

EFFECT OF THE CEMENTATION EXPONENT
ON DETERMINATION OF HYDROCARBON SATURATION
IN LOW RESISTIVITY CARBONATE ROCKS

BY

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ABSTRACT

At the well log interpretation, the most important parameter used to determine hydrocarbon saturation is the formation resistivity factor which was introduced by Archie (1942). The formation resistivity factor (F) is a function of the porosity (ϕ) and is expressed under the form $F = \phi^{-m}$ in carbonate rocks. The parameter m is called cementation exponent or factor which depends on the degree of rock cementation. In fact, m is regulated by the tortuosity of the pore network but this the complement of the matrix geometry, which in turn controlled by the rock texture.

Usually the value of m is assumed to be 2.0 in carbonate rocks, but in reality, this rock type has a wide variety of texture, hence a significant error will be obtained on calculation of hydrocarbon saturation, having to assume a certain value for this parameter.

In the present work, some graphs were established to show the effect of the cementation exponent on water saturation determination

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in three different cases, in which one parameter of true resistivity, formation water resistivity or porosity is variable while the others remain constant. This effect is bigger when the rocks have lower resistivity, lower porosity or its pores filled with higher resistivity water. Also, practical applications have been done to determine hydrocarbon saturation after determining m graphically for some porous zones selected from Rudies Formation in two wells drilled in the Gulf of Suez region.

INTRODUCTION

The determination of hydrocarbon saturation (S_h) is the ultimate aim in formation evaluation. The electrical resistivity and porosity methods measure the water saturation (S_w) and the difference $1 - S_w$ is hydrocarbon saturation.

In clean formations, the empirical formula established by Archie (1942) is still a wide applicable method for water saturation determination. This method gives good results when the different parameters in the formula are taken correctly. Some of these parameters are measured directly by logging tools such as the true electrical resistivity of the undisturbed bulk rock (R_t) using laterolog or induction devices and the radionuclear and acoustic properties of the bulk rock using neutron, density and sonic devices, which from their measurements porosity can be determined. The other parameters such as formation water resistivity (R_w) and cementation

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factor (m) may be measured in laboratory using water and rock samples obtained from the well, but these samples are not always routinely available. Therefore, it is better to determine them graphically from logging data using some resistivity-porosity crossplots (Pickett, 1966). The graphical method gives accurate values of these parameters under formation conditions and in the same time save time and expenses needed for sample analyses.

However, cementation factors measured from carbonate rock samples show generalized associations with textural character. Chombart (1960). reported that cementation factors are generally between 1.8 and 2.0 for crystalline and granular carbonates, 1.7-1.9 for chalky limestones and 2.1-2.6 in carbonate rock with vugs. The presence of fractures causes a reduction in the cementation factor to values in the neighborhood of 1.4 (Suau and Gartner, 1980).

Also Rasums (1983). mentioned that if one uses the conventional $m = 2.0$ in Archie's saturation equation, intervals of the Bluebell Formation that are producing hydrocarbons will be calculated wet and added that in fractured carbonate rocks the value of m is less than 2.0.

SOME PETROPHYSICAL RELATIONS IN WELL LOGGING

hydrocarbon Saturation Determination

Archie (1942) determined experimentally that the resistivity of a clean formation (R_w) is proportional to the resistivity of the brine (R_o), with which it is fully saturated such as:

$$R_o = F R_w \quad (1)$$

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In a formation containing oil or gas, both of which are electrical insulators, the resistivity is a function not only of F and R_w , but also of S_w . Then the true resistivity (R_t) is expressed as:

$$R_t = F R_w / S_w^n \quad (2)$$

Where n is the saturation exponent with a value of order 2.0. if F is replaced by its equivalent ($F = a / \phi^m$), eq. (2) can be rewritten in the following form:

$$R_t = a R_w / \phi^m S_w^n \quad (3)$$

In carbonate rocks, the value of a is considered as unity. Then eq. (3) can be simplified into:

$$R_t = R_w / \phi^m S_w^n \quad (4)$$

Very close to the hole all the formation water and some of the hydrocarbons, if present, are flushed away by the mud filtrate. The resistivity (R_{xo}) of this flushed zone is expressed as:

$$R_{xo} = R_{mf} / \phi^m S_{xo}^2 \quad (5)$$

where R_{mf} is the resistivity of the mud filtrate and S_{xo} is the mud filtrate saturation. S_{xo} is equal to $(1 - S_{hr})$. S_{hr} is the residual hydrocarbons in the flushed zone. The difference $S_{xo} - S_w$ is the movable hydrocarbons (S_{hm}).

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Graphical Determination of R_w and m

There are two graphical methods available for determining R_w and in the same time give a quick idea about hydrocarbon saturation in the zone of interest. The basic necessary measurements are R_t from deep resistivity devices (induction, laterolog, etc.) and ϕ_n , P_b , t or their derived porosity from neutron, density and sonic devices. A further requirement is the presence of a few water-bearing zones of different porosity in the logging interval.

The first crossplot technique to be considered is the Hingle plot (1950). The method is based on a rearranged form of Archie's saturation equation (eq.3) plotted on a special grid-type paper. The rearranged Archie's equation is

$$(R_t)^{-1/m} = (S_w / a R_w)^{1/m} \cdot \phi \quad (6)$$

Eq- (6) describes a set of straight lines fanning out from a common point of origin when plotting porosity (ϕ) versus $(R_t)^{1/m}$. The origin point is at the matrix point where $\phi = 0$ and $R_t = R_{tm}$ keeping in mind, formation water salinity stays constant over the interval of study. Of course, the data points of constant water saturation will lie on a straight line, its maximum slope identify the line corresponding to $S_w = 100\%$. Knowing this line, its slope defines R_w using eq. (1) any where along the water line.

The disadvantage of Hingle crossplots is the cementation factor is assumed in carbonate rocks as 2.0, but in reality this value is variable according to rock texture and the

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geometry of its pore spaces. Also, any error in the matrix point determination causes error in R_w and S_w values.

The second useful graphical technique is pickett crossplot (1966). In this method a knowledge of ϕ is required, but the values of R_w , m and S_w can be obtained. In this technique, the power law expression for saturation is exploited by using log-log graph paper starting with the general equation of Archie (eq.3) and taking the log of both sides of this equation result in:

$$\log R_t = \log R_w - m \log (\phi / a) - n \log S_w \quad (7)$$

In carbonate rocks, eq. (7) can be rewritten as:

$$\log R_t = \log R_w - m \log \phi - 2 \log S_w \quad (8)$$

For a zone with $S_w = 100\%$, eq. (8) is simplified to:

$$\log R_t = - m \log \phi + \log R_w \quad (9)$$

Which is the equation of a straight line on log-log paper in the form:

$$Y = m X + b \quad (10)$$

This means that if we have porosity and resistivity logs in water zone, the data taken from them will plot as a straight line on log-log paper as long as m is constant. The negative slope of this line gives m . The intersection of this line and 100% porosity will be R_w .

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Sensistivity of S_w to the Cementation Exponent

Water saturation (S_w) calculated from Archie formula (eq.4) depends on four parameters; ϕ , R_w , R_t .

To show the effect of determination of m on water saturation estimation in situ, three graphs were constructed of S_w versus m for different values of one parameter of R_t , R_w or ϕ while the other two parameters remain constant.

Fig.1 shows Archie relationship between S_w and m of a rock having 10 % porosity and its R_w is 0.03 ohm.m for different values of R_t (3, 5, 10, 50, 100 ohm.m) It is clear that a small error in determining m value in lower resistivity carbonate rocks cause observal errors in S_w determination. For example, in the present case (Fig.1), if the actual value of m is 1.8 and this value is assumed or wrongly determined to be 2.0 in zone having $R_t = 3.0$ ohm.m, the calculated S_w will be 79 % in the first case and 100 % in the second case. This small difference in m makes a difference in S_w determination (about 21 %). This difference is small (about 3 %) if the same zone having $R_t = 100$ ohm.m.

Fig.2 shows S_w and m relationship for different values of R_w (0.05, 0.03, 0.02, 0.01 ohm.m), while the other two parameters R_t and ϕ remain constant at 5 ohm.m and 10 % respectively. It is evident from fig.2 that a small error in m determination from 1.8 to 2.0 causes an error in S_w estimation. The difference of S_w between two cases is about 21 % when $R_w = 0.05$ ohm.m and 9 % when $R_w = 0.01$ ohm.m This means the error becomes bigger when R_w increases.

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Fig.3 is S_w versus m relationship for different porosity values (5 % , 10 % , 20 %) at constant values of R_t and R_w which are 5 ohm.m and 0.03 ohm.m respectively. A small change of m from 1.8 to 2.0 causes a difference in S_w determination equal to 15 % when the porosity is 10 % and 6 % when ϕ is 20 %.

The previous discussion showed the important effect of cementation exponent on water saturation determination. This effect is bigger when the true resistivity or porosity is lower or the resistivity of water filling the pores is higher.

PRACTICAL APPLICATIONS

The logs of two wells named C3A-1 and C4CB-1 from the middle portion of the Gulf of Suez region (Fig.4) were evaluated to determine hydrocarbon saturation in Rudies Formation.

The basic measurements used in the log interpretation are R_t and R_{xo} from dual induction-laterolog logs , GR from gamma ray logs and ϕ_N , P_b and t from neutron , density and sonic logs respectively. The different logs were examined to identify some porous zones in Rudies Formation of the studied wells, then the different physical logging measurements were taken in front of each zone . Also, the physical parameters of shale were obtained by visual examination of logging responses in each well as listed in Table (1).

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Fig.1 Effect of m on S_w for different values of R_t when R_w and ϕ are constant.

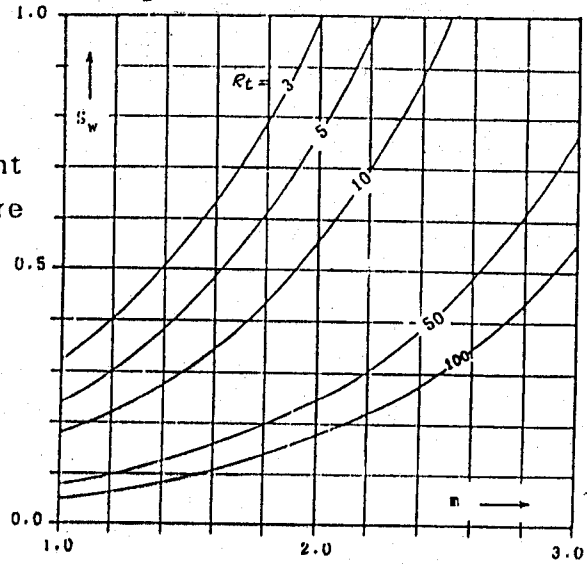


Fig.2 Effect of m on S_w for different values of R_w when R_t and ϕ are constant.

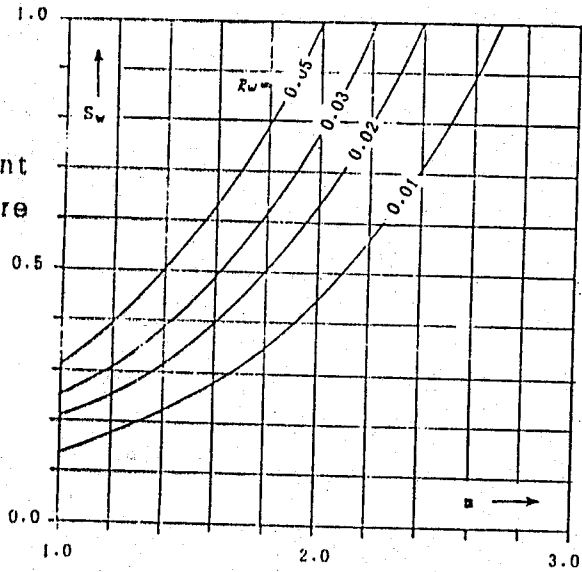
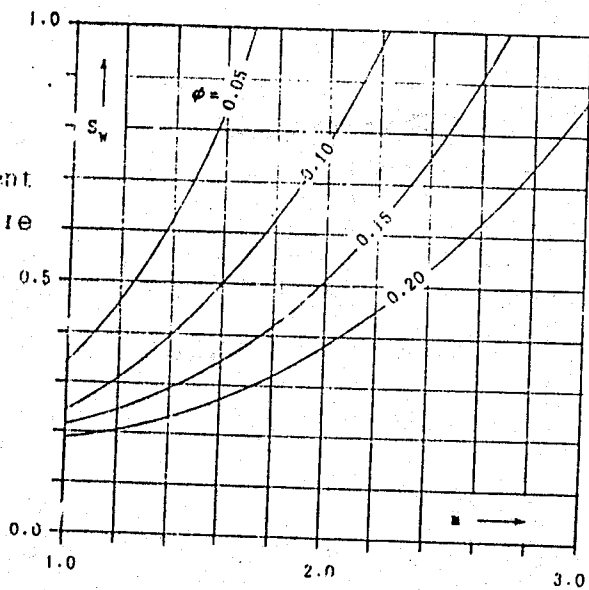


Fig.3 Effect of m on S_w for different values of ϕ when R_t and R_w are constant.



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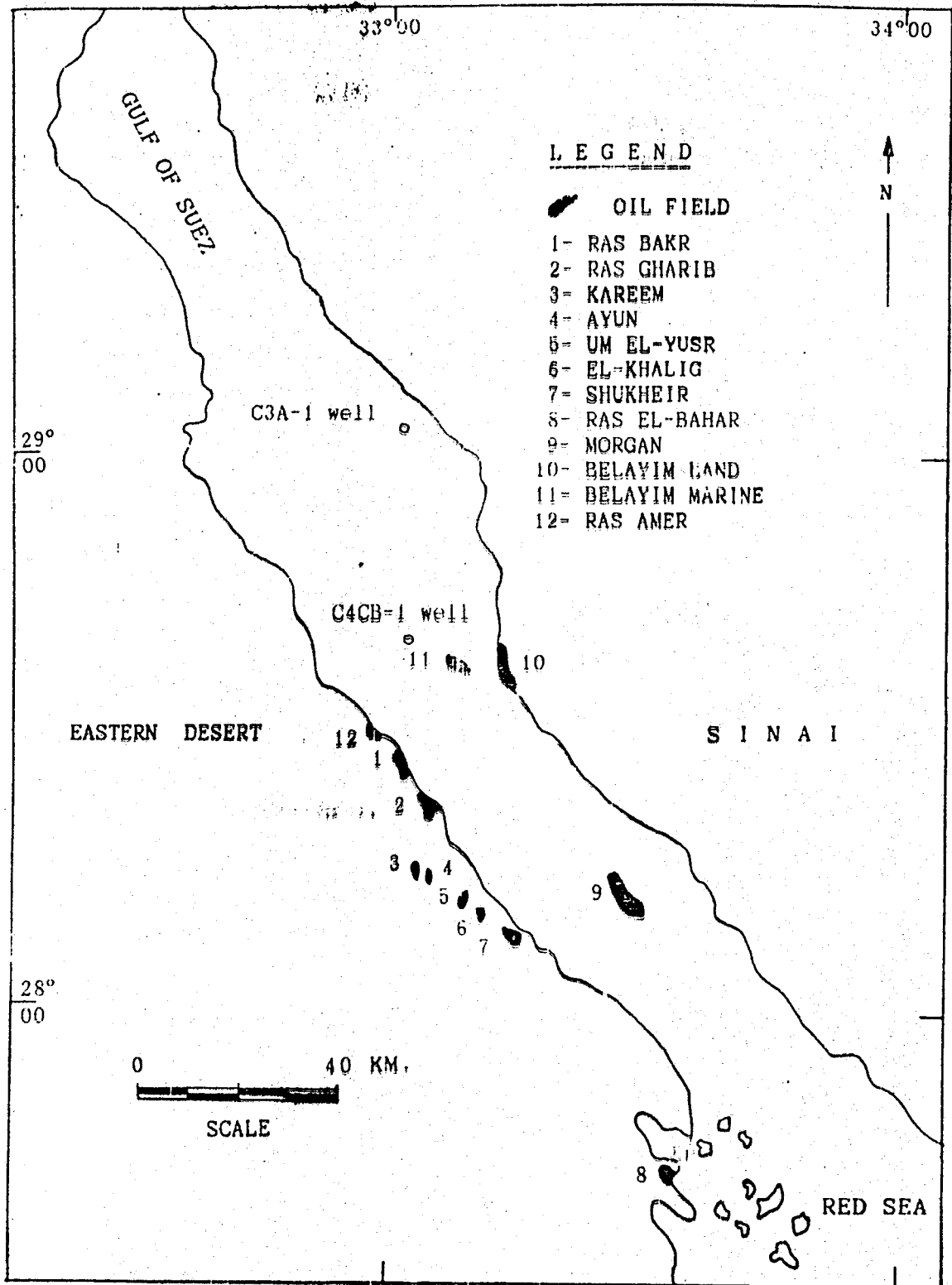


Fig.4 Location map of the studied wells.

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Well	GR _{max}	GR _{min}	$\phi_{N,sh}$	P _{sh}	At _{sh}
C3A-1	50	20	0.42	2.40	125
C4CB-1	48	20	0.44	2.35	125

Table (1): The physical parameters of shale in the studied wells.

To identify the minerals of matrix in the study formation, two M-N crossplots (Burke et al., 1969) were constructed as shown in fig.5 for C3A-1 well and fig.6 for C4CB-1 well. From these figures, it is clear that most of data points are observed between two mineral forming carbonate rocks: lime and dolomite and some of data points are shifted downwards due to shale effect.

The shale volume (V_{sh}) in each porous zone was determined using gamma ray data and gamma ray index was corrected using Stieber equation (1970). The maximum amount of shale calculated in the studied zones is 20 %.

Using neutron and density log data, the total porosity (ϕ_t), the volume fractions of lime (V_1) and dolomite (V_2) were determined after applying in some equations derived from simultaneous solution of a set of equations based on a dual mineral model of lime-dolomite when compensated neutron tool is used in a borehole filled with salty mud. Knowing V_1 and V_2 , the transit time of matrix and the primary (ϕ_p) and secondary (ϕ_s) porosities were determined using sonic log

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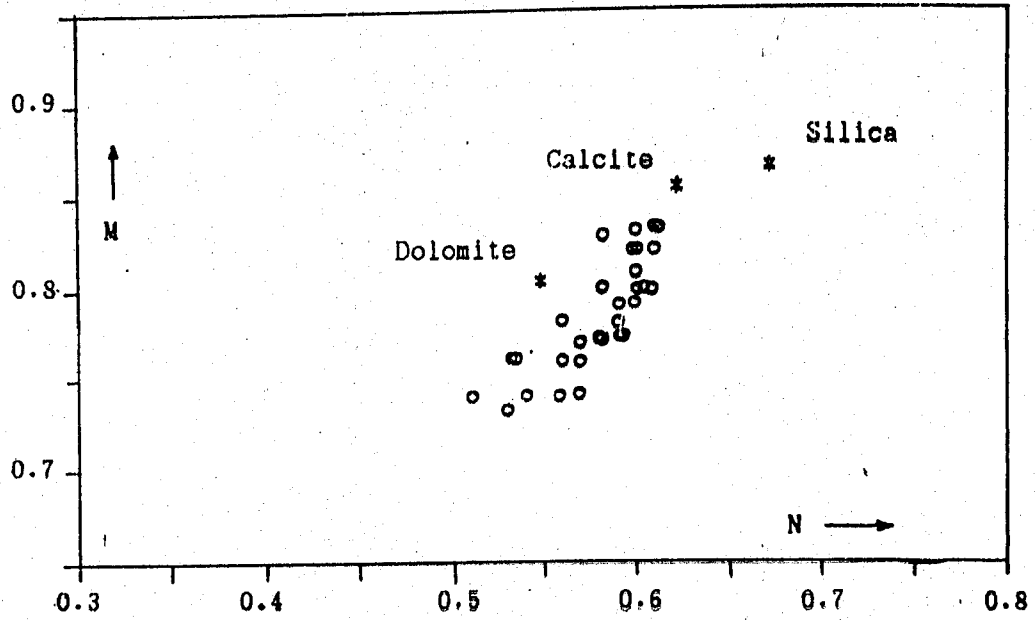


Fig.5 M-N plot for mineral identification in Rudies Formation of C3A-1 well.

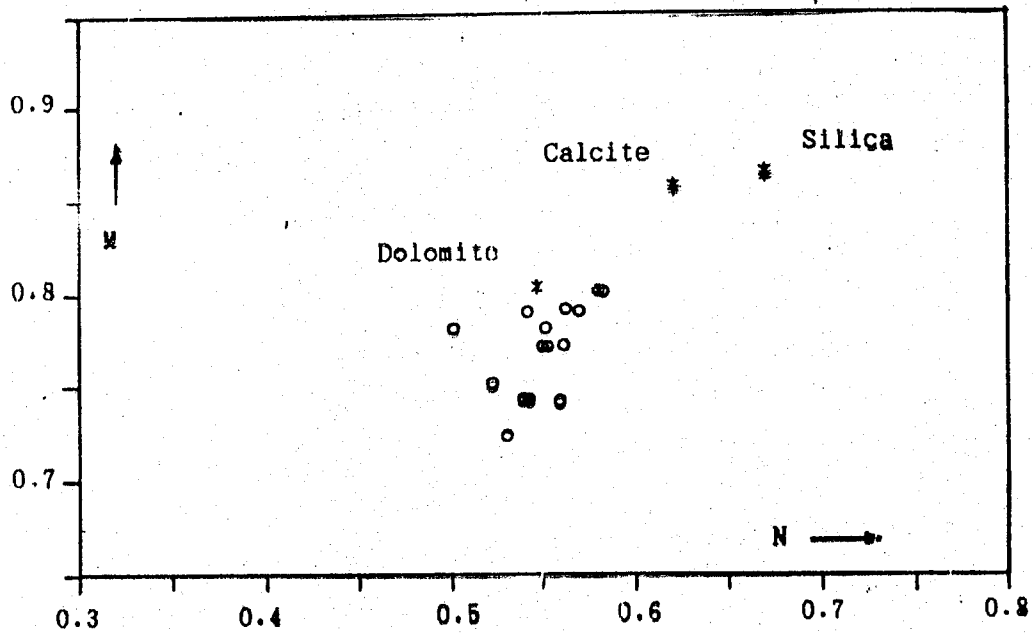


Fig.6 M-N plot for mineral identification in Rudies Formation of C4CB-1 well.

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data, (El Gendy, 1986/1987). In the study section, It was observed that the transit times of shales are about 125 usec/ft which may be due to the presence of fractures. So, the sonic log readings were corrected before calculations of primary and secondary porosities, using Dresser Atlas charts (1983). Due to non-linear effects of both neutron and sonic tool responses, small negative values of secondary porosity could result.

Two resistivity-porosity crossplots of pickett (1966) were constructed to determine the values of m and R_w in the study formation. Fig.7 shows that $m = 1.87$ and $R_w = 0.027$ ohm.m for C3A-1 well, while fig.8 shows that $m = 1.89$ and $R_w = 0.02$ ohm.m for C4CB-1 well.

The resistivity of mud filtrate (R_{mf}) which is an important parameter in determining hydrocarbon saturation in the flushed zone, was estimated for each well using log heading information and corrected to the formation temperature using Batemen and Konen formula (1977). R_{mf} is 0.037 ohm.m at temperature 204 °F and depth 11852 ft. in C3A-1 well and is 0.03 ohm.m at temperature 178 °F and depth 9833 ft. in well C4CB-1 well.

All the physical parameters whether measured directly from different logging tools or derived from the resistivity porosity crossplots or the log heading information were used to determine hydrocarbon saturation and to differentiate between movable and residual hydrocarbons in each selected porous zone. The physical and resulted petrophysical parameters are listed in Table (2) for C3A-1 well and Table (3) for C4CB-1 well. From these two tables, it is evident that some zones may be productive.

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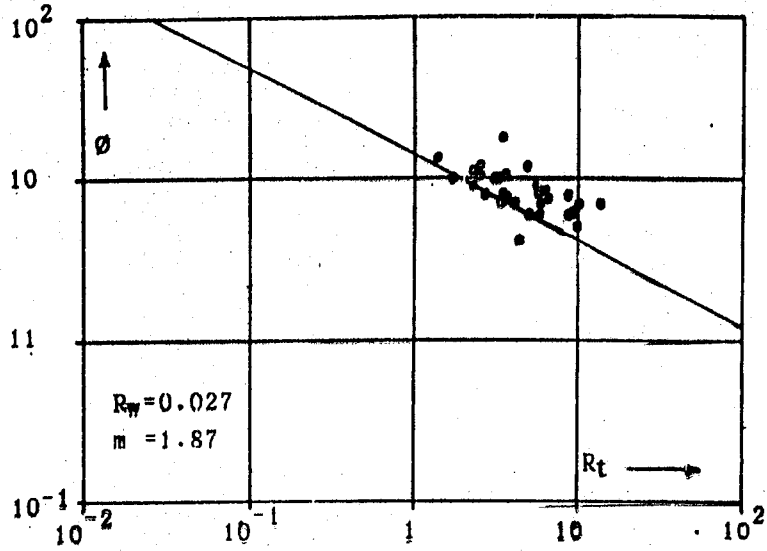


Fig.7 R_t - ϕ crossplot to determine m and R_w in Rudies Formation of C3A-1 well.

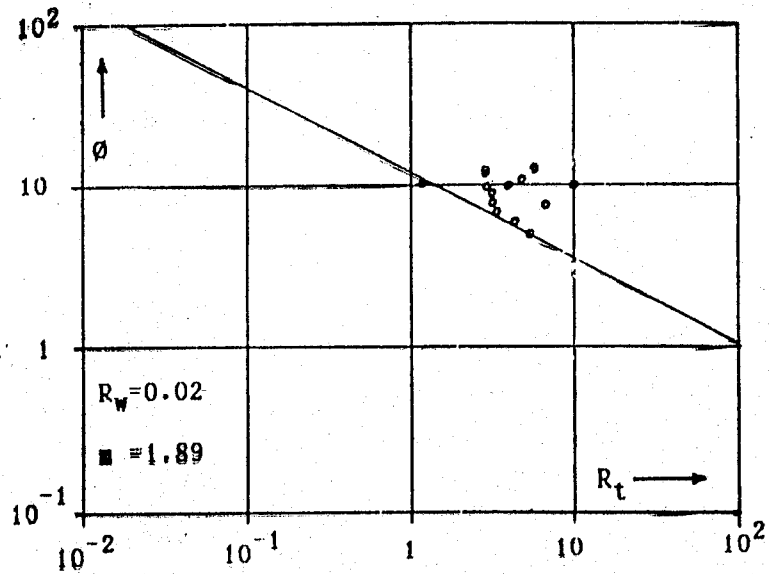


Fig.8 R_t - ϕ crossplot to determine m and R_w in Rudies Formation of C4CB-1 well.

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Table (3) : Logging data and petrophysical results of some porous zones in Rudies Formation of C4CB-1 well.

Interval (Feet)	Logging Data						Petrophysical Results										
	GR	R _c	R _{xo}	ϕ _N	P _b	At	ϕ _t	ρ _p	ρ _s	V _{sh}	V _l	V ₂	S _w	S _h	S _{nr}	S _{hm}	
1	9168-9173	28	4.0	6.0	0.19	2.57	72	0.10	0.09	0.02	0.36	0.42	0.12	0.61	0.39	0.00	
2	9178-9183	29	3.3	6.0	0.18	2.60	70	0.08	0.06	0.02	0.34	0.45	0.14	0.83	0.17	0.00	
3	9187-9194	30	3.0	5.5	0.21	2.57	76	0.10	0.09	0.01	0.26	0.48	0.16	0.72	0.28	0.00	
4	9319-9324	21	3.0	4.7	0.18	2.55	70	0.14	0.13	0.01	0.43	0.42	0.10	0.53	0.47	0.00	
5	9339-9345	31	5.8	8.0	0.13	2.56	70	0.5	0.04	0.01	0.77	0.00	0.18	1.00	0.00	0.00	
6	9369-9373	24	3.1	9.8	0.14	2.59	66	0.09	0.08	0.01	0.56	0.29	0.05	0.77	0.23	0.00	
7	9384-9389	28	7.0	10.1	0.15	2.57	67	0.08	0.05	0.03	0.60	0.20	0.12	0.58	0.42	0.00	
8	9410-9416	25	2000.0	7.8	0.14	2.63	64	0.08	0.07	0.01	0.45	0.41	0.07	0.04	0.96	0.29	
9	9587-9593	21	2000.0	6.0	0.19	2.65	68	0.12	0.13	0.01	0.06	0.81	0.01	0.02	0.54	0.46	
10	9714-9721	30	4.2	3.5	0.16	2.61	70	0.06	0.05	0.01	0.44	0.34	0.16	1.00	0.00	0.00	
11	9729-9735	30	3.4	3.4	0.16	2.59	71	0.07	0.05	0.02	0.50	0.27	0.16	1.00	0.00	0.00	
12	9738-9743	27	10.0	4.0	0.18	2.58	70	0.10	0.08	0.02	0.38	0.42	0.10	0.39	0.61	0.24	
13	9760-9765	29	6.0	3.0	0.24	2.51	74	0.14	0.09	0.05	0.26	0.47	0.14	0.37	0.63	0.36	
14	10044-10048	31	1.3	2.2	0.25	2.58	72	0.11	0.06	0.05	0.00	0.71	0.18	1.00	0.00	0.00	
15	10132-10137	27	5.0	3.0	0.20	2.58	76	0.11	0.12	0.01	0.26	0.53	0.10	0.50	0.50	0.20	

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Interval (Feet)	Logging Data										Petrophysical Results									
	GR	R _L	R _{SO}	ϕ _N	P _b	Ac	ϕ _L	ϕ _D	ϕ _S	V _{sh}	V ₁	V ₂	S _w	S _n	S _{hr}	S _{hm}				
1	11066-11094	34	4.0	5.0	0.17	2.55	74	0.07	0.04	0.3	0.60	0.11	0.22	1.00	0.00	0.00	0.00			
2	11126-11133	25	10.0	14.0	0.10	2.60	62	0.07	0.06	0.01	0.77	0.10	0.06	0.66	0.14	0.14	0.00			
3	11147-11153	30	1.8	3.8	0.19	2.55	75	0.10	0.09	0.02	0.44	0.32	0.14	1.00	0.00	0.00	0.00			
4	11160-11165	30	2.2	3.2	0.18	2.57	76	0.09	0.00	0.44	0.33	0.14	1.00	0.00	0.00	0.00	0.00			
5	11170-11174	22	3.8	8.2	0.11	2.60	65	0.08	0.09	0.10	0.70	0.20	0.02	0.86	0.14	0.14	0.00			
6	11226-11236	26	10.0	16.0	0.08	2.61	60	0.05	0.03	0.02	0.87	0.00	0.08	0.90	0.10	0.10	0.00			
7	11253-11257	22	6.5	17.0	0.10	2.61	63	0.08	0.08	0.00	0.72	0.18	0.02	0.72	0.28	0.28	0.00			
8	11264-11270	25	6.0	13.0	0.10	0.60	65	0.07	0.07	0.00	0.78	0.09	0.06	0.86	0.14	0.14	0.00			
9	11280-11288	20	5.5	9.0	0.11	2.29	64	0.09	0.10	0.01	0.71	0.19	0.00	0.64	0.16	0.16	0.00			
10	11308-11316	25	9.0	14.0	0.10	2.57	63	0.08	0.06	0.02	0.86	0.00	0.06	0.62	0.38	0.38	0.00			
11	11338-11342	24	6.0	9.0	0.10	2.63	64	0.06	0.07	0.10	0.68	0.21	0.05	0.91	0.09	0.09	0.00			
12	11374-11384	26	9.0	14.0	0.10	2.59	63	0.06	0.05	0.10	0.82	0.04	0.08	0.72	0.28	0.28	0.00			
13	11441-11450	31	2.2	4.0	0.18	2.50	77	0.11	0.08	0.02	0.66	0.07	0.16	0.90	0.10	0.10	0.00			
14	11468-11475	26	15.0	18.0	0.11	2.57	64	0.07	0.04	0.03	0.83	0.00	0.11	0.54	0.46	0.46	0.04			
15	11600-11604	20	5.0	14.0	0.13	2.52	70	0.12	0.13	0.01	0.81	0.07	0.00	0.52	0.18	0.18	0.00			
16	11607-11611	22	6.0	90.0	0.10	2.60	60	0.08	0.06	0.02	0.76	0.14	0.02	0.73	0.27	0.27	0.00			
17	11812-11824	30	3.0	4.0	0.17	2.53	76	0.10	0.09	0.01	0.62	0.14	0.14	0.83	0.17	0.16	0.01			
18	11836-11844	29	2.5	3.5	0.22	2.57	73	0.12	0.09	0.03	0.19	0.57	0.13	0.76	0.24	0.24	0.00			
19	11851-11854	28	1.5	3.8	0.27	2.54	78	0.16	0.13	0.03	0.00	0.73	0.11	0.74	0.25	0.25	0.00			
20	11881-11889	31	2.8	4.0	0.17	2.57	71	0.08	0.05	0.03	0.51	0.25	0.16	1.00	0.00	0.00	0.00			
21	12176-12182	26	3.5	5.0	0.15	2.57	70	0.10	0.09	0.01	0.58	0.25	0.08	0.78	0.22	0.22	0.00			
22	12442-12457	30	2.5	3.0	0.20	2.57	77	0.10	0.10	0.00	0.32	0.44	0.14	0.87	0.13	0.07	0.06			
23	12556-12563	31	4.5	3.0	0.21	2.58	73	0.10	0.07	0.03	0.24	0.50	0.16	0.67	0.33	0.04	0.29			
24	12574-12581	30	3.5	2.3	0.26	0.37	79	0.19	0.11	0.08	0.58	0.09	0.14	0.41	0.59	0.41	0.18			
25	12586-12593	24	3.5	4.0	0.12	0.62	66	0.08	0.09	0.10	0.59	0.29	0.05	1.00	0.00	0.00	0.00			
26	12637-12645	28	3.9	4.2	0.14	2.61	70	0.07	0.07	0.00	0.53	0.29	0.11	1.00	0.00	0.00	0.00			
27	12652-12657	23	6.0	6.5	0.12	2.62	64	0.08	0.08	0.00	0.58	0.30	0.04	0.72	0.28	0.19	0.09			
28	12692-12697	30	3.0	3.0	0.20	2.57	76	0.10	0.09	0.01	0.32	0.44	0.14	0.80	0.20	0.07	0.13			
29	12792-12801	26	5.0	4.0	0.10	2.59	67	0.06	0.07	0.01	0.82	0.04	0.08	1.00	0.00	0.00	0.00			
30	12813-12821	33	4.2	4.2	0.12	2.59	71	0.04	0.03	0.01	0.77	0.00	0.20	1.00	0.00	0.00	0.00			

Table (2) : Logging data and petrophysical results of some porous zones in Rudies Formation of C3A-1 well.

CONCLUSIONS

One of the most important factors used for determination of hydrocarbon saturation is the cementation exponent or factor (m) which is a measure of the degree of geometrical complexity of pore spaces in the matrix. In carbonate rocks, this exponent is usually assumed to be 2.0. This assumption may cause errors on applying Archie's formula to evaluate a reservoir, particularly in low resistivity carbonate rocks as shown in the constructed graphs.

Because of the important role of the cementation exponent for determining hydrocarbon saturation, Rudies Formation in the middle portion of the Gulf of Suez region has been re-evaluated through two wells named C3A-1 and C4CB-1. The value of m was determined using some resistivity-porosity crossplots which were also useful to obtain the values of formation water resistivity (R_w) in the studied wells. This technique has an important advantage because both m and R_w are determined under formation conditions. The determined value of m is less than 2.0 (about 1.88) due to the presence of fractures which also reduces the true resistivity of these rocks. The petrophysical results showed some porous zones may be productive, particularly in the presence of secondary porosity which increases the permeability of fluids.

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