Scientific Contributions Oil & Gas, Vol. 47. No. 2, August: 89 - 100

SCIENTIFIC CONTRIBUTIONS OIL AND GAS
Testing Center for Oil and Gas
LEMIGAS

Journal Homepage:http://www.journal.lemigas.esdm.go.id
ISSN: 2089-3361, e-ISSN: 2541-0520

Quantifying the Impact of Siderite Composition and Reservoir Resistivity on Water Saturation Estimation in Low-Resistivity Sideritic Sandstone Reservoirs Using the Graphic Plot Method

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Manuscript received: January 12th, 2024; Revised: April 04th, 2024
Approved: June 10th, 2024; Available online: August 08th, 2024

ABSTRACT - The case studies on low-resistivity-low-contrast (LRLC) reservoirs have started using a conductive matrix model approach based on the assumption that the rock matrix is composed of conductive minerals. The previous studies on reservoir resistivity (Rt) against conductive-minerals-rich sandstone were limited to pyritic types without developing the others such as the sideritic which was found in Indonesia. Therefore, there is a need to determine the relationship between siderite volume within the sandstone reservoir and the reduction number of Rt. Relation profiles were applied to accurately estimate the actual water saturation (Sw) while the resistance of the sandstone samples was determined through the voltage (V, volt) and current (I, ampere). The samples were designed as pseudo-core in the laboratory and simulated to have siderite composition in the range of 0-30% followed by the injection of brine at different saturation conditions. The Rt was calculated through the modification of Wenner and Ohm's Law and later compared graphically with siderite volume of each Sw line. It was observed from the results that siderite led to an exponential reduction in Rt value. Moreover, the threshold volume of siderite required to reduce Rt significantly to 50% of the original value was found to be 6%. The actual Sw was later estimated simply through the application of the Graphic Plot Method from the curves.

Keywords: low resistivity, reservoir, LRLC, siderite, sandstone, water saturation.

How to cite this article:

Sarju Winardi, Sugeng Sapto Surjono, Donatus Hendra Amijaya and Wiwit Suryanto, 2024, Quantifying the Impact of Siderite Composition and Reservoir Resistivity (Rt) on Water Saturation Estimation in Low-Resistivity Sideritic Sandstone Reservoirs Using the Graphic Plot Method, Scientific Contributions Oil and Gas, 47 (2) pp. 89-100. DOI.org/10.29017/SCOG.47.2.1619.

INTRODUCTION

The case studies on the reduction of reservoir resistivity (Rt), popularly known as Low-Res-Low Contrast (LRLC), mostly focused on low resistivity caused by the presence of shale (Waxman & Smith 1968; Asquith 1983; Boyd et al. 1995, Zaemi et al. 2022, Pratami et al. 2023). Those conducted in relation to conductive minerals also emphasized the development of pyrite as observed in (Patnode & Wyllie 1950; Clavier et al. 1976; Prayitno et al. 2001; and Winardi et al. (2021) while only a few studied the other types. For example, (Yanto & Winardi

2015) reported that magnetite led to the exponential reduction of the Rt in sandstone. Winardi et al. (2018) also reported a similar trend for hematite-rich sandstone where the content of the hematite higher than 10% suppressed Rt to 50%.

In Indonesia, some sandstone reservoirs are reported to have some conductive minerals, including siderite as presented in Table 1. The sideritic sandstone is often found at Pre-Ngimbang and Ngrayong Formation (North East Java), Upper Cibulakan and Talangakar (North West Java), and Sihapas Equivalent (North & Central Sumatra) as well as the Nanggulan Formation in Kulon Progo, Yogyakarta where it has been effectively outcropped. Siderite ($Fe_2(CO_3)_2$) is an authigenic iron-rich carbonate mineral often formed as a replacement. Moreover, the mineral is in crystal form from direct precipitation and can be a reworking detritus from previous sediments. It can be found in sandstone as a fine matrix, cement as presented in Figure 1, or concretions. Greywacke is another type of sandstone that commonly has a high content of siderite (Selley 1988). It is also important to state that siderite is generally deposited in back swamps, bay fill, and upper delta plains (Coleman & Prior in Scholle 1998). Studies have not been conducted to comprehensively analyze the presence of siderite in sandstone, specifically to determine its impact on Rt measurement and Sw calculation. This is necessary due to the significant reduction of Rt in siderite-rich sandstone which can lead to some difficulties in calculating water saturation (Sw) using a conventional method such as Archie. Therefore, this study aimed to determine a simple and effective method to estimate Sw for low-resistivity sideritic sandstone reservoirs.

Table 1
Some sandstone reservoirs containing conductive minerals in Indonesia (Atkinson et al. 1993)

Area	Formation	Intervals	Conductive Minerals	Authors
Pageru-ngan	Pre-Ngimbang	Pre-Ngimbang	Pyrite, siderite	Ebanks & Cook in Atkinson et. al. (1993)
Kurau	Lower Sihapas	Lithofacies-1 Lithofacies-4	Siderite, pyrite Siderite, glauconite	Murphy in Atkinson et. al. (1993)
ONWJ	Upper Cibulakan	Facies 3C, Facies 4B, 4C Facies 5	Siderie Siderite Siderite	Atkinson et. al. (1993)
Tuban	Ngrayong	Grigis Barat-1 core #1 Grigis Barat-1 core #2	Siderite and ferroan dolomite cement Glauconite, siderite, pyrite,	Ardhana et. al. in Atkinson et. al. (1993)
OSES & NWJ	Talang Akar	TZ-1 #2	Siderite	Young & Atkinson in Atkinson et. al. (1993)

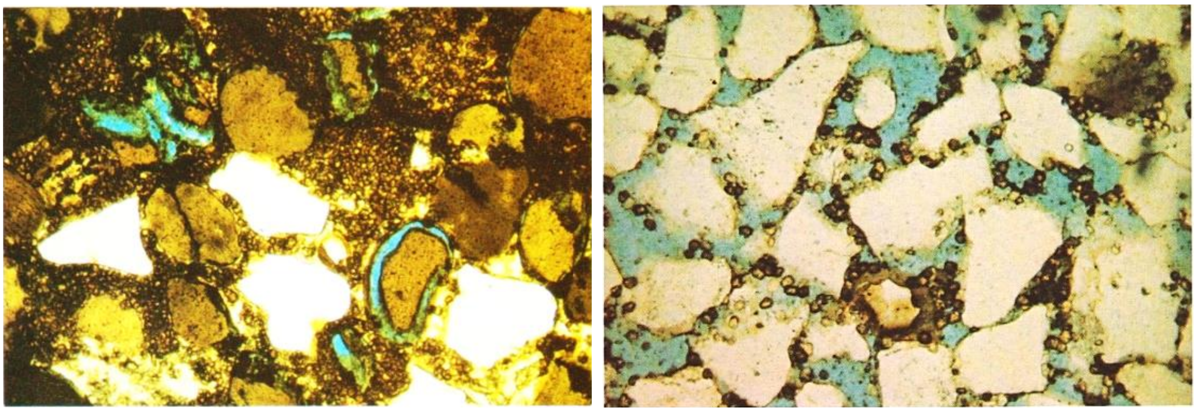

Figure 1
Fine greenish siderite crystals as matrix among colorless quartz grain (left picture) and as cement around white grain quartz (right picture), observed under microscopy view (Scholle, 1979)

METHODOLOGY

This study was conducted in a laboratory to measure the resistivity of sandstone pseudo cores simulated with siderite content varied at 0%-25%, 40% porosity, 20,000 ppm brine salinity, 25-degree Celsius temperature, and oil saturation within 0 to 90%. The resistivity was calculated through the resistance obtained from the measurement of voltage (V) and current (I).

Characteristics of Sideritic Sandstone

The thin section of the pseudo-core sample used for the pyritic sandstone showed the existence of quartz, siderite, and some pores as presented in Figure 2. Moreover, siderite was observed in the polarized microscope to be an angular-shaped opaque mineral between quartz as presented in Figure 2.A. The picture obtained from the microscope in Figure 2.B also showed a special appearance of metal luster using a reflection microscope. XRD analysis applied to the grains from the mixture of pseudo-core samples provided significant evidence of siderite peak curve in Figure 3.

The length of the pseudo-core was recorded to be 0.20 m and the diameter was estimated to be 1.5 inch (0.0381 m) as presented in the left part of Figure 4. The pseudo-cores were produced using 0.3 mm quartz grain, different siderite volumes, and 5% cement. The samples were made by varying siderite content from 0% to 6% while the porosity was set at 40%. Moreover, a total of 20.000 ppm brine was applied at approximately 25^{o}C. All the pseudo-cores were covered with PVC pipe, stainless steel at the mount, and two electrodes placed in-between as presented in the right part of Figure 4. The parameters measured from the analysis conducted were the voltage (V) in volts and current (I) in ampere. It was important to state that the samples were first saturated with 100% brine before oil was subsequently injected at every 10% volume. The process was followed by the calculation of the resistance (r) and resistivity (Rt).

The Calculation of Resistivity

The electric current approximated at 0.01 ampere was set up from the power supply and connected to the electrode metal at the end mount of the sample. The voltage was later measured using a voltmeter at the middle electrodes as presented in Figure 5 The resistance was calculated from I and V using Ohm Law followed by the determination of the resistivity using a combination of Ohm Law and Wenner Method (Winardi et al. 2019) re-arranged as follows:

$$\rho = (V/I) * (A/L) * (G) \qquad (1)$$

ρ: resistivity (ohm.m)
V: voltage (volt)
I: current (ampere)
A: area of sample (m)
L: distance of metal probes (m, 1/3 total length of sample)
G: geometry constant (0.6)

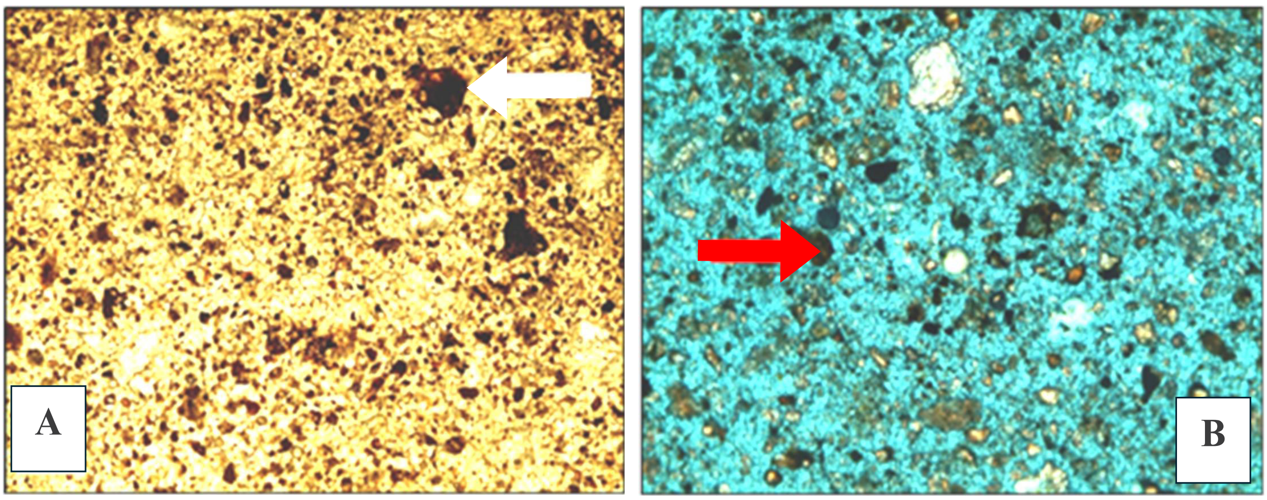

Figure 2
The appearance of siderite minerals (white and red arrows) in sandstone (A) thin section from polarization microscope and (B) photograph using reflection microscope

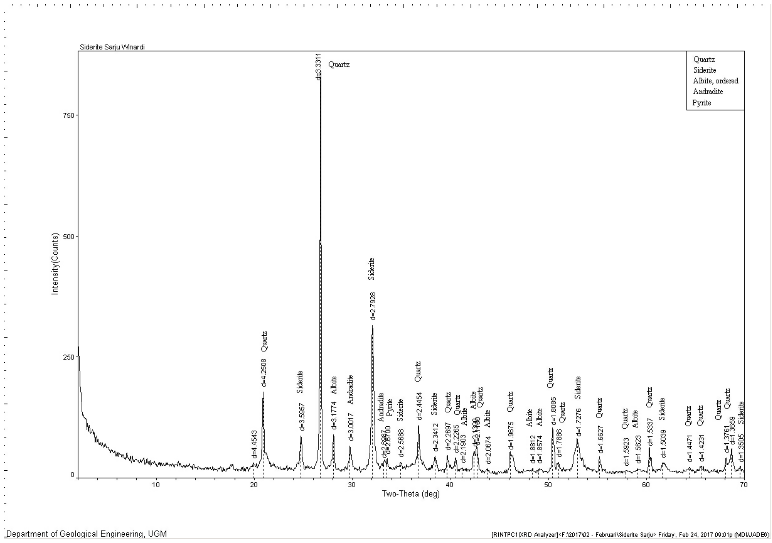

Figure 3
XRD analysis of the pseudo-core showing high content of quarts and siderite

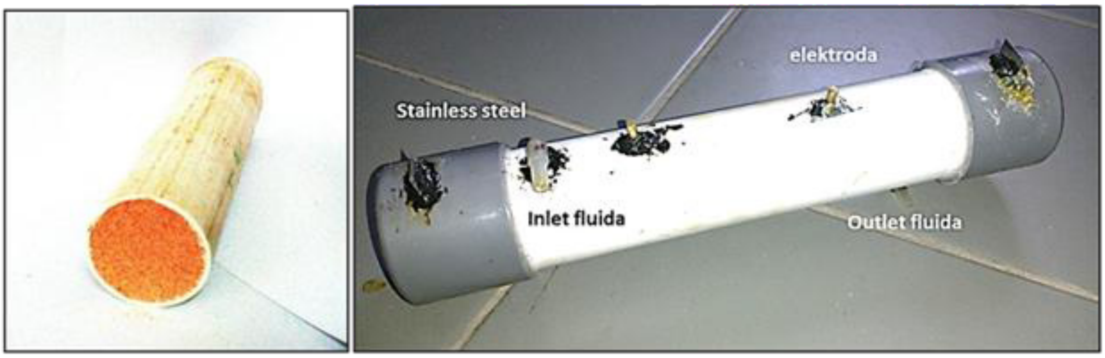

Figure 4
The geometry of the pseudo-core sample and the arrangement of the electrodes with some outlet and inlet fluid used in the brine injection process (Winardi et al. 2021)

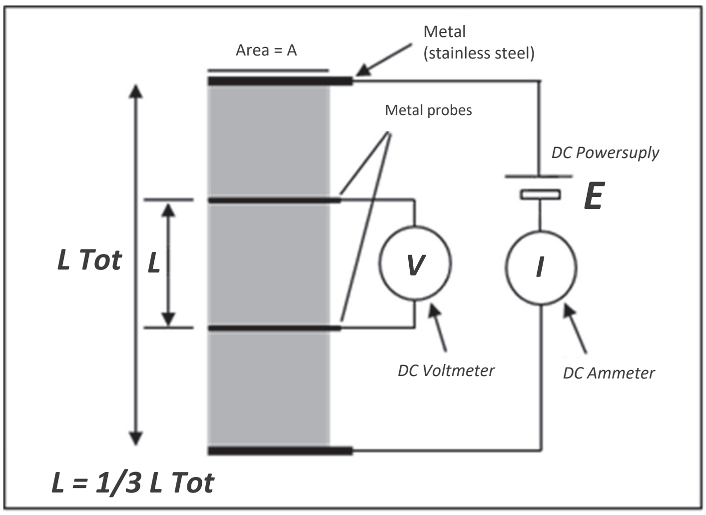

Figure 5
The scheme to measure the voltage (V) of pseudo-core samples in millivolts and current (I) in milliamperes in the laboratory (Winardi et al. 2019)

RESULT AND DISCUSSION

The Relation of Sideritic Volume and Rt Value

The voltage measured in Table 2 as well as the current and resistance in Table 3 were used as the input in Equation (1) to determine the resistivity (Rt) of each pseudo-core sample in Table 4. The results further showed that Rt seemed to be exponentially controlled by water saturation (Sw) and the volume of siderite as presented in Figure 6 and Table 5.

A higher value of Sw and siderite volume led to the reduction of the Rt as shown in Table 6. Moreover, the Rt was extrapolated using the trendline in Table 5 and the results were used to develop the Sw graphic plot in Figure 7, The Rt values showed the same decreasing trend as previously observed in Figure 6. The Rt value on each Sw and siderite volume were compared to determine the percentage of reduction as observed in Table 7 where the grey area represented a reduction of more than 50%. For example, when Sw was 60% and siderite volume was 0%, the Rt was 14.19 ohm.m. An increase in siderite volume by 8% at the same Sw also led to a decrease of 5.84 ohm.m which was a 59% reduction. It was observed from the table that the Rt decreased up to 50% when siderite volume was higher than 6% for all Sw conditions.

Table 2
Voltage (volt) measured at 0.01 ampere

Siderite Volume (%)	Sw								
	1,00	0,90	0,80	0,70	0,60	0,50	0,40	0,30	0,20
0,00	10,60	19,30	25,10	27,00	27,90	28,80	29,60	30,00	30,40
0,45	8,50	13,50	15,50	16,40	17,10	17,40	17,80	18,10	18,40
0,90	9,20	9,30	14,00	14,90	14,40	14,40	15,00	15,30	15,90
1,34	10,00	10,20	13,80	14,40	14,70	14,90	15,10	15,20	15,30
1,79	5,50	5,90	8,40	8,90	9,30	13,60	13,90	13,90	13,90
2,24	3,28	3,44	4,40	6,20	7,10	9,50	9,80	10,10	10,50
3,36	3,70	4,20	5,90	6,10	6,30	6,40	6,60	6,70	6,80
4,48	2,54	2,90	6,00	7,40	7,52	7,70	8,50	8,70	9,30
5,60	4,40	4,50	7,50	8,30	8,50	8,60	8,70	8,80	8,90

Table 3
Resistance (ohm) calculated using V and I

Siderite Volume (%)	Sw								
	1,00	**0,90**	**0,80**	**0,70**	**0,60**	**0,50**	**0,40**	**0,30**	**0,20**
0,00	1.060	1.930	2.510	2.700	2.790	2.880	2.960	3.000	3.040
0,45	850	1.350	1.550	1.640	1.710	1.740	1.780	1.810	1.840
0,90	920	930	1.400	1.490	1.440	1.440	1.500	1.530	1.590
1,34	1.000	1.020	1.380	1.440	1.470	1.490	1.510	1.520	1.530
1,79	550	590	840	890	930	1.360	1.390	1.390	1.390
2,24	328	344	440	620	710	950	980	1.010	1.050
3,36	370	420	590	610	630	640	660	670	680
4,48	254	290	600	740	752	770	850	870	930
5,60	440	450	750	830	850	860	870	880	890

Table 4
Resistivity (ohm.m) calculated using equation 1

Siderite Volume (%)	Sw								
	1,00	0,90	0,80	0,70	0,60	0,50	0,40	0,30	0,20
0,00	10,87	19,79	25,74	27,69	28,61	29,54	30,36	30,77	31,18
0,45	8,72	13,85	15,90	16,82	17,54	17,84	18,26	18,56	18,87
0,90	9,44	9,54	14,36	15,28	14,77	14,77	15,38	15,69	16,31
1,34	10,26	10,46	14,15	14,77	15,08	15,28	15,49	15,59	15,69
1,79	5,64	6,05	8,61	9,13	9,54	13,95	14,26	14,26	14,26
2,24	3,36	3,53	4,51	6,36	7,28	9,74	10,05	10,36	10,77
3,36	3,79	4,31	6,05	6,26	6,46	6,56	6,77	6,87	6,97
4,48	2,60	2,97	6,15	7,59	7,71	7,90	8,72	8,92	9,54
5,60	4,51	4,62	7,69	8,51	8,72	8,82	8,92	9,02	9,13

Table 5
Trendlines for each Sw

Sw	Trendline	Regression
Sw 0,2	y = 16,69e-0,12x	R^2 = 0,74
Sw 0,3	y = 15,54e-0,11x	R^2 = 0,72
Sw 0,4	y = 15,37e-0,11x	R^2 = 0,71
Sw 0,5	y = 14,96e-0,11x	R^2 = 0,68
Sw 0,6	y = 14,19e-0,11x	R^2 = 0,40
Sw 0,7	y = 13,15e-0,11x	R^2 = 0,36
Sw 0,8	y = 10,93e-0,11x	R^2 = 0,22
Sw 0,9	y = 8,85e-0,13x	R^2 = 0,28
Sw 1,0	y = 6,86e-0,15x	R^2 = 0,43

Table 6
Extrapolation result for Rt using the trendlines in Table 5.

Siderite Volume (%)	Sw								
	1,00	0,90	0,80	0,70	0,60	0,50	0,40	0,30	0,20
0,00	6,86	8,85	10,93	13,15	14,19	14,96	15,37	15,54	16,69
2,00	5,10	6,84	8,76	10,58	11,37	11,98	12,40	12,57	13,26
4,00	3,79	5,29	7,01	8,50	9,10	9,59	10,02	10,17	10,54
6,00	2,82	4,08	5,62	6,84	7,29	7,68	8,09	8,23	8,37
8,00	2,10	3,15	4,50	5,50	5,84	6,15	6,53	6,65	6,65
10,00	1,56	2,44	3,60	4,42	4,68	4,93	5,27	5,38	5,29
12,00	1,16	1,88	2,89	3,56	3,75	3,95	4,25	4,35	4,20

Table 6 (continued)
Extrapolation result for Rt using the trendlines in Table 5.

Siderite Volume (%)	Sw								
	1,00	**0,90**	**0,80**	**0,70**	**0,60**	**0,50**	**0,40**	**0,30**	**0,20**
14,00	0,86	1,45	2,31	2,86	3,00	3,16	3,44	3,52	3,34
16,00	0,64	1,12	1,85	2,30	2,40	2,53	2,77	2,85	2,65
18,00	0,48	0,87	1,48	1,85	1,92	2,03	2,24	2,31	2,11
20,00	0,36	0,67	1,19	1,49	1,54	1,62	1,81	1,86	1,67
22,00	0,26	0,52	0,95	1,20	1,23	1,30	1,46	1,51	1,33
24,00	0,20	0,40	0,76	0,96	0,99	1,04	1,18	1,22	1,06
26,00	0,15	0,31	0,61	0,77	0,79	0,83	0,95	0,99	0,84
28,00	0,11	0,24	0,49	0,62	0,63	0,67	0,77	0,80	0,67
30,00	0,08	0,18	0,39	0,50	0,51	0,54	0,62	0,65	0,53

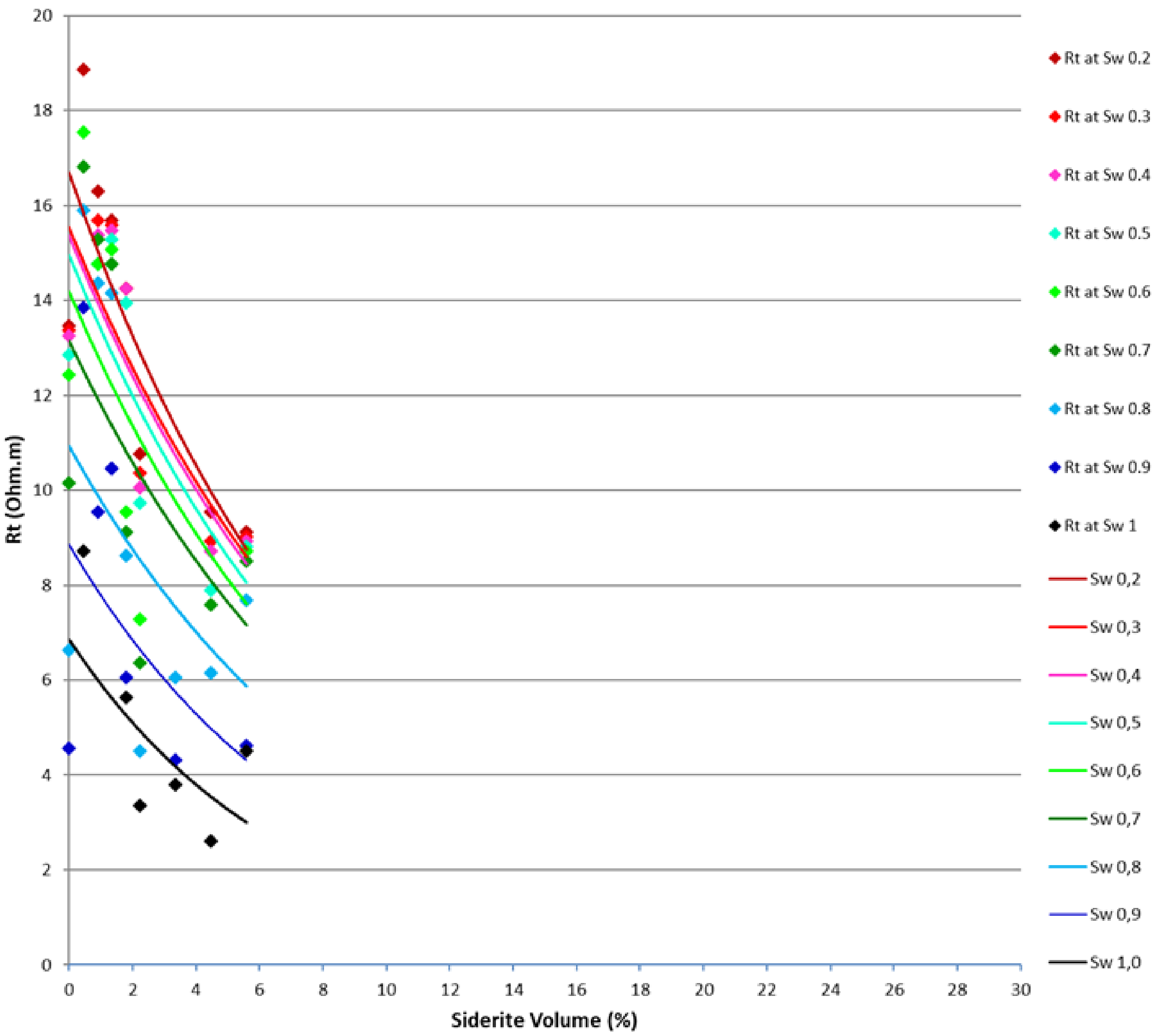

Figure 6
Plotting of Rt vs siderite volume showed an exponential trend

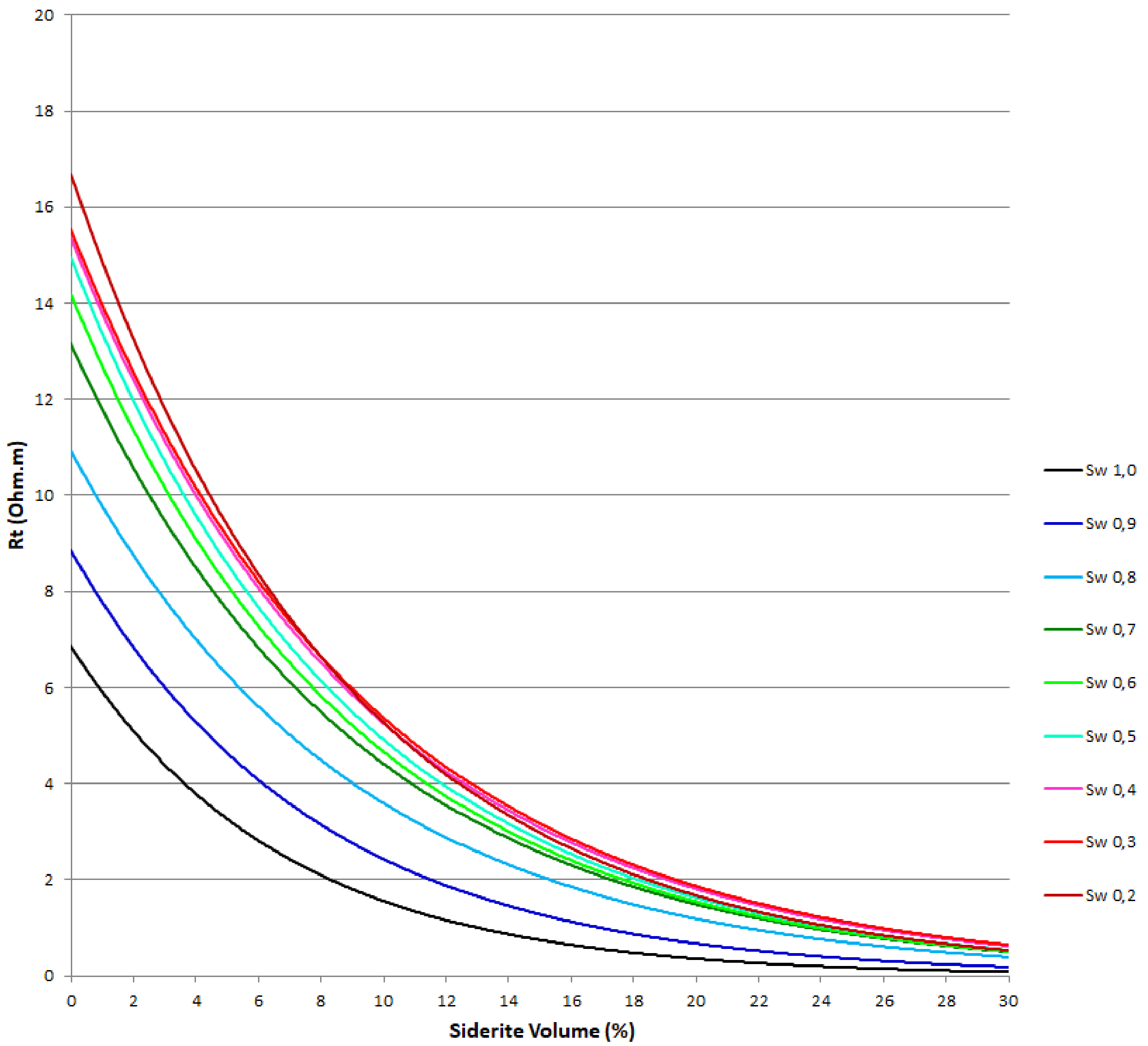

Figure 7
Extrapolation curve for Rt vs siderite volume from Tables 5 and 6 showed that Rt decreased in exponential trendline for each Sw lines

Table 7
Rt percentage reduction due to the presence of siderite

Siderite Volume (%)	Sw								
	1,00	0,90	0,80	0,70	0,60	0,50	0,40	0,30	0,20
0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,00	0,26	0,23	0,20	0,20	0,20	0,20	0,19	0,19	0,21
4,00	0,45	0,40	0,36	0,36	0,35	0,36	0,35	0,35	0,37
6,00	0,59	0,54	0,49	0,49	0,48	0,49	0,47	0,47	0,50
8,00	0,69	0,64	0,59	0,59	0,58	0,59	0,58	0,57	0,60
10,00	0,77	0,72	0,67	0,67	0,66	0,67	0,66	0,65	0,68
12,00	0,83	0,79	0,74	0,74	0,73	0,74	0,72	0,72	0,75

DOI.org/10.29017/SCOG.47.2.1619

Table 7 (continued)
Rt percentage reduction due to the presence of siderite

Siderite Volume (%)	Sw								
	1,00	0,90	0,80	0,70	0,60	0,50	0,40	0,30	0,20
14,00	0,87	0,84	0,79	0,79	0,78	0,79	0,78	0,77	0,80
16,00	0,91	0,87	0,83	0,83	0,83	0,83	0,82	0,82	0,84
18,00	0,93	0,90	0,86	0,86	0,86	0,86	0,85	0,85	0,87
20,00	0,95	0,92	0,89	0,89	0,89	0,89	0,88	0,88	0,90
22,00	0,96	0,94	0,91	0,91	0,91	0,91	0,91	0,90	0,92
24,00	0,97	0,95	0,93	0,93	0,93	0,93	0,92	0,92	0,94
26,00	0,98	0,97	0,94	0,94	0,94	0,94	0,94	0,94	0,95
28,00	0,98	0,97	0,96	0,96	0,95	0,96	0,95	0,95	0,96
30,00	0,99	0,98	0,96	0,96	0,96	0,96	0,96	0,96	0,97

Threshold Number for The Significant Reduction in The Rt

According to (Winardi et al. 2021), the threshold number of conductive minerals to ensure a significant reduction of the Rt by >50% or less than 6 ohm.m was at Sw of 0.55. The results presented in Table 7 showed that the Rt value was less than 6 ohm.m at Sw 0.55 when the volume of siderite was more than 6%. This is slightly higher than pyrite which requires only 4% to achieve the same condition (Winardi etal. 2021). The trend showed the need to correct the Rt in the sideritic sandstone reservoir when the volume of siderite was more than 6%.

The Estimation of Actual Water Saturation (Sw)

In an ideal condition, Sw can best be estimated when the corrected Rt has been obtained. Therefore, (Winardi et al. 2021) proposed a method to determine the resistivity correction factor (Rcf) needed to calculate the original resistivity or corrected Rt (Rto). The purpose was to subsequently use the Rto in estimating the Sw using existing methods. The application of the calculation process has been observed to be limited by an obstacle. The Rcf can only be obtained when the Sw lines already have been predicted. Meanwhile, the Sw is the final result of the calculation and cannot be predicted from the start. The obstacle led to the suggestion of the graphic model to simply estimate the Sw and also Rto. The idea was to use the data from deep resistivity logs (induction or laterolog) as apparent resistivity input (Rta in the Y-axis) and the volume of siderite mineral from XRD data (as SV or siderite volume in the X-axis). The next step was to apply across perpendicular to both variables in order to estimate the Sw from the point on the line or between two lines. For example, at the Rta of 5 ohm.m and the volume of siderite of 10%, the graph in Figure 8 showed that the Sw was approximately 50%. Therefore, the Rto was subsequently estimated at 15 ohm.m along the Sw line of 50%. The Rcf was later calculated by dividing Rto by Rta and found to be 3 in this case.

The advantage of the graphic plot method is that only the Rta from resistivity logs and the volume of siderite are needed as input without the need to know the Rto and Rcf at the initial stage. This method can be used when the condition of environments such as temperature, water salinity, and porosity is suitable with the laboratory condition of 25^{o}C, 20,000 ppm, and using 0.40 for porosity. Meanwhile, the graphic conversion can be redrawn when the method is applied to other conditions.

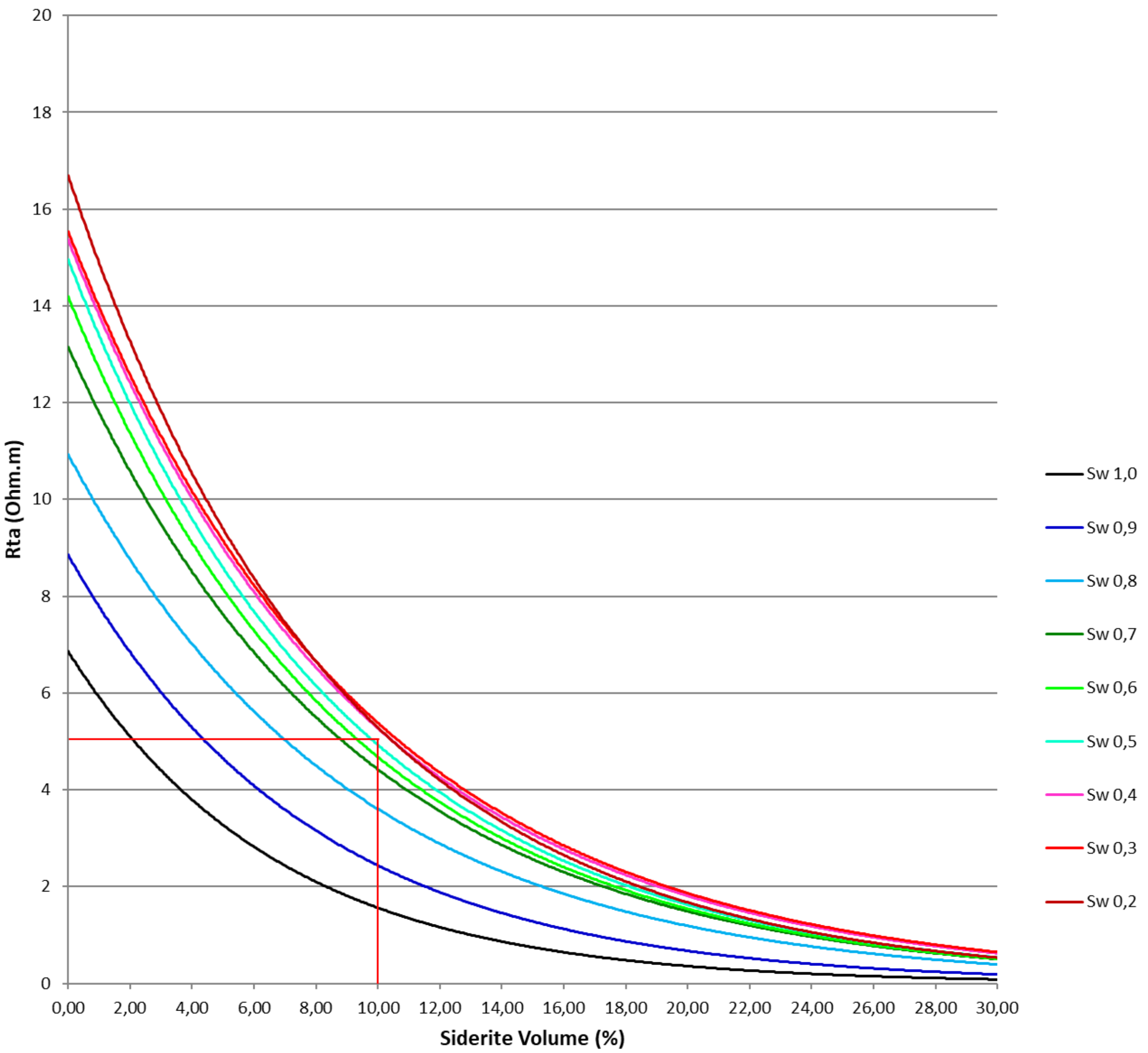

Figure 8
Estimating Sw using the Graphic Plot Method using the volume of siderite from XRD analysis and the Rta from deep induction or laterolog data as the input. For example, the cross perpendicular of 10% siderite volume with 5 ohm.m Rta produced approximately 50% Sw.

CONCLUSION

In conclusion, the presence of siderite content in sandstone reservoirs generally reduced the Rt value exponentially. The threshold value of siderite volume to achieve exponential reduction was found to be 6%. Moreover, the actual Sw in low-resistivity sideritic sandstone was estimated effectively using the Graphic Plot Method without calculating the resistivity correction factor first.

ACKNOWLEDGMENT

This study was fully supported by the Sedimentology Laboratory of the Geological Engineering Department and the Geophysics Laboratory of the Physic Department, Universitas Gadjah Mada.

GLOSSARY OF TERMS

Symbol	Definition	Unit
LRLC	Low res low contrast	
V	Voltage	Volt
I	Current	Ampere
Fe2(CO3)2	Siderite	
PPM	Part per million	
XRD	X-ray diffraction	
ρ	Resistivity	Ohm-m
A	Area of sample	m
L	Distance of metal probes	m
G	Geometry constant	
r	Resistance	Ohm
Rw	Resistivity water	Ohm-m
Rt	Reservoir resistivity	Ohm-m
Rta	Apparent rt	Ohm-m
Sw	Water saturation	% v/v

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