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OFFSHORE GULF COAST FORMATION EVALUATION: COMPARISON AND USE OF UNCONSOLIDATED CORE DATA, WIRELINE LOGS AND SIDEWALL CORE DATA

by

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ABSTRACT

Formation evaluation of geologically young and shaly reservoirs has been a problem in the Gulf Coast for many years. It is often difficult to determine basic parameters such as effective porosity, formation water saturation and net pay. There is a need to use as many different evaluation tools as are economically practical. Some of the tools employed to solve these problems are unconsolidated "softcore" analysis from conventional cores, wireline logs and sidewall core analysis.

An accepted method for obtaining good quality data for formation evaluation is measurements made on plugs from a full-diameter, conventional-type core. Unfortunately, due to financial constraints, a conventional core barrel is not run in the hole on every well. A method is presented to show how calibration of log data to measured softcore analysis data can be achieved, thereby providing better reservoir description. An example of sidewall core analysis data integrated with wireline log data for formation evaluation purposes is presented. The usefulness of sidewall core for deriving data other than routine permeability, summation of fluids porosity and probable production of the reservoir is discussed.

INTRODUCTION

Conventional core is ofttimes obtained to aid in detailed reservoir evaluations. The data generated from these cores include reservoir definition of permeability, porosity, fluid saturations, gas-oil and oil-water levels, and lithology. Extended data include determination of petrophysical parameters needed for wireline log calculations and studies of relative permeability and capillarity.

Core recovery with conventional core barrels is generally good in "hard rock" areas. However, traditional coring methods do not provide good core recovery in the soft, unconsolidated sediments that make up most hydrocarbon producing reservoirs in the offshore Gulf of Mexico. Techniques currently available for soft rock recovery include: 1) rubber sleeve, 2) plastic sleeve,

3) fiberglass and 4) aluminum sleeve. Improved core catchers and core bits tailored for soft sediments also improve core recovery (Bradburn and Cheatham, 1988).

Core analysis of unconsolidated formations is complex. The potential for pore geometry alteration is significant after in-situ conditions are changed. In addition to pore deformation, these sediments contain structural and authigenic clay minerals and can exhibit severe particle movement. Over the past decade, major strides have been made in developing methods to ensure that good quality plug samples are obtained and that sample measurements are accurate.

Much of the data generated from conventional core analysis of unconsolidated formations is used for calibration of wireline logs. The core analysis data and calibrated wireline log data are then used for more accurate determination of porosity, formation water saturation and net feet of pay. Usually no more than one or two wells are conventionally cored in a field due to the high cost of obtaining the core.

In most wells in a Gulf Coast field, sidewall cores are taken as a means of obtaining additional data to aid in formation evaluation. Initially sidewall core samples were examined for qualitative properties which were obvious to the senses of sight, smell and taste. Development of a semi-micro form of conventional core analysis allowed the generation of quantitative data from sidewall cores (Reudelhuber and Furen, 1957).

Although the sidewall samples are still small and usually somewhat altered, new technology has provided a myriad of tests that yield valid and useful data for formation evaluation. This paper discusses the use and application of unconsolidated softcore data and sidewall data in Gulf Coast formation evaluation.

METHODS FOR SOFTCORE HANDLING, SAMPLING AND ANALYSIS

After conventional core has been retrieved from an unconsolidated formation, great care is taken to assure that further alteration of the core material is minimized. Core is usually stabilized by either freezing or by epoxy resin injection into the annular space between the core sleeve and the core. It is then packed in insulated crates and shipped (either frozen or chilled) to the core analysis laboratory.

Once the core is in the laboratory, the process of sample selection begins. The objective is to obtain samples that statistically represent the formation of interest. The generation of representative data is dependent upon the quality of the sample set. Sample selection and quality can often be enhanced by use of X-ray fluoroscopy or computerized tomography should be conducted. Figure 1 is a permeability versus porosity cross-plot of a data set with numerous fractured samples. This is evident by the very high permeabilities measured on relatively low porosity samples. When this occurs, additional samples should be obtained for permeability and porosity determinations. When fractures are confirmed, the relationship between permeability and porosity should be re-evaluated.

CORE-LOG CORRELATION

One major purpose for cutting a conventional core is calibration of wireline log data. By calibrating the calculated log data to measured conventional softcore data, more accurate values for porosity, formation water saturation and net feet of pay can be determined. Figure 2 presents a section of logs and conventional softcore data that were digitized and entered into a computer system for formation evaluation. An examination of the core data and log data was made to check for depth discrepancies. A depth adjustment of eight feet was made to match the core depths to log depths.

Vsh DETERMINATION

It has long been recognized that, in shaly formations, shale can have a significant effect on log readings. The volume of shale (Vsh) needs to be determined in order to make corrections to log derived porosity values and for use in some shaly sand water saturation models. For purposes of this study, shale is defined as the fraction of the rock that is less than four microns in size, including clay and other minerals such as silica, feldspar and mica. Studies of X-ray diffraction data from offshore Louisiana have shown only about two percent of the less than four micron size fraction to be non-clay minerals (Hynson, 1987). Vsh can be calculated from many different logging tools. Some of these are gamma ray (linear and non-linear responses), spontaneous potential, neutron/density cross-plots and sonic/density cross-plots. Calculation by these four different methods can yield Vsh values ranging from a low of about 25 % to a high of about 75 % at the same depth point. Any of these accepted methods can yield the correct Vsh under certain well and formation conditions provided we know which method to use. The actual Vsh can be accurately measured on core samples by several methods. One quick method for measuring Vsh is FTIR (Harville and Freeman, 1988), which was used to measure total clay volume on the samples in this study. The log-derived Vsh was calculated from the gamma ray tool using a non-linear response, which is one of the widely used methods. A calibration of log-calculated Vsh to the measured total clay was made (Figure 3). A least-square, best-fit line of that data is:

$$Vsh_c = 1.75 \times Vsh_{log} + 7.61 \qquad (1)$$

where Vsh_c = log shale volume calibrated to measured data, percent
Vsh_{log} = log-calculated shale volume, percent

This calibrated Vsh was used for calculation of effective porosity from the logs.

CORE-LOG POROSITY CORRELATION

Porosity calculations from the logs proved the density log to yield porosity values most similar to that of the measured core porosity. A plot was then made of the calculated log porosity versus core porosity measured at simulated overburden conditions, and is presented on Figure 4. The plot has a correlation coefficient of 0.744. A least-square, best-fit line for the data was calculated and used to calibrate the log porosity to the measured core porosity. The resulting equation is:

$$\phi c = (\phi log + 14.66)/1.50 \qquad (2)$$

where ϕc = log porosity calibrated to core porosity, percent
ϕlog = original log calculated porosity, percent

This equation was used to determine equivalent core porosities in the zone evaluated.

The equations developed for calibrating the log calculated porosity and Vsh to the measured conventional core data can be used for evaluation of other wells in the same reservoir if a conventional core is not available. However, if significant changes in lithology or rock texture are detected, the calibrations could change.

CORE-LOG INTERSTITIAL WATER COMPARISON

Water saturation (Sw) was calculated from the log using a formation water resistivity (Rw) of 0.05 ohm-meters at formation temperature. Formation resistivity factor and resistivity index were measured on core samples at simulated overburden conditions. These tests revealed a cementation factor (m) of 1.83 with an "a" intercept of 1.0 and a saturation exponent (n) of 1.58. The water saturation values calculated from the logs were then compared to average water saturation distribution as determined by capillary pressure tests to validate the log-calculated water saturation data. Water saturation points from capillary pressure tests were determined by averaging values from samples having porosities ranging from 29% to 33%. Comparative water saturation values calculated from the logs were from depths with porosity values that were also between 29% and 33%. Approximate height calculations were made using published assumed values for interfacial tension and contact angle as no measured data were

(CT) scanning. These procedures aid in the delineation of lithologic and sedimentary structures thereby allowing plugs to be drilled without core slabbing or removal from the core sleeve. When the core is slabbed, the images from X-ray fluoroscopy or CT scanning help to ensure that the slab is made perpendicular to bedding planes.

Core plugs are recovered from softcore by several methods. These include drilling with liquid nitrogen, hydraulic punching with a thin walled plunge cutter, and core pressing using a teflon-sleeve insert in a modified plunge cutter. The objective of each method is to obtain plugs while maintaining the grain to grain integrity.

Plugs from softcore must be encapsulated to preserve sample integrity. Sample encapsulation processes include confinement by lead sleeve, screen-cap-teflon, heat shrinkable (no-cap) teflon, aluminum foil and continuous confinement. As with core stabilization or core plug retrieval, different encapsulation methods are preferable in different sediment types or for different core tests.

Once the core plugs have been retrieved and encapsulated, they are cleaned. Methods used for core cleaning are Dean Stark or Soxhlet extraction, vapor soaking with condensed toluene drip and flow through cleaning (FTC). Again, given different sets of circumstances (coring/drilling method, sediment type and analytical processes), different types of core cleaning methods are appropriate in different cases.

After the samples have been properly prepared, the actual measurements are made. The data routinely generated from softcore analysis are: permeability and porosity at ambient and overburden conditions, fluid saturations, grain density, critical water saturation, percent silt and clay and lithological description. Other data that are routinely determined for use in formation evaluation would be surface core gamma (total or spectral), detailed core description, core photography, grain size and distribution and rapid mineralogical determination by Fourier Transform Infrared Spectroscopy (FTIR).

INTEGRATION OF SOFTCORE ANALYSIS AND LOGS FOR DETAILED FORMATION EVALUATION

PERMEABILITY AND POROSITY TRENDS

In an unconsolidated sand-shale sequence, it is important to compare permeability and porosity trends. Samples can fracture or separate along shale laminae after sample encapsulation, and it is possible for erroneous data to be obtained. If a permeability versus porosity cross-plot shows a drastically atypical relationship, further investigation into data validity available. Agreement of the overall shape of the two curves and the placement of the transition zone supports the height calculation using assumed data.

These data are presented on Figure 5. A systematic difference is noted between the two sets of water saturation data. The log data are seven percent pore space lower than calculated using capillary pressure data. This difference can be caused by using incorrect parameters to calculate Sw from the logs, or by measured laboratory data that does not represent the reservoir. Examination of the laboratory data generated for determination of cementation factor, saturation exponent, and capillary pressure did not reveal any procedural problems. However, the Rw value used for calculation of Sw from the logs was questionable. A water sample was not available for analysis and calculation of Rw from the logs could not be definitive due to the effects of shale on the resistivity log. At this point, through process of elimination, it was decided that Sw from capillary pressure data was the more accurate value, and the log derived Sw values were adjusted to the Sw values from capillary pressure data.

CRITICAL WATER USAGE AND CONVERSION TO EQUIVALENT RESISTIVITY

Routine core analysis provides direct measurement of certain reservoir rock properties which control Sw. However, except in certain circumstances, core analysis does not provide a direct measurement of Sw. The deep resistivity device is commonly used to calculate Sw. Resistivity log determination of Sw does not always permit reliable interpretation of reservoir productivity because a critical upper limit for Sw must be known. Many times a Sw of 60% or more is calculated from the log. Such a zone may produce either hydrocarbon with no water, or 100% water, depending upon certain rock properties discernible only by core analysis.

A method for determining the critical upper limit of Sw or critical water saturation (Sciw) from routine core analysis in Gulf Coast sands was established by Granberry and Keelan (1977). The use of Sciw facilitates a quick and easy method for integrating core data and log data for formation evaluation purposes. The Sciw should be compared to Sw calculated from the logs. Sciw is the upper limit of Sw that can exist in the formation before produced water becomes a concern. In formations where resistivity is not highly suppressed by clays, an interpretation can be made by comparing the log resistivity to a minimum resistivity determined from critical water saturation. This minimum resistivity is termed minimum productive resistivity (Rmp) and is calculated by a reversal of the basic Archie equation (Granberry and Tucker, 1973). Rather than the usual calculation of Sw from the log resistivity, minimum productive resistivity is calculated using the critical water saturation from core analysis:

$$\mathrm{Rmp} = \frac{F \times \mathrm{Rw}}{(\mathrm{Sciw})^n} \qquad (3)$$

where
Rmp = minimum productive resistivity
Sciw = critical formation water saturation
F = formation factor
Rw = formation water resistivity
n = saturation exponent

The Rmp value can then be compared directly to the log deep-resistivity value to make an interpretation. In hydrocarbon-productive zones the log deep resistivity should be greater than the calculated Rmp.

A graphical presentation of the calibrated log data and core data along with Rmp interpretation are presented on Figure 6. The plot shows the entire zone to be hydrocarbon productive as formation resistivity exceeds Rmp. In cases where the log resistivity is highly suppressed by shale, the Rmp technique alone may not define a hydrocarbon-water contact.

MINERALOGY EFFECTS

Bulk and clay mineralogical identification can help determine if low resistivity is due to high Sw, or resistivity suppression by certain minerals in the formation. Figure 7 presents a foot-by-foot display of clay minerals determined by FTIR compared to log resistivity. Although resistivity in this study does not appear to be extremely suppressed, resistivity varies with changes in total clay and clay type. Throughout the zone, resistivity changes almost mirror changes in total clay percentage and clay type.

Using log data calibrated with laboratory measured data to determine Vsh, porosity and Sw should provide data more representative of the reservoir. These data, used in conjunction with Sciw to help define the effective water level in the reservoir, provide much of the data needed to estimate hydrocarbons in place.

It should be noted that in thinly laminated sand-shale sequences having a high volume of shale, this type of calibration may not work. Averaging of log responses across the thin laminae and resistivity suppression by clays often do not permit determination of accurate data for Vsh, porosity, or Sw from the wireline logs. In such cases this direct comparison, or calibration, of the two sets of data are not feasible.

APPLICATIONS OF SIDEWALL CORE ANALYSIS DATA

Early sidewall coring tools provided small samples and were limited to use in very soft formations. Over the years, the art of sidewall analysis progressed, and permeability, porosity and fluid saturations began to be quantitatively determined. This progression has taken us to a point where many parameters can be measured on sidewall samples, and many formation evaluation problems can be solved through use of sidewall core data.

There are problems that are inherent to sidewall core analysis: Is the size of sample adequate for all testing? Does the sample represent formation lithology? Have grains in lower porosity zones been fractured? Has there been extreme flushing by drilling mud filtrate?

Reudelhuber and Furen (1957), Webster and Dawsongrove (1959), and Koepf and Granberry (1961) documented percussion-type sidewall samples from formations with less than about 24% porosity and 20 md permeability yield measured permeability and porosity values that are erroneously high. This is due to shattering of the sample by the percussion bullet. Porosity values on sidewalls from formations of better rock quality are usually within 1.5 to 2 porosity % of the true formation porosity. However, measured permeability on percussion-type sidewall cores are significantly low in formations with more than 300 md permeability. An empirical method was derived to determine more accurate permeability values and, at the same time, save more of the sample for porosity and fluid saturation determination. The empirical permeability was dependent upon measured porosity and sample density, and upon visual estimates of sand grain size, grain size distribution and degree of shaliness. As most of the formations from the offshore Gulf of Mexico area are unconsolidated soft sediment (with a few exceptions), data from sidewall core analysis are useful as a formation evaluation tool. The use of other tools in conjunction with sidewall core data aids in making formation evaluation decisions.

Formation evaluation using sidewall core can be accomplished in much the same way as with a conventional core. The permeability and porosity values are not as accurate as with conventional core, but for the medium-to high-permeability and porosity formations the data have proven reliable.

CORE GRAIN SIZE DISTRIBUTION APPLICATIONS

In 1981 a computerized particle size analyzer was introduced for quick and accurate determination of grain size and sorting of sidewall core samples. This apparatus determines particle size distribution of a disaggregated sample by measuring the settling velocity of particles in water (Gibbs, 1971). This particle size analysis (PSA) replaced the visual estimates that were previously used in the empirical determination of sidewall core permeability. The resulting permeabilities are more consistent, and this leads to more reliable critical water saturation values from sidewall cores.

Textural measurements may aid in evaluating log responses, selecting perforation intervals, and in shot density and gravel pack design. Changes in formation water saturation with depth in a sand interval may indicate either changes in grain size and sorting or a transition zone from hydrocarbon to water. The particle size data can be plotted versus depth to help explain changes in resistivity as recorded by wireline logs (Figure 8). Particle size data can be used in laminated formations to select coarser grained, better quality perforation intervals. Improper perforation can result in failure to drain individual sand lenses within the reservoir. Location of the perforated interval relative to the water level should be decided with full consideration of the reservoir sand texture. The determination of formation grain size is also necessary to select the optimum gravel pack (Maly and Krueger, 1970).

PREDICTION OF PROBABLE PRODUCTION

Prediction of probable production from a reservoir based on residual fluids in sidewall core is routinely done. However, in some instances these fluid saturations are misleading. The following example exhibits two sands in which sidewall samples were taken. Prior to logging the well, an oil additive was put into the drilling fluid system to help free stuck pipe. The invasion of the oil filtrate into the formation made an interpretation based on core fluid saturations invalid. Although the fluid saturations were unreliable for interpretation, the rock property measurements were still good.

Figure 9 shows a comparison of the sidewall core porosity and log porosity. The agreement between the two sets of data is good considering each sidewall core represents only one inch of formation and the log porosity is averaged over a much larger interval.

The Rmp was calculated from critical water saturation determined from routine sidewall core analysis. Core permeability, porosity and Rmp plotted with the log responses are presented on Figure 10. In the upper sand the log resistivity is greater (indicating hydrocarbon production) than Rmp down to 9479 feet. This depth was interpreted to be the hydrocarbon-water contact. The lower sand exhibits a hydrocarbon-water contact at 9523 feet. The zone starting at 9514 feet does not reach 100% Sw through the interval evaluated by sidewall core analysis. The transition zone is longer through the lower interval than the upper interval because of water encroachment through production.

Helpful petrographic analyses can be performed on sidewall core provided enough sample exists. Petrographic work routinely performed on sidewall samples includes X-ray Diffraction, Scanning Electron Microscopy (SEM), thin section analysis and FTIR. Such data from sidewall cores are used to aid in log evaluation and in well completion and stimulation programs.

SUMMARY

Over the past decade new analytical procedures and techniques have made it possible to produce useful core analysis data from unconsolidated formations. The precise procedures and techniques used to retrieve, preserve, transport and analyze the core should be based on the formation characteristics and on the overall objectives of the coring project.

Improved formation evaluation can be achieved by calibrating wireline log data to measured conventional core data. Equations resulting from the calibration can be used for log evaluation in subsequent non-cored wells. Use of this more accurately calibrated data should produce more reliable reserve calculations.

Sidewall cores are used extensively along the Gulf Coast. Due to sample alteration of percussion-type sidewall cores, the petrophysical data generated are not always of sufficient quality to make reserve calculations. However, the data from sidewall cores can be integrated with wireline log data for improved formation evaluation. Sidewall samples and wireline logs compliment each other in that all needed evaluation parameters cannot be revealed by logs or by core alone. Sidewall cores can be used to determine permeability, porosity, grain size and sorting, mineralogy, and Sciw. When combined with log data they allow a more complete evaluation of the type of production and identification of effective water levels in the reservoir.

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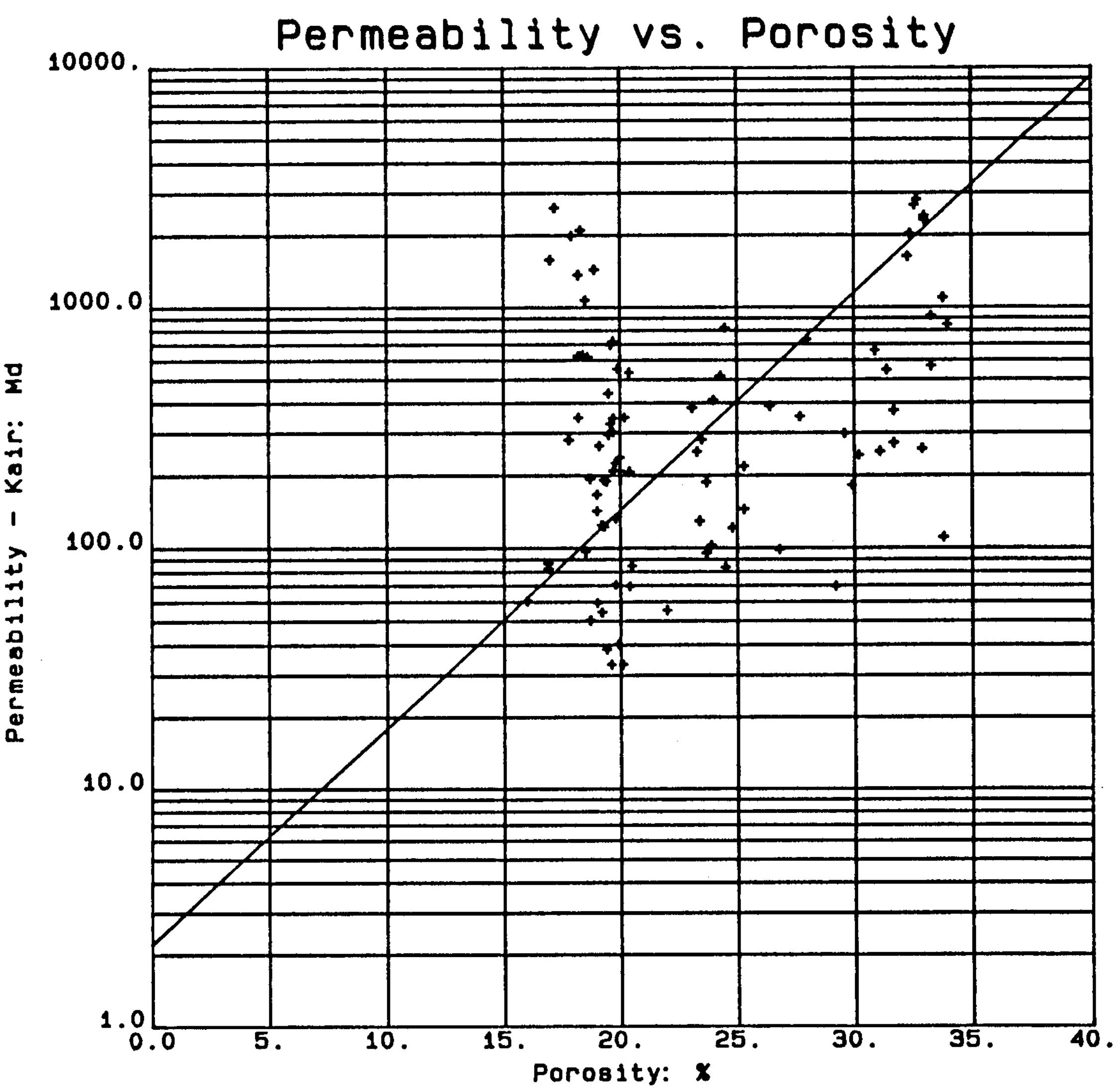

FIGURE 1: Permeability vs. Porosity Crossplot, Data Set with Numerous Fractured Samples.

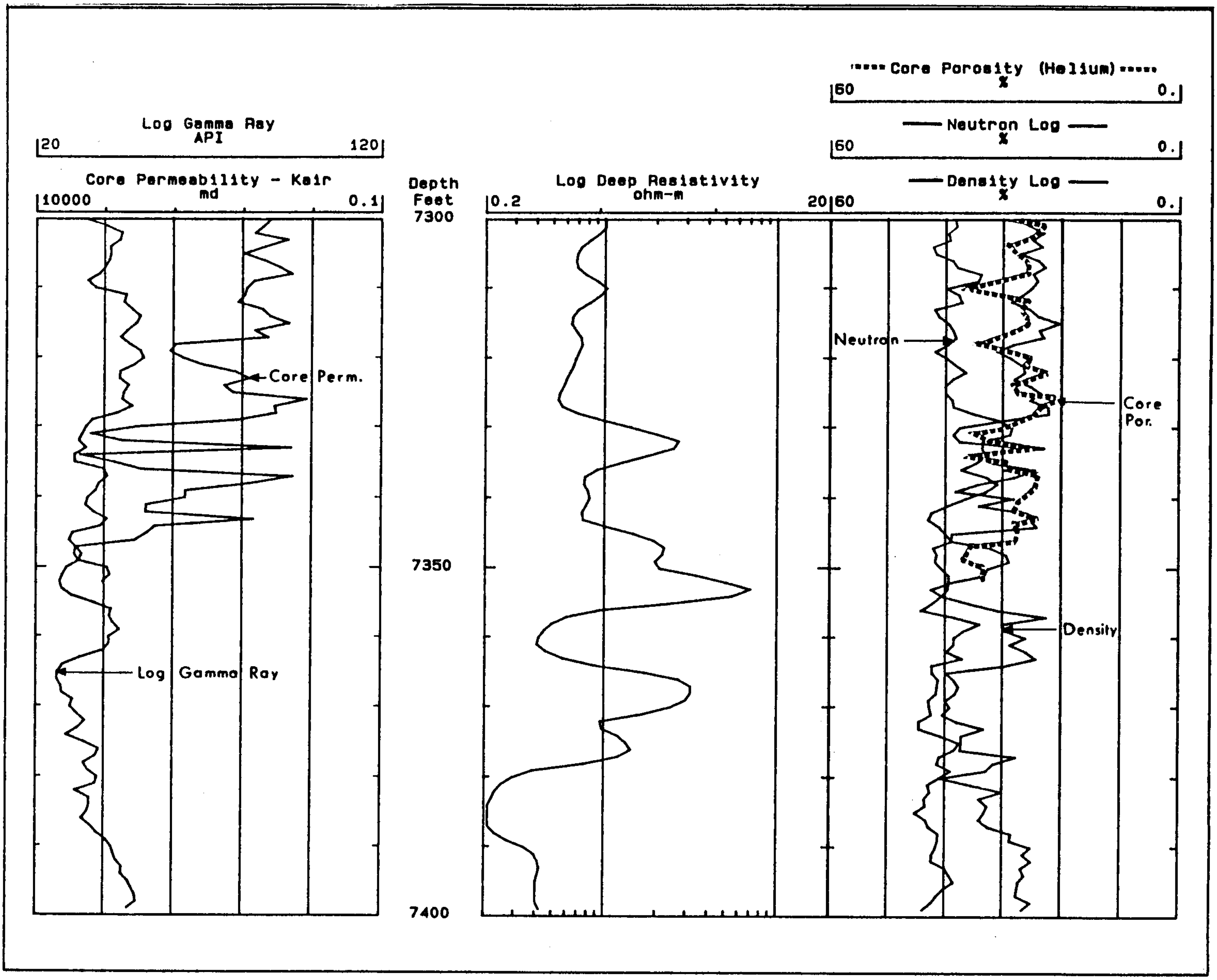

FIGURE 2: Electronically Digitized Log Curves and Core Analysis Data.

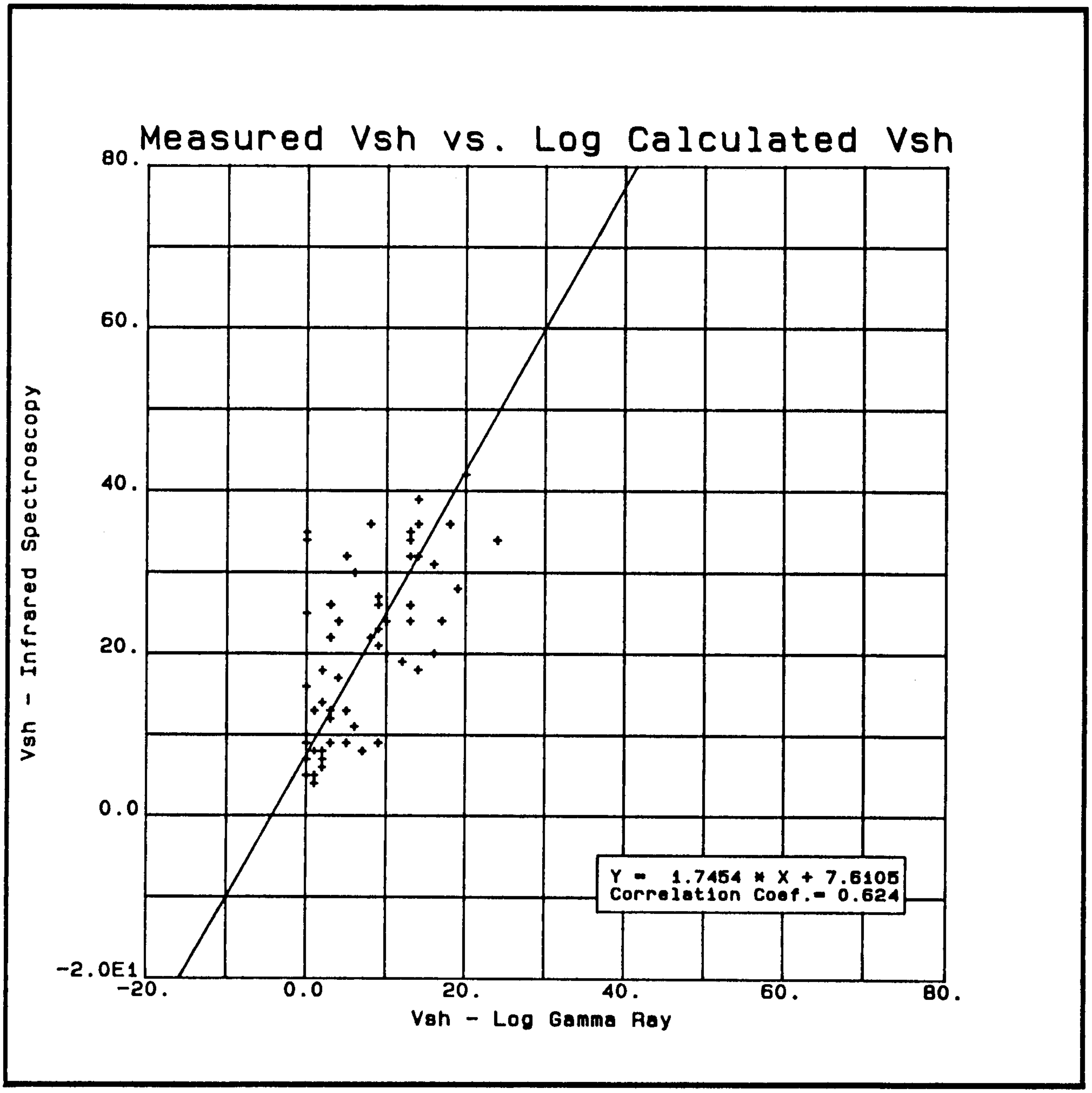

FIGURE 3: Calibration of Log-Calculated Vsh to Measured Total Clay Volume.

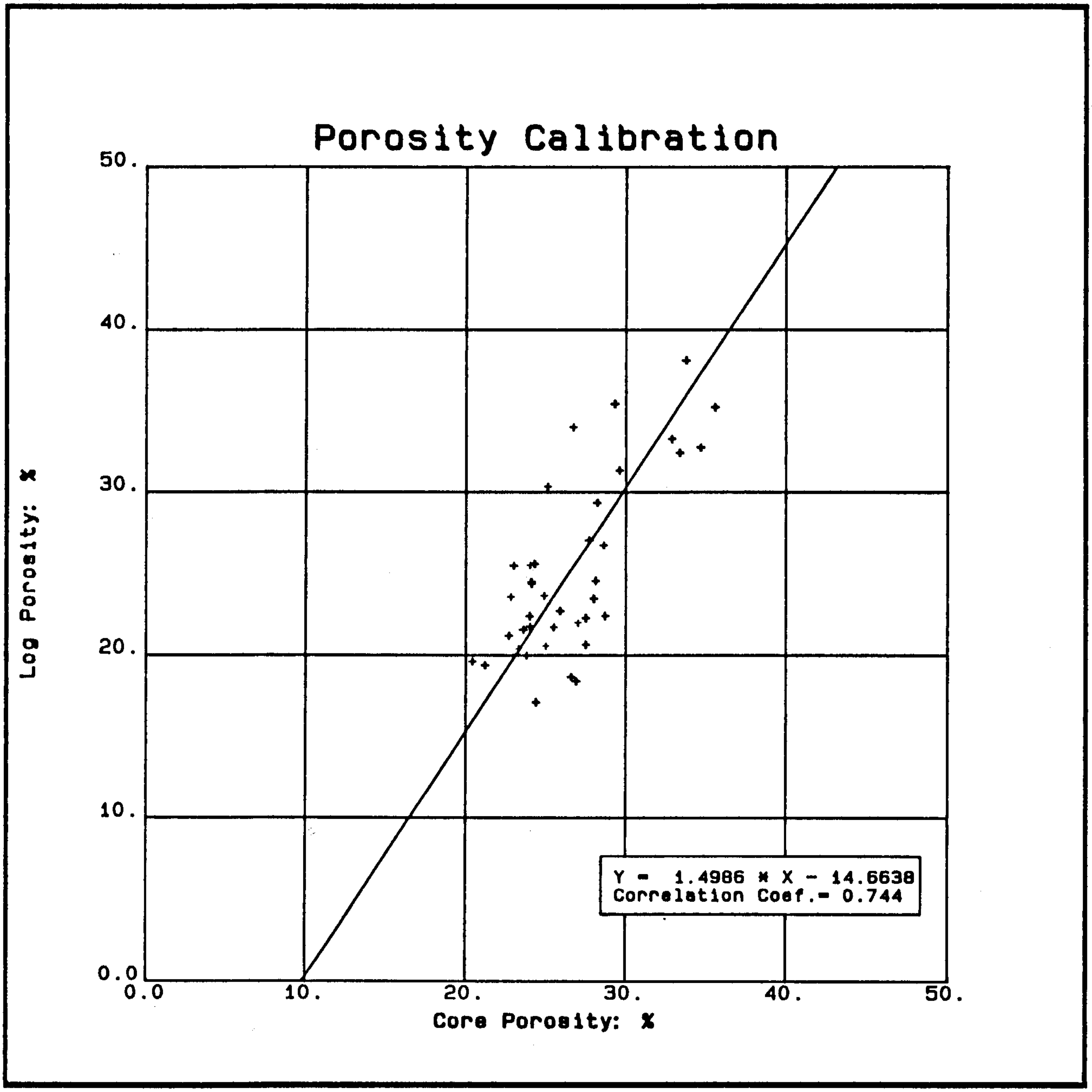

FIGURE 4: Calibration of Log-Calculated Porosity to Measured Core Porosity.

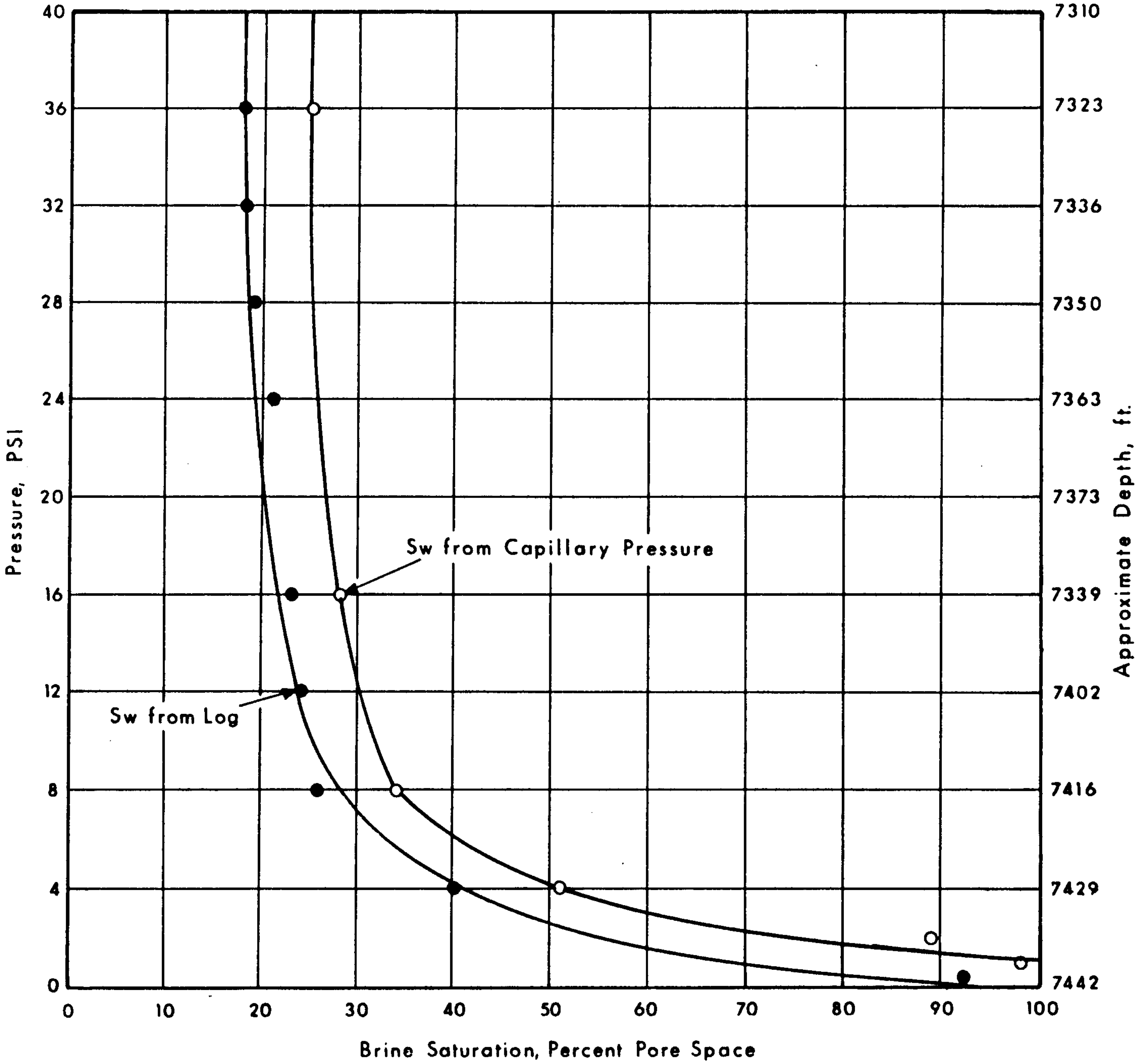

FIGURE 5: Comparison of Log-Calculated Sw to Average Water Saturation Measured by Capillary Pressure Tests.

- Resistivity Parameters -

$Ro = (a / \phi^m) \times Rw$

$Rmp = F \times Rw / Sciw^n$

Depth	Rw	a	m	n	Lithology
7298.00 - 7354.00	0.050	1.00	1.83	1.58	Sd

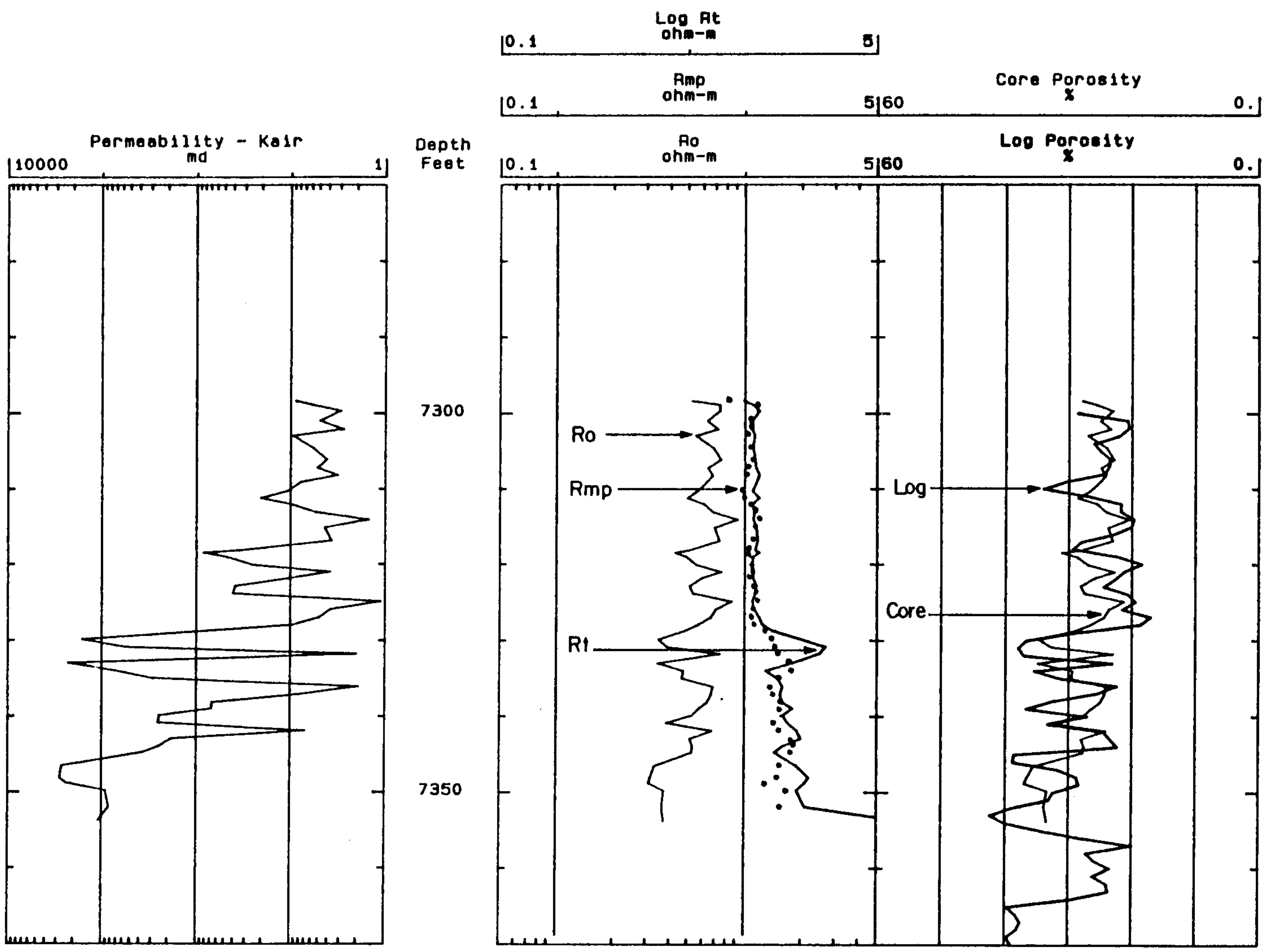

FIGURE 6: Depth Plot of Core Analysis Data, Calibrated Log Analysis Data, and Rmp-Rt Interpretation; No Water Level through Conventionally Cored Zone.

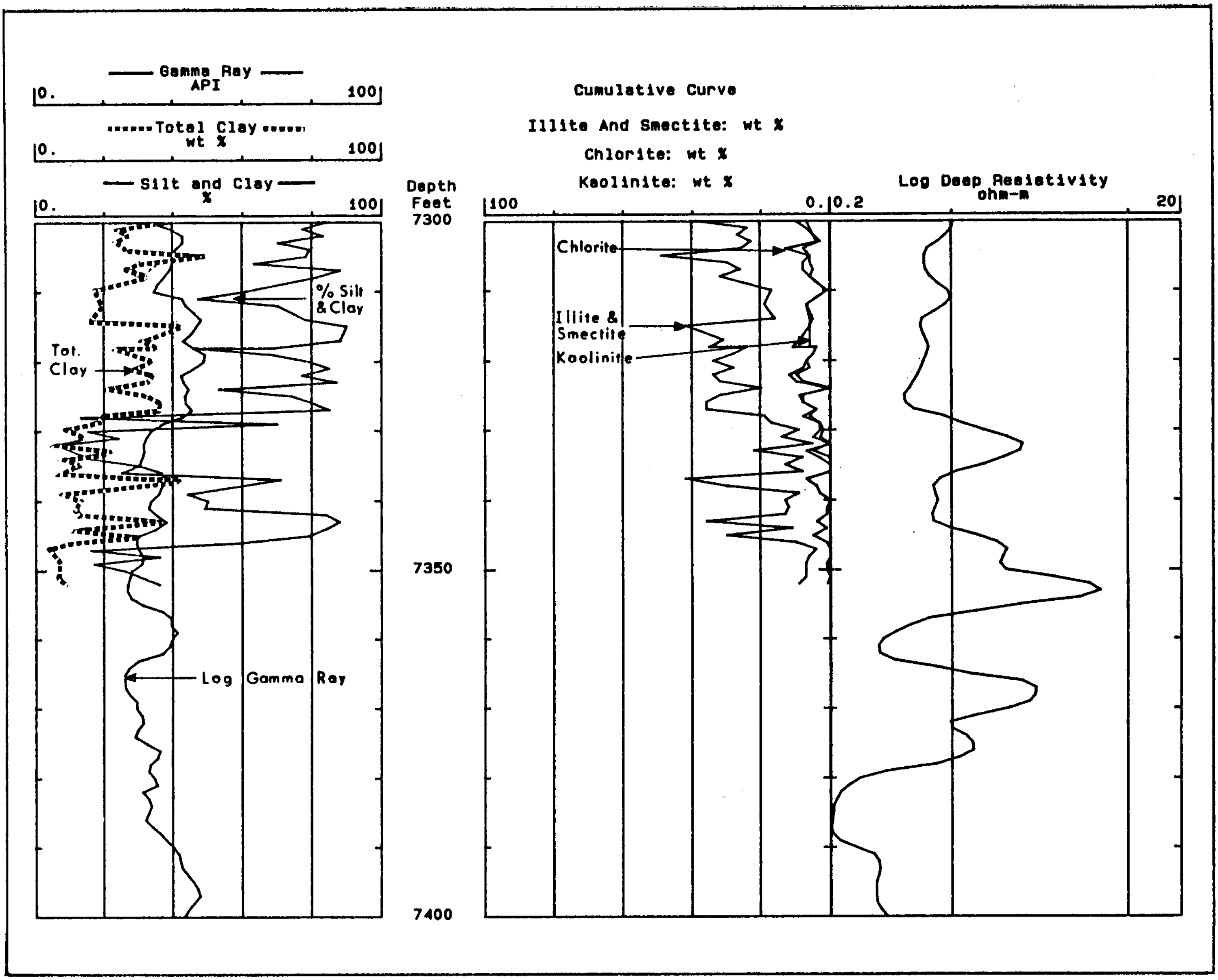

FIGURE 7: Depth Plot Showing Effects of Clay Volume and Clay Type on Rt

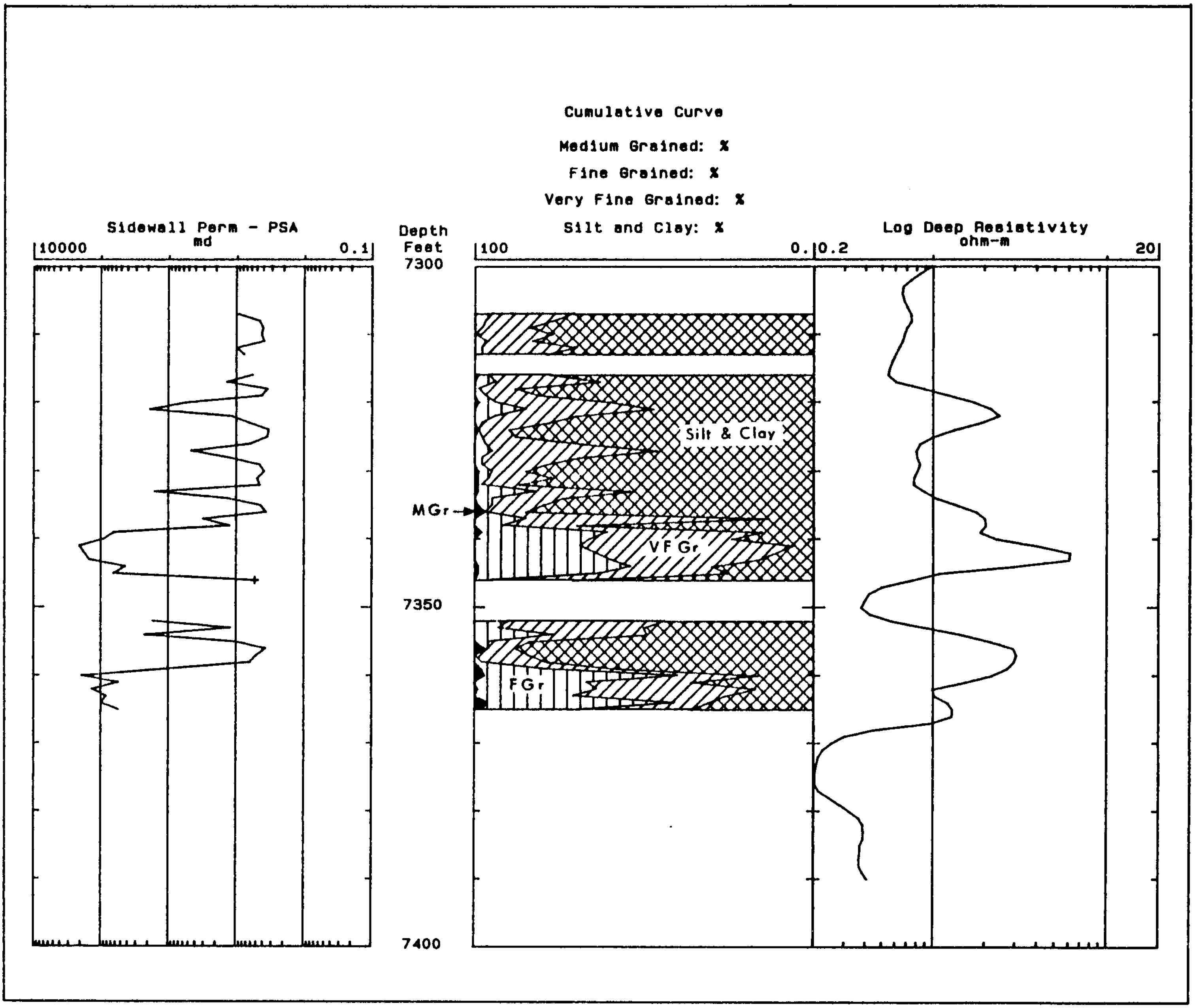

FIGURE 8: Depth Plot Showing Effects of Grain Size and Sorting on Rt.

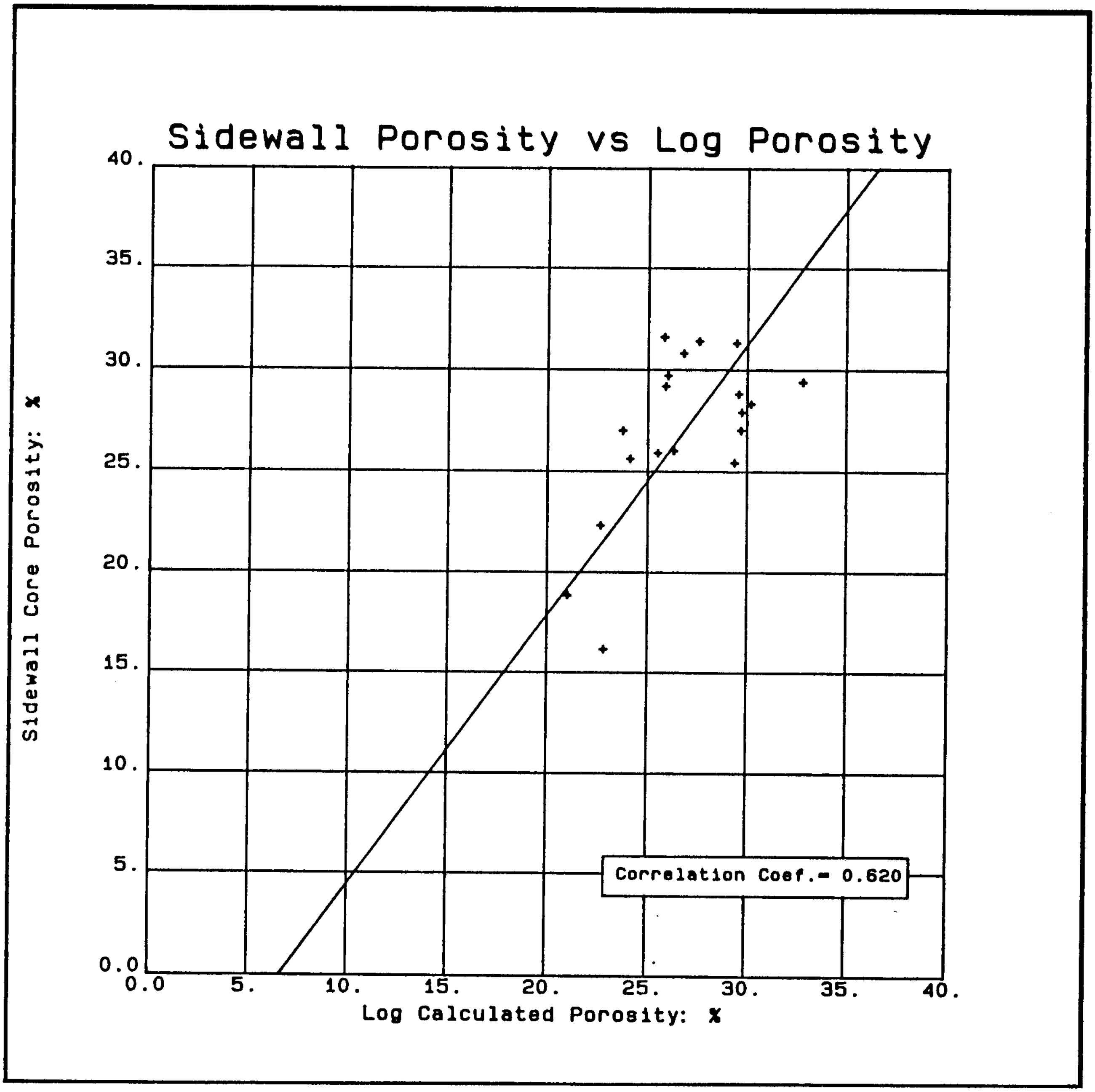

FIGURE 9: Crossplot Comparing Sidewall Core Porosity and Log-Calculated Porosity.

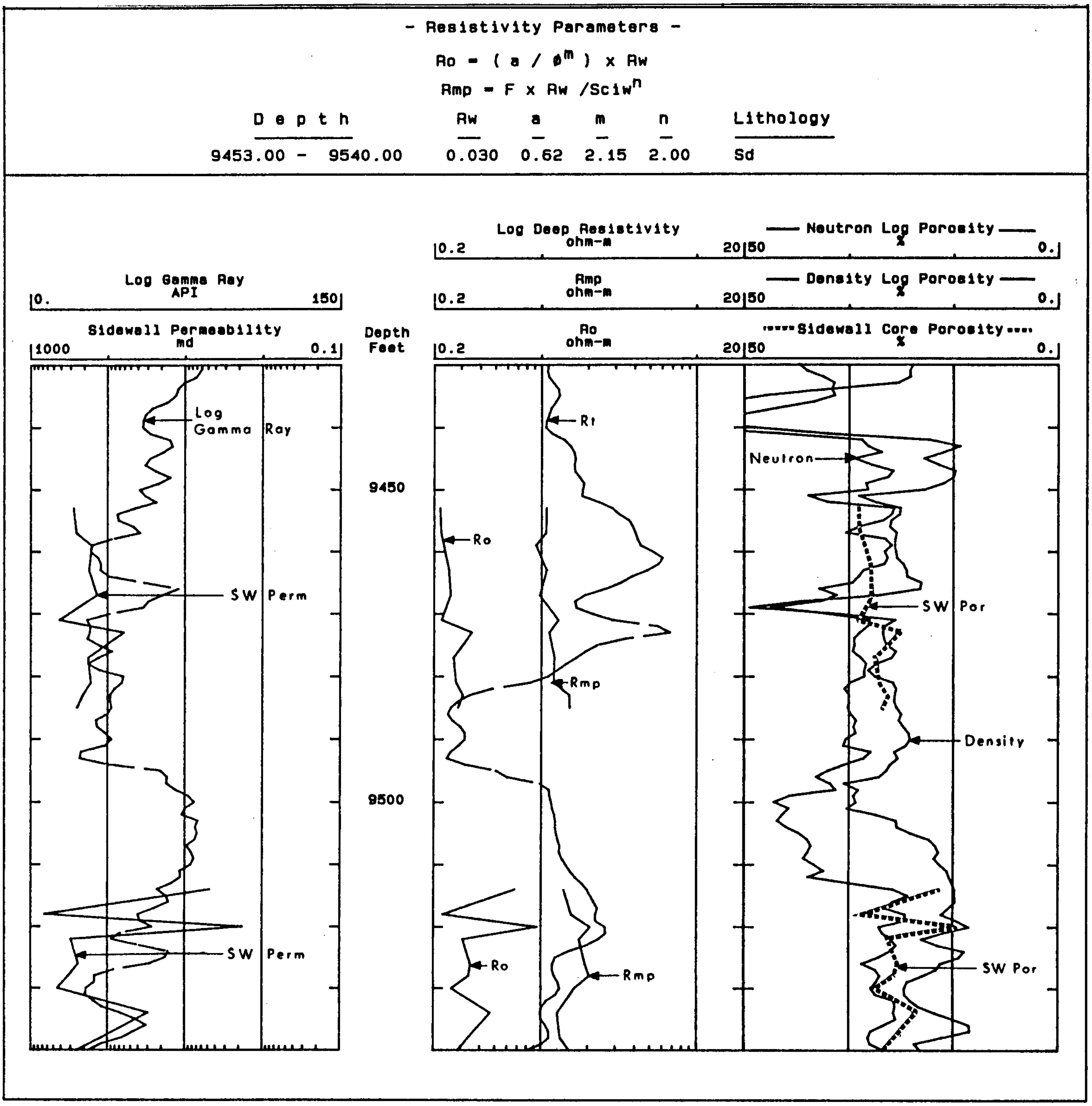

FIGURE 10: Depth Plot Comparing Log Data and Core Data with Rmp-Rt Interpretation.