324-374 SR SEARCH ROOM
OR 3,379,963

April 23, 1968 D. F. SAURENMAN 3,379,963
WELL LOGGING PAD MEMBER CONSTRUCTED TO CONFORM TO BOREHOLE WALL CURVATURE
Filed April 2, 1965 3 Sheets-Sheet 1

Fig. 1

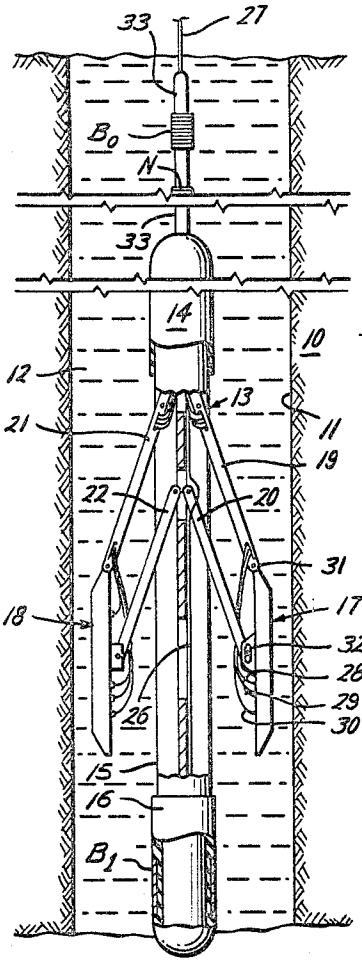
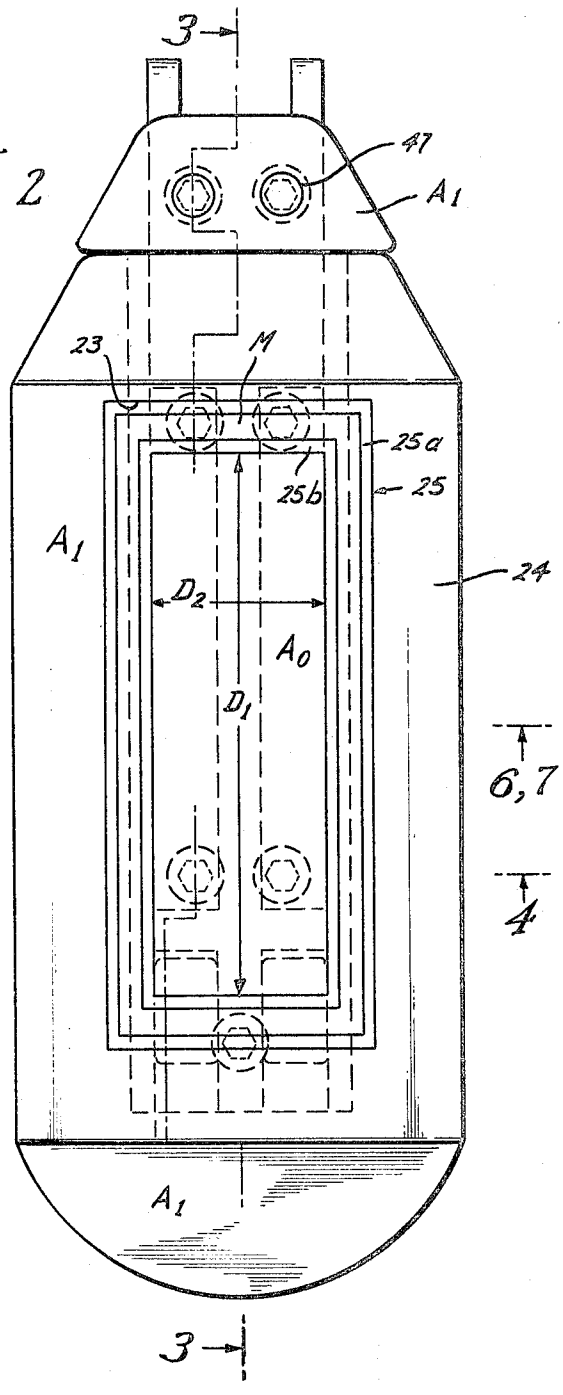


Fig. 2

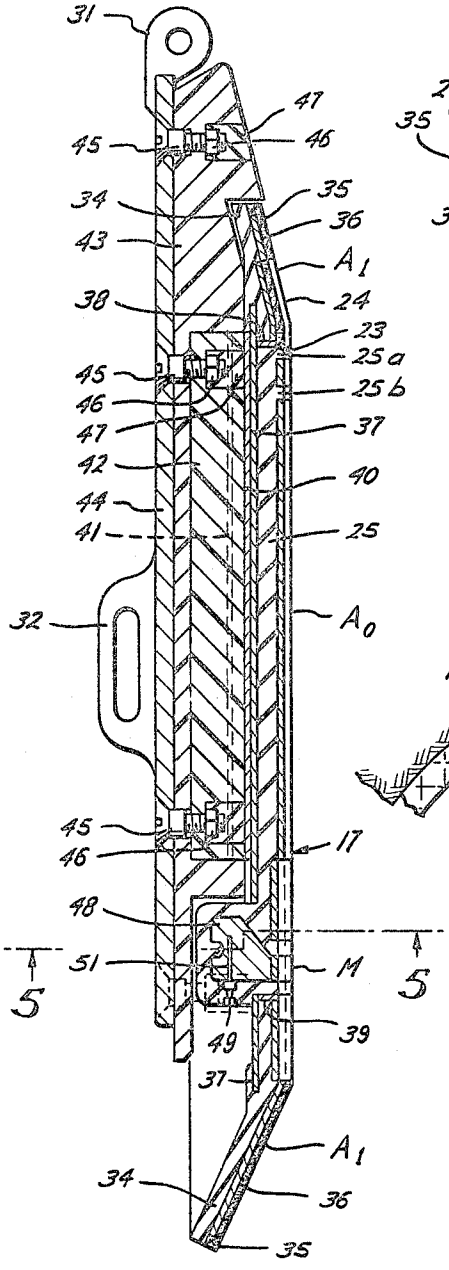


April 23, 1968 D. F. SAURENMAN 3,379,963

WELL LOGGING PAD MEMBER CONSTRUCTED TO CONFORM TO BOREHOLE WALL CURVATURE

Filed April 2, 1965 3 Sheets-Sheet 2

Fig. 3



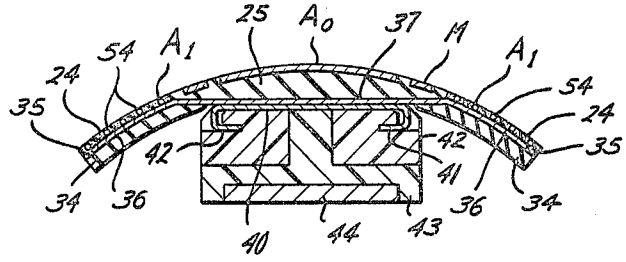


Fig. 6

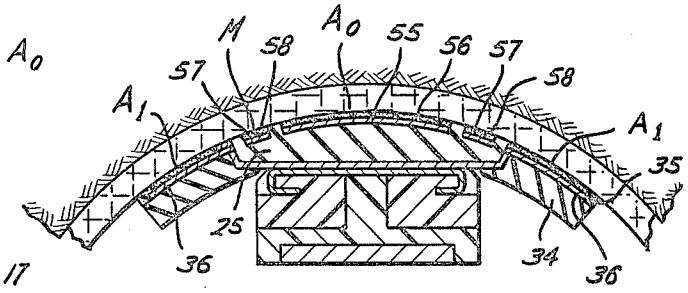


Fig. 7

April 23, 1968 D. F. SAURENMAN 3,379,963

WELL LOGGING PAD MEMBER CONSTRUCTED TO CONFORM TO BOREHOLE WALL CURVATURE

Filed April 2, 1965 3 Sheets-Sheet 3

Fig. 4

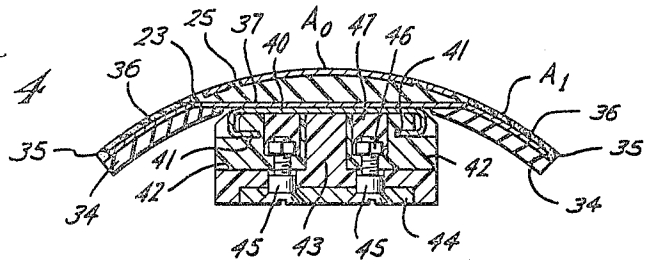
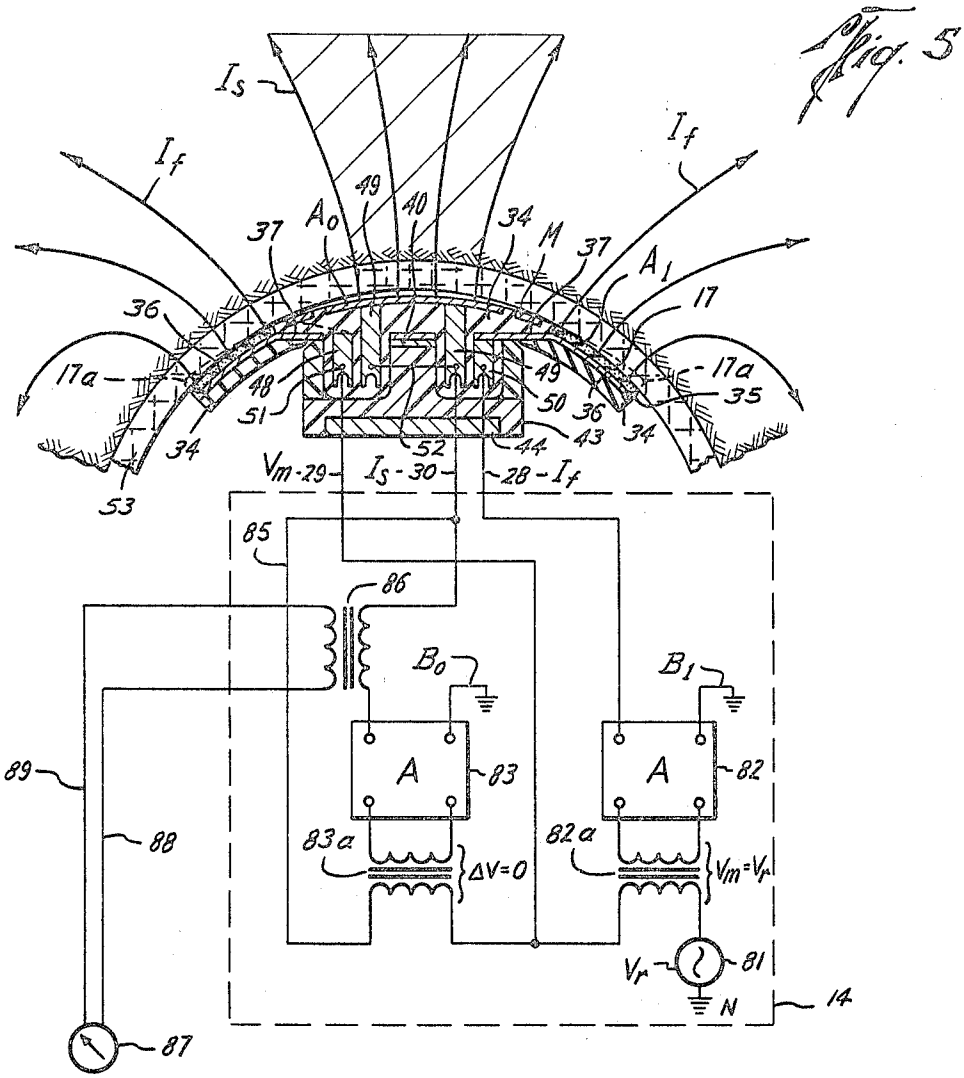


Fig. 5



United States Patent Office 3,379,963 Patented Apr. 23, 1968

3,379,963

WELL LOGGING PAD MEMBER CONSTRUCTED TO CONFORM TO BOREHOLE WALL CURVATURE

Dean F. Saurenman, Friendswood, Tex., assignor, by mesne assignments, to Schlumberger Technology Corporation, Houston, Tex., a corporation of Texas

Filed Apr. 2, 1965, Ser. No. 445,087
13 Claims. (Cl. 324—10)

ABSTRACT OF THE DISCLOSURE

This disclosure shows a borehole wall-engaging pad member having electrodes which can be utilized to investigate earth formations traversed by a borehole. The pad member has a central relatively stiff portion and two adjacent pad portions which are constructed to flex or bend with respect to the central portion. To accomplish this, a metal sheet, which may be perforated is embedded in an elastomeric material which is of a conductive nature on the borehole wall-engaging face of the adjacent pad portions. The metal sheet provides rigidity and springiness to the adjacent pad portions as well as providing an equal potential distribution to the conductive elastomeric material.

This invention relates to electrical apparatus for investigating subsurface earth formations traversed by a borehole and, more particularly, to apparatus for measuring the electrical resistance properties of a subsurface earth formation by means of electrodes in the borehole adapted to be pressed against the borehole wall.

One method of investigating subsurface earth formations traversed by a borehole is to move a system of pad mounted wall-engaging electrodes through the borehole and to determine the resistance presented by the earth formations to the flow of electrical current emitted from one or more of the electrodes. The electrical record or log obtained from this manner of investigation aids in determining the nature and lithological character of the various subsurface earth formations. The resulting data is useful in the case of oil well boreholes in that, among other things, it enables the presence and depth of any oil or gas bearing strata to be determined.

In drilling a borehole by the usual rotary method, the borehole is filled with a drilling mud during the drilling process. This drilling mud will penetrate radially into the subsurface earth formations for a distance dependent upon the porosity of the earth formations. When the drilling mud invades a permeable strata, there is a mudcake remaining on the wall of the borehole. This mudcake is caused by the solid particles of drilling mud being unable to pass through the permeable strata. The mud filtrate which actually invades the permeable zone alters the electrical resistance properties of the earth formation immediately adjacent to the borehole wall and, not uncommonly, increases the resistance of such portions, particularly where fresh muds are used. However, the resistivity of the mud cake which is formed on the borehole wall is usually relatively low compared to the resistivity of the flushed zone.

For the case of pad-mounted electrodes which engage the wall of the borehole, as the mudcake thickness increases, more and more of the electrode current is short circuited back to the borehole current return point by the relative low resistance path formed by the mudcake. This makes the measurements of the flushed zone resistivity and thus, any subsequent formation porosity determination more difficult, because the measurement is influenced to a large degree by the mudcake resistivity. This problem is overcome to a large extent by using a

wall-engaging electrode system of the focused type. Systems of this type are to be found in U.S. Patent No. 2,712,629, granted to H. G. Doll on July 5, 1955, and in U.S. Patent No. 3,132,298, granted to H. G. Doll and J. L. Dumanoir on May 5, 1964. In a wall-engaging electrode system of the focused type, a current flow is emitted by one of the electrodes and used for determining or surveying the formation resistance characteristics. This surveying current flow is constrained to a desired lateral flow pattern by a focusing current emitted by another one of the electrodes which is adjacent to the main surveying electrode. Focusing current emitted by means of the focusing current electrodes opposes any tendency of the survey current to flow in an undesired direction, as for example, along the mudcake. Thus, most of the survey current is caused to penetrate laterally into the earth formations for some appreciable distance. As indicated by the Doll and Dumanoir patent, more elaborate precautions are required as the environment becomes more severe or the requirements on the measurements become more demanding.

The electrode system described in the Doll and Dumanoir patent provides an improved measurement of the resistivity of the invaded zone region of the earth formations even for a case of relatively thick mudcake. Among other things, this is accomplished by utilizing relatively large electrode surfaces on the wall-engaging pad member. It has been found, however, that in some boreholes, undesired variations appear in the measurements. After considerable effort, it has been found that the undesired variations in these instances are caused primarily by relatively large changes or variations of the shape or contour of the borehole wall. If the cross-sectional shape of the borehole remains fairly circular and the diameter fairly constant, results are satisfactory. If, however, a section of the borehole assumes an elliptical or other non-circular shape and if, at the same time, a fairly thick mudcake is present on the borehole wall, then the measured value will be somewhat different depending upon what side of the ellipse is being engaged by the electrode system.

It has been found that this undesired effect can be largely eliminated if a constant relationship can be maintained between the curvature of the borehole wall and the curvature of the wall-engaging face of the electrodes. This requires providing different electrode system curvatures for the different sides of the ellipse, depending upon which side of the ellipse the electrode system is pressed against.

The relationship between the formation resistivity and the measurement made with an electrode system is described by the formula:

$$R = K \cdot \frac{V}{I}$$

where R is the formation resistivity, K is a proportionality constant or calibration constant depending upon the geometry of the electrode array including the size and shape of the individual electrodes and the distance between the electrodes, V the voltage at one of the electrodes, and I the current emitted by one of the electrodes. Either the voltage may be kept constant and current variations measured, or the current kept constant and the voltage variations measured. The curvature of the electrode device is a factor in determining the K coefficient in the above formula. Therefore, changes in the electrode system curvature will tend to introduce corresponding changes into the measured values. Since these changes are independent of the formation resistivity, they are undesirable.

It is an object of the present invention therefore, to

provide new and improved apparatus for measuring electrical resistance properties of subsurface earth formations adjacent to a borehole.

It is another object of the present invention to provide new and improved wall-contact electrode apparatus of the focused type which provides improved focusing action under adverse borehole conditions.

It is a further object of the present invention to provide a new and improved focused-type wall-contact electrode system which is less effected by variations in radius of curvature of the borehole wall.

It is an additional object of the invention to provide a new and improved focused-type wall-contact electrode system which can adapt itself to changes in the curvature of the borehole wall without introducing excessive changes in the calibration constant of the system.

In accordance with the present invention, apparatus for investigating earth formations traversed by a borehole comprises a pad member having a forward face adapted to be pressed against a bolehole wall. This pad member includes a first pad portion having at least one electrode forming part of said forward face and a pad portion adjacent to the central pad portion formed of at least one electrode and an elastomeric material, said electrode including conductive supporting means in the elastomeric material, said supporting means being arranged to enable the adjacent pad portion to bend so that the pad member may more nearly conform to the curvature of the borehole wall.

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 illustrates, partially in cross-section, a representative embodiment of borehole investigating apparatus constructed in accordance with the present invention;

FIG. 2 is an enlarged front view of the wall-engaging face of one of the electrode pads of the FIG. 1 apparatus;

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

FIG. 4 is a cross-sectional view of the electrode pad of FIG. 2 taken along the section line 4—4 thereof;

FIG. 5 is a cross-sectional view of the electrode pad of FIG. 3 taken along the section line 5—5 thereof, the electrode pad being disposed in a borehole with current flow lines indicated therein, and an electrical schematic of the circuitry of the present invention; and

FIGS. 6 and 7 are cross-sectional views corresponding to views taken along the section line 6, 7–6, 7 of FIG. 2 but showing modified forms of construction for the present invention.

Referring to FIG. 1 of the drawings, there is shown a representative embodiment of a downhole portion of an apparatus constructed in accordance with the present invention for investigating a formation **10** traversed by a borehole **11**, the borehole **11** being filled with a conductive fluid or drilling mud **12**. This apparatus includes an elongated support member **13** adapted for movement through the borehole **11**. The support member **13** includes an upper instrument housing portion **14** of a generally cylindrical shape having a hollow fluid-tight interior for enclosing certain downhole electrical circuits to be discussed hereinafter. The support member **13** also includes intermediate frame or chassis portion **15** in the form of an iron or steel I-beam or equivalent structure and a lower nose portion **16** of a generally cylindrical shape.

Supported from an intermediate I-beam portion **15** of the support member **13** on opposite sides thereof are a pair of electrode pad members **17** and **18**, each of which is adapted to be urged against the wall of the borehole **11**. The pad member **17** is supported by way of support arms **19** and **20**, which are pivotally coupled to the pad member **17** and the I-beam portion **15**. Similarly, pad member **18** is supported by way of support arms **21** and **22**, which are pivoted to both the pad member **18** and I-beam portion **15**. A suitable actuating mechanism for extending and retracting support arms **19** and **21** is included within the lower portion of the instrument housing section **14**.

The downhole portion of the apparatus also includes a current return electrode B_1 located on the support member **13** close enough to the location of the pad member **17** so as to be electrically proximate thereto, but longitudinally spaced apart from the location of the pad member **17** so that no portion of this B_1 electrode is located directly behind the pad member **17**. This B_1 current return electrode is of generally cylindrical shape and is mounted on suitable electrical insulation material which either covers or forms the nose portion **16** of support member **13**. Electrical connection to the B_1 current return electrode is made by way of an insulated conductor **26** which extends upwardly along the I-beam portion **15** to the instrument housing **14**.

The downhole support member **13** is suspended in the borehole **11** by way of an armored multi-conductor cable **27** which extends upwardly to a suitable drum and winch mechanism (not shown), located at the surface of the earth for raising and lowering the support member **13**. The first hundred feet or so of the cable **27** immediately above the instrument housing portion **14** is covered with a layer of electrical insulation material **33** such as rubber. Supported on this layer of insulation material **33** towards the upper end thereof are an electrically remote current return electrode B_0 and an electrically remote potential reference electrode N.

Only the electrode pad member **17** will be dealt with in the explanation of this invention. The pad member **18** can be any downhole testing apparatus, the particular apparatus not being a feature of this invention.

Considering the electrode pad member **17**, the FIG. 2 view of electrode pad member **17** shows the face of the pad that is pressed against the borehole wall. An electrode, by definition, must be made of a material which is electrically conductive, and must never be made of insulation or non-conductive material. The major portion of pad member **17** is formed by a generally rectangular pad portion A_1. The wall-engaging portion **24** of the A_1 electrode is made of an electrically conductive material and, as such, constitutes a focusing current electrode for emitting focusing current from the various surface portions thereof. The A_1 electrode has a recess **23** formed in a central portion of the wall-engaging face thereof, which recess **23** is of a rectangular shape. The recess **23** is filled with a suitable electrical insulation material **25** such as rubber.

The electrode pad member **17** also includes an elongated electrode A_0 of rectangular shape centrally located in recess **23** and electrically insulated from the A_1 electrode proper by the portion *25a* of insulation material **25** contained within the recess **23**. The surface portion of the A_0 electrode is thus centrally located relative to the wall-engaging portion **24** of the A_1 electrode. The A_0 electrode has a length D_1 in a direction parallel to the borehole axis which is greater than one-half the length of the electrode A_1 and a width D_2 greater than one-quarter the lenght D_1. Electrode A_0 constitutes a survey current electrode for emitting survey current into the adjacent earth formations.

The electrode pad member **17** further includes a potential monitor electrode M located intermediate the survey current electrode A_0 and the focusing current electrode A_1 and electrically insulated from the survey current electrode A_0 by the portion *25b* of insulation **25** and from the focusing current electrode A_1 by the portion *25a* of insulation **25**. Insulation portion *25b* is also a suitable insulation material such as rubber. This potential monitor electrode M has an exposed surface portion of narrow

width which defines a path encircling the A_0 survey current electrode.

Referring again to FIG. 1, the electrical connections to electrodes A_1, M, and A_0 are made by way of insulated conductors **28**, **29** and **30** respectively. These insulated conductors **28**, **29** and **30** pass upwardly through the hollow interior of the support arm **19** to the electrical circuits contained within the instrument housing portion **14**, or if support arm **19** is not hollow, as for example, a channel shaped member, then conductors **28**, **29** and **30** are secured to support arm **19** to pass upwardly to instrument housing portion **14**. Mechanical connections of the electrode pad member **17** to the support arms **19** and **20** is made by way of lug members **31** and **32** respectively. The electrical continuity of the lug members **31** and **32** may be broken by means of non-conductive inserts.

Referring now to FIG. 3, there is shown a cross-sectional view of electrode pad member **17** taken along the section line **3—3** of FIG. 2. The section line **3—3** is sectioned in FIG. 2 so that the main parts of the cross-section of electrode pad member **17** can be shown in one figure. As a result, the section line **3—3** is not straight and the electrodes A_0, M, and A_1 are somewhat more removed from the front portion of pad member **17** than if section line **3—3** were straight. The dotted line and clear, non-hatched portions of electrodes A_0, M, and A_1 show the electrode portions, which portions are within the area where the cross section line **3—3** of FIG. 2 varies from the middle of pad member **17**, as if section line **3—3** were straight down the middle of pad member **17** of FIG. 2. The survey current electrode A_0 of pad member **17** is centrally located with respect to the other electrodes of pad member **17** and is embedded in a rubber insulation material **25**. The survey current electrode A_0 is relatively stiff and of a suitable conductive material, such as iron. Adjacent to survey current electrode A_0 on both sides is the monitor electrode M, made of a suitable conductive material which is relatively stiff, such as iron. On the upper and lower part of the electrode portion of electrode pad member **17** and adjacent to monitor electrode M is focusing current electrode A_1.

Focusing current electrode A_1 comprises a flexible electrically conductive reinforcing member **36** which is embedded in an electrically conductive elastomeric material **35**. The electrically conductive elastomeric material **35** is preferably a relatively resilient material, such as conductive synthetic rubber, which for example, can be made by embedding small metal or carbon particles in rubber during the manufacturing process. On the back side (or non-wall-engaging side) of reinforcing member **36** and fixed thereto is an insulation or non-conductive elastomeric material **34**. The elastomeric materials **34** and **35** will bend when pressure is applied to one end thereof, but will regain their previous configuration when the pressure is removed. Embedded in the conductive elastomeric material **35** is reinforcing member **36**, which is preferably made from a relatively hard non-flexible electrically conductive material such as iron, but which is constructed in such a manner as to be flexible. Thus, reinforcing member **36** can be constructed of perforated sheet metal or a wire screen or cloth. Reinforcing member **36** should have spring-like qualities so that after bending or deforming, it will tend to return to its former position and shape. Thus, it can be seen that focusing current electrode A_1 can be bent, but will return to its original position and shape when the bending pressure is released.

Reinforcing member **36** is preferably placed close to the wall-engaging surface of this portion of focusing electrode A_1, but is, nevertheless, still covered by conductive rubber **35** so that there is a layer of conductive rubber between the metal reinforcing member **36** and the borehole wall. This is to insure that the metal reinforcing member **36** will not become caught on uneven points along the borehole, which could damage the electrode pad member **17**. Besides providing reinforcing strength to focusing electrode A_1, metal reinforcing member **36** provides a highly conductive path to all portions of focusing electrode A_1, thus providing uniformity of potential throughout. This is desirable since there is usually some resistance associated with conductive rubber. There is, therefore, only a short path through which the focusing current must travel through conductive rubber **35** to the wall-engaging portion **24** thereof, which short path has a negligible effect, if any, on disturbing the potential uniformity along the face **24** of focusing electrode A_1.

Electrodes A_0, M, and A_1 are insulated from one another by insulating rubber **25**. Insulating rubber **25** extends from focusing current electrode A_1 on the upper part of the electrode portion of pad member **17** to electrode A_1 on the lower part of the electrode portion of pad member **17**. Adjacent to insulating rubber **25** is a metal plate **37** which extends between the upper and lower parts of focusing electrode A_1. Metal plate **37** is embedded in a portion of the insulation rubber **34** adjacent to the upper and lower parts of focusing electrode A_1. Metal plate **37** is connected with reinforcing member **36** by a metal member **39** on the lower portion of focusing electrode A_1 and metal member **38** on the upper portion of focusing electrode A_1. Located adjacent to metal plate **37** and secured thereto is another metal plate **40**. Adjacent to metal plate **40** are two insulating blocks **42** made of plastic material, only one of which is visible in FIG. 3. Metal plate **40** is bent along its edges, which edges are embedded in plastic blocks **42**. FIG. 4 shows both plastic blocks **42**. The edge of metal plate **40** that is embedded in plastic block **42** is designated **41** in FIG. 3. Located adjacent to plastic blocks **42** is another plastic block **43**, which extends from the top portion of pad member **17** to a point near the bottom of pad member **17**. Adjacent to plastic block **43** is a metal plate **44** to which is attached metal lug members **31** and **32**. Support arms **19** and **20** (shown in FIG. 1) are connected to lug members **31** and **32**. Plastic blocks **42** and **43** and metal plate **44** are secured together by several screw **45** and nut **46** pairs, shown at different locations in FIG. 3. Plastic insert **47** is inserted in the vacancy left by screw **45** at each screw location.

Referring now to FIG. 4, there is shown a cross-sectional view of electrode pad member **17** taken along the section line **4—4** of FIG. 2. It can be seen in FIG. 4 that the ends **41** of metal plate **40** are embedded in plastic blocks **42** to secure the portion of pad member **17** facing the borehole wall with the portion attached to support member **13**. Plastic block **43** is located between plastic blocks **42** on either side thereof and extended between metal plate **40** and metal plate **44** in a T shape. Plastic block **34** also extends between plastic blocks **42** and metal plate **44**. A plurality of screws **45** and nuts **46** are shown securing metal plate **44**, plastic block **43**, and plastic blocks **42** together. Thus, all parts of electrode pad member **17** are securely fastened together and electrodes A_0, M and A_1 are insulated from one another and from the other metal pieces associated with electrode pad **17** by the plastic and rubber insulation pieces.

Concerning the electrical connection to electrodes A_0, M and A_1 of electrode pad member **17**, there is shown in FIG. 3 a metal connecting piece **48** embedded in insulating rubber **25** and connected to monitor electrode M. Inserted in metal connecting piece **48** is a circular electrical connector **51**, the head portion **49** of which is embedded in insulating rubber **25**, to which is connected the electrical conductor **29** that connects the circuit elements in housing **14** with monitor electrode M.

Looking now at FIG. 5, there is shown a cross-sectional view of electrode pad **17** taken along section line **5—5** of FIG. 3. Metal connector **48** is connected to monitor electrode M by a dotted line (the actual mechanical connection cannot be seen in FIG. 5, because of the location of section line **5—5**, but is represented by a dotted line to gain a better understanding of the electrical schematic of FIG. 5), metal connectors **49** are

connected to survey current electrode A_0, and a metal connector 50 is connected to metal plate 37, which is connected to the metal reinforcing member 36 of focusing current electrode A_1. There is shown a conductor 52 connecting the A_0 electrode connectors 50 together, although separate conductors could connect each connector 50 separately to the circuit contained within housing 14.

Turning now to the schematic diagram portion of FIG. 5, the circuit portion contained within the dash line box 14 corresponds to the circuit portions that are located within the interior of the instrument housing portion 14 of FIG. 1. The electrical connections to the electrodes on pad member 17 are made at the pin 51 in each connector. The circuits are constructed to maintain the potential level V_m of the monitor electrode M relatively constant with respect to a remote reference point and, at the same time, to determine the formation resistance characteristics by measuring the resulting variations in the magnitude of the survey current I_s emitted from the central A_0 electrode. Alternating-current reference voltage V_r is supplied from source 81 by way of input transformer 82*a*, a high-gain amplifier 82, and a conductor 28 to the A_1 focusing current electrode. Also supplied to the input transformer 82*a* of the amplifier 82 via conductor 29 is a signal representative of the potential, V_m, of the potential monitor electrode M. This potential signal V_m is supplied with like polarity to the side of the transformer 82*a* primary winding opposite from the reference voltage V_r, so that if the monitor electrode M is a potential equal to the reference V_r, then the net input signal to the amplifier 82 is nearly zero. If, on the other hand, the potential level V_m of the monitor electrode M differs from the V_r value, then the amplifier 82 input signal, which is in the nature of a degenerative feedback error signal, serves to adjust the amplifier output current I_f which is supplied to the A_1 electrode so as to bring the monitor voltage V_m back to the desired V_r value. Thus, the potential level of the monitor electrode M is kept substantially constant with respect to the remote reference point represented by electrode N.

In addition, the potential difference between monitor electrode M and the A_0 survey current electrode is adjusted so as to be maintained at a value of substantially zero. To this end, the monitor electrode signal V_m is also supplied to an input transformer 83*a* of a high-gain amplifier 83. A signal representative of the potential level of the A_0 electrode is supplied to the opposite side of the primary winding of the input transformer 83*a*. This A_0 signal is supplied by way of conductor 85. Thus, if the M–A_0 potential difference is not substantially zero, then the error signal existing at the input of amplifier 83 serves to adjust the amplifier output current I_s which is supplied to the A_0 electrode by way of conductor 30 to establish this desired zero potential difference.

As the formation resistivity in front of the electrode pad 17 varies, different amounts of survey current I_s will be required to maintain the M–A_0 potential difference at a zero value. The magnitude of this survey current required will be directly proportional to the electrical conductivity of the formation material. This indication is transmitted to the surface of the earth by means of transformer 86 having a low impedance primary winding coupled in series between amplifier 83 and conductor 30 leading to the A_0 electrode. Thus, the voltage signal appearing across the secondary winding of transformer 86 is proportional to the I_s current flow and therefore to the formation conductivity. This voltage signal is transmitted to a galvanometer unit 87 at the surface of the earth by way of cable conductors 88 and 89.

Instead of using the constant voltage circuit of FIG. 4, a constant current circuit such as shown in U.S. Patent No. 3,132,298, supra, could be used. As a further alternative, both the voltage and current may be varied and a suitable ratio circuit or device used for taking a ratio of voltage to current or vice versa for providing the desired output signal.

Electrode pad member 17 is shown pressed against a borehole wall 11 lined with a mudcake 53 in FIG. 5. The dotted line 17*a* indicates the free space shape of electrode pad 17, that is the shape of electrode pad 17 if there were no borehole wall. The solid line 17 indicates the shape of electrode pad 17 in the borehole when the radius of curvature of the borehole is less than the radius of curvature of the surface of electrode pad 17. Thus, it can be seen that the novel design of electrode pad 17 enables the electrode surface portion of pad 17 to conform to variations in the borehole diameter. However, while the focusing electrode A_1 changes shape substantially in conformance with the shape of the borehole, it can be seen that the solid non-flexible portion of pad member 17, electrodes A_0 and M, do not change shape and thus are disposed at a small distance from the mudcake 53. It has been found, however, that it is not so critical to have the survey and monitor electrodes, A_0 and M, in contact with the mudcake 53 as it is to have focusing electrode A_1 in contact with the mudcake. When survey electrode A_0 is not in contact with the mudcake, the potential set up by focusing electrode A_1 will not allow the survey current emitted from survey electrode A_0 to diverge. On the other hand, when focusing electrode A_1 is at a distance from mudcake 53, the focusing current emitted therefrom will diverge rapidly back to the mudcake since there is no potential to keep it from doing so.

Now concerning the focusing action of the present invention, there are seen current flow lines I_s and I_f in FIG. 5. Survey current electrode A_0 emits survey current I_s into the earth formation surrounding the borehole, which current diverges back to the current return electrode B_0 (see FIG. 1). The divergence of the survey current I_s back to the current return electrode B_0 becomes more severe when the mudcake 53 lining the borehole wall 11 is thick, in which case some of the survey current I_s will flow through the mudcake 53 to the current return electrode B_0. However, the focusing current I_f emitted from focusing current electrode A_1 directs the survey current I_s deeper into the earth formation by setting up a potential gradient concentrically surrounding survey current I_s, which maintains survey current I_s in a longitudinal flow away from the borehole.

However, when the mudcake 53 is very thick, and the borehole radius of curvature becomes non-uniform around the circumference of the borehole, an electrode pad of non-flexible construction could not conform to the radius of curvature of the borehole wall at all circumferential points around the borehole. If that electrode pad of non-flexible construction were placed on that portion of the borehole where the radius of curvature of the borehole is greater than the radius of curvature of the electrode pad and the mudcake thickness fairly substantial, some of the focusing current I_f emitted from focusing electrode A_1 would tend to diverge more quickly back through the mudcake 53 to the mud-filled portion of the borehole proper. Thus, the survey current I_s emitted from survey current electrode A_0 would also tend to diverge too quickly.

However, with the flexible features of the present electrode pad member 17, the focusing current electrode A_1 will be pressed against the mudcake 53 lining the borehole wall on any circumferential portion of the borehole wall even when the radius of curvature of the borehole wall differs around its circumference. As seen by the current flow lines of FIG. 5, the focusing current I_f emitted from focusing current electrode A_1 extends laterally outward into the earth because the focusing current electrode A_1 is pressed tightly against the mudcake 53 lining the borehole wall. Thus, there is very little divergence of the focusing current I_f emitted from points on the focusing current electrode A_1 which are nearest to the survey current electrode A_0, which, in turn, extends the survey

current I_s emitted from survey current electrode A_0 laterally outward for an appreciable distance. Thus, it can be seen that there is very little divergence of the survey current I_s under adverse borehole conditions and the accuracy of the resistivity or conductivity readings will be improved under such conditions.

When the physical configuration of an electrode pad member is varied, the proportionality constant K of the device will vary. However, with the novel form of construction of electrode pad **17** shown in the present invention, there will be very little variation in K. One reason for the small variation in K is that the electrodes on the front side of electrode pad **17** are electrically insulated from the back side of electrode pad **17** by the non-conductive rubber **23** and **34** and plastic blocks **42** and **43**. Thus, because the front and back sides of electrode pad **17** are insulated from one another, a single value of K can be utilized in determining the resistivity or conductivity of the adjoining earth over a wide range of radius of curvatures of the borehole.

Referring now to FIG. 6, there is shown another embodiment of the present invention. Both FIG. 6 and 7 are cross-sectional along a line corresponding to section lines **6, 7–6, 7** of FIG. 2, but with certain modifications to the FIG. 2 embodiment, as set forth hereinafter. In FIG. 6, a group of bare metal wires **54** have been attached to the metal reinforcing member **36** in an axial direction with the borehole along the focusing electrode A_1, which metal wires **54** are embedded in the conductive elastomeric material **35**. Metal wires **54** would provide better conductivity between metal reinforcing member **36** and the surface portion **24** of focusing current electrode A_1, which portion is contacting the mudcake surrounding the borehole, without affecting the desirable flexibility characteristics of the electrode pad member **17** shown in FIGS. 2–5. The top and bottom ends of metal wires **54** would bend over away from the surface portion **24** and would be embedded in insulation rubber **34** so as to prevent contact of any jagged ends of wires **54** with the borehole wall. Thus, only the rounded portions of wires **54** would be exposed to the borehole wall, preventing them from being caught on uneven parts of the borehole wall, and at the same time, allowing substantially perfect conductivity between metal reinforcing member **36** and the borehole wall.

Referring now to FIG. 7, there is shown a further embodiment of the present invention. In this embodiment, electrodes A_0 and M have metal reinforcing members embedded in conductive rubber in the same fashion as focusing electrode A_1. Survey current electrode A_0 has a flexible metal reinforcing member **55** embedded in a conductive rubber **56**. In the same fashion, monitor electrode M has a flexible metal reinforcing member **57** embedded in a conductive rubber **58**. By this construction of electrode pad member **17**, electrodes A_0 and M would have the same flexibility as focusing electrode A_1. Thus, it can be seen that the entire electrode pad will have a maximum degree of flexibility, allowing all surface portions of the electrode pad to be in contact with the mudcake on the borehole wall over a wide range of radius of curvatures of the borehole wall.

While there have been described what are at present considered to be preferred embodiments 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. Apparatus for investigating earth formations traversed by a borehole comprising:

a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array;

one electrode of said array being comprised of an electrically conductive material of non-flexible construction forming part of the forward face of said pad member; and

another electrode of said array forming another part of said forward face and comprised of a sheet-type metal material of flexible spring-like construction embedded in an elastomeric material for enabling the pad member to more nearly conform to the curvature of the borehole wall said other electrode including an electrically conductive elastomeric material on the forward face of said other electrode.

2. Apparatus for investigating earth formations traversed by a borehole comprising:

a support member;

a pad member adapted to be pressed against a borehole wall, said pad member having an electrode array on the side facing the borehole wall and a metal body, for attaching the pad member to the support member, on the side farthest from the borehole wall;

an electrically non-conductive body separating said electrode array from said metal body;

a first electrode of said array being comprised of an electrically conductive material of non-flexible construction; and

a second electrode of said array comprised of a sheet-type metal material of flexible spring-like construction embedded in an elastomeric material, the front wall-engaging portion of said second electrode being comprised of a conductive elastomeric material, and an electrically non-conductive elastomeric material fixed to the back side of said second electrode.

3. Apparatus for investigating earth formations traversed by a borehole comprising:

a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array;

a first electrode of said array being comprised of an electrically conductive material of non-flexible construction and forming a portion of said forward face; and

a second electrode of said array forming another portion of said forward face and comprised of a flexible, spring-like, sheet-type metal body embedded in an elastomeric material so that the second electrode will bend upon the borehole radius of curvature becoming less than the electrode pad radius of curvature, the front wall-engaging portion of the second electrode being comprised of a conductive elastomeric material covering the sheet-type metal body, the sheet-type metal body providing a substantially equal potential distribution on the borehole wall-engaging face of the second electrode.

4. Apparatus for investigating earth formations traversed by a borehole comprising:

a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array;

a first electrode of said array being comprised of an electrically conductive material of non-flexible construction and forming a portion of said forward face; and

a second electrode of said array forming another portion of said forward face and comprised of a sheet-type metal material of flexible spring-like construction embedded in an elastomeric material for enabling the pad member to bend about a relatively fixed longitudinal axis between the first and second electrodes to more nearly conform to the curvature of the borehole wall, an electrically conductive elastomeric material comprising the forward wall-engaging face portion of said second electrode, and an electrically non-conductive elastomeric material fixed to the back, non-wall engaging side of said second electrode.

5. Apparatus for investigating earth formations traversed by a borehole comprising:
a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array;
a first electrode of said array being comprised of an electrically conductive material of non-flexible construction forming a portion of said forward face;
a second electrode of said array forming another portion of said forward face and defining a concentric path around the first electrode and insulated therefrom; and
said second electrode comprised of a flexible, spring-like metal body extending concentrically outward from said first electrode, said metal body embedded in an elastomeric material so that the second electrode will bend upon the borehole radius of curvature becoming less than the pad member radius of curvature, the borehole wall-engaging forward face of the second electrode being comprised of an electrically conductive elastomeric material.

6. Apparatus for investigating earth formations traversed by a borehole comprising:
a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array;
a first electrode of said array being comprised of an electrically conductive material of non-flexible construction and forming a portion of said forward face;
a second electrode of said array comprised of a metal material of non-flexible construction forming another portion of said forward face and defining a concentric path around the first electrode and insulated therefrom;
a third electrode of said array forming another portion of said forward face and defining a concentric path around the first and second electrodes and insulated therefrom; and
said third electrode comprised of a flexible, spring-like metal body extending concentrically outward over a substantial distance from said first and second electrodes, said metal body embedded in an elastomeric material so that the third electrode will bend upon the borehole radius of curvature becoming less than the pad member radius of curvature, the borehole wall-engaging forward face of the third electrode being comprised of an electrically conductive elastomeric material.

7. Apparatus for investigating earth formations traversed by a borehole comprising:
a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array;
a first electrode of said array forming a portion of said forward face and being comprised of electrically conductive material of non-flexible construction;
circuit means for energizing the first electrode for emitting survey current into the adjacent earth formation;
a second electrode of said array forming another portion of said forward face and comprised of a non-flexible type material of flexible spring-like construction embedded in an elastomeric material for enabling the pad member to more nearly conform to the curvature of the borehole wall, the borehole wall-engaging portion of the second electrode being comprised exclusively of an electrically conductive elastomeric materials; and
circuit means for energizing the second electrode for emitting focusing current into the adjacent earth formation.

8. Apparatus for investigation earth formations traversed by a borehole comprising:
a support member;
a pad member adapted to be pressed against a borehole wall, said pad member having an electrode array on the side facing the borehole wall and a metal body, for attaching the pad member to the support member, on the side farthest from the borehole wall;
an electrically non-conductive body separating said electrode array from said metal body;
a first electrode of said array being comprised of a solid metal material of non-flexible construction;
circuit means for energizing the first electrode for emitting survey current into the adjacent earth formation;
a second electrode of said array comprised of a sheet-type metal material of flexible spring-like construction embedded in an elastomeric material for enabling the pad member to more nearly conform to the curvature of the borehole wall, the front wall-engaging portion of said second electrode being comprised of an electrically conductive elastomeric material, and an electrically non-conductive elastomeric material fixed to the back side of said second electrode; and
circuit means for energizing the second electrode for emitting focusing current into the adjacent earth formation.

9. Apparatus for investigating earth formations traversed by a borehole comprising:
a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array comprising at least two electrodes; and
at least two electrodes of said array forming portions of said forward face and comprised of a metal material of flexible spring-like construction embedded in an elastomeric material for enabling the pad member to more nearly conform to the curvature of the borehole wall, the borehole wall-engaging forward face of the electrode being comprised exclusively of an electrically conductive elastomeric material.

10. Apparatus for investigating earth formations traversed by a borehole comprising:
a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array;
one electrode of said array being comprised of a solid non-flexible material and forming part of said forward face;
another electrode of said array forming another part of said forward face and comprised of a non-flexible type material of flexible spring-like construction embedded in an elastomeric material for enabling the pad member to more nearly conform to the curvature of the borehole wall, the borehole wall-engaging forward face of said electrode being comprised of an electrically conductive elastomeric material; and
a plurality of metal conductors embedded in said electrically conductive elastomeric material and connected to said non-flexible material of flexible spring-like construction on the side thereof facing the borehole wall.

11. Apparatus for investigating earth formations traversed by a borehole comprising:
a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array;
a non-flexible longitudinally extending first portion of the forward face of said pad member forming at least one electrode; and
a longitudinal extending second portion of the pad member, adjacent to the first portion, formed of at least one electrode and an elastomeric material, said electrode forming part of said forward face and including conductive supporting means in the elastomeric material, said supporting means being arranged to enable the adjacent pad portion to bend about a relatively fixed longitudinal axis located be-

tween the central and adjacent pad portions so that the pad member may more nearly conform to the curvature of the borehole wall.

12. Apparatus for investigating earth formations traversed by a borehole comprising:

a pad member having a forward face adapted to be pressed against a borehole wall, said pad member member having an electrode array;

a non-flexible longitudinally extending first portion of the pad member having at least one electrode forming part of said forward face; and

a longitudinally extending second portion of the pad member, adjacent to the first portion, formed of at least one electrode and an elastomeric material for enabling the adjacent pad portion to flex so that the pad member may more nearly conform to the curvature of the borehole wall, the electrode on the adjacent pad portion formed of a flexible, spring-like metal sheet embedded in an elastomeric material which is conductive on the borehole wall-engaging forward face of the adjacent pad portion.

13. Apparatus for investigating earth formations traversed by a borehole comprising:

a pad member having a forward face adapted to be pressed against a borehole wall, said pad member having an electrode array;

a non-flexible longitudinally extending central portion of the forward face of said pad member forming at least one electrode; and

longitudinally extending portions of the pad member, adjacent to the central pad portion, formed of at least one electrode and having an elastomeric material for enabling the adjacent pad portion to bend about a relatively fixed longitudinal axis between the central and adjacent pad portions so as to more nearly conform to the curvature of the borehole wall, the electrode on the adjacent pad portion having a flexible, spring-like metal member embedded in an elastomeric material which is conductive on the borehole wall-engaging forward face of the adjacent pad portions.

References Cited

UNITED STATES PATENTS

2,649,960	8/1953	Gammeter	324—54 X
2,696,589	12/1954	Bendix et al.	324—54
2,712,629	7/1955	Doll	324—10 X
2,712,630	7/1955	Doll	324—10 X
2,778,951	1/1957	Tittman	324—10 XR
2,961,600	11/1960	Tanguy	324—10 XR
3,068,403	12/1962	Robinson	324—54 X
3,069,620	12/1962	Servos	324—54
3,093,793	6/1963	Hicken	324—54
3,132,298	5/1964	Doll et al.	324—10

RUDOLPH V. ROLINEC, *Primary Examiner.*

WALTER L. CARLSON, *Examiner.*

G. R. STRECKER, *Assistant Examiner.*