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Señor Jefe

DIVISION DE NUEVAS CREACIONES

SUPERINTENDENCIA DE INDUSTRIA Y COMERCIO

Santa Fe de Bogotá, D.C.

Re.: Expediente No. 000-67.783

Solicitud Patente

SCHLUMBERGER HOLDINGS LIMITED

Debidamente traducida, adjunto acompaño la copia oficial de la solicitud de patente básica Estadounidense No. 08/393.559, la cual le solicito agregar a este expediente para los efectos legales respectivos.

De Usted atentamente,

GERMAN CASTILLO GRAU

T.P.#2.978 del C.S.J.

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ESTADOS UNIDOS DE AMERICA

A TODOS A QUIENES LLEGUE EL PRESENTE:

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Oficina de Marcas y Patentes

02 de junio de 2000.

LA PRESENTE CERTIFICA QUE LA ADJUNTA ES UNA COPIA TOMADA DE LOS REGISTROS DE LA OFICINA DE MARCAS Y PATENTES DE LOS ESTADOS UNIDOS, DE LOS DOCUMENTOS DE LA SOLICITUD DE PATENTE ABAJO IDENTIFICADA Y LA CUAL CUMPLE CON LOS REQUISITOS PARA QUE LE SEA CONFERIDA UNA FECHA DE RADICACIÓN SEGÚN 35 USC 111.

NÚMERO DE SOLICITUD 09/393,559

FECHA DE RADICACIÓN: 10 de septiembre de 1999

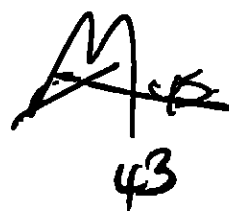
Por Autoridad del

COMISIONADO DE MARCAS Y PATENTES

(FIRMA) W. MONTGOMERY

Oficial de Certificaciones

(SELLO DORADO DE OBLEA)


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No. 00044664-1

Estados Unidos de América
DEPARTAMENTO DE ESTADO

A todos a Quienes Llegue el Presente, Os Saludo:

Certifico que el documento adjunto se encuentra bajo el sello de la Oficina de Marcas y Patentes del Departamento de Comercio de los Estados Unidos de América y que a dicho sello debe dársele plena fe y crédito.

En Testimonio de lo cual, Yo, Madeleine K. Albright, Secretaria de Estado, he ordenado al Oficial de Autenticaciones suscribir mi nombre y colocar el sello del Departamento de Estado en la Ciudad de Washington, Distrito de Columbia, hoy 23 de agosto de 2000.

Madeleine K. Albright - Seecretaria de Estado
Jacqueline Pridgen - Asistente del Oficial de
Autenticaciones. Departamento de Estado

EN ESPAÑOL: La legalización de la firma y cargo anterior por parte del Consulado de Colombia en Washington, D.C. de fecha 23 de agosto de 2000, bajo el No. 2168.

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MÉTODO Y APARATO PARA LA MEDICIÓN DEL TAMAÑO DE UN POZO DE SONDEO Y LA RESISTIVIDAD DE LAS FORMACIONES DE TIERRA QUE LE RODEAN

REIVINDICACIONES:

1. Un método para determinar el calibre de un pozo de sondeo en una formación de tierra utilizando una herramienta de pozos colocada en el pozo; el método consiste en:

- a) modelar respuestas de la herramienta a diferentes parámetros del pozo y de la formación;
- b) determinar un parámetro conocido de fluidos del pozo;
- c) transmitir energía electromagnética dentro del pozo de una estación en la herramienta;
- d) recibir energía electromagnética en múltiples estaciones sensoras arbitrarias en la herramienta;
- e) generar datos de las señales de la herramienta, asociados con la energía recibida; y
- f) cotejar dichos datos de las señales y el parámetro conocido del fluido del pozo contra las respuestas modeladas con el fin de determinar el calibre del pozo.

2. El método de la reivindicación 1, en donde el método es realizado durante o después de la perforación del pozo de sondeo.

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3. El método de la reivindicación 1, en donde el parámetro conocido del fluido del pozo comprende un valor de resistividad de lodo.
4. El método de la reivindicación 1, en donde los datos de las señales generados comprenden valores de resistividad eléctrica.
5. El método de la reivindicación 1, que además consiste en registrar el calibre del pozo determinado en un medio de registro de salida.
6. El método de la reivindicación 1, en donde el paso (f) consiste en realizar una técnica de minimización de cuadrados mínimos para cotejar los datos de las señales generados y el parámetro de fluidos conocido contra las respuestas modeladas:
7. El método de la reivindicación 1, en donde el paso (a) consiste en establecer una tabla de respuestas de modelo teórico de la herramienta del pozo a diferentes diámetros del pozo, resistividades de lodo del pozo y resistividades de la formación.
8. El método de la reivindicación 1, en donde el paso (e) consiste en enviar los datos de las señales de la herramienta a una superficie de la formación.
9. El método de la reivindicación 1, en donde el paso (e) consiste en registrar los datos de las señales en un medio de almacenamiento alojado en la herramienta.
10. Un método para determinar la resistividad de una formación de tierra la cual es atravesada por un pozo de sondeo, utilizando una herramienta de pozos colocada en el pozo; el método consiste en:
 - a) modelar respuestas de la herramienta a diferentes parámetros del pozo y de la formación;
 - b) determinar un parámetro conocido de fluidos del pozo;

- c) **transmitir energía electromagnética dentro del pozo de una estación en la herramienta;**
- d) **recibir energía electromagnética en múltiples estaciones sensoras arbitrarias en la herramienta;**
- e) **generar datos de las señales de la herramienta, asociados con la energía recibida; y**
- f) **cotejar dichos datos de las señales y el parámetro conocido del fluido del pozo contra las respuestas modeladas con el fin de determinar el calibre del pozo.**

11. **El método de la reivindicación 10, en donde el método es realizado durante o después de la perforación del pozo de sondeo.**

12. **El método de la reivindicación 10, en donde el parámetro conocido del fluido del pozo comprende un valor de resistividad de lodo.**

13. **El método de la reivindicación 10, en donde los datos de las señales generados comprenden valores de resistividad eléctrica.**

14. **El método de la reivindicación 10, que además consiste en registrar el calibre del pozo determinado en un medio de registro de salida.**

15. **El método de la reivindicación 10, en donde el paso (f) consiste en realizar una técnica de minimización de cuadrados mínimos para cotejar los datos de las señales generados y el parámetro de fluidos conocido contra las respuestas modeladas.**

16. **El método de la reivindicación 10, en donde el paso (a) consiste en establecer una tabla de respuestas de modelo teórico de la herramienta del pozo a diferentes diámetros del pozo, resistividades de lodo del pozo y resistividades de la formación.**

17. El método de la reivindicación 10, en donde el paso (e) consiste en enviar los datos de las señales de la herramienta a una superficie de la formación.

18. El método de la reivindicación 10, en donde el paso (e) consiste en registrar los datos de las señales en un medio de almacenamiento alojado en la herramienta.

19. Un sistema para calcular el calibre de un pozo de sondeo que incluye una herramienta de pozos multisensora y un aparato adaptado para ser acoplado a la herramienta; la herramienta es colocada en un pozo de sondeo en una formación de tierra y adaptada para transmitir energía electromagnética en la formación de una estación de herramientas, y recibir energía electromagnética en estaciones múltiples arbitrarias sensoras de herramientas; el aparato es adaptado para que responda a datos de las señales generados por la herramienta y asociado con la energía recibida, con el fin de determinar el calibre del pozo de sondeo; el aparato comprende:

medios para recibir datos de las señales;

medios para recibir un parámetro conocido de fluidos del pozo;

medios para almacenar los datos de las respuestas modeladas de la herramienta de pozos; y

medios para procesar los datos de las señales, el parámetro conocido de fluidos y los datos de respuesta modelada para determinar el calibre del pozo de sondeo.

20. El sistema de la reivindicación 19, en donde la herramienta del pozo transmite y recibe la energía electromagnética y genera los datos de las señales durante una operación de medición de línea o medición durante perforación.

21. El sistema de la reivindicación 19, en donde el parámetro conocido de fluido de pozos comprende un valor de resistividad de lodo.

22. El sistema de la reivindicación 19, en donde los datos de las señales generados comprenden valores de resistividad eléctrica.
23. El sistema de la reivindicación 19 cuyo aparato comprende además medios para registrar el calibre del pozo determinado en un medio de registro de salida.
24. El sistema de la reivindicación 19, cuyo medio para almacenar los datos de la respuesta modelada de la herramienta comprende además medios para establecer una tabla de respuestas de modelo teórico de la herramienta del pozo a diferentes diámetro del pozo, resistividades de fluido de pozo y resistividades de la formación.
25. El sistema de la reivindicación 19, cuyo medio de procesamiento comprende además medio para cotejar los datos de la señal y el parámetro conocido de fluidos contra los datos de la repuesta modelada para determinar el calibre del pozo.
26. El sistema de la reivindicación 19, cuyo medio de procesamiento comprende además medios para realizar una técnica de minimización de cuadrados mínimos para cotejar los datos de las señales y el parámetro conocido de fluidos contra los datos de la respuesta modelada para determinar el calibre del pozo.
27. Un dispositivo de almacenamiento de programas legible por un procesador y que codifica un programa de instrucciones que incluye instrucciones para realizar las operaciones del aparato citadas en la reivindicación 19.
28. Un sistema para calcular la resistividad de una formación de tierra que incluye una herramienta de pozos multisensora y un aparato adaptado para ser acoplado a la herramienta; la herramienta es colocada en un pozo de sondeo en la formación de tierra y adaptada para transmitir energía electromagnética en la formación de una estación de herramientas y para recibir energía electromagnética en estaciones múltiples arbitrarias sensoras de herramientas; el aparato es adaptado para que responda a datos de las señales generados por la

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herramienta y asociado con la energía recibida, con el fin de determinar la resistividad de la formación; el aparato comprende:

medios para recibir los datos de las señales;

medios para recibir un parámetro conocido de fluidos del pozo;

medios para almacenar los datos de respuestas modeladas de la herramienta de pozos; y

29. El sistema de la reivindicación 28, en donde la herramienta del pozo transmite y recibe energía electromagnética y genera los datos de las señales durante una operación de línea o de medición durante perforación.

30. El sistema de la reivindicación 28, en donde el parámetro conocido de fluidos del pozo comprende un valor de resistividad de lodo.

31. El sistema de la reivindicación de la reivindicación 28, en donde los datos de la señal generados comprenden valores de resistividad eléctrica.

32. El sistema de la reivindicación 28 cuyo aparato comprende además medios para registrar la resistividad de la formación determinada en un medio de registro de salida.

33. El sistema de la reivindicación 28, cuyo medio para almacenar los datos de respuesta modelada de la herramienta comprende además medios para establecer una tabla de respuestas de modelo teórico de la herramienta de pozo a diferentes diámetros del pozo, resistividades de fluido del pozo y resistividades de la formación.

34. El sistema de la reivindicación 28, cuyo medio de procesamiento comprende además medios para cotejar los datos de las señales y el parámetro conocido de fluidos contra los datos de la respuesta modelada para determinar la resistividad de la formación.

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35. El sistema de la reivindicación 28, cuyo medio de procesamiento comprende además medios para realizar una técnica de minimización de cuadrados mínimos para cotejar los datos de las señales y el parámetro conocido de fluidos contra los datos de la respuesta modelada para determinar la resistividad de la formación.

36. Un dispositivo de almacenamiento de programas legible por un procesador y que codifica un programa de instrucciones que incluye instrucciones para realizar las operaciones del aparato citadas en la reivindicación 28.



CONSULADO DE COLOMBIA
WASHINGTON, D.C.

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No. 2168

EL CONSULADO DE COLOMBIA
CERTIFICA:

Que es auténtica la firma de JACQUELINE PRIDGEN.
quien el día 23 DE AGOSTO DEL 2000
desempeñaba las funciones de XXXXXXXXXXXXOFICIAL DE AUTENTICACIONES DEPARTAMENTO DE ESTADO.
la cual aparece al pie de los documentos anexos relacionados con CERTIFICADO

Dado en Washington, D.C. a los VEINTITRES (23) días del mes de AGOSTO. del año dos mil (2000)

Pagado Impuesto de Timbre

Pagado Derecho Consular

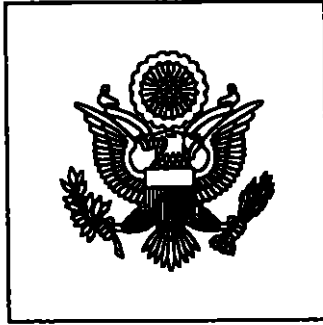
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Handwritten signature of Jacqueline Espitia Arias

JACQUELINE ESPITIA ARIAS
Vicecónsul

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United States of America



DEPARTMENT OF STATE

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In testimony whereof, I, Madeleine K. Albright, Secretary of State, have hereunto caused the seal of the Department of State to be affixed and my name subscribed by the Assistant Authentication Officer, of the said Department, at the city of Washington, in the District of Columbia, this twenty-third day of August, 2000.

Madeleine K. Albright
Secretary of State
By *Gregory E. Kohn*
Assistant Authentication Officer,
Department of State

Issued pursuant to CDDIV, State of
Sept. 15, 1789, 1 Stat. 68-69; 22
USC 2657; 22 USC 2651a; 5 USC
301; 28 USC 1733 et. seq.; 8 USC
1443(f); RULE 44 Federal Rules of
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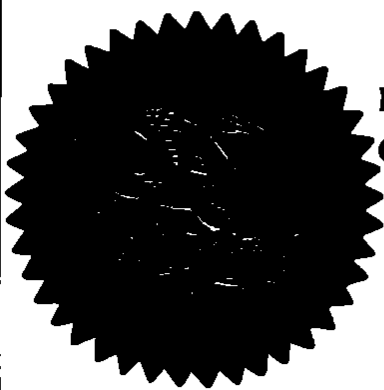
United States Patent and Trademark Office

June 02, 2000

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE UNDER 35 USC 111.

APPLICATION NUMBER: 09/393,559

FILING DATE: *September 10, 1999*



**By Authority of the
COMMISSIONER OF PATENTS AND TRADEMARKS**

W. Montgomery
W. MONTGOMERY
Certifying Officer

I hereby certify this application is being deposited with the United States Postal Service as "Express Mail Post Office to Addressee" under 37 CFR 1.10 in an envelope addressed to Box Patent Application, Assistant Commissioner for Patents, Washington, D.C. 20231 on the date shown below.
Date: September 10, 1999



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James J. Stewart
James J. Stewart

JC712 U.S. PTO
09/10/99

Date: September 10, 1999
Box Patent Application
Assistant Commissioner for Patents
Washington, D. C. 20231

Schlumberger
Oilfield Services
Sugar Land Product Center
200 Gillingham Lane
Sugar Land, Texas 77478
(281) 285-8500

JC712 U.S. PTO
09/10/99

Sir:
RE: Application of: Qiming Li
For: METHOD AND APPARATUS FOR MEASUREMENT OF BOREHOLE SIZE
AND THE RESISTIVITY OF SURROUNDING EARTH FORMATIONS
Docket No.: 24.0807

Enclosed are the following:

- ☒ Application including specification, claims and 9 sheets of drawings;
☐ Declaration;
☐ Information Disclosure Statement;
☐ Priority Document;
☒ Assignment to: SCHLUMBERGER TECHNOLOGY CORPORATION
Please record the Assignment and charge the appropriate fee to Deposit Account No. 19-0610. After recordation, please return the Assignment to the undersigned.

The remittance to cover the fees for filing the application is computed as follows:

FOR	NUMBER FILED	NUMBER EXTRA	RATE	BASIC FEE \$760
TOTAL CLAIMS	36 - 20	16	x \$18	288
INDEPENDENT CLAIMS	6 - 3	3	x \$78	234
ADDITIONAL FEE FOR FILING MULTIPLE DEPENDENT CLAIMS: \$160				. 0

TOTAL FILING FEE: \$ 1282.00

Please charge these fees to Deposit Account No. 19-0610. Please charge any other patent application filing fees under 37 CFR § 1.16 or patent application processing fees under 37 CFR § 1.17 associated with this communication to Deposit Account No. 19-0610. Three copies of this letter are enclosed.

Respectfully submitted,

Victor Segura
Victor H. Segura
Registration No. 44,329

Patent Attorney
IP Law and Contracts
Schlumberger Oilfield Services
200 Gillingham Lane, MD 200-9
Sugar Land, Texas 77478
(281) 285-4562

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PATENT
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APPLICATION FOR UNITED STATES LETTERS PATENT

for

Method and Apparatus for Measurement of Borehole Size and the
Resistivity of Surrounding Earth Formations

by

Qiming Li

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**METHOD AND APPARATUS FOR MEASUREMENT OF BOREHOLE SIZE AND
THE RESISTIVITY OF SURROUNDING EARTH FORMATIONS****1. BACKGROUND OF THE INVENTION****1.1 Field of the Invention**

This invention relates generally to a method and apparatus for measuring a borehole and the surrounding earth formations and, more particularly, to a technique for calculating the diameter of a borehole and the formation resistivity from electromagnetic ("EM") measurements obtained with a well tool. The invention has general application in the well logging art, but is particularly useful in measuring-while-drilling.

1.2 Description of Related Art

In order to improve oil and gas drilling and production operations, it is necessary to gather as much information as possible on the properties of the underground earth formation as well the environment in which drilling takes place. Such properties include characteristics of the earth formations traversed by a well borehole, in addition to data on the size and configuration of the borehole itself. Among the characteristics of the earth formation of interest to drillers and petrophysicists is the resistivity of the rock or strata surrounding the borehole. However, the processes often employed to measure these characteristics are subject to significant errors unless information on the borehole size and configuration is also taken into account in their determination. Knowledge of the borehole size is also useful to estimate the hole volume, which, in turn, is used to estimate the volume of cement needed for setting casing or when hole stability is of concern during drilling.

The collection of downhole information, also referred to as logging, is realized in different ways. A well tool, comprising transmitting and detecting devices for measuring various parameters, can be lowered into the borehole on the end of a cable, or wireline. The cable, which is attached to some sort of mobile processing center at the surface, is the means by which parameter data is sent up to the surface. With this type of wireline

logging, it becomes possible to measure borehole and formation parameters as a function of depth, i.e., while the tool is being pulled uphole.

An improvement over wireline logging techniques is the collection of data on downhole conditions during the drilling process. By collecting and processing such information during the drilling process, the driller can modify or correct key steps of the operation to optimize performance and avoid financial injury due to well damage such as collapse or fluid loss. Formation information collected during drilling also tends to be less affected by the mud fluid invasion processes or other undesirable influences as a result of borehole penetration, and therefore are closer to the properties of the virgin formation.

Schemes for collecting data of downhole conditions and movement of the drilling assembly during the drilling operation are known as measurement-while-drilling ("MWD") techniques. Similar techniques focusing more on measurement of formation parameters than on movement of the drilling assembly are known as logging-while-drilling ("LWD"). However, the terms MWD and LWD are often used interchangeably, and the use of either term in the present disclosure should be understood to include both the collection of formation and borehole information, as well as data on movement of the drilling assembly.

It is known in the art to measure the diameter, also known as the caliper, of a borehole to correct formation measurements that are sensitive to size or standoff. These corrections are necessary for accurate formation evaluation. U.S. Pat. No. 4,407,157 describes a technique for measuring a borehole caliper by incorporating a mechanical apparatus with extending contact arms that are forced against the sidewall of the borehole. This technique has practical limitations. In order to insert the apparatus in the borehole, the drillstring must be removed, resulting in additional cost and downtime for the driller. Such mechanical apparatus are also limited in the range of diameter measurement they provide.

Due to the unsuitability of mechanical calipers to drilling operations, indirect techniques of determining borehole calipers have been proposed. Conventional caliper

measurement techniques include acoustic transducers that transmit ultrasonic signals to the borehole wall. U.S. Pat. No. 5,469,736 describes an apparatus for measuring the caliper of a borehole by transmitting ultrasonic signals during a drilling operation. U.S. Pat. No. 5,397,893 describes a method for analyzing formation data from a MWD tool incorporating an acoustic caliper. U.S. Pat. No. 5,886,303 describes a logging tool including an acoustic transmitter for obtaining the borehole caliper while drilling. However, the techniques proposed with acoustic calipers entail measurements employing standoff and travel time calculations, resulting in data of limited accuracy. Sound wave reflections in soft formations may also be too weak to be accurately detected, leading to loss of signals.

U.S. Pat. No. 4,899,112 (assigned to the assignee of the present invention) discloses a technique for determining a borehole caliper and formation resistivities from downhole measurements obtained with a well tool. This technique determines the borehole caliper and formation resistivity by computing phase differences and attenuation levels from measured data. U.S. Pat. No. 5,900,733 (assigned to the assignee of the present invention) discloses a technique for determining borehole fluid resistivities and diameters by examining the phase shift, phase average, and attenuation of signals from multiple transmitter and receiver locations via electromagnetic wave propagation. However, the disclosed technique is limited to a well tool of wave propagation type incorporating multiple transmitter means with particular spacing conditions. The disclosed technique is also limited in application to boreholes of limited diameters.

An emerging application of borehole caliper measurements, which is not geared towards formation evaluation, is the monitoring of borehole stability while drilling. Keeping track of the dynamic development of the borehole is critical for the successful completion of a well when borehole stability is of issue. In some instances, the borehole has been severely washed out with diameters in excess of seventy inches. This requires a borehole caliper measurement technique that works for a wide range of hole sizes. Not only should the caliper measurement indicate a large hole when severe washout occurs, it

59

should also provide an accurate estimate of the required cement volume for casing upon completion of the well.

It is desirable to obtain a simplified method and system for accurately determining a borehole caliper and the surrounding formation resistivity utilizing EM measurements from a well tool. Still further, it is desired to implement a borehole caliper and formation resistivity calculation technique that works for a wide range of borehole sizes.

2. SUMMARY OF THE INVENTION

A method and system are provided for determining a caliper of a borehole and/or the resistivity of the surrounding earth formations utilizing a well tool disposed in the borehole. In one aspect of the invention, a process for determining the caliper of a borehole comprises modeling responses of the well tool at different borehole and formation parameters; determining a known borehole fluid parameter; transmitting electromagnetic energy into the borehole from a station on the tool; receiving electromagnetic energy at arbitrary multiple sensor stations on the tool; generating signal data, associated with the received energy, from the tool; recording downhole and/or transmitting the signal uphole; and matching the signal data and the known borehole fluid parameter against the modeled responses to determine the borehole caliper.

In another aspect of the invention, a process for determining the resistivity of an earth formation is provided. This process is similar to the process provided for determining a caliper of a borehole, with minor variations.

In another aspect of the invention, a borehole caliper / formation resistivity calculation system, including a multi-sensor well tool and an apparatus, is provided. The apparatus is adapted to be coupled to the well tool, the tool being disposed in a borehole in an earth formation and adapted to transmit EM energy into the formation from a tool station and to receive EM energy at arbitrary multiple tool sensor stations. The apparatus is further adapted to respond to signal data, generated by the tool and associated with the received energy, for determining the borehole caliper and/or formation resistivity. The apparatus comprises means for receiving the signal data; means for receiving a known

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borehole fluid parameter; means for generating and storing modeled well tool response data; and means for processing the signal data, the known fluid parameter, and the modeled response data to determine the borehole caliper and/or formation resistivity.

3. BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

Figure 1 is a cross-sectional view of a well tool embodiment, as described in U.S. Pat. No. 5,339,037, which may be used to implement the present invention.

Figure 2 is a representation of the type of current pattern obtained with the tool embodiment of Figure 1 and the lower part of a drill string on which the well tool is connected when the transmitting coil is energized.

Figure 3 is a graph of a computed tool response in the form of apparent resistivities versus borehole diameter for a fixed formation and borehole resistivity for five sensor measurements from a tool embodiment. The extent of the curves indicates the depth of measurement obtainable with application of the present invention.

Figure 4 is a flow diagram of a method for determining the caliper of a borehole in earth formations and/or the resistivity of the formations in accord with the present invention.

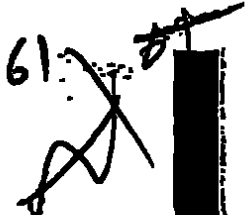
Figure 5 shows a borehole caliper / formation resistivity calculation system including a well tool and a computer apparatus in accord with the present invention.

Figure 6 is a computed crossplot of resistivity measurements obtained from two well tool sensors in accord with the present invention. The caliper and formation resistivity can be read off the chart given two measurements.

Figure 7 is another computed crossplot of resistivity measurements obtained from another two well tool sensors in accord with the present invention. The caliper and formation resistivity can be read off the chart given two measurements.

Figure 8 graphically illustrates a calculated borehole caliper and formation resistivity output obtained with application of the present invention. The Left panel

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61 

displays the apparent resistivity of a well tool in a modeled formation configuration. The middle panel displays the resultant caliper output from application of the present invention. The right panel displays the formation resistivity. The input parameters are shown as dashed curves and the output from application of the present invention is displayed as solid curves.

Figure 9 graphically illustrates a calculated borehole caliper and formation resistivity output, as applied to a cone-shaped borehole, obtained with application of the present invention. The designations of the curves are the same as the curves of Figure 8.

4. DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

In the interest of clarity, not all features of actual implementation are described in this specification. It will be appreciated that although the development of any such actual implementation might be complex and time-consuming, it would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

The present invention utilizes EM measurements to calculate a borehole caliper extending to a wide range of diameters and the resistivity of the surrounding formations. U.S. Pat. Nos. 5,235,285, 5,339,036, 5,339,037 and 5,463,320 (all assigned to the assignee of the present invention) disclose embodiments of well tools that can be used to implement the present invention in the manner of operation described in the respective patent. Figure 1 is representative of such tool embodiments.

As seen in Figure 1, one embodiment of the tool 10 includes a section of tubular drill collar 12 having mounted thereon a transmitter antenna 14, a receiving antenna 16, receiving button sensors 18, 20, 22 and a ring sensor 24. [In the present disclosure, any references to a sensor are intended to encompass an electrode, and vice-versa.] In the illustrated apparatus, the transmitting antenna 14 comprises a toroidal antenna having coil turns wound on a ferromagnetic toroidal core that is axially coincident with the axis of the drill collar 12. The purpose of this toroidal transmitter is to induce a voltage along the drill collar 12 between sections above and below the transmitter 14. The resultant current

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travels in a path that includes the drill string (not shown) and the formations (as well as the borehole fluid, which is assumed to have substantial conductivity). It will be understood that the present invention may be implemented with a well tool 10 comprising more or fewer sensors, receivers, or transmitters than are shown in the embodiment of Figure 1.

With the tool 10 disposed in an earth borehole, the transmitter coil 14 induces a voltage on the drill collar 12. The voltage causes current to flow through the formation. Figure 2 illustrates a general representation of the known type of current pattern that results from energizing the transmitter coil 14 in a well being drilled with mud having substantial conductivity, as described, for example, in U.S. Pat. No. 5,235,285. The pattern will, of course, depend on the formations' bed patterns and conductivities; the example in Figure 2 represents the simplified case of uniform conductivity.

The generated current travels in a path that includes the drill bit 25 (coupled to the drill collar 12) and earth formations around the drill bit 25. The sensors 18, 20, 22, 24 may be located at arbitrary stations on the tool 10 and are utilized to detect and receive currents transmitted by the transmitter coil 14 which return via the formations and borehole. The sensors 18, 20, 22, 24 provide multiple resistivity measurements, containing different contributions from the current conduction through the formation and borehole fluid. See S. Bonner et al., *A New Generation of Electrode Resistivity Measurements for Formation Evaluation While Drilling*, SPWLA THIRTY-FIFTH ANNUAL LOGGING SYMPOSIUM, June 1994.

The mentioned tool embodiments contain internal circuitry (not shown) for implementing the disclosed measurements, as described in U.S. Pat. No. 5,339,037. The button sensors 18, 20, 22, ring sensor 24, and receiver coil(s) 16 are each coupled, via sensing and amplification circuits, to a multiplexer (not shown). The output produced by the circuitry is signal data in the form of electrical resistivity values corresponding to the currents received at the sensors.

The resistivity measurements may be focused into the formation and different depths of investigation may be obtained with additional transmitters located on the tool

63

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10 at different distances from the sensors. Longer transmitter-sensor spacings will generate responses that are relatively deep, while the shorter transmitter-sensor spacings will provide relatively shallow responses. By examining the difference in the sensor responses, an estimate of the borehole caliper and formation resistivity can be derived.

The present invention requires the determination of a known borehole fluid parameter. The borehole mud resistivity is used as an input parameter. The mud resistivity can be determined by taking a mud sample at the surface. Corrections for downhole factors such as temperature can be made to the measured mud resistivity by using formulas known in the art. Mud resistivity can also be measured directly downhole with suitable means. Precise measurement of the downhole mud resistivity will improve the accuracy of the present invention.

Figure 3 illustrates the extended borehole diameter D_h measurement range provided by the present invention. Figure 3 shows a computed tool response (using one of the referenced tool 10 embodiments), representing the depth of measurements obtainable with the disclosed technique. The graph shows the response of the tool's sensors to resistivity measurements in varying borehole diameters D_h with underground conditions comprising 0.2 Ohm-m mud resistivity R_m and a 2.0 Ohm-m formation resistivity R_t . The measurement is borehole corrected assuming a bit size of 12.25 inches. All the measurements start with the formation resistivity R_t at 2.0 Ohm-m and a common borehole diameter D_h of 12.25 inches and end up with a mud resistivity R_m of 0.2 Ohm-m with large borehole diameters D_h . If the borehole diameter D_h were infinite, the sensors would measure only mud, so the measurement should reflect a mud resistivity R_m . For a small borehole, the formation resistivity R_t should be measured. Thus, the greater the diameter of the borehole, the greater the effect of the mud resistivity on the measurement. By observing the effective changes of the measurements versus the borehole diameter D_h , the borehole caliper D_h and formation resistivity R_t can be determined.

As seen in Figure 3, there is a hierarchy of measurements that extend deeper and deeper into the formation, with the bit measurement providing the furthest depth of

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investigation. The resistivity measured at the bit is significantly different from the mud resistivity R_m . Even with a borehole diameter D_h of one hundred inches, the bit measurement is still sensitive to the formation resistivity R_t ; thus it is still sensitive to borehole sizes up to ten feet.

Implementation of the present invention includes the modeling or pre-calculation of theoretical tool responses corresponding to varying borehole diameters and formation and borehole fluid resistivities. For a laterolog measurement at low frequency, the borehole size and the resistivity contrast between formation and mud resistivity control the deviation of the apparent resistivity of the measurement from the true formation resistivity. A resistivity transform can also be applied, if necessary, to remove the effect of skin depth on the apparent resistivity. As known in the art, the response data can be modeled or computed for a particular tool embodiment by using any suitable computer algorithm (e.g., finite element model coding) to calculate the theoretical current flow for the sensors and converting the data to resistivity values. The modeled response data can be generated and stored in a suitable record medium before or after the tool is disposed in the borehole.

As described above, the downhole mud resistivity R_m is either directly measured with a mud sensor or is estimated from a surface sampling measurement. The formation resistivity R_t varies and is unknown. Effective implementation of the present invention uses at least two different sensor 18, 20, 22, 24 measurements to determine the borehole caliper D_h and the formation resistivity R_t . Any two (or more) tool 10 sensor measurements may be chosen. The accuracy of the output, however, may depend on the sensors chosen.

Once the measurements are taken and the signal data are produced by the tool 10, the signal data and the known mud resistivity R_m value can be compared against the modeled data to find a match. The best match determines the borehole caliper D_h and formation resistivity R_t . The borehole caliper and formation resistivity are thus determined for each pair of measurements by plotting the pair of measurements. Greater

accuracy may be obtained by using a least squares technique to match the signal data and mud resistivity R_m value against the modeled data.

With more than two sensor 18, 20, 22, 24 measurements available, a more accurate and stable approach is to formulate a lookup table for all the modeled sensor responses of the particular tool 10 embodiment and then find the borehole caliper D_h and formation resistivity R_t pair that produces the best match between the measured signal data, the known mud resistivity R_m , and the modeled data. Some interpolation between the tabulated values may be done to improve the estimate. Still greater accuracy may be obtained with the pre-calculated tool responses by factoring in the position of the sensors in relation to the bitface in the calculations. This is useful because in MWD techniques, various detection devices are positioned above the drill bit on a downhole toolstring. Thus, the bit measurement may depend on how far away the tool is running from the bitface because the bit measurement uses the whole tool body below the sensor or monitor to conduct electric current.

Figure 4 illustrates a flow diagram of a method 100 for determining a caliper of a borehole in an earth formation and/or the formation resistivity utilizing a well tool disposed in the borehole. The method comprises modeling responses of the well tool to different borehole and formation parameters 105; determining a known borehole fluid parameter 110; transmitting electromagnetic energy into the borehole from a station on the tool 115; receiving electromagnetic energy at arbitrary multiple sensor stations on the tool 120; generating signal data, associated with the received energy, from the tool 125; and matching the signal data and the known borehole fluid parameter against the modeled responses to determine the borehole caliper and/or formation resistivity 130.

4.1 Program Storage Device

It will be apparent to those of ordinary skill having the benefit of this disclosure that the present invention may be implemented by programming one or more suitable general-purpose computers having appropriate hardware. The programming may be accomplished through the use of one or more program storage devices readable by the

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computer processor and encoding one or more programs of instructions executable by the computer for performing the operations described above. The program storage device may take the form of, e.g., one or more floppy disks; a CD ROM or other optical disk; a magnetic tape; a read-only memory chip (ROM); and other forms of the kind well-known in the art or subsequently developed. The program of instructions may be "object code," i.e., in binary form that is executable more-or-less directly by the computer; in "source code" that requires compilation or interpretation before execution; or in some intermediate form such as partially compiled code. The precise forms of the program storage device and of the encoding of instructions are immaterial here.

4.2 Borehole Caliper / Formation Resistivity Calculation System

As shown in Figure 5, the present invention may be implemented in a borehole caliper / formation resistivity calculation system 200 with a multi-sensor well tool 210 and an apparatus (such as the general-purpose computer and program storage device described above) 212 coupled to the tool 210. Certain conventional details are omitted in Figure 5 for clarity of illustration.

It will be appreciated by those skilled in the art that the present invention may be implemented in LWD or wireline (with the drill string removed) operations with any tool 210 capable of obtaining array electrode resistivity measurements. Thus, although Figure 5 shows a tool 210 suspended on a platform as used in a LWD operation, the principles of the invention are also applicable to wireline systems as known in the art.

The borehole caliper and/or formation resistivity can be determined in real-time by sending the measured resistivity signal data from the tool 210 to the surface as they are acquired via a telemetry system, or from a recorded mode by recording the signal data on a suitable storage medium (not shown) included in the tool 210 circuitry as described in the '037 patent. Alternatively, some or all processing may be performed downhole with the results being sent to the surface. The signal data may be sent to the surface computer 212 by MWD telemetry or along a wireline cable as known in the art. It will be understood that alternative means may be employed for communicating the acquired data

to the surface, as the precise form of communication is immaterial to the implementation of the present invention.

The surface computer 212 may be programmed to receive the resistivity signal data and the mud resistivity R_m value as inputs. It may also be capable of generating and/or storing the modeled tool 210 response data. The computer 212 may also be programmed to process the signal data, the borehole mud resistivity R_m , and the modeled data to determine the borehole caliper D_h and/or the formation resistivity R_t in accordance with the disclosed techniques. Once determined, the borehole caliper D_h and/or formation resistivity R_t can be recorded on a suitable storage medium or further processed as desired by the user to generate a borehole caliper or formation resistivity profile.

4.3 Plotted Examples

In this section, computed crossplots of sensor resistivity measurements and the output of borehole caliper and formation resistivity calculations derived in accordance with the present invention are presented. Figure 6 shows a computed crossplot of resistivity measurements obtained from a tool's ring sensor and center button sensor. As described above, any two sensor measurements may be chosen. The ring and center sensors were chosen here for purposes of example. Looking at the crossplot of Figure 6, the solid curves represent constant formation resistivities R_t and the dashed curves constant borehole calipers. A borehole caliper and formation resistivity can be determined from the crossplot by inputting two measurements. That is, a borehole diameter D_h and a formation resistivity R_t can be derived from a known mud resistivity R_m and two given measured resistivity values.

Figure 7 shows another computed resistivity crossplot illustrating the different sensitivities obtainable by choosing current measurements taken from sensors at different tool stations. The ring sensor and bit measurements were chosen for the crossplot in Figure 7. As seen from comparison of Figures 6 and 7, differing ranges of sensitivity are provided from measurements at different sensor stations. Depending on which sensor

measurements are chosen, a greater error may be incurred when determining the borehole caliper from the areas of lower sensitivity, as represented by the crowding of the lines in the crossplots.

Figure 8 illustrates the calculated borehole caliper D_h and formation resistivity R_t outputs obtained with the techniques of the present invention. The left panel is the computed resistivity log that was used as input signal data. Each curve represents a resistivity measurement from a different sensor. A 5% white noise factor was added to the resistivity inputs. The input mud resistivity R_m was set at 0.2 Ohm-m. The borehole is enlarged to sixty inches in the [-20ft., 20 ft.] interval.

Turning to the center and right panels of Figure 8, the respective input borehole diameter D_h and formation resistivities R_t are shown as dashed curves. As seen in the center panel, the correct borehole calipers D_h are obtained, with an exception at the edge where shoulder beds begin to affect the log readings. The formation resistivity R_t output is also very close, displaying less accuracy for larger boreholes because of the insensitivity of the apparent resistivity to the formation resistivity. The dashed line labeled " D_i " in the center panel represents a mud filtrate invasion. Filtrate consists of fluids driven into the rock formation under the high-pressure conditions encountered downhole. As shown in the output, if the invasion is not too large (here it is in the range of twenty inches), the disclosed techniques provide the correct borehole caliper D_h and formation resistivity R_t .

Figure 9 illustrates the calculated borehole caliper D_h and formation resistivity R_t outputs obtained with the technique of the present invention as applied to a cone-shaped borehole. As seen in the panels, the borehole calipers D_h are once again correctly obtained, with an exception at the top edge where the shoulder bed began to affect the tool response.

The accuracy of the disclosed caliper and formation resistivity calculation techniques was computed for different values of R_t/R_m contrasts and different borehole diameters. Assuming a plus or minus 5% sensor measurement accuracy, the borehole calipers and formation resistivities can be determined within 10% of accuracy for

boreholes extending up to one-hundred inches in diameter. Additional error may be incurred from the uncertainty of the mud resistivity in downhole environments.

While the methods and apparatus of this invention have been described as specific embodiments, it will be apparent to those skilled in the art that variations may be applied to the structures and in the steps or in the sequence of steps of the methods described herein without departing from the concept and scope of the invention. All such similar variations apparent to those skilled in the art are deemed to be within this concept and scope of the invention as defined by the appended claims.

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WHAT IS CLAIMED IS:

1. A method for determining a caliper of a borehole in an earth formation utilizing a well tool disposed in the borehole, comprising:

- a) modeling responses of the tool to different borehole and formation parameters;
- b) determining a known borehole fluid parameter;
- c) transmitting electromagnetic energy into the borehole from a station on the tool;
- d) receiving electromagnetic energy at arbitrary multiple sensor stations on the tool;
- e) generating signal data, associated with the received energy, from the tool; and
- f) matching the signal data and the known borehole fluid parameter against the modeled responses to determine the borehole caliper.

2. The method of claim 1, wherein the method is performed during or after drilling of the borehole.

3. The method of claim 1, wherein the known borehole fluid parameter comprises a mud resistivity value.

4. The method of claim 1, wherein the generated signal data comprises electrical resistivity values.

5. The method of claim 1, further comprising recording the determined borehole caliper on an output record medium.

6. The method of claim 1, wherein step (f) comprises performing a least squares minimization technique to match the generated signal data and the known fluid parameter against the modeled responses.

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7. The method of claim 1, wherein step (a) comprises establishing a table of theoretical model responses of the well tool to different borehole diameters, borehole fluid resistivities, and formation resistivities.

8. The method of claim 1, wherein step (e) comprises sending the signal data from the tool to a surface of the formation.

9. The method of claim 1, wherein step (e) comprises recording the signal data in a storage medium housed in the tool.

10. A method for determining the resistivity of an earth formation, the formation being traversed by a borehole, utilizing a well tool disposed in the borehole, comprising:

- a) modeling responses of the tool to different borehole and formation parameters;
- b) determining a known borehole fluid parameter;
- c) transmitting electromagnetic energy into the borehole from a station on the tool;
- d) receiving electromagnetic energy at arbitrary multiple sensor stations on the tool;
- e) generating signal data, associated with the received energy, from the tool; and
- f) matching the signal data and the known borehole fluid parameter against the modeled responses to determine the formation resistivity.

11. The method of claim 10, wherein the method is performed during or after drilling of the borehole.

12. The method of claim 10, wherein the known borehole fluid parameter comprises a mud resistivity value.

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13. The method of claim 10, wherein the generated signal data comprises electrical resistivity values.

14. The method of claim 10, further comprising recording the determined formation resistivity on an output record medium.

15. The method of claim 10, wherein step (f) comprises performing a least squares minimization technique to match the generated signal data and the known fluid parameter against the modeled responses.

16. The method of claim 10, wherein step (a) comprises establishing a table of theoretical model responses of the well tool to different borehole diameters, borehole fluid resistivities, and formation resistivities.

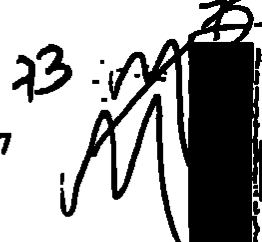
17. The method of claim 10, wherein step (c) comprises sending the signal data from the tool to a surface of the formation.

18. The method of claim 10, wherein step (e) comprises recording the signal data in a storage medium housed in the tool.

19. A borehole caliper calculation system including a multi-sensor well tool and an apparatus adapted to be coupled to the well tool, the tool being disposed in a borehole in an earth formation and adapted to transmit electromagnetic energy into the formation from a tool station and to receive electromagnetic energy at arbitrary multiple tool sensor stations, the apparatus being adapted to respond to signal data, generated by the tool and associated with the received energy, for determining the borehole caliper, the apparatus comprising:

means for receiving the signal data;

means for receiving a known borehole fluid parameter;

23 

means for storing modeled well tool response data; and

means for processing the signal data, the known fluid parameter, and the modeled response data to determine the borehole caliper.

5 20. The system of claim 19, wherein the well tool transmits and receives the electromagnetic energy and generates the signal data during one of a measurement-while-drilling or wireline operation.

10 21. The system of claim 19, wherein the known borehole fluid parameter comprises a mud resistivity value.

22. The system of claim 19, wherein the generated signal data comprises electrical resistivity values.

15 23. The system of claim 19, the apparatus further comprising means for recording the determined borehole caliper on an output record medium.

20 24. The system of claim 19, the means for storing modeled tool response data further comprising means for establishing a table of theoretical model responses of the well tool to different borehole diameters, borehole fluid resistivities, and formation resistivities.

25 25. The system of claim 19, the processing means further comprising means for matching the signal data and the known fluid parameter against the modeled response data to determine the borehole caliper.

26. The system of claim 19, the processing means further comprising means for performing a least squares minimization technique to match the signal data and the known fluid parameter against the modeled response data to determine the borehole caliper.

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27. A program storage device readable by a processor and encoding a program of instructions including instructions for performing the apparatus operations recited in claim 19.

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28. An earth formation resistivity calculation system including a multi-sensor well tool and an apparatus adapted to be coupled to the well tool, the tool being disposed in a borehole in the formation and adapted to transmit electromagnetic energy into the formation from a tool station and to receive electromagnetic energy at arbitrary multiple tool sensor stations, the apparatus being adapted to respond to signal data, generated by the tool and associated with the received energy, for determining the formation resistivity, the apparatus comprising:

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means for receiving the signal data;

means for receiving a known borehole fluid parameter;

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means for storing modeled well tool response data; and

means for processing the signal data, the known fluid parameter, and the modeled response data to determine the formation resistivity.

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29. The system of claim 28, wherein the well tool transmits and receives the electromagnetic energy and generates the signal data during one of a measurement-while-drilling or wireline operation.

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30. The system of claim 28, wherein the known borehole fluid parameter comprises a mud resistivity value.

31. The system of claim 28, wherein the generated signal data comprises electrical resistivity values.

32. The system of claim 28, the apparatus further comprising means for recording the determined formation resistivity on an output record medium.

33. The system of claim 28, the means for storing modeled tool response data further comprising means for establishing a table of theoretical model responses of the well tool to different borehole diameters, borehole fluid resistivities, and formation resistivities.

34. The system of claim 28, the processing means further comprising means for matching the signal data and the known fluid parameter against the modeled response data to determine the formation resistivity.

35. The system of claim 28, the processing means further comprising means for performing a least squares minimization technique to match the signal data and the known fluid parameter against the modeled response data to determine the formation resistivity.

36. A program storage device readable by a processor and encoding a program of instructions including instructions for performing the apparatus operations recited in claim 28.

ABSTRACT

A method and apparatus for determining the size or diameter of boreholes extending to a wide range of dimensions and/or the resistivity of the surrounding earth formations utilizing a well tool disposed in the borehole. The method involves generating model data representative of the well tool responses to different borehole diameters contrasted with formation and borehole fluid resistivity values, determining the borehole fluid resistivity, transmitting electromagnetic energy into the formation, measuring the energy shed back into the borehole at arbitrary sensor stations on the tool and generating resistivity signal data associated with the measured energy, and matching the signal data and the fluid resistivity against the modeled response data to determine the borehole caliper and/or formation resistivity. The apparatus forms part of a system for calculating a borehole caliper and/or the surrounding formation resistivity. The apparatus being coupled to a multi-sensor well tool and adapted to respond to signal data generated by the tool. The apparatus further adapted with means for receiving the signal data; for receiving a known borehole fluid parameter; for storing modeled well tool response data; and for processing the signal data, the fluid parameter, and the modeled data to determine the borehole caliper and/or formation resistivity.

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DECLARATION FOR PATENT APPLICATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name, and

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

METHOD AND APPARATUS FOR MEASUREMENT OF BOREHOLE SIZE AND THE RESISTIVITY OF SURROUNDING EARTH FORMATIONS

the specification of which

[X] is attached hereto.

[] was filed on _____
as United States Application Number or PCT International Application
Number _____

and was amended on (if applicable) _____

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR §1.56.

I hereby claim foreign priority benefits under 35 U.S.C. §119(a)-(d) or §365(b) of any foreign application(s) for patent or inventor's certificate, or §365(a) of any PCT International application which designated at least one country other than the United States, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or PCT International Application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application(s)		Priority Claimed	
_____ (Number)	_____ (Country)	/ / / D/M/YR FILED	[] YES [] NO
_____ (Number)	_____ (Country)	/ / / D/M/YR FILED	[] YES [] NO
_____ (Number)	_____ (Country)	/ / / D/M/YR FILED	[] YES [] NO

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I hereby claim the benefit under 35 U.S.C. §119(e) of any United States provisional application(s) listed below:

<u>Application No.</u>	<u>Filing Date</u>
<u>Application No.</u>	<u>Filing Date</u>
<u>Application No.</u>	<u>Filing Date</u>

I hereby claim the benefit under 35 U.S.C. §120 of any United States application(s), or §365(c) of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. §112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR §1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application.

<u>Application Serial No.</u>	<u>Filing Date</u>	<u>Status-patented, pending, abandoned</u>
<u>Application Serial No.</u>	<u>Filing Date</u>	<u>Status-patented, pending, abandoned</u>

As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith.

John J. Ryberg, #31,134; Steven L. Christian, #38,106; Brigitte L. Jeffery, #38,925 and Victor H. Segura, #44,329.

I hereby request that all correspondence, notices, official letters and other communication be directed to Schlumberger Technology Corporation, ATTN: Patent Counsel, 200 Gillingham Lane MD 200-9, Sugar Land, Texas 77478; and that all telephone calls be directed to: (281) 285-4562.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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SOLE OR FIRST INVENTOR

Signature

Qiming Li

Date

Sept 10, 1989

Full Name QIMING LI

Residence 127 Wilkins Crossing, Sugar Land, Texas 77479, USA

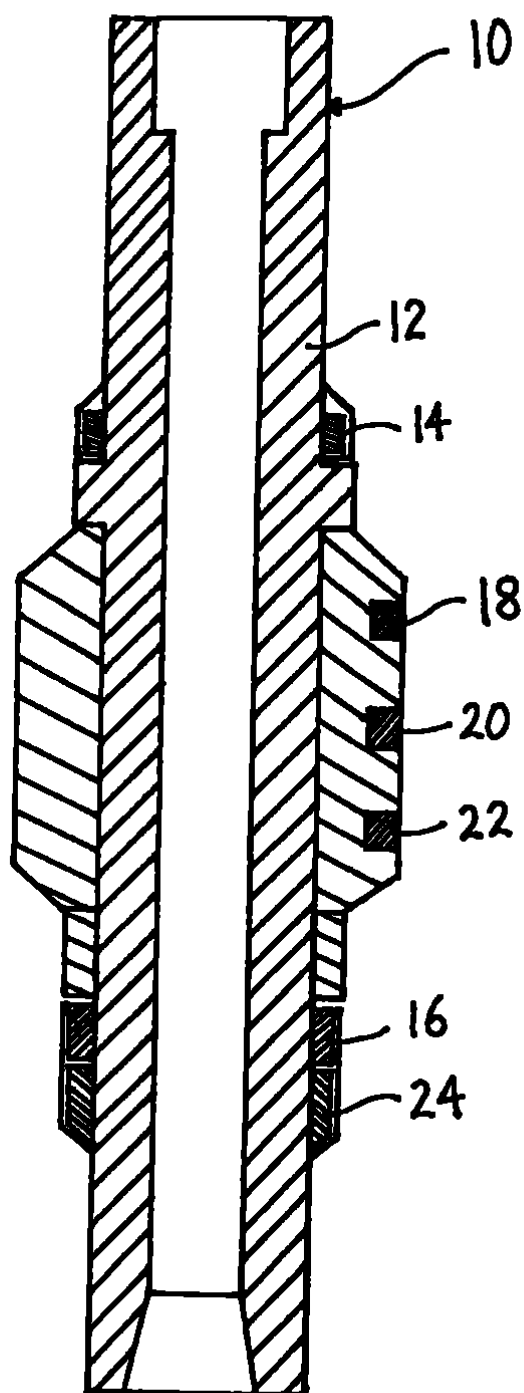
Citizenship People's Republic of China

Post Office Address 127 Wilkins Crossing, Sugar Land, Texas 77479, USA

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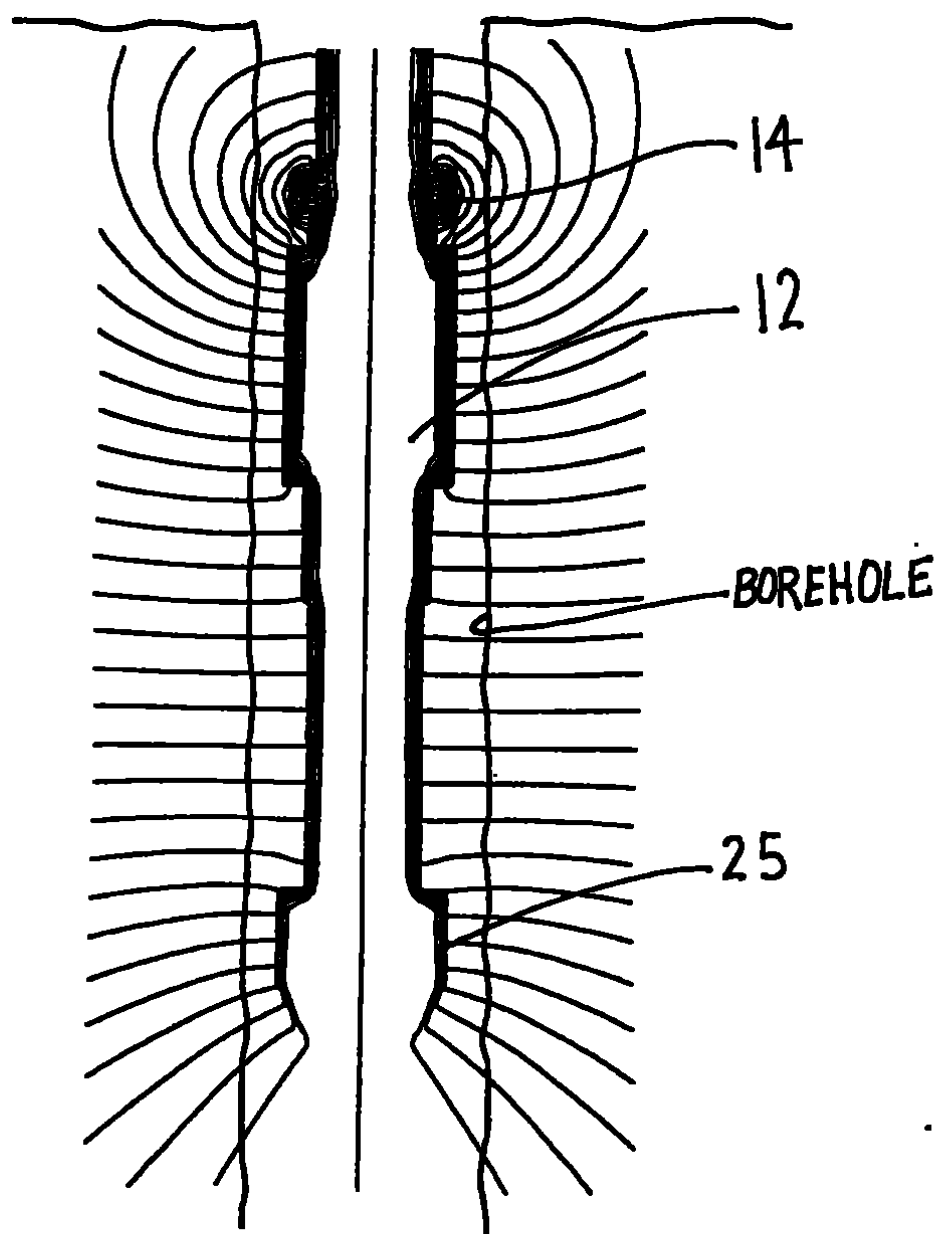


FIG. 2

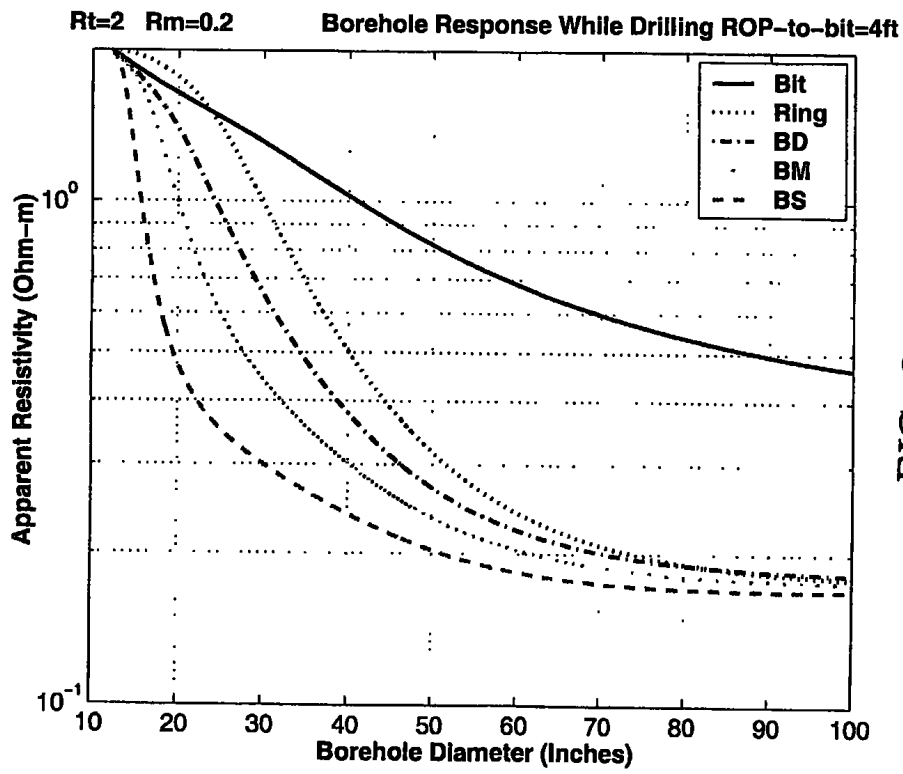


FIG. 3

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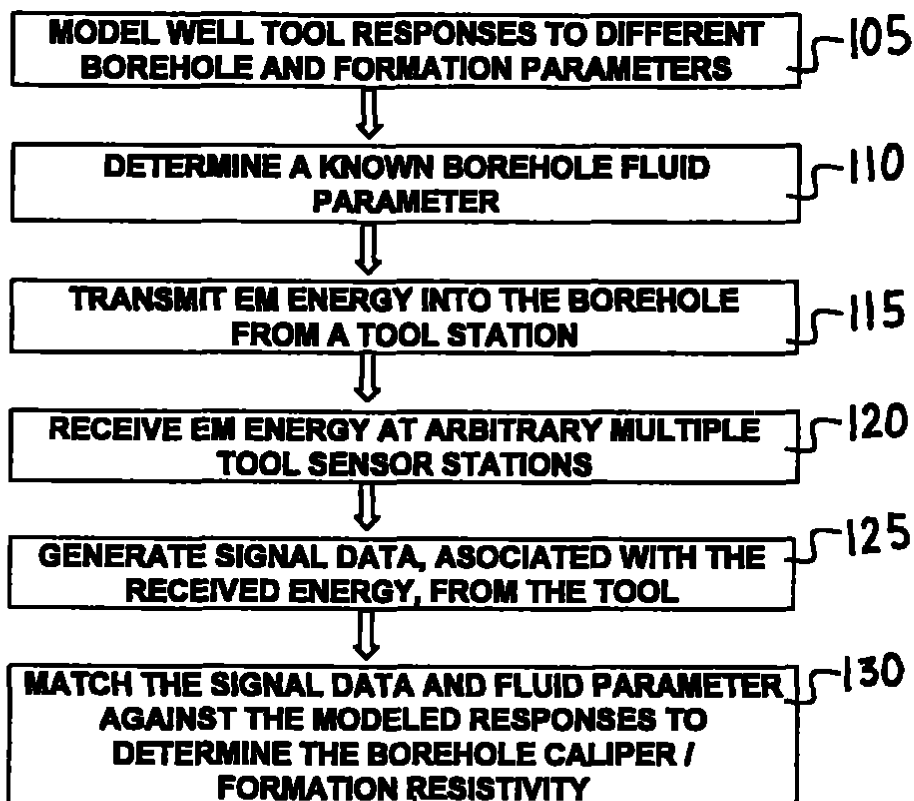


FIG. 4

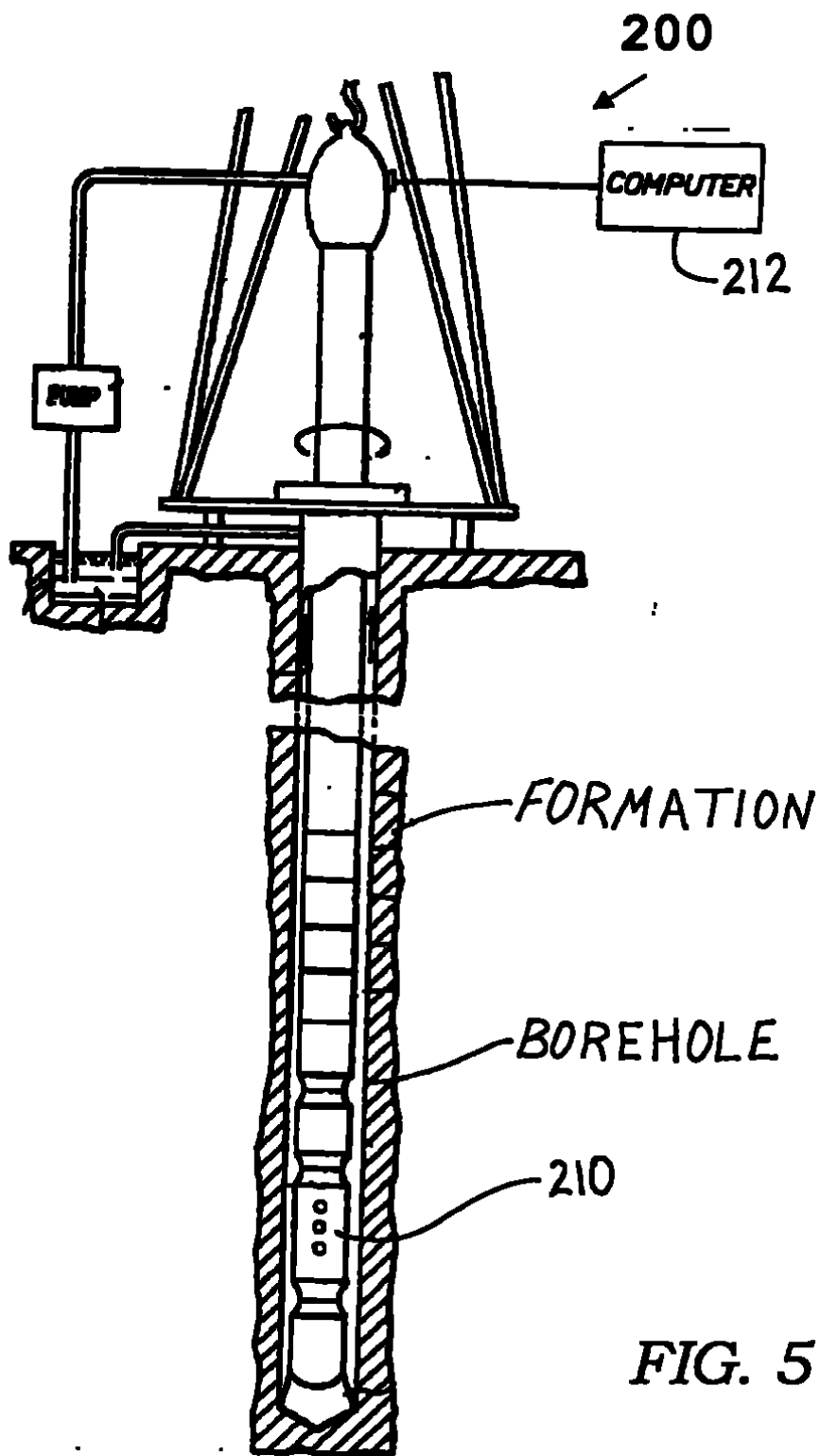


FIG. 5

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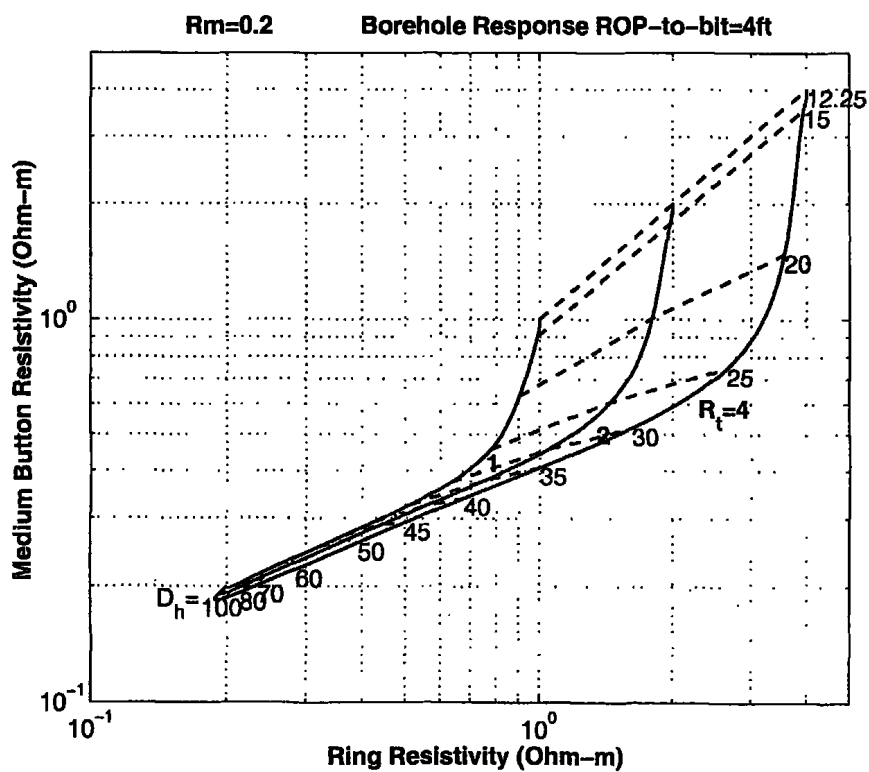


FIG. 6

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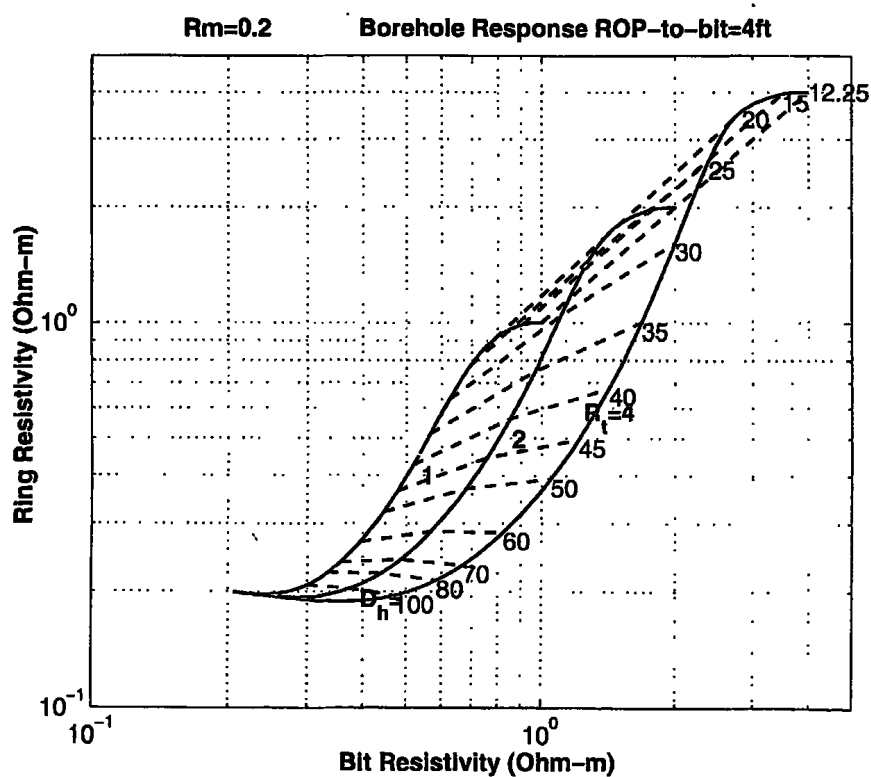


FIG. 7

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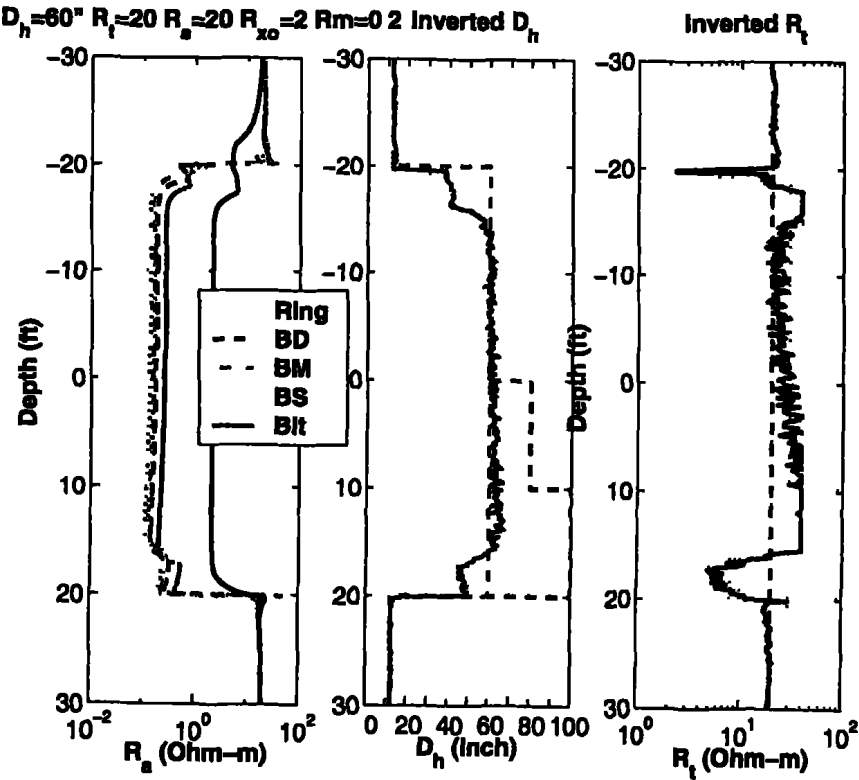


FIG. 8

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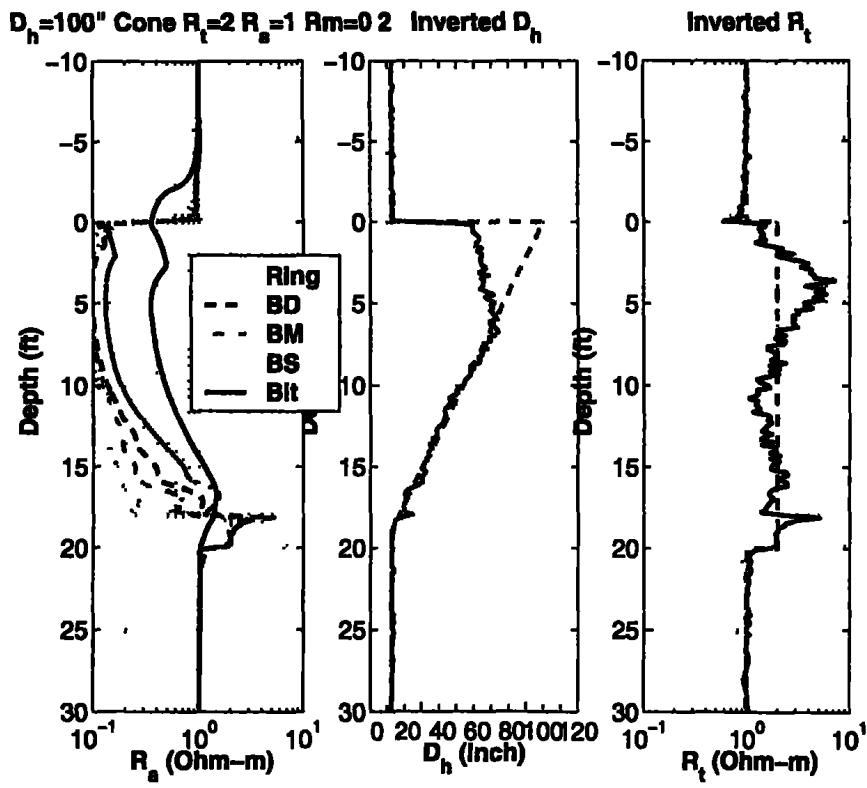


FIG. 9

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