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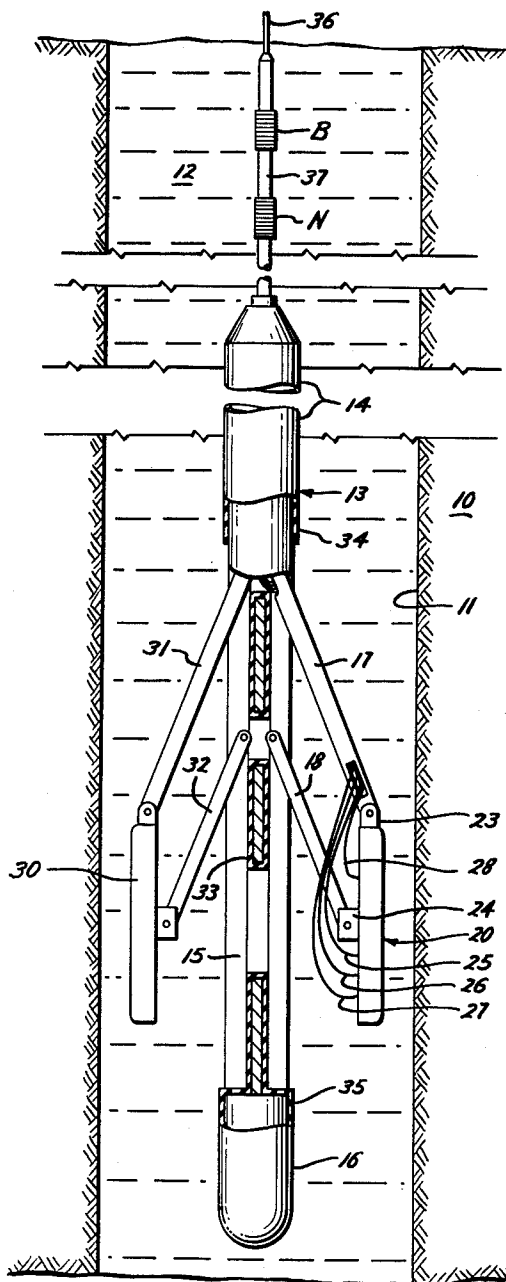
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3,017,566

APPARATUS FOR INVESTIGATING EARTH FORMATIONS

Filed June 16, 1959

4 Sheets-Sheet 1



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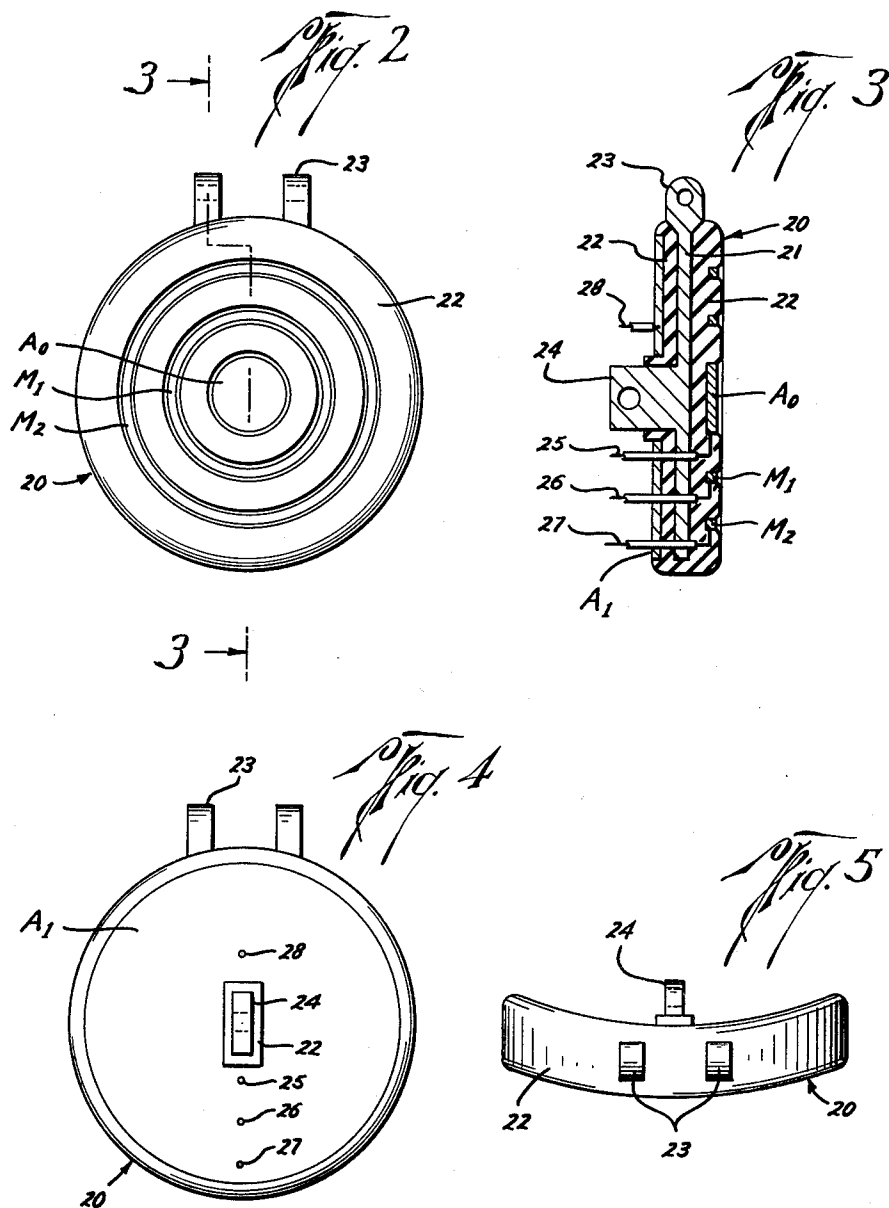
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4 Sheets-Sheet 2



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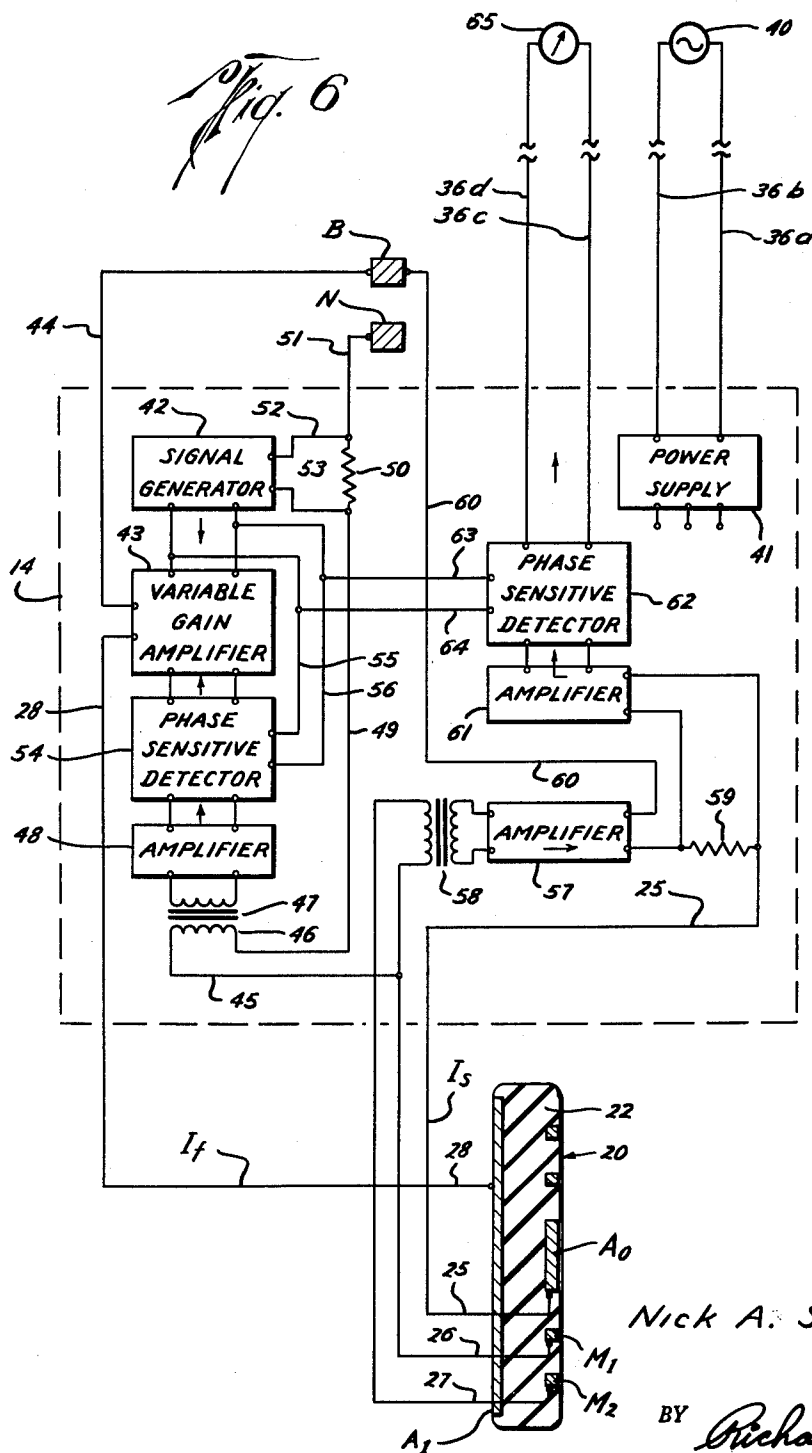
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APPARATUS FOR INVESTIGATING EARTH FORMATIONS

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4 Sheets-Sheet 3



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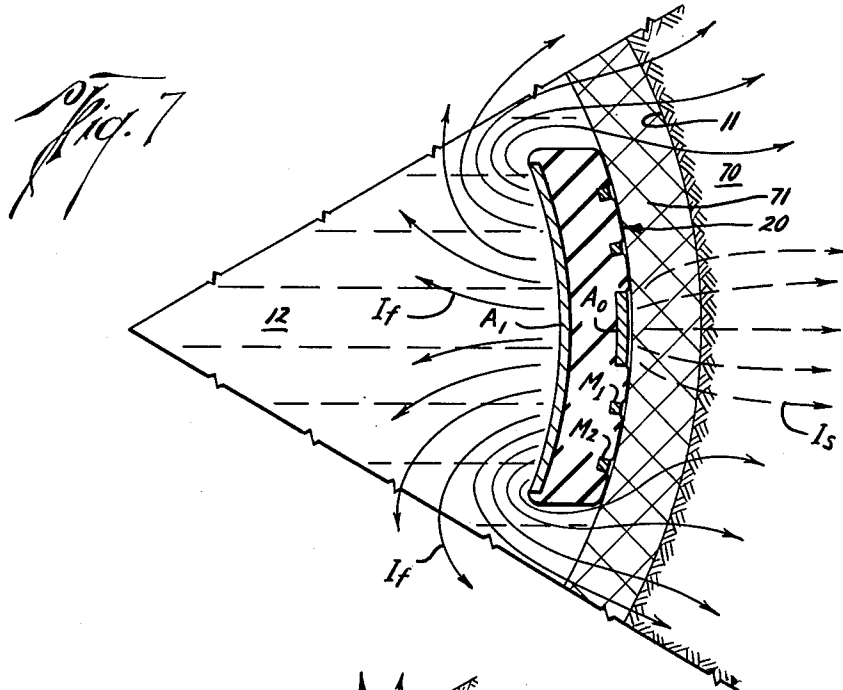
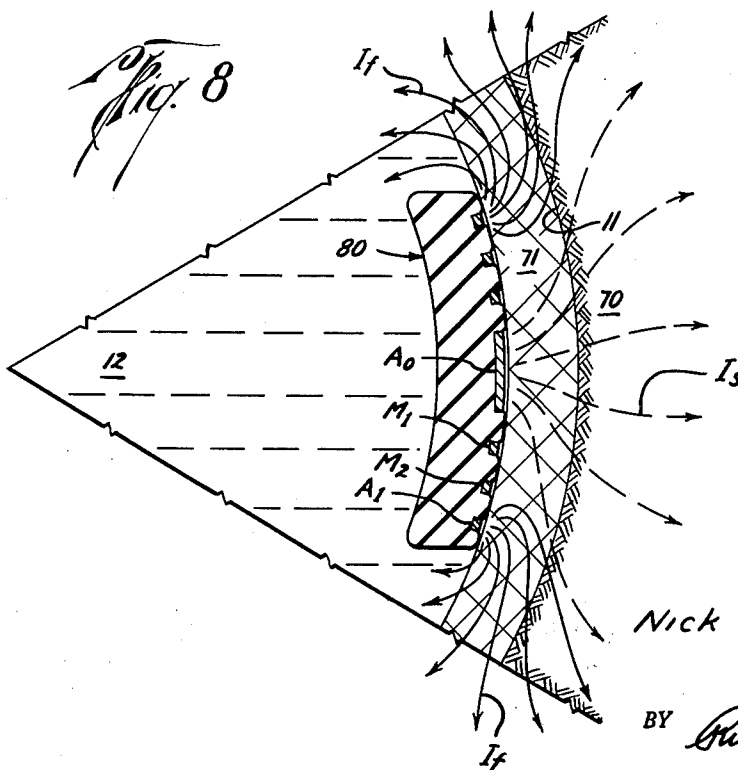
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APPARATUS FOR INVESTIGATING EARTH FORMATIONS

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4 Sheets-Sheet 4



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APPARATUS FOR INVESTIGATING EARTH FORMATIONS

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12 Claims. (Cl. 324-1)

This invention relates to electrical apparatus for investigating subsurface earth formation traversed by a borehole and, particularly, to such apparatus of the type wherein measurements of the electrical resistance properties of subsurface earth formations are made by moving a system of electrodes through a borehole.

It is known that a record or log of the resistivity or conductivity values of the subsurface formations adjacent a borehole drilled into the earth is useful in determining the nature, extent and depth of the various subsurface formations. This information is particularly useful in the case of oil well boreholes in that it enables the presence and depth of any oil or gas-bearing strata to be determined.

Productible oil-bearing and gas-bearing formations are of a "permeable" nature in that the formation pore spaces are interconnected so that fluids and gases may pass into or out of such formations. Many water-bearing formations are also permeable in nature. Consequently, the relatively conductive drilling liquid or drilling mud contained in the borehole at the time electrode-type measurements are made will penetrate or invade laterally into such permeable formations provided, of course, that the hydrostatic pressure of this mud column is greater than the pressure of the liquid or gas contained in the formation. This latter condition usually prevails.

As the drilling mud invades into the adjacent formation, the solid particles suspended in the drilling mud are deposited on the wall of the borehole in the form of a mud cake. What actually invades into the formation is the so-called "mud filtrate" resulting when the solid particles are removed from the drilling mud. Over the first few inches in from the borehole wall this invasion is usually relatively complete in the sense that the mud filtrate completely pushes back or flushes the original connate formation fluid from this region. This region immediately adjacent the borehole wall is, consequently, commonly referred to as the "flushed zone."

Accurate knowledge of the resistivity or conductivity value of the flushed zone enables the "formation factor" and the "porosity" of a permeable formation to be determined. Knowledge of these quantities, in turn, aids in the interpretation of the data obtained with other types of electrical logging apparatus thereby to more accurately distinguish between oil-bearing and nonoil-bearing formations. It also aids in determining the amount of oil present in a given oil-bearing formation.

It is known that the resistivity or conductivity of a relatively small volume of formation material immediately adjacent the wall of the borehole can be determined by the use of certain types of wall-contact electrode systems heretofore proposed. In other words, these wall-contact electrode systems, among other things, are highly useful in determining the formation factor and porosity of permeable formations. In these wall-contact electrode systems, an array of electrodes mounted on the face of a wall-engaging pad are urged against the borehole wall and the pad is moved longitudinally through the borehole. Electrical current is emitted from one or more of the wall-engaging electrodes and the voltage or current or both of one or more of the wall-engaging electrodes is measured to provide an indication of the resistivity or

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conductivity of the relatively small volume of formation material immediately in front of the electrodes.

A problem is sometimes encountered in the use of these wall-contact electrode systems in that it is sometimes difficult to get the electrical current to flow into the flushed zone in the most desirable manner for determining the resistivity or conductivity thereof. This is particularly likely to occur in the case of a permeable formation where the flushed zone resistivity is relatively high while the mud cake is of relatively low resistivity and is fairly thick in nature. In this case, an appreciable amount of the electrode current is shunted or short-circuited by the low resistivity mud cake and fails to penetrate into the flushed zone.

In order to alleviate this difficulty, so-called "focussed" types of wall-contact electrode systems have been proposed. In these focussed systems, the principal current flow used for determining or surveying the formation resistance characteristic is constrained to the desired flow pattern by emitting focussing current from a wall-engaging electrode adjacent thereto for opposing any survey current tending to flow in an undesired direction. In this manner, the survey current is caused to penetrate laterally into the flushed zone. For minimum to moderate thicknesses of mud cake, this focussed system has proved successful in making accurate measurements of the flushed zone resistivity. For very thick mud cakes, however, the measurements made with this type of electrode system become less accurate than is desirable.

It is an object of the invention, therefore, to provide new and improved apparatus for measuring the electrical resistance properties of subsurface earth formations adjacent a borehole.

It is another object of the invention to provide a new and improved focussed type of wall-contact electrode system which is less affected by the presence of thick mud cakes on the borehole wall.

It is a further object of the invention to provide a new and improved focussed type of wall-contact electrode system having a smaller size of wall-contact pad for a given effective electrode spacing.

It is an additional object of the invention to provide a new and improved focussed type of wall-contact electrode system which provides more sensitive and accurate control of the focussing action.

In accordance with the invention, apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid comprises a pad member adapted to be urged against the borehole wall. The apparatus further includes first electrode means for emitting electrical current from the wall-engaging face of the pad member into the adjacent earth formation. The apparatus also includes second electrode means for emitting electrical current from the pad member directly into the adjacent conductive liquid for controlling the flow pattern of the first electrode current and rendering such flow pattern relatively unaffected by the presence of a layer of mud cake on the wall of the borehole. In addition, the apparatus includes means responsive to the flow of the first electrode current for providing an indication representative of formation resistivity.

For a better understanding of the present invention, together with other and further objects thereof, reference is had to the following description taken in connection with the accompanying drawings, the scope of the invention being pointed out in the appended claims.

Referring to the drawings:

FIG. 1 is a partly cross-sectional view of the downhole portion of a representative embodiment of borehole investigating apparatus constructed in accordance with the present invention;

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FIG. 2 is an enlarged elevational view of the wall-engaging face of an electrode pad of the FIG. 1 apparatus;

FIG. 3 is a cross-sectional view taken along the section line 3—3 of FIG. 2 electrode pad;

FIG. 4 is an elevational view of the backside of the electrode pad of FIG. 2;

FIG. 5 is a top view of the electrode pad of FIG. 2; FIG. 6 is a schematic circuit diagram of typical electrical circuits which may be used with the electrode pad of FIG. 2;

FIG. 7 shows a horizontal section of a part of a borehole including an electrode pad constructed in accordance with the present invention; and

FIG. 8 shows a horizontal section of a part of a borehole including an electrode pad of a previously known type.

Referring to FIG. 1 of the drawings, there is shown a representative embodiment of the downhole portion of apparatus constructed in accordance with the present invention for investigating earth formation 10 traversed by a borehole 11. The borehole 11 is filled with a relatively conductive liquid or drilling mud 12. The downhole portion of the apparatus includes an elongated support member 13 which is adapted for longitudinal movement through the borehole 11. This support member 13 includes an upper instrument housing portion 14 having a hollow fluid-tight interior for containing various electrical circuits. The support member 13 also includes a central I-beam portion which, for ease of understanding, is shown in a cross-sectional manner. The lower end of the I-beam 15 terminates in a nose portion or nose piece 16 of generally cylindrical shape.

Attached to the I-beam portion 15 by way of pivoted support arms 17 and 18 is an electrode pad member 20 constructed in accordance with the present invention. This pad member 20 is shown in greater detail in FIGS. 2-5. As shown in the cross-sectional view of FIG. 3, this pad member 20 includes an interior metal support piece 21 which extends nearly the entire longitudinal length of the pad member 20. The outer portions of the pad member 20 are formed of electrical insulation material 22 which is molded around the support piece 21. Suitable lugs 23 and 24 are attached to the support piece 21 and extend beyond the insulation material 22 to provide for mechanical coupling to the support arms 17 and 18 shown in FIG. 1.

The pad member 20 also includes a survey current electrode A_0 forming part thereof and having an exposed surface portion located on the wall-engaging side thereof. As shown in the FIG. 2 view of the wall-engaging face of the pad member 20, this survey current electrode A_0 is centrally located on such face. The pad member 20 further includes a focussing current electrode A_1 forming part thereof and having an exposed surface portion located on the backside of the pad member 20 for making direct contact with the conductive liquid or drilling mud 12. As shown in the backside view of FIG. 4, this focussing current electrode is of relatively large surface area and covers most of the backside of the pad member 20. In addition to these current emitting electrodes, the pad member 20 also includes means for providing an indication of a potential difference adjacent the wall-engaging side of the pad member 20. This means includes a pair of spaced apart potential monitor electrodes M_1 and M_2 located on the wall-engaging face of the pad member 20 outwardly of the survey current electrode A_0 . As seen in the wall-engaging face view of FIG. 2, each of these potential monitor electrodes M_1 and M_2 has exposed surface portions defining a path encircling the survey current electrode A_0 .

As shown in the cross-sectional view of FIG. 3, the electrodes A_0 , M_1 , M_2 and A_1 are inlaid into the surface of the electrical insulation material 22. Also, the exposed surface portion of each of the A_0 , M_1 and M_2 elec-

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trodes is slightly recessed relative to the front surface of the insulation material 22 proper. As seen in the top view of FIG. 5, the contour of the wall-engaging face of the pad member 20 is curved to conform to the curvature of the borehole wall. Electrical connections to the A_0 , M_1 , M_2 and A_1 electrodes are made by way of insulated conductors 25, 26, 27 and 28, respectively. As seen in FIG. 1, these insulated conductors proceed upwardly and through the hollow interior of the support arm 17 to the interior of the instrument housing portion 14.

The downhole portion of the apparatus shown in FIG. 1 also includes a backup pad 30 which is pivoted to the I-beam portion 15 by way of support arms 31 and 32. This backup pad 30 is formed of electrical insulation material in a manner similar to the pad member 20. If desired, suitable electrodes making up a different type of electrode array could be included on the wall-engaging face of the backup pad 30 for providing additional measurements of formation characteristics. For simplicity, no electrodes are shown on the backup pad 30.

A suitable actuating mechanism for extending the upper support arms 17 and 31 is included in the lower portion of the instrument housing section 14. Extension of these arms 17 and 31 urges the pad members 20 and 30 against the borehole wall.

In order to prevent undesired current flow paths, the surfaces of the I-beam portion 15 are covered with a layer 33 of electrical insulation material. Likewise, the surfaces of the instrument housing portion 14 and the nose portion 16 are covered with layers of insulation material 34 and 35, respectively. In addition, the pad support arms 17, 18, 31 and 32 are covered with a layer of nonconductive material such as a nonconductive paint.

Connected to the top of the instrument housing portion 14 is an armored multiconductor cable 36 which extends upwardly through the borehole to a suitable drum and winch mechanism located at the surface of the earth. In this manner, the downhole apparatus shown in FIG. 1 may be raised and lowered through the borehole 11. The first 100 feet or so of the armored cable 36 is covered with a layer of insulation material 37. Towards the upper end of this electrical insulation material 37 are located an electrically-remote current-return electrode B and an electrically-remote potential reference electrode N. The various insulated conductors contained within the armored cable 36 serve to interconnect the downhole electrical circuits in the instrument housing portion 14 with suitable power supply and recorder apparatus located at the surface of the earth.

Referring now to FIG. 6 of the drawings, there are shown suitable electrical circuits for operating the electrode pad member 20. The pad member 20 is shown in a somewhat simplified manner in this figure. The electrical circuits include a source of alternating-current power 40 located at the surface of the earth and connected to a downhole power supply unit 41 by way of insulated conductors 36a and 36b of the armored cable 36. The downhole power supply unit 41 is shown within a dash-line box 14 which corresponds to the instrument housing portion 14 of FIG. 1. This power supply 41 of FIG. 6 serves to develop the operating voltages required by the various downhole electrical circuits. For sake of simplicity, the interconnections between this power supply unit 41 and the other electrical units have been omitted.

Also included within the dash-line box 14 are circuit means for energizing the survey current electrode A_0 for emitting survey current I_s from the surface portion thereof into the adjacent earth formation and circuit means for energizing the focussing current electrode A_1 for emitting focussing current I_f from the surface portion thereof directly into the adjacent drilling mud for controlling the flow pattern of the survey current I_s . Considering first the circuit means for energizing the focussing current electrodes A_1 , this circuit means includes a signal generator 42 which develops a suitable alternating-cur-

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rent voltage which is supplied to a variable-gain amplifier 43. This alternating-current voltage may have a frequency of, for example, 400 cycles per second. This voltage is then amplified by the variable-gain amplifier 43 to produce an alternating output current flow I_f which is supplied to the A_1 focussing current electrode by way of the insulated conductor 28. The other side of the output of the variable-gain amplifier 43 is connected to the remote current-return electrode B by way of an insulated conductor 44. It is thus seen that the signal generator 42, the variable gain amplifier 43, the conductor 28 and the A_1 electrode constitute electrode means for emitting electrical current from the pad member 20 directly into the adjacent drilling mud.

This A_1 electrode circuit means also includes means for adjusting the focussing current I_f for maintaining the potential level of one of the potential monitor electrodes M_1 and M_2 substantially constant relative to an electrically-remote potential reference point. This means includes conductor 26 which is connected by way of a further conductor 45 to the primary winding 46 of an input transformer 47 for an amplifier 48. Amplifier 48 is of the high gain type. The other side of the primary winding 46 is connected by way of a conductor 49, a resistor 50 and a further conductor 51 to the electrically-remote potential reference electrode N. The resistor 50 is also connected to the signal generator 42 by way of conductors 52 and 53. In this manner, the signal generator 42 supplies an alternating current of constant amplitude to and, hence, develops a constant reference voltage across the resistor 50.

The input transformer 47 of amplifier 48 serves to compare this constant reference voltage across resistor 50 with the voltage level of the M_1 potential monitor electrode which is connected to the other side of primary winding 46. If these two potential levels, both taken with respect to the remote potential reference point N, differ from one another, then an error signal is developed across the secondary winding of transformer 47 which is supplied by way of the amplifier 48 to a phase sensitive detector 54. Also supplied to the phase sensitive detector 54 by way of conductors 55 and 56 is an alternating-current phase reference signal from the signal generator 42. Under the control of this phase reference signal, the phase sensitive detector 54 serves to detect the amplified error signal to provide a direct-current output signal which is proportional thereto. This direct-current output signal is then supplied to the variable gain amplifier 43 to bias the gain control elements thereof in the proper direction to adjust the amplifier 43 output current I_f so as to reduce the original error signal across the primary winding 46 substantially to zero. This degenerative feedback action thus serves to maintain the potential level of the monitor electrode M_1 at a constant value equal to the reference voltage developed across the resistor 50.

The apparatus shown in FIG. 6 also includes means for providing an indication of a potential difference adjacent the wall-engaging side of the pad member 20. As mentioned, this means includes the pair of spaced apart potential monitor electrodes M_1 and M_2 located on the wall-engaging face of the pad member 20. This means also includes the conductors 26 and 27 which supply this potential difference indication to the electrical circuits within the instrument housing 14.

One of the A_0 and A_1 energizing circuit means also includes means for adjusting the corresponding current flow until the M_1 — M_2 potential difference becomes substantially zero. For this embodiment of the invention, it is the A_0 electrode energizing circuit means which provides this adjustment. To this end, the A_0 energizing circuit means includes a high-gain amplifier 57, the input side of which is coupled to the conductors 26 and 27 by way of an input transformer 58. In response to the M_1 — M_2 potential difference supplied by way of the input transformer 58, the amplifier 57 is effective to produce an alternating output current I_s which is supplied by

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way of a measure resistor 59 and the insulated conductor 25 to the A_0 electrode on the wall-engaging side of the pad member 20. The other output terminal of the amplifier 57 is connected by way of a conductor 60 to the electrically-remote current-return point B. This amplifier 57 is connected in a degenerative manner so that the amplitude of the alternating survey current I_s is adjusted to reduce the M_1 — M_2 potential difference substantially to zero. In this manner, the conductors 26 and 27, the input transformer 58, the amplifier 57, the resistor 59 and the conductor 25 constitute circuit means for energizing the survey current electrode A_0 and responsive to the potential difference between the monitor electrodes M_1 and M_2 for adjusting the survey current I_s until this potential difference becomes substantially zero.

The electrical circuits of FIG. 6 also include means responsive to flow of at least one of the survey and focussing currents for providing an indication representative of the formation resistivity. In this embodiment, this means includes the measure resistor 59 which is connected in series intermediate the amplifier 57 and the A_0 electrode. This resistor 59 serves to develop thereacross a voltage signal which is proportional to the amount of survey current I_s flowing therethrough. This survey current representative signal is amplified by an amplifier 61 and then supplied to a phase sensitive detector 62. Also supplied to the phase sensitive detector 62 by way of conductors 63 and 64 is an alternating-current phase reference signal from the signal generator 42. The phase sensitive detector 62 is thus effective to detect the amplified survey current representative signal to provide at the output thereof a direct-current signal which is proportional thereto. This direct-current signal is supplied by way of insulated conductors 36c and 36d of the armored cable 36 to a meter or indicating device 65 located at the surface of the earth which then provides an indication of the magnitude of the survey current flow I_s .

The indicating device 65 will usually take the form of one of the galvanometer units of a multiunit galvanometer-type recorder located at the surface of the earth. In this case, the recording medium on which the signal variations are recorded is moved or advanced in synchronism with the movement of the downhole apparatus through the borehole to provide a continuous record or log of the conductivity values along the course of the borehole. Instead of having the electrical circuits shown within the instrument housing portion 14 of FIG. 6 located downhole, all or part of these electrical circuits may, if desired, be located at the surface of the earth.

Considering now the operation of the apparatus described in FIGS. 1–6, as the support member 13 shown in FIG. 1 is moved in an upwardly direction through the borehole 11, the pad support arms 17, 18, 31 and 32 are extended outwardly to urge both the electrode pad member 20 and the backup pad 30 against the wall of the borehole 11. At the same time, the associated electrical circuits which are shown in FIG. 6 are operated to energize both the A_0 and A_1 electrodes to emit, respectively, survey current I_s and focussing current I_f from the exposed surface portions thereof. In order to better understand this part of the operation, reference will also be made to FIG. 7 which shows a horizontal section of a portion of the borehole 11 together with a portion of an adjoining permeable formation 70 which, for example, may be a permeable sand formation. It is seen in the example of FIG. 7 that a relatively thick mud cake 71 has been built up on the wall of the borehole 11 by invasion of the drilling mud 12 into the permeable formation 70. The pad member 20 of the present invention, depicted in a simplified manner, is shown as engaging the inner surface of this mud cake 71.

As the pad member 20 is moved upwardly through the borehole 11, which, in the case of FIG. 7, would be at right angles to the plane of the paper, the signal generator 42 and the variable gain amplifier 43 shown in

FIG. 6 are effective to energize the focussing current electrode A_1 to emit focussing current I_f from the backside of the pad member 20 directly into the drilling mud 12 contained in the borehole. This focussing current I_f diverges as it leaves the A_1 electrode, some of it passing in vertical directions upwardly and downwardly through the borehole in an effort to return to the remote current-return electrode B. Other portions of the focussing current diverge in horizontal directions as shown in FIG. 7 and, hence, pass through the mud cake 71 into the adjacent permeable formation 70, this current likewise eventually returning to the remote current-return electrode B.

As a result of the focussing current flow, the potential level of the monitor electrode M_1 relative to the remote potential reference electrode N is altered. An indication of the M_1 potential level is then supplied by way of the conductor 26 to one side of the primary winding of the input transformer 47, to the other side which is supplied the constant reference voltage developed across the resistor 50. The degenerative feedback action provided by the amplifier 48 and the phase sensitive detector 54 which complete the focussing current feedback control loop serves to continuously adjust the magnitude of the focussing current I_f so as to maintain the M_1 potential level substantially constant and equal in value to the constant reference voltage developed across the resistor 50.

The flow of the focussing current I_f also produces a potential difference between the M_1 and M_2 potential monitor electrodes. An indication of this potential difference is supplied by way of the conductors 26 and 27 shown in FIG. 6 to the amplifier 57. This, in turn, actuates the amplifier 57 to supply survey current I_s to the A_0 survey current electrode. This survey current I_s is then emitted from the surface portion of the A_0 electrode into the adjacent permeable formation 70 as shown in FIG. 7. The degenerative feedback action provided by this survey current feedback control loop serves to continuously adjust the magnitude of the survey current flow I_s until the M_1 — M_2 potential difference becomes substantially zero. When this condition occurs, the I_s and I_f current flow patterns are substantially as shown in FIG. 7. In other words, the I_f focussing current serves to effectively constrain the I_s survey current to a relatively narrow and well-focussed beam.

As is known for the case of feedback loops like the present survey current feedback loop, the input error signal, in this case the M_1 — M_2 potential difference, will never become precisely and exactly equal to zero because a small amount of error signal is necessary to drive the amplifier 57 to produce the output current I_s . Where the amplifier 57 has a relatively high gain factor, however, this residual error signal becomes extremely small and, hence, the M_1 — M_2 potential difference becomes effectively equal to zero as compared to the other electrode voltages.

As the pad member 20 passes different formations having different resistivity values, then differing amounts of survey current I_s will be required in order to keep the M_1 — M_2 potential difference at substantially zero. In view of the fact that the M_1 potential level is being held substantially constant by the focussing current control loop, the magnitude of the survey current required will be directly proportional to the conductivity of the portion of the formation material directly in front of the A_0 electrode. These survey current variations produced as the pad member 20 passes by different earth formations are monitored by the measure resistor 59 and detected by the phase sensitive detector 62 to provide a direct-current signal proportional thereto. This direct-current signal is recorded by the indicating device 65 to provide an indication which is directly proportional to the conductivity of the formation material which, in the case of a permeable formation, is the conductivity of the flushed zone.

In order to understand better how the pad member 20 of the present invention provides improved focussing action under adverse borehole conditions, references will now be made to FIG. 8 which shows in a simplified cross-sectional manner a previously known type of focussed wall-contact electrode pad 80 in the same environment as that shown in FIG. 7 for the pad member 20. For purposes of the present discussion, it will be assumed that the A_0 , M_1 , M_2 and A_1 electrodes of the previously-known pad member 80 shown in FIG. 8 are connected to the same type of electrical circuits as shown in FIG. 6 for the pad member 20. Note that the A_1 focussing current electrode of the previously-known pad 80 is located entirely on the wall-engaging face thereof. It is also assumed that the resistivity of both the drilling mud 12 and the mud cake 71 are relatively low, the resistivity of the mud cake 71 being slightly higher than that of the drilling mud 12. In addition, it is assumed that the resistivity of the flushed portion of the invaded zone of the formation 70 is relatively high compared to the resistivity of the mud cake 71. It is further assumed that the mud cake 71 has a thickness in the range of one-half of an inch to one inch.

Under the foregoing conditions, the thick mud cake 71 shown in FIG. 8 provides a low resistance path around the pad member 80 to the drilling mud 12 contained in the borehole. Most of the focussing current I_f from the pad member 80 follows this low resistance path in order to get into the low resistance drilling mud 12 and then to the remote current-return electrode B by way of the path of least resistance. Note in particular the congestion of the focussing current I_f immediately in front of the two A_1 focussing current electrode portions. The thick mud cake 71 enables the focussing current I_f to diverge in a horizontal sense to both the left and the right of each of the A_1 electrode portions in an effort to reduce the I_f current density. The I_f current flow in towards the center of the pad member 80 then reverses its direction in the mud cake 71 and takes advantage of the low resistance path therethrough back to the borehole. In a sense, the thick mud cake 71 provides enough room for an "eddy" or "backwater" to occur in the case of the I_f focussing current. The monitor electrodes M_1 and M_2 of the pad member 80 are adjacent to this "eddy," thus allowing a zero potential difference to occur with a diverging flow of survey current I_s , as shown in FIG. 8. This appreciable divergence of the survey current means that the major portion of such current will not penetrate sufficiently deep into the flushed zone to provide an accurate measure of the resistivity or conductivity thereof. Also, and, more importantly, it means that undesired extraneous signal variations will be introduced into the output indication as the mud cake thickness varies. It also means that a smaller magnitude of output signal will be produced for the same formation conditions, thus reducing the accuracy of the measurement.

As shown in FIG. 7, on the other hand, where a pad member 20 constructed in accordance with the present invention is utilized, this divergence of the survey current I_s is considerably reduced and, in fact, the survey current flows in a relatively well-defined beam for a substantial distance into the flushed zone. Note that for the present invention, the fact that the focussing current I_f is emitted from the backside of the pad member 20 insures that no current congestion and undesired local potential effects will occur on the front side of the pad member 20 adjacent the monitor electrodes M_1 and M_2 . Also, the fact that the A_1 electrode of the present invention has a relatively large exposed surface area further serves to minimize the possibility of undue current congestion.

Another important feature of the electrode pad member 20 of the present invention is that the effective electrode spacing is the same as though the A_1 focussing current electrode were located beyond the edges of the

pad member 20. Thus, a larger "effective" electrode spacing may be obtained with the same size of pad. Instead, a smaller sized pad may be used to provide the same effective spacing as heretofore obtained with larger sized pads. Also, the fact that the M_1 and M_2 potential monitor electrodes of the pad member 20 are spaced farther apart serves to provide a more sensitive measure of the M_1 — M_2 potential difference and, hence, a greater accuracy in the I_s control action.

It should be noted that, in some cases, it will be more advantageous to omit the inner potential monitor electrode M_1 and to instead use the potential difference between the outer monitor electrode M_2 and the A_0 current-emitting electrode to control the focussing action, which control is provided, in this embodiment, by the adjustment of the survey current. In this case, the potential level of the outer M_2 electrode would be held constant relative to the remote potential reference point N.

As shown in FIG. 1, the metal parts associated with the support member 13 are covered with electrical insulation material. This is done in order to minimize undesired leakage of the currents along such parts to a remote region of the borehole. If the overall length of the support member 13 is sufficiently short, then this electrical insulation can be omitted. For the case of a relatively long support member 13, on the other hand, advantage may be taken thereof to further control the depth of penetration of the survey current beam I_s . This is done by removing the electrical insulation from all of the support member 13 except for the portions located directly in back of the pad member 20. In this manner, an electrically-proximate current-return surface would be provided for the electrode currents by means of the uninsulated portions of support member 13. This would cause the currents to return to the borehole drilling mud somewhat sooner and, hence, reduce the depth of penetration of the I_s survey current beam. A separate electrically-proximate current-return electrode could, instead, be provided on the support member 13 and used in place of the remote current-return electrode B. The important thing is that no low resistance paths should be provided between the region directly in back of the pad member 20 and the current-return point to which the electrode energizing circuits are connected.

The electrical circuits described in connection with FIG. 6 serve to maintain a constant voltage level in the vicinity of the A_0 survey current electrode and then to measure the variations in the survey current I_s to provide indications directly proportional to formation "conductivity." Where desired, a converse type of operation may instead be utilized. In other words, the I_s survey current may instead be held constant and the variations in the potential level adjacent the A_0 electrode measured to provide an output signal which, in this case, would be directly proportional to formation "resistivity." Note that resistivity is the reciprocal of conductivity and that both are determined by the same electrical property of the formation, namely, its resistance characteristic. Also, if desired, neither the voltage level nor the survey current need be held constant. Both may be allowed to vary and suitable ratio circuits or devices utilized to measure the ratio of the voltage to the current, or vice versa.

From the foregoing description of the present invention, it is seen that the present invention provides an improved type of focussed wall-contact electrode system which is less affected by the presence of mud cake on the borehole wall.

While there has been described what is at present considered to be a preferred embodiment of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention and it is, therefore, intended to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What is claimed is:

1. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall; first electrode means for emitting electrical current from the wall-engaging face of the pad member into the adjacent earth formation; second electrode means for emitting electrical current from the pad member directly into the adjacent conductive liquid for controlling the flow pattern of the first electrode current and rendering such flow pattern relatively unaffected by the presence of a layer of mud cake on the wall of the borehole; means for energizing the first and second electrode means; and means responsive to the flow of the first electrode current for providing an indication representative of formation resistivity.

2. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall; first electrode means for emitting electrical current from the wall-engaging face of the pad member into the adjacent earth formation; second electrode means for emitting electrical current from the back side of the pad member directly into the adjacent conductive liquid for controlling the flow pattern of the first electrode current and rendering such flow pattern relatively unaffected by the presence of a layer of mud cake on the wall of the borehole; means for energizing the first and second electrode means; and means responsive to the flow of the first electrode current for providing an indication representative of formation resistivity.

3. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall; a first electrode forming part of the pad member and having an exposed surface portion located on the wall-engaging side thereof; circuit means for energizing the first electrode for emitting electrical current from the surface portion thereof into the adjacent earth formation; a second electrode forming part of the pad member and having an exposed surface portion located on the back side thereof for making direct contact with the conductive liquid; circuit means for energizing the second electrode for emitting electrical current from the surface portion thereof directly into the adjacent conductive liquid for controlling the flow pattern of the first electrode current and rendering such flow pattern relatively unaffected by the presence of a layer of mud cake on the wall of the borehole; and means responsive to the flow of the first electrode current for providing an indication representative of formation resistivity.

4. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall; a first electrode forming part of the pad member and having an exposed surface portion located on the wall-engaging side thereof; circuit means for energizing the first electrode for emitting electrical current from the surface portion thereof into the adjacent earth formation; a second electrode forming part of the pad member and having an exposed surface portion located on the back side thereof for making direct contact with the conductive liquid; circuit means for energizing the second electrode for emitting electrical current from the surface portion thereof directly into the adjacent conductive liquid; and means responsive to the flow of at least one of the currents for providing an indication representative of formation resistivity.

5. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall; a first elec-

trode forming part of the pad member and having an exposed surface portion located on the wall-engaging side thereof; first circuit means for energizing the first electrode for emitting survey current from the surface portion thereof into the adjacent earth formation; a second electrode forming part of the pad member and having an exposed surface portion located on the back side thereof; second circuit means for energizing the second electrode for emitting focussing current from the surface portion thereof directly into the conductive liquid adjacent the pad member; means for providing an indication of a potential difference adjacent the wall-engaging side of the pad member; one of the first and second circuit means including means for adjusting the corresponding current flow until this potential difference becomes substantially zero; and means responsive to the flow of the survey current for providing an indication representative of formation resistivity.

6. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall; a first electrode forming part of the pad member and having an exposed surface portion located on the wall-engaging side thereof; first circuit means for energizing the first electrode for emitting survey current from the surface portion thereof into the adjacent earth formation; a second electrode forming part of the pad member and having an exposed surface portion located on the back side thereof; second circuit means for energizing the second electrode for emitting focussing current from the surface portion thereof directly into the conductive liquid adjacent the pad member; means for providing an indication of a potential difference adjacent the wall-engaging side of the pad member; one of the first and second circuit means including means responsive to this potential difference for adjusting the corresponding current flow until this potential difference become substantially zero; and means responsive to the flow of the survey current for providing an indication representative of formation resistivity.

7. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall and having the outer portions thereof formed of electrical insulation material; a survey current electrode centrally located on the wall-engaging face of the pad member; a pair of spaced apart potential monitor electrodes located on the wall-engaging face of the pad member outwardly of the survey current electrode; a focussing current electrode located on the back side of the pad member; first circuit means for energizing the survey current electrode; second circuit means for energizing the focussing current electrode; means for providing an indication of the potential difference between the potential monitor electrodes; one of the first and second circuit means including means for adjusting the corresponding current flow until this potential difference becomes substantially zero; and means coupled to one of the electrodes for providing indications representative of formation resistivity.

8. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall and having the outer portions thereof formed of electrical insulation material; a survey current electrode centrally located on the wall-engaging face of the pad member; a pair of spaced apart potential monitor electrodes each having exposed surface portions located on the wall-engaging face of the pad member defining a path encircling the survey current electrode; a focussing current electrode located on the back side of the pad member; first circuit means for energizing the survey current electrode; second circuit means for energizing the focussing current electrode; means for providing an indication of the po-

tential difference between the potential monitor electrodes; one of the first and second circuit means including means for adjusting the corresponding current flow until this potential difference becomes substantially zero; and means coupled to one of the electrodes for providing indications representative of formation resistivity.

9. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall and having the outer portions thereof formed of electrical insulation material; a survey current electrode centrally located on the wall-engaging face of the pad member; a pair of spaced apart potential monitor electrodes located on the wall-engaging face of the pad member outwardly of the survey current electrode; a large area focussing current electrode located on and covering most of the back side of the pad member; first circuit means for energizing the survey current electrode; second circuit means for energizing the focussing current electrode; means for providing an indication of the potential difference between the potential monitor electrodes; one of the first and second circuit means including means for adjusting the corresponding current flow until this potential difference becomes substantially zero; and means coupled to one of the electrodes for providing indications representative of formation resistivity.

10. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall and having the outer portions thereof formed of electrical insulation material; a survey current electrode centrally located on the wall-engaging face of the pad member; a pair of spaced apart potential monitor electrodes located on the wall-engaging face of the pad member outwardly of the survey current electrode; a focussing current electrode located on the back side of the pad member; first circuit means for energizing the survey current electrode; second circuit means for energizing the focussing current electrode; one of the first and second circuit means including degenerative feedback circuit means responsive to the potential difference between the potential monitor electrodes for adjusting the corresponding current flow until this potential difference becomes substantially zero; and means coupled to one of the electrodes for providing indications representative of formation resistivity.

11. In apparatus for investigating earth formations traversed by a borehole containing a relatively conductive liquid, the combination comprising: a pad member adapted to be urged against the borehole wall and having the outer portions thereof formed of electrical insulation material; a survey current electrode centrally located on the wall-engaging face of the pad member; a pair of spaced apart potential monitor electrodes located on the wall-engaging face of the pad member outwardly of the survey current electrode; a focussing current electrode located on the back side of the pad member for making direct contact with the conductive liquid; circuit means for energizing the focussing current electrode and for adjusting the focussing current emitted therefrom for maintaining the potential level of one of the potential monitor electrodes substantially constant relative to a remote potential reference point; circuit means for energizing the survey current electrode and responsive to the potential difference between the potential monitor electrodes for adjusting the survey current until this potential difference becomes substantially zero; and circuit means coupled to the survey current electrode for measuring the magnitude of the survey current flow to provide indications directly proportional to the formation conductivity.

12. Electrode apparatus for investigating earth formations traversed by a borehole comprising: a pad member adapted to be urged against the borehole wall and having the outer portions thereof formed of electrical insulation

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material; a survey current electrode centrally located on the wall-engaging face of the pad member; a pair of spaced apart potential monitor electrodes located on the wall-engaging face of the pad member outwardly of the survey current electrode; and a focussing current electrode located on the back side of the pad member. 5

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