Feb. 16, 1954 HENRI-GEORGES DOLL 2,669,688

RESISTIVITY APPARATUS FOR OBTAINING INDICATIONS OF PERMEABLE FORMATIONS TRAVERSED BY BOREHOLES

Original Filed Oct. 18, 1949 5 Sheets-Sheet 1

FIG.1.

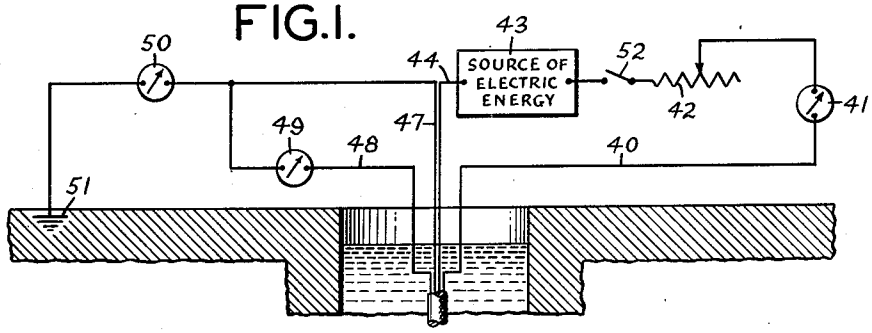


FIG.5.

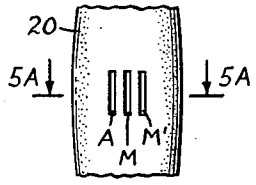


FIG.6.

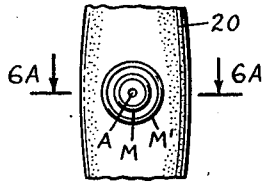
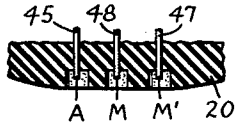


FIG.5A.



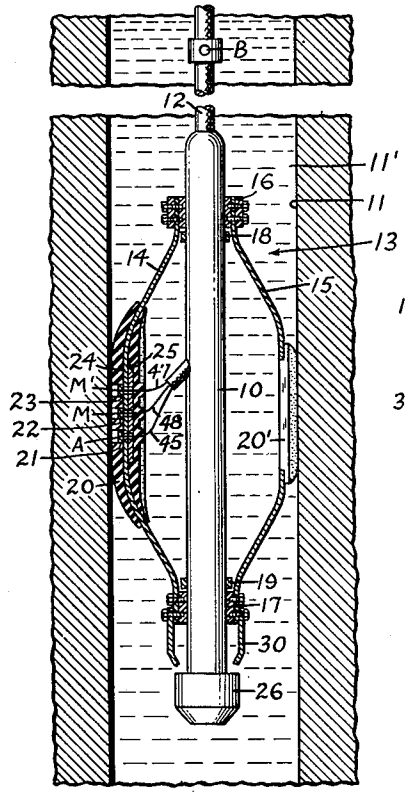


FIG.1C.

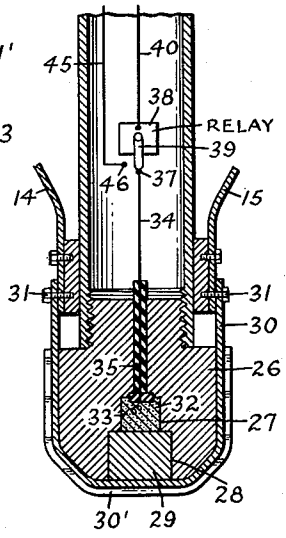
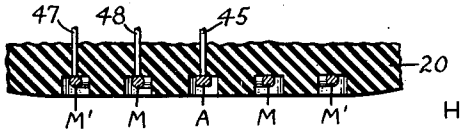


FIG.6A.



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RESISTIVITY APPARATUS FOR OBTAINING INDICATIONS OF PERMEABLE FORMATIONS TRAVERSED BY BOREHOLES

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FIG.1B.

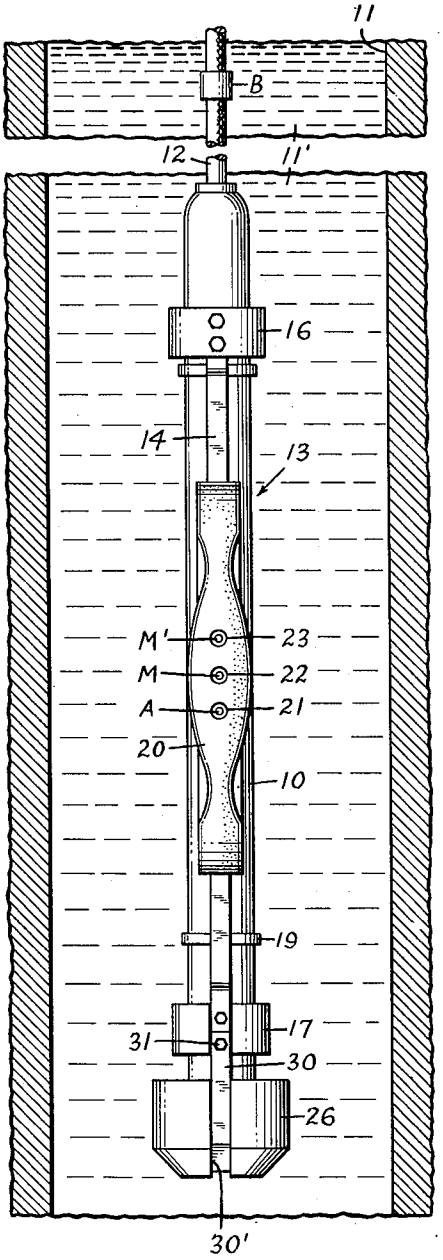
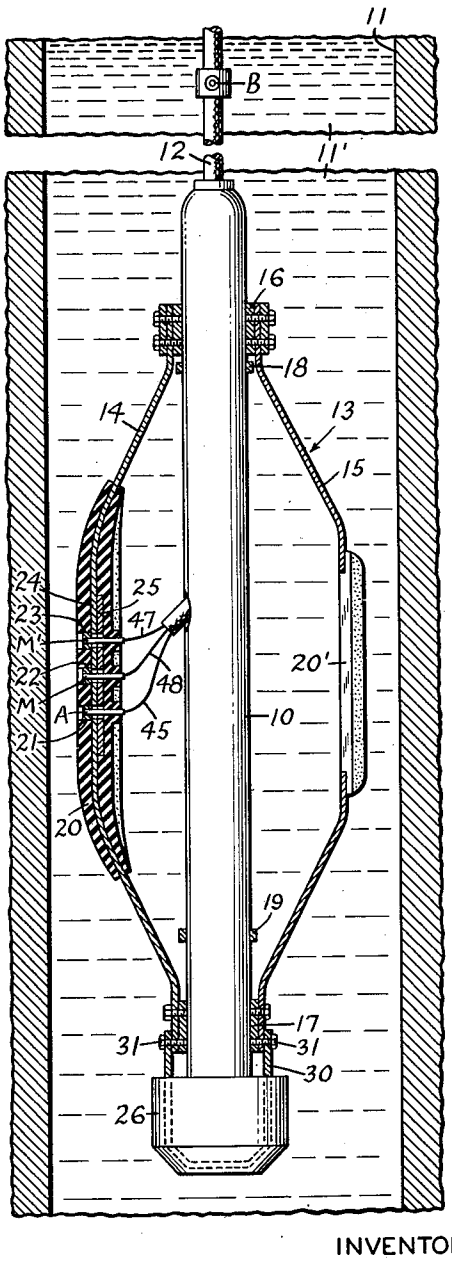


FIG.1A.



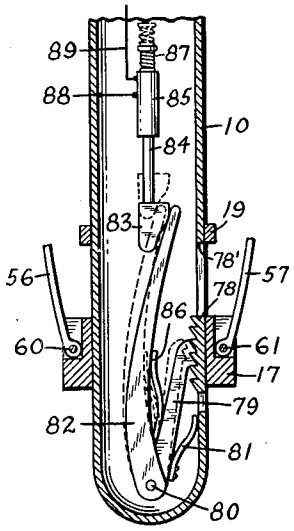
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RESISTIVITY APPARATUS FOR OBTAINING INDICATIONS OF PERMEABLE FORMATIONS TRAVERSED BY BOREHOLES

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FIG. 3C.



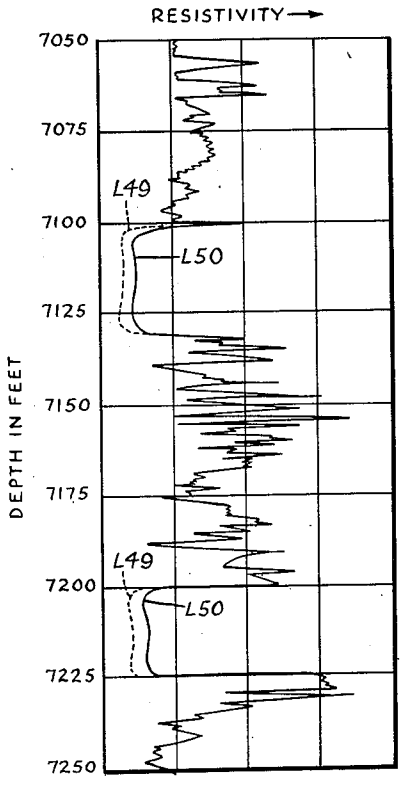


FIG. 7.

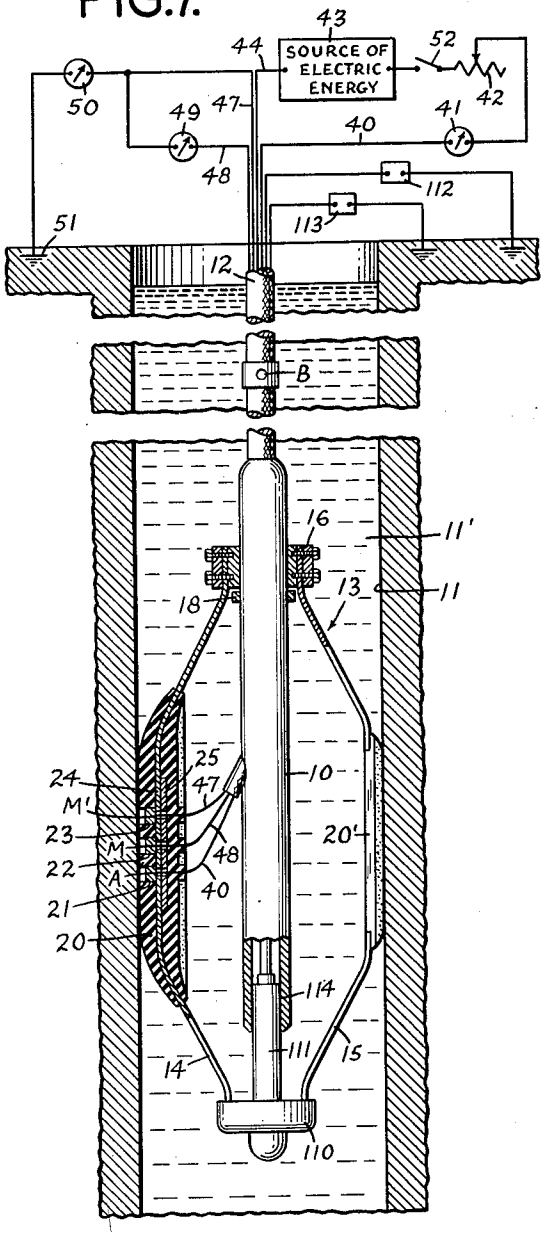


FIG. 2.

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RESISTIVITY APPARATUS FOR OBTAINING INDICATIONS OF PERMEABLE FORMATIONS TRAVERSED BY BOREHOLES

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FIG.3.

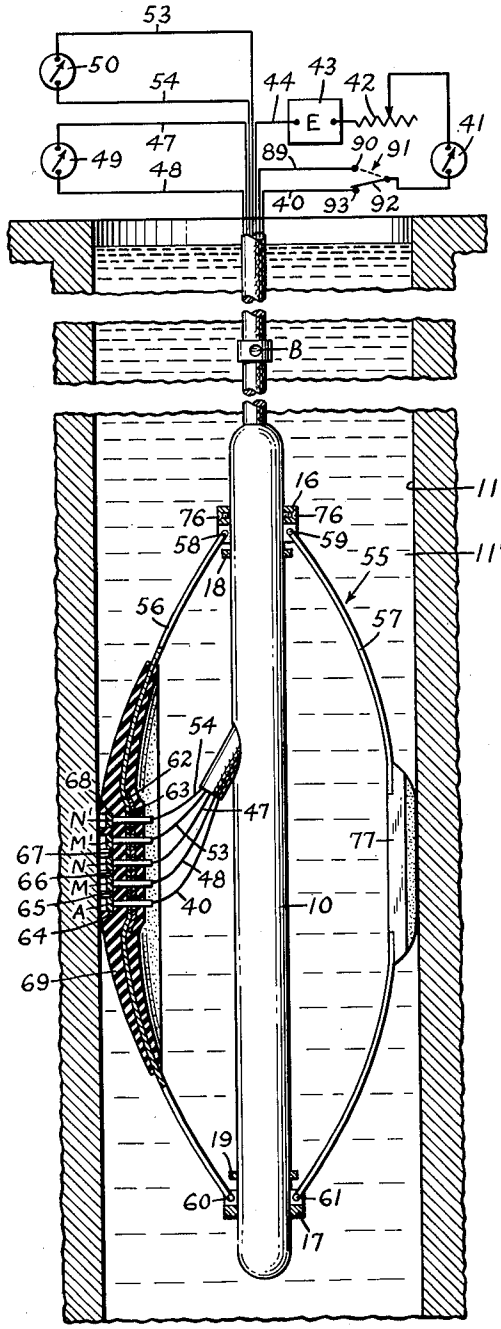
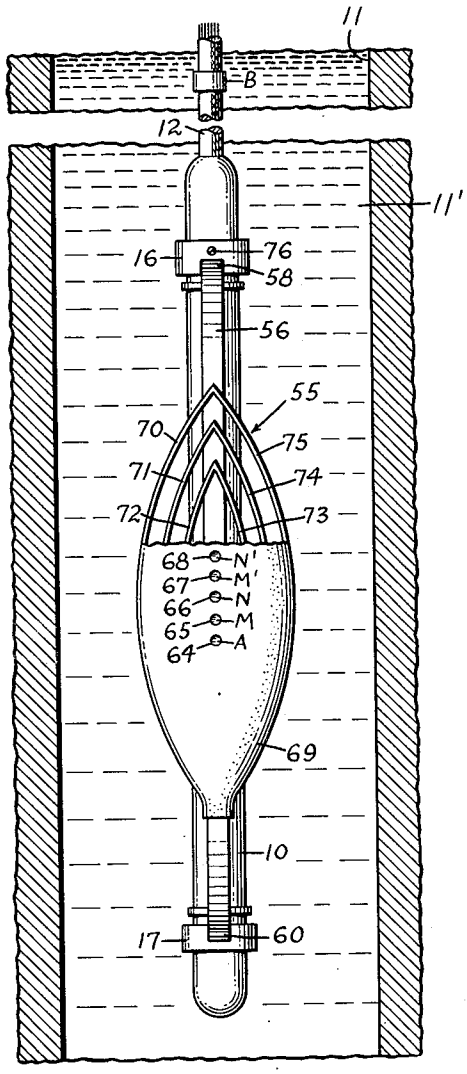


FIG.3A.



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RESISTIVITY APPARATUS FOR OBTAINING INDICATIONS OF PERMEABLE FORMATIONS TRAVERSED BY BOREHOLES

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FIG. 4.

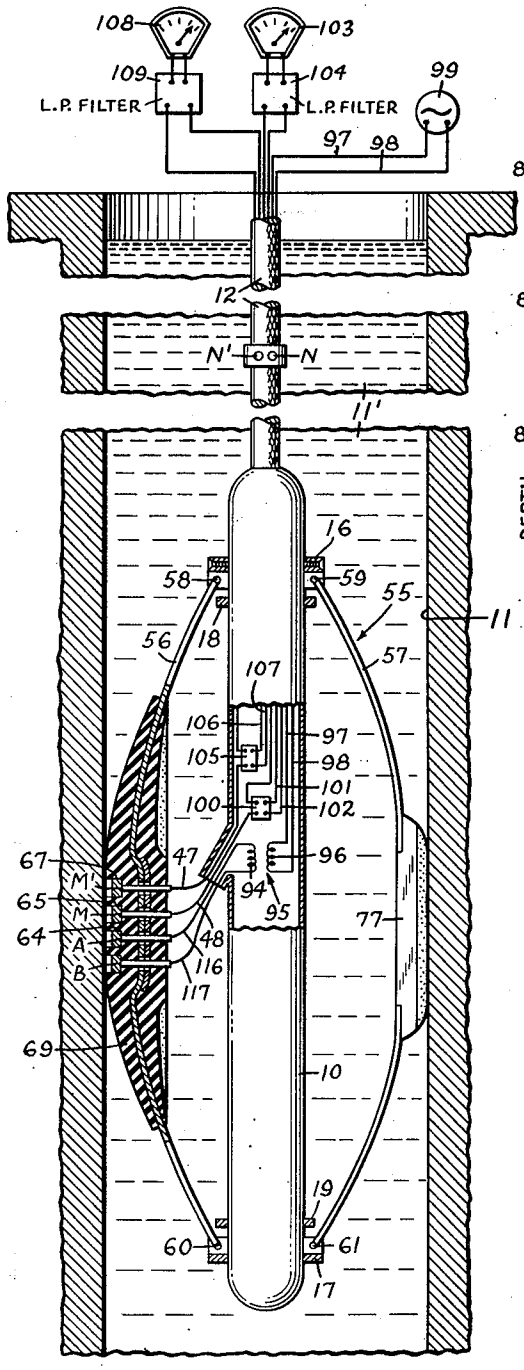
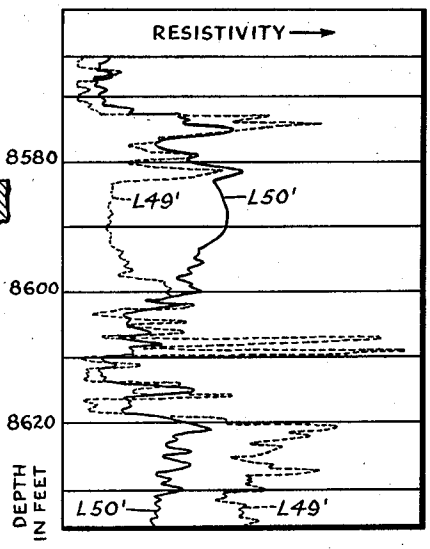


FIG. 2A.



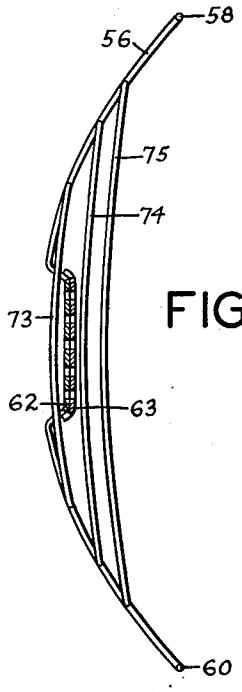


FIG. 3B.

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2,669,688

UNITED STATES PATENT OFFICE

2,669,688

RESISTIVITY APPARATUS FOR OBTAINING INDICATIONS OF PERMEABLE FORMATIONS TRAVERSED BY BOREHOLES

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Original application October 18, 1949, Serial No. 122,102. Divided and this application May 29, 1953, Serial No. 358,426

11 Claims. (Cl. 324—1)

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This invention relates to apparatus for investigating subterranean earth formations. More specifically, it has to do with novel and highly effective well logging apparatus which is of special utility for distinguishing permeable and impervious formations traversed by a well containing a drilling mud or other fluid having finely divided solids in suspension.

This application is a division of my copending application Serial No. 122,102, filed October 18, 1949, for "Resistivity Method and Apparatus for Obtaining Indications of Permeable Formations Traversed by a Bore Hole."

In the present practice, it is customary to use drilling muds in drilling operations in wells. Generally, water base muds comprising finely divided clay or other particles suspended in water are employed for this purpose. Normally, the fluid pressure in the permeable formations traversed by a bore hole is less than the hydrostatic pressure of the column of mud in the hole, so that the mud and mud filtrate flows into those formations. However, such formations tend to screen out the finely divided particles in the mud, so that a substantial "mud cake" is formed on the wall of the bore hole at the levels of the permeable formations. On the other hand, the mud does not flow into the impervious formations so that substantially no mud cake is formed on the wall of the bore hole at the levels where they occur. The presence or absence of a filtration mud cake on the wall of the bore hole, therefore, affords a reliable indication of whether the formations at different depths are permeable or impervious.

It is an object of the invention, accordingly, to provide novel apparatus for determining the presence or absence of mud cake on the wall of a bore hole at different depths therein.

Another object of the invention is to provide novel apparatus in which electrical resistivity measurements are utilized to determine whether or not a mud cake has been formed on the wall of a bore hole.

Yet another object of the invention is to provide novel apparatus for distinguishing permeable and impervious formations traversed by a bore hole by obtaining indications of the electrical resistivity of material contiguous to the wall of the bore hole.

A further object of the invention is to provide novel apparatus of the above character which is capable of indicating at the surface of the earth the approximate thickness of any mud cake on the wall of a bore hole.

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Still another object of the invention is to provide novel apparatus for obtaining simultaneous indications of the diameter of the bore hole and of the presence or absence of a mud cake on the wall of the bore hole whereby more reliable mud cake determinations may be made.

According to the invention, highly localized measurements are made, in situ, of the electrical resistivity of the materials comprising the wall of the bore hole. More particularly, at least two wall resistivity measurements are made at each location, one of which is influenced, to a marked degree, by the material lying in a narrow zone extending laterally from the wall of the bore hole a short distance into the surrounding material. The other resistivity measurement is influenced to a lesser degree by material lying in said narrow zone and to a greater degree by material located beyond said zone.

By making the width of said narrow zone of the same order of magnitude as the anticipated thickness of the mud cake, the first of said resistivity measurements will be influenced by the mud cake to a greater extent than the other. Since the resistivity of the mud cake is usually different from, and relatively low to, the resistivity of other formations surrounding the bore hole, the two resistivity measurements will be relatively low in value and will differ, when a mud cake is present. In regions where no mud cake has been formed, however, they will tend to be substantially the same. It will be apparent, therefore, that the invention enables permeable formations to be readily distinguished from impervious formations traversed by a well.

The invention may be better understood from the following detailed description of several typical embodiments thereof, taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a schematic diagram, partially in longitudinal section, showing typical well logging apparatus constructed according to the invention, in position in a bore hole drilled into the earth;

Fig. 1A is a view in elevation, partially in section, showing the electrode assembly of Fig. 1 in the locked position with the electrode support out of engagement with the wall of the bore hole;

Fig. 1B is an end view of the apparatus shown in Fig. 1A;

Fig. 1C is a view in longitudinal section of the means employed in the apparatus of Fig. 1 for locking the bowed springs to the body and subsequently releasing them;

Fig. 2 is a typical log such as might be obtained

with the well logging apparatus of Fig. 1 in a bore hole;

Fig. 2A is another example of a log illustrating the type results obtained when disturbing effects are present opposite impervious formations;

Fig. 3 illustrates schematically another form of the invention utilizing a different electrode assembly and another form of locking means;

Fig. 3A is an end view of the apparatus shown in Fig. 3 with part of the electrode support broken away to show the interior construction thereof;

Fig. 3B is a detailed view of the reinforcing springs for the electrode support;

Fig. 3C is a view, partially in longitudinal section, illustrating another form of locking and releasing means which is used with the apparatus of Fig. 3;

Fig. 4 is a schematic diagram of another modification shown with the electrode assembly mounted in position in a bore hole;

Figs. 5 and 6 are views in elevation of modified forms of electrodes;

Figs. 5A and 6A are enlarged views in section taken along the lines 5A—5A and 6A—6A of Figs. 5 and 6, respectively, and

Fig. 7 illustrates schematically another modification in which the resistivity measurements are made simultaneously with a calipering operation.

In the form of the apparatus shown in Fig. 1, the electrode assembly comprises a tubular support 10 which is adapted to be lowered into a bore hole 11 on a supporting cable 12 which may be raised and lowered in the well by suitable means (not shown) located at the surface of the earth. The bore hole 11 usually contains a column of more or less conducting liquid 11'.

Mounted on the tubular support 10 is a spring cage assembly 13 comprising a plurality of bowed springs 14 and 15 whose opposite ends may be rigidly secured to a pair of collars 16 and 17, respectively, which are slidably mounted on the tubular member 10. The springs 14 and 15 are so shaped that the intermediate portions thereof are continually urged towards the wall of the bore hole. Stop means 18 and 19 may be formed on the tubular member 10 to provide for limited longitudinal movement of the spring cage assembly 13 with respect to the tubular member 10.

The bowed spring 14 carries a wall engaging cushion member 20 made of suitable flexible insulating material such as rubber, for example. Formed in the side wall of the cushion 20 are a plurality of recesses 21, 22 and 23 within which are embedded a plurality of electrodes A, M and M', respectively. Preferably, the electrodes A, M and M' lie beneath the surface of the cushion 20 so that they are spaced a short distance away from the wall of the bore hole when the apparatus is disposed in the well, as shown in Fig. 1, electrical communication between the several electrodes and the adjacent formation being effected through bore hole liquid entrapped in the recesses 21, 22 and 23. With this construction, rubbing of the electrodes against the wall of the bore hole is prevented so that spurious electric potentials which might be created by the rubbing action are avoided.

In order to maintain the electrodes A, M and M' in fixed, closely spaced relationship with respect to the wall of the bore hole 11, the bowed spring 14 is provided with an intermediate straight portion 24 to which is secured a straight, rigid reenforcing member 25. By virtue of this construction, the electrodes A, M and M' are always maintained in proper relation to the wall of the bore hole 11 as the bowed springs 14 and 15 expand and contract in response to variations in the size of the bore hole. The bowed spring 15 may also be provided with a flexible cushion 20' made of rubber, or other suitable material, to facilitate movement of the spring cage assembly 13 through the bore hole 11.

The cushion 20 may be further designed so that it is not only straight and rigid longitudinally, but is also round and flexible in a radial direction, as shown in Fig. 1B. With this construction, the cushion 20 will exert sufficient pressure against the wall of the hole, for all bore hole diameters lying in a given range, to squeeze out the bore hole fluid from between the cushion 20 and the wall, so that the shunting effect of any remaining film of fluid on the resistivity measurements will be negligible.

In order to facilitate lowering the apparatus in bore holes of small diameter, it is desirable to provide means for locking one of the spring cage collars, say the collar 17, to the tubular member 10 at a position far enough away from the other collar 16 so that the cushions 20 and 20' will be out of engagement with the wall of the bore hole 11. A typical locking device suitable for this purpose is shown in Fig. 1C and it comprises a metal plug 26 threadedly or otherwise secured at the bottom of the tubular member 10 and having a powder chamber 27 formed therein communicating with an opening 23 within which a blunt projectile 29 is adapted to be received.

While the apparatus is at the surface of the earth, the lower collar 17 is pulled downwardly until the cushions 20 and 20' have been moved inwardly the desired amount. The collar 17 may then be locked in this position by means of a metal strap 30 which may be secured to the collar 17 by screws 31, for example. The strap passes around the plug 26 and is held tightly in a slot 30' therein so as to retain the blunt projectile 29 within the chamber 28 as shown in Fig. 1C.

Ignition of the charge in the chamber 27 may be accomplished in any desired manner, as, for example, by means of an electrical igniter 32 grounded to the plug 26 at 33 and having its other end connected to a conductor 34. The conductor 34 passes through suitable insulating material 35 in the plug 26 to one contact 37 of a relay 38.

The relay 38 may be of the type having a movable contact 39 normally engaging the fixed contact 37 and which is connected in series with the relay winding to a conductor 40. The conductor 40 extends through the supporting cable 12 (Fig. 1) to the surface of the earth where it is connected in series with a suitable current indicating instrument 41, a variable resistance 42, a switch 52, a source of electrical energy 43 and a conductor 44 to a ground electrode B which may be formed on the supporting cable 12 a relatively great distance from the electrode A.

The electrode A is connected by a conductor 45 (Figs. 1 and 1C) to another contact 46 on the relay 38. The electrodes M' and M (which are potential measuring electrodes) are connected together by the conductors 47 and 48, respectively, through a conventional high impedance potential recording instrument 49 located at the surface of the earth. The electrode M' is also connected through the conductor 47 to a second high impedance potential recording instrument 50, the other terminal of which is grounded at the point 51 at the surface of the earth.

It will be understood that the electrodes A, M and M' constitute essentially a three electrode resistivity system of the type shown in prior Patent No. 1,819,923 to Conrad Schlumberger. Thus, the log recorded by the instrument 49 is representative of the electrical resistivity of the earth as measured by a three electrode system having an electrode spacing equal to the distance between the electrode A and the midpoint between the electrodes M and M' under the cushion 20. Since the electrodes are substantially insulated from the mud column of the bore hole, substantially "hemispherical" rather than "spherical" resistivity measurements are obtained. Further, the electrode spacing is made very small, i. e., from one to a few times the mud cake thickness so that the log made by the recording instrument 49 will reflect variations in the apparent resistivity resulting from any mud cake that may exist on the wall of the hole. Experience has indicated that the thickness of the mud cake opposite permeable formations is usually of the magnitude of a fraction of an inch. The following electrode spacings have been found satisfactory in the field: A—M=1 inch, A—M'=2 inches.

The electrodes A and M' constitute a two electrode system of the type disclosed in prior Patent No. 1,894,328 to Conrad Schlumberger and the log provided by the recording instrument 50 is representative of the electrical resistivity of the formations as measured by a two electrode system having an electrode spacing equal to the distance between the electrodes A and M' under the cushion 20. It is well known that a three electrode system has a shorter depth of lateral investigation than a two electrode system having the same electrode spacing. For the spacing of two inches suggested above, therefore, the log produced by the two electrode system will reflect the resistivity of any mud cake that may be formed to a lesser extent than the log obtained by the recorder 49, and it will be influenced more by the resistivity of the formation behind the mud cake.

In operation, the spring cage assembly 13 is lowered into the bore hole 11 in the locked position, as shown in Fig. 1A. When the desired level has been reached for the logging operation to begin, the switch 52 at the surface of the earth is closed so that electrical energy from the source 43 is impressed upon the electrical igniter 32 (Fig. 1C). This explodes the charge in the chamber 27, ejecting the projectile 29 and breaking the metal strap 30. The collar 17 is then free to move upwardly until the cushion members 20 and 20' are in engagement with the wall of the bore hole 11, as shown in Fig. 1. The projectile 29 should preferably be made of soft material which will not interfere with subsequent drilling operations.

Simultaneously, the interruption of the current through the relay 38 causes its movable contact 39 to disengage the contact 37 and thereafter to remain continuously in engagement with the contact 46 so that electrical energy is impressed upon the electrodes A and B and current is emitted from the electrode A into the surrounding formations. The flow of current into the formations from the electrode A produces a potential difference between the electrodes M and M' which is a function of the resistivity of the formation in a zone close to the wall of the bore hole 11 where a mud cake may be expected to be present opposite permeable formation. On the other hand, the potential difference between the

electrode M' and the ground 51 at the surface of the earth is a function of the resistivity of the material at a greater lateral distance from the electrode A. That potential difference, therefore, is less influenced by any mud cake that may be present on the wall of the bore hole.

Experience shows that the mud cake which forms opposite permeable formations usually has a lower resistivity than that of a zone of lateral extent in the formation behind the mud cake which has been affected by the filtrate from the drilling mud, and a slightly higher resistivity than the mud itself. Good contrast in resistivities between the mud cake and the formation occurs in those geological strata containing hard formations such as limestone. The important feature in each case is that the resistivity of the mud cake be different from the material behind it. By means of such resistivity contrasts, the presence or absence of a mud cake, therefore, can readily be determined by comparing the logs obtained by the recording instruments 49 and 50, and thereby the presence or absence of permeable strata is indicated.

If the sensitivities of the recording devices 49 and 50 are adjusted so that the logs which they produce have the same amplitude when the resistivities measured in the hole are the same, and are superimposed, a composite log of the type shown in Fig. 2 will be obtained in a typical well in the field. In Fig. 2, the two logs are identical in the range from 7,050–7,100 feet. The logs are also identical between 7,130 and 7,200 feet and between 7,225 and 7,250 feet. The identity of the two logs in these regions indicates that the two resistivity measurements are the same and that a negligible amount of mud cake is present. Hence, the logs provide clear indications that the formations at these levels are impervious.

On the other hand, between 7,100 and 7,130 feet and between 7,200 and 7,225 feet, the log L49 (made with the recording device 49) indicates a lower resistivity than the log L50 (made with the recording device 50). Since the log L49 is a function of the resistivity of the formations in a zone very near the electrode A, while the log L50 is a function of the resistivity of the formations located a greater distance from the electrode A, the discrepancy between the two logs L49 and L50 provides a clear indication that the formations between these levels are covered by a mud cake and are, therefore, permeable.

In practice, it has been found that the curves sometimes become separated opposite impervious formations, but the order of the apparent resistivity values is reversed compared to the curves obtained opposite permeable formations. Such a situation is illustrated in Fig. 2A. The permeable formations are identifiable, however, as in Fig. 2, by the low values of the resistivity indications for the shorter spacing, given by curve L49', compared to the longer spacing curve L50'.

In Fig. 2A, a thick permeable zone is clearly indicated between the depths of 8583' to 8598' by the difference in, and the character of, the resistivity indications of the curves L49' and L50'. In the section below 8619', the curve L49' of the shorter electrode spacing is higher in value compared to the longer electrode spacing curve L59', and this section is known to be impervious. The other parts of the log show the presence of permeable streaks where the curve L49' has minima below the curve L59'.

The situation over the impervious section could be due to the use of a cushion of limited area

with respect to the spacings between the electrodes, in conjunction with the presence of a film of mud remaining between the cushion and the formation. This would provide a shunting effect which would affect the apparent resistivity indication for the longer spacing to a greater degree as compared to the shorter spacing, but nevertheless a discrimination can be made between permeable and impervious formations. If deemed necessary, though, experience shows that the type log of Fig. 2 can be obtained by care in the construction and use of the apparatus.

There is another noticeable distinction, which is of diagnostic use in determining the permeable formations. As illustrated, in Figs. 2 and 2A the resistivity indications obtained opposite permeable formations have an appreciably smoother contour than those resistivity indications opposite impervious formations due to the presence of a substantial mud cake, which is of more uniform composition than the geological formation.

In the embodiment shown in Fig. 3, two simultaneous resistivity measurements are obtained by two pairs of potential electrodes M, N, M', N', the electrodes M, N being connected to the potential recording instrument 49 through the cable conductors 47 and 48, and the electrodes M', N' being connected to the potential recording instrument 50 through the conductors 53 and 54. Three electrode systems are preferable to two electrode systems for investigating thin mud cakes. In a typical case, the electrode spacings A—M, M—N, M'—N', (Fig. 3) may be of the magnitude of one-quarter of an inch, for example, the spacing between the electrodes N—M' being about one-half an inch, for example.

Fig. 3 also illustrates a modified spring cage construction as well as an alternate form of locking device that may be employed in accordance with the invention. As shown, the spring cage 55 comprises a pair of bowed springs 56 and 57 which are pivotally mounted at their upper ends 58 and 59 on the collar 16. The collar is rigidly secured to the tubular member 10 by screws 76, for example. The lower ends of the springs 56 and 55 are pivotally mounted at 60 and 61 on the lower collar 17. The bowed spring 56 is provided with an inwardly depressed straight portion 62 intermediate its ends to which is secured a rigid reenforcing member 63. The electrodes A, M, N, M', N' are embedded in recesses 64, 65, 66, 67 and 68 formed in a cushion member 69 made of flexible insulating material such as rubber, for example, such that a narrow space exists between each electrode and the wall of the bore hole when in the position shown in Fig. 3.

The bowed spring 57 may also be provided with a cushion member 77 to facilitate movement of the apparatus in a well.

Embedded in the cushion member 68 is a plurality of strong flexible springs 70, 71, 72, 73, 74 and 75 which may be secured at their opposite ends to the bowed spring 56, in any suitable manner, as by welding, for example. These springs tend to cause the cushion member 68 to straighten out along a transverse line therein, so that it will remain in engagement with the wall of the bore hole even though the bore hole diameter varies, as where the apparatus is to be used in bore holes of different diameter, for example.

In order to keep the cushion members 68 and 77 out of engagement with the wall of the bore hole as the apparatus is lowered therein, the lower collar 17 is adapted to be pulled downwardly and locked to the tubular member 10 by means of the locking device shown in Fig. 3C. In Fig. 3C, the lower collar 17 is provided with internal teeth 78 which are adapted to slide in a longitudinal slot 78' in the member 10 and which are adapted to be engaged by a pawl 79 pivotally mounted at 80 within the tubular member 10. Secured on the pawl 79 is a conventional spring 81 which serves to keep the pawl 79 normally out of engagement with the internal teeth 78. Also pivoted at 80 is a cam arm 82 engaging a cam member 83 mounted on a rod 84 which is adapted to be actuated by a solenoid 85 secured within the tubular member 10. Mounted on the cam arm 82 is a conventional spring 86 which engages the pawl 79 to cause the latter to move into engagement with the internal teeth 78.

Normally, the cam member 83 is maintained in its uppermost position shown in dotted lines in Fig. 3C by means of a compression spring 87. The solenoid 85 may be energized from the surface of the earth in any suitable manner. For example, one of its terminals may be grounded to the tubular member 10 at 88 and its other terminal may be connected by a conductor 89 to one fixed contact 90 of a switch 91 having a movable contact 92 (Fig. 3). The movable contact 92 may be connected in series with the current measuring instrument 41 and the other fixed contact 93 may be connected to the conductor 40 which leads to the electrode A in the bore hole 11. With this construction, it will be apparent that the source of electrical energy can be connected either to the solenoid 85 or to the electrode A by manipulating the switch 91.

Before the apparatus shown in Fig. 3 is lowered into the well, the lower collar 17 is pulled downwardly a sufficient distance to insure that the cushions 69 and 77 will not engage the wall of the bore hole and the switch contact 92 is moved into engagement with the contact 90 (Fig. 3). This energizes the solenoid 85, moving the cam member 83 downwardly and causing the arm 82 to be moved towards the right to the position shown in full lines in Fig. 3C. This causes the pawl 79 to engage the internal teeth 78, thus locking the lower collar 17 to the tubular member 10.

The spring cage assembly 55 is then lowered into the well, and, when the desired depth has been reached, the movable switch contact 92 (Fig. 3) is disengaged from the fixed contact 90 and moved into engagement with the contact 93. This deenergizes the solenoid 85, releasing the pawl 79 so that the collar 17 can move upwardly until the cushions 69 and 77 are in engagement with the wall of the bore hole. At the same time, the source of electrical energy 43 is connected to the electrode A so that resistivity logs may be obtained as the apparatus is raised in the well.

One advantage of the locking device shown in Fig. 3C is that it enables the collar 17 to be locked to the tubular member 10 after only a portion of the bore hole has been logged. Thus, after completion of the desired portion of the log, the switch 91 (Fig. 3) is manipulated to bring the movable contact 92 into engagement with the contact 90, energizing the solenoid 85 and causing the pawl 79 to engage the internal teeth 78 (Fig. 3C). As the spring assembly 55 is raised in

the bore hole, the collar 17 will be locked in a position corresponding to the smallest bore hole diameter encountered since it can slide downwardly even though the pawl 79 is in the locking position. Hence, the device can be withdrawn from the hole at a greater speed with less wear on the cushions 69 and 77.

In the embodiments shown in Figs. 1 and 3, there is a remote possibility that the insulation between the conductors in the cable may be decreased such that a portion of the current intended for the electrode A may leak into the resistivity measuring circuits, thus giving erroneous indications. To eliminate this possibility, the current source may operate at one frequency and the potentials received by the potential electrodes may be converted to different frequencies before transmission to the indicating apparatus at the surface, as shown in Fig. 4.

In Fig. 4, closely spaced apart current emitting electrodes A and B embedded in the cushion 69 are connected by the conductors 116 and 117 to the secondary winding 94 of a transformer 95, the primary winding 96 of which is connected through the conductors 97 and 98 in the cable 12 to a source of alternating current 99 of suitable frequency, say 400 cycles per second, located at the surface of the earth.

The potential difference between the electrode M and a reference electrode N mounted on the cable a considerable distance therefrom is impressed upon the input terminals of a conventional amplifier rectifier 100 which amplifies the A. C. potential picked up and converts it to direct current. The direct current output of the amplifier 100 is transmitted through the conductors 100 and 102 in the cable 12 to a suitable recording instrument 103 at the surface of the earth, a conventional low pass filter 104 being interposed, if desired, to eliminate A. C.

Similarly, the A. C. potential picked up between the electrode M' and the reference electrode N' is impressed upon the input terminals of another conventional amplifier rectifier 105, the D. C. output of which is transmitted through the conductors 106 and 107 to the conventional D. C. recording instrument 108 at the surface of the earth. If desired or necessary, a conventional low pass filter 109 may be interposed between the instrument 108 and the conductors 106 and 107 to keep A. C. out of the instrument 108. The manner of operation of this embodiment will be readily apparent from the several other forms of the invention that have been described above.

It will be understood that the amplifiers 100 and 105 should have substantially the same temperature characteristics. Obviously, amplifier modulators may be employed instead of the amplifier rectifiers 100 and 105 in case it is desired to convert the potentials picked up to alternating current signals of frequencies other than 400 cycles per second.

If desired, any of the logging devices described above may be combined with a bore hole calipering device so that indications of variations in the bore hole diameter may be obtained simultaneously with the resistivity measurements. Thus, in Fig. 7, for example, a logging device of the type shown in Fig. 1 is combined with a bore hole caliper of the type described in application Serial No. 785,270, for "Mutual Inductance Systems," filed November 12, 1947, by Owen H. Huston.

In Fig. 7, the lower ends of the bowed springs 14 and 15 are secured to a connecting member 110 which carries a rod-like member 111 made of suitable magnetic material. The rod-like member 111 extends into an opening 114 in the bottom of the tubular member 10 and is adapted to modify the coupling between two inductively coupled windings (not shown), one of which is energized by a source of alternating current 112 located at the surface of the earth and the other of which is connected to a suitable recording device 113, also located at the surface of the each. The log made by the recording device 113, therefore, is a function of the diameter of the bore hole 11.

Preferably, the two resistivity measurements recorded by the devices 49 and 50 and the bore hole diameter measurements indicated by the recording device 113 are recorded on the same log. It will be apparent, therefore, that if the cushion 20 were passing an enlargement or cave in the bore hole of such diameter that the cushion would not be pressed against the wall of the hole, the log would indicate this fact. It would then be known that the resistivity indications derived from potential measurements made with the electrodes M and M' at that level will be altered by the resistivity of the drilling mud. This combination is highly desirable since it enables the resistivity logs to be accurately correlated with the caliper log, an object which is very difficult to attain where the resistivity logs and the caliper log are made in separate runs in the well.

In certain cases, the mud used in the bore hole does not form a thick mud cake but is designed to form a thin protective coating over permeable formations to prevent the entry of bore hole fluid thereinto. In order to obtain indications of very thin mud cakes of this type, in accordance with the invention, the spacings between the several electrodes must be made exceedingly small. In such case, if small circular electrodes were employed, as shown in Figs. 1, 3 and 4, their resistance might be so high as to affect the measurements adversely. In such applications, therefore, electrodes of the type shown in Figs. 5, 5A, 6, and 6A may be employed.

In Fig. 5, three thin blade-like electrodes A, M and M' are embedded in the flexible cushion 20. As indicated in greater detail in Fig. 5A, the three electrodes are preferably disposed below the wall of the cushion 20 so that they will not rub against the wall of the hole while the measurements are being made.

It is also possible to achieve the same result with circular electrodes A, M, M' made of thin material such as wire, for example, and embedded in recesses in the cushion 20, as shown in greater detail in Fig. 6A.

It will be understood, from the foregoing description, that the invention provides novel and highly effective apparatus for determining whether or not a mud cake is present on the formations located at different depths in a well. By making extremely localized resistivity measurements at two lateral depths of investigation which are suitably selected to provide measurements that are influenced to different degrees by any mud cake that may be present, the presence or absence of mud cake may be readily accertained, so that permeable and impervious formations may be readily distinguished. In fact, the simultaneous resistivity values obtained for the different spacings can be arranged to be compared automatically, if desired, rather than by a visual examination of the records.

It will be understood that the auxiliary cushions 20' in Figs. 1 and 7 and 77 in Figs. 3 and 4 can also be adapted to carry other electrode arrangements such as, for example, an electrode pressed against the wall of the bore hole for measuring spontaneous potentials.

Where reference is made in any of the following claims to the conversion of a potential difference of one frequency to a signal of different frequency, this is intended to include both the conversion of direct current to alternating current and the conversion of alternating current to direct current or to alternating current of different frequency.

According to conventional usage, which has been followed in the foregoing description, in systems including at least four electrodes (two current and two potential) in which indications representative essentially of potential gradient are obtained (e. g., by means including a pair of nearby electrodes such as the potential electrodes M and M' in Fig. 1, or the current electrodes A and B in the equivalent reciprocal system shown in Fig. 4), the electrode "spacing" is defined as the distance from the midpoint between the two nearby electrodes of the same category (current or potential) to the nearest electrode of different category. On the other hand, where indications of the absolute potential of an electrode are obtained (e. g., the electrode M' in Fig. 1) the electrode spacing is the distance from that electrode to the nearest electrode of different category. Where reference is made in the following claims to the electrode spacing in an electrical logging system, the conventional meaning of this terminology is intended.

In the embodiment shown in Figs. 1A, 1B and 1C any other suitable mechanism may be employed instead of the relay 38 for firing the igniter 32. For example, a conventional dashpot time delay relay of the type used in the selective firing of charges in a gun perforator may be employed for this purpose. Alternatively, the conductor 40 might be directly connected to the electrode A and the igniter 32 connected to the source of electrical energy 43 by means of a separate circuit like that employed for the solenoid 85 in Fig. 3C, for example. In such case, no relay switching means would be required.

Obviously, the several typical embodiments described above are susceptible of numerous modifications in form and detail within the spirit of the invention. For example, any suitable source of electrical energy may be employed such as D. C., A. C. or pulsated D. C., for example, provided that appropriate indicating means are employed, as is well known in the art. Further, either form of cage assembly or locking device may be used indifferently with any three of the specific logging circuits disclosed. Also, any other suitable electrical circuits may be employed for obtaining the two resistivity measurements according to the invention. The specific embodiments disclosed herein, therefore, are not to be regarded as imposing any restrictions whatsoever upon the scope of the following claims.

I claim:

1. In well logging apparatus, the combination of a flexible insulating cushion member mounted for movement through a well and having an outer face, means for urging said member laterally to bring the outer face thereof into engagement with the wall of the well, a plurality of small, closely spaced electrodes embedded in said cushion member outer face at different distances from a first one of said electrodes, each of said electrodes having an exposed portion facing the wall of the well, means for passing electric current between said first electrode and a reference point spaced apart therefrom, a first potential indicating circuit connected to receive the potential difference between a second of said electrodes and a reference point spaced apart therefrom, said first and second electrodes comprising part of a first exploring system having a very small electrode spacing adapted to render the system responsive primarily to the electrical resistivity of the material in a zone on the order of a fraction of an inch in thickness extending laterally and outwardly from the surface boundary of the bore hole, a second potential indicating circuit connected to receive the potential difference between a third of said electrodes and a reference point spaced apart therefrom, said first and third electrodes comprising part of a second exploring system having an electrode spacing greater than said first exploring system and rendering said second exploring system primarily responsive to the electrical resistivity of the earth formation material beyond said zone, and means for recording the potentials indicated by said first and second potential indicating circuits.

2. In combination in the well logging apparatus defined in claim 1, bore hole calipering means mounted for movement through the well in fixed relation to said flexible insulating cushion member and adapted to provide an electric signal responsive to variations in a lateral dimension of the bore hole.

3. In combination in well logging apparatus as defined in claim 1, a support adapted to be lowered into the well, at least two bowed spring elements secured together at opposite ends, at least one of said ends being slidable longitudinally with respect to said support, said flexible insulating cushion member being secured on one of said bowed spring elements, and releasable means carried by the support for locking said bowed spring elements to the support in a contracted position.

4. In combination in well logging apparatus as defined in claim 1, a support adapted to be lowered into a well, and at least two bowed spring elements secured together at their opposite ends, at least one of said ends being mounted on said support for limited longitudinal sliding movement with respect thereto, said flexible insulating cushion member being secured on one of said bowed spring elements, and said one bowed spring element having a substantially straight, inwardly depressed portion suitably reenforced to maintain a portion of said cushion member outer face in engagement with the wall of the well.

5. Well logging apparatus, as defined in claim 1, in which said electrodes comprise closely spaced parallel blade-like elements embedded in said cushion so as to be spaced apart from the wall of a well in close proximity thereto.

6. In combination in well logging apparatus as defined in claim 1, a support adapted to be lowered into the well, at least two bowed spring elements secured together at their opposite ends, at least one of said ends being mounted for relative movement with respect to said support in response to variations in bore hole diameter, said flexible insulating cushion member being secured on one of said bowed spring elements, and means responsive to relative movement of said one end with respect to the support for providing indications of variations in bore hole diameter.

7. In well logging apparatus, the combination of a flexible insulating cushion member mounted for movement through a well and having an outer face, means for urging said member laterally to bring the outer face thereof into engagement with the wall of the well, a plurality of small closely spaced electrodes embedded in said cushion member at different distances from a first one of said electrodes, each of said electrodes having an exposed portion facing the wall of the well, a first electrical circuit having as terminals said first electrode and a reference point spaced apart therefrom, a second electrical circuit having as terminals two other adjacent ones of said electrodes, the spacing between said first electrode and the midpoint between said two other electrodes being not greater than about one and one-half inches, a source of electrical energy in one of said first and second electrical circuits, electrical indicating means in the other of said first and second electrical circuits, a third electrical circuit having as terminals one of said electrodes and a reference point spaced apart therefrom, said last-named electrode cooperating with the one of said first and second electrical circuits containing said source of electrical energy to form an exploring system having an electrode spacing greater than one and one-half inches, and electrical indicating means in said third electrical circuit.

8. Well logging apparatus as defined in claim 7 in which the flexible insulating cushion member is secured on one of two bowed spring elements which are connected together at opposite ends, at least one of said ends being slidable longitudinally with respect to a support adapted to be lowered into a well; the source of electrical energy provides current of one frequency; and both of said indicating means are provided with means for converting potential differences supplied thereto to signals of different frequency.

9. In well logging apparatus, the combination of a flexible insulating cushion member mounted for movement through a well and having an outer face, means for urging said member laterally to bring the outer face thereof into engagement with the wall of the well, a plurality of small, closely spaced electrodes embedded in said cushion member outer face at different distances from a first one of said electrodes, each of said electrodes having an exposed portion facing the wall of the well, means for passing electric current between said first electrode and a relatively remote reference point, means for providing indications of the potential difference between second and third ones of said electrodes, and means for providing indications of the potential difference between one of said second and third electrodes and a reference point substantially at electrical infinity, the distance between said first electrode and the midpoint between said second and third electrodes being of the order of one and one-half inches, and the distance between said

first electrode and said one electrode being greater than the distance between said first electrode and said midpoint.

10. In well logging apparatus, the combination of a flexible insulating cushion member mounted for movement through a well and having an outer face, means for urging said member laterally to bring the outer face thereof into engagement with the wall of the well, a plurality of small, closely spaced electrodes embedded in said cushion member outer face at different distances from a first one of said electrodes, each of said electrodes having an exposed portion facing the wall of the well means for passing electric current between said first electrode and a relatively remote reference point, means for providing indications of the potential difference between second and third ones of said electrodes, and means for providing indications of the potential difference between adjacent fourth and fifth electrodes, the distances between said first and second, second and third, and fourth and fifth electrodes being of the order of one-quarter inch and the distance between said third and fourth electrodes being of the order of one-half inch.

11. In well logging apparatus, the combination of a flexible insulating cushion member mounted for movement through a well and having an outer face, means for urging said member laterally to bring the outer face thereof into engagement with the wall of the well, a plurality of small, closely spaced electrodes embedded in said cushion member outer face at different distances from a first one of said electrodes, each of said electrodes having an exposed portion facing the wall of the well, means for passing electric current between said first electrode and a second of said electrodes adjacent thereto, a first potential indicating circuit connected to receive the potential difference between a third of said electrodes and a reference point substantially at electrical infinity, and a second potential indicating circuit connected to receive the potential difference between a fourth of said electrodes and a reference point substantially at electrical infinity, the distance between said third electrode and the adjacent one of said first and second electrodes being not greater than about one inch, and the distance between said fourth electrode and said adjacent one of said first and second electrodes being greater than the distance between said adjacent one electrode and said third electrode.

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