An Integrated Approach To Determine Shale Volume And Hydrocarbon Potential In Shaly Sand

*G.M. Hamada**

ABSTRACT

One of the most controversial problems in formation evaluation is the shale effect in reservoir rocks. An accurate determination of formation porosity and fluid saturation in shaly sand is subjected to many uncertain parameters, all are induced by the existence of shale in pay formation.

This paper presents a comprehensive approach for handling this problem of shaly sand. An integrated algorithm is provided to calculate the accurate value of shale volume from different shale indicator tools and thereafter the effective porosity is determined. For different shale models, the water saturation and movable oil profiles are produced. The hydrocarbon saturation profiles have been calculated using a laminated shale model . Applying the present technique, two actual cases were processed, where shale volume, hydrocarbon saturation and movable hydrocarbon are determined directly for given sets of data. The validity of the values of petrophysical parameters determined by the presented integrated approach is confirmed through the comparison with measured petrophysical parameters on collected core samples from shaly sand sections from the same wells.

INTRODUCTION

Through the years, log interpretation has been performed in a sequential process of logical operation. The log analyst determines one parameter and then another until the the problem is solved. This approach has the advantage of being understandable, independently structured and logically acceptable. In this paper, the developed approach to evaluate shaly sands is a computer-processed log interpretation scheme designed around that concept. It uses a structure independent of logging suite and models to determine shale characteristics and hydrocarbon potential of a shaly sand formation.

The occurrence of shale in reservoir rocks can result in erroneous values of water saturation and porosity as calculated from well logs. Doll (1953) referring to the log interpretation of resistivity logs wrote that the most important problem that has received thus for no satisfactory solution is that of shaly sand. Doll's goal of solving this problem is as worthy and difficult today as it was 40 years ago. Aside from shale effects on porosity and permeability, the electrical properties of reservoir rocks, consequently their fluid saturation are sensitively affected by the

* Petroleum Engineering Dept., Faculty of Engineering, Cairo University, Giza, Egypt

existence of shale. The way shaliness affects log responses depends on the proportion of shale, the physical properties of shale, and the way it is distributed in the host layer. Shaly material can be distributed in the host layer in three ways (laminar , structural, and dispersed), **Fig.** 1. All these forms may occur simultaneously in the same formation. Frequently, however, shale in only one form is predominant and simplified models can provide reasonable porosity and water saturation (Schlumberger, 1967; Clavier et al, 1977; Hilchie, 1982; Worthington, 1985; Oil Field Review, 1989; Saner et al, 1994) .

There are basically two main problems in the evaluation of shaly sand; porosity and water saturation. In the determination of effective porosity and water saturation, shale characteristics and volume must be accurately calculated. The determination of water saturation in shaly sand can not be accurately obtained by the use of classical water saturation equation. Therefore, it is necessary either to modify the saturation equation or to develop a new model to relate rock resistivity to water saturation in shaly sand. In the Gulf of Suez region, qualitative evaluation of shaly sand may be considered simple. In the other side, an accurate quantitative evaluation of shaly sand reservoirs requires the use of adequate logging suites. In this paper, an integrated approach is developed to provide reasonable values of effective porosity and oil potential of shaly sand formations using most of the available logging information. This approach is applied on two wells in the Gulf of Suez producing from shaly sand formations.

DETERMINATION OF SHALE VOLUME AND POROSITY

The way shale affects a log response is controlled by type of shale, shale volume and mode of shale distribution. There are two types of shale, effective shale (montmorillonite and bentonite) and passive shale (kaolinite and chlorite) . Effective shale has significant CEC (cation exchange capacities), while passive shale has essentially zero CEC. Effective shale can be identified by most of the shale indicator tools, whereas, passive shale is recognized only by neutron tool. This means that the latter type of shale is difficult to distinguish from the sand on logs other than neutron. Regional experience is required to determine the mode of shale distribution. Derived log porosity value is composed from two terms, an effective porosity term and a shale porosity term (shale porosity and shale volume). Therefore, in order to obtain the effective porosity of a shaly sand , both shale volume and shale porosity should be accurately defined.

Shale Volume Determination

The determination of shale content is necessary to accurately derive porosity from porosity logs. Shale volume may be determined easily by one of three techniques. These are the gamma ray log, the resistivity log, and the density-neutron logs. **Fig. 2** .illustrates the available log data for Well 1 , Gulf of Suez. In this case, shale volume will be calculated using three techniques. The lowest value of shale volume will be used in the calculation, in order to minimize errors due to the possible existence of passive shales and radioactive sands.

Gamma Ray Shale Volume The gamma ray (GR) has been used as one of the independent shale indicators in the evaluation of shaly sand. In the qualitative evaluation of shale content, it is assumed that radioactive minerals other than shale are absent.

Shale volume ,Vsh, is derived from GR response through the relationship;

$$\mathbf{Vsh = 0.33\,(2^{2 I_{GR}} - 1)} \qquad \text{(1) (Dresser, 1982)}$$

$$\text{and } \mathbf{I_{GR} = (GR - GR_{cl}) / (GR_{sh} - GR_{cl})}$$

Where GR_{cl} is GR against clean sand , GR_{sh} is GR against adjacent shale layer and GR is the log response for the target layer. Equation (1) is used to determine shale volume using the GR readings for shaly sand reservoirs encountered in well 1, Fig. 1. The presence of other radioactive minerals will cause the calculated shale volume in this case to be too high. Therefore, it is not recommended to rely on GR only and go for another technique to determine the accurate shale volume. **Figure** 3 includes the GR as first option , shale volume determination, of the developed approach to evaluate shaly sand.

Resistivity Shale Volume The use of resistivity log data as a shale indicator is dependent on the contrast of the resistivity response in shale and in a clean pay sand. Dependent on porosity, lithology and water salinity different resisitivity contrasts are normally seen. This means that the calculated shale volume from resitivity may be too high, too low or both.
Poupon et al (1970) proposed the following relation for estimating shale volume Vsh from resistivity data,

$$\mathbf{V_{sh} = [\,(R_{sh}\,(R_{max} - R_t)) / (R_t\,(R_{max} - R_{sh}))\,]^{1/b}} \qquad \mathbf{(2)}$$

Where R_{max} is maximum resistivity in clean pay sand , R_t is the shaly sand layer resistivity and b is an empirical constant which for the reservoir rock studied was assumed to be 1.4. Shale volume calculated by **Eq**. 2 is considered in the algorithm shown in **Fig** 3. In this algorithm, Rsh is taken against the near by shale while Rmax is measured against the most clean oil sand for Wells 1 and 2.

Neutron- Density Shale Volume The neutron - density crossplot can be used to determine shale volume and effective porosity if the zone is composed of only effective shales and sands. The presence of passive shales or other reservoir rocks will result in a too high calculated shale volume and too low effective porosity.

Shale volume (Vsh) and effective porosity (ϕe) are calculated by the solution of the simultaneous equations 3 and 4 for density and neutron responses.

$$\mathbf{\phi d = \phi e + Vsh\,\phi dsh} \qquad \mathbf{(3)}$$

$$\mathbf{\phi n = \phi e + Vsh\,\phi nsh} \qquad \mathbf{(4)}$$

ϕ_d is the density derived porosity, ϕ_n is the neutron derived porosity, ϕ_{dsh} is shale density porosity, ϕnsh is shale neutron porosity and ϕe is the shaly sand effective porosity. These equations are written assuming that neutron and density responses are not affected by the mode of shale distribution. The calculated shale volume can be optimistic or pessimistic depending on the considered matrix parameters. **Fig.** 3 illustrates flow chart for the developed approach to calculate shale volume using the density- neutron crossplot together with the GR and Resistivity methods. In this approach three values of shale volumes are produced , but the lowest value is considered the shale volume value in the consequent calculation of porosity and hydrocarbon saturation. **Fig**. 4 shows shale volume distribution profiles for Well 1 and Well 2 . From **Fig**.4, it is obvious that the shale is a laminated shale with sand layers containing different percentages of shales.

Porosity Determination

In determining the effective porosity in a shaly sand, the characteristics of the shale and shale volume must be well known. In hydrocarbon bearing shaly sand formations, the problem is further complicated by the effect of residual hydrocarbon on the porosity logs. Therefore, the porosities ϕd and ϕn in Equations (3& 4) must have been corrected for the effect of residual hydrocarbon before dealing with the equations.

The density derived porosity ϕd is corrected from the residual hydrocarbons by the formula;

$$\phi d = [\delta ma - \delta + 1.07 (Rmf/ Rxo)^{1/2} (1.11- 1.24\delta h)] / (\delta ma - 1 + 1.07(1.11-1.24\delta h)) \quad (5)$$

Where; δma is the matrix density, δ is the log reading δh is the hydrocarbon density, Rmf is the mud filtrate resistivity, Rxo is the flushed zone resistivity, and ϕd is the residual hydrocarbon corrected porosity(Schlumberger, 1967).

The neutron derived porosity ϕn is corrected from the residual hydrocarbon by the formula;

$$\phi n = \phi na / \{(1-Shr) [(\delta mf (1- P) - \delta h - 0.3) / \delta mf (1- P)] \} \quad (6)$$

Where ϕna is the apparent neutron porosity , P is the mud filtrate salinity (10^6 ppm) and ϕn the neutron porosity corrected from hydrocarbon effect (Dresser, 1982).

In order to determine the effective formation porosity, shale volume has to be accurately determined and the residual hydrocarbon effect removed. This is following the proposed scheme in **Fig.** 3. **Fig.** 4 depicts the effective porosity profiles for Wells 1 and 2 together with the shale volume. Depending on the available data, porosity could be determined either by neutron - density equations or by the proposed approach. In the case of neutron- density , the two Equations (3 & 4) are solved together and provide shale volume and effective porosity. In the case of the developed approach, shale volume is calculated , the neutron and density porosity are corrected for the effect of residual hydrocarbons and then the effective porosity is calculated using the following formula (Schlumberger, 1987).

$$\phi_e = (\phi_d + \phi_n) / 2 \qquad (7)$$

The porosity profile which is shown in **Fig.** 4 is produced using Equation (6) after carrying out the corrections due to the presence of shale and hydrocarbon effect .

DETERMINATION OF WATER SATURATION

Shaly sand corrections all tend to reduce the water saturation relative to that which be calculated if the shale effect is ignored in the evaluation processes. Over the years, for shaly sands a large number of models relating fluid saturation to resistivity have been developed according to the geometric form of existing shales (laminated, dispersed and structural). All these models are composed of a shale term and a sand term. The shale term may be independent or not of the sand term. All models are reduced to the clean sand model when the volume of shale is insignificant. For relatively small shale volumes, most shale models might yield quite similar results (Waxman and Smits, 1968 ; Poupon et al , 1970; Bussian, 1984 and Schlumberger, 1987).

The comparison of the various water saturation equations in shaly sand shows that: 1) The clean sand equation does not compensate for clay conductivity, the water saturation it computes is too high; 2) Simandoux or Indonesia equation (Dresser, 1982) is essentially applicable to laminated clay models, with some adaptation for non linear behavior of shale electrical properties and 3) Waxman- Smits or Dual Water model (Clavier et al , 1977) is essentially designed for the case of dispersed or structural clay models and as they account for the effects occurring in the pore space, they provide lower water saturation than laminated models (DeWhite, 1950;, Simandoux, 1963; Waxman and Smits, 1968; Fertl and Hammack, 1971; Clavier et al, 1977 and Dresser, 1982).

Local experience in the Gulf of Suez for Wells 1 and 2 showed that the geometric form of the existing shale is a laminated one. Consequently, the Indonesia equation was used to calculate water saturation in this shaly sand case. Indonesia Equation is defined as ;

$$1 / R_t = [((V_{sh}^{1-Vsh/2}) / R_{sh}^{0.5} + \phi_e^{m/2}))^2 . S_w^n \qquad (8)$$

For the case where a = 0.81 and m = n = 2 Equation (8) will take the form;

$$S_w = [1 / ((V_{sh}^{1-Vsh/2} / R_{sh}^{0.5}) + \phi_e / (0.81 R_w^{0.5}))] . 1/R_t^{0.5} \qquad (9)$$

Equation (9) represents the basic formula to determine the water saturation and hydrocarbon saturation (1-Sw) for the studied reservoirs in the two wells. The proposed approach to evaluate shaly sand uses Equation (9) to determine the hydrocarbon potential. **Fig. 5** illustrates water and hydrocarbon volume profiles for the studied reservoirs ,Wells 1 and 2, derived from the application of Equation (9). Against shale streaks, both water saturation and hydrocarbon saturation are not calculated, only for layers of shaly sand (Vsh less than 20%) are the water saturation and hydrocarbon saturation profiles are produced for the corresponding section for Wells 1 and 2 in the Gulf of Suez. It is worth to emphasize that the effective porosity, ϕe, in Equation (9) is the porosity corrected for shale and residual hydrocarbon effects. In this way, the integrated approach provides the user with a good idea about the formation lithology and an accurate determination of the hydrocarbon potential and effective porosity of the shaly sand formation. It is easy to change the input parameters and equations depending on the available data and also it is designed to quit or enter the program at any desired stage.

DETERMINATION OF MOVABLE HYDROCARBON VOLUME

The ability of the mud filtrate to move oil in the invasion processes implies that the formation exhibits permeability to oil and that it could be a hydrocarbon potential formation. This ability is diagnosed by the difference between flushed zone saturation, Sxo, and virgin zone saturation , Sw, (Sxo- Sw).ϕe. Sxo is determined in the shaly sand layer considering the existing shale is following the laminated model. The Indonesia equation is written for Sxo as follows;

$$S_{xo} = [\, 1 / ((V_{sh}^{\,1-Vsh/2} \; / \; R_{sh}^{\,0.5}) + \phi_e / (0.81\, R_{mf}^{\,0.5})) \,] \,.\, 1 / R_{xo}^{\,0.5} \qquad (10)$$

The bulk volume of moved hydrocarbons is evaluated for producing sections in Wells 1 and 2 using Equations (9 & 10) and the definition of the moved hydrocarbon volume (Sxo- Sw). ϕe. **Fig. 6** shows the water volume profile together with the moved volume hydrocarbon profile. The area of the moved hydrocarbon shown in **Fig. 6** indicates the quantity of the hydrocarbon which could be produced with a primary or secondary recovery method . The integrated approach illustrated in **Fig. 3** including Equation (9) was used to determine the movable hydrocarbon.

In the approach developed to evaluate shaly sand layer, the effective porosity, water saturation, and movable hydrocarbon saturation were determined using the available logging data.. This approach could be modified depending on the available log data and shale model. These modifications might be possible, keeping in mind ,the concept that any system should remain balanced or over determined (i.e. the number of logging input parameters should not be less than the number of expected unknown variables).

COMPARISON BETWEEN COMPUTED AND MEASURED VALUES

This section is devoted to test the degree of validity of the values of shale volume, effective porosity and water saturation for shaly sand layers which are determined from the presented integrated approach and also to test the reliability of the developed technique. In order to achieve this goal a certain number of core samples were analyzed for Well 1 (8 core samples) and for Well 2 (10 core samples) from the Nubian sandstone formation. The core samples were selected at certain depths shown in Table 1 and were specially preserved. This preservation was to keep the samples under conditions as similar as possible to reservoir conditions. This is an essential requirement for carrying out special core analyses (water saturation and effective porosity measurements).

From the core samples descriptions and analyses performed by the Suez Oil Company, it was found that the core samples varied from shale to shaly sand. Table 1 contains the details of samples description. From the table, it is obvious that there is no significant difference between the calculated shale volume values and the measured ones.

The effective porosity of the core samples was measured using gas Porosimeter, the confining pressure was arranged in such a way to keep the samples under pressure conditions similar to the reservoir conditions. Table 1 shows the measured effective porosity for samples from Wells 1 and 2 together with the effective porosity determined by the proposed technique. It is worthy to notice the high accuracy between the measured and determined effective porosity for the two wells.

To measure core sample water saturation, the core sample resistivity, Rt, ohm-m. is measured by the Resistivity meter, for the unknown water saturation. Formation water resistivity , Rw, ohm-m, is defined for a given formation water salinity (12,0000 ppm) and formation temperature 180° F and the effective porosity, ϕ, is taken from the Porosity meter measurement values. Now, with the use of the empirical relationship for water saturation calculation (Sw = SQRT (0.81 ϕ^{-2} Rw/ Rt) for shaly sand core samples, the water saturation is calculated for each core sample (Wells 1 & 2). Table 1 illustrates the measured water saturation values and the values determined by the developed technique for the two wells. There are some differences between the calculated and measured values of water saturations. These differences might be caused by errors in the laboratory measured saturation, the preservation conditions of core samples, and certain assumptions in the water saturation formula used in calculating water saturation of the core sample.

Table 2 illustrates the average water saturation determined by the proposed shaly sand approach for the existing shale model and the values of the average water saturation determined by clean sand equation for samples from Wells 1 and 2, (Sw = (Rw/ϕ^2 . Rt)$^{0.5}$). The standard deviation (σ_{sw}) in water saturation values is also shown in the table. By inspecting the water saturation values and the associated errors shown in table 2, it can be noticed that the values predicted by the present technique are more accurate than those calculated by the clean sand equation. We believe that this conclusion must be strongly considered in the evaluation of any shaly sand producing sections taking into consideration the type, model , and volume of shale in the sand section.

The foregoing comparison between the measured and computed shale volume, effective porosity, and water saturation values confirms the reliability of the developed integrated approach to evaluate shaly sand petrophysical parameters for this case and for similar cases in other areas, and the validity of the values of shale volume, effective porosity and hydrocarbon potential of shaly sand layer provided by the proposed technique.

CONCLUSIONS

1- Evaluation of shaly sands is somewhat complex. All logging responses and interpretation techniques are influenced by the shale. Regardless of the basic assumptions, most of the shaly sand models employ a weighted average technique to account for the relative contributions of the sand term and the shale term to the overall shaly sand response.

2- The developed integrated approach to determine shale volume and hydrocarbon potential in shaly sands can provide the user with the most important petrophysical parameters; shale volume, effective porosity, water saturation, and movable hydrocarbon potential.

3- The presented approach encompasses the following objectives:
- Uses all available information- log data, interpretation models and local knowledge,
- Provides results that optimize the input data,
- Ensures quality control of interpretation results, and
- Easy to implement new logging data or different interpretation models depending on the local experience and available data.

4- The validity of shale volume , effective porosity, and water saturation values derived from the proposed approach and the reliability of the presented integrated approach are confirmed through the comparison with the measured parameters with high confidence.

NOMENCLATURE

a	Tortousity factor
b	Empirical local factor
d	Formation density, g / cc
δ_h	Hydrocarbon density, g / cc
δ_{mf}	Mud filtrate density, g / cc
δ_{ma}	Matrix density, g / cc
GR	Gamma ray, API
I_{GR}	Index of Gamma ray
m	Cementation factor
n	Water saturation exponent
NA	Not available
P	Mud filtrate salinity, ppm
σ_{sw}	Standard error in water saturation
R_{sh}	Shale density, g / cc
R_c	Clay density, g / cc
R_t	Formation resistivity, Ohm meter
R_{xo}	Flushed zone resistivity, Ohm meter
S_w	Water saturation, %
S_{xo}	Flushed zone saturation, %

S_{hr} Residual hydrocarbon saturation, %
ϕ_d Density derived porosity, %
ϕ_n Neutron porosity, %
ϕe Effective formation porosity, %
V_{sh} Shale volume, fraction

ACKNOWLEDGMENT

I thank the Suez Oil Company (SUCO) for releasing log and core data, for core laboratory assistance, and for permission to publish this paper. I also thank Prof. A.M. Abouzeid , Cairo University, for critically reviewing the manuscript and for technical conversations.

REFERENCES

Bussian, A.E., 1984, A Comparison of Shaly Sand Models, Paper E, in 24th Annual Logging Symposium: Society of Professional Log Analysts

Clavier, C., Coates, G. and Dumanoir, J., 1977, Theoretical and Experimental Bases for The Dual Water Model for Interpretation of Shaly Sands, Paper SPE 6859, in 52nd Annual Technical Conference and Exhibition: Society of Professional Engineers

DeWhite, L., 1950, Relation Between Resistivities and Fluids Contents of Porous Rocks: Oil and Gas Journal (August, 24), p. 120-132

Dresser Atlass, 1982, Well Logging and Interpretation Techniques, Dresser Ind. Inc.

Fertl, W.H. and Hammack, C.W., 1971, A Comparative Look at Water Saturation in Shaly Pay Sand, in 12th Annual Logging Symposium Transaction: Society of Professional Logging Analysts

Hilchie, D.S., 1982, Applied Open Hole Log Interpretation for Geologist and Engineers: Douglas W. Hilchie Inc., Golden Colorado

Oil Field Review, 1989, Electrical Conduction in Shaly Sands: Schlumberger Oilfield Review, v.2, no. 3, p. 43-55

Poupon,A., Clavier, C., Dumanoir,J., Gaymard,R. and Misk, A., 1970, Log Analyses of Sand-Shale Sequences- A Systematic Approach: JPT (July, 1970)

Saner, S., Cagotry,M.N. and AlFassail, Kh., 1994, Shaliness Effect on The Log-Derived Archie m Cementation Factor: Study of a Saudi Arabian Sandstone Reservoir: The Log Analyst, v. 35, no. 6, p. 16-27

Schlumberger, 1967, Well Evaluation Conference, Middle East .

Schlumberger, 1987, Log Interpretation Principle / Application, NewYork.

Simandoux, P., 1963, Mesure Dielectriques en Milieu Poroux, Application a Mesure des Saturations en Eau, Etude du Compartement des Massif Argileaux: Reveu de l' Institute Francais du Petrole (Supplementary Issue, 1963).

Waxman,M.H. and Smits, L.J.M., 1968, Electrical Conductivity in Oil Bearing Shaly Sands: Society of Petroleum Engineers Journal, June, p. 107-122.

Worthington, P.E., 1985, The Evolution of Shaly Sand Concepts in Reservoir Evaluation: The Log Analyst, v. 26, no. 1, p. 23-40.

Table 1 Comparison between the computed and measured core samples values: effective porosity, shale volume, and water saturation for wells 1 and 2

Depth, ft.	Effective porosity, frac.		Shale volume, frac.		water saturation, frac.	
	Measured	Computed	Measured	computed	Measured	Computed
Well 1						
11142	0.172	0.153	0.021	0.0267	0.112	0.109
11230	0.135	0.133	0.0142	0.0133	0.070	0.068
11540	0.130	0.122	0.15	0.1466	0.105	0.102
11635	NA	NA	0.74	0.69	NA	NA
11740	0.132	0.133	015	0.147	0.101	0.0138
12045	0.125	0.120	0.085	0.0867	0.24	0.208
12255	0.0921	0.104	0.129	0.133	0.131	0.144
12340	0.0891	0.0933	0.149	0.1533	0.181	0.169
Well 2						
11430	0.118	0.123	0.092	0.0969	0.205	0.203
11550	NA	NA	0.405	0.385	NA	NA
11740	0.098	0.0923	0.081	0.0615	0.131	0.133
11910	NA	NA	0.388	0.343	NA	NA
12030	0.110	0.102	0.152	0.154	0.08	0.076
12130	0.172	0.176	0.241	0.246	0.071	0.049
12175	0.132	0.138	0.158	0.152	0.107	0.121
12250	NA	NA	0.84	0.787	NA	NA
12270	NA	NA	0.76	0.692	NA	NA
12350	0.134	0.1338	0.12	0.108	0.67	0.581

Table 2 Comparison between the average saturation values computed by clean sand Eq. and used Eq. for shaly sand sections in wells 1 and 2

Well No.	Clean Sand Equation		Used Equation	
	Sw %	σ_{sw}	S_w %	σ_{sw}
1	17.7	0.34	13.3	0.0725
2	16.1	0.38	11.2	0.0686

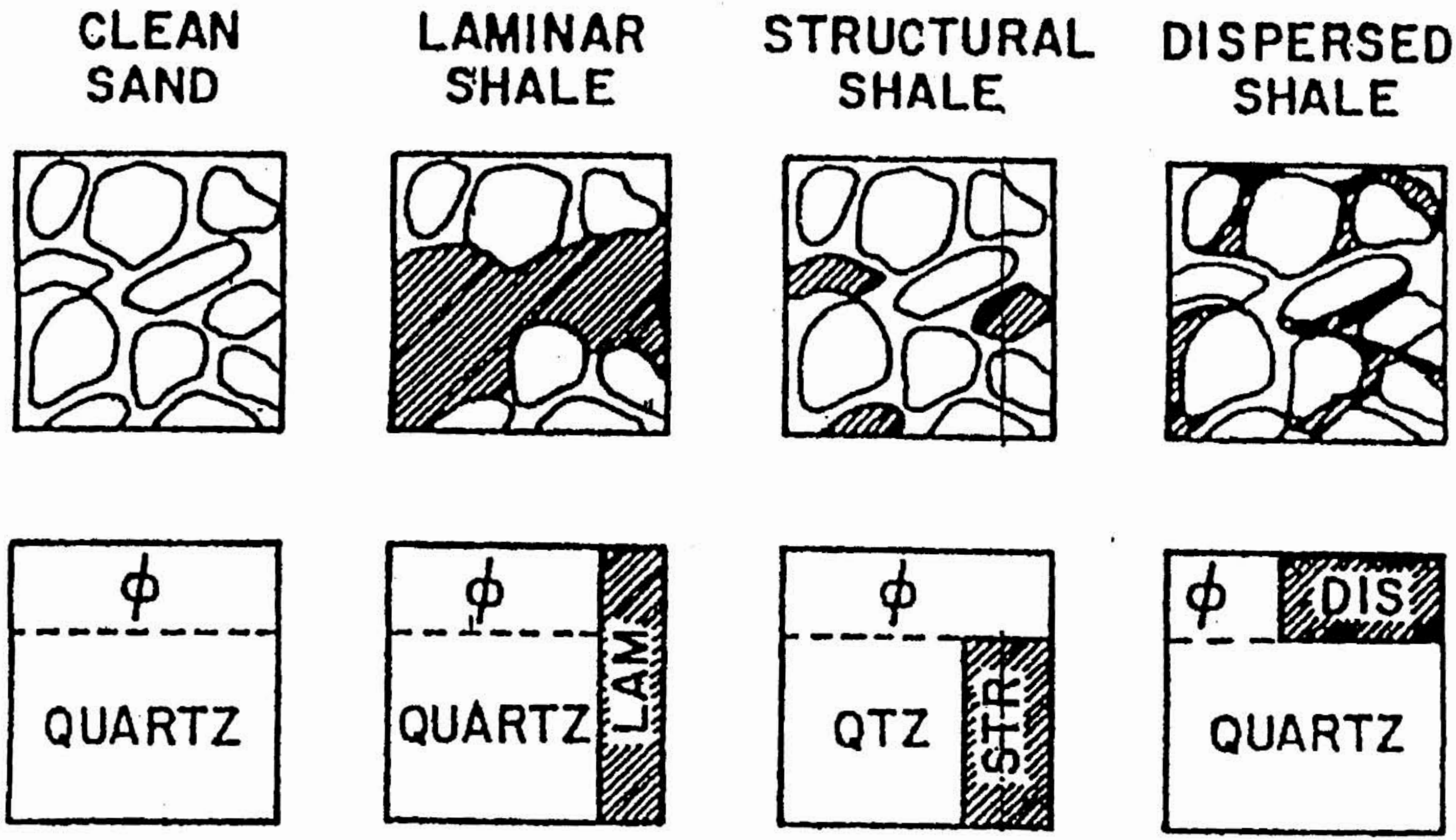

Fig. 1 Forms of shale classified by mode of distribution, (Schlumberger,1987)

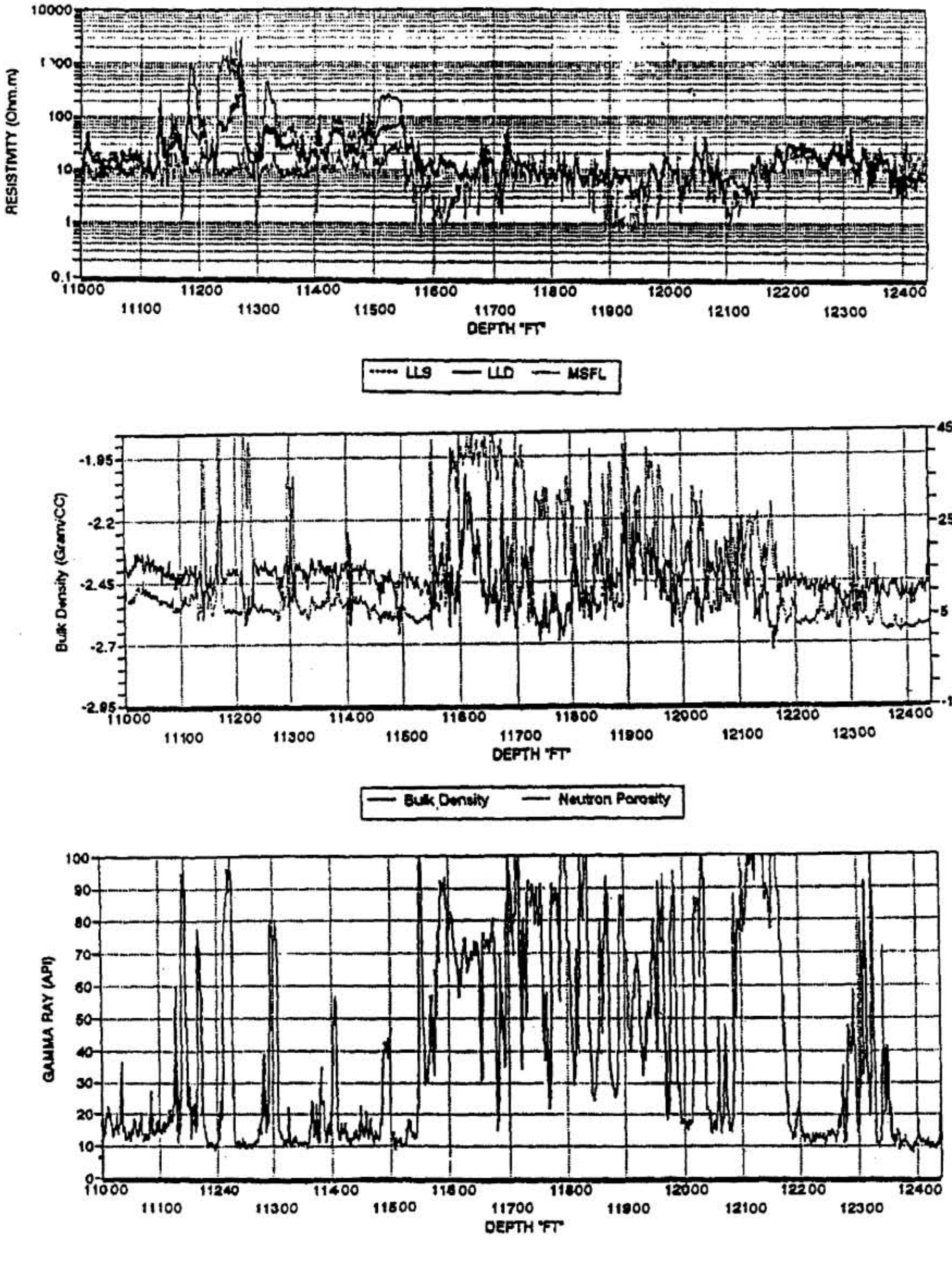

Fig. 2 Log data record for shaly sand sections, well 1, (SUCO documents)

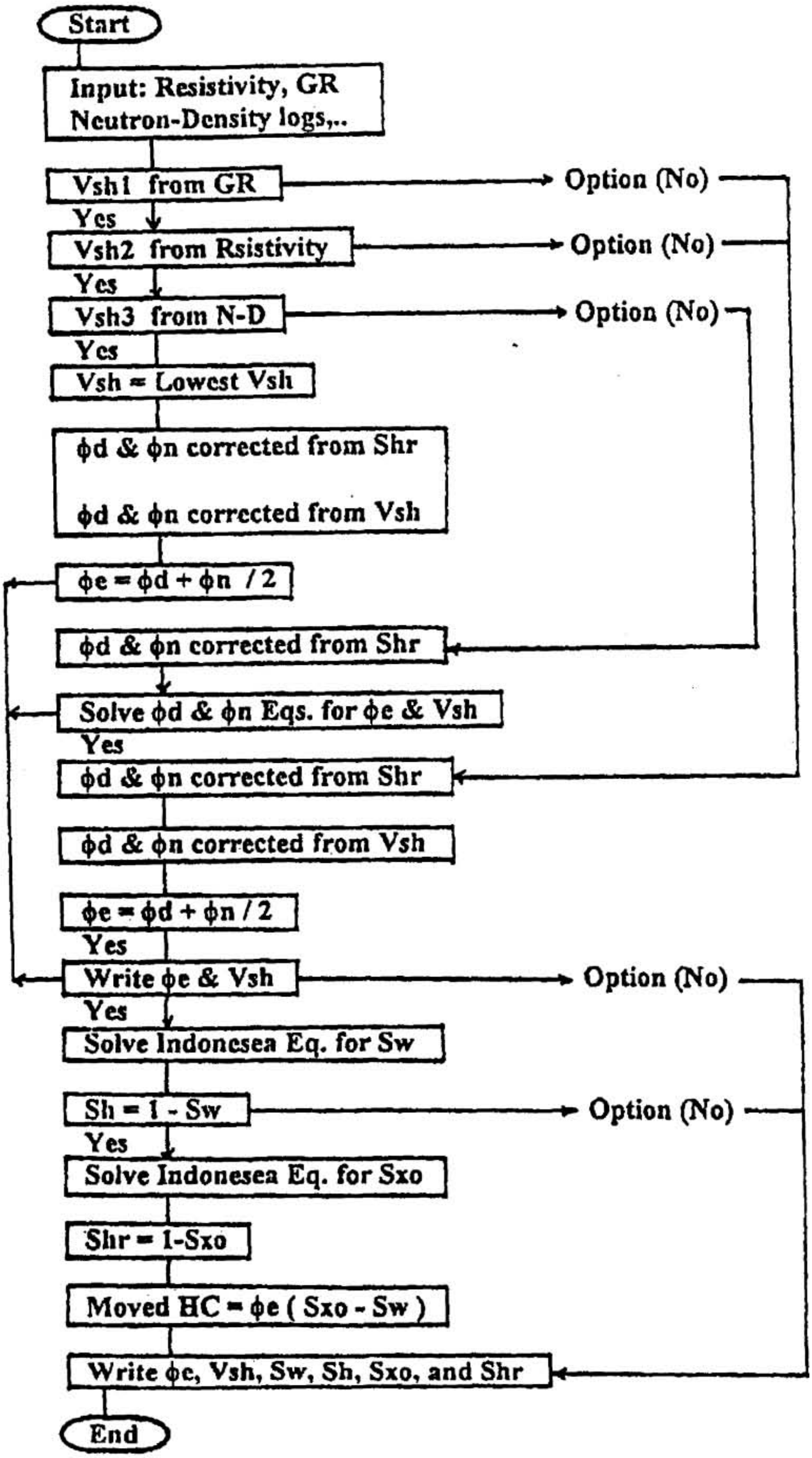

Fig. 3 Flow chart of the used technique to evaluate shaly sand

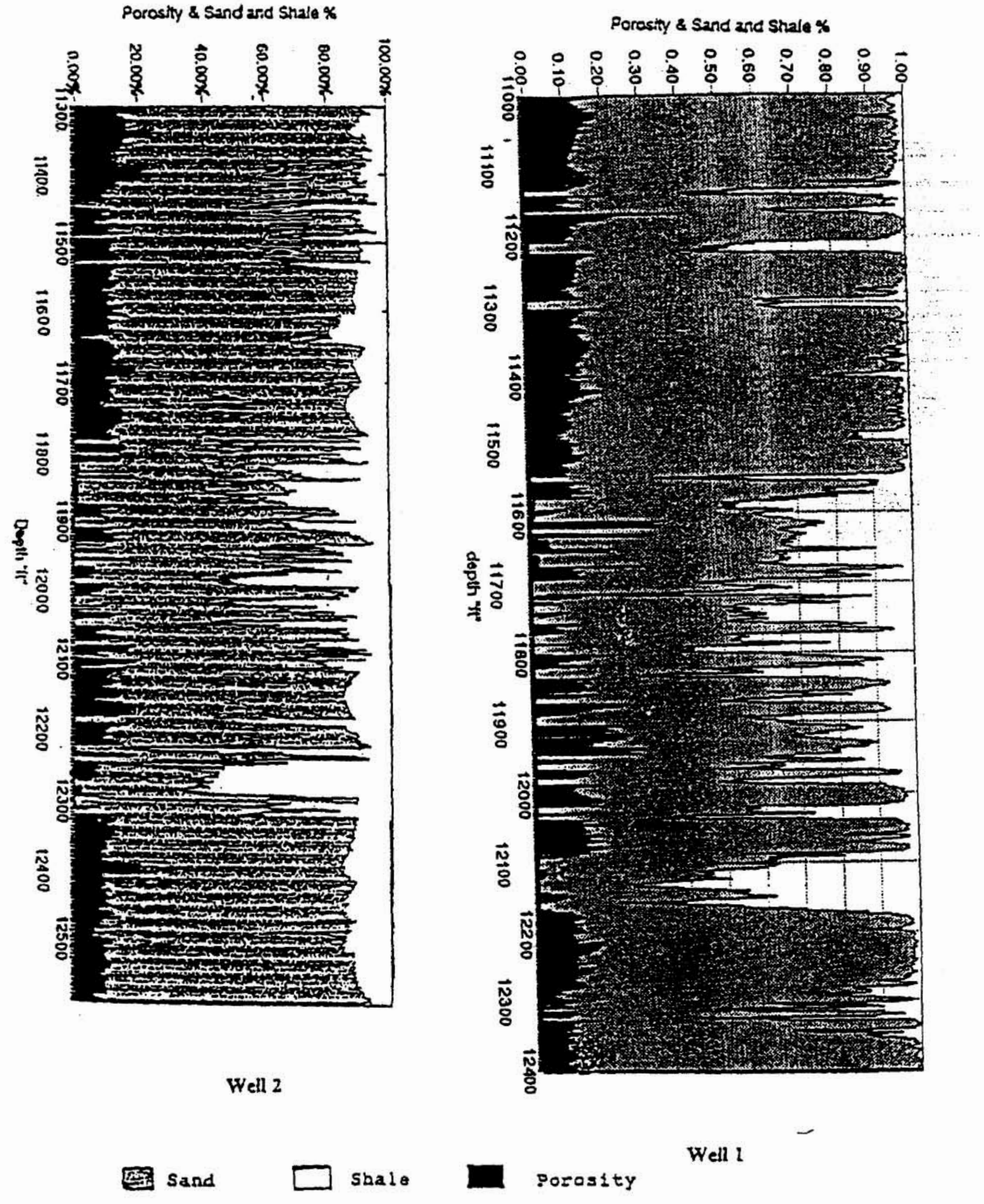

Fig.-4 Porosity and shale volume for shaly sand sections in wells 1 and 2

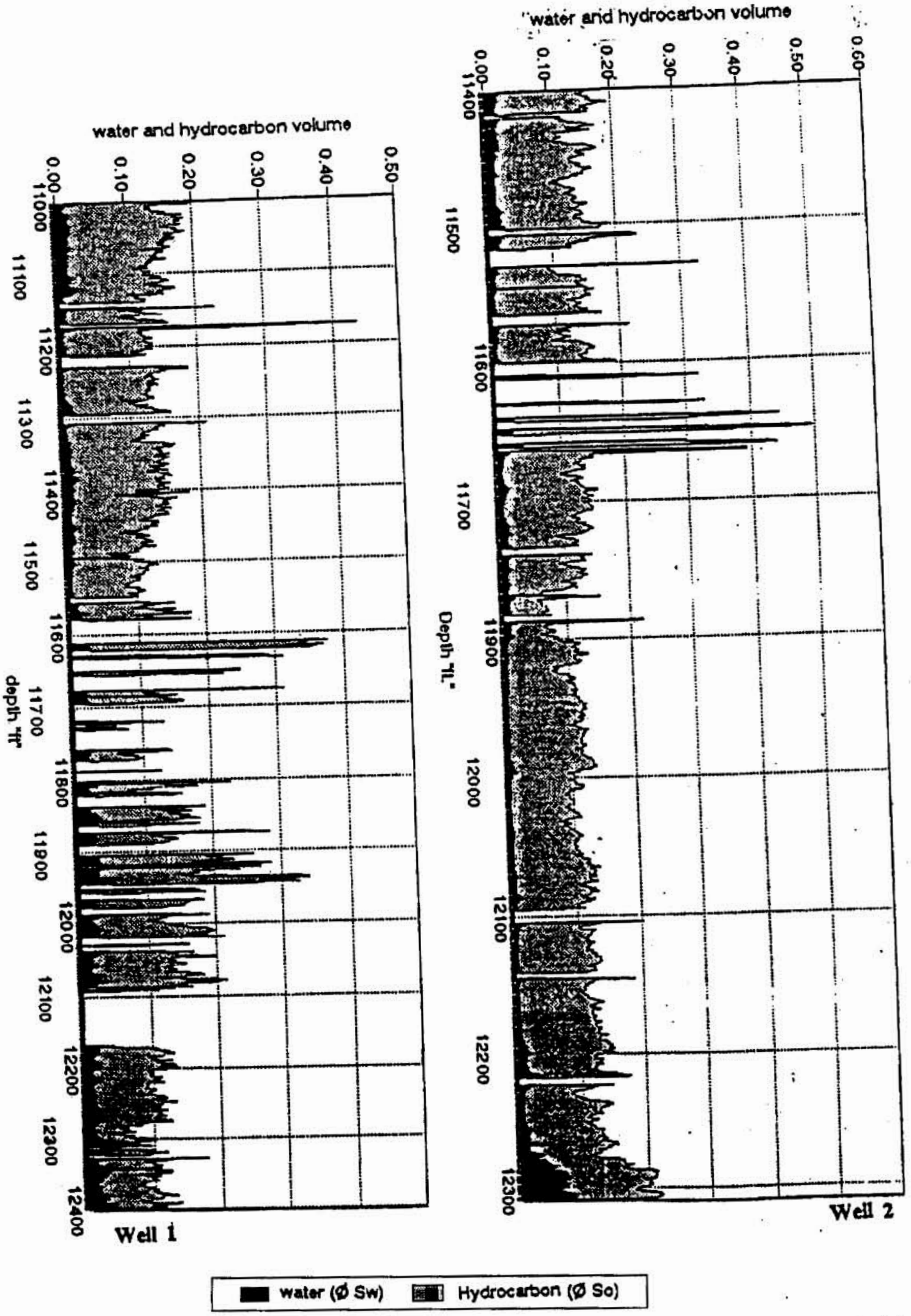

Fig. 5 Water volume and hydrocarbon volume for shaly sand sections in wells 1 and 2

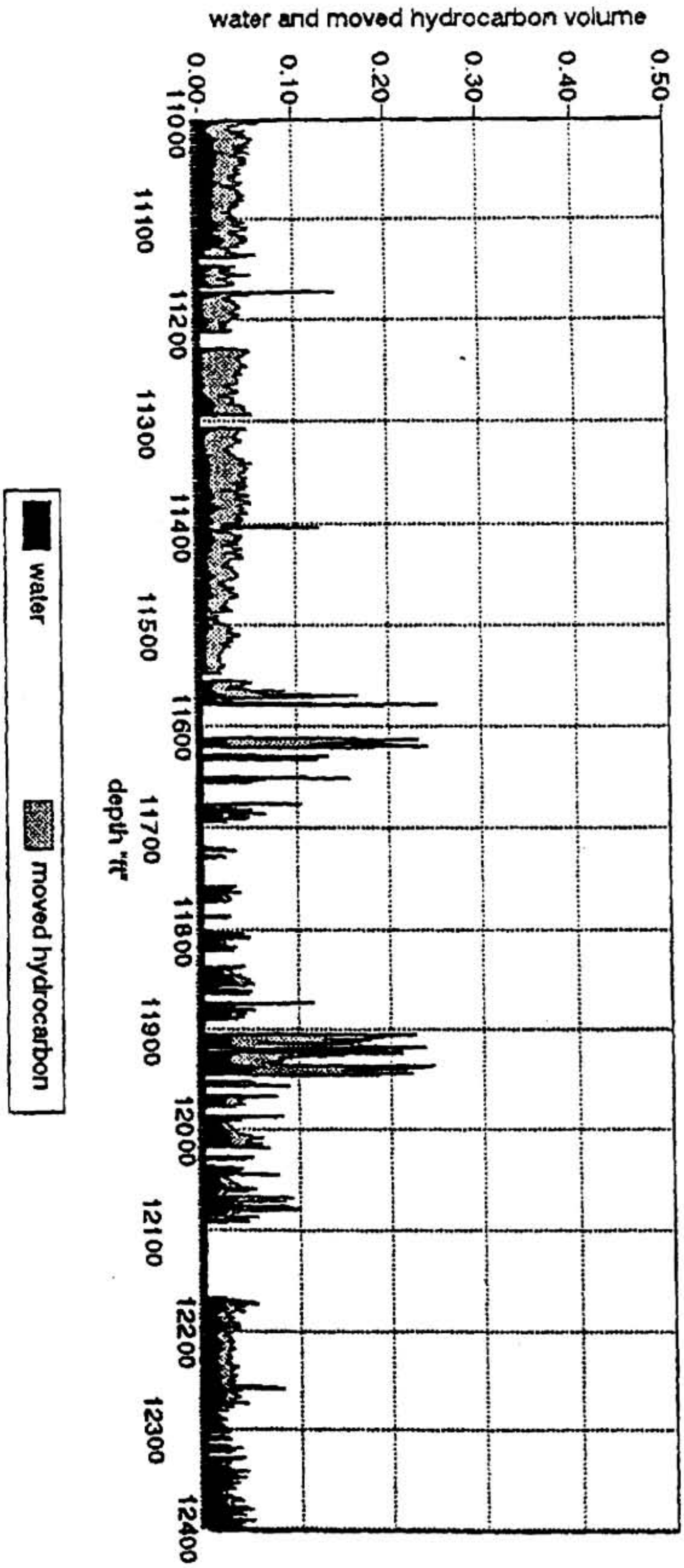

Fig. 6 Water and moved hydrocarbon volumes for shaly sand sections in well 1