without the influence of the metallic mineral(s). The subscript of *met* marks properties of metallic mineral(s). It is clearly seen in Equation 3 that there are two components contributing to the total conductivity namely conductivities of metallic mineral and formation rock without the presence of the metallic mineral. For correction purpose, Equation 3 is rearranged into:

$$\frac{1}{R_t}\,(corrected) = \frac{1}{R_t}\,(reading) - \frac{V_{met}}{R_{met}}\,\left(1-\frac{\phi^m}{a}\right) \qquad (4)$$

where R_t(corrected) is$1/C_{fm}$, in Ohm-m, is the true formation resistivity after correction. This corrected resistivity is to be used in calculation of water saturation.

To make the use of Equations 2 to 4 practical a set of nomographs have been presented (Widarsono, 1999). Figure 2 presents an example for values of R_{pyrite} = 0.5 Ohm-m and cementation factor (m) = 1.8. It is important to note at this point that uncertainty (i.e wide range of values) in R_{pyrite} is potentially harmful for accurate correction. Dortman dan Olhoeft, as quoted in Schon

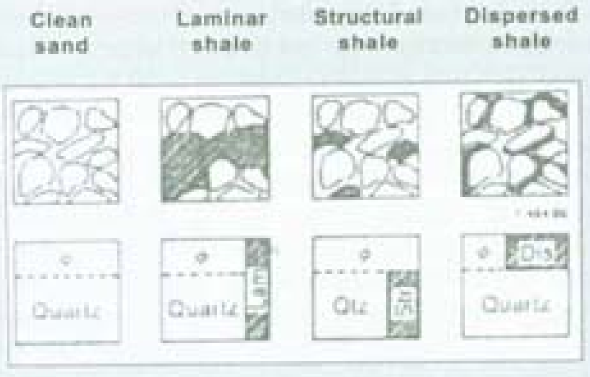

Figure 1
Forms of shale distribution in sedimentary rocks (from Schlumberger, 1989)

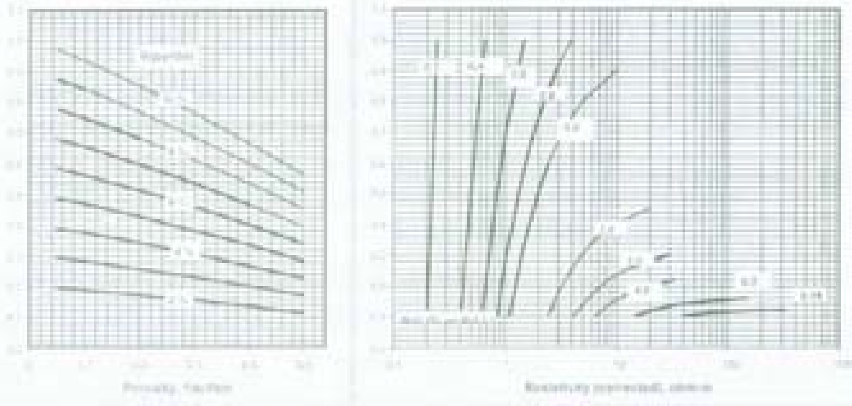

Figure 2
Nomograph for correction (Pyrite = 0.5 Ohm-m,a = 1,m = 1.8).

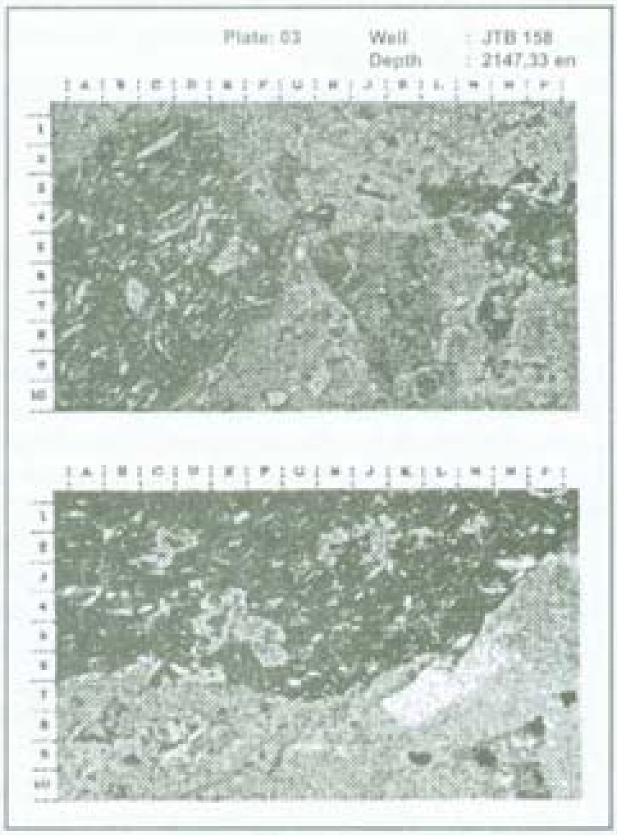

Figure 3
Thin section from well X-2, D=2147

(1996), reported a set of R_{pyrite} values that fall between 0.0001 – 0.1 Ohm-m. Furtherback, Serra (1986) stated that in general R_{pyrite} values are lower than 1 Ohm-m, depending on degree of impurities. However, this study proves that the use of values lower than 0.1 Ohm-m is considered unrealistic since the resulted corrections show too large corrected R_t values. Therefore, values of 0.1 and 0.5 Ohm-m have been used in this study.

Other information that can be drawn from the investigation is that the amount of correction is not very sensitive to variation in cementation factor (m) when compared to the effect of variation in V_{pyrite} and R_{pyrite} values. Cementation factor values of 1.8, 1.5, and 1.2 are considered representative for consolidated, unconsolidated, and fractured clastic rocks, respectively.

III. CASE STUDY

For the purpose of application data taken from two production wells (X-1 and X-2) in West Java has been used. In accordance with the standard approach normally used in log interpretation, log analysis on the two wells has been performed using all data available including geological information, core analysis, and well production tests.

A. *General Information and Indication Upon Presence of Heavy-conductive Minerals*

Several core samples have been taken from oil-productive layers in West Java. Visual descriptions on the samples indicate that the productive rocks are mainly formed by tuff, tuff lapili, aglomerate, vulcanic breccia, with sandstone and clay interlayers. General information concerning rock lithology has indicated presence of quartz (up to 30 %), andesite fragments (up to 50 %), plagioclas (up to 40 %), and some clay minerals (mainly kaolinite, up to 20 %). It has also been indicated that the presence of heavy-conductive minerals (mainly pyrite and iron-related oxides) as a matrix volume fraction, in some samples, reaches as high as 10 %. As has been discussed earlier most of their presence takes the form of replacement. Figure 3 presents a thin section observation on a sample containing iron-oxide (in circled areas), taken from depth of 2120 m. In general, the thin section semi-quantitative analysis has concluded the presence of 2 – 8 % of mainly pyrite and ferro-oxide heavy-conductive minerals.

This presence of heavy-conductive minerals is further strengthened by an evidence shown by matrix density values measured in laboratory. Matrix density data measured on samples taken from the same interval range between 2.8 – 2.85 gr/cc, even higher (Figure 4).

B. *Preliminary Calculation of S_w*

In estimating water saturation (S_w) a standard log analysis has been performed using data from core samples (Archie parameters: a = 1, m = 1.8, n = 1.44 – 1.7), geological analysis, and well tests (RFT, fluid sampling). Estimations of shale fraction (V_{shale}) and porosity were performed using the most appropriate models, supported by comparisons with corresponding values obtained from core analysis.

Considering the role played by formation water resistivity in Archie-style conventional S_w analysis, careful examinations have been spent on choosing the most representative value. Water resistivity used in the calculation is basically based on results of formation water analysis. With average water salinity of 30,000 ppm, confirmed by using standard graphic methods, the most representative value of R_w is taken at 0.19 Ohm-m @ 75 °F.

In S_w calculations, a careful examination has also been performed in choosing the most appropriate water saturation model. Accordingly, factors such as shale type, shale distribution, local experience, degree of conformity with fluid sampling data, and data availability were taken into consideration. The examination led to Waxman and Smits model (Waxman and Smits, 1968) as the most appropriate model for the rocks under investigation.

In order to observe more easily the consistency of an S_w calculation result when compared to production test results a plot between porosity, water volume (S_w * f, in %), and water cut from production test of the interval of interest. Figure 5 presents the plot for the two wells. Diagonal lines represent certain S_w values whereas the two dots represent average calculated S_w at certain water cut values.

Production tests conducted on the wells X-1 and X-2 are 0.1 % and 45 %, respectively. Water saturation estimates for the intervals of interest, represented by the two dots indicate that the S_w values are too high (pessimistic). With irreducible water saturation (S_{wirr}) of approximately 35 % (Figures 6 and 7) it is obvious that an average S_w of 50 % is too high for water cut value of 0.1 %. If the approximate S_{wirr} value of 35 % is considered true for the reservoir rocks, the corresponding S_w values should be 30 – 40 %. Similar to the case of X-1 well, an average S_w of 75 % is indeed too high for water cut value of 45 %. Considering the normal practices that usually takes cut off S_w value of around 70 % for moderately viscous oil.

The fact of too low estimated S_w values has led to a presumption that the true formation resistivity (R_t) is somewhat too low and does not specifically represent the real water saturation. Having performed a careful examination over all data used in the S_w calculation it is concluded that the presence of non-clay conductive minerals is a probable cause for the occurrence.

C. *Application of Correction Method*

For practical purpose, the first step toward application of the correction method is assuming that all non-shale conductive minerals (i.e. metallic minerals) are represented by pyrite. This assumption can be justified by the fact that those minerals have a similar range of resistivity values (see table of mineral electrical properties in Schon, 1996).

The next step is the use of the correct nomograph (similar to the one presented in Figure 2). It is worth

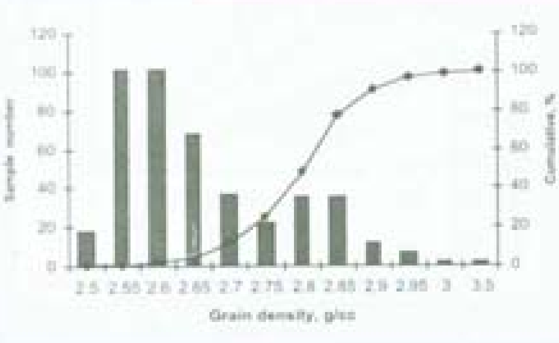

Figure 4
Grain density versus sample number

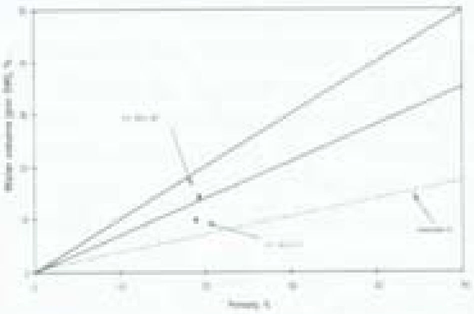

Figure 5
Plot between water volume versus porosity before correction. The point represents average porosity and water saturation of the interval of interest

noting, as previously discussed, the use of R_{pyrite} of 0.5 Ohm-m comes from experience over the use of various values reported in literatures. The trial of various R_{pyrite} values in correction had led to a conclusion that, theoretically, the presence of pyrite with resistivity values of less than 0.1 Ohm-m and with quantity of between 2 – 10 % (the common quantity for trace elements) will result in unrealistically low measured resistivity. Figure 8 presents an example of correction in a productive interval in well X-1. Depth interval of 2110 – 2125 m has seen a significant improvement that is justifiable when compared with swab test result.

The result of correction is presented in the same manner as in the preliminary S_w calculation. The plot presented in Figure 9 has confirmed improvement in the calculated S_w. Using the same set of data, the correction on R_t has improved calculated average S_w from 50 % to 40 % for well X-1 and from 75 % to 55 % for well X-2. This new S_w result is undoubtedly more easily to verify when compared to the corresponding water cut. Therefore, the calculation result has confirmed the most representative values of V_{met} (or V_{pyrite} in this case) of 6 – 8 %. This figure agrees well with the result of the semi-quantitative thin section analysis.

The application of the corrected method has shown that this practice can be integrated into the standard log interpretation whenever required.

IV. FURTHER DISCUSSION

The use of the correct nomograph for practical purposes has left one question: " what if there is no or scarce petrographic data that gives V_{met} estimates ?" Such situation is the rule rather than an exception in Indonesia's petroleum industry, usually due to either financial reasons or lack of technical foresight. In this condition, the V_{met} can be estimated by trial after confirmation upon its presence has been achieved (e.g from Neutron log – Density log crossplot).

In this approach, a kind of iteration is performed until a reasonable V_{met} is obtained by using comparison between calculated S_w and production test data (or comparison with other tested layer or wells in case the interval is untested). The estimated V_{met} can then be used for other wells in the same reservoir whenever confirmation upon the presence of heavy-conductive minerals has been achieved.

V. CONCLUSIONS

From this study a set of conclusions has been drawn:

1. A method for reducing uncertainty and bias in log interpretation as the result of heavy-conductive minerals has been developed and is ready to be used practically.
2. Theoretically, resistivity of heavy-conductive minerals present in reservoir rocks is unlikely to be less than 0.1 Ohm-m without producing unrealistically low measured resistivity. Therefore R_{pyrite} of 0.1 and 0.5 Ohm-m are used in calculation.
3. Difficulty in estimating volume fraction of heavy-conductive minerals can be reduced by a kind of iteration using comparison between S_w and water cut either from the same well or from other well in the same reservoir.
4. Further efforts have to be spent to determining a more refined method for estimating volume fraction of heavy-conductive minerals in wells with no production test data.

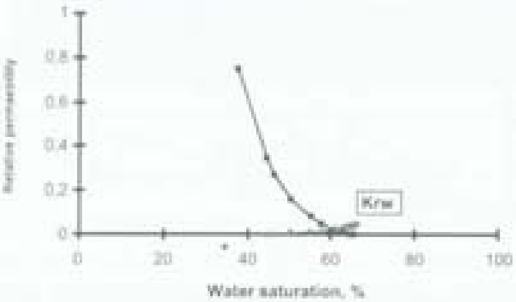

Figure 6
Relative permeability curves, K= 7mD

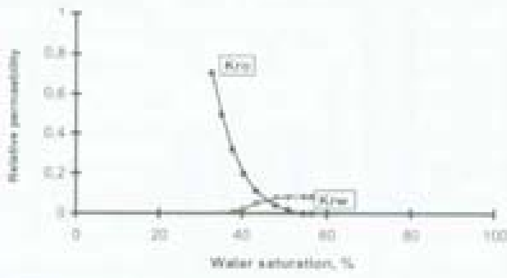

Figure 7
Relative permeability curves, K = 21 mD

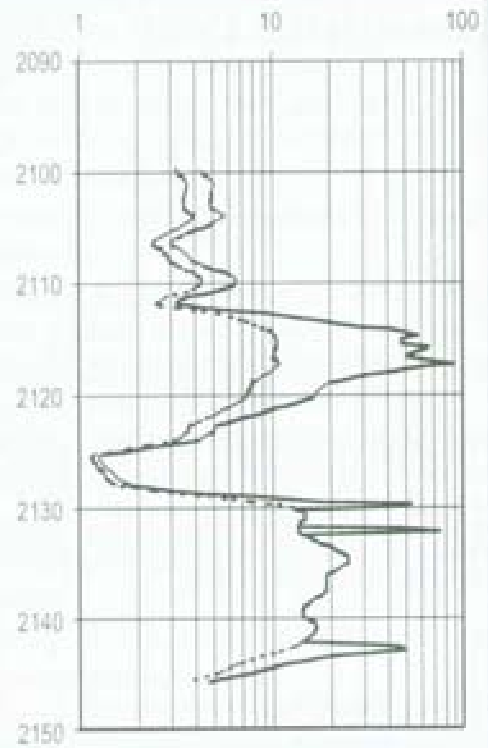

Figure 8
Result of correction on deep resistivity

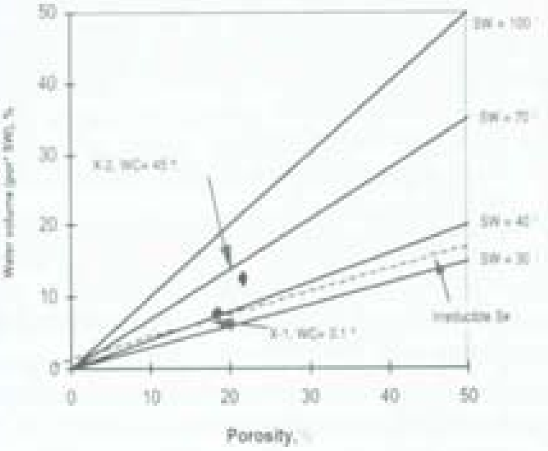

Figure 9
Plot between water versus porosity before correction. The points represent average porosity and water saturation of the interval of interest

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