

May 31, 1960

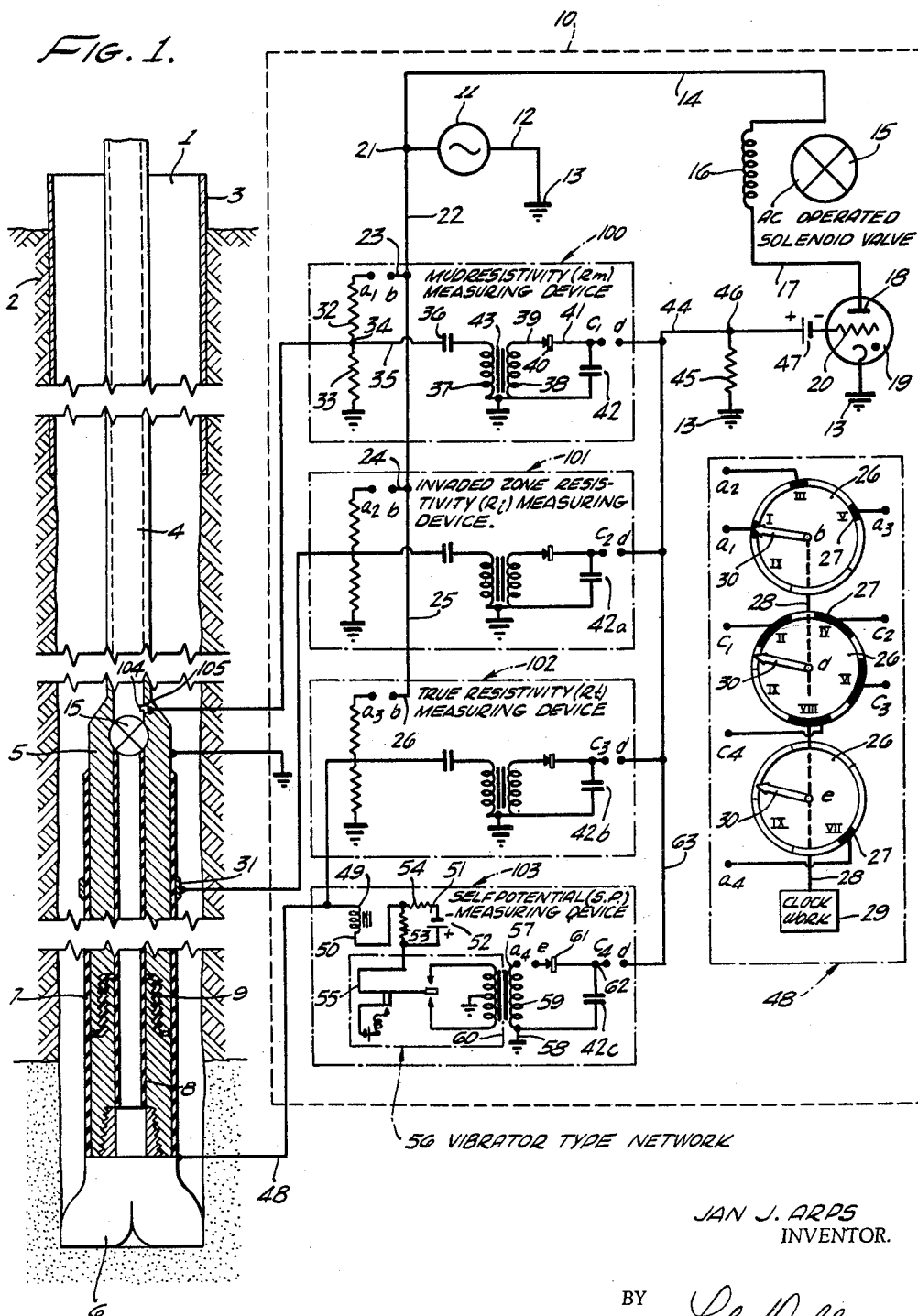
J. J. ARPS
SIMULTANEOUS DRILLING AND ELECTRICAL LOGGING
OF HYDROCARBON CONTENTS OF FORMATIONS

2,938,708

Filed Sept. 19, 1957

4 Sheets-Sheet 1

FIG. 1.



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4 Sheets-Sheet 2

FIG. 2.

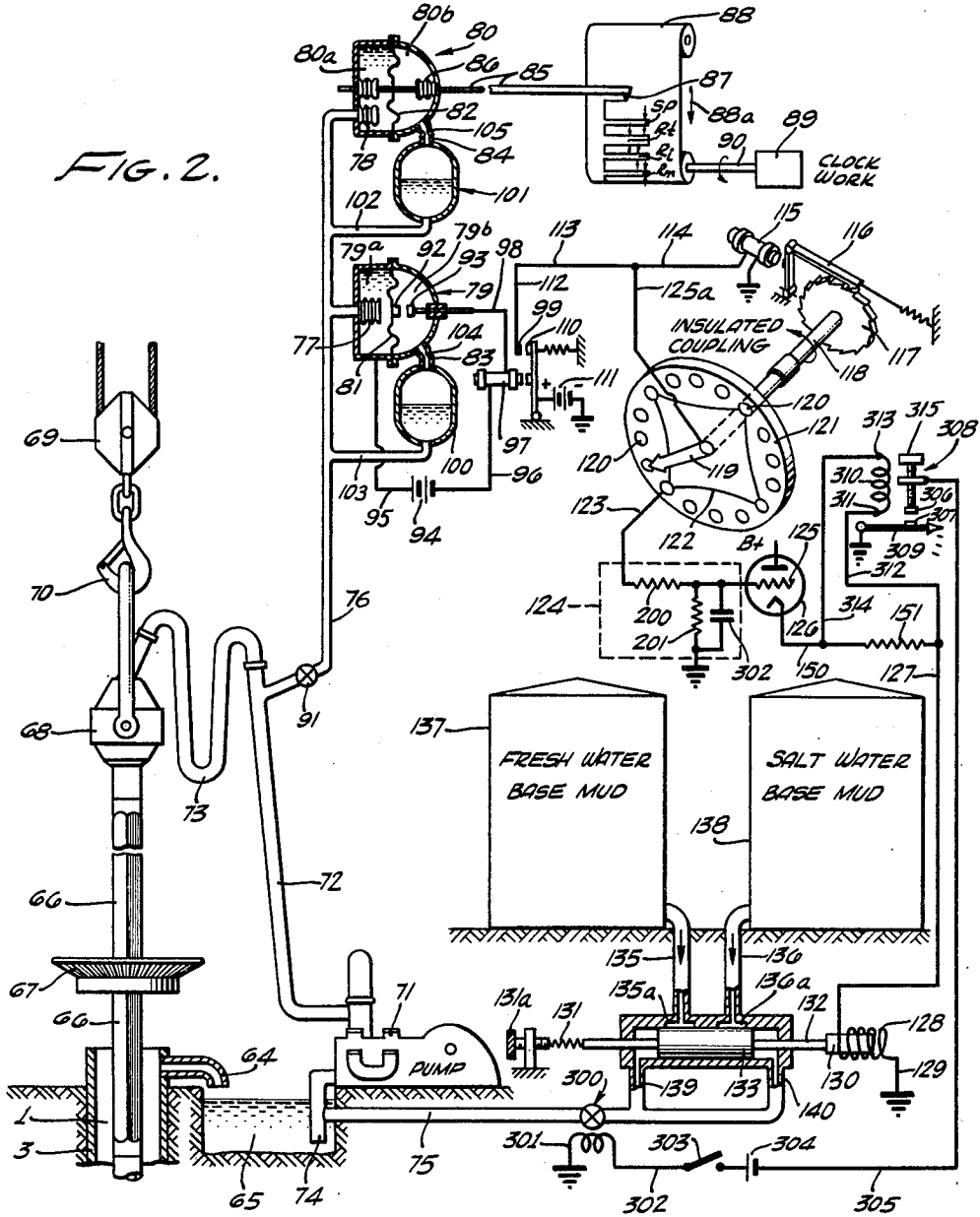


FIG. 3.

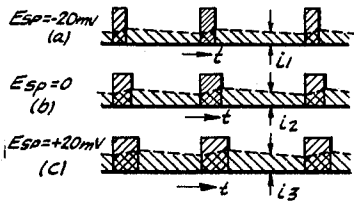
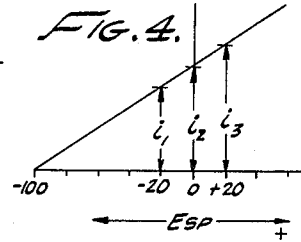


FIG. 4.



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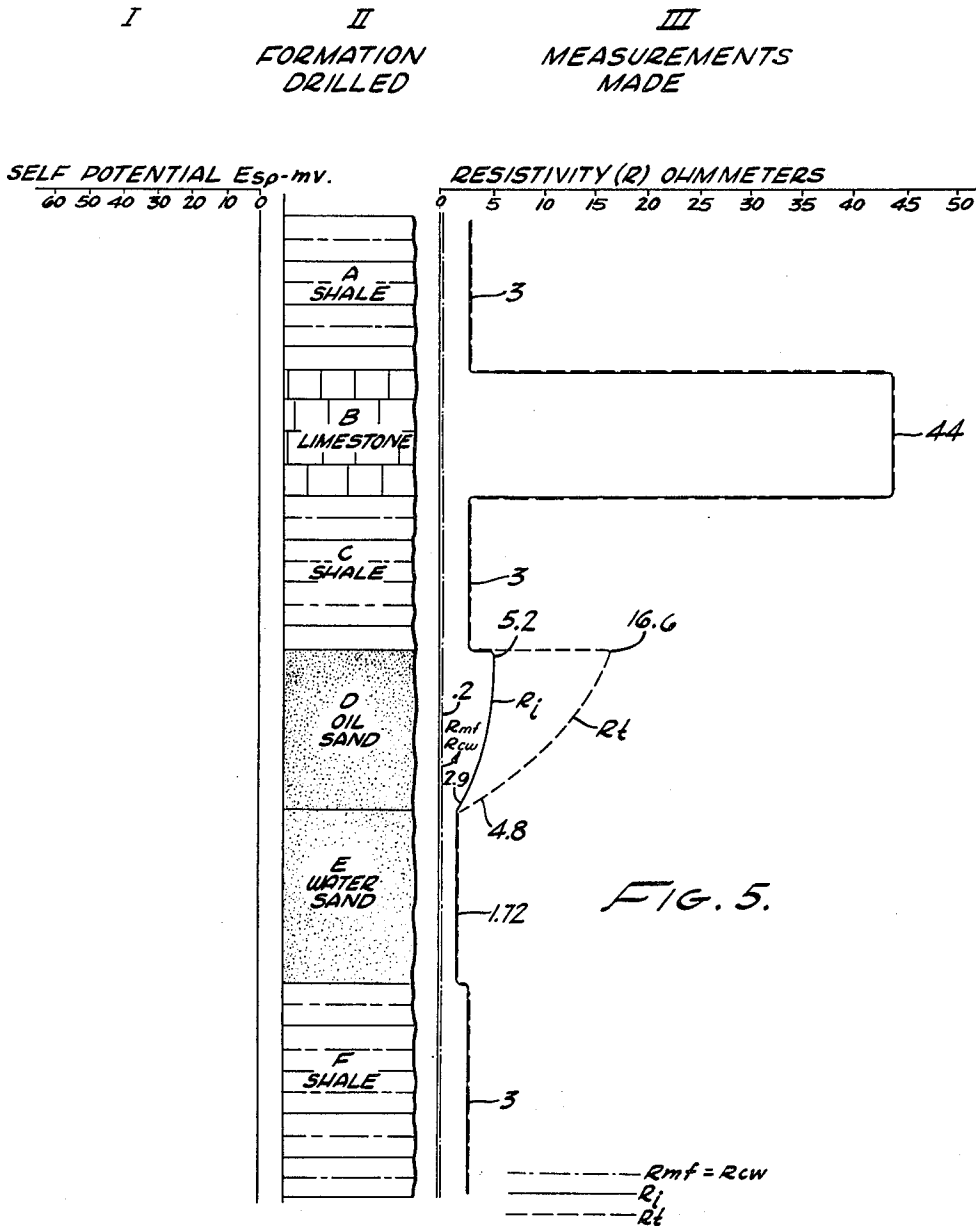
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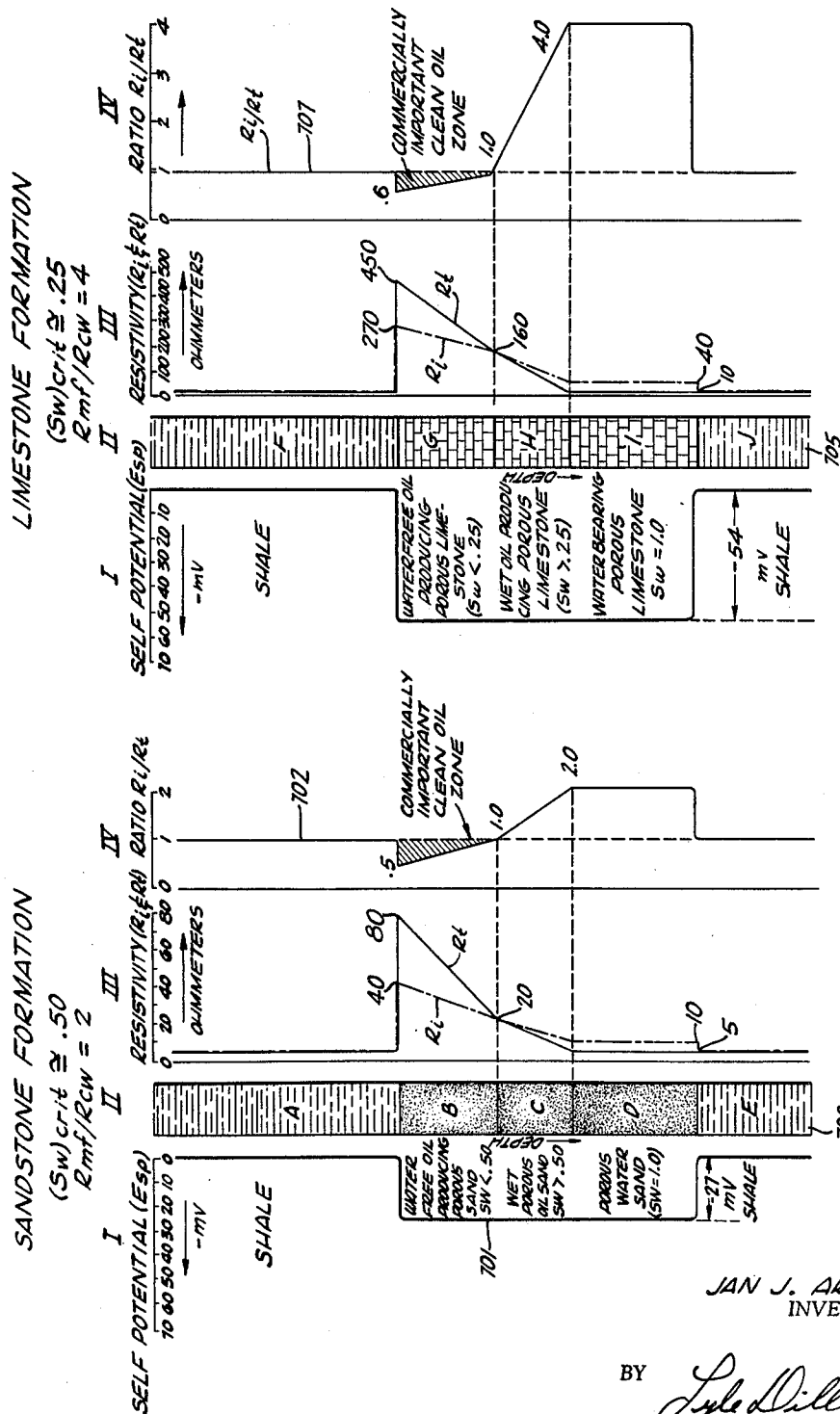


FIG. 7.

FIG. 6.

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2,938,708

SIMULTANEOUS DRILLING AND ELECTRICAL LOGGING OF HYDROCARBON CONTENTS OF FORMATIONS

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28 Claims. (Cl. 255—1.8)

This invention relates generally to well and earth borehole logging, and more specifically to the determination of the character of earth strata penetrated by well boreholes, particularly the character of the connate or interstitial fluid content thereof.

This application is a continuation-in-part of copending application Serial No. 346,457, filed April 2, 1953, now abandoned.

In drilling wells by means of conventional rotary drilling methods, drilling fluid comprising a mixture of clay and water, sometimes referred to as "drilling mud," is circulated down through the rotating drill string to the drill bit, from where it returns to the surface through the annular space between the drill string and the wall of the borehole.

Cuttings or samples of the formation freshly penetrated by the drill are carried by the returning drilling mud stream to the surface, and careful inspection of these samples, together with observation of any oil or gas which may be present in the returning mud stream, may provide clues regarding potential oil- or gas-producing horizons which may have been encountered. If such indications are favorable, it is customary in conventional rotary drilling practice to withdraw the drill string from the hole and run in with a core bit to secure a core of the formation in question, or to run a drill stem test to test the productivity of the formation. An alternative method is, after withdrawing the drill string, to run a conventional electric logging device on a conductor cable into the borehole to measure the formation resistivity and the natural or self-potential existing at various depths in the borehole.

Such electrical measurements made after the drilling of the borehole may provide some indications of possible productivity of certain of the penetrated formations, although the fact that the penetrated porous formations will have been invaded by the mud filtrate by the time the electrical log is made, makes accurate interpretation of such logs in terms of porosity and potential productivity very difficult and often misleading.

It is therefore, an object of primary importance of this invention to furnish a logging system by means of which a log can be made capable of positively identifying penetrated formations that contain oil, gas or the like nonconductive fluid.

Another object of primary importance of this invention is to provide a new electrical logging method of operation and apparatus therefor by which electrical logs of earth boreholes can be made which directly indicate porous and permeable formations which contain oil, gas or the like nonconductive fluid contents.

Another primary object of this invention is to furnish a method and means for continuous electrical logging from which information may be had for determining the connate or interstitial water content and the formation factor (or porosity) of formations penetrated by the borehole as well as the ability of these formations to produce waterfree oil or gas.

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Since the drilling fluid or mud used in conventional rotary drilling is almost always of a lesser salinity than the connate water present in the formations penetrated, certain osmotic effects are set up, particularly between the penetrated shales and the mud fluid, which cause these shale formations to absorb water from the mud, often with consequent swelling, crumbling and sloughing of the shales into the borehole. It is a common experience in rotary drilling, when caliper logs are run afterward, to find the borehole through such shale formations very much enlarged. This sloughing of the shale formations is well known as a common cause of the sticking of drill pipe when circulation is interrupted for some reason, such as for the addition of another stand or joint of pipe to the drill string, or the like operation. In extreme cases, the so-called heaving effect of such shales caused by such absorption of water, when drilled with conventional drilling mud, may even be so severe that drilling operations cannot be continued.

Potentially productive sands also frequently contain small quantities of shale, silt, colloidal clay, or bentonite. Contact thereof with a drilling fluid of a lower salinity than that of the connate water contained in such formations causes these shaly or benonite substances to absorb water and swell, thereby closing the pores of the potentially productive formation. This phenomenon is well known as one of the major reasons why certain oil-bearing formations cannot be made to produce properly after being exposed to fresh water muds.

In previous attempts to prevent these detrimental osmotic effects between the drilling fluid and the connate, interstitial waters of the formations and the consequent hydration of the colloidal shales therein, high salinity muds have been employed, but the choice of the salt concentrations of such saline drilling muds has been based only haphazardly on general experience in a given area.

Another object of this invention is, therefore, to furnish a method and apparatus for maintaining continuous control of the salinity of the mud in the drilling fluid circulatory system in such a way as to systematically and accurately maintain the salinity of the mud filtrate at a known value which bears a predetermined relation to the value of the salinity of the connate water in the formation being drilled at the bottom of the borehole. When the salinity of the mud filtrate is equal to or greater than that of the connate water, the osmotic effects between the shales and the drilling mud are found to be substantially eliminated, thereby preventing hydration of the shales and the before-mentioned sloughing and caving of the colloidal shaly sections with the consequent formation of enlarged cavities and danger of freezing the drill pipe and bit.

Another object of this invention is to prevent hydration of the shaly and colloidal material contained within silty or shaly productive sands by maintaining the salinity of the drilling mud substantially equal to that of the interstitial, connate water in the formation, thereby avoiding the reduction of the producing ability of such oil-bearing strata.

The objects of this invention are accomplished, in brief, by continuously, during drilling, adjusting the drilling mud salinity to maintain a given predetermined relationship between the drilling mud salinity and the connate water salinity of the penetrated formation, and while maintaining such conditions, measuring the resistivity of the penetrated formation both before and after invasion thereof by the mud filtrate, measuring the resistivity of the mud filtrate itself under bottom hole conditions, and then transmitting these measurements continuously from the bottom of the borehole to the surface during drilling. Since a connate water content or saturation of less than 100% in porous formations indicates the presence in the

pore spaces of insulating material, such as gas, oil or other hydrocarbons, the practice of this invention in wells drilled for oil or gas thus provides the operator with a continuous oil- or gas-detecting tool with which to explore the formations traversed.

Research by various investigators during the past twenty years has clarified the physical principles which cause the phenomenon of natural or spontaneous electrical potential in earth boreholes. One of the most recent investigators who defined the quantitative aspects of the self-potential in boreholes is M. R. J. Wyllie, who published the results of his work in a recent book, which also contains a discussion and references on earlier work on this subject: "The Fundamentals of Electric Log Interpretation," Academic Press Inc., New York, 1954.

According to these investigations the basic relationship which appears to correlate best with field-observed data reads:

$$E_{sp} = K \log_{10} R_{mf}/R_{cw} \quad (1)$$

in which E_{sp} is the amplitude of the self potential deflection, in millivolts, measured from the shale or base line, R_{mf} is the electrical resistivity of the mud filtrate in ohmmeters, R_{cw} is the electrical resistivity of the interstitial or connate water, in ohmmeters, and K is a constant which appears to vary between -70 and -110 ; the low value applying to shaly sands, whereas higher values are more common in carbonate rocks. For wells drilled in the Rocky Mountain area of the United States an average empirically derived constant K of -90 appears to be the most satisfactory (see "Electric Log Analysis in the Rocky Mountains" by M. P. Tixier, Oil and Gas Journal, June 23, 1949).

From the foregoing it is apparent that the self potential (E_{sp}) is directly indicative of the ratio of the resistivity of the drilling mud filtrate (R_{mf}) to the resistivity of the connate or interstitial water (R_{cw}). The resistivity of the connate or interstitial water (R_{cw}) is a characteristic of a formation which is normally unknown and obviously cannot be changed or controlled. On the other hand, the resistivity of the mud filtrate (R_{mf}) can be controlled by adding salt water or salt water base mud to the circulating drilling mud stream to decrease its resistivity (R_{mf}) or by adding fresh water or fresh water base mud to the stream to increase its resistivity (R_{mf}).

Inasmuch as the ratio of the resistivity of the drilling mud filtrate (R_{mf}) to the resistivity of the connate or interstitial water (R_{cw}) as hereinbefore stated, is indicated by the value of the natural or self-potential (E_{sp}), an important feature of this invention resides in the continuous observation or measurement of the value of the self-potential of the formation being penetrated by the drill at the bottom of the borehole, and guided by or in response thereto varying or adjusting the salinity of the circulating drilling mud in the before-described manner, as it is pumped down the drill stem into the borehole, so as to maintain at the bottom of the borehole a resultant, predetermined value of self-potential (E_{sp}) for the formation in question being drilled. For example, if a ratio of (R_{mf}/R_{cw}) = 2 is chosen to be maintained within the borehole, then, in accordance with the hereinbefore discussed Equation 1 when the constant -90 is employed,

$$E_{sp} = -90 \log_{10} (R_{mf}/R_{cw})$$

the value of the self-potential (E_{sp}) would be maintained at -27 millivolts. On the same basis, by adjusting the salinity of the drilling mud such that the self potential (E_{sp}) is maintained at -54 millivolts the ratio of (R_{mf}/R_{cw}) will be maintained at a value of 4.

In the same manner, if it is desired to maintain the salinity and resistivity of the mud filtrate R_{mf} at substantially the same value as that of the interstitial or connate water R_{cw} , so that $R_{mf}/R_{cw} = 1$, the self potential E_{sp} would have to be maintained at zero value.

As hereinbefore mentioned, in the practice of this in-

vention, the self-potential effect of the formation being drilled at the bottom of the borehole is continuously utilized to keep the ratio of the resistivities of mud filtrate and interstitial water of the formation being drilled at substantially the predetermined, chosen value. At the same time, the formation resistivity R_t (before invasion) and resistivity R_i (after invasion) are, in a manner herein-after more fully described, continuously measured and telemetered to the surface during drilling, and recorded there so that a prompt evaluation of the interstitial water saturation (S_w), and hence the oil- or gas-productive possibilities of a new formation encountered, may be had and proper measures taken to drill-stem test such a formation and, if oil or gas is thereby found to be present, complete the well for production from such formation.

In order to produce such a continuous log of the formation, in accordance with this invention, measurements of the electrical resistivity (R_m) of the drilling fluid or mud at the bottom of the hole are made continuously while drilling, which measurements are relayed to the surface continuously.

After application of a minor correction factor to these measurements (R_m) which has previously been established for the type of drilling fluid or mud used ("Relationship of Drilling Mud Resistivity to Mud Filtrate Resistivity," by H. W. Patnode, Trans. A.I.M.E. (1949), 186, 14-16) the operator converts the mud resistivity (R_m) measured under bottom hole conditions to the mud filtrate resistivity (R_{mf}) under the same conditions, which, as before mentioned, may be maintained equal, or at a predetermined ratio, to the electrical resistivity of the interstitial water in the formation. The mud filtrate resistivity (R_{mf}) can also be measured in the mud stream at the surface and corrected to bottom hole conditions by taking into account the difference in resistances caused by the higher temperature existing at the bottom of the borehole.

It is also an important feature of this invention to utilize the factors obtainable by the foregoing procedure to gain more quantitative information as to the character and fluid contents of drilled formations by means of which not only the oil- or gas-containing formation can be located but the portions of such formations chosen which will be commercially productive.

The following relationships between the characteristics of the reservoir rock and the fluids contained therein have been established. ("The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics," G. E. Archie, Trans. A.I.M.E. (1942), vol. 146.)

$$R_t = FR_{cw}/(S_w)^2 \quad (2)$$

$$R_i = FR_{mf}/S_{iw}^2 \quad (3)$$

where F is the formation factor, S_w and S_{iw} are the fractional degrees of water saturation of the pores of an oil-bearing formation respectively before and after invasion by the mud filtrate, and where, as beforementioned, R_{mf} and R_{cw} are the resistivities of the mud filtrate and the connate water of the formations, and R_t and R_i are the measured resistivities of the formations prior to invasion and subsequent to invasion, respectively.

The following empirical relationship also appears valid for certain invaded porous oil-bearing formations ("Electric Log Analysis in the Rocky Mountains" by M. P. Tixier, Oil and Gas Journal, June 23, 1949):

$$S_{iw} = (S_w)^{1/2} \quad (4)$$

From a combination of the foregoing Formulae 2, 3 and 4 the following formula is obtained:

$$S_w = (R_i/R_t) \cdot (R_{cw}/R_{mf}) \quad (5)$$

Since the interstitial water salinity generally increases with depth, the mud filtrate salinity will, in the practice of this invention, likewise be increased with depth of the borehole as drilling progresses, and therefore will generally be higher than the salinity of the connate or interstitial water in the previously penetrated formations

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higher up in the borehole, thereby insuring the avoidance of the hydration of those overlying shaly formations, which would take place with conventional fresh water drilling fluids.

These and various other objects, advantages and features of novelty of the invention will become apparent from the following more detailed description of the invention.

In the drawings, which show, by way of illustration, a preferred embodiment and the best mode contemplated for carrying out the invention, and in which like reference characters designate the same or similar parts throughout the several views:

Figure 1 shows a cross-section of the lower end portion of a drilling well borehole in which subsurface apparatus of this invention is illustrated;

Figure 2 shows the upper end portion of the borehole of Figure 1 in which the surface apparatus of this invention is illustrated;

Figure 3 shows graphically the electrical characteristics of a subsurface portion of the electrical apparatus of Figure 1;

Figure 4 shows graphically the electrical characteristics of a subsurface portion of the electrical apparatus of Figure 1;

Figure 5 shows an example of the type of logging measurements obtained continuously while drilling, while maintaining the ratio of (R_{mf}/R_{cw}) equal to 1;

Figure 6 shows an example of the type of logging measurements obtained continuously while drilling, while maintaining the ratio of (R_{mf}/R_{cw}) equal to 2; and

Figure 7 shows an example of the type of logging measurements obtained continuously while drilling, while maintaining the ratio of (R_{mf}/R_{cw}) equal to 4.

Referring now primarily to Figure 1, the numeral 1 indicates a borehole being drilled in the earth 2 by means of conventional rotary drilling apparatus. The upper part of this borehole is lined with the usual steel surface casing 3. The rotary drill string 4, suspended from a conventional drilling rig as partially illustrated in Figure 2, supports an insulated drill collar 5, to the lower end of which is attached a rotary drill bit 6. The drill collar 5 is insulated externally by a jacket or covering 7 of a suitable insulating material such as rubber or Bakelite, and it is lined internally in the fluid passage with a covering or tubular lining 8 of similar insulating material. The top and bottom portions of the drill collar 5 are electrically insulated one from the other, between corresponding threaded portions thereof, by means of a bushing 9 of suitable insulating material.

On the outside of the insulating jacket 7 of drill collar 5 is positioned a metal electrode 31. This electrode is preferably ring-shaped and is located a sufficient distance above bit 6 so that invasion of a porous formation by rotary mud filtrate has ample time to take place between the time such formation is first penetrated by the bit 6 and the time when sufficient additional drilling has taken place to bring the electrode 31 opposite the same formation. The resistivity measured by this electrode 31 will therefore be essentially the resistivity (R_i) of the invaded formation, while the resistivity measured at the drill bit 6 will be essentially the true resistivity (R_t) of the formation before invasion by drilling mud filtrate.

The upper part of drill collar 5 is equipped with a metal electrode 104 which is located within the drilling fluid passage and supported by and insulated from the drill collar by suitable insulating material 105. Measurement of the resistivity (R_m) of the drilling mud between this electrode 104 and the surrounding grounded metal portion of the drill collar fluid passage will be representative of the resistivity (R_{mr}) of the mud filtrate under bottom hole conditions, for a given drilling mud. The drill collar 5 is equipped with suitable logging instrumentation located within the drill collar inside of a suitable fluid-tight container (not shown) diagramma-

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tically illustrated by the broken line enclosure 10. The drill collar 5 is also equipped with an electromagnetically-operated mud valving mechanism, the valving portion 15 of which is controlled by the before-mentioned logging instrumentation in the container within the drill collar. Both the logging instrumentation in the container and the electromagnetically-operated mud valving mechanism are shown diagrammatically within the dashed rectangle 10 to the right of the sectional elevation of the borehole in Figure 1.

The instrumentation necessary for the logging operations is activated by a switching mechanism shown diagrammatically within the dot-dashed rectangle 48. The source of power 11 for the logging and signaling apparatus may be of any suitable type, such as, for example, a drilling mud turbine-operated alternating current generator or a conventional battery-operated A.-C. supply. One terminal of such a power supply 11 is connected through a lead 12 to a common ground 13, which corresponds to the upper portion of the insulated drill collar 5, and the drill string thereabove.

The other side of the A.-C. supply 11 is connected through lead 14 to one end of the windings 16 of the electromagnetically-operated valve 15. This valve may be of any suitable type, such as that, for example, shown in the copending application of Otis and Alder, Serial No. 237,786, filed July 20, 1951, now Patent No. 2,700,131, and is adapted to throttle or impede the flow of mud through the drill collar whenever its electromagnet is energized. The other end of the windings 16 of the electromagnet is connected by means of lead 17 to an anode 18 of a Thyatron 19. This gas-filled tube 18 will become conductive whenever the potential of grid 20 is above a certain predetermined value relative to the cathode, thereby closing the circuit from A.-C. source 11 through lead 14, windings 16 and lead 17 to ground 13. Valve 15 will thereby be moved to a throttling or flow-impeding position whenever the Thyatron is conductive, which, in turn, as beforementioned, is governed by the potential on grid 20 relative to the cathode.

Terminal 21 of A.-C. current supply 11 is also connected through lead 22 and lead 23 to terminal *b* of the mud filtrate resistivity (R_{mf}) measuring device illustrated within the rectangular enclosure 100. At the same time this terminal is connected through leads 24, 25, and 26 to the *b* terminals of the invaded zone resistivity (R_i) and true resistivity (R_t) measuring devices, respectively designated by numerals 101 and 102.

These and other terminals correspond to the terminals designated by the same letters on the switching device diagrammatically shown within dot-dashed rectangle 48. This switching device 48 may be located within the same container 10 within the drill collar which houses the logging instrumentation. The switching device comprises a series of three stationary, insulated discs 26 provided with electrical contact strips 27 located in prearranged, spaced-apart positions around the periphery of each disc. A common shaft 28, which is lengthwise electrically interrupted by suitable insulating couplings between discs, is driven by suitable drive means, such as, for example, a clockwork mechanism 29, and serves to rotate the three sliding contacts 30 fixed thereto at a constant rate and in synchronism. Whenever these contacts 30 touch the conductive strips 27, electrical contact is thereby made between the separate center connections *b*, *d*, and *e* of the discs and the metal strips 27. The drive mechanism 29 is designed to operate in such a manner that one complete revolution of shaft 28 corresponds to one complete logging cycle consisting of measuring and transmitting in succession: (1) mud resistivity (R_m), (2) mud filtrate-invaded formation resistivity (R_i), (3) true uninvaded formation resistivity (R_t), and (4) natural potential or self-potential (E_{sp}).

By the proper location and length of the peripheral contact strips 27, the before-mentioned sequence of mak-

ing four independent measurements and the sending of four different signals are made to occupy four-fifths of one full revolution of shaft 28. During the remaining one-fifth revolution, no contacts are made, and both measuring and signaling devices are disconnected. This period of silence or absence of signalling occurring after every four signals serves to identify the beginning and end of the cycle from which the four-intervening signals may also be identified individually.

Whenever sliding contacts 30 are in the position I indicated in Figure 1, contact is made between terminals *b* and *a*, thereby admitting alternating current to the network consisting of resistor 32, resistor 33, and the conductive path, having resistance (R_m) through the borehole mud present between electrode 104 and the surrounding grounded metal of the fluid passage within drill collar 5.

Since the resistance of resistor 32 is made large compared to the resistance of the drilling mud between the electrode 104 and the surrounding walls of the drilling fluid passage, the current through this resistor 32 is essentially constant. At the same time, the resistance of resistor 33 is also chosen such that it is large with respect to the same mud resistance, so that the voltage at point 34 is, therefore, essentially proportional to the mud resistivity (R_m) opposite electrode 104. This alternating voltage at point 34 is then applied through lead 35 and condenser 36 to the primary winding 37 of a transformer 43.

The purpose of transformer 43 is to step up the voltage applied to the primary winding 37. One terminal of the secondary winding 38 of this transformer 43 is connected through lead 39 to rectifier 40, and the resulting unidirectional current is then applied through lead 41 to condenser 42. The other terminal of condenser 42 is connected to the ground terminal of the secondary winding 38 of the transformer 43. During the period when terminals *a*₁ and *b* are connected, therefore, condenser 42 will be charged to an electrical potential difference which is proportional to the resistivity of the borehole mud (R_m) or for a given drilling mud to a voltage indicative of the resistivity of the drilling mud filtrate (R_{mf}) in the vicinity of electrode 104.

Whenever drive means 29 moves the sliding contacts 30 from position I into position II, contact between terminals *a*₁ and *b* is broken, and contact is next made between terminals *c*₁ and *d*. When such contact is made, condenser 42 discharges through lead 44 and resistor 45 to ground.

The resistance of resistor 45 is chosen with a value which brings the length of time for condenser 42 to discharge therethrough within the desired limits of operation of valve 15. During this period of discharge of condenser 42, terminal 46 of resistor 45 will, due to the voltage drop across resistor 45, have a positive potential of sufficient magnitude to overcome the negative bias of battery 47 so that grid 20 of Thyatron 19 will assume a positive potential relative to the cathode. When this occurs, the gas in the Thyatron tube 19 becomes ionized and the tube becomes conductive, thereby activating the electromagnet 16 and moving the electromagnetically operated valve 15 into a fluid-flow throttling position. As soon as condenser 42 is discharged through resistor 45, the positive potential at terminal 46 disappears and the bias battery 47 renders grid 20 negative, thereby terminating the current passage through the electromagnet windings 16 and through the Thyatron 19. The duration of the interval when valve 15 is in a throttling position is, therefore, proportional to or indicative of the potential on condenser 42 and hence proportional to or indicative of the resistivity (R_m) of the borehole mud in the vicinity of the electrode 104. For a given mud, therefore, the duration of the interval when valve 15 is in a throttling position will be proportional to or indicative of and can

be calibrated in terms of the resistivity (R_{mf}) of the mud filtrate.

During the throttling position of valve 15, the pressure on the mud system at the surface increases, and the duration of the resultant pressure pulse received or observed at the surface is therefore representative of and may be made to give an indication or to make a record which is indicative or representative of the resistivity (R_{mf}) of the borehole mud filtrate in the vicinity of electrode 104.

When drive means 29 moves the sliding contacts 30 to the position III, as indicated in Figure 1, electrical contact is made between terminals *a*₂ and *b*, thereby activating a resistivity measurement of the invaded formation near the electrode 31. The instrumentation and operation of the invaded zone resistivity measuring device 101 are identical to those described heretofore for the mud resistivity measuring device 100. In a manner as described hereinbefore, condenser 42a is charged to a potential difference substantially proportional to the resistivity of the invaded borehole formation near electrode 31.

Whenever drive means 29 moves contacts 30 to position IV, terminals *a*₂ and *b* are disconnected and terminal *c*₂ is connected to terminal *d*, so that condenser 42a will be discharged through resistor 45, thereby actuating the electro-magnetically operated valve 15 in a manner similar to that described hereinbefore. The pressure pulse created in the mud system by the throttling action of valve 15 during this part of the cycle has a duration, therefore, which is proportional to or representative of the resistivity of the invaded formation near electrode 31.

Whenever drive means 29 moves sliding contacts 30 to position V, as indicated in Figure 1, electrical contact is made between terminals *a*₃ and *b*, thereby activating a resistivity measurement (R_{cw}) of the uninvaded formation near the drill bit 6 at the bottom of the hole. The instrumentation and operation of the true resistivity measuring device 102 are in principle identical to those described hereinbefore for the mud resistivity measuring device 100. In the same manner as described hereinbefore, condenser 42b is charged to a potential substantially proportional to the resistivity of the uninvaded formation near bit 6.

Whenever drive means 29 moves sliding contacts 30 to position VI, terminals *a*₃ and *b* are disconnected and terminal *c*₃ is connected to terminal *d* so that condenser 42b is discharged through resistor 45, thereby actuating electromagnetically-operated valve 15 in a manner similar to that described hereinbefore. The pressure pulse created in the mud system by the throttling valve 15 during this part of the cycle has a duration, therefore, which is proportional to or indicative of the resistivity of the uninvaded formation near the bit 6.

Whenever drive means 29 moves contacts 30 to position VII, as indicated in Figure 1, electrical contact is made between terminals *a*⁴ and *e*, thereby activating a measurement of the self-potential or natural potential (E_{sp}) existing in the borehole drilling mud as picked up by the drill bit 6. The natural potential or self-potential measuring device 103 is shown schematically within the dot-dashed rectangle 103 in Figure 1. The potential difference existing between the drill bit 6 and the grounded upper portion of drill collar 5 and drill string 4, which is substantially equal to the self-potential (E_{sp}) appearing between the drill bit 6 and the adjacent formation being drilled thereby, is applied through lead 48 to choke coil 49 to eliminate any undesirable A.-C. components. The output terminal 50 of choke coil 49 is connected to a resistance network 51 consisting of a bias battery 52 and two resistors 53 and 54. Resistor 54 has a resistance of, for example, 1400 ohms, while resistor 53 has a resistance of only 100 ohms. The one-cell battery 52 will therefore create a bias voltage between terminal 50 and terminal 55 of the order of 100 millivolts.

Since the self-potential or natural potential (E_{sp}) input under normal operating conditions will rarely ex-

ceed a negative value of -100 millivolts, it is obvious that the potential at terminal 55 will always be positive with respect to ground. This potential at terminal 55 is then applied to a vibrator-type inverter network 56 of conventional design which produces at the output terminals 57 and 58 of the secondary winding 59 of transformer 60 an alternating voltage which will be substantially proportional to or a function of the before-mentioned self-potential or natural potential at the bottom of the borehole, plus a constant bias voltage to make the potential applied to the self-potential measurement network always positive. Terminal 57 of transformer 60, which corresponds to electrical contact a_4 , is, when contacts 30 are in position VII, connected to terminal e and through rectifier 61 to terminal 62 of condenser 42c. The other side of this condenser is connected to the grounded terminal 58 of the secondary winding 59 of transformer 60.

Whenever drive means 29 moves the contacts 30 to position VIII, electrical contact between terminals a_4 and e is disrupted and contact is made between terminals c_4 and d . Whenever such contact is made, condenser 42c will discharge through leads 63, 44 and resistor 45 to ground, thereby actuating the electromagnetically-operated valve 15 in the same manner as described hereinbefore. The duration of this throttling period of the electromagnetically-operated valve 15 will be substantially proportional to or representative of the magnitude of the self-potential (E_{sp}) at the bottom of the borehole plus the before-mentioned constant amount of bias voltage. The duration of this pressure pulse observed or recorded at the surface is therefore a measure of or representative of this self-potential.

When drive means 29 moves the contacts 30 to the position IX, all contacts are opened and remain so during this last one-fifth of the logging cycle, and during this time interval no measurements are made or transmitted. As mentioned hereinbefore, this period of silence serves as a reference signal for identifying the four different measurement pulses transmitted in the cycle.

Now, referring again principally to Figure 2, a sectional elevation of the upper part of borehole 1 is shown, lined with steel surface casing 3, which is provided with a side outlet 64 for discharging the returning drilling mud into mud pit 65. Extending into borehole 1 is a kelly 66 rotated by a rotary table 67 of conventional design. Kelly 66 is supported by swivel 68, which in turn is suspended from traveling block 69 by means of hook 70. Drilling mud is circulated through the entire system in a conventional manner by mud pump 71, which discharges through standpipe 72 and rotary hose 73 into swivel 68 and kelly 66, and then down through the drill stem to be discharged through the drill bit in the bottom of the borehole, from whence it flows upward in the annular space in the borehole to the top of the borehole and return to the mud pit, as before mentioned. The suction pipe 74 of mud pump 71 extends into mud pit 65. A separate feed line 75 is connected to suction pipe 74 to admit either salt water base mud or fresh water base mud to the circulating system to adjust the salinity of the drilling mud, as will be described hereinafter.

The drilling mud pressure in the top of the drill string and in standpipe 72 is applied through a branch pipe connection 76 and thence through lateral pipe connections and bellows 77 and 78 to suitable pressure pulse detecting devices 79 and 80. These pressure pulse detecting devices 79 and 80 as herein illustrated are pressure chambers each provided with a transverse, pressure-sensitive membrane or diaphragm 81 and 82 respectively dividing chambers 79 into two opposite compartments 79a and 79b and similarly dividing chamber 80 into two opposite compartments 80a and 80b. Compartments 79a and 80a, into which the bellows 77 and 78 respectively extend, are filled with oil or other suitable liquid. The compartments 79b and 80b are maintained filled with a suitable

gas. Compartments 79a and 79b are interconnected by a pressure equalization system comprising tube 83, pressure fluid accumulator reservoir 100 and pipe 103 which make connection with the lateral pipe leading from branch pipe 76 to the bellows 77. Similarly, compartments 80a and 80b are interconnected by a pressure equalization system comprising tube 84, pressure fluid accumulator reservoir 101 and pipe 103 which makes connection with the lateral pipe leading from branch pipe 76 to the bellows 78.

The pressure accumulator reservoirs are maintained partially filled with liquid under pressure from the branch pipe 76, the top portions thereof forming gas spaces which are connected to the gas-filled compartments 79b and 80b through the beforementioned tubes 83 and 84 respectively. Tubes 83 and 84 are preferably provided with capillary or orifice means 104 and 105 such that pressure differences across the diaphragms 81 and 82 of comparatively short duration, such as applied by fluid signal pulses, will not be quickly equalized, but will cause movement of the diaphragms substantially in accordance with the duration of the signal pulse, but will permit equalization of pressure differences thereacross of relatively long duration. Thus pressure changes due to general changes in the drilling mud pressure in the circulating system will not result in any appreciable movement of the diaphragms. The signal pulse induced movements of diaphragm 82 are transmitted through rod 85 which extends through fluid seal bellows 86, to pen 87 of recorder 88. Recorder 88 is operated by a suitable drive mechanism 89, which may be a clockwork mechanism, which, by means of shaft 90, moves the paper record strip of recorder 88 in a downward direction, as indicated by arrow 88a, at a constant rate and in correlation with a known time reference, so that the time duration and time of occurrence of each of the signal pressure pulses is continuously recorded thereon.

A throttling valve 91 may be provided in line 76 to dampen out high frequency, small amplitude pressure fluctuations, such as generated by the reciprocating action of mud pump 71, but which will pass the pressure pulses of longer duration constituting the logging measurement signals.

Each time a logging signal pulse is applied to pressure detecting device 79, electrical contact is made between movable contact point 92, attached to diaphragm 81, and stationary contact point 93. This closes the electrical circuit from battery 94 through leads 95, 96, relay electromagnet coil 97 and lead 98. Whenever the relay electromagnet coil 97 is thus energized, it moves contact point 110 into electrical contact with point 99, thereby connecting the battery 111 through the ground connection and through leads 112, 113 and 114 to relay electromagnet coil 115.

The relay coil 115 is thus energized each time a pressure pulse signal arrives at the surface, and at such times it attracts armature 116 of ratchet device 117, thereby rotating shaft 118 stepwise through a predetermined angle in a counterclockwise direction. Rotation of shaft 118 moves electrical contact arm 119 fixed thereto, correspondingly stepwise into contact with each of a series of contacts disposed in a circle on stationary insulating disc 121. It may be noted that every fourth contact 120 on disc 121 is connected together through common leads 122, and these leads are in turn connected through lead 123 to a filter circuit 124. The ratchet device 117 is adjusted and synchronized with the sequences of fluid pressure signal pulses such that the contacts 120, which are connected to leads 122, will be in electrical contact with sliding contact arm 119 only during the time when a self-potential pressure pulse signal arrives at the surface.

Sliding contact arm 119 is in turn connected through lead 125a to lead 113, by means of which the voltage of battery 111 is applied through contacts 110, 99, leads 112, 113, 125a, sliding contact arm 119, contacts 120 and leads 122 to the input lead 123 of filter network 124,

each time a self-potential signal pulse arrives at the top of the drill string. The duration of each of these self-potential signal pulses, as discussed hereinbefore, is proportional to or indicative of the magnitude of the self-potential picked up at the bottom of the borehole plus the beforementioned constant amount of bias voltage.

Filter network 124, consisting of resistors 200, 201 and condenser 202, is designed to have a sufficiently long time constant to convert the electric signal pulses, applied through lead 123, into a unidirectional potential output having an average value which is proportional to the duration of these input pulses and therefore also proportional to the self-potential or natural potential plus the constant bias voltage.

The characteristic operation of the filter network 124 is illustrated in Figure 3(a), (b) and (c), in which are graphically plotted, with respect to time, a series of typical current pulses arriving through lead 123 at the input of network 124, such current pulses corresponding, for example, to self-potential values of -20 mv., 0 mv., and $+20$ mv., respectively. The resultant, substantially continuous current i_1 , i_2 and i_3 , respectively, which will flow through resistor 201, is proportional to the average duration of the respective self-potential pressure signal pulses. Figure 4 illustrates the over-all relationship between the current through resistor 201 of the filter network 124 and the self-potential at the bottom of the borehole. It may be observed from this figure that there is a linear relationship between the magnitude of current i and the self-potential (E_{sp}) and that, due to the constant bias voltage supplied by battery 52, these current values under normal conditions will always be positive.

The current i through resistors 200 and 201 of filter network 124 results in a proportional voltage drop there-through which is applied to the grid 125 of triode 126. The cathode of triode 126 is connected through lead 150, resistor 151 and conductor 127 to the windings of solenoid 128, the other terminal of which is grounded through lead 129. The position of the plunger 130 of the solenoid 128, which is also affected by the biasing tension of a spring 131 as adjusted by tension adjusting screw 131a, is governed by the cathode current passing through triode 126 and is, therefore, in turn controlled by the voltage on grid 125.

The plunger 130 is connected through rod 132 to a balanced valve 133 operating within cylinder 134. The position of valve 133 with respect to inlet ports 135a and 136a in the cylinder 134 governs the rate of admission of fresh water base mud from storage tank 137, or salt water base mud from storage tank 138, respectively, to cylinder 134 and thence through pipes 139 and 140 and through pipe 75 into the before-mentioned suction pipe 74 of mud pump 71.

The solenoid-operated mud control valve 133 therefore admits either salt water base mud or fresh water base mud into the mud circulatory system at a rate depending on the magnitude of the current passing through solenoid 128 and the adjustment of the tension of spring 131, and hence depending on the value of the grid voltage of triode 126, which in turn depends on the duration of the self-potential pressure signal pulses arriving at the surface. Thus, whenever the salinity of the borehole mud is less than that necessary to maintain the predetermined ratio thereof with respect to the salinity of the connate water in the formation, a negative self-potential in excess of the predetermined value is generated at the bottom of the borehole, which, added to the beforementioned positive bias voltage, causes a self-potential signal fluid pulse of fairly short duration to be transmitted and to appear in the drilling fluid stream at the surface. This short pressure pulse, connected to a corresponding electric signal pulse as beforementioned, results in a lowered average potential on the grid of triode 126, thereby decreasing the average current flow through the triode 126 and solenoid 128 and thereby permitting valve 133 under

influence of the biasing spring 131 to move to the left, as viewed in Figure 2, thereby admitting through pipe 136, inlet port 136a and pipes 140 and 75, concentrated salt water base mud into the drilling mud circulating system, which shortly thereafter raises the over-all salinity of the system.

Whenever the salinity of the borehole mud is in excess of that necessary to maintain the predetermined ratio thereof with respect to the salinity of the connate water in the formation, a self-potential will appear at the bottom of the borehole which is less negative than the predetermined value. Together with the beforementioned positive bias voltage, this will cause a pressure pulse of relatively long or increased duration, to be transmitted to the surface. Such long duration pressure pulse will result in a correspondingly higher average voltage to appear on the grid 125 of triode 126, thereby resulting in a correspondingly greater average current through solenoid 128. This greater average current flow in solenoid 128 in turn causes the plunger to move to the right, as viewed in Figure 2, against the biasing tension of spring 131, thereby admitting fresh water base mud through pipe 135, inlet port 135a and pipes 139 and 75 to the drilling mud circulating system, and thereby lowering the over-all salinity of the circulating drilling mud to the equilibrium value.

The continuous measurement of the self-potential at the bottom of the borehole, and its substantially immediate transmission to the surface during drilling by means of and in accordance with this invention, make it possible to continuously control the salinity of the rotary mud such that it will have at all times substantially the value required to maintain a constant predetermined relation thereof to the salinity of the connate water in the formation being drilled; in other words, the effect will be such as to maintain the ratio (R_{mf}/R_{cw}) at the predetermined value.

Since the salinity of the connate water contents of subsurface formations is preponderately due to the sodium chloride contents of such connate water, it has been found that adjustment of the drilling mud salinity by adjustment of its sodium chloride concentration, as hereinbefore described, will accomplish the attainment of a drilling mud filtrate with a resistivity which is in a given ratio to the resistivity of the connate water, for the purpose of this invention.

Under all operating conditions herein described (except that particular condition where the drilling mud filtrate resistivity (R_{mf}) is to be maintained equal to the connate water resistivity (R_{cw}) under which condition the self-potential (E_{sp}) would be maintained substantially at a zero value throughout the logging run) when a shale formation interval is encountered during the drilling of the borehole, the self-potential (E_{sp}) would drop and remain at a zero value, and the effect of this on the system would be the same as when a low negative self-potential measurement had been obtained opposite a porous sand. This would, in accordance with the operation before described, activate the fresh water base mud injection into the circulating drilling mud stream in an effort to increase the negative self-potential to the predetermined value, and this action would continue throughout the time interval required to drill through the shale body, with the result that by the time the drill had passed through the shale body into the next sand interval, enough fresh water base mud might have been added to greatly overbalance the self-potential opposite such sand interval, thereby resulting in an initial large deviation from the predetermined ratio of mud filtrate resistivity to connate water resistivity required to be maintained, and this latter condition would immediately reactivate the system to add salt water base mud to counteract the previous unbalance. Such action would be undesirable because it would result in excessively wide departures of the drilling mud salinity desired to be maintained and

this in turn would result in waste of the reserve of fresh water and salt water base muds required to effect the salinity adjustments, and what is most important, considerable time would be required to complete each such readjustment, and the portion of the borehole drilled during such readjustment time would be improperly logged.

To avoid the foregoing undesirable effects of the shale self-potential upon the action of the mud salinity adjusting system, a solenoid-operated valve 300 (Figure 2) is provided in the before-described mud injection pipe line 75 leading into the suction pipe 74 of the drilling mud circulating pump 71. The magnet winding 301 of the solenoid valve 300 is connected through conductor 302 and switch 303 to battery 304 which in turn is connected through conductor 305 to an adjustable contact 306 of a sensitive relay 308. The relay is provided with a movable armature 309 carrying electrical contact 307 which is magnetically moved into electrical contact with contact 306 whenever the current in windings 310 rises to a predetermined value. A relay sold by Weston Electrical Instrument Corporation under the trade name of "Sensitrol" has been found suitable for this purpose. The terminals 311 and 313 of the relay coil 310 are connected through conductors 312 and 314 respectively across the beforementioned resistor 151 located in series in the line 150 leading from the cathode of the triode 126 of the filter circuit, to the solenoid 128 of the balanced valve 133.

The adjustable set screw 315 carrying the contact point 306 is provided for adjustment such that the contacts 306 and 307 close whenever the current through the windings 310 increases to a predetermined value. Since this current through windings 310 results from the voltage drop across resistor 151, which in turn depends upon the current therethrough and in turn depends upon the negative self potential picked-up at the bottom of the borehole, the closing of the relay contacts 306 and 307 can be so adjusted as to close when such self-potential decreases to a predetermined minimum negative value, such as for example, approximately -10 millivolts. Thus, in operation, whenever a shale body is encountered by the drill in the borehole in which the self-potential (E_{sp}) is zero, or a sandy shale is encountered in which the self-potential (E_{sp}) is less than approximately -10 millivolts, the resulting pressure pulse arriving in the drilling fluid stream at the top of the drill stem will be of relatively long duration, which results in a relatively large average current through resistor 151 which in turn results in a current through windings 310 of the relay 308 sufficient to activate the relay armature 309 and close contacts 306 and 307. The closing of contacts 306 and 307 completes the electrical circuit through conductor 305, battery 304, switch 303, conductor 302, valve solenoid electromagnet 301 and return through the ground connection to armature 309, thereby closing valve 300 which deactivates the drilling mud salinity adjusting system during the intervals while drilling through shale or sandy shale earth formations. Whenever the drill emerges from the shale or sandy shale bodies into porous formations in which the negative self-potential again exceeds the value of approximately -10 millivolts, the relay 308 opens, thereby opening the valve 300 and reactivating the mud salinity adjusting system to operate again in the manner before-described.

Under the conditions where the operations are such as to maintain, during logging and drilling, a predetermined ratio of mud filtrate resistivity to the connate or interstitial water resistivity (R_{mf}/R_{cw}) greater than one, the switch 303 is maintained closed. However, under the condition where the operations are such as to maintain, during logging and drilling, the ratio of mud filtrate resistivity to interstitial water resistivity (R_{mf}/R_{cw}) substantially equal to one, with the resulting self-potential remaining at or close to zero, the switch 303 is maintained

open to prevent activation of the solenoid valve 300, as before described.

In Figure 5, under column II, is shown a vertical section through a series of earth strata typical of those which may be encountered in a borehole drilled for oil or gas. Opposite this series of strata, in columns I and III, are plotted the results of the resistivity and natural potential measurements respectively, obtained from recorder 88 in the practice of this invention under the chosen condition where the salinity of the mud filtrate was maintained at all times equal to the salinity of the interstitial water of the porous formations. The resistivity and natural potential measurements are shown on recorder 88 as recorded pressure pulses, the time durations of which are representative of the values of such measurements. The operator obtains the time of occurrence and duration of these recorded pressure pulses from the record strip on recorder 88, and, after making the conventional correction for borehole effect, electrode arrangement and character of drilling mud, replots the corrected values for E_{sp} , R_{mf} , R_i and R_t against the known borehole depth at the time of the recording, on the resistivity log, as shown in columns I and III of Figure 5. For this purpose, a record of the depth of the borehole, with respect to time, is made by suitable means (not shown) from which the recorded pressure pulses of recorder 88 and the corresponding resistivity values may be correlated with the borehole depth. Since the value of R_i , for example, is representative of the resistivity of the formation at a certain constant distance above the drill bit corresponding to the position of electrode 31 relative to drill bit 6, the recorded signal pulses for this measurement will be lagging behind the R_t values by this same distance, and the operator corrects for this difference in depth when plotting the data.

It may be observed that the shale sections at A, C and F have measured R_i and R_t values which are essentially equal to each other (since there is no drilling mud filtrate invasion of the substantially impermeable shale) and have a magnitude of about 3 ohm-meters. The mud filtrate resistivity (R_{mf}), which in the particular logging operation represented by this log, as before stated, is maintained equal to the interstitial water resistivity (R_{cw}), is approximately constant at 0.2 ohm-meter through the section shown in this example. Under the condition where the salinity of the mud filtrate and interstitial water were maintained equal, in other words, where $R_{cw}/R_{mf}=1$, the self-potential remains at zero as shown in column I of the log.

The limestone bed B has measured R_i and R_t values, as shown in column III, which again are essentially equal and have a magnitude of about 44 ohm-meters. Therefore, $R_i/R_t=1$ and $R_{cw}/R_{mf}=1$ and substituting these values in Formula 5 it is seen that the interstitial water saturation (S_w) in this limestone formation is therefore 100%, which indicates that this zone is of no commercial importance for the production of oil or gas. Equation 5 is valid only for permeable and porous formations.

If the limestone bed V were dense and impervious, the R_i and R_t values would still be equal, since no invasion would take place. In that case a computation of the fractional interstitial water content would have no practical significance. The fact that the ratio $R_i/R_t=1$, however, still rules out any commercial importance for oil and gas production from this zone and it is therefore not necessary to know whether such a zone is impervious or not; as long as R_i and R_t are equal no commercial oil or gas production can be expected.

The water-bearing, porous sand section E also has measured R_i and R_t values which are equal to each other at a value of 1.72 ohm-meters. This likewise means that this sand is fully saturated with water and (S_w) is therefore 100%.

The oil-bearing, porous sand section D shows a logged R_i value which decreases from 5.2 ohm-meters near the

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top of the section to 1.72 ohm-meters near the bottom, while the R_t value goes down over the same interval from 16.6 ohm-meters near the top to 1.72 ohm-meters near the bottom of the section, making $R_1/R_t=.31$ at the top and $R_1/R_t=1$ at the bottom. Substituting these values in Formula 5 indicates a connate water saturation (S_w) which is relatively low, namely approximately 31% near the top of the sand section D and which increases to 100% water saturation near the bottom.

Since the drilling mud filtrate resistivity (R_{mf}) has been maintained substantially equal to the interstitial water resistivity (R_{cw}) this departure of the R_t curve from the R_1 curve indicates that insulating material, such as oil or gas, has been displaced from the porous sands by the invasion of the conductive drilling mud filtrate. This departure of the two curves is therefore a direct indication of the presence of oil or gas in this porous formation.

It is known that the actual displacement mechanism by means of water drive in the productive reservoir is quantitatively very similar to the invasion effects by mud filtrate, and it is possible, therefore, to estimate possible recoveries by water drive from such formations directly from the data obtained in the practice of this invention.

Reference is now made primarily to Figures 6 and 7, which illustrate the kinds of logs obtained while drilling under conditions where a given predetermined ratio of mud filtrate resistivity to interstitial water resistivity (R_{mf}/R_{cw}) greater than one is maintained during the drilling and logging operations.

In Figure 6, column II is illustrated schematically typical formation strata penetrated by a borehole in which the formations comprise alternate beds of shale and sand which have the following sequence with respect to depth: a layer of low resistivity, substantially impermeable shale A, a so-called water-free porous oil sand B, a so-called wet, porous oil sand C, a porous water sand D, and a low resistivity, substantially impermeable shale body E. In this case the ratio of R_{mf}/R_{cw} was maintained at a value of two throughout the drilling and logging operations, which for a constant $K=-90$ corresponds to a control self-potential (E_{sp}) of -27 millivolts opposite the uninvaded porous formations. Column I of Figure 6 shows the plotted log of the measured, bottom hole self-potential (E_{sp}) with respect to the borehole depth, as plotted from recorded data obtained during drilling, in accordance with the method and apparatus of this invention, as hereinbefore described.

Column III of Figure 6 shows the plotted log of resistivities of the penetrated formations with respect to borehole depth, the curve R_t indicating the resistivities of the formations measured at the bottom of the borehole during drilling prior to invasion thereof by mud filtrate, and the curve R_1 indicating the resistivities of the same formations measured after invasion thereof by mud filtrate. Column IV of Figure 6 shows the ratios of R_1/R_t with respect to borehole depth as computed from the data of column III.

In Figure 7, column II illustrates schematically typical formation strata penetrated by a borehole in which the formations comprise alternate beds of shale and porous limestone which have the following sequence with respect to depth: a layer of low resistivity impermeable shale F, water-free, clean oil-producing, porous limestone bed G, a wet oil-producing porous limestone bed H, a porous water-bearing limestone bed I, and a low resistivity, impermeable shale body J. In this case the ratio of $R_{mf}/R_{cw}=4$, was maintained throughout the drilling and logging operations, which for a constant $K=-90$ corresponds to a bottom-hole, control self-potential (E_{sp}) of -54 millivolts opposite the uninvaded porous beds. Column I of Figure 7 shows the plotted log of the measured bottom hole self-potential (E_{sp}) with respect to the borehole depth as plotted from recorded data obtained during drilling in accordance with the hereinbefore described method and apparatus of this invention.

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Column III of Figure 7 shows the plotted log of resistivities of the penetrated formations with respect to borehole depth, the curve R_t indicating the resistivities of the formations measured at the bottom of the borehole during drilling, prior to invasion thereof by mud filtrate, and the curve R_1 indicating the resistivities of the same formations measured after invasion thereof by mud filtrate.

Column IV of Figure 7 shows the ratios of R_1/R_t with respect to borehole depth as computed from the data of column III.

Referring again to Figure 6, it is seen, in column III, that the logged values of R_1 and R_t for the shale bodies A and E are substantially equally to each other (because there is substantially no drilling mud filtrate invasion of the impermeable shale) and have values of approximately 5 ohmmeters. As before stated, during the drilling and logging represented by this log, the ratio of mud filtrate resistivity to interstitial water resistivity (R_{mf}/R_{cw}) was maintained at a value of two under which condition the control self-potential (E_{sp}) opposite the porous formations B, C and D remained at -27 millivolts, as shown in column I.

The logged values for R_t and R_1 for formation D are seen to have values of approximately 5 ohm-meters and 10 ohm-meters respectively, or a ratio of $R_1/R_t=2$. Since the ratio of the mud filtrate resistivity (R_{mf}) to interstitial water resistivity (R_{cw}) was 2, as before stated, substitution of these values in Formula 5 results in a figure which indicates that formation D is a porous water sand with a water saturation (S_w) of 100%.

The logged values for R_t and R_1 for formation C are seen to have values which increase from approximately 5 ohmmeters and 10 ohmmeters respectively at the lower boundary thereof to a common value of approximately 20 ohmmeters at the upper boundary, with the ratio R_1/R_t varying accordingly from $R_1/R_t=2$ at the lower boundary to $R_1/R_t=1$ at the upper boundary. Substitution of the values in Formula 5 results in a figure which indicates that the formation C is a porous sand having a water saturation (S_w) varying from 100% at the lower boundary to 50% at the upper boundary.

The logged values for R_t and R_1 for formation B are seen to have values which increase from the common value of 20 ohmmeters at the lower boundary thereof to values of, respectively, 80 and 40 ohmmeters at the upper boundary, with the ratio R_1/R_t varying accordingly from a value of one at the lower boundary to a value of .5 at the upper boundary. Substitution of the values in Formula 5 indicates that the interstitial water saturation S_w increases in this sand from 25 percent at the upper boundary to 50 percent at the lower boundary.

It has been found that for most permeable sands there is a critical interstitial water saturation value of approximately 50%, above which saturation value water will be produced from them with or without oil, and below which saturation value clean, substantially water-free oil production may be expected. As shown in the log of Figure 6 the point of critical water saturation (50%) is reached at the interface between formations B and C where the ratio of R_1/R_t is indicated as equal to 1.0, while for wet oil sands or water sands such as formations C and D the ratio R_1/R_t will be greater than one, and for substantially water-free-oil producing sands such as formation B, the ratio R_1/R_t will be less than one. From the foregoing the zone of probable commercially-important clean oil production can be chosen as indicated by the diagonally hachured area opposite formation B where the ratio of R_1/R_t is less than one.

Referring again to Figure 7, it is seen, in column III, that the logged values of R_1 and R_t for the shale bodies F and J are substantially equal to each other (because there is substantially no drilling mud filtrate invasion of the impermeable shale) and have values of approximately 5 ohm-meters. As hereinbefore stated, during the drilling

and logging represented by this log, the ratio of mud filtrate resistivity to interstitial water resistivity (R_{mf}/R_{cw}) for the limestone formation common to this area was maintained at a value of 4, under which condition the control self potential (E_{sp}) opposite the porous formations G, H and I remain at -54 millivolts, as shown in column I.

The logged values for R_t and R_l for formation I are seen to have values of approximately 10 ohm-meters and 40 ohm-meters respectively or a ratio of $R_l/R_t=4$. Since the ratio of the mud filtrate resistivity (R_{mf}) to interstitial water resistivity (R_{cw}) was 4, as before stated, substitutions of these values in Formula 5 produces a figure which indicates that formation I is a porous water-bearing limestone with a water saturation (S_w) of 100%.

The logged values of R_t and R_l for formation H are seen to have values which increase from approximately 10 ohm-meters and 40 ohm-meters respectively at the lower boundary thereof to a common value of approximately 160 ohm-meters at the upper boundary, with the ratio R_l/R_t varying accordingly from $R_l/R_t=4$ at the lower boundary to $R_l/R_t=1$ at the upper boundary. Substitution of these values in Formula 5, as before, indicates that formation H is a porous wet limestone body having a water saturation (S_w) ranging from 100% at the lower boundary to 25% at the upper boundary.

The logged values for R_t and R_l for formation G are seen to have values which increase from a common value of approximately 160 ohm-meters at the lower boundary to approximately 450 ohm-meters and 270 ohm-meters respectively at the upper boundary, with the ratio of R_l/R_t varying accordingly from $R_l/R_t=1$ at the lower boundary to $R_l/R_t=6$ at the upper boundary. Substitution of these values in Formula 5, as before, indicates that the formation G is a porous limestone having a water saturation (S_w) varying from 25% at the lower boundary to 15% at the upper boundary.

It has been found that for most permeable oil-bearing limestones there is a critical water saturation value of approximately 25% above which saturation value water will be produced from them with or without oil, and below which saturation value clean, substantially water-free oil production may be expected. As shown in the log of Figure 7, the point of critical water saturation (25%) is reached at the interface between formations G and H where the rate of R_l/R_t is indicated as 1.0, while for wet oil-producing limestone bodies such as formations H and I, the ratio R_l/R_t will be greater than one, and for substantially water-free oil-producing sands such as formation G, the ratio R_l/R_t will be less than one. From the foregoing the zone of probable commercially important clean oil production can be chosen as indicated by the diagonally hachured area opposite formation G where the ratio of R_l/R_t is less than one.

It will be apparent from the foregoing that this invention will result in a log obtained while drilling, which is the nearest thing yet devised to a positive oil- or gas-finding tool. The need for such an instrument is apparent when it is considered that with conventional logging techniques it happens not infrequently that potentially oil- or gas-bearing horizons are overlooked or misinterpreted while drilling through them with the conventional rotary method.

In summation, the present invention offers numerous advantages and improvements over conventional drilling and logging systems some of which are as follows:

First for example and most important the continuous maintenance of a salinity equilibrium between the bore-hole mud filtrate and the connate water in the formation simplifies the usual relationships to such an extent that the R_l and the R_t curves, as shown in columns III of Figure 5, and columns III and IV of Figures 6 and 7, are in themselves direct oil- or gas-detecting means, since a departure of the R_t curve to the right from the R_l curve, as shown in column III of Figure 3, is only ob-

tained in porous oil- or gas-bearing formations, while impervious or completely water-saturated oil-free formations show no such response on this log. Whenever the R_{mf}/R_{cw} value is maintained at an appropriate ratio larger than one (which depends on the critical water saturation for the geologic section encountered), the practice of this invention enables the operator to distinguish continuously and while drilling between:

(a) Impervious formations, such as shale sections A and E of Fig. 6, and F and J of Fig. 7, where the R_l and R_t curves read the same value.

(b) Porous 100 percent water-bearing formations such as the porous water sand D of Fig. 6 and the porous water-bearing limestone of Fig. 7, where the R_t curve departs to the left of the R_l curve in the same proportion as the ratio of R_{cw} to R_{mf} .

(c) Wet porous oil formations such as the wet porous oil sand C of Fig. 6 and the wet oil-producing limestone H of Fig. 7, where the R_t curve still shows departure to the left of the R_l curve but to a lesser degree than under b.

(d) Clean oil- or gas-producing porous formations such as the water-free oil-producing porous sand B of Fig. 6 or the water-free oil- or gas-producing porous limestone of Fig. 7, where the R_t curve shows departure to the right of the R_l curve.

Secondly, the danger of sticking the drill pipe or bit because of sloughing or caving shale formations is considerably reduced particularly when the salinity of the mud filtrate is maintained equal to the salinity of the formation waters, thereby eliminating a substantial number of fishing jobs normally encountered in the drilling of a well.

Thirdly, the maintenance of a salinity balance between mud and connate or interstitial water is also helpful in preventing damage to potentially oil- or gas-productive sands containing silt, bentonitic or the like materials. In certain oil-producing regions this danger is well recognized and is sometimes overcome by drilling into such productive formations with oil or oil base muds which do not contain water. Such a practice, however, is expensive, and the operator should be able to obtain better results at less expense and time through the practice of the present invention.

Since in the practice of this invention it will be necessary to use muds of higher salinity, the use of normal bentonitic muds may not be practical, as such muds are susceptible to the flocculating effects of the dissolved salts, thereby possibly eliminating the use of bentonite as a viscosity and fluid loss controlling agent. It will therefore be desirable and in some cases necessary to use certain organic additives in the mud, such as starches, gums, Irish moss, or methylcellulose compounds, as are well known in the art, which will maintain their colloidal and low water-loss properties under highly saline conditions.

By the term interstitial water as used herein is meant the water present in the formation interstices at the time of penetration by drilling and prior to any substantial disturbance or change thereof by reason of invasion of displacement by drilling fluid filtrate. Normally the interstitial water would appear to be the connate water assuming no changes had taken place therein since the origin of the formations concerned.

The terms "measuring resistivity," "natural potential," "self-potential" and the like, as used herein in the specification and claims, are not to be necessarily limited in meaning to actual quantitative determination of such values in terms of volts, ohms and the like units, but are to include the actuation of any indicator or recording means or device, such as, for example, the recorder 88 or the valve 113, whereby visual indications or graphical records or actuations of apparatus elements may be obtained which are measures of, representative of, or effected in accordance with such values.

It is to be understood that the foregoing is illustrative

only and that the invention is not limited thereby, but may include various modifications and changes made by those skilled in the art without distinguishing from the scope of the invention as defined in the appended claims.

What is claimed is:

1. In a method of simultaneous drilling and logging earth formations the steps comprising: circulating a saline drilling fluid through the borehole during such drilling thereof; measuring during such drilling the natural potential in the borehole adjacent the porous formations being drilled and maintaining the salinity of said drilling fluid during said drilling at such a value as to maintain the thus measured natural potential of the said porous formations being drilled at a predetermined value.

2. In a method of simultaneous logging and drilling earth formations the steps comprising: circulating a saline drilling fluid through the borehole during drilling thereof; measuring during such drilling the natural potential within the borehole adjacent the formation being drilled prior to substantial invasion of drilling fluid filtrate into such formation; and while drilling, maintaining the salinity of such drilling fluid at such a value as to maintain said measured natural potential substantially at a predetermined value.

3. In a method of investigating earth formations penetrated by a borehole containing conductive, aqueous fluid, the steps comprising: measuring the natural potential of the formation being investigated prior to substantial invasion thereof by filtrate from said fluid; adjusting the resistivity of the said fluid to maintain said measured natural potential at a predetermined value; measuring the resistivity of the fluid filtrate of the thus adjusted fluid; measuring the resistivity of the said formation prior to substantial invasion thereof by filtrate from said fluid; and measuring the resistivity of the said formation after invasion thereof by filtrate from said fluid whereby the resistivity of the fluid filtrate and the different resistivity measurements of said formation thus obtained may be compared to obtain thereby an indication of whether interstitial insulating fluid is present in said formation.

4. In a method of investigating earth formations penetrated by a borehole containing conductive, aqueous fluid, the steps comprising: measuring the natural potential of the formation being investigated prior to substantial invasion thereof by filtrate from said fluid; adjusting the resistivity of the said fluid to maintain said measured natural potential at a predetermined value; measuring the resistivity of the thus adjusted fluid; measuring the resistivity of the said formation prior to substantial invasion thereof by filtrate from said fluid; and measuring the resistivity of the said formation after invasion thereof by filtrate from said fluid whereby the resistivity of the fluid and the different resistivity measurements of said formation thus obtained may be compared to obtain thereby an indication of whether interstitial insulating fluid is present in said formation.

5. A method according to claim 3 in which the said predetermined value is approximately zero potential.

6. A method according to claim 3 in which the said predetermined value is approximately -27 millivolts.

7. A method according to claim 3 in which the said predetermined value is approximately -54 millivolts.

8. A method according to claim 4 in which the said predetermined value is approximately zero potential.

9. A method according to claim 4 in which said predetermined value is approximately -27 millivolts.

10. A method according to claim 4 in which the said predetermined value is approximately -54 millivolts.

11. In a method of simultaneous drilling and logging earth formations the steps comprising: circulating a saline drilling fluid through the borehole during drilling thereof; measuring during drilling the natural potential of the formation being drilled; maintaining during said drilling the salinity of such drilling fluid at such a value as to maintain said measured natural potential at a pre-

determined value; measuring the resistivity of said formation after drilling thereof after substantial invasion thereof by drilling fluid filtrate, whereby the resistivity measurements thus made may be compared to obtain thereby an indication of whether such drilled formation contains high resistivity interstitial fluid such as hydrocarbons.

12. In a method of simultaneous drilling and logging earth formations the steps comprising: circulating a saline drilling fluid through the borehole during drilling thereof; measuring during drilling the natural potential of the formation being drilled; maintaining during said drilling the salinity of such drilling fluid at such a value as to maintain said measured natural potential at a predetermined value; making a measure during such drilling indicative of the resistivity of the filtrate of said drilling fluid; measuring the resistivity of said formation being drilled; measuring the resistivity of said formation after drilling thereof after substantial invasion thereof by drilling fluid filtrate, whereby the resistivity measurements thus made may be compared to obtain thereby an indication of whether such drilled formation contains high resistivity interstitial fluid such as hydrocarbons.

13. In a method of simultaneous drilling and logging earth formations the steps comprising: circulating a saline drilling fluid through the borehole during such drilling thereof; maintaining the salinity of said drilling fluid during said drilling at such a value as to maintain the natural potential of the porous formations being drilled at a predetermined value; measuring the resistivity of the said formations being drilled; and measuring the resistivity of the said formations after drilling thereof after substantial invasion thereof by drilling fluid filtrate, whereby the resistivity measurements thus obtained may be compared to obtain thereby indications of whether such drilled formations contain high resistivity interstitial fluid.

14. In a method of investigating earth formations penetrated by a borehole, the steps comprising: introducing a saline fluid into said borehole; measuring the natural potential of the formation being investigated prior to substantial invasion thereof by filtrate from said fluid; adjusting the salinity of said fluid to such a value as to maintain said measured natural potential at a predetermined value; measuring the resistivity of said formation prior to substantial invasion thereof by said filtrate from said fluid; and measuring the resistivity of said formation after substantial invasion thereof by said filtrate from said fluid, whereby the resistivity measurements thus obtained may be compared to obtain indications of whether such formation contains high resistivity interstitial fluid.

15. In apparatus for investigating earth formations penetrated by a borehole, the combination comprising: means for introducing a saline fluid into the borehole into contact with the formation being investigated; means for measuring the natural potential of the said formation prior to substantial invasion thereof by filtrate from said fluid; means for adjusting the salinity of said fluid to maintain said measured natural potential at a predetermined value; means for measuring the resistivity of said formation prior to substantial invasion thereof by said filtrate from said fluid; and means for measuring the resistivity of said formation after substantial invasion thereof by said filtrate from said fluid, whereby the resistivity measurements made by said means are indicative of whether said formation contains high resistivity interstitial fluid.

16. In apparatus for investigating earth formations penetrated by a borehole, the combination comprising: means for introducing a saline fluid into the borehole into contact with the formation being investigated; means for measuring the natural potential of the said formation prior to substantial invasion thereof by filtrate from said fluid; means responsive to the value of said natural potential for adjusting the salinity of said fluid to maintain said measured natural potential at a predetermined

value; means for measuring the resistivity of said formation prior to substantial invasion thereof by said filtrate from said fluid; and means for measuring the resistivity of said formation after substantial invasion thereof by said filtrate from said fluid, whereby the resistivity measurements made by said means are indicative of whether said formation contains high resistivity interstitial fluid.

17. In apparatus for investigating earth formations penetrated by a borehole being drilled by means of a drill bit on the lower end of a hollow drill stem through which a saline drilling fluid is circulated, the combination comprising: means for picking up the natural potential appearing between the drilling fluid and the formation being drilled; and means responsive to the value of said potential for modifying the salinity of said drilling fluid such as to maintain said potential at a predetermined value.

18. Apparatus in accordance with claim 17, in which said means responsive to said natural potential for modifying the salinity of the drilling fluid comprises: means to admix fluid comprising relatively fresh water with the said circulating drilling fluid when the said natural potential exceeds a predetermined value, and to admix fluid comprising relatively saline water with the said circulating drilling fluid when the said natural potential is less than a predetermined value.

19. In apparatus for investigating earth formations penetrated by a borehole being drilled by means of a drill bit on the lower end of a hollow drill stem through which saline drilling fluid is circulated, the combination comprising: means for picking up the natural potential appearing between the drill bit and the formation being drilled; and means responsive to the value of said potential for modifying the salinity of said drilling fluid such as to maintain said potential at a predetermined value.

20. In apparatus for investigating earth formations penetrated by a borehole being drilled by means of a drill bit on the lower end of a hollow drill stem through which saline drilling fluid is circulated, the combination comprising: means for picking up the natural potential appearing between the drill bit and the formation being drilled; means responsive to the value of said potential for modifying the salinity of said drilling fluid such as to maintain said potential at a predetermined value; and means for measuring the resistivity of said drilling fluid at a location adjacent the drill bit.

21. In apparatus for investigating earth formations penetrated by a borehole being drilled by means of a drill bit on the lower end of a hollow drill stem through which saline drilling fluid is circulated, the combination comprising: means for picking up the natural potential appearing between the drilling fluid and the formation being drilled; means responsive to the value and polarity of said potential for modifying the salinity of said drilling fluid such as to maintain said potential at a predetermined value; and means for measuring the resistivity of said drilling fluid flowing to said drill bit at a location in the vicinity of the drill bit.

22. In apparatus for investigating earth formations penetrated by a borehole being drilled by means of a drill bit on the lower end of a hollow drill stem through which a saline drilling fluid is circulated, the combination comprising: means adjacent the lower end of the drill stem to measure the natural potential between the said drill bit and an adjacent formation being drilled by said drill bit; means adjacent the lower end of the drill stem to measure the resistance between said drill bit and a grounded connection spaced a substantial distance away from said drill bit; insulated electrode means carried by said drill stem and located a substantial distance longitudinally above said drill bit; means adjacent the lower end of said drill stem for measuring the resistance between said electrode means and a grounded connection spaced a substantial distance above said electrode means;

means to transmit signals indicative of said measurements, to the top of said borehole while drilling; and means adjacent the top of the borehole, responsive to the said signal which is indicative of the said natural potential measurement, to modify the salinity of said drilling fluid being circulated through said drill stem to maintain said natural potential at a predetermined value.

23. In apparatus for investigating earth formations penetrated by a borehole being drilled by means of a drill bit on the lower end of a hollow drill stem through which a saline drilling fluid is circulated, the combination comprising: means adjacent the lower end of the drill stem to measure the natural potential between the said drill bit and an adjacent formation being drilled by said drill bit; means adjacent the lower end of the drill stem to measure the resistivity of said formation being drilled; means carried by said drill stem for measuring the resistivity of a penetrated formation surrounding the borehole a substantial distance above said drill bit; means to transmit signals indicative of said measurements, to the top of said borehole while drilling; and means adjacent the top of the borehole, responsive to the said signal which is indicative of the said natural potential measurement, to modify the salinity of said drilling fluid being circulated through said drill stem to maintain said natural potential at a predetermined value.

24. In apparatus for investigating earth formations penetrated by a borehole being drilled by means of a drill bit on the lower end of a hollow drill stem through which a saline drilling fluid is circulated, the combination comprising: means adjacent the lower end of the drill stem to measure the natural potential between the said drill bit and an adjacent formation being drilled by said bit; means adjacent the lower end of the drill stem to measure the resistance between said drill bit and a grounded connection spaced a substantial distance away from said drill bit; insulated electrode means carried by said drill stem and located a substantial distance longitudinally above said drill bit; means adjacent the lower end of said drill stem for measuring the resistance between said electrode means and a grounded connection spaced a substantial distance above said electrode means; means to transmit repeatedly a series of signals in predetermined succession, each of which signals is indicative of one of said measurements, to the top of said borehole while drilling; and means adjacent the top of the borehole, responsive to the said signal which is indicative of the said natural potential measurement, to modify the salinity of said drilling fluid being circulated through said drill stem to maintain said natural potential at a predetermined value.

25. In apparatus for investigating earth formations penetrated by a borehole being drilled by means of a drill bit on the lower end of a hollow drill stem through which a saline drilling fluid is circulated, the combination comprising: means adjacent the lower end of the drill stem to measure the natural potential between the said drill bit and an adjacent formation being drilled by said drill bit; means adjacent the lower end of the drill stem to measure the resistance between said drill bit and a grounded connection spaced a substantial distance away from said drill bit; insulated electrode means carried by said drill stem and located a substantial distance longitudinally above said drill bit; means adjacent the lower end of said drill stem for measuring the resistance between said electrode means and a grounded connection spaced a substantial distance above said electrode means; means adjacent the drill bit for measuring the resistivity of the circulating drilling fluid adjacent said drill bit; means to transmit repeatedly a series of signals in predetermined succession, each of which signals is indicative of a separate one of said measurements, to the top of said borehole while drilling; and means adjacent the top of the borehole, responsive to the said signal which is indicative of the said natural potential measurement, to

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modify the salinity of said drilling fluid being circulated through said drill stem to maintain said natural potential at a predetermined value.

26. Apparatus according to claim 25, and recording means responsive to said signals for making a record indicative of the separate values of said measurements.

27. In apparatus for investigating earth formations penetrated by a borehole, the combination comprising: a drill stem having an internal drilling fluid circulation passage therethrough; a drill bit on the lower end of and electrically insulated from said drill stem; an elongated insulating covering on the interior surface of said fluid passage and on the exterior surface of said drill stem and arranged to electrically insulate a substantial length of said drill stem extending upward from said drill bit, from drilling fluid, whereby said drill bit can act as a first, substantially isolated electrode; a second electrode intermediate the upper and lower ends of said insulating covering, outside of and insulated from said drill stem and adapted to make electrical contact with surrounding drilling fluid; means to measure the electrical resistance between said drill bit and a grounded connection effectively remote from said drill bit; means to measure the resistance between said second electrode and a grounded connection effectively remote from said second electrode; a third electrode insulated from the drill stem and positioned within said drilling fluid passage within said drill stem; means to measure the resistance between said third electrode and another conductive surface in said fluid passage; and means for transmitting said measurements to the top of the borehole.

28. In apparatus for investigating earth formations penetrated by a borehole, the combination comprising: a drill stem having an internal drilling fluid circulation passage therethrough; a drill bit on the lower end of and

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electrically insulated from said drill stem; an elongated insulating covering on the interior surface of said fluid passage and on the exterior surface of said drill stem and arranged to electrically insulate a substantial length of said drill stem extending upward from said drill bit, from drilling fluid, whereby said drill bit can act as a first, substantially isolated electrode; a second electrode intermediate the upper and lower ends of said insulating covering, outside of and insulated from said drill stem and adapted to make electrical contact with surrounding drilling fluid; means to measure the electrical resistance between said drill bit and a grounded connection effectively remote from said drill bit; means to measure the resistance between said second electrode and a grounded connection effectively remote from said second electrode; a third electrode insulated from the drill stem and positioned within said drilling fluid passage within said drill electrode and another conductive surface in said fluid passage; means to measure the natural potential appearing between said drill bit and a grounded electrode effectively remote from said drill bit; and means for transmitting said measurements to the top of the borehole.

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