Reservoirs resistivity correction factor in low resistivity pyritic sandstone reservoirs

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Abstract The presence of pyrite in sandstone reservoirs will cause a problem known as low resistivity reservoirs case. The impact of pyrite volume in sandstone reservoirs is very important to be determined, especially to conduct its resistivity correction factor (Rcf). This research was done in the laboratory used nine sandstone pseudo-cores with various pyrite contents. Some data parameters such as voltage (V) and current (I) are directly measured and others (resistance R and reservoirs resistivity Rt) are calculated. The resistivity of pseudo-core data is calculated using the combined method between Ohm Law and Wenner. The result of this research shows that pyrite will reduce sandstone reservoirs resistivity exponentially. Pyrite will significantly reduce reservoirs resistivity if its presence > 4% and the Rt needs to be corrected. Plotting data between Rt and pyrite volume number for every Sw line can guide us to build a resistivity correction factor (Rcf). This Rcf will drive us to obtain the original resistivity reservoirs (Rto) from apparent well log resistivity reading (Ra) in case of low resistivity caused by pyrite mineral.

1. Introduction
The presence of pyrite in sandstone reservoirs will reduce the value of reservoir resistivity [1]. These reducing resistivity will cause some problems in log interpretation, mainly for water saturation (Sw) calculation. Reservoirs with resistivity below 5 ohm.m, which is well known as low resistivity reservoirs, will be indicated as water-bearing zones [2] & [3] if we analyze using conventional approaches. The relation between pyrite volume presence in reservoirs and its resistivity is very important to be determined. Then this laboratory-based research was conducted, aimed at two useful benefits i.e. (1) could set the threshold value of pyrite volume which significantly influenced the resistivity, and (2) could determine resistivity correction factor (Rcf). Rcf is needed in correcting apparent resistivity (Ra) which reads directly from resistivity log data and this Rcf can be used to obtain the original reservoir resistivity (Rto). Rto is reservoir resistivity in the assumption there is no pyrite presence (the reservoirs just consist of matrix resistive). It can be used to calculate correct Sw. This research has done in a laboratory using some pseudo-cores which have simulated contained various certain pyrite mineral volume.

2. Literature review

2.1. The presence of pyrite in sandstone
Iron sulfide (FeS\textsubscript{2}) as the main component of pyrite will be formed in reductive environments, anaerobic, and rich in sulfur. Some examples of those environments are stagnant sea basins, tidal flat, and organic-
rich lacustrine environments. Iron sulfide also can be found in sulfides hydrothermal veins at mid-oceanic ridges [4]. On other hand, pyrite minerals will widely be deposited in back swamp and bay fill deposits [5]. Pyrite is an opaque heavy mineral that can be found in sandstone as detritus, nodule, authigenic mineral, or replacement mineral. Pyrite is a conductive mineral and has a very low value of resistivity. Its resistivity can be compared to other conductive minerals (Table 1) that compiled from Parasnis [6], Milsom [7] and Telford et al. [8]. Some sandstone reservoirs in Indonesia (Table 2) are indicated contained by conductive minerals as well as pyrite [9].

Table 1. Resistivity value of pyrite compared to other conductive minerals.

| Minerals   | Resistivity (ohm.m) |
|------------|---------------------|
|            | Parasnis [6] | Milsom [7] | Telford et al. [8] |
| Pyrite     | $10^4 - 10$     | $2 \times 10^4 - 9 \times 10^2$ | $3 \times 10^{-7}$ |
| Magnetite  | $10^2 - 10$     | $10^2$      | $5 \times 10^2 - 5.7 \times 10^2$ |
| Hematite   | $10^4 - 10^2$   | $5 \times 10^2$ | $3.5 \times 10^{-3} - 10^{-7}$ |

Table 2. Some sandstone reservoirs in Indonesia with conductive minerals content including pyrite [9].

| Area      | Formations   | Intervals            | Conductive Minerals       | Authors                  |
|-----------|--------------|----------------------|---------------------------|--------------------------|
| Pagerangan| Ngampong Clastics Pre-Ngampong | Lower Sandstone Member | pyrite                    | Ebanks & Cock in Atkinson et al. [9]. |
| Kuran     | Lower Shapas  | Lithofacies-1, Lithofacies-2, Lithofacies-4, Lithofacies-5 | siderite, pyrite siderite, glauconite siderite, pyrite siderite, glauconite glyconite       | Murphy in Atkinson et al. [9]. |
| ONWJ      | Upper Cibulakan  | Facies 3-C, Facies 4-B, Facies 4-C, Facies 5 | siderite siderite siderite | Atkinson et al. [9]. |
| Tuban     | Ngrayong     | Grpis Barat-1 core #1, Grpis Barat-1 core #2, Gondang-1 core #1 & 2, Ngarin-1 core #1 | siderite glauconite, siderite, pyrite glyconite | Ardhana et al. in Atkinson et al. [9]. |
| OSES & NWJ| Talang Akar   | TZ-1 #1, TZ-1 #2         | pyrite siderite | Young & Atkinson in Atkinson et al. [9]. |
| NWJ       | Jatiluhur    | OC-2 #3               | pyrite, ferroan dolomite & ferroan calcite cement | Butterworth & Atkinson in Atkinson et al. [9]. |

2.2. Resistivity of Conductive Reservoirs
The reservoir model proposed by Archie [10] was the non-conductive model. Rock matrix in those models had been assumed resistive and conductivity of reservoirs came from saline formation water. Some authors then have developed different models. They are Patnode and Wyllie [11], Clavier et al. [12], and Givens [13]. They proposed another perspective that some components in the matrix could give a contribution to reservoirs conductivity.
Patnode and Wyllie [11] calculated the impact of the presence of conductive material into total resistivity. They used a slurry of silica and attapulgite (as a conductive fraction) and found some relation below.

\[ \frac{1}{R_t} = V_S x \left( 1 - \frac{1}{F^*} \right) + \frac{1}{F^* R_f} \]  

\( R_t \) = resistivity of slurry, ohm.m
\( R_s \) = resistivity of conductive solid material, ohm.m
\( R_f \) = resistivity of fluids, ohm.m
\( V_S = \) fraction of conductive material, %
\( x = \) heterogeneity factor
\( F^* = \) apparent formation factor

Clavier et al. [12] observed the influence of pyrite on the conductivity of core samples (Figure 1). They found that samples with more abundant pyrite will give higher conductivity than smaller ones. They also illustrated the total conductivity model for saline formation water and conductive matrix or pyrite.

**Figure 1.** Analysis of the influence of pyrite on samples conductivity [12]. The left figure is a conductivity comparison between high content pyritic samples with low content of pyritic samples. The right figure is a combination model of total resistivity from a conductive matrix (pyrite) and saline formation water.

Givens [13] proposed a model called the conductive rock matrix model (CRMM). He found that conductive matrix could contribute to the total conductivity of rock. So total resistivity of saturated rock came from formation water resistivity and resistivity of the matrix. He arranged the relation as follows.
Prayitno et al. [14] measured some pseudo-core that contain pyrite in the range of 0% to 34% (Figure 2). They did not mention the reservoir condition such as salinity, temperature, and porosity in their research. They found that pyrite can reduce the value of $R_t$, but the lowest of their measurement just reached around 10 ohm.m. $S_w$ line of oil-bearing samples ($S_w < 60\%$) still above 20 ohm.m. These results didn’t yet represent low resistivity reservoir cases that usually the resistivity reach below 5 ohm.m. We tried to improve that research in such a way so the result would be meet the actual low resistivity cases.

\[
\frac{1}{R_t} = \frac{1}{R_{pt}} + \frac{1}{R_r} \quad S_w = \left[ \frac{R_w (1/\Omega_e)^m (1/R_t - 1/R_r)}{n} \right]^{1/n}
\]

Figure 2. The relation of $R_t$ and pyrite volume [14].

3. Research methodology
This research used sandstone pseudo-cores with various pyrite contents. Some data parameters are directly measured and others are calculated. The resistivity of pseudo-core data is determined using a combined method between Ohm Law and Wenner [15].

3.1. Data Parameter
The geometry of the pseudo-core has a total length of 0.20 m and its diameter is 0.038 m (left part of Figure 3). Pseudo-cores are made from medium sand size of quartz (around 0.3 mm), various pyrite volumes, and 5% cement. There are nine (9) pseudo-core samples with pyrite content from 0% to 25% and the porosity is set up for 40%. We used 20,000 ppm of formation water and data measured at surface...
temperature (about 25° C). Pseudo-cores are covered with PVC pipe, stainless steel at both of the end, and two electrodes between them (right part of Figure 3).

![Figure 3. Pseudo-core sample geometry and the arrangement of electrodes at the sample. Some outlet and inlet fluid pipes are prepared in the fluids injecting process.](image)

We measured data parameters during this research i.e. voltage (V in mV) and current (I in mA). Samples are saturated first with 100% formation water and injected by oil subsequently every 10% of volume. Then resistance (R) and resistivity (Rt) are calculated. So, we have parameters V, I, R, Rt, Sw, and volume conductive mineral (CM).

### 3.2. Data Measurement

The current was set up from a power supply of around 10 milliamperes and connected at the end of the sample. Then voltage was measured by ohm meter from electrodes set up in the body of the sample (Figure 4). Resistance is calculated from parameters I and V using Ohm Law and resistivity then calculated using a combination method of Ohm Law and Wenner Method [15] as expressed in equation 3.

![Figure 4. Measurement scheme of pseudo-core sample in the laboratory [15.]](image)
\[ \rho = \left( \frac{V}{I} \right) \times \left( \frac{A}{L} \right) \times (0.04/L) \]  

\( \rho \) = resistivity (ohm.m)  
\( V \) = voltage (volt)  
\( I \) = current (amper)  
\( A \) = the acreage of sample section (m²)  
\( L \) = 1/3 total length of sample

4. Results

4.1. Characteristic of a pyritic sandstone sample

A thin section of pyritic sandstone from the pseudo-core sample shows the presence of quartz, pyrite, and some pores (left side of Figure 5). In a polarized microscope (Figure 5.A) pyrite (P) is observed as an angular shape opaque mineral between quartz (Q) and in the reflected microscope (Figure 5.B) it gives a special appearance of metal luster. XRD data analysis from pyrite grains that are used in the mixture of pseudo-core gives strong evidence of the pyrite peak curve (right side of Figure 5).

![Figure 5](image_url)

**Figure 5.** The appearance of pyrite minerals in sandstone. Figure 5.A show of thin section from polarization microscope and figure 5.B is a photograph of the same section using reflection microscope. The right side of figure 5 is XRD analysis from pyrite grains before used in pseudo-core forming grains.

4.2. Relationship Between Pyrite Volume and Rt

Measurement of voltage (in volt) of pyritic pseudo-core sandstone using 10 milliamperes of DC-current (0.01 A) gives range value from 1.6 – 8.3 volts (Table 3), whereas for non-pyritic pseudo-core sandstone gives values 3.25 – 13 volts. The values are controlled by the volume of pyrite (CM) in samples and its water saturation (Sw) value that injecting in samples. Resistance (R in ohm) can be calculated from those measurements (using Ohm Law) and gives values of R from 160 – 830 ohm (Table 4). Resistivity
(Rt) then derived from the value of resistance using the Winardi et al. approach [15] and gives values from 1.64 – 8.51 ohm.m (Table 5).

Plotting of each value of Rt vs CM for every Sw line gives the illustration of the relation between pyrite volume and decreasing value of Rt (figure 6). It is clear evidence that pyrite will reduce Rt value exponentially (Table 6). Compare to Prayitno et al. [14], this research shows the decreasing value of Rt can reach a value below 5 ohm.m and meet the common cases of low resistivity reservoirs. We calculate the percentage of decreasing value of Rt (Table 7) and it is observed when pyrite more than 4% Rt will reduce to around 50%. It means that samples with a pyrite content of more than 4% will give an apparent resistivity value (Rta) less than half of its original resistivity (Rto).

**Table 3.** The result of voltage (V in volt) measurement of pseudo-core.

| Sw    | 1.00 | 0.90 | 0.80 | 0.70 | 0.60 | 0.50 | 0.40 | 0.30 | 0.20 |
|-------|------|------|------|------|------|------|------|------|------|
| 0     | 3.25 | 4.40 | 6.40 | 9.80 | 12.00| 12.40| 12.80| 12.90| 13.00|
| 2     | 2.90 | 3.03 | 4.27 | 6.00 | 7.22 | 7.43 | 7.50 | 7.90 | 8.30 |
| 4     | 2.60 | 2.80 | 3.90 | 5.80 | 7.10 | 7.40 | 7.40 | 7.80 | 7.80 |
| 6     | 2.30 | 2.40 | 3.80 | 5.00 | 6.60 | 6.80 | 7.00 | 7.20 | 7.40 |
| 8     | 1.90 | 2.20 | 3.40 | 5.00 | 5.20 | 5.30 | 5.40 | 6.40 | 6.70 |
| 10    | 1.90 | 2.20 | 3.20 | 4.20 | 4.90 | 5.50 | 5.70 | 6.00 | 6.40 |
| 15    | 1.60 | 2.50 | 2.70 | 3.10 | 4.90 | 5.40 | 5.50 | 5.90 | 6.20 |
| 20    | 1.80 | 2.40 | 2.55 | 3.10 | 3.60 | 3.90 | 4.20 | 4.50 | 5.20 |
| 25    | 1.90 | 2.10 | 2.50 | 2.90 | 3.80 | 4.20 | 4.30 | 4.40 | 4.40 |

**Table 4.** The result of resistance calculation (R in ohm).

| Sw    | 1.00 | 0.90 | 0.80 | 0.70 | 0.60 | 0.50 | 0.40 | 0.30 | 0.20 |
|-------|------|------|------|------|------|------|------|------|------|
| 0     | 325  | 440  | 640  | 980  | 1200 | 1240 | 1280 | 1290 | 1300 |
| 2     | 290  | 303  | 427  | 600  | 722  | 743  | 750  | 790  | 830  |
| 4     | 260  | 280  | 390  | 580  | 710  | 740  | 740  | 780  | 780  |
| 6     | 230  | 240  | 380  | 500  | 660  | 680  | 700  | 720  | 740  |
| 8     | 190  | 220  | 340  | 500  | 520  | 530  | 540  | 640  | 670  |
| 10    | 190  | 220  | 320  | 420  | 490  | 550  | 570  | 600  | 640  |
| 15    | 160  | 250  | 270  | 310  | 490  | 540  | 550  | 590  | 620  |
| 20    | 180  | 240  | 255  | 310  | 360  | 390  | 420  | 450  | 520  |
| 25    | 190  | 210  | 250  | 290  | 360  | 420  | 430  | 430  | 440  |

**Table 5.** The result of resistivity calculation (Rt in ohm.m).

| Sw    | 0.00 | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 | 0.70 | 0.80 |
|-------|------|------|------|------|------|------|------|------|------|
| 0.00  | 3.33 | 5.15 | 5.65 | 10.05| 12.31| 12.72| 13.23| 13.33| 13.33|
| 2.00  | 2.97 | 3.11 | 4.38 | 6.15 | 7.40 | 7.62 | 7.69 | 8.10 | 8.51 |
| 4.00  | 2.67 | 2.87 | 4.00 | 5.95 | 7.28 | 7.59 | 7.59 | 8.00 | 8.00 |
| 6.00  | 2.36 | 2.46 | 3.90 | 5.13 | 6.77 | 6.97 | 7.18 | 7.38 | 7.59 |
| 8.00  | 1.95 | 2.26 | 3.49 | 5.13 | 5.33 | 5.44 | 5.54 | 6.56 | 6.87 |
| 10.00 | 1.95 | 2.26 | 3.28 | 4.31 | 5.03 | 5.64 | 5.85 | 6.15 | 6.56 |
| 15.00 | 1.64 | 2.55 | 2.77 | 3.18 | 5.03 | 5.54 | 5.64 | 6.05 | 6.36 |
| 20.00 | 1.85 | 2.46 | 2.62 | 3.18 | 3.69 | 4.00 | 4.31 | 4.62 | 5.33 |
| 25.00 | 1.95 | 2.15 | 2.56 | 2.97 | 3.69 | 4.31 | 4.41 | 4.41 | 4.51 |
Figure 6. Data plotting between $R_t$, pyrite volume (CM) for every $Sw$ line.

Table 6. The relation patterns of decreasing $R_t$ for every $Sw$ line.

| $Sw$   | Relation $R_t$ vs CM | Regression $R^2$ |
|--------|----------------------|------------------|
| $Sw \ 0.2$ | $y = 10.03e^{-0.03x}$ | $0.83$           |
| $Sw \ 0.3$ | $y = 9.81e^{-0.04x}$ | $0.83$           |
| $Sw \ 0.4$ | $y = 9.24e^{-0.04x}$ | $0.75$           |
| $Sw \ 0.5$ | $y = 9.10e^{-0.04x}$ | $0.77$           |
| $Sw \ 0.6$ | $y = 8.92e^{-0.04x}$ | $0.82$           |
| $Sw \ 0.7$ | $y = 7.38e^{-0.04x}$ | $0.84$           |
| $Sw \ 0.8$ | $y = 4.96e^{-0.03x}$ | $0.80$           |
| $Sw \ 0.9$ | $y = 3.24e^{-0.02x}$ | $0.46$           |
| $Sw \ 1.0$ | $y = 2.83e^{-0.02x}$ | $0.62$           |

Table 7. Percentages of decreasing number of $R_t$ caused by pyrite mineral.

| $Pyrite$ Volume (%) | $Sw \ 0.00$ | $Sw \ 0.00$ | $Sw \ 0.00$ | $Sw \ 0.00$ | $Sw \ 0.40$ | $Sw \ 0.30$ | $Sw \ 0.20$ |
|---------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 0.00                | 0.00        | 0.00        | 0.00        | 0.00        | 0.00        | 0.00        | 0.00        |
| 2.00                | 0.11        | 0.31        | 0.33        | 0.39        | 0.40        | 0.41        | 0.39        | 0.36        |
| 4.00                | 0.20        | 0.36        | 0.39        | 0.41        | 0.41        | 0.40        | 0.42        | 0.40        | 0.40        |
| 6.00                | 0.29        | 0.45        | 0.41        | 0.49        | 0.45        | 0.45        | 0.45        | 0.44        | 0.43        |
| 8.00                | 0.42        | 0.50        | 0.47        | 0.49        | 0.57        | 0.58        | 0.58        | 0.50        | 0.48        |
| 10.00               | 0.42        | 0.50        | 0.50        | 0.57        | 0.59        | 0.55        | 0.55        | 0.53        | 0.51        |
| 15.00               | 0.51        | 0.43        | 0.58        | 0.68        | 0.59        | 0.56        | 0.57        | 0.54        | 0.52        |
| 20.00               | 0.45        | 0.45        | 0.60        | 0.68        | 0.70        | 0.69        | 0.67        | 0.65        | 0.60        |
| 25.00               | 0.42        | 0.52        | 0.61        | 0.70        | 0.70        | 0.66        | 0.65        | 0.67        | 0.66        |
4.3. Threshold number
We obtained the volume of pyrite that will influence Rt significantly. We simulated the relation between Sw and Rt and put the number of Sw 0.55 as the threshold number of Sw cut-off. This number will be reached when Rt is around 6 ohm.m (Figure 7). Based on table 5, for Sw around 0.55 and the value of Rt around 6 ohm.m will be reached if the volume of pyrite more than 4%. It means that in oil zones (Sw<0.55) the presence of pyrite > 4% will give the value of Rt less than 6 ohm.m and cause low resistivity reservoir cases.

![Figure 7. Simulation to obtain threshold number of Sw dan Ra. From the simulation hydrocarbon zone and water are distinguished using Sw 0.55 and Rt 6 ohm.m.](image)

4.4. Resistivity correction factor
The resistivity correction factor will be calculated using this equation;

\[
R_{cf} = \frac{R_{to}}{R_{a}}
\]  

Rcf = resistivity correction factor  
Rto = original resistivity reservoir  
Ra = apparent resistivity reservoir

Therefore, every Sw line will have its Rcf. Table 8 shows the result of the Rcf calculation. This Rcf can be used to obtain corrected Rto.

| Sw   | EQUATION | 0  | 2  | 4  | 5  | 8  | 10 | 12 | 14 | 15 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
|------|----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 0.2  | y = 10.02e^5.03x | 1.00 | 1.07 | 1.14 | 1.22 | 1.30 | 1.39 | 1.49 | 1.59 | 1.70 | 1.81 | 1.93 | 2.07 | 2.21 | 2.36 | 2.52 | 2.69 |
| 0.3  | y = 9.81e^6.04x | 1.00 | 1.07 | 1.15 | 1.24 | 1.33 | 1.43 | 1.54 | 1.66 | 1.78 | 1.91 | 2.05 | 2.21 | 2.37 | 2.55 | 2.74 | 2.94 |
| 0.4  | y = 9.24e^6.04x | 1.00 | 1.07 | 1.15 | 1.24 | 1.33 | 1.43 | 1.54 | 1.66 | 1.78 | 1.91 | 2.05 | 2.21 | 2.37 | 2.55 | 2.74 | 2.94 |
| 0.5  | y = 9.10e^6.04x | 1.00 | 1.07 | 1.15 | 1.24 | 1.33 | 1.43 | 1.54 | 1.66 | 1.78 | 1.91 | 2.05 | 2.21 | 2.37 | 2.55 | 2.74 | 2.94 |
| 0.6  | y = 8.92e^6.04x | 1.00 | 1.05 | 1.15 | 1.24 | 1.33 | 1.43 | 1.54 | 1.66 | 1.78 | 1.91 | 2.05 | 2.21 | 2.37 | 2.55 | 2.74 | 2.94 |
| 0.7  | y = 7.38e^5.04x | 1.00 | 1.05 | 1.15 | 1.24 | 1.33 | 1.43 | 1.54 | 1.66 | 1.78 | 1.91 | 2.05 | 2.21 | 2.37 | 2.55 | 2.74 | 2.94 |
| 0.8  | y = 4.95e^5.04x | 1.00 | 1.05 | 1.15 | 1.24 | 1.33 | 1.43 | 1.54 | 1.66 | 1.78 | 1.91 | 2.05 | 2.21 | 2.37 | 2.55 | 2.74 | 2.94 |
| 0.9  | y = 3.24e^5.03x | 1.00 | 1.04 | 1.10 | 1.16 | 1.23 | 1.31 | 1.39 | 1.48 | 1.57 | 1.66 | 1.75 | 1.84 | 1.93 | 2.02 | 2.12 | 2.23 |
| 1.0  | y = 2.83e^5.03x | 1.00 | 1.04 | 1.06 | 1.14 | 1.21 | 1.28 | 1.36 | 1.44 | 1.53 | 1.62 | 1.71 | 1.80 | 1.89 | 1.98 | 2.07 | 2.16 |

Table 8. The result of calculation of Rcf for every Sw line and volume of pyrite contents.

An example to use Table 8 in calculating Rto:
- From resistivity log data (Ra) we have 4 ohm.m. This interval has a pyrite content of 20% and Sw is predicted around 0.6.
- \( R_{to} = R_{cf} \times R_{a} \)
- From table 8, Rcf for Sw 0.6 and pyrite volume 20% is 2.27.
- So \( R_{to} = 2.27 \times 4 \text{ ohm.m} = 9.08 \text{ ohm.m} \).
5. Conclusions
This research gives strong evidence that pyrite will reduce sandstone reservoirs resistivity exponentially. The presence of pyrite in a sample for > 4% needs to be corrected, because it will reduce Rt > 50% and cause a low resistivity case (Rt < 6 ohm.m). Resistivity correction factor (Rcf) can be calculated from the graphic plot for every Sw line and the number of pyrite volume. This Rcf will drive us to obtain original resistivity reservoirs (Rto) from log resistivity reading when dealing with low resistivity cases caused by pyrite minerals.

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