BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1984/8

RECORD

A DUAL WATER WIRELINE LOG
INTERPRETATION MODEL,
COMPUTER PROGRAM DW.

by

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1. Introduction

Development of the "Dual Water" wireline log interpretation model started in May 1983 and was adapted over a period of ten months so that it could cope with a wide variety of field conditions. The computer program itself is written in Fortran 77 language and is based on the "Cyberlook" program used by the Schlumberger wireline well logging company. The main sources of information in the form of equations and theoretical explanation of the model have come from Schlumberger publications. The aim of the program is to determine effective water saturation and porosity from raw wireline log data.

The dual water model is not intended to replace the program LOG4 (a shaly-sand log interpretation program) written by L.E. Kurylowicz in 1978. It is, however, presented as an alternative log interpretation model, as the water saturation equations used in the "dual water" model program (program DW) are derived from a different source to the Simandoux equation used in LOG4. The dual water model has two advantages over the LOG4 program. Firstly, the water saturation equation in the dual water model can be used world wide (theoretically), whereas the Simandoux water saturation equation in LOG4 has been developed for the type of conditions found in Indonesia and Australia. Secondly, the dual water model equations appear to be a lot more robust than the LOG4 equations, in that they can handle 100% shaly formations and 100% water filled reservoir sands without encountering the arithmetic problems found with the LOG4 program.

The dual water model has been designed to be completely compatible with LOG4 data files and hence no extra effort is required to run the DW program. The model has found a place in BMR's log interpretation capability and is currently used to calculate an initial estimate of porosity and water saturation over an entire hydrocarbon bearing interval. LOG4 is then used for a more qualitative calculation of these parameters over specific reservoir sands.

2. Background and Theory of the Dual Water Model

The name, "dual water model" is derived from the two types of water present in a shaly-sand formation. (Note: the terms "shale" and "sand" are used in the nomenclature of a log interpreter, rather than being strictly geological. Here, a sand is used to define any porous reservoir rock, while shale is used to describe a mixture of silt and clay and is regarded as having little or no porosity). The two waters involved are (i) the free connate formation water attached by surface tension to the reservoir sand and (ii) the immovable water which is bound to the shale interspersed within the sand. This latter water is bound by the alignment of the dipolar water molecule and the behaviour of the ions dissolved in this water to the electric field generated by the overall negative charge of the clay crystals.

The clay mineral family consists mainly of montmorillonite, kaolinite, vermiculite, illite and chlorite. Each of these five minerals has an overall negative charge (in their dehydrated form) except chlorite. The reason for the negatively charged clay crystal is due to the process of ionic substitution. In montmorillonite for example, the Al^{3+} ion can be substituted by the Mg^{2+} ion in the clay crystal lattice. This substitution would result in one excess electron charge unit. This process occurs in all the negatively charged clay minerals. In chlorite however, there is an excess of positively charged ions in the crystal lattice and this explains the net positive charge of the chlorite crystal. However, the chlorite crystal lattice rarely forms completely and as a consequence, partially formed chlorite crystals are neutralized by hydrated cations in the same manner as the rest of the clay mineral family (Hausenbuiller, 1978).

The Waxman-Smits model first proposed in 1967, suggested that a shaly formation behaved like a clean formation (i.e. a porous sand containing conductive water) except that the bound water appears to be more conductive than expected from its bulk salinity. The dual water model is an improvement over the Waxman-Smits model, as it better fits their experimental data (J.L. Dumanoir).

In terms of the negatively charged clay minerals, this unexpected increase in conductivity is due to the overall negative charge of the dehydrated clay crystal and the behaviour of the ions dissolved in the free formation water near the clay crystal surface. Figure 1 (W.R. Almon, 1981), shows the local ionic concentration as a function of distance from the clay surface. This figure shows how the positively charged ions are attracted to the negative charge of the clay crystal while the negatively charged ions are repelled. The zone in which the cation concentration exceeds the anion concentration is described by the distance Xd and is known as the "diffuse layer" or Gouy layer. The distance Xd has been found to be inversely proportional to the square root of the salinity of the free formation water (W.R. Almon, 1981).

$$\text{i.e.} \quad Xd \propto \left(\frac{1}{\text{salinity}}\right)^{\frac{1}{2}}$$

The positively charged ions are kept some distance from the clay crystal surface by the bound water. Around each clay crystal is a thin layer of water molecules which align themselves in the electric field generated by the overall negative charge of the clay crystal. This thin layer of water is said to be adsorbed to the clay surface. Beyond the adsorbed water is the layer of positively charged ions which are also surrounded by water molecules and are aligned in the electric field of the positive ions. This latter water is known as the water of hydration. Figure 2 (W.R. Almon, 1981) shows the relationship between the clay crystal, positive ions and water molecules. The distance Xh is known as the Helmholtz plane and it describes the minimum possible distance from the clay crystal to the first layer of positively charged ions. The distance Xd = Xh only when the salinity of the free formation water is large enough.

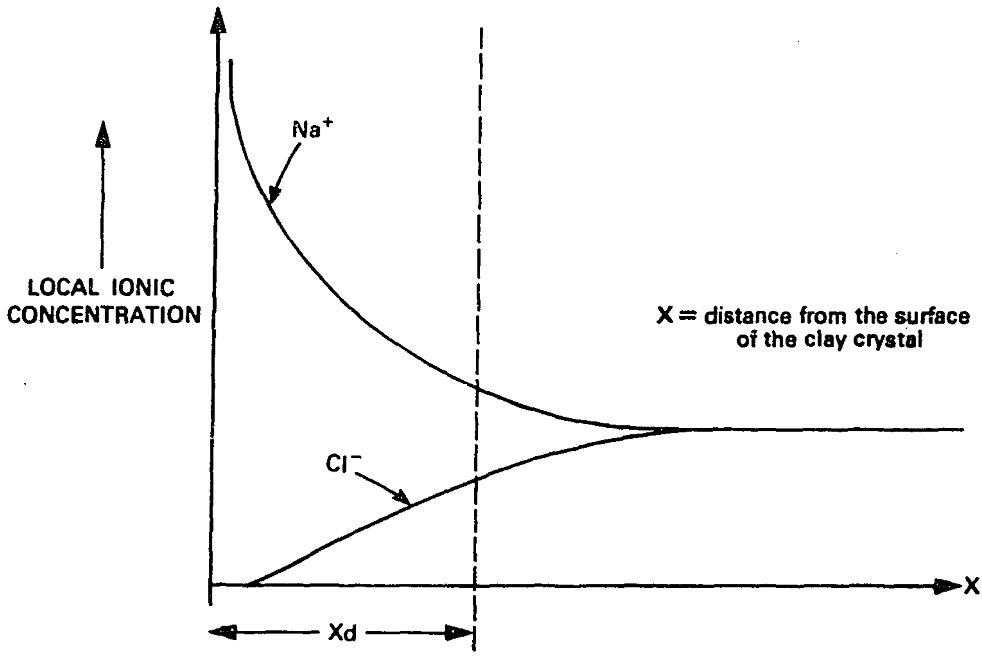

Fig. 1. Local ionic concentration as a function of distance from the clay crystal surface.

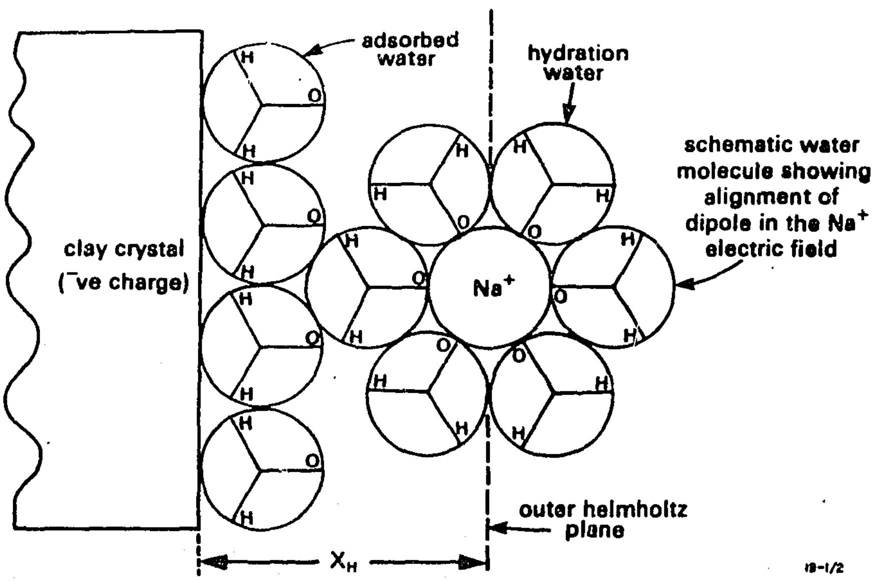

Fig. 2. Schematic view of outer helmholtz plane (ref. W.R. Almon, 1981. Fig. 1 & 2).

Although the distance Xh may be in the order of 6Å (for Na^+), such a fine layer soon becomes significant if the surface area to volume ratio of the clay crystal is taken into account. Calculation of this area to volume ratio yields a figure in the order of 6300 acres per cubic foot compared to 0.1 to 0.2 acres per cubic foot for an average reservoir sand. (J.L. Dumanoir).

The main conclusions derived in this section are summarised by the three points below:

(i) The conductivity of the clay crystal is due to the presence of the positive ions near the clay crystal surface. The exception being fully formed chlorite clay crystals.

(ii) The numbers of sodium ions within the distance Xh is directly related to the surface area of the sodium clay crystal (e.g. kaolinite, illite and montmorillinite).

(iii) Water far from the clay crystal surface has the same properties as the free formation water i.e. distances greater than Xd.

3. Derivation of the Water Saturation Equations (reference Schlumberger 1983 course notes: "Log Evaluation Techniques in Shaly Sands and Complex Lithologies")

The equations developed for the dual water log interpretation model are based on the saturation of the conductive fluids in the shale and the reservoir rock. The equations are derived to satisfy two cases i.e. either the bound water resistivity Rwb is less than the free formation water resistivity Rwf or visa versa. In the first case the theoretical water saturation equation is developed. This equation can be used irrespective of the relative magnitude of Rwb and Rwf however for practical purposes it is only used when Rwb < Rwf. An approximate equation for Swt is generated in case 2 when Rwb > Rwf which cuts down on computer processing time.

(i) Case 1 Rwb < Rwf: Figure 3 below dissects a shaly-sand formation into its various segments.

Clay Crystal	Conductive fluids Øt Swt		hydro-carbon	reservoir rock
	Øt Swb	Øt (Swt-Swb)	Øt (1-Swt)	
	total porosity Øt			

Figure 3

See Appendix 1 of this report for the definition of the symbols used in the diagram above and in the following equations.

The conductivity of the fluids Cf, is obtained from summing their respective conductivities multiplied by the fraction of space they occupy within the total porous space Øt.

Expanding on this statement:

$$Cf = \frac{Swt - Swb}{Swt} Cwf + \frac{Swb}{Swt} Cwb$$

The true formation resistivity is then given by the Archie equation:

$$Rt = \frac{Rf}{\emptyset t^2 Swt^2}$$

and as $Rf = \frac{1}{Cf}$

$$Rf = \frac{1}{\frac{Swt-Swb}{Swt}Cwf + \frac{Swb}{Swt}Cwb}$$

$$Rf = \frac{Swt}{Swt\ Cwf - Swb\ Cwf + Swb\ Cwb}$$

and $Rwf = \frac{1}{Cwf}$

$$Rwb = \frac{1}{Cwb}$$

$$Rf = \frac{Swt\ Rwb\ Rwf}{Swt\ Rwb + Swb\ (Rwf-Rwb)}$$

substituting this equation for Rf into the Archie equation and cancelling excess terms yields:

$$Rt = \frac{Rwf\ Rwb}{[Swt\ Rwb+Swb(Rwf-Rwb)]Swt\ \emptyset t^2}$$

to obtain an equation for Swt requires further algebraic manipulation

i.e. $Swt^2\ Rwb\ \emptyset t^2 + Swt\emptyset t^2 Swb(Rwf-Rwb) = \frac{Rwf\ Rwb}{Rt}$

$$(Rwb\ \emptyset t^2)Sw^2t + [\emptyset t^2 Swb(Rwf-Rwb)]Swt - \frac{Rwf\ Rwb}{Rt} = 0$$

This is a quadratic equation in Swt, the positive root being used to calculate the total water saturation.

Solving for Swt yields:

$$Swt = \frac{-B \pm \sqrt{B^2 - 4\ AC}}{2A}$$

where $A = Rwb\emptyset t^2$

$B = [\emptyset t^2 Swb(Rwf-Rwb)]$

$C = \frac{-Rwf\ Rwb}{Rt}$

(ii) Case 2: $Rwb > Rwf$

In this section an equation to approximate the theoretical water saturation equation is developed. This equation is accurate to 2 significant figures in the case when $Rwb > Rwf$ and is used to cut down on computer processing time.

If the hydrocarbons are regarded as being non-conductive but still part of the pore space Øt, Figure 3 which dissected the formation previously can now be simplified to the water wet formation shown on Figure 4 below:

Clay Crystal	Conductive fluids. total porosity Øt		reservoir rock
	Øt Swb	Øt (1-Swb)	

Figure 4

The volume of conductive fluids is now given by $Vf = \emptyset t$

Again, the conductivity of the Fluid Cf is given by summing their respective conductivities multiplied by the fraction of space they occupy within the total porous space Øt.

i.e. $Cf = (1-Swb)\ Cwf + Swb\ Cwb$

The true formation resistivity is again obtained from the Archie equation:

$$Rt = \frac{Rf}{\emptyset t^2\ Sw^2 t}$$

and as $Rf = \dfrac{1}{Cf}$

$$Rf = \frac{1}{(1-Swb)Cwf+Swb\ Cwb}$$

and $Rwf = \dfrac{1}{Cwf}$

$$Rwb = \frac{1}{Cwb}$$

$$Rf = \frac{1}{\frac{(1-Swb)}{Rwf} + \frac{Swb}{Rwb}}$$

$$Rf = \frac{Rwf\ Rwf}{(1-Swb)\ Rwb + Swb\ Rwf}$$

$$Rf = \frac{Rwf\ Rwb}{[Rwb-Swb(Rwf-Rwb)]}$$

substituting this equation into the Archiė equation yields an equation for Swt:

$$Swt^2 = \frac{Rf}{\emptyset t^2 Rt} = \frac{Rwf\ Rwb}{[Rwb-Swb(Rwf-Rwb)]\emptyset t^2 Rt}$$

To summarise the two cases above, the theoretical equation for total water saturation Swt within the total pore space Øt is:

$$Swt = \frac{-B + \sqrt{B^2-4AC}}{2A}$$

where $A = Rwb\ \emptyset t^2$

$B = [\emptyset t^2 Swb(Rwf-Rwb)]$

$C = \frac{-Rwf\ Rwb}{Rt}$

This equation can be used irrespective of the relative magnitude of Rwb and Rwf. However for practical purposes, computer processing time can be cut down if this equation is used only in the case when Rwb < Rwf. In the case when Rwb > Rwf, an equation approximating the theoretical water saturation equation above can be used with only small loss in accuracy. This equation approximating Swt is:

$$Sw^2t = \frac{Rwf\ Rwb}{[Rwb-Swb(Rwf-Rwb)]\emptyset t^2 Rt}$$

The mud filtrate saturation in the invaded zone Sxo, can be determined by substituting Rmf for Rwf and Rxo for Rt in the two equations for Swt generated in this section.

4. Auxiliary Equations used in the Program

(i) Bound and Free Formation Water Resistivities, Rwb and Rwf

Rwf and Rwb are determined from the Archie equation in a clean water bearing sand and a 100% shale zone respectively. Here the shaly formation is treated as if it behaved like a clean formation consisting of clay crystals, silt and adsorbed and hydration water. The only difference being that this water is immovable or bound. Rwf is calculated externally from the program using the equation:

$$Rwf = \frac{Rt\emptyset^{m}}{a} \qquad \text{where } Sw = 100\%$$

Rwb is calculated within the program using the same equation i.e.

$$Rwb = Rsh\emptyset^{2}_{sh}$$

where a = 1.0 and m = 2.0, which are values recommended for a shaly formation based on experimental results (J.L. Dumanoir).

The parameters Rwf, Rsh and Øsh are all entered into the program from the data file. The resistivity of the 100% shale formation Rsh should be taken from a zone adjacent to the reservoir sand.

(ii) Volume of shale, Vsh

In the computer program DW, Vsh can be calculated from either the gamma ray or the SP log (but not both logs), depending on the value of the ISP switch entered from the data file. Refer to the BMR publication "A Review of the Concepts and Practices of Wireline Log Interpretation" by L.E. Kurylowicz, 1978 for the data file format or Appendix 2 page 60 of this record.
i.e. If ISP = 0, Vsh is computed from the gamma ray log.

$$Vsh\ (gamma) = \frac{GR\ log - GR\ min}{GR\ max - GR\ min}$$

where GR max = gamma ray log reading in a 100% shale

GR min = gamma ray log reading in the clean reservoir rock

If ISP = 1, Vsh is computed from the SP log.

$$Vsh(SP) = \frac{SSP - SP\ log}{SSP - SP\ min}$$

where SSP = reservoir rock SP log response

SP min = shale base line SP log response.

The volume of shale calculated from the SP log is only used as a back-up for the gamma-ray in cases of non-radioactive clays and an unreliable gamma-ray log.

(iii) Bound water Saturation, Swb

The bound water saturation is defined as the fraction of total porosity Øt, occupied by bound or immovable water.
Swb is given by the equation:

$$Swb = \frac{Vsh\ Øsh}{Øt}$$

where the product Vsh Øsh defines the amount of apparent shale pores within the total porosity Øt.
This equation reduces to

(a) Swb = Vsh = 1.0 in a 100% shale

(b) Swb = 0.0 in a clean reservoir rock.

(iv) Effective Porosity, Øe

The total porosity Øt is the sum of the effective porosity and the apparent shale porosity Øsh. The effective porosity is calculated by removing the fraction of apparent shale pores from the total porosity, the apparent shale porosity being entirely saturated with bound water.

i.e. $Øe = Øt - Vsh.\ Øsh$

This calculation must be performed because the logs from the neutron-density tool combination once crossplotted measure Øt not Øe. (See section 5 part (i) for a definition of "crossplot". As a consequence of this crossplot, the bound water in the shale will appear to be water contained in the pores of the reservoir rock. As this water is immovable, the fraction of bound water occupying the total porous space Øt must be removed to calculate the effective porosity of the reservoir sand.

(v) Effective Water Saturation Swe

The effective water saturation is the saturation of the free formation water in the effective pores of the reservoir sand. This is calculated by removing the bound water saturation from the total water saturation Swt.

The equation below shows how Swe is calculated:

$$Swe = 1 - \frac{\emptyset t \quad (1 - Swt)}{\emptyset e}$$

This equation calculates the hydrocarbon saturation in the total pore space Øt and converts it to a saturation in the effective pore space Øe. From this hydrocarbon saturation the effective water saturation is calculated.

5. Empirically Based Equations used in the Program

This section details the equations used to simulate log interpretation charts as well as the equations used to correct for the effects of light hydrocarbons on the neutron-density log combination. In the following account, reference is made only to the Schlumberger log interpretation chart book (1979 edition) and Schlumberger logging tools. However, other wireline logging companies such as Gearheart Owen which operate in Australia have published similar charts and use comparable logging equipment. Schlumberger techniques and equipment are referred to here because they appear to be used by the majority of petroleum exploration companies in Australia.

(i) Total porosity $\emptyset t$ and matrix density ρma

In the computer program DW, the total porosity and matrix density are calculated from the neutron-density logging tool combination. This tool combination however, was originally calibrated in a limestone block with water filled pores. Consequently, if the true total porosity and matrix density of a different formation is to be calculated, the readings from the 2 logging tools must be crossplotted. The neutron log porosity is corrected for the borehole environment through Schlumberger charts Por-14b or Por-14bm before being used on the crossplot. Schlumberger charts CP-1c and CP-14a are charts onto which neutron-density log readings can be plotted and $\emptyset t$ and ρma can be obtained respectively. By crossplotting the log readings the effect of the limestone calibration has been removed.

The equations below are used to simulate the charts CP-1c, Por-5 and CP-14a respectively. A definition of the symbols used in these equations is given in Appendix 1 page 57.

Total porosity, $\emptyset t = \frac{\emptyset log\ corr + \emptyset d}{2}$ (Chart CP-1c)

where $\emptyset$iog corr = $\emptyset$ neutron log + $\Sigma\emptyset$

$\Sigma\emptyset$ comes from chart Por-14b or Por-14bm

$\emptyset$d = density log porosity

$$\emptyset d = \frac{2.71 - \rho b}{2.71 - \rho mf}$$ (chart Por-5)

and 2.71 g/cc = the density of the limestone calibration block with water filled pores.

Matrix density, $\rho ma = \frac{\rho b - \emptyset t.\rho mf}{1 - \emptyset t}$ (chart CP-14a)

The effect of a light hydrocarbon in the pores of the formation on the neutron-density tool combination is to reduce $\emptyset$t and ρma calculated by the equations above. The effect of shale on the response of the neutron-density tool combination is to increase ρma.

(ii) True formation resistivity Rt

The true formation resistivity is calculated from one of a choice of three resistivity logging tool combinations. These three choices are (a) Induction resistivity tool, the spherically focussed log and the latterlog 8 resistivity tool. This combination can be abbreviated as ILd-ILm-LL8 and the program simulates Schlumberger chart Rint-2a (Kurylowicz, 1978).

(b) The dual latterlog - micro-spherically focussed logging tool combination. This combination is abbreviated as LLd-LLs-Rxo and the program simulates Schlumberger chart Rint-9 (Bateman and Konen, 1977).

(c) The dual latterlog resistivity tool without the micro-spherically focussed log can also be used to calculate Rt. This combination is abbreviated as LLd-LLs and simulates the Schlumberger chart Rint-9 in the absence of an Rxo log (Bateman and Konen, 1977).

Note that Rxo can be approximated by the micro-spherically focussed log once it is corrected for the effect of the mud-cake through Schlumberger chart Rxo-2. In the case where no micro-spherically focussed log is present the saturation of the mud filtrate in the invaded zone Sxo, cannot be determined accurately. However, it has been determined empirically that at "average" residual oil saturations, $Sxo = 5\sqrt{Sw}$ (Schlumberger, 1972). This equation is used in the program to determine Sxo in the case where no mud-cake log (Rxo) is present.

(iii) <u>Hydrocarbon Correction</u>

As mentioned previously in section (i), crossplotted values of Øt and ρma are affected by the presence of light hydrocarbons and as a consequence of this, are underestimated. To understand the reason for this "hydrocarbon effect", the measuring principles of the neutron and density logging tools must be discussed.

Firstly, the neutron porosity tool directs a beam of neutrons into the formation and 2 detectors located a measured distance from the source send a signal to the surface instrumentation. The ratio of the "counts" recorded by the 2 detectors is calculated to give (indirectly) a figure for porosity. The interaction of the neutrons with the formation depends on the amount of energy the neutron loses on collision with the nuclei of the formation material. The neutrons lose the largest amount of energy with nuclei of similar mass in "billiard ball" type collisions. As a consequence, the neutron porosity tool measures the fraction of light nuclei (such as hydrogen atoms) present in the formation which is estimated to coincide with the porosity of the formation. This is a reasonable approximation as the vast majority of hydrogen atoms do reside in the pore space in the form of water molecules and hydrocarbons. However, in the case of light hydrocarbons (in the gaseous phase particularly) the fraction of hydrogen atoms in the pore space is less than if the pores were occupied by water. As a result, the neutron tool underestimates porosity in formations containing light hydrocarbons.

Similar reasons can be given for the underestimation of ρb by the density logging tool in the presence of light hydrocarbons. The density tool directs a focussed beam of gamma-rays into the formation which interact with the formation material by the process of Compton scattering. Two detectors placed a measured distance from the gamma-ray source are used to send a signal to the surface instrumentation which converts this signal through a "spine and rib" plot to a formation density corrected for mudcake effects. The density actually measured by this tool ρb, is expressed by the formula below:

$$\rho b = \emptyset . \rho f + (1-\emptyset) . \rho ma.$$

Here the density of the formation ρma is measured as well as the density of the fluid ρf in the pore space $\emptyset$. As the density of the fluid decreases below the density of the water in which the tool was originally calibrated, the density read by the tool is also decreased. In the case of heavy hydrocarbons whose density may be close to that of water, no "hydrocarbon effect" is seen. In the case of light hydrocarbons, such as gases, the density tool underestimates the true formation density. (reference: "Schlumberger Log Interpretation, Volume 1 - Principles, 1972 edition).

The maximum possible correction to ρma for the presence of hydrocarbons is given by the formula for DGC (density grain corrected) below:

$$DGC = \rho^*ma + Vsh\ (\rho sh - \rho^*ma)$$

where ρ^*ma is the expected clean matrix density in a clean water bearing formation. DGC is usually underestimated in 100% shale formations and overestimates the amount of hydrocarbon correction required in the reservoir rock. Because DGC tends to overestimate in the latter case, the actual hydrocarbon correction in the program is an iterative process calculated from the equations for $\Delta\rho$ and $\Delta\emptyset$ shown below:

$$\Delta\rho = -1.07\emptyset t(1-Sxo)[(1.11-0.15P)\rho mf-1.15\rho hr]$$

where $\Delta\rho$ = hydrocarbon correction to the density log

and $\Delta\emptyset$ = hydrocarbon correction to the neutron porosity log:

$$\Delta\emptyset = \frac{-1.3\emptyset t(1-Sxo)[\rho mf(1-P)-1.5\rho hr + 0.2]}{\rho mf(1-P)}$$

(all these variables have been defined in Appendix 1 page 57)

Within each iteration new values of $\emptyset t$, Sxo and Swt are calculated. No hydrocarbon correction is applied if the value of ρma crossplotted initially is greater than DGC. Also, no correction is applied to the neutron porosity tool if $\Delta\emptyset$ in the equation above is greater than zero. The effect of these two decisions is to stop the iterative hydrocarbon correction being applied when it is not required.

The hydrocarbon correction is applied until either convergence is attained or the corrected ρma exceeds DGC. Convergence occurs if the density correction $\Delta\rho$ is less than -0.005. This is an arbitrary figure selected by the author and it ensures that the density log is corrected for hydrocarbon effects to three significant figure accuracy. The overall iterative process for the hydrocarbon correction is displayed on the flowchart, section 10, page 51.

(iv) Averaging of Pay, Effective Porosity and Water Saturation

Gross pay interval is calculated by subtracting the minimum depth from the maximum depth entered from the data file. Gross average effective porosity and water saturation are calculated by using geometric averaging over the gross pay interval.

The formula for the geometric average of a variable "X" is given below:

$$\bar{X} = \frac{\sum_{i=1}^{NSP} Xi}{NSP}$$ where NSP = the number of sample points

Averaging of the net pay, effective porosity and water saturation is accomplished in the same manner as the gross parameters are determined, except that the data averaged has to be below certain "cut off" criteria. The three values tested for net properties are the volume of shale, effective porosity and water saturation. The current cut-off values can be seen at the top of page 38, section 9, of this record. These cut-off values can be changed by editing this section of the program or by manually over-riding them during a program run. An example of this is shown in section 7, page 21.

(v) <u>Net Hydrocarbon pore thickness, NHPT</u>

The net hydrocarbon pore thickness NHPT, is calculated from the formula:

$$NHPT = h\emptyset e(1-Swe)$$

where each of the variables; net pay (h), effective porosity (Øe) and effective water saturation (Swe) are calculated from the average net results mentioned in the preceeding section (iv). This NHPT result can be used to determine an initial hydrocarbons in place figure providing the reservoir area and volume factors are known.

6. Operating Instructions for the Dual Water Wireline Log Interpretation Model, Computer Program "DW".

The data files accessed by the program "DW" are entirely compatible with those used by the program LOG4. The only logs required for running the program are the gamma-ray log, neutron porosity log, density log and resistivity measurements for the invaded zone, the transition zone and the uninvaded zone. Of these resistivity measurements, the invaded zone resistivity is not an essential log but its absence means a loss of accuracy in calculating Rt and Sxo.

The SP log can be used as an alternative method for calculating the volume of shale. It is recommended for use only when the gamma ray log is unreliable (i.e. in the presence of non-radioactive shales or radioactive sands) or absent. The sonic log is not required for this program. This is because the author does not consider the sonic logging tool is as reliable for determining porosity as the neutron porosity tool. The reader is referred to the BMR publication "A Review of the Concepts and Practices of Wireline Log Interpretation", by L.E. Kurylowicz, 1978, for definitions and methods of selecting the formation and drilling parameters entered from the data file.

The results generated by the program "DW" are printed out on three pages.

page 1: the summary of computational parameters, an example of page 1 is shown on page 22 , section 8 . In this section, the formation properties and drilling details are displayed as they are read from the first seven lines of the data file.

page 2: Summary of level by level input. Here the log data read from the remainder of the data file is listed. An example of page 2 is shown on page 23, section 8 . The program "DW" is capable of processing 300 lines of log data. This is equivalent to 149.5 metres (or feet) of wireline log data entered at half metre (or feet) intervals.

Page 3: Here a summary of the results computed by "DW" are displayed in a level by level format. Following this are the gross and net pay results and the net hydrocarbon pore thickness. An example of page 3 is shown on page 24, section 8.

A definition of the symbols used on these three pages of output from the program appears in Appendix 1. Note that the "No. of iterations" on the page 3 heading (example on page 24) refers to the number of hydrocarbon iterations taken for $\Delta\rho$ to reach convergence. An example program compilation, load and run is shown in section 7, page 21. The format required for the data entered into the program DW is detailed in Appendix 2, page 60.

7. Example Program compilation, loading and run.
The underlined print represents the program user input.

```
 FT,&DW,,%DW                    <------------------ compile the program
!END FTN7X:  No disasters,  No errors,  No warnings,
!


 RU,LOADR                       <------------------ load the program
 /LOADR:   EB
 /LOADR:   REL,%DW
 /LOADR:   EN
   /LOADR:DW     READY AT  1:37 PM  MON..  5  MAR.. 1984
   /LOADR:$END
 !


 RU,DW                          <------------------ run the program


 INPUT FILE NAME  (I.E.  name:SC:CRT)
WELL:919:9                      <------------------ enter the data file name

        THE FOLLOWING CUT-OFF LIMITS HAVE BEEN SELECTED FOR AVERAGING THE NET PAY PARAMETERS:
        (1) VOLUME OF SHALE CUT-OFF=  70.%
        (2) EFFECTIVE POROSITY CUT-OFF=   6.%
        (3) EFFECTIVE WATER SATURATION CUT-OFF=  55.%

        TO CHANGE ANY CUT-OFF LIMIT TYPE IN THE BRACKETED NUMBER.
        FOR NO CHANGE TYPE IN 0 (=ZERO)              eg change the effective water
 3      <----------------------------------------     saturation cutoff
        ENTER NEW EFFECTIVE WATER SATURATION CUT-OFF AS A PERCENTAGE
 60.0


        THE FOLLOWING CUT-OFF LIMITS HAVE BEEN SELECTED FOR AVERAGING THE NET PAY PARAMETERS:
        (1) VOLUME OF SHALE CUT-OFF=  70.%
        (2) EFFECTIVE POROSITY CUT-OFF=   6.%
        (3) EFFECTIVE WATER SATURATION CUT-OFF=  60.%

        TO CHANGE ANY CUT-OFF LIMIT TYPE IN THE BRACKETED NUMBER.
        FOR NO CHANGE TYPE IN 0 (=ZERO)
 0      <---------------------------------------- no more changes, type zero
    NORMAL TERMINATION
DW   LUN 06  SPOOL FILE -0122
!LP,-N    <-------------------------------------- print out the spool file
 YOUR OUTPUT FILE - TF0123
!
```

8. Example results

(i) Example 1, no micro-spherically focussed log present

Page 1:

DUAL WATER MODEL
CONFIDENTIAL
GUSHER (3186.0M-3192.5M) RUN 0001 DATE 09-02-84
SUMMARY OF COMPUTATIONAL PARAMETERS

NUMBER OF SAMPLE POINTS= 14.
FORMATION TEMPERATURE= 88.3 DEGREES CENTIGRADE (190.9 DEGREES FAHRENHEIT)
NEUTRON LOG POROSITY CORRECTION= 0.000

MUD FILTRATE PROPERTIES

SALINITY (% NaCl E.Q.)= .268
RESISTIVITY (OHM.M)= .015
DENSITY (G/CC)= 1.00
INTERVAL TRANSIT TIME= 620.0 uS/metre (189.1 uS/foot)

MATRIX PROPERTIES

GAMMA RAY MINIMUM (API UNIT)= 70.0
CROSSPLOTTED DENSITY (G/CC)= 2.663
INTERVAL TRANSIT TIME= 0.0 uS/metre (0.0 uS/foot)
STATIC SPONTANEOUS POTENTIAL (mV)= 0.0

SHALE PROPERTIES

GAMMA RAY MAXIMUM (API UNIT)= 200.0
RESISTIVITY (OHM.M)= 10.00
CROSSPLOTTED DENSITY (G/CC)= 3.000
INTERVAL TRANSIT TIME= 0.0 uS/metre (0.0 uS/foot)
CROSSPLOTTED NEUTRON POROSITY= .150
SPONTANEOUS POTENTIAL (mV)= 0.0

RW-FORMATION WATER RES. (OHM.M)= .0900
HYDROCARBON DENSITY (GM/CC)= .800
BOREHOLE/BIT SIZE (INCHES)= 9.880

NOTES:
(A) CUT-OFF LIMITS : (1) Sw= 55.% (2) VSH= 70.% (3) PHIeff= 6.%
(B) CROSSPLOT POROSITY IS DETERMINED FROM THE NEUTRON-DENSITY TOOL COMBINATION.
(C) VOLUME OF SHALE IS COMPUTED FROM THE GAMMA RAY
(D) Rt IS CALCULATED FROM THE DUAL LATTERLOG RESISTIVITY TOOL CHART
(E) AS NO MSFL LOG IS PRESENT Sxo IS CALCULATED FROM THE FIFTH ROOT OF Sw

CONFIDENTIAL
GUSHER (3186.0M-3192.5M)
SUMMARY OF LEVEL BY LEVEL INPUT

RUN 0001 DATE 09-02-84

DEPTH (metres)	GAMMA RAY	DENSITY G/CC	NEUTRON POROSITY	SONIC uS/m	SP mV	<-----RESISTIVITY------> MSFL	SHALLOW	DEEP
3186.0	95.0	2.250	.205	0.0	0.0	0.0	20.0	30.0
3186.5	91.0	2.280	.235	0.0	0.0	0.0	15.0	23.0
3187.0	95.0	2.250	.210	0.0	0.0	0.0	28.0	48.0
3187.5	82.0	2.290	.190	0.0	0.0	0.0	17.0	29.0
3188.0	99.0	2.300	.200	0.0	0.0	0.0	16.0	24.0
3188.5	90.0	2.220	.225	0.0	0.0	0.0	20.0	40.0
3189.0	80.0	2.220	.215	0.0	0.0	0.0	50.0	90.0
3189.5	80.0	2.250	.200	0.0	0.0	0.0	15.0	15.0
3190.0	100.0	2.360	.170	0.0	0.0	0.0	9.0	11.0
3190.5	100.0	2.250	.180	0.0	0.0	0.0	9.0	10.0
3191.0	97.0	2.130	.230	0.0	0.0	0.0	6.0	11.0
3191.5	80.0	2.250	.185	0.0	0.0	0.0	3.5	14.0
3192.0	70.0	2.350	.180	0.0	0.0	0.0	4.1	9.0
3192.5	80.0	2.360	.160	0.0	0.0	0.0	3.0	5.0

CONFIDENTIAL

GUSHER (3186.0M-3192.5M) RUN 0001 DATE 09-02-84

RESULTS

(metres) DEPTH	VSH	PHIxplt	RHOxplt	DGC	RHOma	NO. OF ITERATIONS	PHIeff	Rt	Sxo	Swe
3186.0	.192	.237	2.64	2.73	2.73	16	.167	37.0	.724	.134
3186.5	.162	.243	2.69	2.72	2.72	5	.205	28.6	.731	.164
3187.0	.192	.240	2.64	2.73	2.73	13	.172	62.0	.676	.062
3187.5	.092	.218	2.65	2.69	2.70	9	.182	36.0	.746	.204
3188.0	.223	.220	2.67	2.74	2.74	16	.153	29.6	.746	.160
3188.5	.154	.256	2.64	2.71	2.72	10	.200	54.0	.683	.095
3189.0	.077	.251	2.63	2.69	2.69	7	.212	118.0	.642	.078
3189.5	.077	.235	2.63	2.69	2.69	13	.198	15.0	.812	.340
3190.0	.231	.187	2.67	2.74	2.67	0	.153	12.4	.834	.365
3190.5	.231	.225	2.61	2.74	2.64	8	.177	10.7	.825	.347
3191.0	.208	.285	2.58	2.73	2.74	28	.187	14.5	.791	.269
3191.5	.077	.227	2.62	2.69	2.69	16	.183	21.3	.793	.298
3192.0	0.000	.195	2.68	2.66	2.68	0	.195	12.4	.847	.436
3192.5	.077	.182	2.66	2.69	2.66	0	.171	6.4	.916	.640

GROSS PAY INTERVAL= 6.5 METRES (21.3 FEET)
GROSS POROSITY= .182
GROSS WATER SATURATION= .256

NET PAY INTERVAL= 6.25 METRES (20.49 FEET)
NET POROSITY= .183
NET WATER SATURATION= .227

NET HYDROCARBON PORE THICKNESS= .88592 METRES (2.90464 FEET)

DUAL WATER MODEL
CONFIDENTIAL
WELL A1 (2751.5M TO 2768.0M) RUN 0001 DATE 23-02-84
SUMMARY OF COMPUTATIONAL PARAMETERS

NUMBER OF SAMPLE POINTS= 34.
FORMATION TEMPERATURE= 90.7 DEGREES CENTIGRADE (195.3 DEGREES FAHRENHEIT)
NEUTRON LOG POROSITY CORRECTION= 0.000

MUD FILTRATE PROPERTIES

SALINITY (% NaCl E.Q.)= .040
RESISTIVITY (OHM.M)= .066
DENSITY (G/CC)= 1.00
INTERVAL TRANSIT TIME= 620.0 uS/metre (189.1 uS/foot)

MATRIX PROPERTIES

GAMMA RAY MINIMUM (API UNIT)= 59.0
CROSSPLOTTED DENSITY (G/CC)= 2.650
INTERVAL TRANSIT TIME= 0.0 uS/metre (0.0 uS/foot)
STATIC SPONTANEOUS POTENTIAL (mV)= 0.0

SHALE PROPERTIES

GAMMA RAY MAXIMUM (API UNIT)= 200.0
RESISTIVITY (OHM.M)= 15.00
CROSSPLOTTED DENSITY (G/CC)= 2.940
INTERVAL TRANSIT TIME= 0.0 uS/metre (0.0 uS/foot)
CROSSPLOTTED NEUTRON POROSITY= .200
SPONTANEOUS POTENTIAL (mV)= 0.0

RW-FORMATION WATER RES. (OHM.M)= .1695
HYDROCARBON DENSITY (GM/CC)= .800
BOREHOLE/BIT SIZE (INCHES)= 8.500

NOTES:
(A) CUT-OFF LIMITS : (1) Sw= 60.% (2) VSH= 70.% (3) PHIeff= 6.%
(B) CROSSPLOT POROSITY IS DETERMINED FROM THE
NEUTRON-DENSITY TOOL COMBINATION.
(C) VOLUME OF SHALE IS COMPUTED FROM THE GAMMA RAY
(D) Rt IS CALCULATED FROM THE DUAL LATTERLOG RESISTIVITY TOOL CHART

CONFIDENTIAL
WELL A1 (2751.5M TO 2768.0M) RUN 0001 DATE 23-02-84
SUMMARY OF LEVEL BY LEVEL INPUT

DEPTH (metres)	GAMMA RAY	DENSITY G/CC	NEUTRON POROSITY	SONIC uS/m	SP mV	RESISTIVITY MSFL	RESISTIVITY SHALLOW	RESISTIVITY DEEP
2751.5	80.0	2.300	.110	0.0	0.0	3.0	9.0	11.0
2752.0	80.0	2.320	.140	0.0	0.0	2.9	9.0	11.0
2752.5	80.0	2.330	.140	0.0	0.0	3.0	9.0	11.0
2753.0	75.0	2.320	.140	0.0	0.0	3.0	10.0	13.0
2753.5	65.0	2.280	.160	0.0	0.0	2.9	10.0	15.0
2754.0	70.0	2.250	.160	0.0	0.0	2.9	10.0	15.0
2754.5	95.0	2.330	.160	0.0	0.0	4.0	9.0	12.0
2755.0	80.0	2.320	.165	0.0	0.0	4.0	11.0	16.0
2755.5	75.0	2.280	.150	0.0	0.0	3.0	8.0	10.0
2756.0	85.0	2.320	.150	0.0	0.0	2.4	7.2	10.0
2756.5	72.0	2.300	.160	0.0	0.0	3.5	8.0	11.0
2757.0	72.0	2.300	.155	0.0	0.0	2.6	7.0	9.5
2757.5	65.0	2.300	.160	0.0	0.0	3.0	7.0	10.0
2758.0	70.0	2.300	.145	0.0	0.0	2.9	8.0	11.0
2758.5	75.0	2.300	.165	0.0	0.0	2.5	6.0	8.0
2759.0	75.0	2.330	.155	0.0	0.0	3.2	6.2	9.0
2759.5	71.0	2.320	.150	0.0	0.0	2.5	6.7	9.2
2760.0	60.0	2.320	.155	0.0	0.0	2.5	7.2	10.0
2760.5	65.0	2.270	.160	0.0	0.0	2.4	7.1	10.0
2761.0	95.0	2.320	.160	0.0	0.0	2.1	6.2	8.3
2761.5	140.0	2.400	.200	0.0	0.0	6.0	7.0	9.0
2762.0	75.0	2.300	.170	0.0	0.0	3.8	5.9	8.0
2762.5	60.0	2.280	.165	0.0	0.0	2.5	5.3	7.5
2763.0	61.0	2.280	.160	0.0	0.0	2.4	5.5	8.0
2763.5	60.0	2.280	.160	0.0	0.0	2.1	4.2	6.2
2764.0	65.0	2.280	.170	0.0	0.0	2.5	4.5	6.9
2764.5	59.0	2.270	.165	0.0	0.0	2.2	4.0	6.0
2765.0	59.0	2.270	.170	0.0	0.0	2.1	3.4	5.0
2765.5	60.0	2.300	.165	0.0	0.0	2.1	3.0	4.5
2766.0	61.0	2.310	.160	0.0	0.0	2.1	2.5	3.5
2766.5	61.0	2.250	.195	0.0	0.0	1.6	1.7	2.2
2767.0	68.0	2.250	.205	0.0	0.0	1.5	1.7	2.2
2767.5	60.0	2.250	.180	0.0	0.0	1.9	1.9	2.5
2768.0	100.0	2.300	.170	0.0	0.0	2.0	2.2	3.0

CONFIDENTIAL

WELL A1 (2751.5M TO 2768.0M) RUN 0001 DATE 23-02-84

RESULTS

(metres) DEPTH	VSH	PHIxplt	RHOxplt	DGC	RHOma	NO. OF ITERATIONS	PHIeff	Rt	Sxo	Swe
2751.5	.149	.175	2.58	2.69	2.58	0	.145	14.1	.905	.600
2752.0	.149	.184	2.62	2.69	2.62	0	.154	14.1	.864	.563
2752.5	.149	.181	2.62	2.69	2.62	0	.151	14.1	.864	.574
2753.0	.113	.184	2.62	2.68	2.62	1	.160	16.8	.842	.517
2753.5	.043	.206	2.61	2.66	2.66	10	.174	19.7	.835	.492
2754.0	.078	.215	2.59	2.67	2.67	15	.164	19.7	.854	.485
2754.5	.255	.191	2.64	2.72	2.69	10	.120	16.2	.798	.521
2755.0	.149	.197	2.64	2.69	2.69	9	.143	21.4	.760	.452
2755.5	.113	.201	2.60	2.68	2.65	10	.158	13.0	.845	.609
2756.0	.184	.189	2.63	2.70	2.63	0	.152	13.2	.957	.562
2756.5	.092	.200	2.62	2.68	2.68	10	.156	14.9	.800	.588
2757.0	.092	.197	2.63	2.68	2.63	4	.172	12.6	.858	.590
2757.5	.043	.200	2.62	2.66	2.67	8	.173	13.7	.825	.605
2758.0	.078	.192	2.61	2.67	2.63	6	.166	14.6	.849	.575
2758.5	.113	.202	2.63	2.68	2.64	4	.173	10.7	.858	.627
2759.0	.113	.189	2.64	2.68	2.67	7	.153	12.8	.842	.636
2759.5	.085	.189	2.63	2.67	2.63	0	.172	12.2	.886	.609
2760.0	.007	.192	2.63	2.65	2.64	2	.187	13.2	.865	.600
2760.5	.043	.209	2.60	2.66	2.64	8	.185	13.2	.866	.575
2761.0	.255	.194	2.64	2.72	2.64	0	.143	10.9	1.000	.613
2761.5	.574	.191	2.73	2.82	2.76	7	.063	16.2	.618	.328
2762.0	.113	.205	2.63	2.68	2.68	7	.160	12.0	.727	.635
2762.5	.007	.208	2.62	2.65	2.65	8	.190	10.4	.852	.667
2763.0	.014	.206	2.61	2.65	2.64	8	.188	11.0	.871	.648
2763.5	.007	.206	2.61	2.65	2.62	2	.201	8.8	.877	.685
2764.0	.043	.211	2.62	2.66	2.66	9	.184	10.2	.855	.667
2764.5	0.000	.211	2.61	2.65	2.64	7	.198	8.8	.874	.701
2765.0	0.000	.214	2.62	2.65	2.64	7	.201	7.6	.881	.743
2765.5	.007	.202	2.63	2.65	2.63	0	.201	7.3	.878	.753
2766.0	.014	.197	2.63	2.65	2.63	0	.194	6.5	.905	.824
2766.5	.014	.232	2.63	2.65	2.63	2	.226	2.4	.891	1.000
2767.0	.064	.237	2.64	2.67	2.64	0	.224	4.2	.902	.860
2767.5	.007	.225	2.61	2.65	2.64	7	.210	2.8	.882	1.000
2768.0	.291	.205	2.63	2.73	2.63	0	.147	3.3	1.000	1.000

GROSS PAY INTERVAL= 16.5 METRES (54.1 FEET)
GROSS POROSITY= .170
GROSS WATER SATURATION= .644

NET PAY INTERVAL= 6.50 METRES (21.31 FEET)
NET POROSITY= .151
NET WATER SATURATION= .525

NET HYDROCARBON PORE THICKNESS= .46628 METRES (1.52878 FEET)

9. Program Print-out and Explanation of each Segment

The following 21 pages contain a print-out of the program DW used to generate effective porosity and water saturation from raw wireline log data. The text below summarises the various sections of this program and indicates the page(s) on which they appear.

```
      PROGRAM DW
C
C     -THIS PROGRAM CALCULATES WATER SATURATION USING THE DUAL
C      WATER MODEL AND IS BASED ON SCHLUMBERGER'S "CYBERLOOK" PROGRAM.
C     -PROGRAM DEVELOPED BY G.R.MORRISON ,MAY 1983 TO FEBUARY 1984.
C     -REFERENCE THE SPWLA ARTICLE "THE LOG ANALYST AND THE
C      PROGRAMABLE POCKET CALCULATER" - BY R.M.BATEMAN AND C.E.KONEN - 1977
C      FOR THE ALGORITHM WHICH DETERMINES TRUE FORMATION RESISTIVITY
C      FROM THE DUAL LATTERLOG RESISTIVITY TOOL.
C     -REFERENCE L.E.KURYLOWICZ FOR THE ALGORITHM WHICH DETERMINES Rt
C      FROM THE INDUCTION RESISTIVITY TOOL.
C     -ALL OTHER FORMULAE ARE CARE OF SCHLUMBERGER.
C      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C      A LISTING OF THE VARIABLES USED IN THE PROGRAM APPEARS BELOW.
C      THOSE PREFIXED BY AN ASTERISK (*) ARE USED IN LOG4 BUT NOT IN
C      THIS PROGRAM. THESE VARIABLES WERE INCLUDED SO THAT THIS PROGRAM
C      WOULD BE COMPATABLE WITH LOG4 DATA-FILES AND IN CASE OF
C      FUTURE DEVELOPMENT.
C      ---------------------------------------------------------------
C      NOTE:
C      TO ALTER THE POROSITY, WATER SATURATION AND VOLUME OF
C      SHALE CUT-OFF VALUES EDIT LINES 251,252 AND 253.
C      ----------------------------------------------------------------------
C      A= VARIABLE IN THE RESISTIVITY SECTION
C      B= VARIABLE IN THE RESISTIVITY SECTION
C      BB= VARIABLE IN THE RESISTIVITY SECTION
C     *BORE= BOREHOLE SIZE
C      C= EQUATION IN THE RESISTIVITY SECTION
C      CC= VARIABLE IN THE RESISTIVITY SECTION
C      D= VARIABLE IN THE RESISTIVITY SECTION
C      DATE= DATE OF THE RUN
C      DELDEN= HYDROCARBON CORRECTION TO THE DENSITY LOG
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C        DELNEU= HYDROCARBON CORRECTION TO THE NEUTRON LOG
C        DELPCR= THE NEUTRON LOG CORRECTION FOR THE BOREHOLE ENVIRONMENT
C        DEN(I)= DENSITY LOG VALUES
C        DENHYD= DENSITY OF THE HYDROCARBON
C        DENMA= DENSITY OF THE MATRIX
C        DENMF= DENSITY OF THE MUD FILTRATE
C        DENSH= DENSITY OF THE SHALE
C        DEPTH(I)= LOG DEPTHS
C        DGC= DENSITY GRAIN CORRECTED
C        GPINT= GROSS PAY INTERVAL
C        GPINTIMP= IMPERIAL CONVERSION OF GPINT
C        GPINTMET= METRIC CONVERSION OF GPINT
C        GR(I)= GAMMA RAY LOG VALUES
C        GRYMAX= SHALE GAMMA RAY READING
C        GRYMIN= CLEAN FORMATION GAMMA RAY READING
C        IHYDR= HYDROCARBON DETECTION SWITCH (SHOWS PRESENCE OF MSFL LOG)
C       *IPL= PLOT SWITCH
C       *IPORF= SWITCH FOR METHOD OF DETERMINING POROSITY
C       *IPRINT= OUTPUT PRINTING DEVICE SWITCH
C        IRM= RESISTIVITY COMBINATION SWITCH
C        ISP= 1 FOR VSH FROM THE SP; 0 FOR VSH FROM THE GAMMA RAY
C       *LUN= INTERMEDIATE CALCULATIONS PRINT-OUT SWITCH
C        MDPH= METRIC OR IMPERIAL DEPTH SWITCH
C        MSFL(I)= MICRO SPHERICALLY FOCUSSED LOG VALUES
C        MTAC= METRIC OR IMPERIAL SONIC VALUE SWITCH
C        MTEM= CENTIGRADE OR FAHRENHEIT TEMPERATURE SWITCH
C        NAMDAT= NAME OF THE DATA FILE ACCESSED BY DW
C        NEU(I)= NEUTRON LOG VALUES
C        NHPT= NET HYDROCARBON PORE THICKNESS
C        NHPTIMP= IMPERIAL CONVERSION OF NHT
C        NHPTMET= METRIC CONVERSION OF NHT
C        NI= THE NUMBER OF HYDROCARBON CORRECTION ITERATIONS
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C       *NLTYPE= NEUTRON LOG TYPE SWITCH
C        NP= NET PAY THICKNESS
C        NPIMP= IMPERIAL CONVERSION OF NP
C        NPMET= METRIC CONVERSION OF NP
C        NNPP= NUMBER OF NET PAY POINTS
C        NSP= NUMBER OF SAMPLE POINTS
C        PHICUT= POROSITY CUT-OFF
C        PHID= DENSITY POROSITY
C        PHIE(I)= EFFECTIVE POROSITY INDEPENDANT OF LITHOLOGY
C        PHIT= TOTAL FORMATION POROSITY INDEPENDANT OF LITHOLOGY
C        PHITG= TOTAL GROSS POROSITY
C        PHITN= TOTAL NET POROSITY
C        PHIX= CROSSPLOT POROSITY
C        PMF= MUD FILTRATE SALINITY
C        PORNSH= NEUTRON LOG POROSITY OF 100% SHALE ZONE
C        Q= QUESTION VARIABLE FOR CHANGING A CUT-OFF LIMIT
C        RHOMA= APPARENT MATRIX DENSITY
C        RHOX= CROSSPLOT DERIVED MATRIX DENSITY
C        RILD= INDUCTION LOG DEEP RESISTIVITY
C        RILM= INDUCTION LOG MEDIUM RESISTIVITY
C        RLD= RESISTIVITY LOG DEEP
C        RLL8= LATTERLOG 8 RESISTIVITY
C        RLS= RESISTIVITY LOG SHALLOW
C        RMF= RESISTIVITY OF THE MUD FILTRATE
C        RO= RESISTIVITY OF A CLEAN FORMATION 100% SATURATED WITH FORMATION WATER
C        ROXO= RESISTIVITY OF A CLEAN FORMATION 100% SATURATED WITH MUD FILTRATE
C        RSH= RESISTIVITY OF THE SHALE
C        RT= TRUE RESISTIVITY OF THE FORMATION
C        RUN= RUN NUMBER
C        RW= FREE FORMATION WATER RESISTIVITY
C        RWB= BOUND (SHALE) WATER RESISTIVITY
C        SP(I)= SPONTANEOUS POTENTIAL LOG VALUES
```

```
C        SPMIN= VALUE OF SP IN A 100% SHALE
C        SSP= VALUE OF SP IN A 100% CLEAN FORMATION
C        SW= TOTAL WATER SATURATION
C        SWCUT= WATER SATURATION CUT-OFF
C        SWB= BOUND (SHALE) WATER SATURATION
C        SWE(I)= EFFECTIVE OR FREE WATER SATURATION
C        SWTG= TOTAL GROSS WATER SATURATION
C        SWTN= TOTAL NET WATER SATURATION
C        SXO= MUD FILTRATE SATURATION IN THE INVADED ZONE
C       *TACF= SONIC TRANSIT TIME OF THE FORMATION FLUID
C        TACFIMP= IMPERIAL CONVERSION OF TACF
C        TACFMET= METRIC CONVERSION OF TACF
C       *TACMA= SONIC TRANSIT TIME OF THE MATRIX
C       *TACSH= SONIC TRANSIT TIME OF THE SHALE
C        TACSHIMP= IMPERIAL CONVERSION OF TACSH
C        TACSHMET= METRIC CONVERSION OF TACSH
C        TEM= FORMATION TEMPERATURE
C        TEMIMP= IMPERIAL CONVERSION OF TEMPERATURE
C        TEMMET= METRIC CONVERSION OF TEMPERATURE
C        TITLE= TITLE OF THE DATA FILE
C       *TT(I)= SONIC LOG VALUES
C        VSH(I)= VOLUME OF SHALE; SEE ISP FOR METHODS OF CALCULATION
C        VSHCUT= VOLUME OF SHALE CUT-OFF VALUE
C        X= VARIABLE USED TO CALCULATE SW IF RWB`RW
C        XO= VARIABLE USED TO CALCULATE SXO IF RWB`RW
C        ------------------------------------------------------------
      REAL DEPTH(300),GR(300),DEN(300),NEU(300),TT(300),SP(300),
     2MSFL(300),RLS(300),RLD(300),NP,SWE(300),VSH(300),PHIE(300)
     3,NPIMP,NPMET,NHPT,NHPTIMP,NHPTMET
      INTEGER Q
      CHARACTER*40 TITLE
```

```
      CHARACTER*4 RUN
      CHARACTER*8 DATE
C     ------------------------------------------------------------------
C      READ IN THE DATA FILE NAME
      CHARACTER *20 NAMDAT
      WRITE(1,5)
5     FORMAT(//,1X,'INPUT FILE NAME  (I.E.  name:SC:CRT)')
      READ(1,10)NAMDAT
10    FORMAT(A)
      OPEN(4,FILE=NAMDAT,STATUS='CLD')
C     ------------------------------------------------------------------
C      READ IN THE INITIAL VALUES
      READ(4,'(A40)')TITLE
      READ(4,'(A4,A8)')RUN,DATE
      READ(4,*)IPORF,IHYDR,IPL,IRM,MDPH,MTAC,MTEM,LUN,NLTYPE,IPRINT,ISP
      READ(4,*)NSP,TEM,PMF,RMF,DENMF,TACF,DELPOR
      READ(4,*)GRYMIN,DENMA,TACMA,SSP
      READ(4,*)GRYMAX,RSH,DENSH,TACSH,PORNSH,SPMIN
      READ(4,*)RW,DENHYD,PORE
C     ------------------------------------------------------------------
C      PRINT OUT A SUMMARY OF THE COMPUTATIONAL PARAMETERS.
      WRITE(6,201)
201   FORMAT(5(/),50X,'DUAL WATER MODEL')
      WRITE(6,501)
501   FORMAT(52X,'CONFIDENTIAL')
      WRITE(6,202)TITLE,RUN,DATE
202   FORMAT(46X,A40,' RUN ',A4,'  DATE ',A8)
      WRITE(6,203)
203   FORMAT(40X,'SUMMARY OF COMPUTATIONAL PARAMETERS')
      WRITE(6,204)
```

```
204   FORMAT(40X,35('-'))
      WRITE(6,205)NSP
205   FORMAT(/,30X,'NUMBER OF SAMPLE POINTS=',F4.0)
      IF(MTEM.EQ.1)THEN
      TEMIMP=TEM*9.0/5.0+32.0
      WRITE(6,206)TEM,TEMIMP
206   FORMAT(30X,'FORMATION TEMPERATURE= ',F4.1,' DEGREES CENTIGRADE'
     2,5X,'(',F5.1,' DEGREES FAHRENHEIT)')
      ELSE
      TEMMET=(TEM-32.0)*5.0/9.0
      WRITE(6,306)TEM,TEMMET
306   FORMAT(30X,'FORMATION TEMPERATURE= ',F5.1,' DEGREES FAHRENHEIT'
     2,5X,'(',F4.1,' DEGREES CENTIGRADE)')
      END IF
      WRITE(6,207)DELPOR
207   FORMAT(30X,'NEUTRON LOG POROSITY CORRECTION= ',F5.3)
      WRITE(6,208)
208   FORMAT(/,30X,'MUD FILTRATE PROPERTIES')
      WRITE(6,209)
209   FORMAT(30X,23('-'))
      WRITE(6,210)PMF
210   FORMAT(30X,'SALINITY (% NaCl E.Q.)= ',F5.3)
      WRITE(6,211)RMF
211   FORMAT(30X,'RESISTIVITY (OHM.M)= ',F5.3)
      WRITE(6,212)DENMF
212   FORMAT(30X,'DENSITY (G/CC)= ',F4.2)
      IF(MTAC.EQ.1)THEN
      TACFIMP=TACF*0.305
      WRITE(6,213)TACF,TACFIMP
213   FORMAT(30X,'INTERVAL TRANSIT TIME= ',F5.1,' uS/metre'
```

```
     2,14X,'(',F5.1,' uS/foot)')
      ELSE
      TACFMET=TACF/0.305
      WRITE(6,313)TACF,TACFMET
313   FORMAT(30X,'INTERVAL TRANSIT TIME= ',F5.1,' uS/foot'
     2,15X,'(',F5.1,' uS/metre)')
      END IF
      WRITE(6,214)
214   FORMAT(/,30X,'MATRIX PROPERTIES')
      WRITE(6,215)
215   FORMAT(30X,17('-'))
      WRITE(6,216)GRYMIN
216   FORMAT(30X,'GAMMA RAY MINIMUM (API UNIT)= ',F5.1)
      WRITE(6,217)DENMA
217   FORMAT(30X,'CROSSPLOTTED DENSITY (G/CC)= ',F5.3)
      IF(MTAC.EQ.1)THEN
      TACMAIMP=TACMA*0.305
      WRITE(6,218)TACMA,TACMAIMP
218   FORMAT(30X,'INTERVAL TRANSIT TIME= ',F5.1,' uS/metre'
     2,14X,'(',F5.1,' uS/foot)')
      ELSE
      TACMAMET=TACMA/0.305
      WRITE(6,318)TACMA,TACMAMET
318   FORMAT(30X,'INTERVAL TRANSIT TIME= ',F5.1,' uS/foot'
     2,15X,'(',F5.1,' uS/metre)')
      END IF
      WRITE(6,219)SSP
219   FORMAT(30X,'STATIC SPONTANEOUS POTENTIAL (mV)= ',F5.1)
      WRITE(6,220)
220   FORMAT(/,30X,'SHALE PROPERTIES')
```

```
      WRITE(6,221)
221   FORMAT(30X,16('-'))
      WRITE(6,222)GRYMAX
222   FORMAT(30X,'GAMMA RAY MAXIMUM (API UNIT)= ',F5.1)
      WRITE(6,223)RSH
223   FORMAT(30X,'RESISTIVITY (OHM.M)= ',F5.2)
      WRITE(6,224)DENSH
224   FORMAT(30X,'CROSSPLOTTED DENSITY (G/CC)= ',F5.3)
      IF(MTAC.EQ.1)THEN
      TACSHIMP=TACSH*0.305
      WRITE(6,225)TACSH,TACSHIMP
225   FORMAT(30X,'INTERVAL TRANSIT TIME= ',F5.1,' uS/metre'
     2,14X,'(',F5.1,' uS/foot)')
      ELSE
      TACSHMET=TACSH/0.305
      WRITE(6,325)TACSH,TACSHMET
325   FORMAT(30X,'INTERVAL TRANSIT TIME= ',F5.1,' uS/foot'
     2,15X,'(',F5.1,' uS/metre)')
      END IF
      WRITE(6,226)PORNSH
226   FORMAT(30X,'CROSSPLOTTED NEUTRON POROSITY= ',F5.3)
      WRITE(6,227)SPMIN
227   FORMAT(30X,'SPONTANEOUS POTENTIAL (mV)= ',F5.1)
      WRITE(6,231)RW
231   FORMAT(/,30X,'RW-FORMATION WATER RES. (OHM.M)= ',F6.4)
      WRITE(6,232)DENHYD
232   FORMAT(30X,'HYDROCARBON DENSITY (GM/CC)= ',F5.3)
      WRITE(6,233)BORE
233   FORMAT(30X,'BOREHOLE/BIT SIZE (INCHES)= ',F6.3)
C     ------------------------------------------------------------
```

```
C       SET THE CUT-OFF VALUES FOR PHI,Sw AND VSH
      PHICUT=0.06
      SWCUT=0.55
      VSHCUT=0.70
C       SEE IF ANY CUT-OFF LIMIT NEEDS TO BE CHANGED
509   WRITE(1,510)
510   FORMAT(//,10X,'THE FOLLOWING CUT-OFF LIMITS HAVE BEEN SELECTED'
     2,' FOR AVERAGING THE NET PAY PARAMETERS:')
      WRITE(1,512)VSHCUT*100.0
512   FORMAT(10X,'(1) VOLUME OF SHALE CUT-OFF= ',F4.0,'%')
      WRITE(1,514)PHICUT*100.0
514   FORMAT(10X,'(2) EFFECTIVE POROSITY CUT-OFF= ',F4.0,'%')
      WRITE(1,516)SWCUT*100.0
516   FORMAT(10X,'(3) EFFECTIVE WATER SATURATION CUT-OFF= ',F4.0,'%')
      WRITE(1,518)
518   FORMAT(/,10X,'TO CHANGE ANY CUT-OFF LIMIT TYPE IN THE'
     2,' BRACKETED NUMBER.')
      WRITE(1,520)
520   FORMAT(10X,'FOR NO CHANGE TYPE IN 0 (=ZERO)')
      READ(1,522)Q
522   FORMAT(I1)
      IF(Q.EQ.1)THEN
      WRITE(1,524)
524   FORMAT(10X,'ENTER THE NEW VOLUME OF SHALE CUT-OFF AS A'
     2,' PERCENTAGE')
      READ(1,*)VSHCUT
      VSHCUT=VSHCUT/100.0
      END IF
      IF(Q.EQ.2)THEN
      WRITE(1,526)
```

```
526   FORMAT(10X,'ENTER NEW EFFECTIVE POROSITY CUT-OFF AS A PERCENTAGE')
      READ(1,*)PHICUT
      PHICUT=PHICUT/100.0
      END IF
      IF(Q.EQ.3)THEN
      WRITE(1,528)
528   FORMAT(10X,'ENTER NEW EFFECTIVE WATER SATURATION CUT-OFF'
     2,' AS A PERCENTAGE')
      READ(1,*)SWCUT
      SWCUT=SWCUT/100.0
      END IF
      IF(Q.NE.0)GOTO 509
C     ------------------------------------------------------------
C      WRITE OUT THE OPERATING NOTES FOR THE PROGRAM
      WRITE(6,530)
530   FORMAT(/,30X,'NOTES:')
      WRITE(6,228)SWCUT*100.0,VSHCUT*100.0,PHICUT*100.0
228   FORMAT(30X,'(A) CUT-OFF LIMITS : (1) Sw= ',F4.0,'%  (2) VSH= ',
     2,F4.0,'%  (3) PHIeff= ',F4.0,'%')
      WRITE(6,229)
229   FORMAT(30X,'(B) CROSSPLOT POROSITY IS DETERMINED FROM THE')
      WRITE(6,230)
230   FORMAT(30X,'    NEUTRON-DENSITY TOOL COMBINATION.')
      IF(ISP.EQ.1)THEN
      WRITE(6,331)
331   FORMAT(30X,'(C) VOLUME OF SHALE IS COMPUTED FROM THE SP LOG')
      ELSE
      WRITE(6,332)
332   FORMAT(30X,'(C) VOLUME OF SHALE IS COMPUTED FROM THE GAMMA RAY')
      END IF
```

```
      IF(IRM.EQ.1.AND.IHYDR.EQ.1)THEN
      WRITE(6,532)
532   FORMAT(30X,'(D) Rt IS CALCULATED FROM THE INDUCTION'
     2,' RESISTIVITY TOOL CHART')
      END IF
      IF(IRM.EQ.2.OR.IHYDR.EQ.0)THEN
      WRITE(6,534)
534   FORMAT(30X,'(D) Rt IS CALCULATED FROM THE DUAL LATTERLOG'
     2,' RESISTIVITY TOOL CHART')
      END IF
      IF(IHYDR.EQ.0)THEN
      WRITE(6,536)
536   FORMAT(30X,'(E) AS NO MSFL LOG IS PRESENT Sxo IS CALCULATED')
      WRITE(6,538)
538   FORMAT(30X,'    FROM THE FIFTH ROOT OF Sw')
      END IF
C     ---------------------------------------------------------------
C      PRINT OUT THE LOG DATA READ FROM THE DATA-FILE
      WRITE(6,502)
502   FORMAT(1H1,//,48X,'CONFIDENTIAL')
      WRITE(6,33)TITLE,RUN,DATE
33    FORMAT(43X,A40,' RUN ',A4,'  DATE ',A8)
      WRITE(6,22)
22    FORMAT(40X,'SUMMARY OF LEVEL BY LEVEL INPUT')
      WRITE(6,23)
23    FORMAT(40X,31('-'))
      WRITE(6,30)
30    FORMAT(7X,'DEPTH',6X,'GAMMA',4X,'DENSITY',4X,'NEUTRON'
     2,6X,'SONIC',10X,'SP',7X,'`-----RESISTIVITY------`')
      IF(MDPH.EQ.1)THEN
```

```
      WRITE(6,24)
24    FORMAT(7X,'(metres)',4X,'RAY',7X,'G/CC',5X,'POROSITY',5X
     2,'uS/m',11x,'mV',7X,'MSFL',4X,'SHALLOW',5X,'DEEP')
      ELSE
      WRITE(6,324)
324   FORMAT(7X,'(feet)'6X,'RAY',7X,'G/CC',5X,'POROSITY',5X
     2,'uS/ft',10X,'mV',7X,'MSFL',4X,'SHALLOW',5X,'DEEP')
      END IF
      WRITE(6,25)
25    FORMAT(7X,92('-'))
      DO 21 K=1,NSP
      READ(4,*)DEPTH(K),GR(K),DEN(K),NEU(K),TT(K)
     1,SP(K),MSFL(K),RLS(K),RLD(K)
      WRITE(6,26)DEPTH(K),GR(K),DEN(K),NEU(K),TT(K)
     2,SP(K),MSFL(K),RLS(K),RLD(K)
26    FORMAT(3X,2(F10.1),5X,F5.3,6X,F5.3,7X,F5.1
     2,8X,F5.1,3(F10.1))
21    CONTINUE
C
C      SET INITIAL VALUES TO ZERO
      PHITG=0.0
      SWTG=0.0
      PHITN=0.0
      SWTN=0.0
      NP=0.0
      NNPP=0.0
C
C      PRINT OUT THE HEADING FOR THE RESULTS.
      WRITE(6,503)
503   FORMAT(1H1,//,41X,'CONFIDENTIAL')
```

```
      WRITE(6,32)TITLE,RUN,DATE
32    FORMAT(35X,A40,' RUN ',A4,'  DATE ',A8)
      WRITE(6,27)
27    FORMAT(45X,'RESULTS')
      IF(MDPH.EQ.1)THEN
      WRITE(6,28)
28    FORMAT(5X,'(metres)',32X,7('-'),14X,'NO. OF')
      ELSE
      WRITE(6,328)
328   FORMAT(5X,'(feet)',34X,7('-'),14X,'NO. OF')
      END IF
      WRITE(6,15)
15    FORMAT(5X,'DEPTH',8X,'VSH',5X,'PHIxplt',2X'RHOxplt',5X,'DGC'
     2,6X,'RHOma',4X,'ITERATIONS',3X,'PHIeff',5X,'Rt',9X,'Sxo',6X,'Swe')
      WRITE(6,16)
16    FORMAT(5X,108('-'))
C     ------------------------------------------------------------------
C      START OF THE CALCULATIONS
      DO 20 I=1,NSP
C
C      CORRECT THE NEUTRON POROSITY FOR THE BOREHOLE ENVIRONMENT
      NEU(I)=NEU(I)+DELPOR
C      SET THE NUMBER OF HYDROCARBON CORRECTION ITERATIONS TO ZERO
      NI=0.0
C     ----------------------------------------------------------------------------
C      THIS SECTION CALCULATES 'PHIX' THE CROSSPLOT POROSITY.
C      CALCULATE THE POROSITY FROM THE DENSITY LOG
      PHID=(2.71-DEN(I))/(2.71-DENMF)
C      CALCULATE THE CROSSPLOT POROSITY 'PHIX'
      PHIX=(PHID+NEU(I))/2.0
```

```
C      ------------------------------------------------------------
C       THIS SECTION CALCULATES RT, THE TRUE FORMATION RESISTIVITY
      IF(IRM.EQ.1.AND.IHYDR.EQ.1)THEN
C       THIS SECTION IS TAKEN DIRECTLY FROM THE LOG4 PROGRAM
C       SUBROUTINE "DIND" WRITTEN BY L.E.KURYLOWICZ
      RLL8=MSFL(I)
      RILM=RLS(I)
      RILD=RLD(I)
      A=(RLL8/RILD)-1.0
      B=(RILM/RILD)-1.0
      C=A/B
      BB=(0.59*A)-(2.21*C)+1.35
      CC=-((1.44*A)-(2.47*C)+2.76)
      D=-0.5*(SQRT((BB*BB)-(4.0*CC))+BB)
      IF(D.GT.1.0)THEN
      RT=RILD
      ELSE IF(D.LT.0.4)THEN
      RT=0.4*RILD
      ELSE
      RT=RILD*D
      END IF
      END IF
C
      IF(IRM.EQ.2.AND.IHYDR.EQ.1)THEN
C      THIS SECTION CALCULATES RT FROM THE LATTERLOG BUTTERFLY CHART
C      REFERENCE R.M.BATEMAN AND C.E.KONEN - 1977
      A=RLD(I)/MSFL(I)
      B=RLD(I)/RLS(I)
      IF(A.LE.1.0)RT=1.7*RLD(I)-0.7*RLS(I)
      IF(B.LE.1.1)RT=1.1*RLD(I)
```

```
      IF(A.GT.1.0.AND.B.GT.1.1)THEN
      C=(RLS(I)/MSFL(I))*(RLD(I)-MSFL(I))/(RLD(I)-RLS(I))
      RT=(2.18*C*RLD(I))/(1.78*C-1.0)
      END IF
      END IF
C
C      THIS SECTION CALCULATES RT WHEN NO MUDCAKE RESISTIVITY LOG IS PRESENT
C      REFERENCE R.M.BATEMAN AND C.E.KONEN - 1977
      IF(IHYDR.EQ.0)THEN
      B=RLD(I)/RLS(I)
      IF(B.GE.1.0)RT=1.7*RLD(I)-0.7*RLS(I)
      IF(B.LT.1.0)RT=2.4*RLD(I)-1.4*RLS(I)
      END IF
C
C      CHECK THAT RT IS NOT OUTSIDE MAXIMUM BOUNDS
      IF(RT.LE.0.0)RT=0.5*RLD(I)
      IF(RT/RLD(I).GT.2.0)RT=1.1*RLD(I)
C      ------------------------------------------------------------------
C      COMPUTE THE BOUND WATER RESISTIVITY FROM 100% SHALE
C      PARAMETERS USING THE ARCHIE EQUATION.
      RWB=RSH*PORNSH*PORNSH
C
C      COMPUTE THE VOLUME OF SHALE FROM EITHER THE GAMMA
C      RAY OR THE SP LOG
      VSH(I)=(GR(I)-GRYMIN)/(GRYMAX-GRYMIN)
      IF(ISP.EQ.1)VSH(I)=(SSP-SP(I))/(SSP-SPMIN)
      IF(VSH(I).GT.1.0)VSH(I)=1.0
      IF(VSH(I).LT.0.0)VSH(I)=0.0
C
C      COMPUTE THE BOUND WATER SATURATION
```

```
      SWB=VSH(I)*PORNSH/PHIX
      IF(SWB.GT.1.0)SWB=1.0
C
C      COMPUTE THE CROSSPLOT MATRIX DENSITY
      RHOX=(DEN(I)-PHIX*DENMF)/(1.0-PHIX)
C
C      COMPUTE THE DENSITY GRAIN CORRECTED
      DGC=DENMA+VSH(I)*(DENSH-DENMA)
C
C      EQUATE CROSSPLOT VALUES TO THE TRUE MATRIX VALUES
      RHOMA=RHOX
      PHIT=PHIX
C
C      IF THE VOLUME OF SHALE IS GREATER THAN THE CUT-OFF VALUE
C      THEN JUMP OVER THE HYDROCARBON CORRECTION.
      IF(VSH(I).GT.VSHCUT)GOTO 430
C     ------------------------------------------------------------------
C      COMPUTE THE WATER AND MUD FILTRATE SATURATIONS
420   IF(RWB.GE.RW)THEN
      RO=RW*RWB/((RWB+SWB*(RW-RWB))*PHIT*PHIT)
      ROXO=RMF*RWB/((RWB+SWB*(RMF-RWB))*PHIT*PHIT)
      SW=(RO/RT)**0.5
      SXO=(ROXO/MSFL(I))**0.5
C
      ELSE
      X=SWB*(RWB-RW)/(2.0*RWB)
      SW=(RW/(RT*PHIT*PHIT)+X*X)**0.5+X
      XO=SWB*(RWB-RMF)/(2.0*RWB)
      SXO=(RMF/(MSFL(I)*PHIT*PHIT)+XO*XO)**0.5+XO
      END IF
```

```
C
C      IF MSFL LOG IS NOT PRESENT SIMULATE Sxo
      IF(IHYDR.EQ.0)SXO=SW**0.2
C
C      ENSURE SW AND SXO ARE NOT UNREALISTIC VALUES
      IF(SW.GT.1.0)SW=1.0
      IF(SXO.GT.1.0)SXO=1.0
C      ---------------------------------------------------------------
C      CALCULATE THE HYDROCARBON CORRECTION TO THE DENSITY LOG
      DELDEN=-1.07*PHIT*(1.0-SXO)*((1.11-0.15*PMF)
     2*DENMF-1.15*DENHYD)
C
C      DETERMINE IF ANY HYDROCARBON CORRECTION IS REQUIRED
      IF(DELDEN.LE.-0.005.AND.RHOMA.LE.DGC)THEN
C
C      CALCULATE THE HYDROCARBON CORRECTION TO THE NEUTRON LOG
      DELNEU=-1.3*PHIT*(1.0-SXO)*(DENMF*(1.0-PMF)
     2-1.5*DENHYD+0.2)/(DENMF*(1.0-PMF))
      IF(DELNEU.GT.0.0)DELNEU=0.0
      DEN(I)=DEN(I)-DELDEN
      NEU(I)=NEU(I)-DELNEU
C
C      FIND THE DENSITY POROSITY
      PHID=(2.71-DEN(I))/(2.71-DENMF)
C
C      FIND THE NEW TOTAL FORMATION POROSITY
      PHIT=(NEU(I)+PHID)/2.0
C
C      FIND THE NEW MATRIX DENSITY
      RHOMA=(DEN(I)-PHIT*DENMF)/(1.0-PHIT)
```

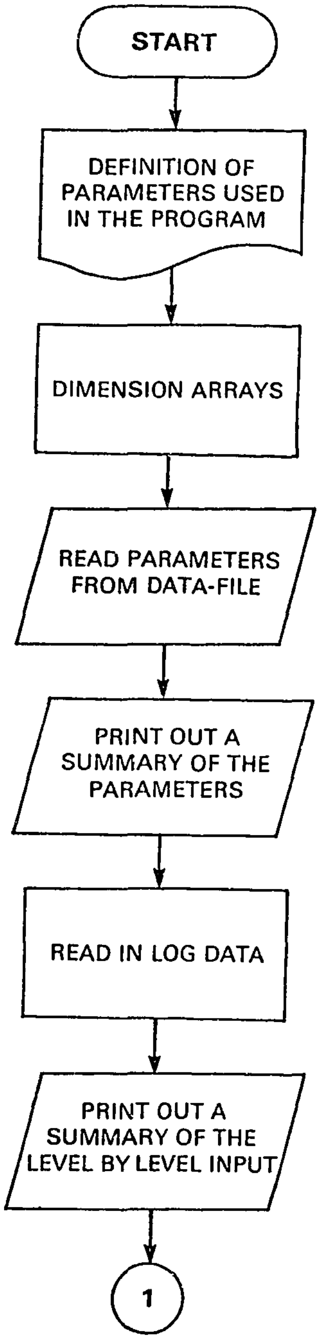
```
C
C      CALCULATE THE NUMBER OF ITERATIONS
      NI=NI+1
      GOTO 420
      END IF
C     ------------------------------------------------------------------
C      COMPUTE EFFECTIVE POROSITY
430   PHIE(I)=PHIT-VSH(I)*PORNSH
      IF(PHIE(I).LT.0.0)PHIE(I)=0.0
C
C      IF THE EFFECTIVE POROSITY IS LOWER THAN THE CUTOFF VALUE
C      EQUATE SXC AND SWE
      IF(PHIE(I).LT.PHICUT.OR.VSH(I).GT.VSHCUT)THEN
       SXC=1.0
       SWE(I)=1.0
      ELSE
C      CALCULATE THE EFFECTIVE OR FREE WATER SATURATION
      SWE(I)=1.0-(1.0-SW)*PHIT/PHIE(I)
C      CALCULATE THE EFFECTIVE MUD FILTRATE SATURATION
      SXO=1.0-(1.0-SXC)*PHIT/PHIE(I)
       END IF
C
C      CHECK THAT SWE AND SXO ARE NOT UNREALISTIC
      IF(SWE(I).LT.0.0)SWE(I)=1.0
      IF(SXO.LT.0.0)SXO=1.0
C     ------------------------------------------------------------------
C      WRITE OUT THE RESULTS
      WRITE(6,200)DEPTH(I),VSH(I),PHIX,RHOX,DGC,RHOMA,NI
     2,PHIE(I),RT,SXO,SWE(I)
200   FORMAT(5X,F6.1,2(F10.3),3(F10.2),7X,I2,3X,F10.3,,4X,F6.1
```

```
     2,5X,F5.3,5X,F5.3)
C     ------------------------------------------------------------
C      THIS SECTION CALCULATES GROSS PAY, POROSITY AND WATER SATURATION
      PHITG=PHITG+PHIE(I)
      SWTG=SWTG+SWE(I)
C     --------------
20    CONTINUE
C     --------------
C
C      CALCULATE GROSS PAY INTERVAL
      GPINT=DEPTH(NSP)-DEPTH(1)
      IF(MDPH.EQ.1)THEN
      GPINTIMP=GPINT/0.305
      WRITE(6,100)GPINT,GPINTIMP
100   FORMAT(//,30X,'GROSS PAY INTERVAL= ',F6.1,' METRES'
     2,10X,'(',F6.1,' FEET)')
      ELSE
      GPINTMET=GPINT*0.305
      WRITE(6,400)GPINT,GPINTMET
400   FORMAT(//,30X,'GROSS PAY INTERVAL= ',F6.1,' FEET'
     2,11X,'(',F6.1,' METRES)')
      END IF
C
C      CALCULATE GROSS AVERAGE POROSITY
      PHIG=PHITG/NSP
      WRITE(6,101)PHIG
101   FORMAT(30X,'GROSS POROSITY= ',F5.3)
C
C      CALCULATE GROSS AVERAGE WATER SATURATION
      SWG=SWTG/NSP
```

```
      WRITE(6,102)SWG
 102  FORMAT(30X,'GROSS WATER SATURATION= ',F5.3)
C     ----------------------------------------------------------------
C      COMPUTE NET PAY, POROSITY, WATER SATURATION
C      AND HYDROCARBON PORE THICKNESS.
      DO 300 J=1,NSP
      IF(VSH(J).LE.VSHCUT.AND.SWE(J).LE.SWCUT.AND.PHIE(J).GE.PHICUT)THEN
      PHITN=PHITN+PHIE(J)
      SWTN=SWTN+SWE(J)
      NNPP=NNPP+1
C
C      COMPUTE NET PAY
      IF(J.EQ.1)NP=NP+(DEPTH(J+1)-DEPTH(J))/2.0
      IF(J.EQ.NSP)NP=NP+(DEPTH(J)-DEPTH(J-1))/2.0
      IF(J.NE.1.AND.J.NE.NSP)NP=NP+(DEPTH(J+1)-DEPTH(J-1))/2.0
      END IF
 300  CONTINUE
C
C      PRINT OUT THE NET PAY DATA
      IF(MDPH.EQ.1)THEN
      NPIMP=NP/0.305
      WRITE(6,103)NP,NPIMP
 103  FORMAT(/,30X,'NET PAY INTERVAL= ',F7.2,' METRES'
     2,10X,'(',F7.2,' FEET)')
      ELSE
      NPMET=NP*0.305
      WRITE(6,403)NP,NPMET
 403  FORMAT(/,30X,'NET PAY INTERVAL= ',F7.2,' FEET'
     2,11X,'(',F7.2,' METRES)')
      END IF
```

```
C
C      PRINT OUT THE NET EFFECTIVE POROSITY AND THE NET WATER SATURATION
      PHIN=PHITN/NNPP
      WRITE(6,104)PHIN
104   FORMAT(30X,'NET POROSITY= ',F5.3)
      SWN=SWTN/NNPP
      WRITE(6,105)SWN
105   FORMAT(30X,'NET WATER SATURATION= ',F5.3)
C
C      PRINT OUT THE NET HYDROCARBON PORE THICKNESS
      NHPT=NP*PHIN*(1.0-SWN)
      IF(MDPH.EQ.1)THEN
      NHPTIMP=NHPT/0.305
      WRITE(6,110)NHPT,NHPTIMP
110   FORMAT(/,30X,'NET HYDROCARBON PORE THICKNESS= ',F10.5,' METRES'
     2,10X,'(',F10.5,' FEET)')
      ELSE
      NHPTMET=NHPT*0.305
      WRITE(6,410)NHPT,NHPTMET
410   FORMAT(/,30X,'NET HYDRCCARBON PORE THICKNESS= 'F10.5,' FEET'
     2,11X,'(',F10.5,' METRES)')
      END IF
C      -------------------------------------------------------------
      CLOSE(4)
      WRITE(1,500)
500   FORMAT(5X,'NORMAL TERMINATION')
      STOP
      END
      END$
```

10. Program flowchart of the dual water wireline log interpretation model.



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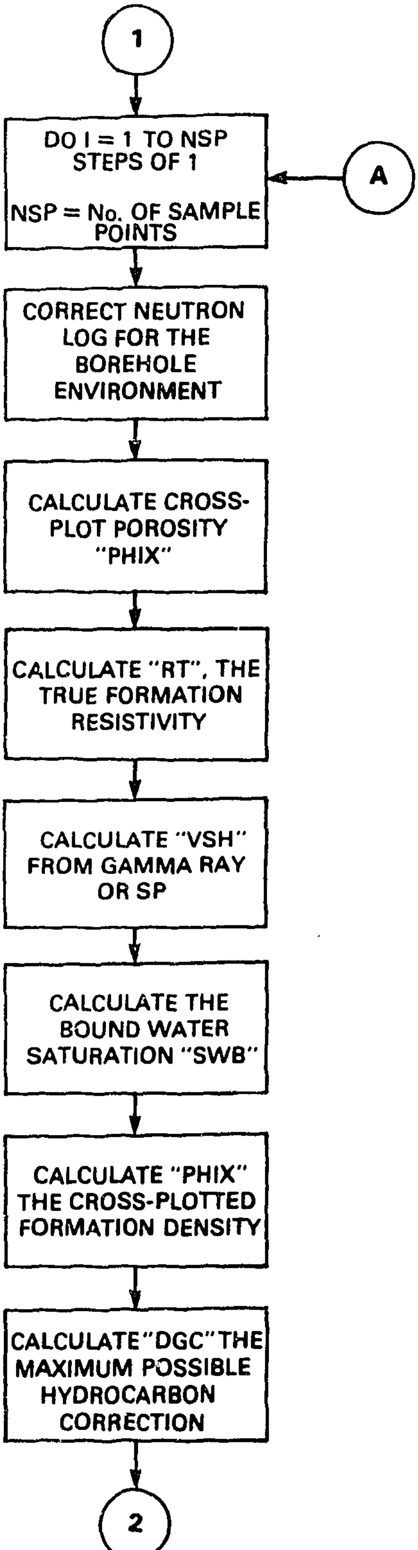
1
DO I = 1 TO NSP
STEPS OF 1
NSP = No. OF SAMPLE POINTS
A
CORRECT NEUTRON LOG FOR THE BOREHOLE ENVIRONMENT
CALCULATE CROSS-PLOT POROSITY "PHIX"
CALCULATE "RT", THE TRUE FORMATION RESISTIVITY
CALCULATE "VSH" FROM GAMMA RAY OR SP
CALCULATE THE BOUND WATER SATURATION "SWB"
CALCULATE "PHIX" THE CROSS-PLOTTED FORMATION DENSITY
CALCULATE "DGC" THE MAXIMUM POSSIBLE HYDROCARBON CORRECTION
2

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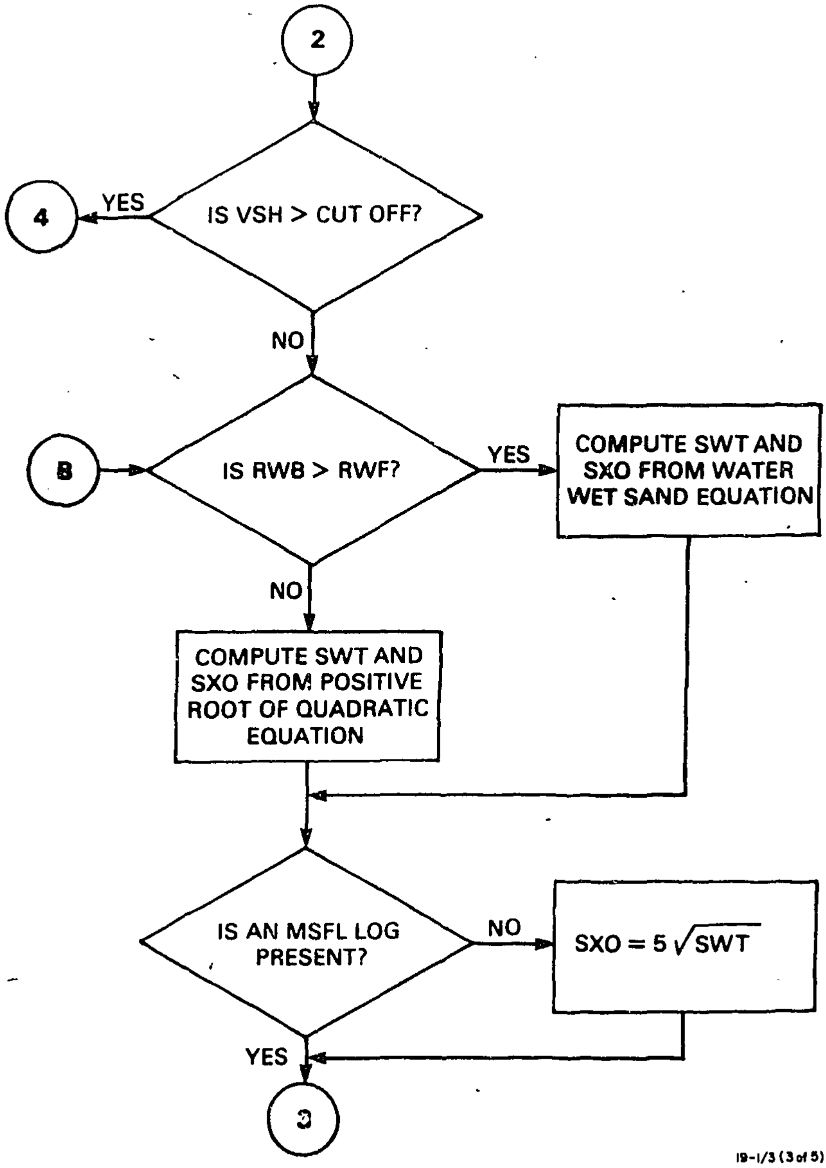
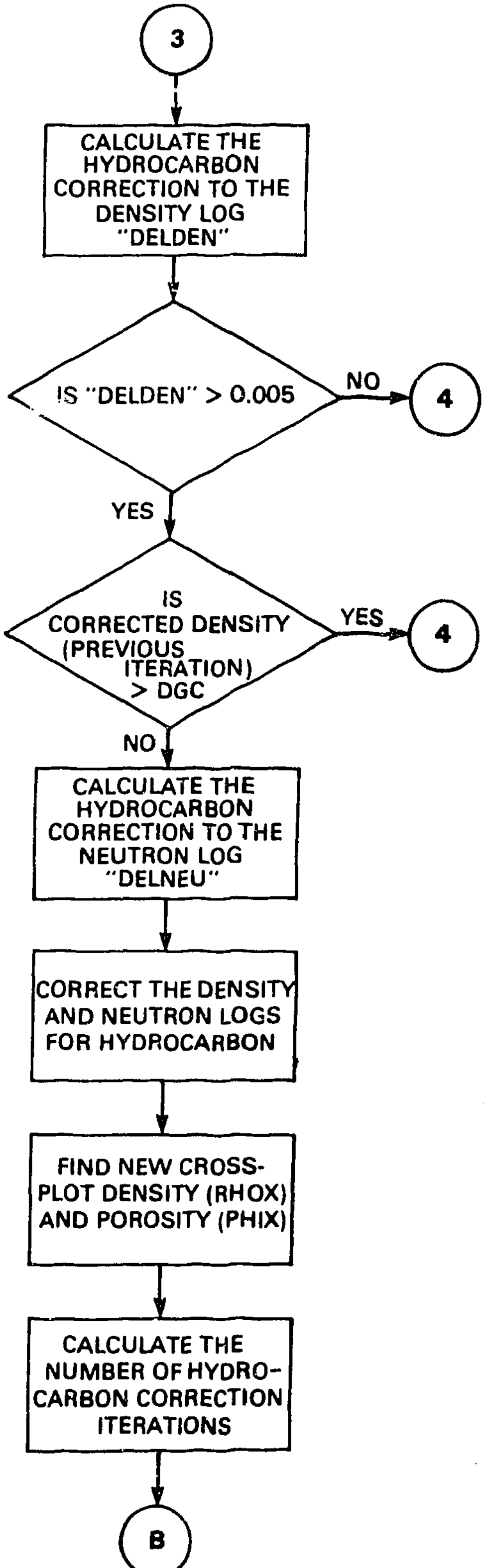
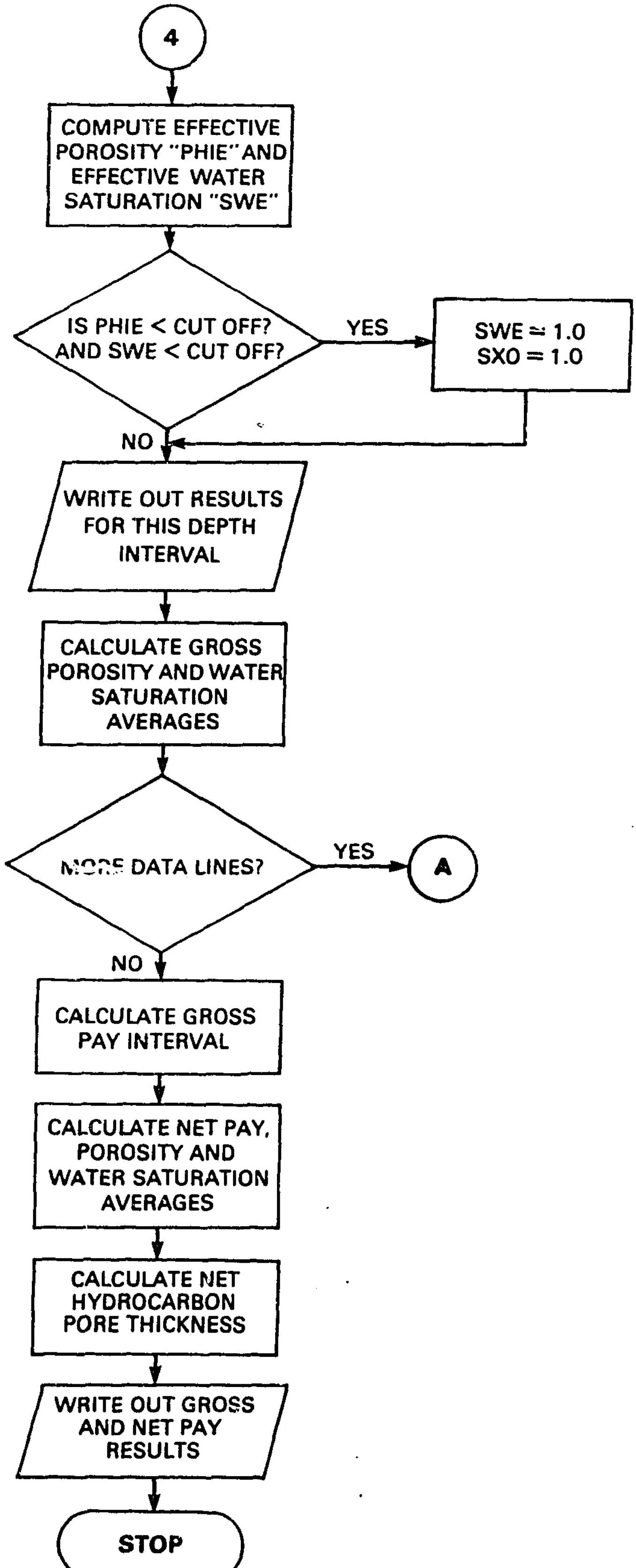

2
IS VSH > CUT OFF?
YES
4
NO
B
IS RWB > RWF?
YES
COMPUTE SWT AND SXO FROM WATER WET SAND EQUATION
NO
COMPUTE SWT AND SXO FROM POSITIVE ROOT OF QUADRATIC EQUATION
IS AN MSFL LOG PRESENT?
NO
SXO = 5 √SWT
YES
3

19-1/3 (3 of 5)


3
CALCULATE THE HYDROCARBON CORRECTION TO THE DENSITY LOG "DELDEN"
IS "DELDEN" > 0.005
NO
4
YES
IS CORRECTED DENSITY (PREVIOUS ITERATION) > DGC
YES
4
NO
CALCULATE THE HYDROCARBON CORRECTION TO THE NEUTRON LOG "DELNEU"
CORRECT THE DENSITY AND NEUTRON LOGS FOR HYDROCARBON
FIND NEW CROSS-PLOT DENSITY (RHOX) AND POROSITY (PHIX)
CALCULATE THE NUMBER OF HYDROCARBON CORRECTION ITERATIONS
B

19-1/3 (4 of 5)


4
COMPUTE EFFECTIVE POROSITY "PHIE" AND EFFECTIVE WATER SATURATION "SWE"
IS PHIE < CUT OFF? AND SWE < CUT OFF?
YES
SWE = 1.0
SXO = 1.0
NO
WRITE OUT RESULTS FOR THIS DEPTH INTERVAL
CALCULATE GROSS POROSITY AND WATER SATURATION AVERAGES
DATA LINES?
YES
A
NO
CALCULATE GROSS PAY INTERVAL
CALCULATE NET PAY, POROSITY AND WATER SATURATION AVERAGES
CALCULATE NET HYDROCARBON PORE THICKNESS
WRITE OUT GROSS AND NET PAY RESULTS
STOP

19-1/3 (5of5)

11. Bibliography

(1) W.R. Almon, 1981

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Published by the Petroleum Exploration Society of Australia, 1981.

(2) R.M. Bateman and C.E. Konen, 1977

"The Log Analyst and the Programmable Pocket Calculator", paper in the Society of Professional Well Log Analysts publication, 1977.

(3) J.L. Dumanoir, no date given

Paper titled "Dual Mineral, Dual Water Model" incorporated in the "Cyberlook" section of Schlumberger course notes "Log Evaluation Techniques in Shaly Sands and Complex Lithologies", 1983.

(4) R.L. Hausenbuiller, 1978

"Soil Science, Principles and Practices", second edition, Brown Publishing Company, 1978.

(5) L.E. Kurylowicz, 1978

"A Review of the Concepts and Practices of Wireline Log Interpretation" BMR internal publication, 1978.

(6) Schlumberger Wireline Well Logging Company Publications,

no authors given.

(a) "Log Interpretation, Volume 1 - Principles" 1972 edition.

(b) "Log Interpretation Charts" 1979 edition.

(c) "Log Evaluation Techniques in Shaly Sands and Complex Lithologies" 1983 Course Notes.

12. Appendix 1; A List of the Variables used in this Record and their Definitions.

a = the Archie coefficient

Cf = conductivity of the fluids contained within the total porous space Øt

Cwb = conductivity of the bound or immovable water

Cwf = conductivity of the free formation water

DGC = the maximum value ρma may take once corrected for hydrocarbons, stands for "density grain corrected"

GR log = gamma ray log reading

GR max = gamma ray log reading in a formation composed of 100% radioactive shale

GR min = gamma ray log reading in the clean non-radioactive reservoir rock

h = net pay thickness

m = cementation factor used in the Archie equation

NHPT = the net hydrocarbon pore thickness

NSP = number of sample points

P = salinity of the mud filtrate expressed as a fraction

PHIeff = effective porosity

PHIxplt = crossplot porosity (uncorrected for hydrocarbon effects)

Rf = resistivity of the fluid, see Cf

RHOma = matrix density (corrected for hydrocarbon effects)

RHOxplt = crossplot density (uncorrected for hydrocarbon effects)

Rmf = resistivity of the mud filtrate

Rsh = resistivity of a 100% shale formation adjacent to the reservoir sand

Rt = true formation resistivity

Rwb = bound water resistivity

Rwf = free formation water resistivity

Rxo = resistivity of the invaded zone, can be approximated by the resistivity generated from the micro-spherically focussed log corrected for mud cake effects

SP log	=	spontaneous potential log reading
SP min	=	SP log reading in a 100% shale formation
SSP	=	SP log reading in the clean reservoir rock
Sw	=	water saturation
Swb	=	bound water saturation
Swe	=	effective water saturation
Swt	=	total water saturation of the formation, includes Swb
Sxo	=	saturation of the mud filtrate in the invaded zone
Vf	=	volume of fluid within the pore space Øt, expressed as a fraction
Vsh	=	volume of shale, calculated here from either the gamma ray or the SP log
Ø	=	porosity of the formation
Ød	=	porosity from the density log
Øe	=	effective porosity
Ø log corr	=	neutron log porosity reading corrected for the borehole environment
Ø neutron log	=	porosity read directly from the neutron log
Øsh	=	apparent shale porosity, calculated from the neutron - density crossplot in a 100% shale formation
Øt	=	total porosity of the formation, includes Øsh
ΔØ	=	hydrocarbon correction to the neutron porosity log
ΣØ	=	correction for the borehole environment to the neutron porosity log
ρb	=	density log reading (or "bulk" density)
ρf	=	density of the fluid in Øt
ρhr	=	density of the hydrocarbon
ρma	=	matrix density
ρ*ma	=	matrix density of the clean reservoir rock with water filled pores

ρmf	=	density of the mud filtrate
ρsh	=	density of shale, calculated from a neutron - density crossplot in a 100% shale formation
$\Delta\rho$	=	hydrocarbon correction to the density log.

Note: density values are in units of grams per cubic centimetre

gamma ray values are in API units

SP values are in millivolts

depths are in metres or feet

12. Appendix 2; Input Data Format.

The following section details the format required for the data entered into the LOG4 and DW programs. This appendix is an excerpt from the BMR publication; "A Review of the Concepts and Practice of Wireline Log Interpretation" by L.E. kurylowicz, 1978.

Line 1 - Title of up to 40 characters is entered.
Line 2 - Run number (e.g. 0001) four digits and date (21-10-78) are entered.
Line 3 - Values for various switches (IPORF, IHYDR, IPL, IRM, MDPH, MTAC, MTEM, LUN, NLTYPE, IPRINT) used in program

IPORF = 1 (Final porosity is from neutron-density cross-plot
= 2 (Final porosity is average of sonic plus neutron-density)
= 3 (Final porosity is average of Simplex, plus sonic, plus neutron-density)

IHYDR = Hydrocarbon detection switch (i.e. Rxo log present)
1 = Yes; 0 = No.

IPL = Plot Switch (1 = Yes; 0 = No)

IRM = Resistivity combination in order to apply correct 'butterfly' chart correction for Rt
1 = LL8, ILM, ILD; 2 = Rxo, LLs, LLd;
0 = No Rm log or some other resistivity combination is present.

MDPH = Metric depth (1 = metres; 0 = feet)

MTAC = Metric interval transit time (1 = microseconds/ m; 0 = microseconds/foot)

NOTE: Simplex is the technique of optimizing the solution of a set of simultaneous linear equations (used in LOG4 only).

MTEM = Metric temperature (1 = Centigrade; 0 = Fahrenheit)

LUN = Intermediate calculations print-out (debug)
(6 = Yes; 11 = No)
No other values are permitted.

NLTYPE = Type of neutron log (1 = SNP; 2 = CNL; 3 = API units)

If NLTYPE = 3, then the constants (A,B) of the equation of best fit of API versus porosity (calibrated before-hand against either density, sonic, or core values) are entered on line 3 B.

Eqn is: Neutron porosity = A-B log (API)

IPRINT = 6, normal output printing device; = 7 for Gould printer.

ISP = is SP reliable 1 = yes, 0 = No.

Line 4 - NSP, TEM, PMF, DENMF, TACF

NSP = Number of sample points (maximum of 100 for LOG4, 300 for DW)

TEM = Formation temperature

PMF = Mud filtrate salinity (fraction in parts per million)

RMF = Mud filtrate resistivity at formation temperature

DENMF = mud filtrate density (gm/cc)

TACF = mud filtrate interval transit time

DELPOR = log porosity correction, entered as a fraction (neutron log)

Line 5 - GRYMIN, DENMA, TACMA, SSP

GRYMIN = Gamma Ray reading opposite clean sandstone section.

DENMA = Matrix density (i.e. sandstone or limestone) - gm/cc.

TACMA = Matrix interval transit time.

SSP = SP deflection in clean sandstone (maximum)

Line 6 - GRYMAX, RSH, DENSH, TACSH, PORNISH, SPMIN

GRYMAX = Gamma Ray reading opposite a nearby shale-section

RSH = Resistivity of shale section

DENSH = Density of shale

TACSH = Shale interval transit time

PORNSH = Neutron porosity reading in shale section.

SPMIN = SP deflection in shale.

Line 7 - RW, DENHYD, BORE

RW = Formation water resistivity (from DST, or cross-plot)

DENHYD = Hydrocarbon density (gm/cc - from hydrocarbon analysis).

BORE = Bore hole diameter (inches -) size of drill bit will suffice for correction to density log readings.

Lines 8 up to 10 - DPH, GRY, DENA, PORNLI, TAC, PSP, RXO, RM, RD, CAL for LOG4

- or DEPTH, GR, DEN, NEU, TT, SP, MSFL, RLS, RLD, CAL for DW respectively

DPH = Depth (metres or feet)

GRY = Gamma Ray (API)

DENA = Density (gm/cc)

PRONLI = Neutron Porosity (porosity units or API units)

TAC = Interval transit time (microseconds/m or microseconds/foot)

PSP = Spontaneous Potential reading (relative to shale line or an arbitrary base line - millivolts)

RXO = flushed zone resistivity

RM = invaded zone resistivity

RD = deep resistivity (equals Rt in most cases).

CAL = optional: size of hole in inches (I.E. bore diameter minus mud cake thickness)

IEND = -1.

NOTE: (1) that CAL is an optional input at this stage for both LOG4 and DW.

(2) DELPOR was introduced in this segment on 1 March 1983. DELPOR is determined from Schlumberger chart Por-14a and is added to the porosity read from the neutron log to correct it for borehole environmental factors. This correction is generally in the range 0.00 to 0.05 and is usually only above 0.03 in high temperature wells. Where Por-14a in the 1977 edition of Schlumber charts is equivalent to Por-14b in the 1979 edition.

The input format for the first seven lines of data entered into the LOG4 and DW programs is shown on Table 1, page 63.

1	TITLE (UP TO 40 CHARACTERS)

	RUN	DATE
2		– –

	IPORF	IHYDR	IPL	IRM	MDPH	MTAC	MTEM	LUN	NLTYPE	IPRINT	ISP
3	,	,	,	,	,	,	,	,	,	.	

	NSP	TEM	PMF	RMF	DENMF	TACF	DELPOR
4	,	,	,	,	,	,	

	GRYMIN	DENMA	TACMA	SSP
5	,	,		

	GRYMAX	RSH	DENSH	TACSH	PORNSH	SPMIN
6	,	,	,	,		

	RW	DENHYD	BORE
7	,	,	

Notes:

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Table 1 Format of input for program LOG 4 and DW.