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(54) Titre : METHODE DE MESURE DE LA POROSITE DE FRACTURES DANS LES COUCHES DE HOUILLE UTILISANT DES DIAGRAPHIES GEOPHYSIQUES

(54) Title: METHOD FOR MEASURING FRACTURE POROSITY IN COAL SEAMS USING GEOPHYSICAL LOGS

(57) Abrégé/Abstract:

A novel method for measuring fracture porosity in coal seams is disclosed. Knowledge of fracture porosity is critical to methane production from coal seams as fractures form the main permeable pathways for gas migration. The disclosed invention can be used to determine likely locations where commercially significant amounts of fracturing have occurred in the coals. These locations pose prime targets for methane exploration, and the disclosed invention comprises a significant new tool in methane exploration. The disclosed invention uses existing geophysical well log data, a screening process and calculations based on the characteristics of the fluid used to drill the hole. Using these data, the volume of invaded coal is determined, as well as the volume of drilling fluid available to create this invasion. The volume fraction of the invading drilling fluid divided by the volume of the invaded rock produces a measure of the fracture porosity of the coal. Locations that exhibit higher values of fracture porosity are more commercially attractive as methane exploration targets.

Abstract:

A novel method for measuring fracture porosity in coal seams is disclosed. Knowledge of fracture porosity is critical to methane production from coal seams as fractures form the main permeable pathways for gas migration. The disclosed invention can be used to determine likely locations where commercially significant amounts of fracturing have occurred in the coals. These locations pose prime targets for methane exploration, and the disclosed invention comprises a significant new tool in methane exploration. The disclosed invention uses existing geophysical well log data, a screening process and calculations based on the characteristics of the fluid used to drill the hole. Using these data, the volume of invaded coal is determined, as well as the volume of drilling fluid

available to create this invasion. The volume fraction of the invading drilling fluid divided by the volume of the invaded rock produces a measure of the fracture porosity of the coal. Locations that exhibit higher values of fracture porosity are more commercially attractive as methane exploration targets.

Title: Method for measuring fracture porosity in coal seams using geophysical logs

References Cited

U.S. Patents

5,663,499	9/97	Semmelbeck et al.
5,519,668	5/96	Montaron
4,961,343	7/90	Boone
4,716,973	1/88	Cobern

European Patent

EP0363259	11/90	Luthi

Other References

Puri, R, King, G.E., and Palmer, I.D. 1991, Damage to coal permeability during hydraulic fracturing, Proceedings of the 1991 Coalbed Methane Symposium. The University of Alabama, Tuscaloosa, May 13-16, 1991.

Background of the Invention

The subject matter of the present invention relates to a method for determining fracture porosity in coals using existing wellbore induction logging data produced by an induction tool disposed in the well bore. The disclosed invention uses conventional well log data in an unconventional manner to determine new and useful information regarding wellbore formation properties, specifically the amount of fracture porosity.

During the drilling of a wellbore, mud pumps introduce mud into the well in order to flush rock chips and other unwanted debris out of the wellbore. The mud is introduced into the wellbore under pressure, the mud pressure being slightly greater than the pressure of a formation traversed by the wellbore thereby preventing a phenomenon known as well blowout. The resultant differential pressure between the mud column pressure and the formation pressure forces mud filtrate into the permeable formation, and solid particles of the mud are deposited on the wellbore wall, forming a mudcake.

The mudcake usually has a very low permeability, and once developed, considerably reduces the rate of further mud filtrate invasion into the wellbore wall. In a region very close to the wellbore wall, most of the original formation may be flushed away by the mud filtrate. This region is known as the "flushed zone" or the "invaded zone". If the flushing is complete, the flushed zone pore space contains only mud filtrate.

Further out from the wellbore wall, the displacement of the formation fluids by the mud filtrate is less and less complete. This results in a second region, this region undergoing a transition from mud filtrate saturation to original formation water saturation. The second region is known as the "transition zone". The extent or depth of the flushed and transition zones depends on many parameters. Among them is the type and characteristics of the drilling mud, the formation porosity, the formation permeability, the pressure differential and the time since the well was first drilled. The undisturbed formation beyond the transition zone is known as the "uninvaded, virgin or uncontaminated zone".

FIGS. 1 and **2** show prior art representations of an invasion and resistivity profile in a water-bearing zone. **FIG. 1**, illustrates a cross section of a wellbore showing the locations of the flushed zone, the transition zone and the uninvaded zone extending radially from the wellbore wall. **FIG. 2** illustrates a radial distribution of formation resistivity extending radially from the wellbore wall, into the flushed zone, into the transition zone, and into the uninvaded zone. Sometimes, in oil and gas bearing formations, where the mobility of the hydrocarbons is greater than that of the water, because of relative permeability differences, the oil or gas moves away faster than the interstitial water. In this case, there may be formed, between the flushed zone and the uninvaded zone, an "annular zone or annulus", with a high formation water saturation. Annuli probably occur in most hydrocarbon bearing formations; and their influence on measurement depends on the radial location of the annulus and its severity.

The existence of these zones (the flushed, transition, annular and uninvaded zones) influence resistivity log measurements and therefore the accuracy of the resistivity log itself that is presented to a client. In it's conventional use the resistivity log is utilized by the client to determine if oil exists in the formation traversed by the wellbore. The client is mainly interested in the true and correct value of Rt, the resistivity (reciprocal of the conductivity) of the uninvaded zone, since high values of Rt indicate the presence of an insulator, possibly oil, in the formation. Conventionally, it is therefore desirable to correct for the effect of mud filtrate invasion on formation resistivity.

Conventionally, mud filtrate invasion analysis from resistivity logs is attempted by qualitative inspection of the separation between measurement displays representing different depths of investigation. The purpose of this analysis is to determine the radial geometric function of the logging tool response in order to correct for invasion and generate a more accurate value of Rt. However, in the disclosed invention, Rt is of no interest, but a new and novel use for the conventional depth of invasion measurements is disclosed.

Conventional log analysis techniques require correction for hydrocarbon saturation in the void spaces, and are complicated by depth based variation in the hydrocarbon saturation gradient through the flushed zone/undisturbed zone interface that may confuse invasion character. Variations in drilling mud properties between wells that change the radial resistivity profile, and differences in the properties of the formation water can cause errors in conventional interpretation. As well, laboratory measurements of fracture porosity in coal may not be applicable to the bulk reservoir properties due to sampling error, the inherent friability of coal, and the sensitivity of coal to changes in stress regime.

To correct these deficiencies in the prior art, the disclosed invention is volume based and requires no correction for hydrocarbon saturation or depth based variations. As all effectively connected fractures in coal are filled with water, hydrocarbon saturation variations are immaterial. Variations in mud properties are screened out or are of no impact to the disclosed invention, as the true value of Rt is irrelevant. As well, data used in the disclosed invention are collected from the formation *in situ*, with the coals under actual temperature and pressure conditions and are more representative of the bulk reservoir properties. Fracture porosity calculations in coal should be performed in the volume domain in accordance with the present invention. This volume domain mud filtrate invasion analysis minimizes the effect of all of these variables and is useful for comparing well to well and between zones within a well for determining measures of fracture porosity, and hence, methane production potential in the coal seams.

Fracture detection in coal seams is critical for the recovery of economic quantities of methane. Coal is a dual porosity medium, comprising a matrix containing abundant micro-scale pores intersected by larger macro-scale fractures. The micro-scale pores are of the size that gas movement occurs via diffusion, resulting in a very slow rate of gas exchange per unit volume. The larger macro-scale fractures act as the conduits for connecting the gas-diffusing matrix to a well bore. For economic quantities of methane to be recoverable, extensive well-developed macro-scale fractures must be present to connect a large enough volume of coal matrix such that the total volume of gas diffused becomes significant. Thus, the detection of subsurface fracture systems is critical for delineating desirable locations for methane exploration.

After an exploration well is drilled, specialized tools are lowered down the bore hole to test and record the responses of the different rock formations to various electrical, acoustic and radioactive stimuli. This process is termed geophysical logging, and the recorded data are termed geophysical logs. In one petroleum producing region of the world, the Western Canada Sedimentary Basin, approximately 280,000 wells have been drilled to date, and geophysical logs exist for virtually all of them. Geophysical logs have been used extensively in the past in conventional oil and gas exploration, but little data exist on their use in fracture detection in coal.

Some highly specialized geophysical logs are able to detect fractures in coal under very specific conditions, but the data are prone to error and the logging techniques have seen limited use. Advancement in the art delineated by the disclosed invention is that a large portion of previously unused data can now be processed for a new and useful result.

Various geophysical techniques exist to detect mud filtrate invasion and/or mudcake. One such device is an electrical pad containing regularly spaced electrodes. As the pad moves across the target formation, variations between the voltages are recorded, detecting the existence of mudcake on the borehole wall. This device relies on a solid contact with the bore hole wall and any variations in the size of the hole can disrupt its operation. This is significant as, over time, coals tend to cave-in resulting in rugose and irregular bore holes, thus limiting the utility of the pad contact type device.

Other types of electrical logging devices exist, but all have the goal of determining the rock properties away from the invasive and damaging effects of the well bore. In general, most of these devices are able to accurately detect the depth to which the drilling fluid has invaded. However, because of the complex geometry of the pore spaces in conventional clastic and carbonate reservoir rocks and variation in hydrocarbon saturation, invasion has not been previously considered a quantifiable indicator of porosity.

U.S. patent # 5,663,449 discloses a method for estimating permeability using geophysical well log data. This method interprets data from a multi-array induction device having at least five resistivity measures for a given formation and uses a variety of complex estimates, measurements and calculations. The measurements required include estimates of gas gravity, cementation factor, saturation exponent, shale volume and, and many others. The method requires a specialized logging apparatus to generate the required data and is unable to examine pre-existing data.

European patent EP0363259 discloses a method for interpreting data from a formation micro-scanner, a pad contact type of device, to detect and estimate width of fractures intersecting a borehole. It is limited in use and unable to examine pre-existing data.

U.S patent # 5,379,216 discloses a method and a highly specialized apparatus for measuring invading volumes of mud filtrate to determine relative measurements of permeability. However, this patent is limited to analysis of data generated by its own disclosed apparatus, and is unable to analyze pre-existing data for indications of fracture porosity.

U.S. patent 4,961,343 discloses a method for determining permeability of a subsurface earth formation in real time during drilling operations through monitoring volumes of drill fluid lost into the formation and volumes of gas liberated. Geophysical log responses are not used. As well, this patent is limited in utility as no means of examining pre-existing data is disclosed.

Summary of the invention

This invention relates methods of detecting fracturing in rock using geophysical logs, and in particular to the use of electrical type logging devices. The disclosed invention seeks to remedy these deficiencies in the prior art of fracture detection in coal through a method that incorporates previously unused data into a new and useful result. Coals are uniquely suited to this method, as the fractures tend to occur in a regularly spaced orthogonal geometry. This type and pattern of fracturing simplifies the determination of invading and invaded volumes.

As well, coals comprise a special case where only fractures that are effectively connected to the borehole are available to invasion of drilling fluids. Fracture porosity is then directly related to the volume of coal effectively connected for gas diffusion, and therefore, is a major indicator of economic methane production. The disclosed invention represents a significant advancement in the art as previously by-passed reservoirs of methane can now be found.

The disclosed invention screens existing geophysical well logs to ensure reliable data by discarding wells where the resistivity of the drilling mud (Rm) is less than 1.0. Experience has shown that below this value, induction logs are affected by the conductivity of the drilling mud and unreliable values of depth of invasion are produced. A second screening procedure involves the examination of the borehole caliper log. This log measures the size of the borehole. Measurements of the borehole diameter that exceed 200% of the bit size are considered unreliable and screened out. Measurements of the thickness of the coal seam of interest, the bit size and the depth of invasion of drilling fluids define an invaded volume of coal.

From records of the characteristics of the drilling fluid, a measure of the amount of fluid available to create this invasion can be made. The volume of fluid available for invasion is then divided by the volume of the invaded rock. The resulting volume fraction equals the effective void space occupied by the invading fluid.

In coal, this volume fraction of effective void space is fracture porosity, as only fractures are able to accept invading fluids; the matrix is impermeable. The disclosed invention outlines a new, useful and unconventional method for interpreting previously unused data and delineating methane exploration targets.

Brief Description of the Drawings

FIGS. 1 and **2** show prior art representations of an invasion and resistivity profile in a water-bearing zone. **FIG. 1**, illustrates a cross section of a wellbore showing the locations of the flushed zone, the transition zone and the uninvaded zone extending radially from the wellbore wall. **FIG. 2** illustrates a radial distribution of formation resistivity extending radially from the wellbore wall, into the flushed zone, into the transition zone, and into the uninvaded zone. **FIG. 3** illustrates a schematic of a typical well log header, showing various data collected from drilling and logging operations. **FIG. 4** illustrates the bore hole caliper and induction geophysical logs for a coal interval. **FIG. 5** illustrates an industry-standard interpretation chart provided by a well log service company, in this case Schlumberger Corporation. This chart can be used to determine depth of mud filtrate invasion.

Description of the Preferred Embodiment

FIG. 3 shows a schematic of typical log header of an induction type geophysical log records data used in this method. The following data collected from such a log header are tabulated in **Table 1**:

Resistivity of the mud (R_m)	3.0 ohmm at 15° Celsius
Fluid Loss (Water Loss W.L)	7.0 cm^3
Bore Hole size (Bit Size)	200 mm

Table 1 – Data collected from a well log header

A first data screening procedure is done. The resistivity of the mud is greater than 1.0 ohmm at 15° Celsius. The bore hole caliper size is less than 200% of the bit size. The data are thus far deemed acceptable for use.

FIG. 4 illustrates the caliper log and induction geophysical log for a coal interval. The coal is present from 453.0 m to 457.6 meters. The single solid line in the left track is the borehole caliper. The resistivity measurements are recorded on the right hand track.

In the right track, the solid line represents the shallow-reading resistivity device, the dotted line represents the medium-reading resistivity device and the long dashed line represents the deep-reading resistivity device. The resistivity is recorded in ohm-meters on a logarithmic scale. From this log, the following data are recorded in **Table 2:**

Bore Hole Caliper Size	220 mm
Coal Seam Thickness	4.6 meters
Deep Resistivity (RID)	100 ohmm
Medium Resistivity (RIM)	113 ohmm
Shallow Resistivity (RSH)	550 ohmm

Table 2- Data collected from the caliper log and induction log

A second data screening procedure is done at this time. The bit size from **Table 1** is compared to the bore hole caliper size from **Table 2** and the bore hole caliper size is less than 200% of the bit size. The data are deemed acceptable for use.

From the data in **Table 2** above, the following ratios are calculated and recorded in **Table 3:**

RIM/RID (110/100)	1.13
RSH/RID (550/100)	5.5

Table 3 –Ratios of resistivity curves

With these ratios, it is possible to determine the depth of mud filtrate invasion using industry-standard interpretation charts provided by well-log service companies. **FIG. 5** illustrates one such chart, as published by Schlumberger Corporation. By plotting the ratios from **Table 3** onto the chart in **FIG. 5**, a depth of invasion of mud filtrate (*di*) of 0.75 meters is determined.

With knowledge of the depth of invasion, the bit size (*bts*) and the thickness (*th*) of the coal seam, the volume of invaded coal can be determined. This calculation is made by determining the volume of a cylinder defined by the diameter of the bit plus the depth of invasion and the thickness of the coal seam. As coal seams tend to cave over time, the bit size is most indicative of borehole size in the critical few hours after bit penetration. Once this volume is determined, the volume of the borehole is subtracted to yield a volume of invaded coal (*VIC*). The calculation is outlined in **Formula 1**.

$$VIC = (((di + bts/2)^2 \times \Pi \times th) - (bts/2)^2 \times \Pi \times th \qquad \textbf{(Formula 1)}$$

Substituting the values $di = 0.75$, $bts = 0.2$ m and $th = 4.6$ m, it is determined that $VIC = 10.3$ m^3.

The next step is to determine the amount of fluid available to create this invaded volume of coal. From **Table 1**, fluid loss (or water loss, W.L.) is listed at 7.0 cm^3. This volume is determined from a standard American Petroleum Institute (API) test which uses a filter of 45.8 cm^2. This volume of fluid is lost through this filter in 30 minutes under a pressure of 689.5 Kpa (100 psi). A 689.5 Kpa differential serves as a reasonably good proxy to relative pressures between the invaded coal seam and the invading column of drilling fluid.

Dividing the fluid loss value by the area of the filter results in a volume per cm^2 yields a Standardized Fluid Loss (SFL). This is outlined in **Formula 2**:

$$SFL = \text{Fluid loss/ API filter Area} \qquad \textbf{(Formula 2)}$$

By substituting 7.0 for Fluid loss and 45.8 cm^2 for filter area, the Standardized Fluid Loss can be determined to be 0.15284 cm^3/cm^2 in a 30 minute period.

The next step involves determination of the amount of time available for invasion to occur. This value is controlled by the sensitivity of the coal seam to formation damage. Research (Puri, et al. 1991) has shown that formation damage to coals can occur in about 24 hours (1440 minutes), after which permeability is effectively destroyed. **Formula 3** is an American Petroleum Institute standard formula for calculating total volume of fluid passing through a mudcake in a given time and illustrates this calculation.

$$Qt = WL\ x\ \ (t/30)^{1/2} \qquad \textbf{(Formula 3)}$$

Substituting t = 1440 minutes (24 hours), it is calculated that the volume of invading fluid available is 48.5 cm^3 in 24 hours. To correct for the API filter size, 48.5 cm^3 is substituted into **Formula 2,** thus yielding a time corrected Standardized Fluid Loss (SFL_{TC}) of 1.06 cm^3/cm^2. With SFL_{TC} determined, it is now possible to calculate the total volume of invaded filtrate by taking into account the bit size and the thickness of the coal seam.

From the bit size and the coal seam thickness, the surface area of the borehole (*SAbh)* can be calculated. This calculation is outlined in **Formula 4**.

$$SAbh = bts \times \Pi \times th \qquad \textbf{(Formula 4)}$$

By substituting *bts* =0.2 m (from **Table 1**) and *th*= 4.6 m (from **Table 2**), *SAbh* can be calculated as 2.89 m^2 or 28,900 cm^2. With *SAbh* and SFL_{TC} determined, the volume of invading fluid (*VIF*) can be calculated. **Formula 5** illustrates the calculation:

$$VIF = SAbh \times SFL_{TC} \qquad \textbf{\textit{(Formula 5)}}$$

Substituting $SAbh$ = 28,900 cm^2 and SFL_{CT} = 1.06 cm^3/cm^2 yields a value of *VIF* = 30,634 cm^3 or 0.0306 m^3 .

With *VIC* and *VIF* now known, the volume fraction of void space (porosity) occupied by the invading fluid in the invaded coal can be calculated. As only fractures are available for invasion in coal, the resulting value is fracture porosity (Φ_{FRAC}).

Formula 6 outlines the calculation of Φ_{FRAC}.

$$\Phi_{FRAC} = VIF/VIC \qquad \textbf{(Formula 6)}$$

By substituting $VIF = 0.0306\ \text{m}^3$ and $VIC = 10.3\ \text{m}^3$, Φ_{FRAC} can be determined to be 0.297%.

Claims

I claim:

1. A method for identifying fractures in coal seams using measurements of medium and deep resistivities taken from induction type geophysical logs, said method comprising:

a). a first screening means whereby said geophysical logs exhibiting resistivity of drilling fluid greater than 1.0 ohm-meter at 15 degrees Celsius contain a measurement of medium resistivity acceptable for use and a measurement of deep resistivity acceptable for use;

b). a first calculation means in which said measurement of medium resistivity acceptable for use is divided by said measurement of deep resistivity acceptable for use yielding a first ratio whereby a first ratio of less than two indicates commercially significant fracturing in the coal.

2. A method for identifying fractures in coal seams using measurements of medium and deep resistivities taken from induction type geophysical logs, said method comprising:

a). a first screening means whereby said geophysical logs exhibiting resistivity of drilling mud greater than 1.0 ohm-meter at 15 degrees

Celsius contain a measurement of medium resistivity acceptable for use and a measurement of deep resistivity acceptable for use;

b). a second screening means whereby said geophysical logs exhibiting a borehole caliper size through the target zone of less than 200% of bit size are acceptable for use;

c). a first calculation means in which said measurement of medium resistivity acceptable for use is divided by said measurement of deep resistivity acceptable for use yielding a first ratio whereby a first ratio of less than two indicates commercially significant fracturing in the coal.

3. A method for identifying fractures in coal seams using measurements of drilling fluid resistivity, drilling fluid loss, surface area of the filter used to measure drilling fluid loss, well bore hole diameter, drill bit size, thickness of the coal seam, measurements of shallow, medium and deep resistivities of the coal seams taken from geophysical logs, said method comprising:

a). a first screening means whereby said geophysical logs exhibiting resistivity of drilling mud greater than 1.0 ohm-meter at 15 degrees Celsius contain a measurement of shallow resistivity acceptable for use, a measurement of medium resistivity acceptable for use and a measurement of deep resistivity acceptable for use;

b). a second screening means whereby said geophysical logs exhibiting a borehole caliper size through the target zone of less than 200% of bit size are acceptable for use;

c). a first calculation means whereby said measurement of medium resistivity acceptable for use is divided by said measurement of the deep resistivity acceptable for use yielding a first ratio;

d). a second calculation means whereby said measurement of shallow resistivity acceptable for use is divided by said measurement of the deep resistivity acceptable for use yielding a second ratio;

e) a third calculation means whereby the first ratio and second ratio can be used to calculate a depth of invasion for said drilling fluid, said third calculation means comprising geophysical interpretation chart books published by geophysical well logging service companies;

f). a fourth calculation means whereby said depth of invasion defines a cylindrical volume of invaded coal, said calculation comprising the radius of said bit size plus said depth of invasion, squared, times Π, times the thickness of said coal seam, yielding a fluid affected volume;

g) a fifth calculation means comprising the radius of said bit size, squared, times Π, times the thickness of said coal seam minus, yielding a borehole fluid volume, said borehole fluid volume subtracted from said fluid affected volume yielding a volume of invaded coal;

h). a sixth calculation means whereby said drilling fluid loss defines a gross volume of invading fluid, said sixth calculation means comprising the drilling fluid loss times the square root of the time available for fluid loss divided by 30 minutes;

i). a seventh calculation means whereby said gross volume of invading fluid is divided by said surface area of the filter used to measure said drilling fluid loss, times said well bit size diameter, times Π, times said coal seam thickness, resulting in a corrected volume of invading fluid;

j). an eighth calculation means whereby said corrected volume of invading fluid is divided by said volume of invaded coal to yield a volume fraction, said volume fraction being equal to the fracture porosity of said coal seam.

Figure 1 - Prior Art

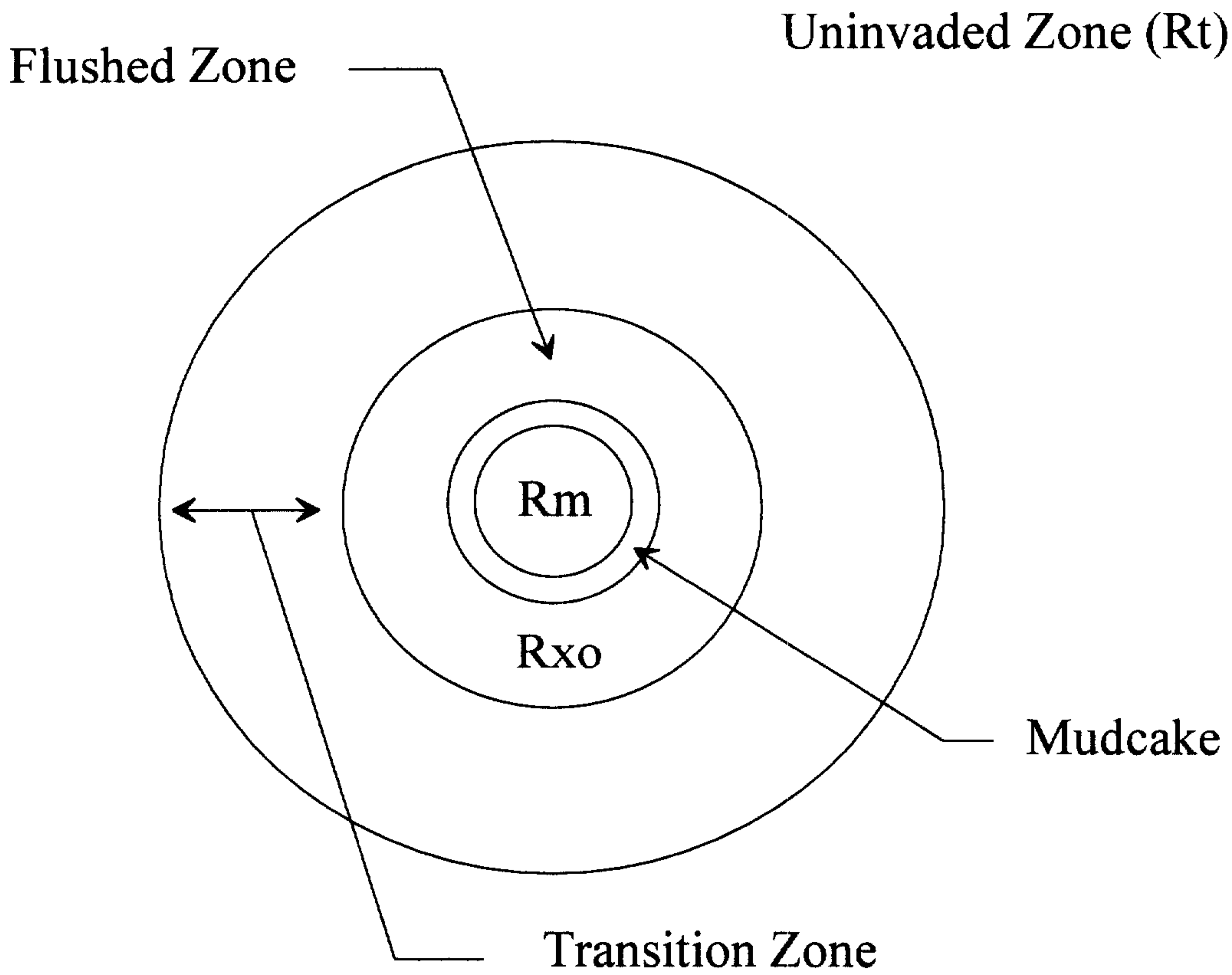


Figure 2 - Prior Art

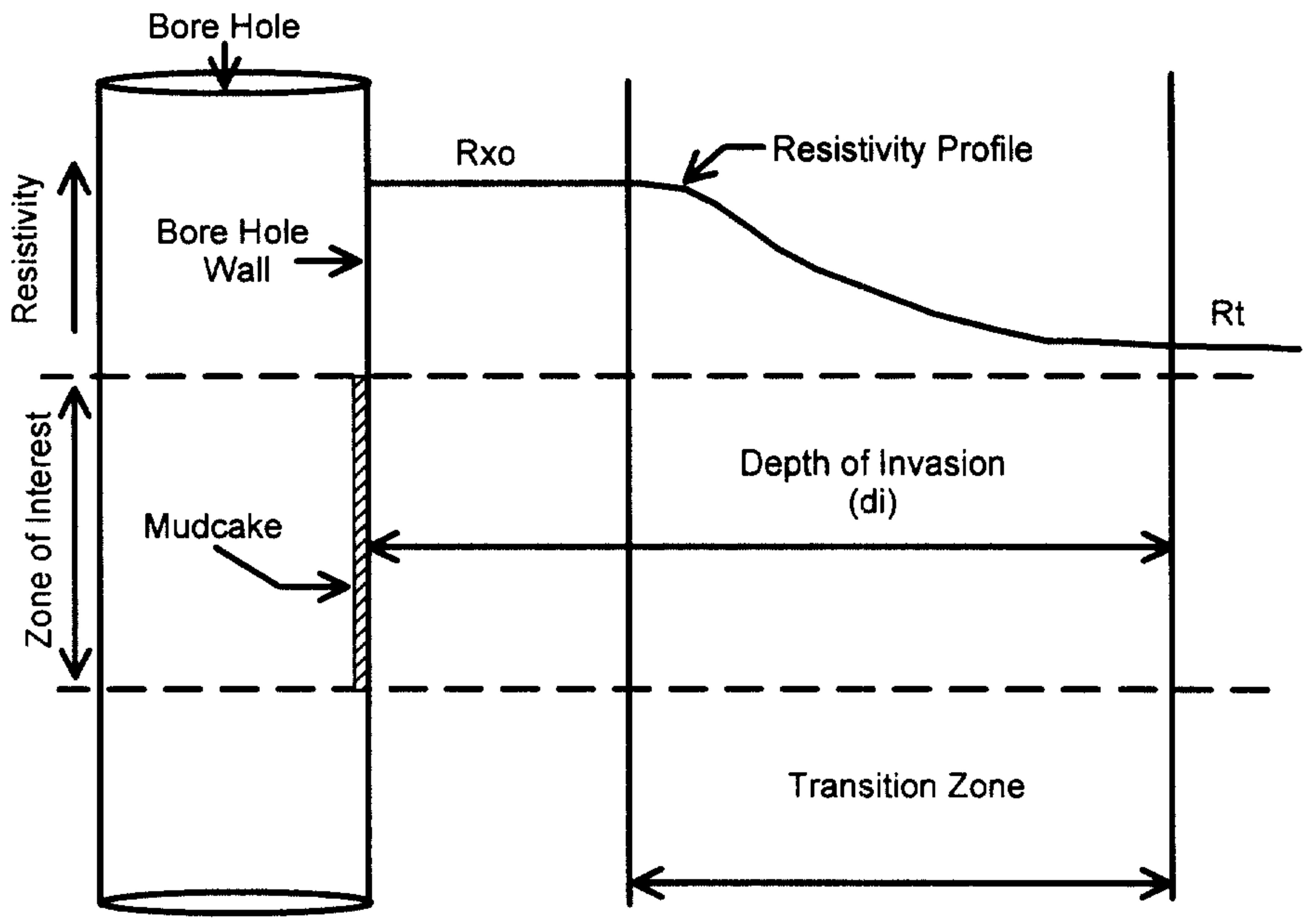


Figure 3

Elizabeth Well Log Services	Bore Hole Caliper and Induction Log

Company: Barich Petroleum Inc.

Well: Barich Spencer Lake 01-02-03W4M

Location: 01-02-03W4M Field: Spencer Lake Province: Alberta

Date: January 23, 1999	Depth – Driller 1522.0 m
Type of Fluid in Hole: Gel Chem	Fluid Loss: 7.0 cm^3
Bit size: 200 mm	
Rm at Measured Temperature: 3.0 ohmm @ 15 degrees Celsius	

Figure 4

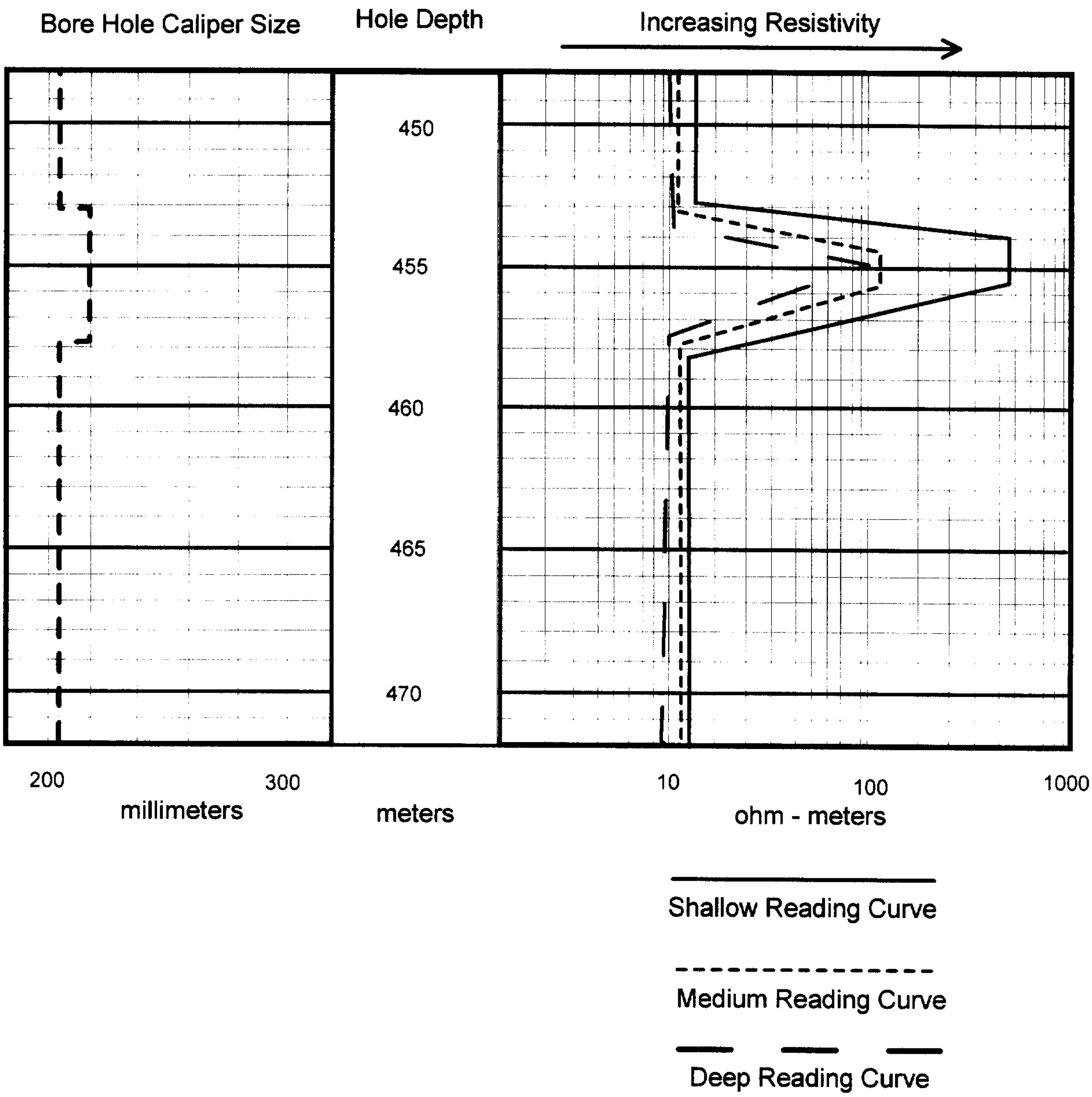
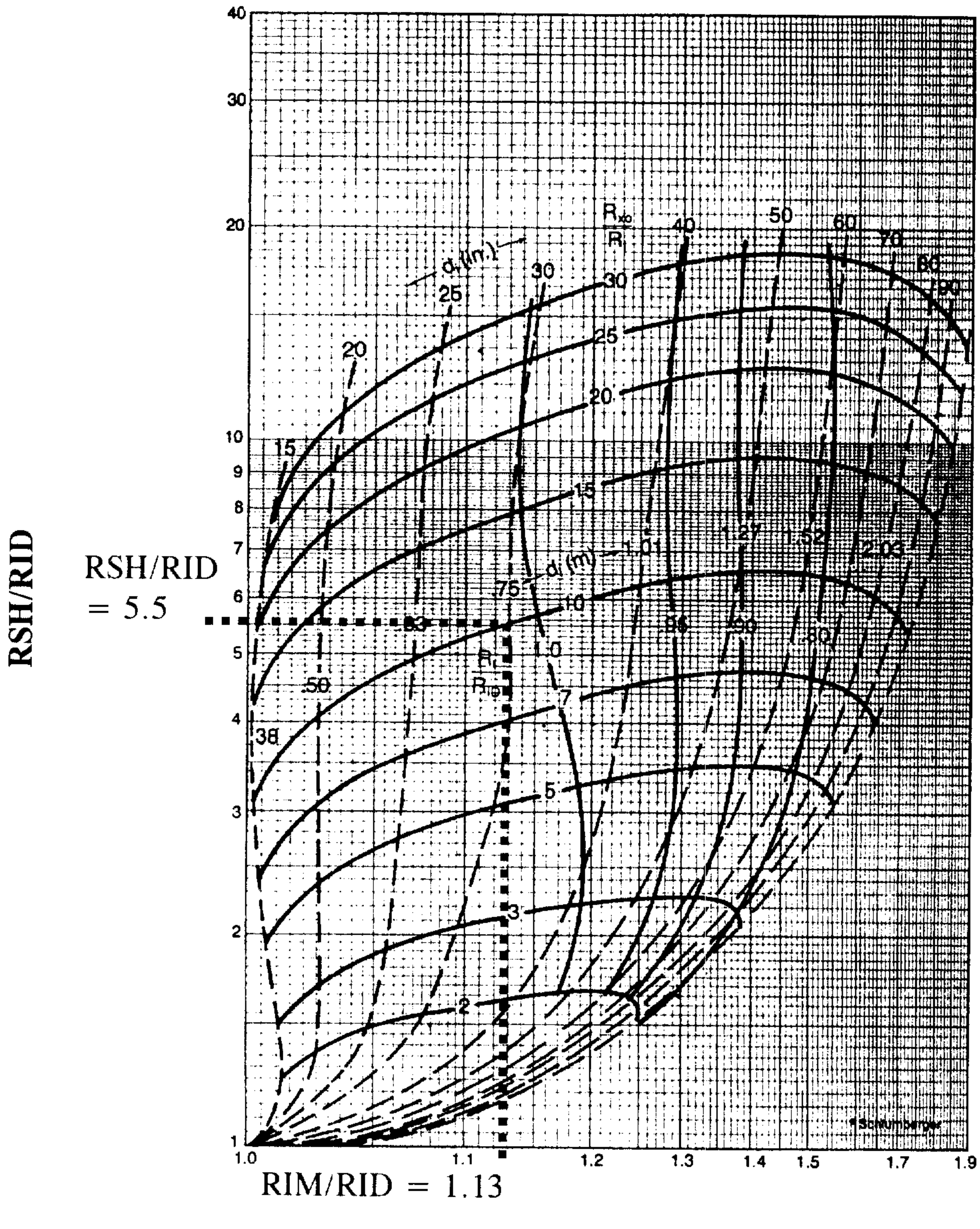

Bore Hole Caliper Size
Hole Depth
Increasing Resistivity
450
455
460
465
470
200
300
millimeters
meters
10
100
1000
ohm - meters
Shallow Reading Curve
Medium Reading Curve
Deep Reading Curve

Figure 5


RSH/RID
RSH/RID = 5.5
RIM/RID = 1.13
RIM/RID
1.0
1.1
1.2
1.3
1.4
1.5
1.7
1.9
40
30
20
10
9
8
7
6
5
4
3
2
1