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**LOG II:
A General Purpose Automated
Well Log Evaluation System**

Ricardo A. Olea

Kansas Geological Survey

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Cover: Electron photomicrograph of a pore cast of Masillon Sandstone, approximately 200 \times .
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PREFACE

This publication is a result of cooperative research work conducted by Empresa Nacional del Petróleo (ENAP) of Chile, and the Kansas Geological Survey. The LOG II program was developed during the author's tenure as Visiting Research Scientist (1974-1975) with the Kansas Geological Survey, and completed subsequently in Chile.

This publication demonstrates the truth of the old adage that man cannot be an island unto himself. Much of what one knows and can share through a publication such as this depends upon the assistance of others; it is a pleasure to acknowledge this help. The continued cooperation and mutual exchange between Empresa Nacional del Petroleo (ENAP) and the Kansas Geological Survey has created an environment in which research such as this is possible. Professor W. W. Hambleton, State Geologist and Director, extended the official invitation on behalf of the Kansas Geological Survey; in Chile, Ingenieros Carlos Mordojovich, Oscar Schneider, and Eduardo González of ENAP were responsible for official approval of the exchange. I am indebted to Survey staff members for their assistance, particularly to Dr. John H. Doveton who devoted more time than he could properly spare to contribute ideas, offer suggestions, and read the manuscript; and to Dr. John C. Davis who carefully read the text and proposed valuable additions and corrections.

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LOG II: A GENERAL PURPOSE AUTOMATED WELL LOG EVALUATION SYSTEM

by Ricardo A. Olea¹

ABSTRACT

Petrophysical characteristics of the subsurface can be estimated using information from geophysical logs. The diversity and accuracy of the estimates depends upon the number of logs available. Models presented in this work are designed to produce formation evaluation reports which are as complete as possible, using a minimum number of logs. The models were translated to computer routines monitored under LOG II. A special lexicon was developed to insure flexibility that will allow convenient, optimum use of the available data and at the same time make the system usable even by those analysts without previous programming experience. Several examples are presented which illustrate the use of the lexicon and the capabilities of the program.

1. INTRODUCTION

The primary purpose of well logging in petroleum exploration is to provide clues that will aid in exploitation of producing wells and in the search for new reservoirs. Well logs contain information about subsurface conditions. This information may be extracted by visual inspection by an experienced interpreter, or by mathematical transformation of readings from one or more logs, using standard engineering formulas.

Graphs and nomograms greatly facilitate log analysis and are a quick and practical alternative to the drudgery of manual computation. Even so, interpretation using charts can be a lengthy process; evaluation of a single well may involve hundreds of readings. In addition, only a few of the possible combinations of values can be put on charts in the form of curves. The use of these charts therefore requires approximation or interpolation in the reading of graphical values. More serious is the fact that in order to simplify logging charts, only simple analytical expressions have been utilized in their construction. Engineering charts are

useful for obtaining answers rapidly, but the resulting analyses, based on such simple models, may be far from reality.

Digital computers are a significant aid in resolving the limitations of manual and graphic calculation of log properties. Routine management of massive quantities of data is no longer a problem. Digitized well logs and the results of processing stored on magnetic tapes or discs allow efficient manipulation of the stored information. More sophisticated analyses involving complex formulas can be performed with any desired accuracy. Finally, with appropriate software and a dedicated or time-sharing computer, well-log interpretations can be produced almost instantaneously, not only in tabular but also in graphical form.

LOG II is a computer program for subsurface formation evaluation that uses both core analyses and well-log information which has either been digitized or recorded directly in digital mode. The program can process individual logs or combine a logical sequence of logs for calculation of petrophysical parameters and statistics such as means, semivariograms, and variances. LOG II has been specifically designed for formation evaluation in wells for which limited log combinations are available. The information from such wells is inadequate for elaborate techniques requiring several porosity logs. Multiple porosity logs allow greater definition in the interpretation of formation lithologies and hydrocarbon type; however, high logging costs restrict their availability. In addition, appropriate logging tools were not developed until the 1960's and wells drilled prior to that time were rarely surveyed with more than one porosity device. The limited information available on many older wells requires a simpler approach for their evaluation.

LOG II is designed to operate with a basic suite of three types of petrophysical well logs: (1) a "shale" log (SP or gamma ray); (2) a porosity log (either sonic, density or neutron); (3) a resistivity log (either a deep induction or laterolog). These combinations correspond to the majority of logging programs run on Kansas wells in the last 20 years.

LOG II assumes that the logged interval consists of shale and a single reservoir rock type (sandstone, limestone, dolomite, or chert). Stratigraphic sequences including horizons of differing lithologies must be analyzed by separate computational runs on subdivisions of the log containing a single reservoir lithology.

LOG II includes subroutines that allow use of core measurements in the computation of permeability and numerical constants of Archie's equation. In all phases of the program's

operation, values of basic petrophysical parameters (such as grain and fluid densities) may be entered by the user. If these parameters are not specified, default values will be used which correspond to a typical Midcontinent Pennsylvanian or Permian limestone/shale sequence.

Although the primary purpose of LOG II is to evaluate individual wells, the summary statistics computed for each well are useful in areal studies of lithological and petrophysical variation. The program incorporates some statistical subroutines that are not available in any current commercial log analysis package. These are especially designed to aid in the analysis of repetitive sequences of lithologies. Numerical values, even in tabulated form, are difficult to analyze when voluminous. Graphical display is the best alternative in this instance. Using either a line printer or an electromechanical plotter, according to the user's convenience and available equipment, LOG II has the capability to present original log readings or computed results in the form of logs.

2. THEORETICAL REVIEW

2.1 Shale Logs

The percentage of shale in a zone of interest is conventionally estimated from an SP or gamma ray trace if a multiple porosity log combination is not available. The simplest procedures estimate shale content as a linear function of the formation natural radioactivity as measured by the gamma ray response, or as a reverse linear relationship of the spontaneous potential (when the formation water is more saline than the drilling mud). Either method provides satisfactory logs of simple lithologies under suitable borehole conditions.

The SP log is influenced to some degree by hydrocarbon saturation and there may be problems in establishing a static self-potential value in relatively shaly sequences which do not have clean, permeable units. Evaluation of the gamma ray log requires recognition of normal shales, as opposed to highly radioactive black shales. Also, the clean lithologies are assumed to be relatively free of radioactive material such as feldspars or heavy minerals. Even in the absence of these disturbing influences, shale estimations from these two equations may be in error because the relationship between an SP or gamma ray response and the shale content of the rock may not necessarily be linear.

2.2 Porosity Logs

Although they are based on different physical measurements, computations of porosity from either sonic, density, or neutron logs are similar in form. If porosity estimates are made from a combination of a shale log and a single porosity log, any zone of interest is assumed to consist of three components: shale, the matrix, and a fluid occupying the pore space. If a linear relationship is assumed between the log responses and the quantities of these components, simultaneous equations may be solved to determine the porosity. These equations are of the form:

$$V_{sh} \times P_{sh} + V_{ma} \times P_{ma} + \phi \times P_{fl} = P_{LOG} \quad (2.2.1)$$

$$V_{sh} + V_{ma} + \phi = 1$$

where

V_{sh} is the fraction of the rock which is shale;

V_{ma} is the fraction of the rock composed of matrix mineral;

ϕ is the porosity, or fractional volume of pore space;

P_{sh} , P_{ma} , and P_{fl} are porosity log coefficients for the endmembers of 100% shale, 100% matrix, and 100% fluid;

P_{LOG} is the porosity log reading.

Since the quantity of shale is determined from the "shale log" derived from either the SP or gamma ray response, the equations may be uniquely solved for the unknown proportions of matrix mineral and porosity. The pore fluid may contain variable amounts of oil and water, but since these fluids have similar properties with respect to porosity tools, only a minor source of error is introduced because of fluid composition. High gas saturations, however, cause significant deviations; an additional porosity tool response is required if gas is present.

Acoustic Velocity Log

The acoustic velocity log measures the shortest time required for a sonic pulse to travel between a transmitter and a receiver located on the logging tool. Wyllie (1956) introduced the time average equation which relates porosity to transit time quantities:

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \quad (2.2.2)$$

where

ϕ is the porosity of the measured interval;

Δt is the transit time through the interval;

Δt_{ma} and Δt_f are the transit time for the pure matrix mineral and the porosity fluid.

The equation gives reasonably accurate estimates of the porosity in clean lithologies where porosity is intergranular or intercrystalline in nature.

The presence of shale in the interval introduces another unknown into the porosity evaluation. However, since the Wyllie equation is a linear relation between transit times and porosity, the influence of a shale component may be evaluated by an expanded equation:

$$\phi = \frac{\Delta t - \Delta t_{ma} - V_{sh} (\Delta t_{sh} - \Delta t_{ma})}{\Delta t_f - \Delta t_{ma}} \quad (2.2.3)$$

This is simply a condensation of two simultaneous equations of the general form given by equation (2.2.1). It is assumed that: (1) there are only three different wave velocities (for matrix mineral, shale, and fluid) in the material; (2) the shortest path between any two points in the interval is a straight line; and (3) that the lithology is sufficiently compacted so the matrix provides a rigid framework for primary wave transmission.

The first assumption is met provided that relative amounts of each mineral in the interval are constant or the lithology consists of a single mineral in addition to shale. Since the porosity evaluation is made primarily in the flushed zone, a composite fluid transit time may be used, corresponding to mud filtrate. Residual oil saturations have similar transit time characteristics and residual gas saturations usually introduce only minor errors in the porosity evaluation.

The second assumption holds true provided the porosity is either intercrystalline or intergranular. Vugs or fractures are not detected by acoustic velocity determinations, so the porosities estimated are "primary" porosity. The amount of "secondary" porosity in the form of vugs or fractures may be estimated by subtraction from density or neutron "total" porosity measurements.

The third assumption is valid for almost all formation evaluations made in the Midcontinent area. If the equation is applied to unconsolidated formations, however, a corrective compaction constant must be applied to reduce high apparent porosities to their true values.

Density Log

The density log is produced by a gamma-gamma device which irradiates the interval with gamma rays. The relative reduction in gamma ray flux by the formation is measured by a detector. The reduction in gamma ray intensity is related to the electron density of the rocks penetrated. There is an approximately constant relationship between electron density and bulk density for most light elements, which constitute the bulk of typical minerals in sedimentary lithologies.

A typical density log trace is calibrated in grams per cubic centimeter. As a consequence, porosity may be estimated by simple mass balance relationships. These can be solved as simultaneous equations which can be combined to yield:

$$\phi = \frac{\rho_{ma} - \rho_b - V_{sh}(\rho_{ma} - \rho_{sh})}{\rho_{ma} - \rho_f} \quad (2.2.4)$$

where

ρ_b is the bulk density measured in the interval;

ρ_{ma} , ρ_{sh} , ρ_f are the densities of the matrix mineral, shale and the fluid, respectively.

Oil and mud filtrate densities are approximately the same, so a fluid density corresponding to mud filtrate introduces only minor errors in porosity evaluation. A significant residual gas saturation, however, will introduce an error into the porosity equation such that computed porosities are higher than the true values. Allowance must be made for this factor in intervals which are suspected to be gas-bearing. Alternatively, gas-bearing intervals should be evaluated with a dual porosity combination (either sonic-neutron, sonic-density or neutron-density). The porosity estimated by density calculations is a measure of "total" porosity and includes both vuggy and fracture porosity as well as intercrystalline and intergranular porosity.

Neutron Log

Neutron log sondes contain radioactive sources which emit high energy neutrons that penetrate the adjacent formation. Neutrons travelling through the rock collide with atomic nuclei which change their path and initially reduce the energy of the neutrons. When the incident neutrons are reduced to thermal equilibrium, they are captured by atomic nuclei in the rock, which then emit gamma rays. Reduction of neutron energy is in large part a function of the hydrogen content of the rock, as hydrogen has a mass most similar to a neutron and consequently produces the largest energy loss per collision. The dominant influence of hydrogen on neutron energy is the basis for porosity measurements made from neutron logs. The calculated hydrogen density may be directly related to pore fluid volumes after correcting for hydrogen concentrations associated with shale in the tested interval.

The exact relationship between emitted radiation and porosity in a water-saturated porous interval composed of a single mineral can be deduced theoretically or obtained experimentally. Although the conversion factor is unique for each mineral, a conversion table may be used to translate measured radioactivity into a pseudo-porosity. For instance, the neutron porosity value for shale is simply the level of radioactivity measured by the receiver in a shale interval, converted to porosity units with the assumption the interval is shale-free. The resulting value is characteristic of shale and can be used in the evaluation of porosity in shaly formations, rather than as a practical measure of effective porosity.

For the purposes of formation evaluation, a simplified model considers the total gamma radiation received by the sensor to be proportional to the relative abundance of the constituents in the interval. The measured radioactivity is first converted to a pseudo-porosity scale. Formation porosity can then be estimated by solving a set of simultaneous equations similar to those used for other porosity tools. The set of simultaneous equations condenses to a single equation:

$$\phi = \frac{N_{ma} - N - V_{sh} (N_{ma} - N_{sh})}{N_{ma} - N_f} \quad (2.2.5)$$

where

N is the neutron porosity of the interval;

N_{ma} , N_{sh} , N_f are the neutron pseudo-porosities of the matrix mineral, shale and fluid, respectively.

Sondes are generally calibrated in such a way that N_{ma} is zero for either calcite, quartz, or dolomite. These minerals form the matrix component of limestone, sandstone, chert, and dolomite intervals. The fluid neutron pseudo-porosity value is equal to 1.00 when the pore fluid is pure water. The hydrogen density of any residual oil in the pore fluid differs from that of water to some degree depending on the hydrocarbon composition of the oil. For most Midcontinent oils the difference is too small to significantly affect porosity estimates, so the fluid neutron pseudo-porosity value may be approximated as 1.

When the neutron porosity calibration mineral matches the lithology of the interval measured, the porosity equation may be simplified to:

$$\phi = N - V_{sh} \times N_{sh} \quad (2.2.6)$$

The presence of significant quantities of residual gas adversely affects neutron porosity estimates. The hydrogen density of gas is markedly lower than either water or oil, so porosity estimates in gas zones may be pessimistically low. Implicit allowances must be made for this effect, or more precise evaluations made by using an additional porosity tool.

Although most modern neutron logs are directly recorded in pseudo-porosity units, older neutron logs record the amount of induced radioactivity measured by the tool in API units. To evaluate these older logs, the pseudo-porosity must be calculated from conversion tables and corrections made for several disturbing effects which may be difficult to eliminate. Relationships between neutron API units and porosity are of the form:

$$\phi = a + b \times 10^{-R/c} + e \times 10^{-D/f} \quad (2.2.7)$$

where

R is the neutron radioactivity API reading;

D is the hole diameter;

a, b, c, e, f are constants depending on the specific tool and drilling mud.

Since many neutron logs run for Kansas wells are recorded in API neutron radiation units, LOG II can translate radiation readings to equivalent porosity values provided the proper count-porosity calibration data is available.

2.3 Shale Characteristics

To obtain accurate estimates of porosity and water saturation in shaly intervals, it is necessary to provide measures of shale characteristics to be used in the analytical equations of LOG II. The term "shale" is extremely general and may represent a spectrum of mixtures of clays and other minerals, widely differing in compaction and fabric. The most representative values for shale properties can be derived from an inspection of log traces run through the interval to be analyzed. LOG II requires estimates of the equivalent shale porosity and shale resistivity values.

The shale porosity value is a generalized quantity which best typifies the porosity tool response in shale zones. This value may be either a shale transit time (for sonic logs), a shale density (for density logs) or a shale neutron reading (in count units for a neutron radiation log or porosity units for a neutron porosity log). When used in conjunction with the proportion of shale estimated from a "shale log," a porosity equation may be solved for an estimate of the true porosity in shaly formations.

Since shales act as conductors transmitting current through an interval, a representative value for the resistivity of shale must be supplied to the program in order to calculate water saturation in shaly zones. This conductivity value may be derived by inspection of the induction or laterolog within a shale interval indicated on the SP or gamma ray log.

2.4 Formation Factor and Archie's Equation

Porosity and formation factor are related by the generalized form of Archie's equation:

$$F = \frac{a}{\phi^m} \quad (2.4.1)$$

where

a is a constant;

m is the "cementation factor."

The most widely used numerical form of Archie's equation for sandstones is the Humble formula, $F = 0.62/\phi^{2.15}$, which was derived from an empirical study of a suite of North American reservoir sandstones (Winsauer and others, 1952). The equation most often used (Schlumberger, 1972) for limestones and dolomites is:

$$F = \frac{1}{\phi^2} \tag{2.4.2}$$

These two equations are satisfactory for evaluation of sandstones and carbonates when more precise estimates of the constants a and m are not available. They are also used where lithologies are considered fairly typical and the potential errors are deemed acceptable.

The choice of the numerical values in Archie's equation becomes more critical if the analyzed intervals have relatively low porosities and accurate water saturations are required. LOG II can derive optimum numerical estimates of the parameters in Archie's equation. The constants are found by a regression analysis subprogram which relates water saturation, water resistivity, porosity and shale characteristics to the unknown constants a and m. The subprogram requires measurements of these variables derived from core or log analyses.

The basic equation for solution of water saturation in a shaly formation can be written in logarithmic form as:

$$\log \left[\frac{R_w}{S_w} \left(\frac{1}{R_t \times S_w} - \frac{V_{sh}}{R_{sh}} \right) \right] = \log \left(\frac{1}{a} \right) + m \log \phi \tag{2.4.3}$$

The equation may be expressed in a general form if $\log (1/a)$ is denoted as A, $\log \phi$ is denoted as X, and the left-hand side is denoted as Y. The equation can then be written $Y = A + B \times X$. With sufficient measurements of X and Y for a number of intervals, a regression line may be computed by least squares. The coefficient B is the slope of the line and A is the intercept of the line on the Y-axis. Quantitative estimates of a and m may be found from the regression coefficients, as $a = e^{-A}$ and $m = B$. These values may then be used in Archie's equation in the main log analysis phase of LOG II. The regression may be completely misleading in water saturation readings from cores not corrected to take into account mud filtrate flushing.

2.5 Water Saturation Evaluation

Several models, both theoretical and empirical, have been proposed for obtaining a satisfactory relationship between resistivity and water saturation in shaly intervals. The following relationship is cited by Schlumberger (1972) and is widely used:

$$\frac{1}{R_t} = \frac{S_w^2}{F \times R_w} + \frac{V_{sh} \times S_w}{R_{sh}} \quad (2.5.1)$$

where

R_t is resistivity measured in the uninvaded formation;

S_w is the fraction of water saturation;

F is the formation factor computer by Archie's equation;

R_w is the resistivity of formation water at the temperature of the interval;

R_{sh} is shale resistivity.

If R_t is the resistivity measured by a microresistivity tool (i.e., R_{xo}), R_w may be replaced by the mud filtrate resistivity (R_{mf}). The equation can then be used to evaluate water saturation in the flushed zone and the residual hydrocarbon saturation.

Where the evaluated zone does not contain shale, the equation condenses to the simpler form:

$$S_w = \frac{\sqrt{F \times R_w}}{R_t} \quad (2.5.2)$$

This corresponds to the basic equation used in formation evaluation. Either equation (2.5.1) or equation (2.5.2) presumes that the saturation exponent is equal to two.

2.6 Apparent Water Resistivity

The "reconnaissance water resistivity" (R_{wa}) method is widely used by log analysts as a quick method to estimate true connate water resistivity and hydrocarbon saturations in zones of interest.

For clean formations, by definition,

$$F = R_o/R_w \quad (2.6.1)$$

The "resistivity index" is by definition

$$I = R_t/R_o \quad (2.6.2)$$

and, from empirical results,

$$I \approx S_w^{-2} \quad (2.6.3)$$

From equation (2.6.1) it follows that:

$$R_w = R_o/F$$

An apparent water resistivity, R_{wa} , may be calculated for any zone:

$$R_{wa} = R_t/F \quad (2.6.4)$$

where R_t is read from the resistivity log and F computed from the porosity reading inserted into Archie's equation (2.4.1) with appropriate values for a and m . For zones which are water saturated, the apparent water resistivity will be coincident with the true value since $R_t = R_o$. In all other cases, R_{wa} will be higher than R_w since:

$$R_{wa} = R_t/F = I \times R_o/F = R_o/F \times S_w^2$$

In evaluating a typical reservoir unit, apparent water resistivity values will be high in the producing interval but will stabilize at a lower bounding value below the hydrocarbon/water contact and is an estimate of the true connate water resistivity. This estimate of R_w may be used in conjunction with R_{wa} values for producing zones to compute water saturations by the simple relationship:

$$S_w = \sqrt{R_w/R_{wa}} \quad (2.6.5)$$

since $R_w/R_{wa} = R_o \times F/R_t \times F = 1/I = S_w^2$.

The development of these equations in the reconnaissance technique presupposes that the zones evaluated are shale-free. Allowance for the presence of shale may be made through an adaptation of the relationship of equation (2.5.1):

$$R_{wa} = \frac{R_t \times R_{sh}}{F(R_{sh} - V_{sh} \times R_t)} \quad (2.6.6)$$

This modified formula is used in computations of apparent water resistivity in LOG II. In water-saturated shaly or clean zones the R_{wa} values will be estimates of the true connate water resistivity. In productive zones which are shale-free, the apparent and real water resistivity values are related to water saturation by equation (2.6.5); in shaly productive zones the relationship is more complex.

2.7 Permeability Estimation

The most widely used estimators of permeability are of the form

$$K^{0.5} = \frac{C \times \phi^p}{S_{w_{irr}}} \quad (2.7.1)$$

$$S_{w_{irr}} = B_i/\phi + F_{sh} \times V_{sh}$$

where

K is permeability in millidarcies;

C and p are constants depending on such formation characteristics as capillary pressure, hydrocarbon density, and lithology;

$S_{w_{irr}}$ is the fraction of irreducible water saturation;

B_i is the fraction of the formation volume occupied by the irreducible amount of connate water in a hydrocarbon-bearing rock;

ϕ is the fraction of the rock which is pore space;

F_{sh} is a constant relating the effect of the shale fraction V_{sh} on the irreducible water saturation.

In the absence of experimental values from cores, a reasonable approximation for this equation is:

$$K^{0.5} = \frac{100 \phi^{3.25}}{B_i} \quad (2.7.2)$$

However, given core measures of permeability and porosity plus additional knowledge of the minimum water saturation of the reservoir, LOG II yields an optimum set of coefficients C and p for equation (2.7.1). As in Section 2.4, the constants are found by running a regression analysis on the pseudovariables which result from the following logarithmic equation for permeability:

$$\log [K^{0.5} (B_i/\phi + F_{sh} \times V_{sh})] = \log (C) + p \times \log (\phi) \quad (2.7.3)$$

This equation may be rewritten in linear form as $Y = A + B \times X$. Y is the left-hand side of equation (2.7.3); A is $\log (C)$; B is the exponent of porosity, p; and X is the logarithm of porosity. Provided at least two observations are available to evaluate X and Y, regression analysis will yield numerical values for A and B. An inverse transformation can then be used to obtain C and p.

Since B_i and F_{sh} are incorporated within one of the pseudovariables used in regression, some preliminary estimates must be made of these quantities. B_i can generally be established satisfactorily from core measurements, since it is the product of the irreducible water saturation and porosity. F_{sh} is a function of shale composition and dispersion characteristics which

will be specific to the reservoir unit evaluated. In selecting an appropriate value, the best procedure is a repetitive application of the regression procedure, each employing a different quantity from a feasible range of F_{sh} values. The optimum value for F_{sh} will then coincide with the solution which provides the best least squares fit.

It is often useful to restrict the application of the regression to permeabilities below a specified bounding value in order to avoid the disruption of a normal fabric-permeability relationship by excessive values introduced by major fracture systems or other causes.

3. USER'S MANUAL

3.1 General Description

The basic input required for the LOG II program consists of a suite of well logs ("shale," porosity, and resistivity logs) digitized at regular or irregular intervals; a sequence of commands which specify program operations; and values of "global variables," such as shape characteristics, which are necessary for solution of the log analysis equations.

A maximum percent shale must be specified to differentiate shale beds from clean or shaly formation zones. If this cutoff value is not specified by the user, LOG II assumes an arbitrary figure of 50 percent shale. Petrophysical computations are confined to those zones identified as formation lithology having less than this specified shale content.

A minimum porosity value and maximum water saturation may also be specified to distinguish viable productive zones from those of marginal or academic interest. These limits do not affect computations, but are used when certain statistics are calculated which summarize the entire well section. These statistics include the cumulative thickness of intervals containing porosity greater than the specified minimum, the average porosity in these higher porosity intervals, the cumulative thickness of higher porosity intervals with water saturations of less than the input maximum water saturation, and the average water saturation in these low water saturation intervals. If limiting values are not specified, the program uses arbitrary values of 5 percent for minimum porosity and 50 percent for maximum water saturation. Use of selected cutoff values allows rapid assessment of the potential productivity of a well.

In order to solve the complete set of log analytical equations, the following variables are required:

1. Shale resistivity
2. Formation water resistivity at formation temperature
3. Values for a and m in Archie's equation

4. Spontaneous potential (SP) of clean, water saturated intervals (if an SP log is used), or
5. Gamma ray values for clean intervals and "normal" shale (if a gamma ray log is used)
6. Porosity log characteristics for shale (shale transit time, shale density, or shale neutron porosity)
7. Porosity log characteristics for the matrix mineral (matrix transit time or grain density)
8. Porosity log characteristics for the fluid (fluid transit time or density)
9. Permeability equation parameters.

However, it is not necessary to perform the complete set of log calculations if these results are not of interest, or if the necessary information is not available. In most instances the program will assume default values which correspond to typical parameters for a Midcontinent Pennsylvanian limestone section.

LOG II incorporates a subroutine which allows computation of the constants in the permeability equation as well as the a and m constants of Archie's equation, using a regression analysis of log measurements and core data supplied as input. These options are particularly recommended when evaluating intervals having relatively low porosities. For high porosity intervals or when rapid evaluations are required, published constants for Archie's equation, such as the Humble formula, may be used.

3.2 Data Input

The digitized log data to be analyzed are read first by LOG II. These data consist of two alphanumeric information cards, a format specification card, and a sequence of data cards containing depth and log readings. The log sequence is terminated by an end-of-sequence card containing any number not less than 9998.

The first and second cards contain alphanumeric information to identify the well. The identification is printed on the output sheets and plotted on the resulting logs, if any. The content and format is free if no plotting is required, but if a plot is necessary, then the

identification goes into the heading and the following information must be given according to the format shown below:

First Card

Columns 1 - 20	Company name
Columns 31 - 50	Field name
Columns 61 - 80	Well name

Second Card

Columns 1 - 20	State
Columns 31 - 50	County
Columns 61 - 80	Township and range

LOG II uses a free format convention so that different sources of digitized log information can be input directly without reformatting. The third data card stipulates the format of the log readings; the format must specify eight FORTRAN real variable fields, such as (F5.0,4X,7F6.0). The first field is always assumed to be the depth.

The third card is followed by a sequence of data cards, each of which contains the depth of the log reading in the first field and log response readings, and (where appropriate) core measurements. There is no prescribed order for these variables as the meaning of each of the seven possible fields is assigned by the commands. The program assumes all readings come from the same common depth shown in the first field. The final card must be followed by an end-of-file card containing any number larger than or equal to 9999 in the first field. This signals the program that the data sequence is complete.

LOG II incorporates subroutines that check for certain errors in the digitized input. These routines will assign default values where required and store the information in the internal format required by the program.

A data set to be processed might have the following form:

SKELLY OIL COMPANY		CAHOJ		BARTOSOVSKY NO.1	
KANSAS		RAWLINS		SE SW SW 9 1S 34W	
(F5.0,7F6.0)					
3970	107.9	81.4	288.8		
3971	100.5	80.5	299.5		
3972	97.1	81.2	289.8		
3973	105.1	81.5	240.9		
3974	100.0	84.0	192.0		
3975	78.4	57.6	143.2		
3976	56.8	54.5	94.3	9.3	
3977	48.4	68.0	64.6	3.9	
3978	55.2	68.0	67.5	7.0	
3979	51.2	64.4	74.0	8.0	
3980	57.3	62.8	66.6	6.1	
3981	54.0	61.2	58.4	6.3	
3982	49.1	62.5	50.2	6.2	
3983	44.2	59.2	42.1	4.4	
3984	39.4	56.0	33.9	5.9	
3985	42.8	55.0	25.7	1.8	
3986	39.1	57.1	17.5	4.7	
3987	35.6	57.1	26.6	8.0	
3988	36.6	54.4	54.5	6.2	
3989	34.8	57.8	82.7	4.4	
3990	50.3	66.6	112.7	12.7	
.					
.					
.					
4242	113.7	63.4	160.5		
4243	89.9	79.8	209.1		
4244	89.3	91.0	257.7		
4245	93.5	77.6	306.3		
4246	97.8	80.9	337.6		
4247	93.2	88.2	354.5		
4248	96.3	91.8	330.4		
4249	97.9	93.8	292.9		
4250	87.9	75.6	255.3		
9999					

3.3 Results

LOG II generates a variety of parameters, tables, graphs, and logs to assist in subsurface evaluation. Output includes identification information provided for labelling purposes such as company name, field and well names, state, county, and township and range where the well is located.

LOG II computes mean gamma ray values in API units or mean spontaneous potential in millivolts for both the entire section analyzed within a well and for only the non-shale intervals. When converted to equivalent shale ratios, these values reflect the proportion of shale in the entire section and the relative shale content of potential reservoir zones. The program also

calculates the cumulative thickness of non-shale intervals and the proportion of their occurrence in the analyzed section.

In addition to mean values, LOG II also computes standard deviations of the gamma ray or spontaneous potential trace, which are a measure of the average deviation of the section from its mean. In geological terms, these values are measures of the relative "interbedded character" of the section. High standard deviations represent a high degree of interbedding of shales with units of non-shale lithology. Low standard deviations suggest that the shale content of the section is more uniformly distributed throughout the section.

LOG II is able to calculate and display a semivariogram of any of the input log traces. The log normally used is the gamma ray, since the results may be directly interpreted in terms of "cyclic" alternations in lithology. A sequence of semivariances may be computed for different lag intervals by the formula:

$$\gamma^*(h) = \frac{0.5}{n-h} \sum_{i=1}^{n-h} (Y_{i+h} - Y_i)^2 \quad (3.3.1)$$

where

Y_i is a sequence of n readings of a log variable taken at regular depth intervals;
 $\gamma^*(h)$ is the estimated semivariance for readings separated by a "lag" or distance which contains $(h+1)$ successive log readings.

The semivariogram is a plot of semivariance against lag and is an expression of the degree of autocorrelation between log readings separated by different distances. Log readings taken h units apart in the sequence will, in general, have different values. Their differences will result in some positive value calculated by equation (3.3.1) as the estimated semivariance at lag h . These values have a maximum bounding value equal to the variance of all the readings and a minimum value of zero.

If the log trace does not contain a periodic component, the semivariogram will ideally be a curve which originates at zero and converges asymptotically to a limit equal to the variance of

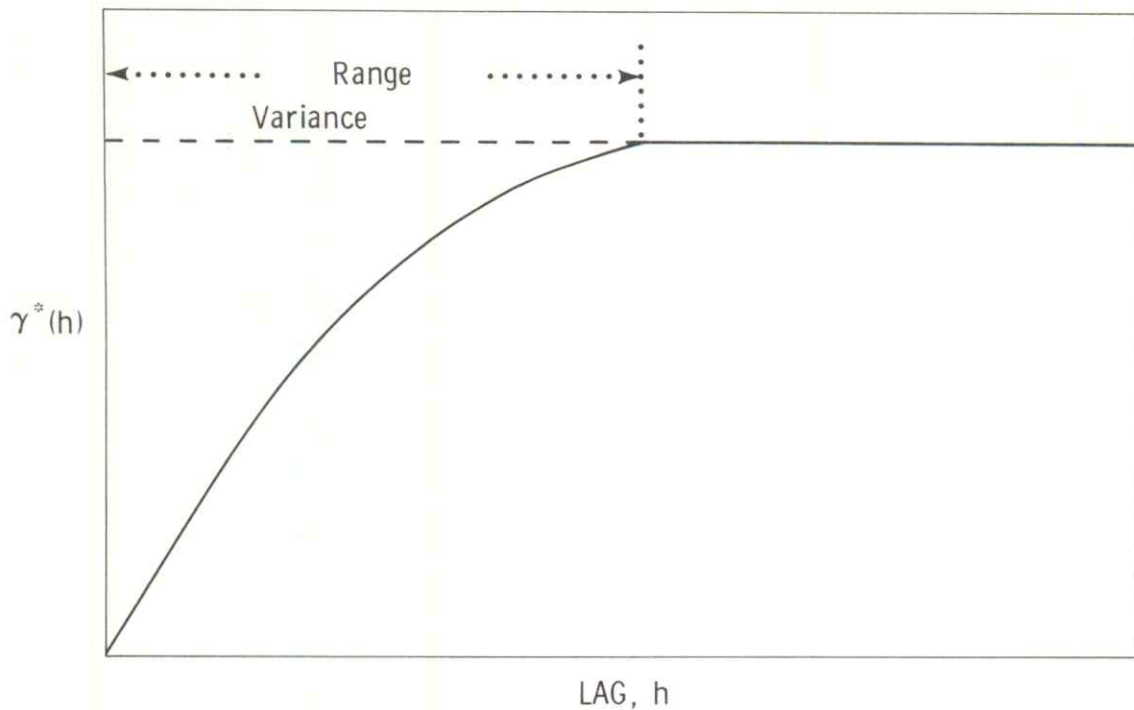


Figure 3.3.1.--Ideal asymptotic semivariogram. The shortest lag for which the semivariance does not differ from the variance is the range.

the digitized log readings (Fig. 3.3.1). The lag distance at which the semivariance becomes essentially equal to the variance is called the "range" of the data. Within the range, all measurements have some degree of interrelationship or autocorrelation.

If a perfect periodic component is present in the trace and it has a wavelength of λ intervals, the semivariogram will return to zero at lag λ and multiples of λ (Fig. 3.3.2). Perfect periodicity is seldom found in nature, but approximate periodicities will appear in a semivariogram as a distinctive drop in the semivariance which recurs at regular intervals.

The shape of the semivariogram, and in particular its slope near the origin, is useful in studying the rate of change in a stratigraphic sequence. Such information is not expressed by statistics such as the means or standard deviations, since these do not consider the relative order of the log readings.

Where periodic components can be recognized in a stratigraphic interval, estimates of the periodicity can be made at each well and mapped. In a similar fashion, the semivariogram slope near the origin may be computed and mapped. Maps of these statistics are a useful aid in the interpretation of subsurface lithofacies, since they represent the areal variation in the characteristic cyclic component and the relative rate of vertical change in the stratigraphic interval.

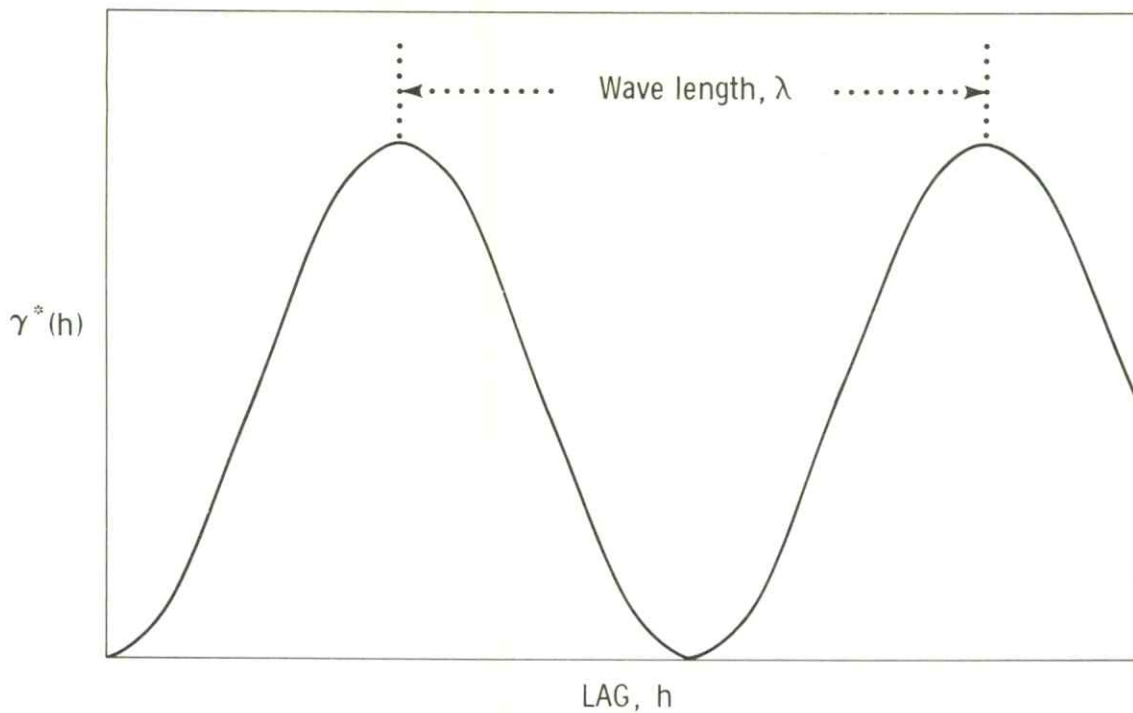


Figure 3.3.2.--Semivariance for a sinusoidal sequence of wavelength λ .

The decision to abandon or to complete a well is usually based on computation of a few global parameters which depend on three critical values provided by the analyst:

- C_s : Maximum percent shale allowed for a level. Levels with amounts of shale over C_s are skipped in all formation computations
- C_p : Critical porosity
- C_w : Critical water saturation.

The global parameters are:

1. Cumulative thickness of all those levels with shale percent below C_s
2. Cumulative thickness of all the levels with percent shale below C_s and porosity above C_p
3. Cumulative thickness of levels simultaneously having a shale percentage below C_s , porosity over C_p , and water saturation below C_w
4. Average porosity of those levels with shale percentage below C_s
5. Average porosity in the intervals with shale percentage below C_s and porosity above C_p

6. Average permeability in those levels with shale percentage below C_s
7. Average permeability in the levels with shale percentage below C_s and porosity above C_p
8. Average water saturation for those levels below C_s in percent shale and below C_w in water saturation.

LOG II produces tables at the end of each evaluation containing data and results level by level. Over long intervals, these tables may become tedious and difficult to analyze. To avoid such inconvenience, the system offers the alternative of graphic presentation either using the line printer or an electromechanical plotter.

Line printer plots have an advantage in that they can be produced at almost no additional cost and need no additional hardware other than the basic computer installation required to run LOG II. Limitations include their accuracy, especially in the depth scale, and the need for some handwork to complete the plots.

The final product of an electromechanical plotter, if available, is certainly of superior quality. However, plotting requires installations in addition to the main computer, and the plotter configuration may be as expensive as the computer itself. Logs can be produced by electromechanical plotter using several pen types and colors of ink. No manual finishing is necessary. Precision is superior to that of manmade graphs and the time required to produce the same drawing is several orders of magnitude shorter.

3.4 Command Lexicon

The digitized log data are followed by commands that specify information about the lithology and depth of the sequence, types of logs run, values of fundamental analytical variables, and limits to be applied in calculating the summary statistics. Each command is specified by a name having up to ten characters. (Only the first four characters are actually used to distinguish a command. So, for example, the command LITHOLOGY can either be written in full or abbreviated as LITH; both forms will be read correctly by the program.) The command name is followed by up to ten parameters written as real numbers in an F5.0 format. Sixteen alphanumeric characters may be placed in columns 65-80.

Commands are executed in the correct sequence regardless of the order in which they are entered. Each block of commands must be terminated by the command PERFORM. A block may have up to 50 commands and a run of LOG II may have as many blocks as necessary. A typical sequence of commands might be:

```
0000000001111111111222222222233333333334
1234567890123456789012345678901234567890
```

```
LITHOLOGY      0
EXTREMES      3976 4242    0
GAMMARAY      25  110    2
SONIC         80  45  189    1    3
RESISTIV      1.0  2.0 0.07  2.5    2    4
CUTOFFS       40   8   50
SEMIVAR       100   0    2
PERFORM
```

This command set specifies that the section to be analyzed is a limestone/shale sequence between an upper depth of 3976 ft and a lower depth of 4242 ft. The shale log used is a gamma ray log whose clean reading is 25 API units and whose "normal shale" reading is 110 API units. The porosity tool used is a sonic log, with shale, matrix, and fluid transit times estimated to be 80, 45, and 189 microseconds per foot. Resistivity log readings will be input in ohm-meter units; the resistivity of the formation water and shale are 0.07 and 2.5 ohm-m. The constants to be used in Archie's equation are $a = 1.0$ and $m = 2.0$. The gamma ray, sonic, and resistivity readings will be read as the second, third, and fourth variables on the input file. The shale percent value that distinguishes shale intervals from non-shale intervals is set at 40; the cutoff values of 8 percent minimum porosity and 50 percent maximum water saturation are to be used in the summary statistics. A semivariogram will be computed for the gamma ray trace using a sampling interval of 100 observations.

The division of the command into successive blocks, each terminated by a PERFORM command, allows multiple log analyses to be made in a single computer run. This is especially useful if the proper values for basic input parameters are not known and alternative choices must be examined. The command structure also allows simultaneous processing of a sequence of well sections having the same or different lithologies, and the repeated processing of the same well using different porosity or resistivity tools.

Unless expressly altered, the parameters set by earlier commands are used as the critical values in analyses performed subsequently. Therefore, parameters do not have to be repeatedly

specified unless they are to be changed. If parameters are not given, the program will assume default values that are broadly consistent with a typical Midcontinent Pennsylvanian limestone/-shale sequence. The following is a list of all commands available.

<u>General Commands</u>	<u>Graphic Commands</u>	<u>Shale Commands</u>	<u>Porosity Commands</u>	<u>Resistivity Command</u>
ARCHIE	CORE	GAMMARAY	CPOROSITY	RESISTIV
CUTOFFS	ENDR	SP	DENSITY	
DARCY	HEAD		NEUTRON	
EXTREMES	PLOT		SONIC	
LITHOLOGY	PRNT			
NCONVERS	SHOT			
NEWZ	TEST			
PERFORM				
PERMEABIL				
SEMIVAR				

The initial ten columns of a card are reserved for the command name. The associated parameters must be placed in successive five-column fields. The parameter field specification is F5.0; parameter values should contain a decimal point or be right-justified within the field. Columns 65 to 80 are for alphanumeric information. A complete description of all commands follows.

'ARCH' IE -- Computes a linear regression to estimate the parameters in Archie's equation relating porosity and formation factor.

ARCH

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Brine resistivity in ohm-m	0.01
2	Resistivity of shale in ohm-m	2.5
3	Scale of measurement used for readings If 0, the readings are from a resistivity log in ohm-m and the scale is linear. If 1, the readings are from a resistivity log in ohm-m and the scale is logarithmic. The sampling was done as a linear interpolation between 1 and 100. If 2, the readings are from a conductivity log in mmho/m and the scale is linear.	0
4	Data field which contains resistivity or conductivity readings from a log	4
5	Data field which contains water saturations as determined by core analyses	5

'CORE'

-- Shows intervals on the log where cores were cut and actually recovered.

CORE

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Top of the cored section	0
2	Bottom of the cored section	0
3	Recovery and identification number If -1, the interval will show as an effectively recovered piece of core. If 0, the interval corresponds to a cored interval. If 1 or larger, the interval is a cored section whose identification number is that shown in the third field.	0
4	Penholder number to be used to post the cored interval. The options are 1, 2, 3, or 4.	1
5	Gridding option If 0, no grid will be drawn. If 1, a reference grid will be drawn.	0

The two different posting options allow the user to distinguish between cored intervals and location of these fractions effectively recovered on surface, if any. Effectively recovered core fractions are posted as heavy vertical lines. The coring interval is shown as a thin vertical line with a short line across on the extremes. A missing short line on a cored interval at the top or the bottom of the log indicates that the core interval goes beyond the log limits. The gridding option is usually not necessary as other commands provide the reference grid, commonly a 'PLOT' command in the block.

'CPOR'OSITY -- Enters direct porosity measurements from laboratory core analyses.

CPOR

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Data field which contains core porosities	3

'CUTO'FFS -- Specifies extremes to be considered during log evaluation. If this command is omitted, the assumed values are used.

CUTO

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Maximum percent shale. If the shale content for an interval is greater than this amount, the interval will be assumed to be 100% shale.	50
2	Minimum porosity for an interval to be considered potentially productive. The interval is evaluated even though the porosity is lower than this parameter, but is not counted as a high porosity interval in the final statistics.	5
3	Maximum water saturation for an interval to be considered possibly productive. The interval is evaluated even though the water saturation is higher than this parameter, but is not counted as a low water saturated interval in the final statistics.	50

'DARC'Y -- Computes a linear regression to estimate the parameters in the permeability equation.

DARC

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Irreducible water volume, as a fraction of total formation volume	0.04
2	Shale effect factor on irreducible water saturation	0.0
3	Maximum permeability value of core samples in millidarcies. Permeabilities larger than this limit will be discarded.	3000.0
4	Data field which contains permeabilities as determined by core analyses.	5

Requires prior execution of a shale command and a porosity command.

'DENS'ITY -- Converts readings from a density log into estimated porosities.

DENS

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Shale density, in gm/cc	2.5
2	Density of the non-shale component, in gm/cc	2.7
3	Density of the pore fluid, in gm/cc	1.0
4	Data column which contains density readings from a log	3

Requires prior execution of a shale command. The effect of shale content is eliminated. It is assumed that the fluid in the pores is a mixture of oil and water. If gas is present, porosities will be overestimated.

'ENDR'EMARKS -- Ends the text to be added to the log immediately after the heading.

ENDR

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
	NO PARAMETERS	

The omission of this command will cause abnormal termination of LOG II in case there is text following the 'HEAD' command.

'EXTR'EMES -- Sets the upper and lower depth limits of the interval to be evaluated.

If this command is omitted, the assumed values are used.

EXTR

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Depth to top of interval	0
2	Depth to bottom of interval	9900
3	Depth of unit	0
	If 0, in feet.	
	If 1, in meters.	

'GAMM'ARAY -- Calculates percent shale from a gamma ray log scaled in API units.

GAMM

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Theoretical reading for the gamma ray log in a clean formation	0
2	Theoretical reading for the gamma ray log in a shale interval	100
3	Data field which contains the gamma ray intensities from a log	2

'HEAD' ING -- Plots a heading for those logs produced by a plotter and as an option allows display of additional remarks.

HEAD

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Depth scale. As usual for any scale, this number is the conversion factor to go from log paper length to actual interval in the well. Depth scale units depend on the depth units as specified in the 'EXTR' command. In the British system of units, depth scale units are given as ft/in; in the metric system, the units are dimensionless numbers.	200
2	Remarks. Following the heading, LOG II has the option to transfer a text from file to log without any length limit. If 0, no remarks are following. If 1, text follows to be plotted as remarks.	0
3	Log name starting in column 65	Blank

'HEAD' produces a formatted heading based on the information contained in fields 1 and 2 plus the well identification information given at the beginning of the data file. In addition, field 2 allows the display of a free format text containing any additional remarks.

The text is given in columns 1-79 of as many cards as necessary immediately following the 'HEAD' command. This text is not treated as a command. The 'ENDR' command is used to end the text. Column 80 is reserved for pen selection and line control purposes to add some flexibility to the text transfer.

- If 1, penholder 1 is turned on and text copied on the next line.
- If 2, penholder 2 is turned on and text copied on the next line.
- If 3, penholder 3 is turned on and text copied on the next line.
- If 4, penholder 4 is turned on and text copied on the next line.
- If 5, penholder 1 is turned on and text is overprinted over current line.
- If 6, penholder 2 is turned on and text is overprinted over current line.
- If 7, penholder 3 is turned on and text is overprinted over current line.
- If 8, penholder 4 is turned on and text is overprinted over current line.

Any other digit, blank, or character in column 80 is treated as a 1. If field 2 is zero, the 'ENDR' command is not required at any place in the block of commands.

'LITH'LOGY -- Establishes the type of "clean" lithology or formation rock to be evaluated. If this command is omitted, LOG II will assume that the digitized sequence consists of limestone and shale.

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Formation lithology If 0, clean intervals are evaluated as limestone. If 1, clean intervals are evaluated as sandstone. If 2, clean intervals are evaluated as dolomite. If 3, clean intervals are evaluated as chert.	0

'NCON' VERSION -- Transforms neutron log readings to porosities from a scale other than porosity, by logarithmic interpolation using a monotonic sequence (increasing or decreasing without duplicating values) of five pairs of control points. If this command is omitted, LOG II assumes neutron log readings are in a percentage porosity scale.

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1,3,5,7,9	Neutron log reading on scale used in digitized log	Required
2,4,6,8,10	Porosity corresponding to the neutron log reading given in the preceding parameter field	Required

'NEUT'RON -- Provides porosity estimates based on neutron log reading.

NEUT

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Neutron log reading in shale, as apparent percentage porosity	30
2	Data field which contains the neutron log readings	3

Requires prior execution of a shale command and may require data conversion using 'NCON' command. The effect of shale content is corrected. It is assumed that fluid in the pores is a mixture of oil and water. If gas is present, porosities will be underestimated.

'NEWZ'

-- Allows changes to be made in the depth values.

NEWZ

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1, 3, 5, 7, 9	Depth currently on file for convenient, arbitrarily selected control points.	0
2, 4, 6, 8, 10	New depth value to be assigned to level whose current depth is that shown in the preceding parameter field.	0

LOG II relabels all depth values by linear interpolation based on the pairs of points specified by the control card. Should five control points be insufficient, more than one 'NEWZ' command can be used. The sequence may be either increasing or decreasing in depth, but must be monotonic. Only one pair will result in a shift of the origin. Blank or zero values for both depths in the pair will be ignored. The command is intended to refer levels to a new datum, to convert depth scale to a different unit system, or to refer all readings to a vertical scale in a slant-hole well. Original depth scale is lost with the transformation. An inverse transformation can always be used to restore the original depth values.

'PERF'ORM -- Ends a sequence of commands and begins program execution.

PERF

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
	NO PARAMETERS	

A single run of LOG II may contain several 'PERF'ORM commands. In such instances, all parameters set initially will remain and only those specifically altered by commands after the first 'PERF' will be changed. In this way, the same data can be processed several times in one computer run, using alternative parameters. The number of commands preceding a 'PERF' command is limited to 50.



'PERM'EABIL -- Yields permeability estimates based on a "shale" and a porosity log.

The effect of shale content is corrected.

PERM

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Constant "C" in permeability equation	100.0
2	Exponent "p" in permeability equation	0.0
3	Irreducible water volume, as a fraction of total formation volume	0.08
4	Shale effect on irreducible water saturation	0.0

Requires prior execution of a shale command and a porosity command.

'PLOT' -- Drafts electric logs and petrophysical parameters using an electro-mechanical plotter.

PLOT

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Left-most value on the petrophysical variable scale	0
2	Right-most value on the petrophysical variable scale	0
3	Code number to specify curve to be plotted If 1 to 8, the field number in the input data for the variable to be plotted. If 9, shale percent. If 10, porosity. If 11, the product of (porosity) (water saturation). If 12, water saturation. If 13, apparent water resistivity. If 14, permeability.	Required
4	Number of the track which the curve is to occupy. Tracks on the log are designated 1, 2, and 3 from left to right.	Required
5	Posting selection. The choices are: If 0, straight continuous lines will join consecutive values. The location of the values themselves will not be posted. If 1, straight dashed lines will join consecutive values. The location of the values themselves will not be posted. If 2, circles are posted at the location of those values within the limits given by fields 1 and 2 above. Values equal to those extremes or outside the scale limits are not shown.	0
6	Scale type If 0, scale is linear.	0

If 1, scale is logarithmic.

7

Penholder number. The selection of the physical device used to plot the curve is done by giving the penholder number to turn on at plotting time. The type, width, and color of the resulting curve depends on the pen physically mounted on the plotter penholder at the time the log is plotted. The choices are 1, 2, 3, and 4.

1

8

Alphanumeric comments starting in column 65. This information is used to identify the curve in the scale heading.

Blank

The program checks all parameters and discards any instructions which are in error. All 'PLOT' commands within the same block of instructions are overprinted on the same graph up to a maximum of 5 curves per track. A reference network is automatically drawn, one for all 'PLOT' commands in a block.

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Left-most value on the petrophysical variable scale	0
2	Right-most value on the petrophysical variable scale	0
3	Code number to specify curve to be plotted If 1 to 8, the field number in the input data for the variable to be plotted. If 9, shale percent. If 10, porosity. If 11, the product of (porosity) (water saturation). If 12, water saturation. If 13, apparent water resistivity. If 14, permeability.	Required
4	Track number which the curve is to occupy. Tracks on the log are designated 1, 2, and 3 from left to right.	Required
5	Depth scale. As usual for any scale, this number is the conversion factor to go from length in the paper to actual length in the well. Depth scale units depend on depth units as specified in the 'EXTR' command. In the British system of units, depth scale units are given as ft/in; in the metric system, units are given as dimensionless numbers. Note that precision may be seriously distorted by the minimum increment in the printer, which is several times that of a plotter.	200
6	Scale type If 0, scale is linear. If 1, scale is logarithmic.	0
7	Alphanumeric comments starting in column 65	Blank

The program checks all parameters and discards any instructions which are in error. All 'PRNT' commands within the same block of instructions are overprinted on the same graph up to a maximum of 5 curves per track. Curves in the same track are posted using different symbols. If more than one symbol must be printed at the same location, the program will plot the letter X.

'RESI'STIVIT -- Computes water saturation from measurements of formation resistivity. The effect of shale content is corrected.

RESI

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Constant "a" in Archie's formula	1
2	Cementation factor "m" in Archie's formula	2
3	Brine resistivity	0.1
4	Resistivity of shale	2.5
5	Scale of measurement used for readings If 0, the readings are from a resistivity log in ohm-m and the scale is linear. If 1, the readings are from a resistivity log in ohm-m and the scale is logarithmic. The sampling was done as a linear interpolation between 1 and 100 ohm/m. If 2, the readings are from a conductivity log in mmho/m and the scale is linear.	0
6	Data field which contains resistivity or conductivity readings from a log	4

Requires prior execution of a shale and a porosity command.

'SEMI'VARIQG -- Estimates a semivariogram for a stationary function sampled at regular intervals and considered to be a regionalized variable.

SEMI

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Number of samples to be considered in each interval	4
2	Type of log for which the semivariogram is to be calculated If 0, gamma ray. If 1, neutron. If 2, sonic. If 3, resistivity. If 4, conductivity. If 5, density.	0
3	Data field which contains the digitized log values	2

'SHOT'

-- Shows casing perforations done for testing or production purposes.

SHOTS

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Top of perforations	0
2	Bottom of perforations	0
3	Penholder required to plot the perforations. The options are 1, 2, 3, and 4.	1
4	Gridding option If 0, no reference network is plotted. If 1, a reference network is plotted.	0

As the reference network needs to be drawn once per log, the gridding option will normally not be necessary because the grid will be automatically done by a 'PLOT' command. The perforated interval in the casing will show as a vertical line with short lines across.

'SONI'C -- Determines formation porosity from acoustic velocity log readings.

The effect of shale content is corrected.

SONI

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Transit time in shale, in msec/ft	80
2	Transit time in the non-shale lithology	45
3	Transit time in the pore fluid, in msec/ft	189
4	Compaction factor	1
5	Data field which contains transit times from an acoustic velocity log	3

Requires prior execution of a shale command.

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Spontaneous potential of a clean, water saturated interval	50
2	Data field which contains spontaneous potential readings from an SP log	2

'TEST'

-- Displays the well intervals tested to evaluate production potential.

TEST

<u>Field Number</u>	<u>Parameter Description</u>	<u>Assumed Value</u>
1	Top of tested interval	0
2	Bottom of tested interval	0
3	Test number	0
	If 0, the test number is not posted.	
	If 1 or larger, the number in this field is posted as the test identification number.	
4	Penholder number to be used on displaying the tested interval. The options are 1, 2, 3, or 4.	1
5	Gridding option	0
	If 0, no grid will be drawn.	
	If 1, a reference grid will be drawn.	

The grid option is rarely necessary as other commands in the block will draw the reference network, usually a 'PLOT' command. Tested intervals will show as brackets. If the tested interval extends outside the log limits, this fact will be implied by omitting the corresponding horizontal short line at the bracket extreme.

4. ILLUSTRATIVE EXAMPLES

4.1 Evaluation of a Midcontinent Limestone/Shale Sequence

The first example shows the use of LOG II in the analysis of an interval through the Pennsylvanian Lansing-Kansas City Group in the Bartosovsky #1 well in Rawlins County, Kansas. The data file for the well was already given as an example on page 22 above. Figure 4.1.1 is a listing of all commands and remarks. The line printer listing begins with a summary of the input variables which have been specified in the command statements and a summary of resulting statistics (Fig. 4.1.2). These are followed by a level-by-level analysis of the input section (Fig. 4.1.3). Note that zones which exceed the maximum percent shale specified in the input commands are skipped. These shale zones are shown as blank lines in the listing and subdivide the section into zones of non-shale lithology.

Many stratigraphic successions appear to be composed of a repeating sequence of rock types. The Pennsylvanian limestone/shale sequence of Kansas is one of the most famous examples of such "cyclic" intervals, although similar characteristics are observed in coal measures around the world. The origin of these cycles is a subject for geological debate and its terminology a matter of controversy. However, measurement of any periodic component in a well section may be useful in evaluation of lithofacies geometry and for predicting stratigraphic traps.

The next part of the output consists of a semivariogram, or plot of the semivariance of the gamma ray trace against the lag spacing in feet, in tabular (Fig. 4.1.4) and graphical form (Fig. 4.1.5). As explained in Section 3.3, the semivariogram of the Lansing-Kansas City interval in the Bartosovsky well shows a distinctive periodic wavelength of 48 feet. A listing of the semivariances by lag sequence and an estimate of the semivariogram slope at the origin are also printed.

Figure 4.1.6, included in the pocket, is a graphic display of the shale content, porosity and water saturation of the interval. Core porosity measurements as well as other remarks are given to critically examine the evaluation. Note estimated porosities are consistently smaller

EXTR	3970.00	4250.00	0.			
CUTO	40.00	8.00	50.00			
LITH	0.					
GAMM	25.00	110.00	2.00			
SONI	80.00	45.00	189.00	1.00	3.00	
RESI	1.00	2.00	0.07	2.50	2.00	4.00
SEMI	100.00	0.	2.00			
HEAD	20.00	1.00				

TOTAL DEPTH 4300 FT.
 DRILLING COMMENCED JULY 31 1959
 DRILLING COMPLETED AUGUST 22 1959

COMPUTED LOGS

STRATIGRAPHIC MARKERS

 TOP OF THE LANSING GROUP 3976 FT
 BASE OF THE KANSAS CITY GROUP 4243 FT

CORES

 EIGHT CORES WERE TAKEN FROM 3850 TO 4246 FT IN A CONTINUOUS CORING OPERATION. RECOVERY WAS ALMOST PERFECT AS ONLY ONE FOOT INTERVAL WAS MISSING. A COMPLETE DESCRIPTION OF THESE CORES IS IN

HARBAUGH, J. H. AND W. DAVIE, JR., 1964, UPPER PENNSYLVANIAN CALCAREOUS ROCKS CORED IN TWO WELLS IN RAWLINS AND STAFFORD COUNTIES, KANSAS, STATE GEOLOGICAL SURVEY OF KANSAS BULLETIN, BULLETIN 170, PART 6, P 3-19.

ADDITIONAL LABORATORY MEASUREMENTS ARE AVAILABLE IN A CORELAB REPORT.

DRILL STEM TESTS

 A TOTAL OF 6 TESTS WERE MADE IN THE WELL, 5 OF THEM IN THE LANSING-KANSAS CITY INTERVAL.

DST #2 FROM 3973 TO 4012

THE TEST RUN FOR 2 HOURS. THERE WAS A FAIR BLOW THROUGHOUT THE TEST. THE RECOVERY WAS 320 FT OF GAS, 160 FT OF 32 API OIL, NO WATER.
 IBHP 1280, IFP 50, FFP 80, FBHP 1120. 7

DST #3 FROM 4026 TO 4074

THE TEST RUN FOR 1 HOUR. THERE WAS A WEAK BLOW FOR 5 MINUTES. THE RECOVERY WAS 5 FT OF MUD WITH SPECKS OF OIL.
 IBHP 130, IFP 0, FFP 0, FBHP 0.

DST #4 FROM 4124 TO 4159

THE TEST RUN FOR TWO HOURS. THERE WAS A STRONG BLOW THROUGHOUT THE TEST. THE RECOVERY WAS 2249 FT OF GAS AND 1880 FT OF OIL WITH A GRAVITY OF 28.3 API. NO WATER. 7

IBHP 1305, IFP 135, FFP 745, FBHP 1250. 7

DST #5 FROM 4178 TO 4204

THE TEST RUN FOR 2 HOURS. THERE WAS A STRONG BLOW THROUGHOUT THE TEST. THE RECOVERY WAS 3360 FT OF OIL WITH 33.8 API GRAVITY, NO WATER.
 IBHP 1305, IFP 160, FFP 1250, FBHP 1280. 7

DST #6 FROM 4210 TO 4246

THE TEST RUN FOR 1 HOUR. THERE WAS A WEAK BLOW FOR 5 MINUTES. THE RECOVERY WAS 60 FT OF MUDDY SALT-WATER WITH A FEW SPECKS OF OIL.
 IBHP 1330, IFP 0, FFP 0, FBHP 1120.

COMPLETION

 PRODUCTION STARTED FROM 4170-4182, 4128-4134, 4079-4083 AND FROM 3978-3990 AT A RATE OF 3000 BOPD.

ENDR								
PLOT	0.	100.00	9.00	1.00	0.	0.	3.00	SHALE %
PLOT	100.00	0.	10.00	1.00	1.00	0.	2.00	SONIC POROSITY %
PLOT	100.00	0.	12.00	2.00	0.	0.	2.00	WATER SATUR. %
PLOT	30.00	0.	11.00	3.00	1.00	0.	2.00	(WAT.SAT.)*(POR)
PLOT	30.00	0.	10.00	3.00	0.	0.	3.00	SONIC POROSITY %
PLOT	30.00	0.	9.00	3.00	2.00	0.	3.00	CORE POROSITY %
CORE	3966.00	4016.00	3.00	0.	0.	0.		
CORE	3966.00	4015.00	-1.00	0.	0.	0.		
CORE	4016.00	4074.00	4.00	0.	0.	0.		
CORE	4016.00	4074.00	-1.00	0.	0.	0.		
CORE	4074.00	4119.00	5.00	0.	0.	0.		
CORE	4074.00	4119.00	-1.00	0.	0.	0.		
CORE	4119.00	4159.00	6.00	0.	0.	0.		
CORE	4119.00	4159.00	-1.00	0.	0.	0.		
CORE	4159.00	4204.00	7.00	0.	0.	0.		
CORE	4159.00	4204.00	-1.00	0.	0.	0.		
CORE	4204.00	4246.00	8.00	0.	0.	0.		
CORE	4204.00	4246.00	-1.00	0.	0.	0.		
TEST	3973.00	4012.00	2.00	0.	0.	0.		
TEST	4026.00	4074.00	3.00	0.	0.	0.		
TEST	4124.00	4159.00	4.00	0.	0.	0.		
TEST	4178.00	4204.00	5.00	0.	0.	0.		
TEST	4210.00	4243.00	6.00	0.	0.	0.		
SHOT	2128.00	2182.00	0.	0.	0.	0.		
SHOT	4079.00	4083.00	0.	0.	0.	0.		
SHOT	3978.00	3990.00	0.	0.	0.	0.		
PERF								

Figure 4.1.1.--Commands and remarks used to process a Pennsylvanian interval in the Bartosovsky #1 well, Rawlins County, Kansas.

GAMMA RAY LOG

GAMMA RAY IN SHALE 110.0 API UNITS .
GAMMA RAY IN LIMESTONE 25.0 API UNITS .
SHALINESS CUT-OFF 40.0 PER CENT .

GAMMA-RAY AVERAGE 83.5 API UNITS
STANDARD DEV. FOR GAMMA-RAY 27.1 API UNITS
CUMULATIVE THICKNESS OF LIMESTONE 61.0 FEET
LIMESTONE FRACTION IN INTERVAL 22.8 PER CENT
AVERAGE GAMMA-RAY IN LIMESTONE 44.2 API UNITS
STAND. DEV. OF GAMMA-RAY IN LIMESTONE 8.1 API UNITS

SONIC LOG

TRANSIT TIME FOR SHALE 80.0 MICSEC/FT
TRANSIT TIME FOR LIMESTONE 45.0 MICSEC/FT
TRANSIT TIME FOR TRAPPED FLUID 189.0 MICSEC/FT
COMPACTION FACTOR 1.00

AVERAGE POROSITY IN LIMESTONE 6.0 PER CENT
LIMESTONE POROS. LARGER THAN 8.0 % 18.0 FEET
AVER. POROS. IN HIGH POROS. LIMESTONE 10.6 PER CENT

RESISTIVITY LOG

SHALE RESISTIVITY 2.5 OHM-M
BRINE RESISTIVITY 0.070 OHM-M
ARCHIE'S FORMULA $F = 1.00 / \text{POROSITY}^{2.00}$

HIGH POROS. LIMESTONE UNDER 50.0 % WATER 11.0 FEET
AVER. WAT. SAT. IN LIMESTONE UNDER 50.0% WATER 29.1 %

Figure 4.1.2.--Input parameters and resulting statistics for a Pennsylvanian interval of the Bartosovsky #1 well.

EVALUATION STARTS AT 3976.0 FEET
EVALUATION ENDS AT 4242.0 FEET

DEPTH FEET	GAMMA R API U.	SONIC MSEC/FT	RESIST. OHM-M	SHALE PERCENT	POROSITY PERCENT	WT SAT. PERCENT	PERM. MD	RWA OHM-M
3976.0	56.8	54.50	10.6	37.4	0.	100.0		1.00
3977.0	48.4	68.00	15.5	27.5	9.3	40.4		-0.19
3978.0	55.2	68.00	14.8	35.5	7.3	39.2		-0.07
3979.0	51.2	64.40	13.5	30.8	6.0	49.8		-0.07
3980.0	57.3	62.80	15.0	38.0	3.1	42.2		-0.01
3981.0	54.0	61.20	17.1	34.1	3.0	41.2		-0.01
3982.0	49.1	62.50	19.9	28.4	5.3	39.0		-0.04
3983.0	44.2	59.20	23.8	22.6	4.4	41.4		-0.04
3984.0	39.4	56.00	29.5	16.9	3.5	44.8		-0.04
3985.0	42.8	55.00	38.9	20.9	1.9	30.1		-0.01
3986.0	39.1	57.10	57.1	16.6	4.4	24.0		-0.04
3987.0	35.6	57.10	37.6	12.5	5.4	40.1		-0.12
3988.0	36.6	54.40	18.3	13.6	3.2	81.8		-11.68
3989.0	34.8	57.80	12.1	11.5	6.1	88.8		0.10
3990.0	50.3	66.60	8.9	29.8	7.8	64.5		-0.95
4030.0	45.9	54.50	7.2	24.6	0.6	100.0		0.00
4031.0	40.5	56.70	12.9	18.2	3.7	86.2		0.31
4032.0	40.9	59.10	14.8	18.7	5.2	66.7		-0.37
4033.0	50.0	60.90	12.9	29.4	3.9	59.5		-0.04
4036.0	51.6	62.40	15.5	31.3	4.5	46.7		-0.03
4037.0	51.9	56.50	16.8	31.6	0.3	47.1		-0.00
4052.0	54.1	52.90	6.9	34.2	0.	100.0		1.00
4079.0	56.6	60.40	7.4	37.2	1.7	89.1		-0.02
4080.0	39.2	62.90	13.8	16.7	8.4	58.1		1.21
4081.0	41.7	64.90	23.5	19.6	9.0	35.4		-0.23
4082.0	47.3	62.10	24.2	26.2	5.5	34.5		-0.05
4083.0	46.0	59.40	19.1	24.7	4.0	47.7		-0.03
4084.0	48.8	64.50	17.9	28.0	6.7	40.5		-0.08
4085.0	47.5	60.90	16.8	26.5	4.6	49.3		-0.05
4086.0	51.4	61.50	15.8	31.1	3.9	47.0		-0.03
4087.0	58.2	60.50	15.0	39.1	1.3	42.5		-0.00
4128.0	38.5	60.60	7.0	15.9	7.0	100.0		0.06
4129.0	35.1	63.80	19.3	11.9	10.2	45.3		2.37
4130.0	39.9	66.40	29.1	17.5	10.6	29.3		-0.31
4131.0	48.2	72.20	33.1	27.3	12.3	19.9		-0.19
4132.0	52.6	71.70	38.3	32.5	10.6	16.6		-0.11
4133.0	49.4	61.60	43.1	28.7	4.6	19.3		-0.02
4134.0	57.1	54.80	41.7	37.8	0.	100.0		1.00
4135.0	58.8	55.70	24.6	39.8	0.	100.0		1.00
4168.0	56.3	70.40	8.3	36.8	8.7	57.4		-0.28
4169.0	43.2	62.80	9.9	21.4	7.2	72.9		0.33
4170.0	35.0	60.40	12.1	11.8	7.8	73.8		0.17
4171.0	38.5	58.40	16.2	15.9	5.4	67.1		-1.62
4172.0	39.6	56.40	23.0	17.2	3.7	54.6		-0.06
4173.0	36.7	58.80	29.5	13.8	6.2	42.9		-0.18
4174.0	35.8	72.60	40.0	12.7	16.1	20.0		-1.00
4175.0	35.2	73.40	33.7	12.0	16.8	21.8		-1.54
4176.0	39.9	61.50	39.4	17.5	7.2	28.0		-0.12
4177.0	45.0	58.10	47.2	23.5	3.4	21.7		-0.02
4178.0	37.8	54.80	59.2	15.1	3.1	26.4		-0.02
4179.0	34.1	61.10	55.9	10.7	8.6	25.6		-0.30
4180.0	34.6	64.20	34.7	11.3	10.6	30.6		-0.68
4181.0	43.1	64.00	24.0	21.3	8.0	35.4		-0.15
4213.0	32.4	67.10	4.3	8.7	13.2	90.2		0.09
4214.0	36.2	62.40	6.1	13.2	8.9	99.8		0.07
4215.0	39.9	56.40	9.6	17.5	3.7	100.0		0.04
4216.0	32.5	56.80	15.3	8.8	6.0	83.1		0.12
4217.0	28.2	60.40	14.4	3.8	9.8	66.0		0.18
4218.0	27.1	60.90	13.3	2.5	10.4	66.3		0.17
4219.0	46.8	59.90	11.5	25.6	4.1	72.1		-0.11
4234.0	50.1	69.70	5.7	29.5	10.0	76.6		0.18

Figure 4.1.3.--Level-by-level analysis of a Pennsylvanian interval of the Bartosovsky #1 well.

SKELLY OIL COMPANY CAHOJ BARTOSOVSKY NO. 1
 KANSAS RAWLINS SE SW SW 9 15 34W

SEMIVARIOGRAM FOR THE GAMMA RAY LOG

SV(0)	0.	SV(25)	924.4	SV(50)	452.4	SV(75)	798.1
SV(1)	65.4	SV(26)	924.9	SV(51)	503.7	SV(76)	801.4
SV(2)	187.2	SV(27)	914.4	SV(52)	564.2	SV(77)	791.0
SV(3)	306.7	SV(28)	897.2	SV(53)	640.2	SV(78)	778.2
SV(4)	416.3	SV(29)	877.2	SV(54)	731.8	SV(79)	763.6
SV(5)	522.5	SV(30)	844.3	SV(55)	818.6	SV(80)	743.1
SV(6)	626.8	SV(31)	811.6	SV(56)	889.1	SV(81)	713.0
SV(7)	724.1	SV(32)	792.4	SV(57)	940.6	SV(82)	680.3
SV(8)	806.5	SV(33)	782.5	SV(58)	981.2	SV(83)	650.6
SV(9)	860.6	SV(34)	769.3	SV(59)	1014.5	SV(84)	625.1
SV(10)	894.3	SV(35)	759.2	SV(60)	1034.7	SV(85)	616.5
SV(11)	912.2	SV(36)	756.4	SV(61)	1027.3	SV(86)	624.1
SV(12)	912.8	SV(37)	746.6	SV(62)	984.9	SV(87)	628.6
SV(13)	895.4	SV(38)	719.3	SV(63)	921.5	SV(88)	620.7
SV(14)	866.5	SV(39)	689.6	SV(64)	858.0	SV(89)	606.8
SV(15)	829.8	SV(40)	664.4	SV(65)	809.4	SV(90)	590.7
SV(16)	795.9	SV(41)	630.4	SV(66)	769.8	SV(91)	577.9
SV(17)	770.5	SV(42)	588.2	SV(67)	740.6	SV(92)	567.8
SV(18)	754.7	SV(43)	549.4	SV(68)	723.7	SV(93)	559.1
SV(19)	751.7	SV(44)	513.6	SV(69)	711.1	SV(94)	556.5
SV(20)	763.3	SV(45)	467.2	SV(70)	708.1	SV(95)	505.6
SV(21)	790.0	SV(46)	425.2	SV(71)	730.1	SV(96)	498.7
SV(22)	836.4	SV(47)	399.4	SV(72)	765.7	SV(97)	435.8
SV(23)	885.9	SV(48)	396.0	SV(73)	787.6	SV(98)	428.0
SV(24)	914.6	SV(49)	415.5	SV(74)	795.4	SV(99)	460.2

SLOPE AT THE ORIGIN

65.4 SQ. API UNITS/FOOT

Figure 4.1.4.--Average semivariogram for the gamma ray log using a sliding window of 100 ft. The interval corresponds to a Pennsylvanian alternation of limestones and shales in the Bartosovsky #1 well.

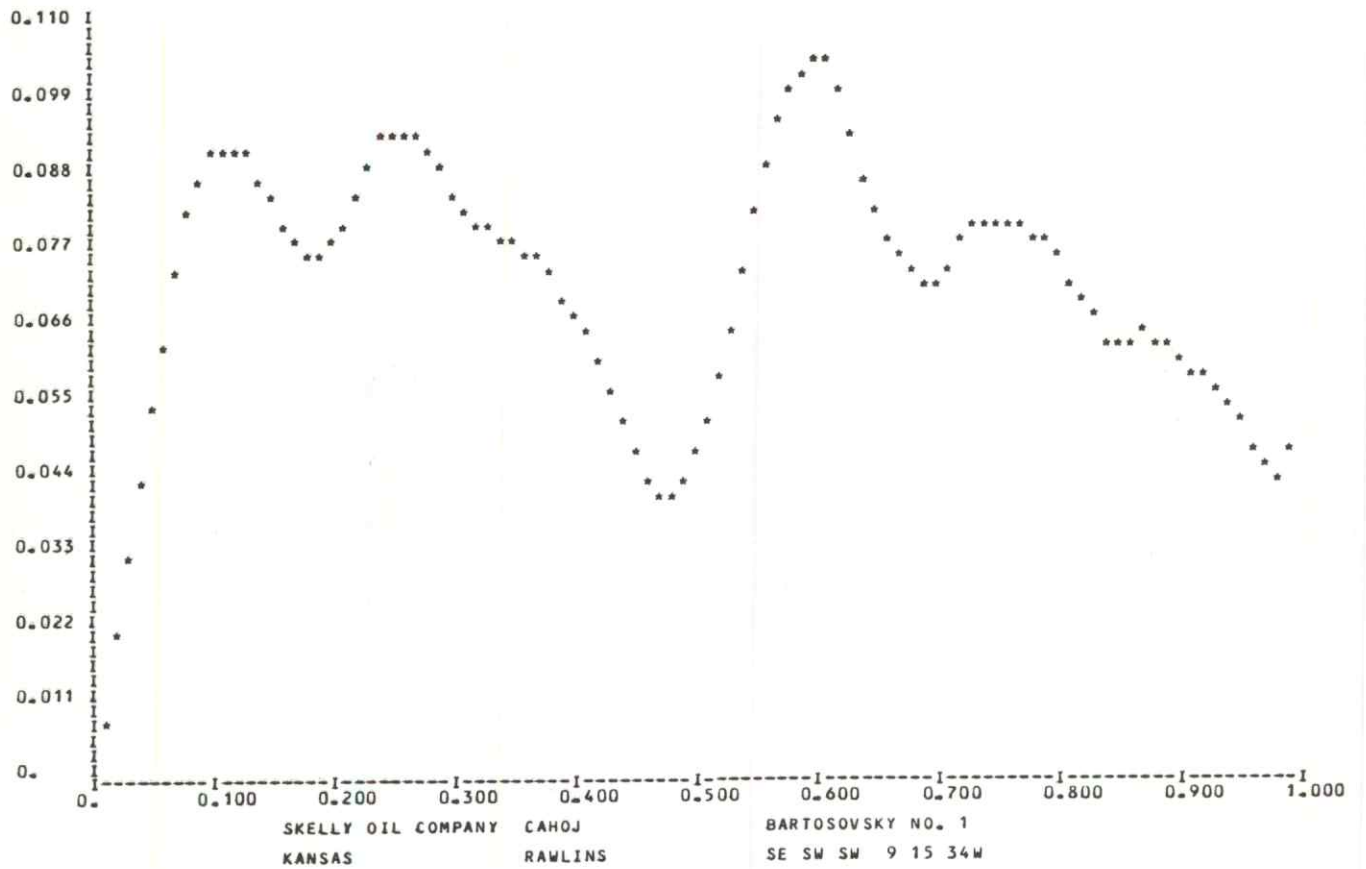


Figure 4.1.5.--Semivariogram for the values shown in Figure 4.1.4.

than laboratory measurements. As explained in Section 2.2, sonic log readings account only for intercrystalline or intergranular porosity, ignoring the contribution of vugs and fractures. Therefore, estimated water saturation values may be considered as pessimistic or maximum values.

4.2 Estimation of Archie's Equation Constants

The second example illustrates the procedure for direct evaluation of the Archie equation constants, a and m , through utilization of log and core information from a well section. The computations are initiated by the command 'ARCH'IE according to the theoretical relationships discussed earlier. The subroutine 'ARCH'IE draws on shaliness estimates from the gamma ray or SP log, resistivity values from the resistivity log, and porosities and water saturations from core data. Note that estimation of connate water saturation from core-measured water saturation is a matter to be determined by the user. The sequence of commands was:

```

0          1  2  2  3  3
1          5  0  5  0  5

ARCH      0.07 2.50  0  4  5

CPOR      3

EXTR      3693 3927

GAMM      25  110  2

PERF

```

The regression is calculated relating two composite variables in a linear relationship; the slope and intercept provide statistical predictions of the Archie constants, a and m . The example shown is from the Reiher #2 well in Hitchcock County, Nebraska, and the Archie constants were calculated for limestones of the Pennsylvanian Lansing-Kansas City Group. Percent shale estimates were computed from the gamma ray log, resistivity derived from an induction log, and porosity and water saturation values taken from core analyses. Output includes log readings (Fig. 4.2.1), statistics on goodness-of-fit, estimates of the Archie constants (Fig. 4.2.2), a crossplot of input core water saturations and regression, and estimates of water saturations (Fig. 4.2.3).

SKELLY OIL COMPANY , REIHER #2 S28 - 1N - 32W C NW NE
 FIELD : REIHER 7/27/59 HITCHCOCK, NEBRASKA

EVALUATION STARTS AT 3693.0 FEET
 EVALUATION ENDS AT 3927.0 FEET

DEPTH FEET	GAMMA R API U.	CORE FOR PERCENT	RESIST. SHALE OHM-M	POROSIITY PERCENT	WT SAT. PERCENT	PERM. MD	RWA OHM-M
3693.0	38.8	2.00	50.3	16.2	2.0	34.0	1.00
3694.0	36.0	5.20	60.1	12.9	5.2	32.0	1.00
3695.0	34.5	6.20	65.2	11.2	6.2	32.0	1.00
3733.0	59.1	11.10	8.2	40.1	11.1	65.0	1.00
3737.0	60.7	11.10	10.3	42.0	11.1	42.0	1.00
3770.0	41.9	16.10	9.6	19.9	16.1	65.0	1.00
3771.0	50.9	14.70	9.8	30.5	14.7	46.0	1.00
3772.0	58.9	11.10	9.8	39.9	11.1	44.0	1.00
3824.0	41.5	17.10	10.1	19.4	17.1	53.0	1.00
3825.0	44.6	21.70	8.8	23.1	21.7	53.0	1.00
3826.0	49.3	18.80	9.2	28.6	18.8	48.0	1.00
3827.0	49.9	17.90	10.8	29.3	17.9	44.0	1.00
3828.0	52.3	13.50	13.0	32.1	13.5	50.0	1.00
3876.0	57.8	11.90	11.4	38.6	11.9	44.0	1.00
3920.0	44.0	14.90	16.2	22.4	14.9	41.0	1.00
3921.0	50.5	14.00	15.6	30.0	14.0	38.0	1.00
3922.0	46.8	4.90	14.2	25.6	4.9	65.0	1.00
3923.0	40.4	7.40	13.0	18.1	7.4	93.0	1.00
3925.0	37.7	10.20	11.3	14.9	10.2	85.0	1.00
3926.0	41.1	11.30	11.5	18.9	11.3	68.0	1.00
3927.0	57.8	16.50	12.0	38.6	16.5	38.0	1.00

Figure 4.2.1.--Core values and log readings used to estimate Archie's equation constants in a Pennsylvanian interval of the Reiher #2 well, Hitchcock County, Nebraska.

	1	2	3	4	5	6	7	8
1	-2.957	-9.889	-7.999	-1.890	0.716	1.597	32.000	31.239
2	-2.781	-7.257	-7.437	0.180	0.597	1.547	32.000	32.338
3	-2.198	-5.835	-5.575	-0.260	0.323	1.464	65.000	62.722
4	-2.198	-4.554	-5.575	1.022	0.323	1.464	42.000	49.798
5	-1.826	-4.745	-4.387	-0.358	0.398	1.482	65.000	57.388
6	-1.917	-4.186	-4.678	0.492	0.360	1.472	46.000	53.045
7	-2.198	-4.464	-5.575	1.111	0.323	1.464	44.000	54.049
8	-1.766	-4.239	-4.194	-0.045	0.428	1.490	53.000	52.125
9	-1.528	-4.127	-3.433	-0.694	0.568	1.537	53.000	40.631
10	-1.671	-4.114	-3.891	-0.222	0.480	1.506	48.000	44.514
11	-1.720	-4.211	-4.048	-0.162	0.452	1.498	44.000	41.814
12	-2.002	-5.640	-4.950	-0.690	0.335	1.466	50.000	44.368
13	-2.129	-4.939	-5.353	0.414	0.319	1.463	44.000	47.107
14	-1.904	-4.562	-4.634	0.072	0.365	1.474	41.000	41.855
15	-1.966	-4.714	-4.834	0.120	0.344	1.469	38.000	39.005
16	-3.016	-7.386	-8.189	0.802	0.758	1.616	65.000	66.914
17	-2.604	-7.168	-6.871	-0.297	0.486	1.508	93.000	89.695
18	-2.283	-5.612	-5.846	0.233	0.340	1.468	85.000	90.919
19	-2.180	-5.228	-5.518	0.290	0.321	1.463	68.000	73.688
20	-1.802	-4.426	-4.308	-0.117	0.410	1.485	38.000	36.970

- OL 1 = X PSEUDO-VARIABLE
- OL 2 = Y PSEUDO-VARIABLE
- OL 3 = Y VALUE BASED ON REGRESSION EQUATION .
- OL 4 = COL 2 - COL 3
- OL 5 = 95 P.C. HALF CONFIDENCE BAND FOR THE TRUE MEAN OF Y .
- OL 6 = 95 P.C. HALF CONFIDENCE BAND FOR THE OBSERVATIONS OF Y .
- COL 7 = WATER SATURATION FROM CORE ANALYSIS .
- OL 8 = ESTIMATED WATER SATURATION .

NUMBER OF SAMPLES = 20
 TOTAL SUMS OF SQUARES = 42.8319
 SUMS OF SQUARES DUE TO REGRESSION = 34.4010
 SUMS OF SQUARES DUE TO DEVIATION = 8.4309
 GOODNESS OF FIT = 0.803163
 CORRELATION COEFFICIENT = 0.896193

ARCHIE'S EQUATION GIVEN BY THE REGRESSION

$$F = 0.23 / \text{POROSITY}^{3.20}$$

Figure 4.2.2.--Archie's equation constants and supporting calculations of a Pennsylvanian interval of the Reiher #2 well.

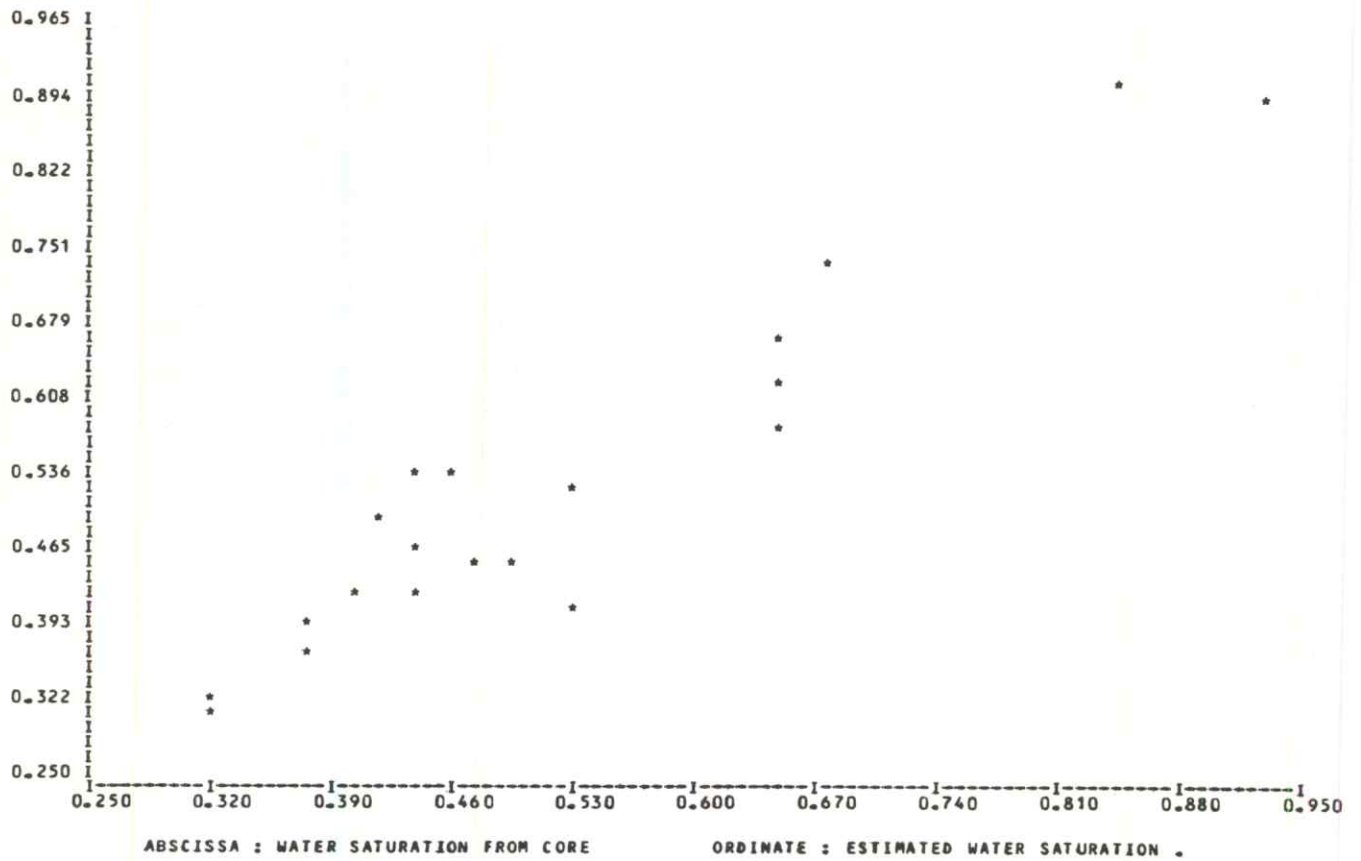


Figure 4.2.3.--Cross-plot of estimated and measured water saturations of a Pennsylvania interval of the Reiher #2 well.

4.3 Estimation of the Constants in the Permeability Equation

The third example shows the use of the command 'DARC'Y in the establishment of an equation relating core-measured permeabilities with porosities in terms of the constants B_i (bulk volume fraction occupied by irreducible connate water), F_{sh} (factor relating influence of shale content on the irreducible water saturation) and C and p (capillary pressure, hydrocarbon density and lithology determined characteristics). The subroutine applies a regression procedure to solve for the constants C and p as already described on pages 16 and 17.

The command was applied to measurements from core samples of the Springhill Sandstone (Lower Cretaceous, Chile) for subsequent use in the log analysis described in the next example (Fig. 4.3.1). A value for B_i of 0.02 was established from the core analysis. A single computer

SPRINGHILL SANDSTONE
OFFSHORE STRAITS OF MAGELLAN

EVALUATION STARTS AT 2015.0 METERS
EVALUATION ENDS AT 2055.0 METERS

DEPTH METERS	GAMMA R API U.	CORE POR PERCENT	RESIST. OHM-M	SHALE PERCENT	POROSITY PERCENT	WT SAT. PERCENT	PERM. MD	RWA OHM-M
2026.4	15.0	17.90		4.3	17.9		526.	
2027.5	19.0	20.60		5.1	20.6		2524.	
2031.0	17.0	20.50		3.6	20.5		2946.	
2032.6	19.0	21.50		5.1	21.5		1428.	
2033.8	19.0	21.80		5.1	21.8		2673.	
2035.0	18.0	23.50		4.3	23.5		2784.	
2036.0	17.0	21.50		3.6	21.5		1409.	
2038.0	19.0	19.30		5.1	19.3		692.	
2039.0	20.0	21.30		5.8	21.3		1792.	
2039.2	21.0	12.00		6.5	12.0		b.	
2039.5	23.0	23.20		8.0	23.2		2054.	
2054.6	55.0	13.10		31.2	13.1		63.	

Figure 4.3.1.--Basic core and log information from a Lower Cretaceous sandstone in a well in Magallanes, southern Chile.

run was made with six repetitive applications of 'DARC'Y using a range of F_{sh} values from 0 to 1.0 and alternative upper cutoff values for permeability of 1600, 2200, and 2900 md. The command sequence was:

```

0          1    2    2    3
1          5    0    5    0

EXTR      2015 2055    1
CUTO      80   20   50
LITH      1
GAMM      12  150    2
CPOR      3
DARC      0.02 0.10 1600    4
DARC      0.02 0.10 2200    4
DARC      0.02 0.00 2900    4
DARC      0.02 0.10 2900    4
DARC      0.02 0.20 2900    4
DARC      0.02 1.00 2900    4
PERF

```

The most satisfactory solution is shown in Figure 4.3.2 which lists the regression statistics together with optimal values for the constants B_i , F_{sh} , C, and p. These latter values correspond to the parameters of the command 'PERM' that may be used in conjunction with log readings in the prediction of permeabilities on a zone-by-zone basis as shown in the next example. Figure 4.3.3 is a crossplot of estimated and measured permeabilities.

	1	2	3	4	5	6	7	8
1	-1.720	0.941	0.816	0.125	0.162	0.537	526.000	410.033
2	-1.580	1.585	1.236	-0.347	0.152	0.537	2524.000	1261.123
3	-1.537	1.257	1.366	-0.109	0.174	0.541	1428.000	1775.309
4	-1.523	1.557	1.408	0.149	0.179	0.542	2673.000	1983.358
5	-1.448	1.502	1.633	-0.131	0.212	0.554	2784.000	3315.751
6	-1.537	1.271	1.366	-0.095	0.174	0.541	1459.000	1775.309
7	-1.645	1.003	1.042	-0.039	0.154	0.535	692.000	748.789
8	-1.546	1.380	1.338	-0.042	0.171	0.540	1792.000	1647.460
9	-2.120	-0.752	-0.383	-0.369	0.372	0.632	8.000	16.747
10	-1.461	1.363	1.594	-0.231	0.206	0.552	2054.000	3262.687
11	-2.033	0.192	-0.120	0.312	0.315	0.601	63.000	33.772

- L 1 = X PSEUDO-VARIABLE
- L 2 = Y PSEUDO-VARIABLE
- L 3 = Y VALUE BASED ON REGRESSION EQUATION .
- L 4 = COL 2 - COL 3
- L 5 = 95 P.C. HALF CONFIDENCE BAND FOR THE TRUE MEAN OF Y .
- L 6 = 95 P.C. HALF CONFIDENCE BAND FOR THE OBSERVATIONS OF Y .
- OL 7 = PERMEABILITY FROM CORE ANALYSIS .
- L 8 = ESTIMATED PERMEABILITY .

NUMBER OF SAMPLES = 11
 TOTAL SUMS OF SQUARES = 5.0371
 SUMS OF SQUARES DUE TO REGRESSION = 4.5506
 SUMS OF SQUARES DUE TO DEVIATION = 0.4865
 GOODNESS OF FIT = 0.903415
 CORRELATION COEFFICIENT = 0.950482

PERMEABILITY EQUATION GIVEN BY REGRESSION

$$\text{PERMEABILITY } K^{0.5} = (394. * \text{POROSITY}^{3.00}) / \text{SWIRR}$$

$$\text{SWIRR} = 0.02 / \text{POROSITY} + 0. * \text{FSHALE}$$

Figure 4.3.2.--Regression statistics and permeability equation for a Lower Cretaceous sandstone in a well in Magallanes, southern Chile.

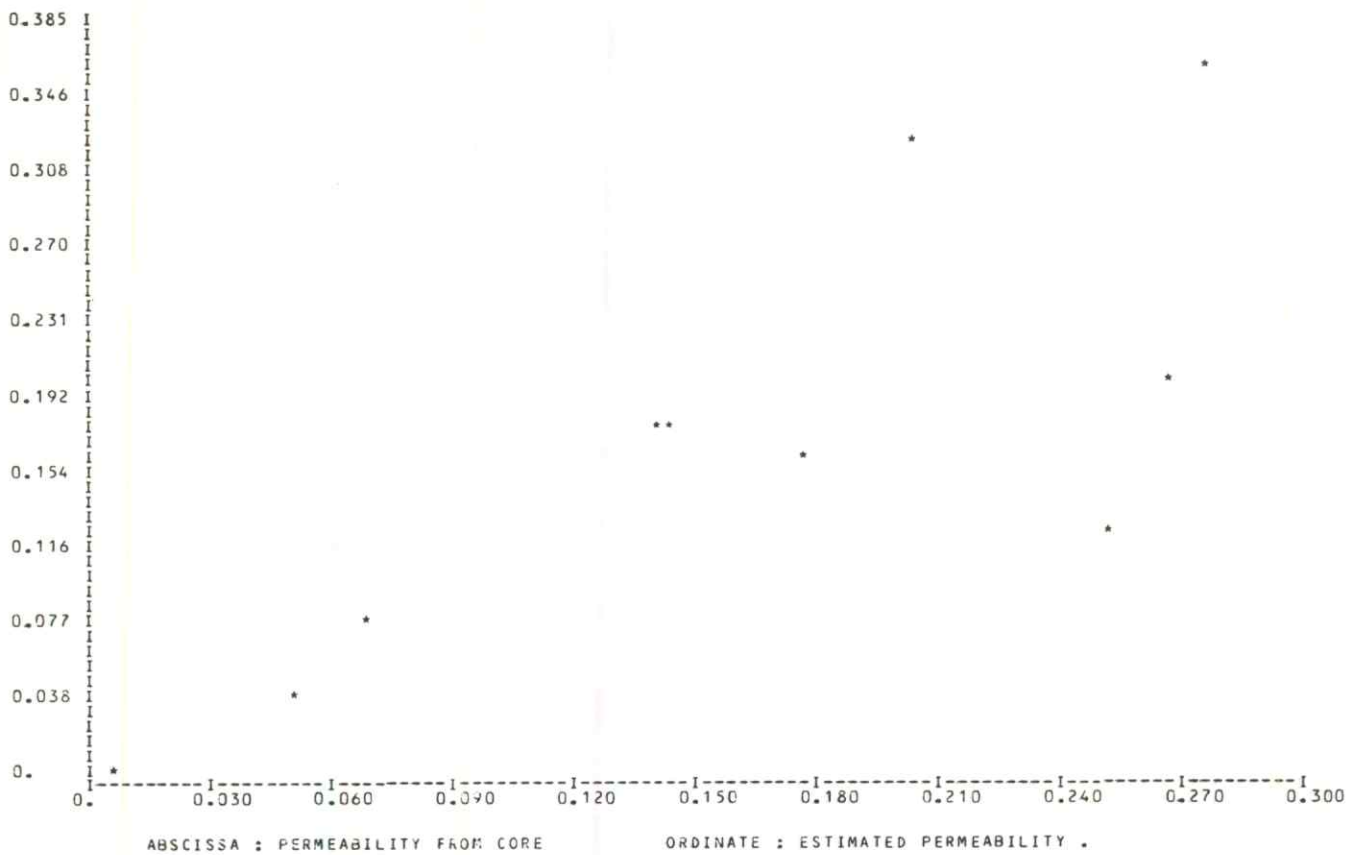


Figure 4.3.3.--Cross-plot of estimated and measured permeabilities in a Lower Cretaceous sandstone in a well in Magallanes, southern Chile.

4.4 Evaluation of a Productive Chilean Sandstone

This example illustrates the application of LOG II to a Lower Cretaceous sandstone/shale sequence in southern Chile. It includes an additional estimation of permeability and illustrates the use of the line printer graphic option generated by the command 'PRNT'. Shown in this example are the analysis of gamma ray, density, and resistivity logs together with the output of porosity, shale content, water saturation and permeability, both as listings (Figs. 4.4.1 and 4.4.2) and as line-printer graphic display (Fig. 4.4.3). The list of commands was:

```

0          1  2  2  3  3  4          6
1          5  0  5  0  5  0          5

CUTO      50  12  50

LITH      1

EXTR      2015 2042  1

GAMM      12  150  2

DENS      2.55 2.65 1.00 5.00

PERM      393 3.00 0.02 0.00

RESI      0.62 2.15 0.12 3.00  0  6

PRNT      0  100  9  1  0  0          SHALE, %
PRNT      100  0  10  1  0  0          DENS. POROSITY, %
PRNT      10000  1  14  2  0  1          PERMEABILITY, MD
PRNT      10000  1  4  2  0  1          CORE PERM., MD
PRNT      100  0  12  2  0  0          WATER SATUR., %
PRNT      40  0  11  3  0  0          (WAT. SAT.)(POR.)
PRNT      40  0  10  3  0  0          DENS. POROSITY, %
PRNT      40  0  3  3  0  0          CORE POROS., %

PERF

```

The command 'PERM' utilizes values for parameters established in the previous example. The multiple application of command 'PRNT' produces log analysis results together with input core porosities and permeabilities for purposes of comparison.

SPRINGHILL SANDSTONE
OFFSHORE STRAITS OF MAGELLAN

GAMMA RAY LOG

GAMMA RAY IN SHALE 150.0 API UNITS .
GAMMA RAY IN SANDSTONE 12.0 API UNITS .
SHALINESS CUT-OFF 50.0 PER CENT .

GAMMA-RAY AVERAGE 25.2 API UNITS
STANDARD DEV. FOR GAMMA-RAY 17.6 API UNITS
CUMULATIVE THICKNESS OF SANDSTONE 23.8 METERS
SANDSTONE FRACTION IN INTERVAL 96.9 PER CENT
AVERAGE GAMMA-RAY IN SANDSTONE 23.1 API UNITS
STAND. DEV. OF GAMMA-RAY IN SANDSTONE 13.4 API UNITS

DENSITY LOG

SHALE DENSITY 2.55 GRAM/CC
SANDSTONE DENSITY 2.65 GRAM/CC
TRAPPED FLUID DENSITY 1.00 GRAM/CC

AVERAGE POROSITY IN SANDSTONE 17.9 PER CENT
SANDSTONE POROS. LARGER THAN 12.0 % 20.4 METERS
AVER. POROS. IN HIGH POROS. SANDSTONE 19.2 PER CENT

PERMEABILITY

PERMEABILITY $K = \frac{0.5}{393 \cdot \text{POROSITY} + 0.5 \cdot \text{FSHALE}}$
SWIRR = 0.02 * POROSITY + 0. * FSHALE

AVERAGE PERMEABILITY IN SANDSTONE 770.9 MILLIDARCS
AVER. PERM. IN HIGH POROS. SANDSTONE 872.8 MILLIDARCS

RESISTIVITY LOG

SHALE RESISTIVITY 3.0 OHM-M
BRINE RESISTIVITY 0.120 OHM-M
ARCHIE'S FORMULA $F = 0.62 / \text{POROSITY}^{2.15}$

HIGH POROS. SANDSTONE UNDER 50.0 % WATER 19.3 METERS
AVER. WAT. SAT. IN SANDSTONE UNDER 50.0% WATER 17.3 %

Figure. 4.4.1.--Basic information and statistics for a Lower Cretaceous sandstone interval in a well in Magallanes, southern Chile (same interval and well as in Example 4.3).

SPRINGHILL SANDSTONE
OFFSHORE STRAITS OF MAGELLAN

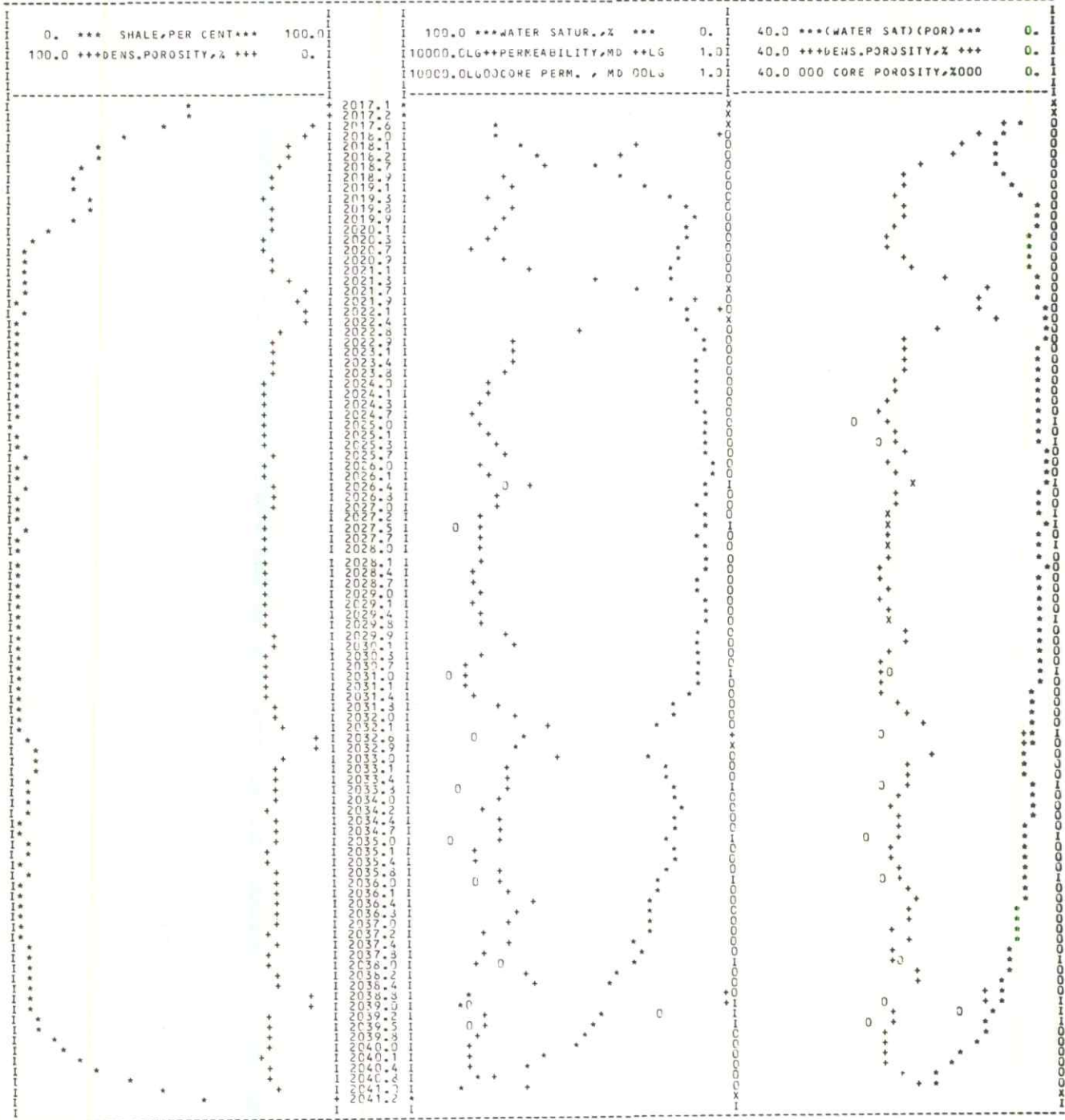


Figure 4.4.3.--Line-printer graphical display of results of analysis shown in Figure 4.4.2.

4.5 Mapping of Statistical Variables

Automated log analysis has been used almost exclusively for conventional formation evaluation to determine the production characteristics of potential reservoir horizons. However, increasing interest in delineation of stratigraphic traps has encouraged research into the use of geophysical well logs to produce mappable petrophysical variables.

The summary statistics generated by LOG II for a series of wells penetrating a common stratigraphic sequence may be mapped as an aid in exploration. Contour maps of gamma ray statistics indicate the basic geometry of lithologic variation in the interval across an area and can be used for lithofacies studies. The mapped variation of porosity and water saturation may be useful in delineating favorable productive areas.

Such maps are best used as reconnaissance tools for rapid evaluation of subsurface variation in selected intervals. More detailed analyses can be made by a careful study of cores and chip samples, but require a significantly greater investment of time and money. The mapping of log-derived variables is a comparatively rapid procedure if done by computer. Statistics generated by LOG II may be used by an automated contouring program to produce maps directly. Areas of particular interest on such maps can then be investigated in more detail by conventional geological methods. Figure 4.5.1 is an example of a typical log variable map, showing the areal variation in percent limestone in the Lansing-Kansas City Group (Pennsylvanian) in Rawlins County, Kansas. The map was generated by the Kansas Geological Survey's automated contouring package, SURFACE II (Sampson, 1978).

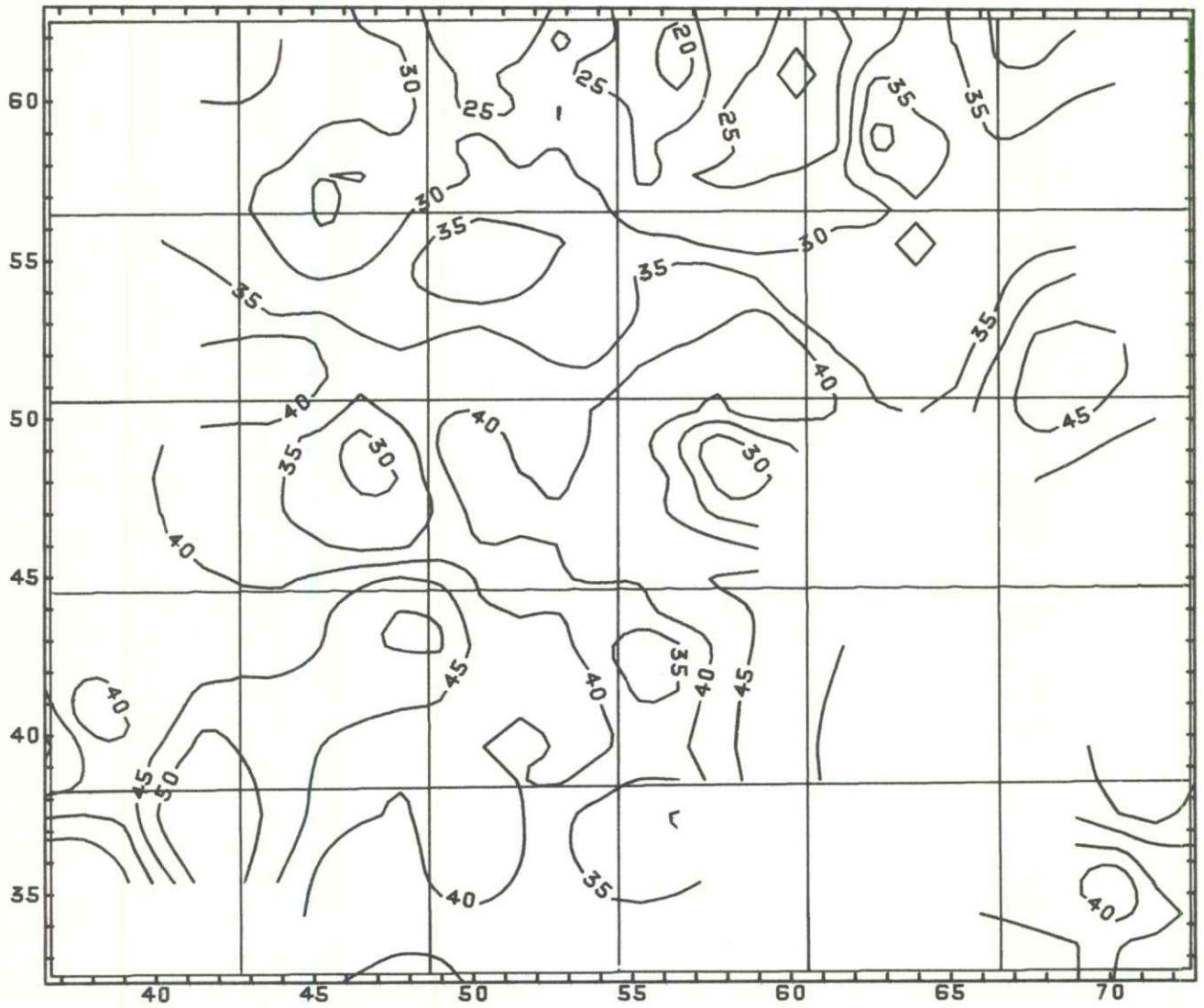


Figure 4.5.1.--Areal variation of percent limestone in the Lansing-Kansas City Group in Rawlins County, Kansas.

5. CONCLUSIONS

LOG II can advantageously replace nomograms and desk calculators in the processing of geophysical logs and laboratory measurements for formation evaluation purposes. The possibility of calculation errors in long and tedious computations is eliminated, and graphics capabilities allow easy and rapid interpretation for enhanced understanding of final results.

There are certain intrinsic limitations to all methods of formation evaluation when using single porosity tools. Misleading results usually are obtained from radioactive porosity tools if there are significant changes in formation lithology in the presence of variable amounts of gas near the borehole. Porosity estimates based on sonic logs ignore secondary porosity in the form of large vugs, and account only for intercrystalline and intergranular microporosity. Some of these drawbacks can be corrected and even turned to advantage when a second porosity tool allows two different evaluations. LOG II performs simultaneous evaluations with ease, and is designed to perform as optimally as possible using only a single porosity tool.

Although the primary purpose of LOG II is evaluation of individual wells, the summary statistics of all wells in an area can be combined to produce contour maps for use in regional studies.

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COMPANY	SKELLY OIL COMPANY
FIELD	CAHOJ
WELL	BARTOSOVSKY NO. 1
STATE	KANSAS
COUNTY	RAWLINS
LOCATION	SE SW SW 9 1S 34W
LOG II	
COMPUTED LOGS	
COMPANY	SKELLY OIL COMPANY
FIELD	CAHOJ
WELL	BARTOSOVSKY NO. 1
STATE	KANSAS
COUNTY	RAWLINS
LOCATION	SE SW SW 9 1S 34W
SCALE	20 FEET PER INCH

REMARKS

TOTAL DEPTH 4300 FT.
 DRILLING COMMENCED JULY 31, 1959.
 DRILLING COMPLETED AUGUST 22, 1959.

STRATIGRAPHIC MARKERS

 TOP OF THE LANSING GROUP 3976 FT
 BASE OF THE KANSAS CITY GROUP 4243 FT

CORES

 EIGHT CORES WERE TAKEN FROM 3860 TO 4246 FT IN A CONTINUOUS CORING OPERATION. RECOVERY WAS ALMOST PERFECT AS ONLY ONE FOOT INTERVAL WAS MISSING. A COMPLETE DESCRIPTION OF THESE CORES IS IN

HARRAUGH, J. H. AND M. DAVIE, JR., 1964, UPPER PENNSYLVANIAN CALCAREOUS ROCKS CORED IN TWO WELLS IN RAWLINS AND STAFFORD COUNTIES, KANSAS, STATE GEOLOGICAL SURVEY OF KANSAS BULLETIN 170, PART 6, P. 3-19.

ADDITIONAL LABORATORY MEASUREMENTS ARE AVAILABLE IN A CORELAB REPORT.

DRILL STEM TESTS

 A TOTAL OF 6 TESTS WERE MADE IN THE WELL, 5 OF THEM IN THE LANSING-KANSAS CITY INTERVAL.
 DST #2 FROM 3973 TO 4012
 THE TEST RUN FOR 2 HOURS. THERE WAS A FAIR BLOW THROUGHOUT THE TEST. THE RECOVERY WAS 320 FT OF GAS. 160 FT OF 32 API OIL, NO WATER. IBHP 1280, IFF 50, FFP 80, FBHP 1120.
 DST #3 FROM 4026 TO 4074
 THE TEST RUN FOR 1 HOUR. THERE WAS A WEAK BLOW FOR 5 MINUTES. THE RECOVERY WAS 5 FT OF MUD WITH SPECKS OF OIL. IBHP 130, IFF 0, FFP 0, FBHP 0.
 DST #4 FROM 4124 TO 4159
 THE TEST RUN FOR TWO HOURS. THERE WAS A STRONG BLOW THROUGHOUT THE TEST. THE RECOVERY WAS 2249 FT OF GAS AND 1880 FT OF OIL WITH A GRAVITY OF 28.3 API, NO WATER. IBHP 1305, IFF 135, FFP 745, FBHP 1250.
 DST #5 FROM 4178 TO 4204
 THE TEST RUN FOR 2 HOURS. THERE WAS A STRONG BLOW THROUGHOUT THE TEST. THE RECOVERY WAS 3360 FT OF OIL WITH 33.8 API GRAVITY, NO WATER. IBHP 1305, IFF 160, FFP 1250, FBHP 1280.
 DST #6 FROM 4210 TO 4246
 THE TEST RUN FOR 1 HOUR. THERE WAS A WEAK BLOW FOR 5 MINUTES. THE RECOVERY WAS 60 FT OF MUDDY SALT-WATER WITH A FEW SPECKS OF OIL. IBHP 1330, IFF 0, FFP 0, FBHP 1120.

COMPLETION

 PRODUCTION STARTED FROM 4170-4182, 4128-4134, 4079-4083 AND FROM 3978-3990 AT A RATE OF 3000 BOPD.

