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FOOT BY FOOT EVALUTION IN SOME CHALKY LIMESTONE FORMATIONS

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ABSTRACT

Hydrocarbon detection in carbonate formations requires great attention due to the complexity of this rock type. The complexity arises from rapid variations in petrographical characteristics, chemical compositions and petrophysical properties. In particular, the changes in the lime to dolomite ratio in lithology matrix, the presence of clay, silica and/or fractures render well log interpretation a difficult task.

In this work carbonate formation properties have been determined using direct application of sets of simple linear equations. The method is applicable to both clean and shaly formations. Two examples of chalky limestone formation from the middle portion of the Gulf of Suez, Egypt were used to illustrate the mentioned method. The study section is Sudr Formation. The evaluation of this section has been carried out on a continuous foot by foot basis. The calculation results are used to construct continuous presentation logs of petrophysical characteristics for both wells. Generally, this study shows that there are some

intervals in Sudr Formation which may be considered as reservoirs particularly in its lower parts.

INTRODUCTION

Chalk formations are not usually considered as potential reservoirs. Under certain circumstances they may qualify as reservoir rocks particularly when they are fractured or dolomitized.

Carbonate rocks can be classified according to their petrophysical properties into three types A, B and C [6]. Type A, is characterized by low porosity. This porosity usualy ranges from 1 to 5% and is completely water saturated in most cases. This rock may produce oil if secondary porosity is present. Type B, exhibits primary porosity which usually ranges from 20 to 40% , water saturations are high, frequently more than 40% and secondary porosity is rarely present. Type C, is intermediate between the principal types A and B and represents every gradations between them in all aspects.

In order to determine reservoir characteristics, neutron, density and sonic logs are generally, used as main sources of information. Any one these logs is usually enough to evaluate a liqued clean formation composed of one known mineral. However, when the lithology consists of more than one mineral and secondary porosity is present, the three logs are needed.

In general, the minimum logging program required for well log interpretation in a dual mineral model contaminated with shale, consists of gamma ray to determine shale content, neutron and density logs to estimate total porosity and lithology and induction or laterologs to calculate water saturation. The addition of sonic and shallow electric tools permit the determination of secondary porosity and movable hydrocarbons respectively.

POROSITY AND LITHOLOGY DETERMINATION USING SIMULTANEOUS EQUATIONS

It is well known that each logging device has its different response to the different rock components. A system of equations can then be constructed based on the different components in that rock (minerals and fluids). The set of equations is solved simultaneously to give better results about reservoir characteristics at each level of stratigraphic section under study.

Total Porosity And Lithology Determination

In a clean carbonate rock composed of two minerals and its pore spaces filled with fluid, density and neutron logs are often used to determine the total porosity and bulk volume fraction of each mineral in the matrix. The responses of neutron ($\emptyset_N$) and density (p_b) logs in this case can be expressed by the following linear equations:

$$\emptyset_N = \emptyset_{Nf}\ \emptyset + \emptyset_{Nma1}\ V_1 + \emptyset_{Nma2}\ V_2 \qquad (1)$$

$$p_b = p_f\ \emptyset + p_{ma1}\ V_1 + p_{ma2}\ V_2 \qquad (2)$$

where $\emptyset$ is total porosity, V_1 and V_2 are volume fractions of the first and second mineral respectively, $\emptyset_{Nf}$, $\emptyset_{Nma1}$ and $\emptyset_{Nma2}$ are neutron logging device responses for pure fluid and minerals seperately, and p_f, p_{ma1} and p_{ma2} are their density logging device responses .

The sum of all components should equal to unity such as:

$$1 = \emptyset + V_1 + V_2 \qquad (3)$$

The above three linear equations in three unknowns $\emptyset$, V_1 and V_2 can be solved simultaneously using matrices as follows:

$$\begin{bmatrix} \emptyset_{nf} & \emptyset_{Nma1} & \emptyset_{Nma2} \\ P_f & P_{ma1} & P_{ma2} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \emptyset \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} \emptyset_N \\ P_b \\ 1 \end{bmatrix} \qquad (4)$$

The above system of equations may be simlified as

$$AX = Y \quad (5)$$

where (A) is the coefficient matrix, (X) is the column vector of the bulk volume fractions of fluid and mineral components and (Y) is the column vector of the logging measurements in that rock.

The unknown component fractions can obtained by multiplying both sides of eq. (5) by the inverse matrix (A^{-1}) which yield :

$$X = A^{-1}Y \quad (6)$$

This way, the petrophysical parameters $\emptyset$, V_1 and V_2 of a clean carbonate formation composed of two minerals can be determined by direct application of the following equations

$$\emptyset = K_1 \emptyset_N + K_2 P_b + K_3 \quad (7)$$

$$V_1 = K_4 \emptyset_N + K_5 P_b + K_6 \quad (8)$$

$$V_2 = K_7 \emptyset_N + K_8 P_b + K_9 \quad (9)$$

where K_1 to K_9 are coefficients calculated using inverse matrix. Their values vary from case to another with the two minerals forming the rock, nature of mud fluid in the borehole, and type of neutron tool used, i.e. CNL or SNP.

Secondary Porosity Determination

The sonic log has bean a useful tool for identification of secondary porosity. It is speculated that the sonic is blind to such secondary porosity , because the acoustic energy bypass the relatively large cavities. So the secondary porosity ($\emptyset_S$) can be determined using the following equation .

$$\emptyset_S = \emptyset - \emptyset_P \qquad (10)$$

where $\emptyset$ represents total porosity determined from the set of eqs. (7), (8) and (9), and $\emptyset_P$ is the primary porosity determined from sonic logging measurements as follows:

$$\emptyset_P = (\Delta t - \Delta t_{ma})/(\Delta t_f - \Delta t_{ma}) \qquad (11)$$

where Δt is sonic log reading and Δt_f and Δt_{ma} are interval transit times of the fluid and the matrix respectively.

The mud type determines the value of Δt_f. Δt_{ma} value varies continuously from level to level according to the ratio of the two minerals making up the lithology. Δt_{ma} is calculated from:

$$\Delta t_{ma} = (V_1 \; \Delta t_{ma1} + V_2 \; \Delta t_{ma2})/(V_1 + V_2) \qquad (12)$$

where V_1 and V_2 are bulk volume fractions of the two minerals determined from eqs. (8) and (9) and Δt_{ma1} and Δt_{ma2} are their corresponding interval transit times.

Primary and Secondary Porosity Determination in Shaly Carbonate Formations

Generally, all logging devices are affected to a different extent, by the presence of shale . The presence of shale, if not accounted for, yields too optimestic values of neturon or acoustic derived porosity . Porosity calculated from density device will be low, when shale density is greater than the clean matrix density, and high when shale density is smaller than the clean matrix density.

If shale is present the two-mineral reservoir model described above can be modified to the following system of equations:

$$\emptyset_N = \emptyset_{Nf}\,\emptyset + \emptyset_{Nma1}\,V_1 + \emptyset_{Nma2}\,V_2 + \emptyset_{Nsh}\,V_{sh} \qquad (13)$$

$$P_b = P_f\,\emptyset + P_{ma1}\,V_1 + P_{ma2}\,V_2 + P_{sh}\,V_{sh} \qquad (14)$$

$$1 = \emptyset + V_1 + V_2 + V_{sh} \qquad (15)$$

where, $\emptyset_{Nsh}$ and P_{sh} are the responses of neutron and density tools in the shale present in the studied interval. These two parameters are taken either from crossplots of gama ray against both neutron and density log responses or from visual inspection of logs.

V_{sh} is the shale content determined from the natural radioactivity log using well known methods (Clavier et al., [2]; Stieber, [10] and Dresser Atlas [3].

The system of eqs. (13), (14) , and (15)can be rewritten as follows:

$$\emptyset'_N = \emptyset_{Nf}\,\emptyset' + \emptyset_{Nma1}\,V'_1 + \emptyset_{Nma2}\,V'_2 \quad (16)$$

$$P'_b = Pf\,\emptyset' + P_{ma1}\,V'_1 + P_{ma2}\,V'_2 \quad (17)$$

$$1 = \emptyset + V'_1 + V'_2 \quad (18)$$

where:

$$\emptyset' = \emptyset / (1- V_{sh}) \quad (19)$$

$$V'_1 = V_1 / (1- V_{sh}) \quad (20)$$

$$V'_2 = V_2 / (1- V_{sh}) \quad (21)$$

$$\emptyset'_N = (\emptyset_N - \emptyset_{Nsh}\,V_{sh})/(1-V_{sh}) \quad (22)$$

$$P'_b = (P_b - P_{sh}\,V_{sh})/(1-V_{sh}) \quad (23)$$

The set of eqs. (16), (17) and (18) is similar in form to the set of eqs. (1), (2) and (3) written for clean formation. The later set can be solved using the described method to determine $\emptyset'$, V'_1 and V'_2 . The value of $\emptyset$, V_1 and V_2 can subsequently be calculated from eqs. (19), (20) and (21). The secondary porosity can also be calculated usind eqs. (10), (11) and (12). However a $\Delta t'$value corrected for shale effect is used in place of Δt. $\Delta t'$ is defined as:

$$\Delta t' = (\Delta t - \Delta t_{sh} V_{sh})/(1-V_{sh}) \qquad (24)$$

where Δt_{sh} is the interval transit time of shale.

In very shaly formations ($V_{sh} \geq 40\%$), the porosity value can be futher corrected for shale effect using the following eqation suggested by Frost and Fertl [4]:

$$\emptyset_c = \emptyset\,(1 - ((0.5\,V_{sh} - 0.08)/0.3)) \qquad (25)$$

where $\emptyset_c$ is the corrected porosity value.

WATER SATURATION DETERMINATION

In clean carbonate formations, water saturation (S_w) can be estimated using Archie formula [9] .

$$S_w = (F\,R_w / R_t)^{1/n} \qquad (26)$$

where R_t and R_w are the resistivities of uninvaded zone and formation water respectively, F is the formation resistivity factor, and n is the saturation exponent usually taken as 2.

Formation resistivity factor can be determined from porosity value as follows:

$$F = a / \emptyset^m \qquad (27)$$

where "m" is the cementation exponent and "a" is a constant, usually taken as 1 in carbonate rocks.

The value of m and R_w can be estimated statistically through $R_t - \emptyset$ crossplots [7] . This technique is based on Archie equation which can be written as follows:

$$\log(\emptyset) = -\frac{1}{m}\log(R_t) + \frac{1}{m}\log(R_w) - n\log(S_w) \quad (28)$$

For a constant water resistivity and saturation, this relation shows that a plot of log (R_t) versus log (Ø) will exhibit a line on which fall the points of 100% water bearing zones. This is called water line. The formation water resistivity and cementation exponent are determined by the extrapolation of water line to 100% porosity and by negative inverse of its slope respectively.

FIELD APPLICATIONS

Two example were taken from two wells named C4SA-1 and C4NA-1 drilled in the middle portion of the Gulf of Suez, Egypt (Fig.1). The study section is Sudr Formation which is composed in the wells of chalky limestone in its lower part, while the upper part consists of argillaceous to highly argillaceous limestone with mudstone in some parts.

Logging Data

The available logging data include standard and spectral gamma ray, caliper, compensated neutron log (CNL) for both wells. Compensated formation density (FDC), sonic (BHC) and dual induction resistivity logs are available for C4SA-1 well. Litho-density and dual laterologs are available for C4NA-1 well.

Crossplot Analyses

A series of crossplots is generated for the study zone in the two wells. Where the sonic log is availabe, the lithoporosity (M-N) crossplot [1] is used to determine the lithology. Fig. 2,a is the M-N crossplot of C4SA-1 well. The figure shows that of the data points are situated around the $CaCO_3$ point within the lime-dolomite-quartz triangle. The presence of clay causes the spreading of data points in the southwest direction. Data points shifted towards the north show the effect of secondary porosity.

Neutron-density crossplots give a general idea about the lithology and porosity. Figs. 2,b and 2,a show that the predominent mineral in the analyzed interval of C4SA-1 and C4NA-1 wells is $CaCO_3$. They also show that rock is partly dolomitic. The porosity ranges from 6 to about 20% .

To select physical parameters of clay minerals existing in the study zone, crossplots of spectral gama total count (CGR) versus neutron, density and sonic separately were constructed. The highest values of CGR indicate the clay point. One should be careful on the presence of some radioactive minerals other than clays.

On these crossplots, neutron log response of clay is taken as 19% in C4SA-1 well (Fig. 2,c) and as 14% in C4NA-1 well (Fig.3,b). Density of clay is taken as 2.61 gm/cc. for C4SA-1 (Fig. 2,d) and as 2.68 gm / cc . for C4NA-1 (Fig. 3,c). Also, interval transit time of clay is picked as 79 usec/ft (Fig. 2,e) in C4SA-1 well. The cross-plot of phototoelectric effect (P_e) versus thorium concentration (Fig. 3,d) of C4NA-1 well, indicates that the type of clay minerals present in the formation is chlorite [8]

Step by Step Calculations:

The previously discussed crossplot analyses used to determine the predominant lithology and clay properties is the first step in the evaluation. The second step includes the determination of shale content at each level. For this purpose, the spectralog total count (CGR) was chosen to determine the shale index I . Stieber's equation [10] is selected to calculate V_{sh} values from the shale index .

The next step was the correction of logging data to eliminate shale effect. This was carried out using eqs. (22), (23) and (24). The method described by eqs. 1 to 9 was then applied. Two two-mineral model options lime-dolomite and lime-silica are available. To select the approriate option the parameter (N) described by Burke et al. [1] was calculated at each foot. N is defined as :

$$N = (\emptyset_{Nf} - \emptyset_{N}) / (P_b - P_f) \qquad (29)$$

If the value of calculated N is less than N of pure lime, the lime-dolomite model is selected and if it is bigger, the lime-silica is selected. The selected dual mineral, mud type of neutron tool used determines the values of coefficient K_1 to K_9 appearing in eqs. (7), (8) and (9).

In the zone, salt water base mud and compensated neutron tool were used . The K coefficients calculated using inverse matrix are listed in table (1). Fluid and mineral coefficients were taken according to Schlumberger [9]. On calculating K, the matrix coeffient of dolomite whose porosity ranges from 5.5-30% was used, because, porosity less than 5.5% is not important economically.

Table (1): The K coefficients for both lime-dolomite and lime-silica models when CNL used in borehole filled with salt water base mud.

		lime-dolomite	lime-silica
ϕ	K_1	+0.5389927	+ 0.4270460
	K_2	-0.2863399	- 0.3558720
	K_3	+0.7759810	+ 0.9644132
V_1	K_4	-5.9626073	+11.0320300
	K_5	-3.0823648	- 7.4733120
	K_6	+9.3532086	-19.2526800
V_2	K_7	+5.4236146	-11.4590800
	K_8	+3.3687047	- 7.1174400
	K_9	-9.1291898	+19.2882600

Negative values which may result from applying the system of equations means that minerals other than considered are present. For this case, Harris and McCommon [5] suggested statistical solution using a minimum variace approximation. Due to non-linear effects of both neutron and sonic tool responses, small negative values of secondary porosity could result.

The next step after determining porosity is the calculation of water saturation at each level. The use of Archie's formula, requires the knowledge of the formation water resistivity (R_w) and cementation factor (m). To determine these two parameters, two crossplots of R_t versus Ø were constructed for C4SA-1 and C4NA-1 wells as shown in figs. 4 and 5 respectively. From these crossplots, R_t values of 0.02 and 0.03 ohm-m were obtained in C4SA-1 and C4NA-1 wells respectively. A value of m = 1.9 was obtained in both wells.

To determine movable hydrocarbons (S_{hm}), which is defined by :

$$S_{hm} = S_{xo} - S_w \qquad (30)$$

where S_{xo} is water saturation in flushed zone, the following form of Archie's formula is used:

$$S_{xo} = (F \cdot R_{mf} / R_{xo})^{0.5} \qquad (31)$$

R_{mf} and R_{xo} are the resistivities of mud filtrates and flushed zone respectively. R_{mf} values corrected for formation temprature are 0.045 and 0.052 Ohm-m . for C4SA-1 and C4NA-1 respectively.

Finally, all the calculation results are used to construct continuous presentation logs for petrophysical characteristics. Figs. 6 and 7 show continuous presentation of lithology and some petrophysical characteristics for C4SA-1 and C4NA-1 wells respectively. The right hand track is the lithology from the composite log. The second track shows the lithology analysis from well log interpretation in terms of clay, volume fractions of lime, dolomite and silica present in the matrix and porosity. The third track shows porosity analysis in terms of total porosity and secondary porosity . The fourth track gives fluid analysis in terms of movable ϕ (S_{xo} - S_w) and residual ϕ (1 - S_{xo}) hydrocarbons and water ϕ (S_w) volumes.

Well log analysis in the studied sections, indicates that the major lithology is limestone. Small amounts of dolomite and silica are present. The two sections are contaminated with a considerable amount of clay reaching a maximum in its upper parts. The porosity in C4SA-1 well is more than that in C4NA-1 well and it increases downwards. Secondary porosity in sufficient amount is present in C4SA-1 well. There are some intervals containing residual hydrocarbons which may be formed in situ. In contrast, C4NA-1 well is a tight formation and almost fully water saturated.

CONCLUSIONS

The neutron and density porosity tools are adequate diagonestic tools when used in combinations in evaluation of dual mineral reservoirs. They give accurate values about total porosity and bulk fractions of each mineral existing in a rock. once the ratio of minerals in the lithology matrix is known, the interval transit time of matrix will be determined accurately. The sonic log is also a good identification tool of secondary porosity which is responsible of permeability in chalky limestone reservoirs.

The determination of clay in shaly formations before using simultaneous equations insures that the chosen clay indicator is representative of actual clay content.

Well log analysis has proved that Sudr Formation in C4SA-1 may be considered as a good reservoir due to its considerable amount of secondary porosity particularly in its lower part. In the study section of C4NA-1 well, the rock is very tight and completely water saturated.

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REFERENCES

1- Burke, J., Campbell, R., and Schmidt, A., (1969). The Litho-Porosity Crossplot., The Log Analyst, 10 (6), 25-43.

2- Clavier, C., Hole, W. and Meunier, D., (1971). Quantitative Interpretation of Thermal Neutron Decay Time Logs: Part I-Fundamentals and Techniques., J.Pet. Tech., 743-755.

3- Dresser Atlas, (1983). Log Interpretation Charts.

4- Frost, E., and Fertl, W.H., (1981). Prolog Wellsite Analysis, Part II, The Log Analyst, 22 (1), 14-32.

5- Harris, H.H., and McCammon, R.B., (1969). A Computer-Oriented Generalized Porosity-Lithology Interpretation of Neutron, Density and Sonic Logs., AIME , Denver, Colorado, USA.

6- Lynch, E.J., (1962). Formation Evalution., Harper & Row, New York, 422.

7- Pickett, G.R., (1966). A review of Current Techniques for Determination of Water Saturation from Logs., J. Pet. Tech ., Nov., 1425-1433.

8- Schlumberger LDT., (1986). Log Interpretation Charts.

9- Sclumberger LDT., (1987). Log Interpretation Principles/ Application.

10- Stieber, S.J., (1970). Pulsed Neutron Capture Log Evaluation in the Louisiana Gulf Coast., SPE 2961.

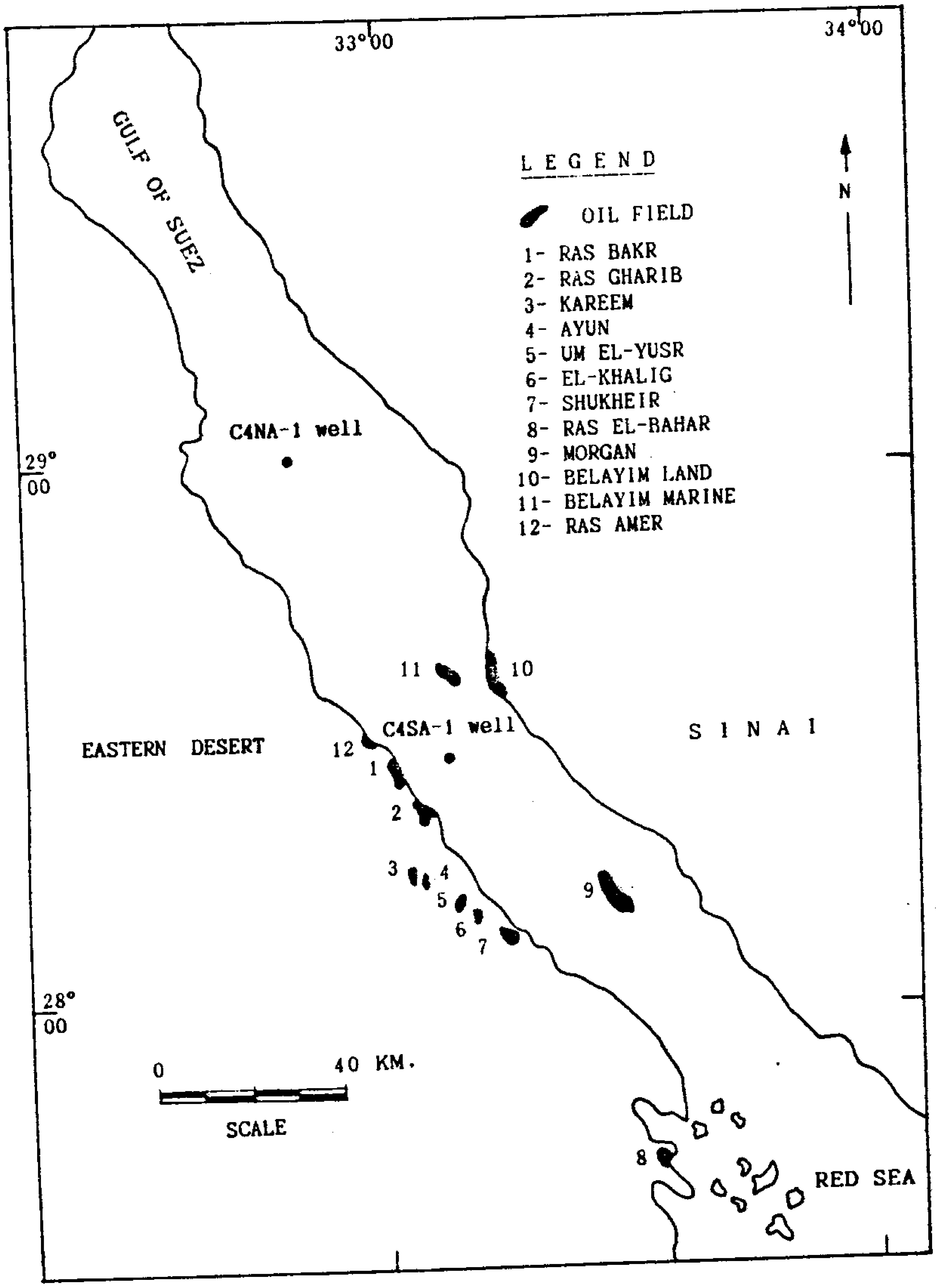

Fig.1 Location map of the studied wells.

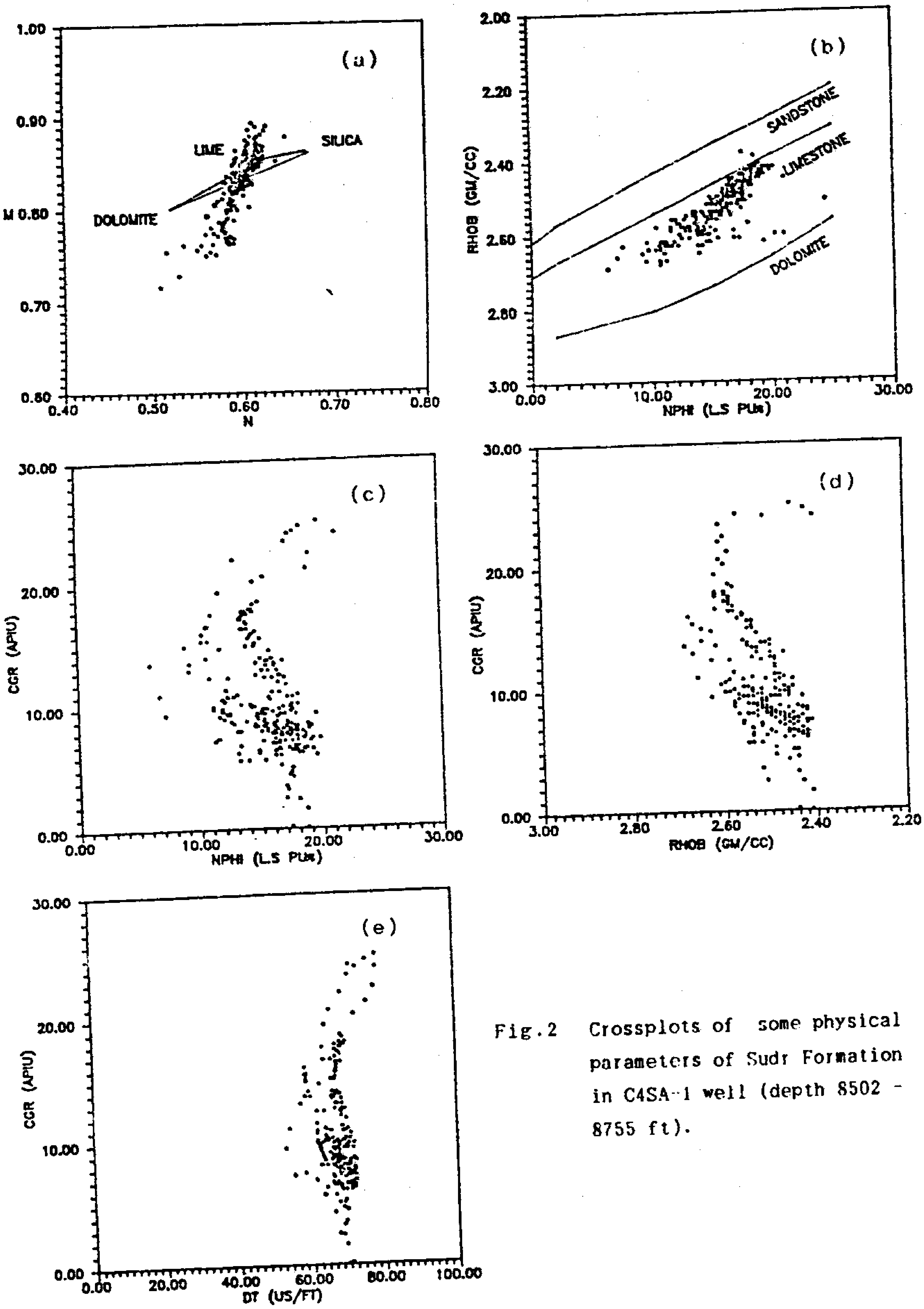

Fig.2 Crossplots of some physical parameters of Sudr Formation in C4SA-1 well (depth 8502 - 8755 ft).

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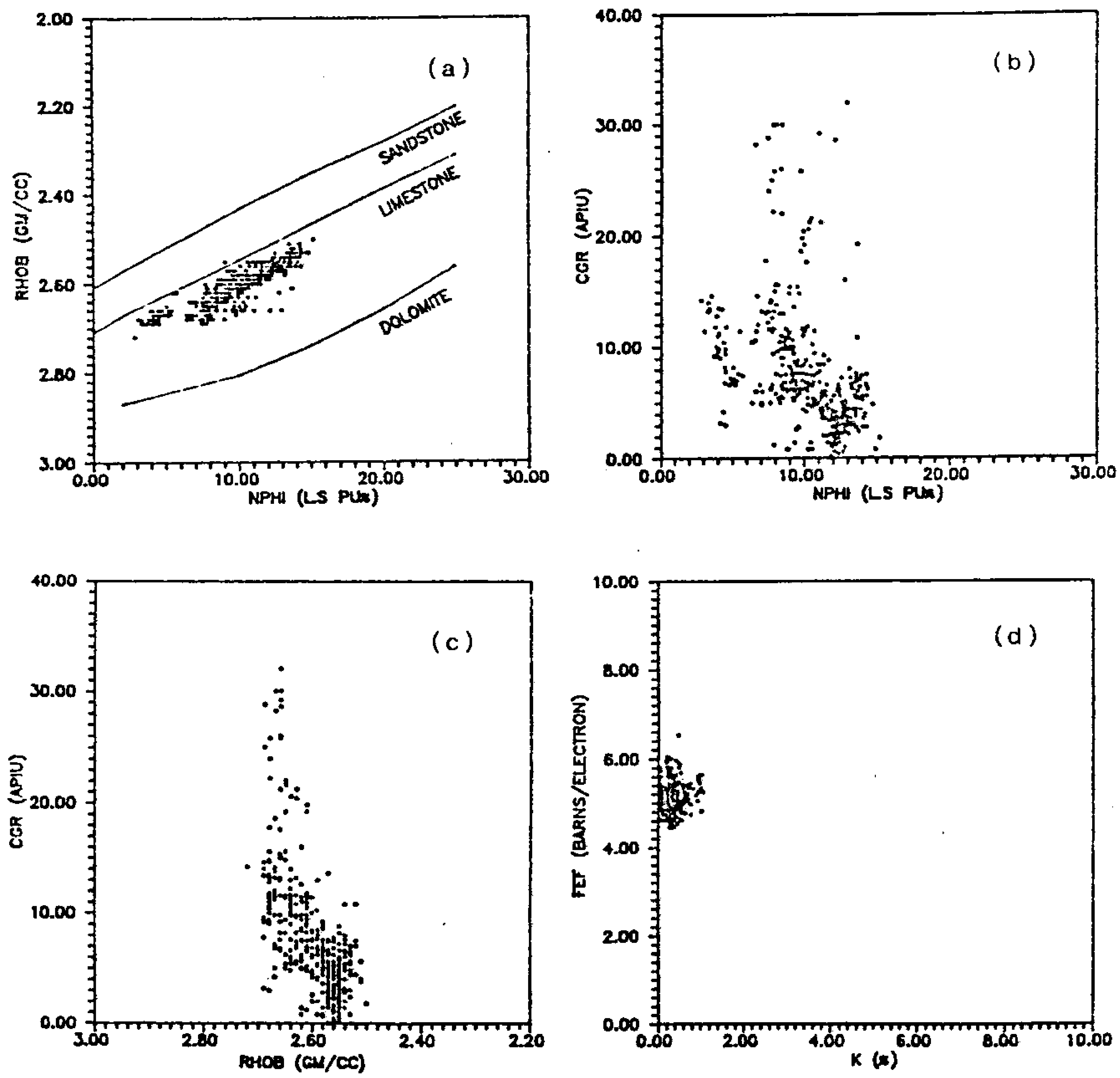

Fig.3 Crossplots of some physical parameters of Sudr Formation in C4NA-1 well (depth 9234 - 9626 ft).

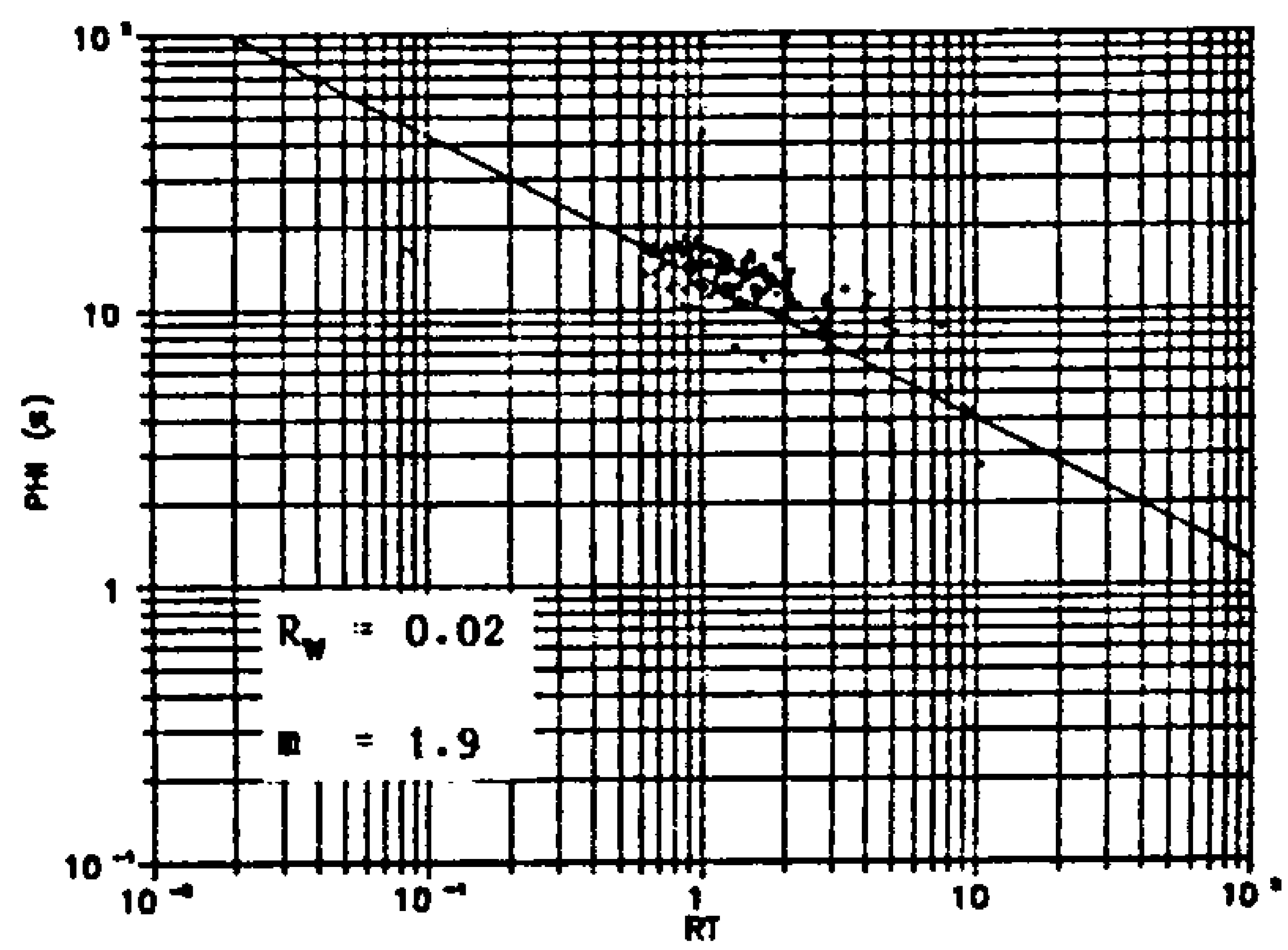

Fig.4 Determination of R_w and m for Sudr Formation in C4SA-1 well.

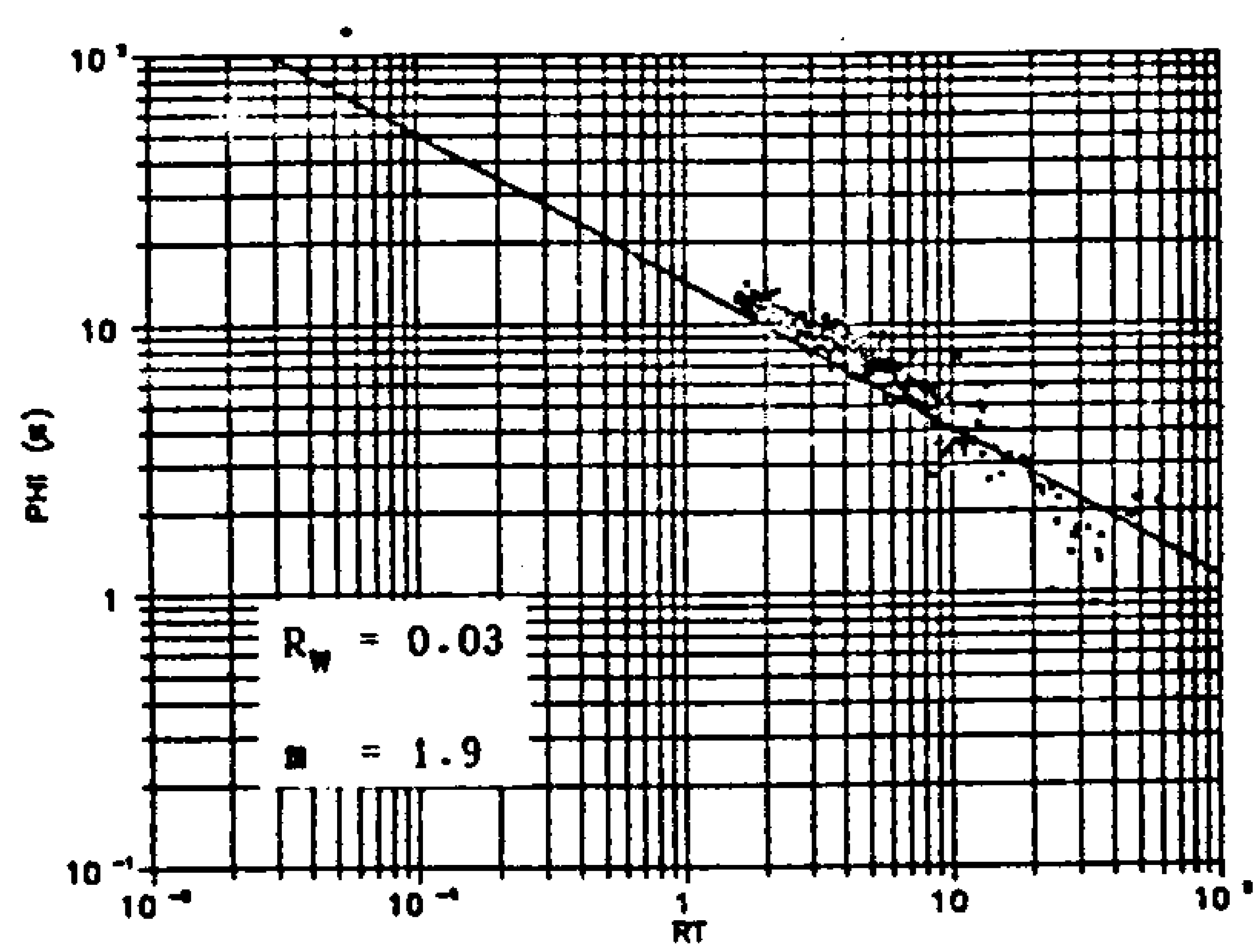

Fig.5 Determination of R_w and m For Sudr Formation in C4NA-1 well.

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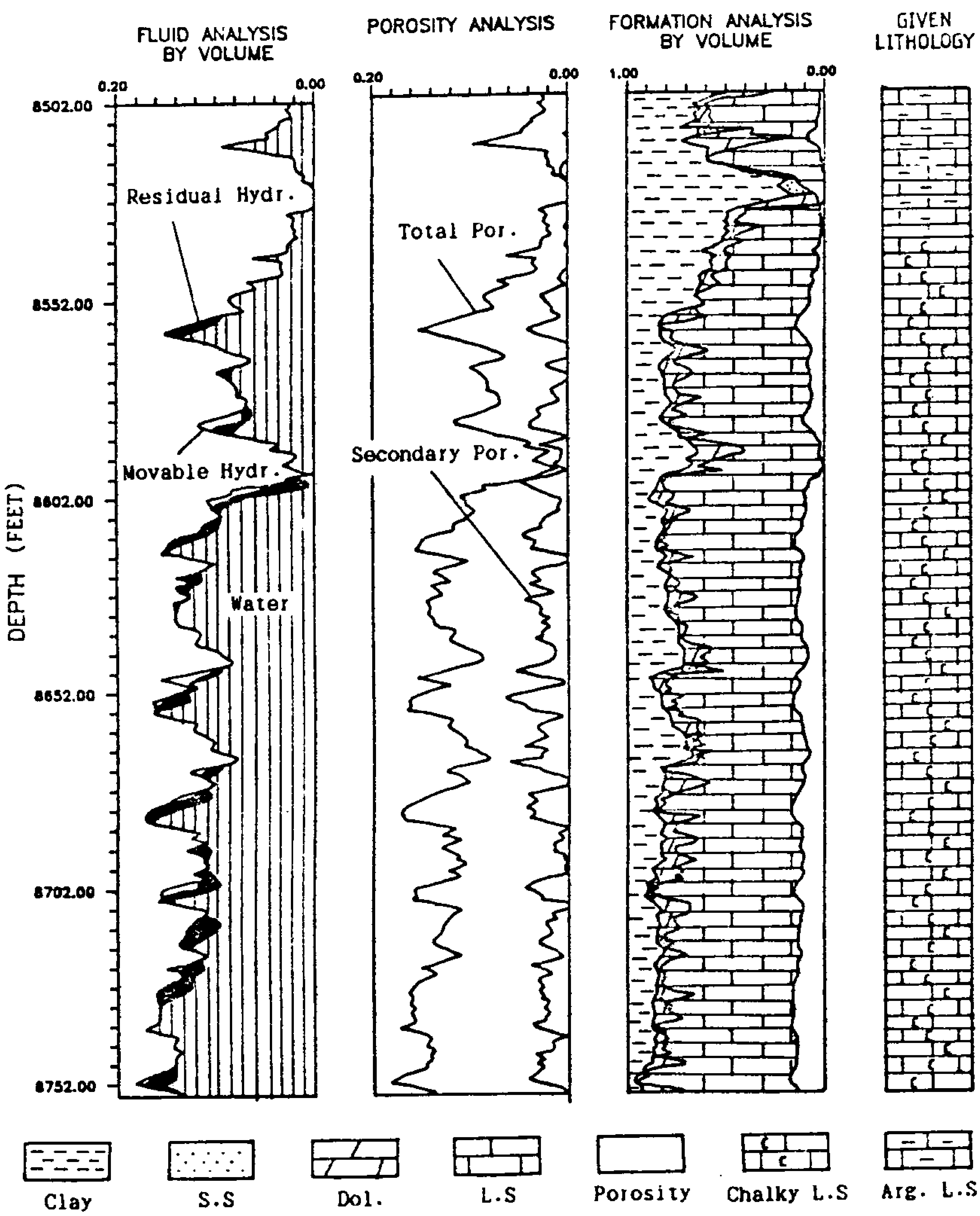

Fig.6 Continuous representation of fluid, porosity and lithology foot by foot in C4SA-1 well.

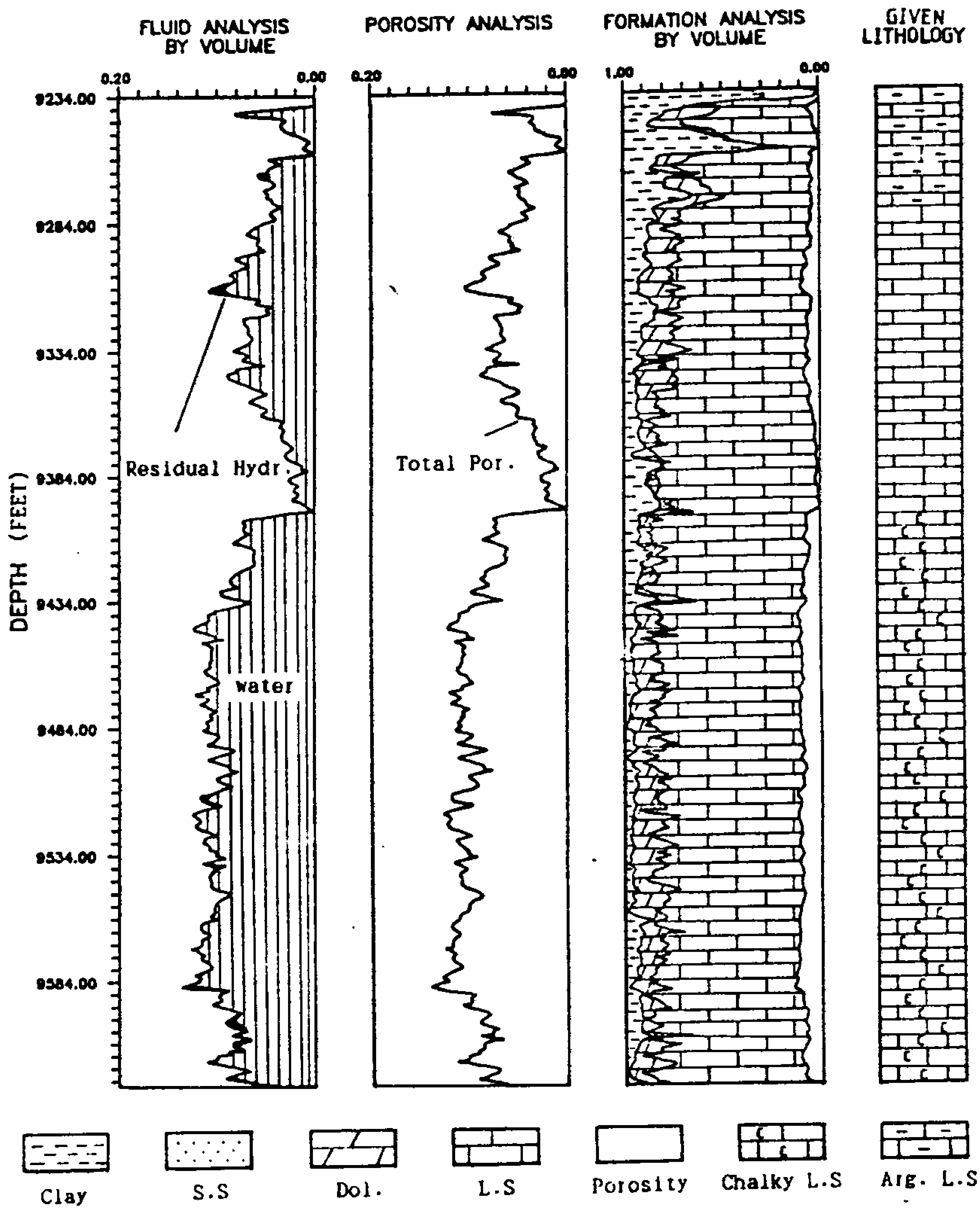

Fig.7 Continuous representation of fluid, porosity and lithology foot by foot in C4NA-1 well.

قدم بعد قدم تقيما لبعض تكاوين الحجر الجيرى الطباشيرى

للدكتور / نادر حسنى الجندى
كليه العلوم - جامعه طنطا

لا تعتبر عادة تكاوين صخر الطباشير من صخور خزانات البترول إلا تحت ظروف معينه مثل تعرضها لعملية التكسير أو التحول إلى صخر الدولوميت وذلك لزياده المساميه المؤثرة وبالتالى النفاذيه ومن هنا كان ضروريا عدم اغفال مثل هذه النوعيه من الصخور عند البحث عن البترول ٠

ويهتم هذا البحث بتقيم تكوين سدر المكون من صخور الطباشير من خلال بئرين حفرا فى الجزء الاوسط بخليج السويس وذلك بالتطبيق المباشر فى بعض المعدلات المبسطه المقترحه ٠ وقد مثلت نتائج الدراسه البتروفيزيقيه لكل عمق بيانيا ٠ واثبتت الدراسات وجود بعض الطبقات ذات المساميه الجيده ولكنها فقيره بالبترول فى القطاع المدروس ٠