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METHOD AND APPARATUS FOR WELL LOGGING

Filed Dec. 13, 1946

3 Sheets-Sheet 1

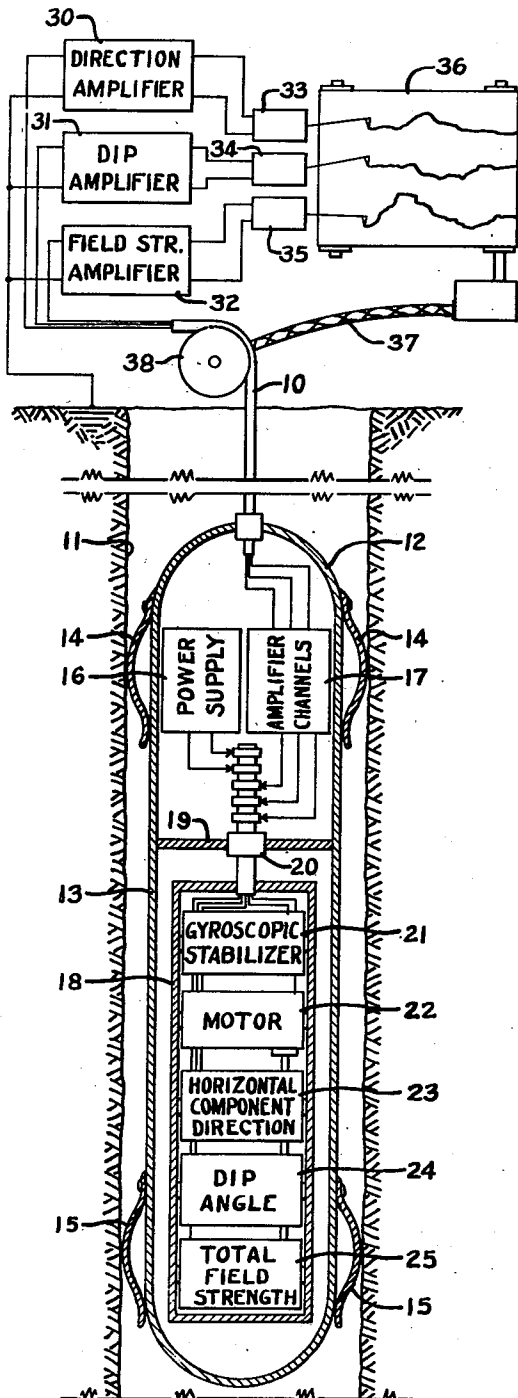


Fig. 1

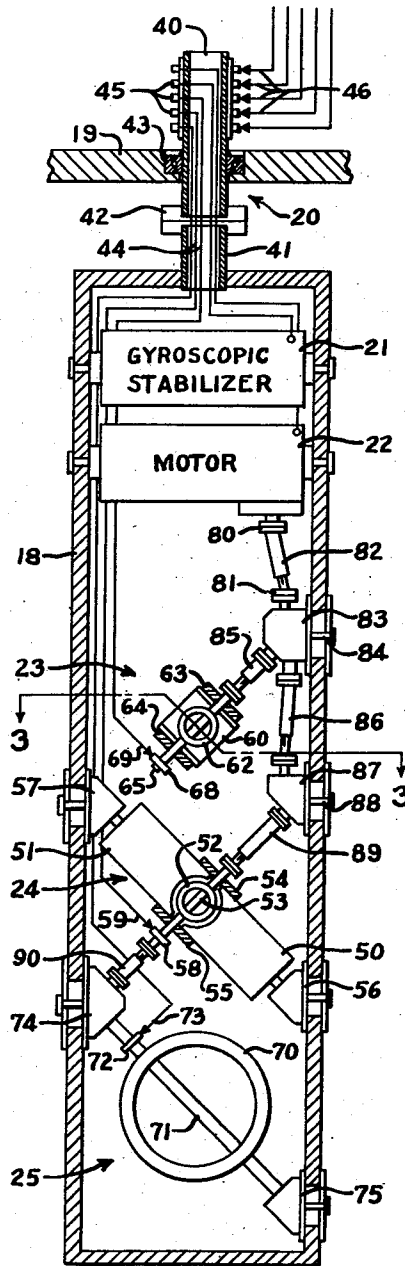


Fig. 2 INVENTOR:
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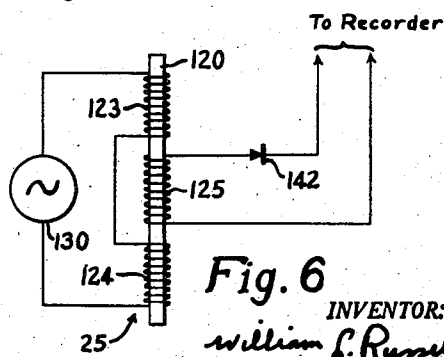
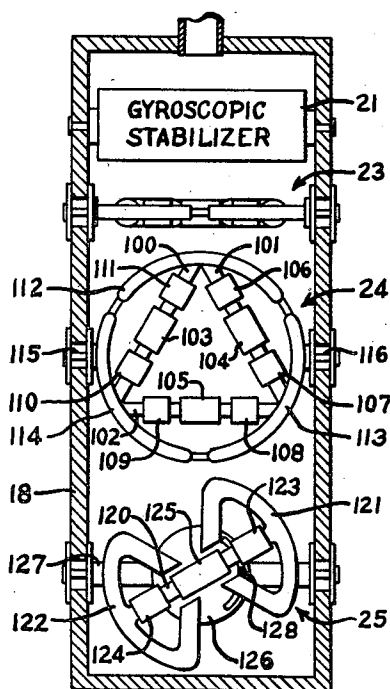
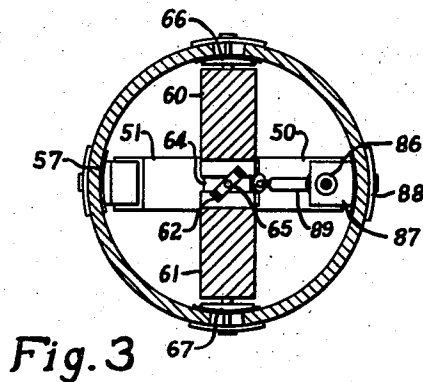
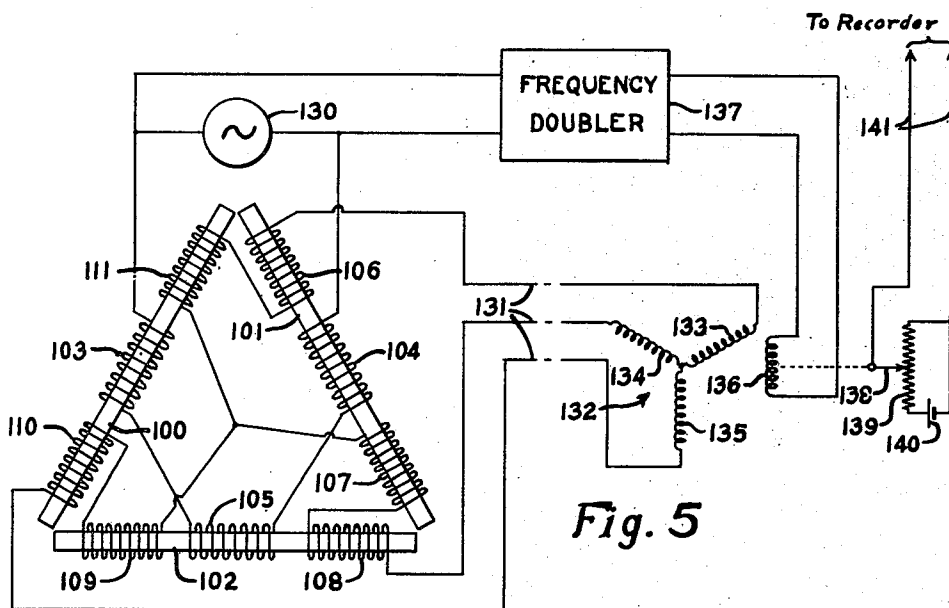
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3 Sheets-Sheet 3

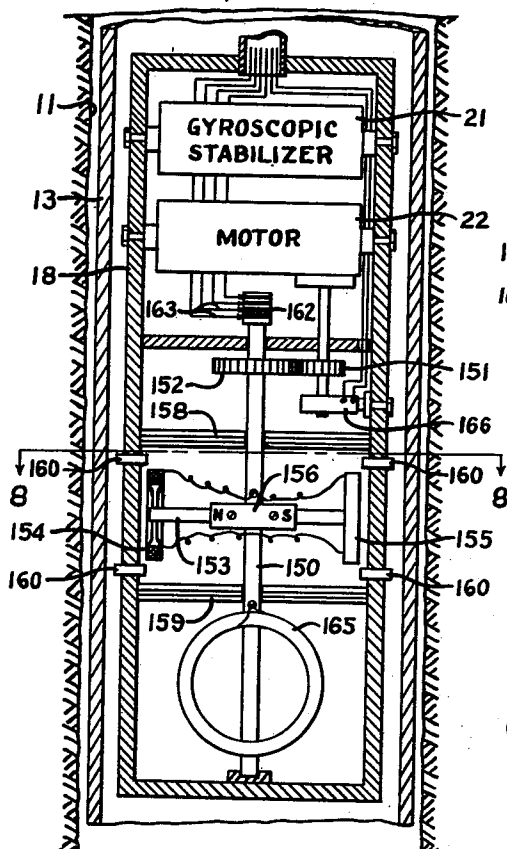


Fig. 7

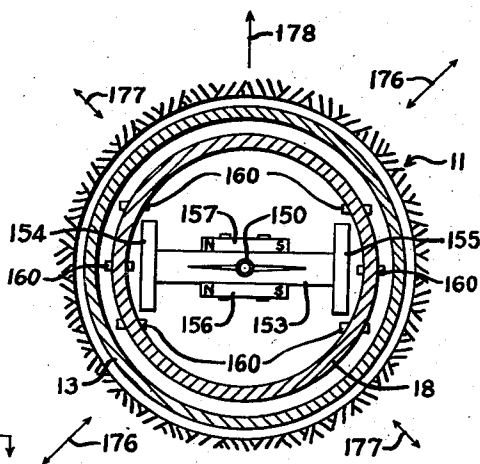


Fig. 8

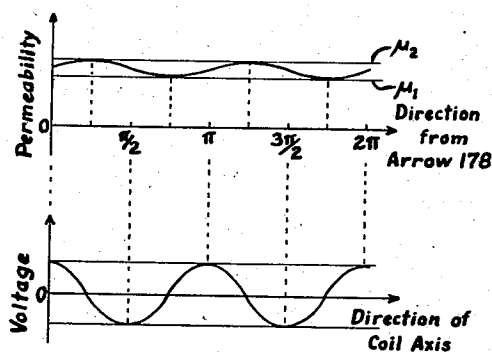


Fig. 10

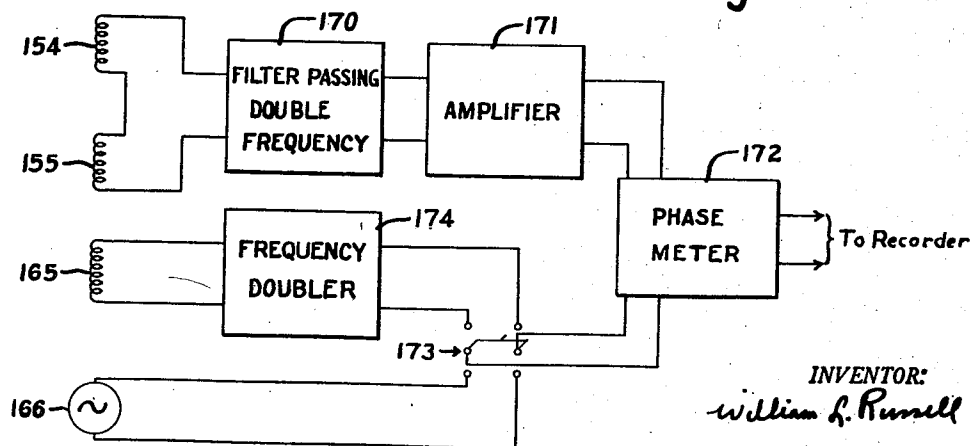


Fig. 9

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UNITED STATES PATENT OFFICE

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METHOD AND APPARATUS FOR WELL LOGGING

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This invention relates generally to the logging of wells and is directed particularly to the logging of certain magnetic properties of well formations by which correlations may be carried out over large distances independent of the occurrence of marker fossils or lithologic similarities. The data so obtained are also of considerable value in improving magnetic core-orientation methods.

For correlation over short distances electrical, radioactivity, and drill-cutting or core-sample logs have proved very useful and reliable. However, since they are dependent on lithologic variations, they may be used only over those distances where the lithologic succession is persistent. These distances may vary from a few hundred feet to hundreds of miles.

For correlation over larger distances and where the lithology is not persistent, fossils have heretofore been relied on with considerable success. However, because the volume of material brought up during the drilling of wells is comparatively limited, fossils easily found at surface exposures may by chance be absent from the particular subsurface samples obtained or may be so damaged by the drill as to be unrecognizable. Further and varying factors such as, for example, changes in environment or separation of the areas of deposition by barriers often so complicate the fossil-correlation method as to make it impractical or impossible to apply. Also, large areas where fossil correlation would be desirable are covered to great depths by red beds and other strata of non-marine origin which are nearly always devoid of fossils suitable for correlation.

In the orientation of cores by measuring their weak remanent magnetism, the accuracy of the results is dependent on the precision with which the direction of the remanent field in the particular stratum is known or can be ascertained. It is often necessary to assume a remanent field direction parallel to the present earth's induced field. However, from observations at outcrops and other information, it is well known that remanent field directions vary, so that any assumption that they are constant or the same is bound to lead to serious errors upon occasion.

It is accordingly a primary object of my invention to provide a method and apparatus for making well logs correlatable over great distances regardless of lateral changes in lithology. Another object is to provide a method and apparatus for logging certain magnetic properties of well formations, which properties are related to the earth's magnetic field at the time of deposi-

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tion of each stratum rather than to the nature of the materials forming the stratum. A further object is to provide a method and apparatus for making well logs that are correlatable on the basis of the time of deposition of the various strata rather than the nature of the minerals in the strata, so that strata of the same age in different locations may be identified as such even though their mineral compositions differ. Still another object is to provide a method and apparatus for obtaining data from which the nature of the variations in the earth's magnetism in past geological ages may be determined. A still further object is to provide a method and apparatus for obtaining remanent field direction data for the various well strata, which data are directly applicable to improving the interpretation of magnetic core-orientation measurements. Many other and further objects, uses, and advantages of my invention will become apparent as the description proceeds.

In general terms the essence of my invention by which the foregoing and other objects are accomplished comprises the logging or measurement in wells of the variations in the orientation and inclination of certain residual or remanent magnetic properties.

The magnetic field encountered in wells may be considered as arising from two sources: the flux induced in the strata by the earth's present magnetic poles, and the remanent field. The former is generally the major component of the resultant field, while the remanent magnetism is usually quite small by comparison. Whereas the variations in the strength of both the induced and the remanent magnetic fields are often considerable, they are generally related to the kind and composition of each rock, being dependent on the content of magnetite. To be distinguished from these variations, on the other hand, are the variations in direction of the remanent field which are related to the changes in direction of the earth's magnetic field during the time of deposition of the sedimentary rocks. These latter variations result from the movements of the magnetic poles which both have in the past and do now affect the entire earth in a related and determinable manner. As they are thus independent of the nature of the rocks, well logs based on these variations can be correlated over distances unlimited by the persistence of the lithologic succession or the occurrence of marker fossils, and the directional information they contain can be readily employed in core-orientation measurements.

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The remanent magnetism of rocks is apparently produced almost entirely by the mineral magnetite. Since magnetite rarely forms in unmetamorphosed sediments, the magnetite now in them was probably derived from igneous and metamorphic rocks. This limits its occurrence to clastic strata. As the clastic particles containing some magnetite settle through the water or air from which they are deposited, the magnetite tends to become oriented so that its magnetic field is parallel to the earth's field. As the particles come to rest on the surface beneath the fluid, they tend to retain the same orientation, and once they have been buried by later deposits they are unable to move in response to subsequent changes in the orientation and dip of the earth's field.

The magnetic permeability of rocks appears also to be due to the magnetite content, and like the process of orientation of a particle by its remanent field, a certain amount of orientation of the particles occurs due to this property. In other words, in so far as a particle has a greater permeability in one direction than in any other direction, this will be the direction in which the particle becomes magnetized while exposed to the earth's magnetic field during settling to the bottom of the fluid. Fixing of the particle in place by later deposits thus prevents further movement to align the maximum permeability axis with the shifting direction of the earth's field in the same way that the remanent magnetism becomes fixed. There are thus two properties—the direction of the remanent magnetism and the direction of the axis of maximum permeability—available for the purposes of this invention.

All rocks deposited from solution would be devoid of magnetite if pure, so that their magnetic properties could not be logged. However, many limestones, dolomites, and other rocks deposited primarily from solution are found to contain in their clastic impurities sufficient magnetite for logging. Moreover 80 per cent or more of all sedimentary rocks are clastic.

Whereas it is a relatively simple matter to measure the directional magnetic properties of small rock samples in the laboratory, the measurement of these properties in wells is tremendously complicated by the presence of the earth's field. Consequently the magnetic field observed by the well-logging instrument, while it involves rock masses many times the size of laboratory samples, is the resultant of the two fields: the induced field and the remanent field of which it is desired to measure the orientation and dip. While it is quite difficult or impossible to eliminate completely the effect of the induced field on the measurements, it can be evaluated with sufficient accuracy for the purposes of this invention.

Since the induced field is generally many times larger than the remanent field, for the purpose of estimating the magnetite content of rocks, the remanent field strength may be neglected and the resultant and induced fields considered equal. It is chiefly their magnetite content which determines the permeability of rocks and gives rise to the variations in the induced flux. As the strength of the remanent field is also approximately proportional to the magnetite content to which it is due, this same measurement of the resultant field strength is useful for the purpose of estimating the remanent field strength. Therefore, in the practice of my invention the strength of the resultant field in the various strata is logged along with the variations in its direction, or the

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variations in direction of the maximum permeability, or both. By properly employing the data thus obtained logs related to the direction of the remanent field, or to the direction of the maximum permeability, which is generally the same, may be computed. These are the logs useful for both long and short distance correlations, and from which information may be derived as to the variations in the earth's magnetism in past geological ages.

These principles and their relation to my invention will be better understood by reference to the accompanying drawings forming a part of this application for purposes of illustration. In these drawings the same reference numeral is applied to the same or a corresponding part in the different figures. Thus,

Figure 1 is a cross section of a well with an instrument embodying the invention shown generally therein;

Figure 2 is a cross section of one embodiment of the detectors of my invention;

Figure 3 is a cross section of Figure 2 on the lines 3—3;

Figure 4 is a cross section of an alternative embodiment of the detector units of my invention;

Figure 5 is a circuit diagram applicable to the detector embodiment of Figure 4;

Figure 6 is a circuit diagram of the field-strength detector of Figure 4;

Figure 7 is a cross section of a third embodiment of my invention adapted to measuring the anisotropy of permeability around a well bore;

Figure 8 is a cross section of Figure 7 on the lines 8—8;

Figure 9 is a circuit diagram of the apparatus of Figures 7 and 8 showing the method of recording the data; and

Figure 10 is a graphical representation of an assumed permeability distribution and the resultant detector signal.

In Figure 1 is illustrated a general arrangement of the apparatus for making measurements of the various directional properties of the earth's magnetism in accordance with my invention. Adapted to be lowered on a cable 10 into a well 11 is a subsurface instrument 12 having a rigid outer housing 13 of non-magnetic material strong enough to withstand the hydrostatic pressures encountered in wells. Centralizing springs 14 and 15 at either end of housing 13 may be provided to hold the instrument 12 in the center of the well when it is necessary to do so.

In suitable spaces within housing 13 are located power-supply equipment 16, which may include batteries or alternating-current sources or both, depending on the specific types of detectors employed, and amplification equipment 17 consisting of one or more separate amplifier channels, as needed, for signal transmission and the like. Mounted in a frame 18, which is preferably freely suspended from the center of a cross member 19 by a rotatable and flexible connection 20 so as to hang vertically in a compartment near the lower end of housing 13, is the magnetic-field or permeability-direction measuring equipment. When and if housing 13 tends to rotate, a gyroscopic stabilizer 21 mounted in frame 18 keeps it oriented in a fixed predetermined direction. Where the magnetism-measuring devices are such as to require mechanical power for their operation, it is supplied by an electric motor 22 likewise fixed in frame 18, it being understood that precautions as by shielding or otherwise (not shown)

will be taken to minimize interference between the magnetic fields and materials of the motor and gyro and the earth's directional magnetic properties being measured.

The apparatus carried by frame 18 for these measurements includes at least one, and preferably two or more detectors sensitive to the directions or direction changes of components of the remanent magnetic property in different planes. Thus, a detector 23 is primarily sensitive to changes in direction in a horizontal plane of the horizontal component of the measured property, while the detector 24 is sensitive to changes in its dip, or more generally to changes in direction of the component lying in a given vertical plane. A detector 25 is responsive to changes in the total magnetic-field strength or induction in the well formations so that the effect of these changes on the direction measurements can be allowed for.

After amplification of the responses of detectors 23, 24, and 25, as necessary, by suitable channels in amplifier 17, the resulting three signals may be transmitted to the top of well 11 over separate insulated leads in cable 10. Such further amplification as is necessary for recording is provided by a horizontal-direction signal amplifier 30, a dip signal amplifier 31, and a field-strength signal amplifier 32, each of which amplifiers drives one of the respective recording devices 33, 34, 35, and thereby records on a moving chart 36. Movement of chart 36 in accordance with the depth of instrument 12 in the well is accomplished by any of the conventional expedients of well logging, such as by a driving connection 37 actuated from a depth-measuring sheave 38 over which cable 10 passes. Since the signal transmission and recording in correlation with instrument depth may follow any of several suitable and conventional practices, no further detailed description of them is believed necessary herein. Such modifications of these parts of the system as may be required to adapt them to the various specific embodiments of the detection equipment described hereinafter will be apparent to those skilled in the art of well logging.

One such embodiment of the measuring equipment is shown in some detail in Figures 2 and 3, where it will be seen that the suspension 20 for frame 18 includes an upper 40 and a lower tubular member 41 connected by a flexible or universal joint 42, upper tubular member 40 being held inflexibly but free to rotate by a bearing 43 in cross-member 19. Electrical conductors 44 supplying power to or carrying signal currents from the apparatus mounted in frame 18 extend through tubes 40 and 41 and are brought out to slip rings 45 mounted on tube 40 and contacted by brushes 46. It is to be understood that the number of these slip rings and brushes will vary depending on the number of independent electrical-circuit connections to be made between the fixed and the suspended equipment in housing 13.

Best shown in Figure 2 is the dip-detector assembly 24 which in this embodiment is adapted for measuring the angle of inclination of the magnetic field intersecting the well bore at various depths. The assembly consists of a pair of highly permeable ferromagnetic bars 50 and 51 placed end to end and having between their adjacent ends an air gap in which is located a rotatable inductor coil 52. This coil is mounted for rotation about its diameter on a shaft 53 journaled in a pair of non-magnetic bearing members 54 and

55, which may also help to support the bars 50 and 51 as a rigid unit. The outer ends of the bars 50, 51 are adjustably clamped to frame 18 by the clamps 56 and 57 movable in slots in the frame 18. The winding of coil 52 may have one terminal grounded and the other brought out to an insulated slip ring 58 contacted by a brush 59 connected to one of the leads 44.

The horizontal-component direction detector 23 is generally similar to the dip detector 24, as can be seen by referring to Figure 3. Detector 23, like dip detector 24, consists of a pair of highly permeable ferromagnetic bar members 60 and 61 aligned end to end with an inductor coil 62 in an air gap between them. Non-magnetic bearing members 63 and 64 carry a shaft 65 on which the inductor coil 62 is mounted for rotation about its diameter and also support the bars 60 and 61 as a unit, their outer ends being adjustably fixed to the frame 18 by clamps 66 and 67. One terminal of the coil 62 is grounded, and the other is brought out to a slip ring 68 contacted by a brush 69 connected to another one of the leads 44.

The field-strength detector 25 may be simply an inductor coil 70 (Figure 2) fixed on a shaft 71 for rotation about its diameter, one end of the coil winding being grounded and the other brought out to the slip ring 72 contacted by the brush 73 connected to a still different one of the leads 44. Shaft 71 rotates in bearings contained in a gear box 74 and an adjustable support member 75, both of which are clamped in slots in the frame 18.

In order to generate voltages indicative of the magnetic fields surrounding them, the inductor coils 52, 62, and 70 are rotated by suitably coupling them to the motor 22, which is preferably of a constant-speed type. While this coupling is a positive one in order to preserve the phase relations between the various coils, it is also flexible so as to allow some adjustment of the measuring units in the frame 18. Thus, the motor shaft is connected by universal joints 80 and 81 and a spline 82 to a gear box 83 adjustably clamped in a slot in frame 18 by a clamp 84. Thence torque is transmitted by a similar universal joint and spline coupling 85 to the shaft 65 of the inductor coil 62. Another flexible coupling 86 simultaneously transmits power from the box 83 to a second gear box 87 held by the clamp 88. From here the shaft 63 of the inductor 52 is driven by a coupling 89. A similar coupling 90 from shaft 53 to the gear box 74 provides for rotation of the inductor coil 70. It is thus seen that all of the inductor coils are linked together so as to be driven in unison by the motor 22, but the flexibility of the couplings permits limited movement of the various units in the frame 18.

The adjustment and operation of this embodiment of my invention may follow either of two general procedures. It is assumed that the magnetic field observed at the earth's surface at the well location represents the normal values of both the direction and intensity in that area relatively unaffected by the remanent fields and the varying permeabilities of the strata below. It is also assumed, from the known fact that the contributions of the remanent fields to the observed total field strengths are small, that the variations in direction of the resultant fields in the strata will not exceed relatively narrow limits. Further, it is obvious that when the axes of the bars 50, 61 and 50, 51 are perpendicular to a magnetic field, the induction in each is equal,

and no flux crosses the gaps between them to be intercepted by the inductor 52 or 62 during rotation.

One adjustment procedure therefore consists in so adjusting and setting the clamps and bars that the axis of bars 50, 51 is horizontal and perpendicular to one of the expected limiting directions of the magnetic field horizontal component to be encountered in the well. Bars 50, 51 are so oriented and clamped as to lie in the vertical plane which includes the surface direction of the magnetic field, their axis being turned in this plane so as to be perpendicular to one of the limits of variation in magnetic dip to be expected. The axis of rotation, i. e., shaft 71, of inductor 70 is placed as nearly as possible perpendicular to the direction of the surface magnetic field. It may or may not lie in the same vertical plane as bars 50, 51. The axes of rotation of the small inductors 52 and 62, i. e., the shafts 53 and 65, are oriented approximately parallel to the surface field direction so that substantially the only flux intercepted by them during rotation will be that crossing the gap from one bar to another.

The apparatus is thus adjusted at the surface with the gyro 21 in operation to maintain the orientation, and with motor 22 running so as to provide an output signal from the various detectors which will serve as a reference, the respective amplitudes at the surface and in the well being the significant indications. The instrument is then passed through the well, and the amplitudes of the three signals are recorded as functions of depth on the chart 36.

It is believed apparent that in this case the amplitudes of the two directional detectors 23 and 24 will vary with both field strength and direction. Neglecting variations in strength for a moment, the outputs will be zero for the limiting field directions that are perpendicular to the bar axes, of medium amplitudes for directions parallel to the surface field, and of maximum amplitudes for field directions approaching the other assumed limit of directional variation. The influence of variations in field strength is eliminated from the final logs, however, by applying to the uncorrected values a correction factor which is the ratio of the total field strength at the surface to its value at the stratum in question in the well. This is the ratio of the signal amplitude of the inductor 70 at the surface to its value in the well, and may be employed either in the subsequent preparation of corrected logs, or at the time of the logging operations. In the latter case recorders 33 and 34 may be adapted to record, not the signal amplitudes directly, but their respective quotients with the total field strengths for the corresponding strata.

In the second and ordinarily preferred adjustment procedure, the bar axes are oriented perpendicular to the surface directions of the components of the magnetic field to which they are responsive, instead of perpendicular to one of the limiting directions expected in the well. Consequently the outputs of the inductors 52 and 62 are zero whenever the field component direction in the well is the same as it is at the surface, and the direction of a variation from the surface direction is easily ascertained from the fact that the alternating-current output of the inductors 52 and 62 shifts 180 degrees in phase as the direction changes from one side of the surface reference direction to the other.

As the amplitude is, as before, a function of both the strength and the direction of the resultant field in a stratum, the indications may be corrected in a manner similar to the first operating procedure: either by applying the correction factor previously mentioned or by recording the quotients of the outputs of each of the directional detectors by the output of the field-strength detector. The polarity of the variations may conveniently be determined by using the signal from the inductor 70 as a reference with which to compare the phases of the signals from the inductors 52 and 62, for the reason that the phase variations in the field-strength signal are small because the changes in total field direction are small. The manner of applying a phasemeter to this determination will be apparent to those skilled in the art.

In Figure 4 is shown an alternative embodiment of my invention which is simpler mechanically than the embodiment of Figures 2 and 3 in that no rapidly moving parts are employed corresponding to the various rotating inductor coils. Briefly, these detectors comprise stationary ferromagnetic cores exposed to the steady magnetic field and periodically saturated by additional pulsating or alternating fluxes induced therein by exciting windings. Pickup coils about the cores are so arranged that when there is no external steady field the voltages induced in them by the additional fluxes balance out. But in the presence of such a field the balance is disturbed, giving a resultant voltage which may be used to indicate the field strength or its direction relative to the cores, or both.

As, in this embodiment, the horizontal-component detector 23 and the dip detector 24 may be practically identical except for their orientation in the frame 18, only the latter will be described in detail, since it is shown to better advantage in the drawing. For clarity the electrical leads and connections have been omitted here.

Arranged as the sides of a triangle, preferably equilateral, are the three highly permeable, saturable ferromagnetic cores 100, 101, 102, carrying the respective exciting windings 103, 104, 105 and the respective sets of pickup windings 106, 107, 108, 109; and 110, 111. Although they are not strictly essential, the induction in the cores due to an external field is increased by the arcuate pole pieces 112, 113, 114, each of which is located at an apex of the triangle. These pole pieces may conveniently carry the clamps 115, 116 by which the unit 24 is fastened in the supporting frame 18.

The field-strength detector 25 in this embodiment may consist of a single permeable, saturable ferromagnetic core 120 having arcuate pole pieces 121 and 122, the tips of which are bent backward towards the central part of core 120 so as to form nearly closed flux paths with the two halves of the core. Within each flux path and surrounding core 120 are the exciting windings 123 and 124, while a single pickup winding 125 encircles core 120 at its center. Mounting of the entire assembly on a disc or plate 126, pivoted to a cross-member 127 clamped to frame 18, provides for adjusting the direction of the core axis, plate 126 being fixed in a desired position by a screw 128 clamping it to cross-member 127.

The circuit connections of this embodiment of my invention are shown in Figure 5. Although the exciting coils 103, 104, 105 are there shown connected in series and to a suitable source 130

of alternating current, they can equally well be in parallel rather than series. The pickup coils are Y-connected in pairs, coils 106 and 111 forming one pair, 107 and 108 another, and 109 and 110 a third. As may be observed from an inspection of the drawing the relative directions of these pickup and exciting windings are such that the voltages induced in each coil of a pickup pair by the alternating exciting fluxes tend to balance out; for example, the voltage in coil 111 due to the flux excited by coil 103 in its core is equal and opposite to the voltage in coil 106 due to excitation by coil 104, and so on for the other two pairs. However, a resultant voltage appears in each coil pair, considered as a unit, if the induction due to an external steady field (which depends both on the field strength and its direction relative to the core) brings one core closer to saturation than another, so that the induced voltage is distorted by a saturation "cut-off" effect in one coil different from that in the other coil of the pair.

In the presence of such an external field, each of the three coil pairs will generally show such a resultant voltage, each proportional to the component of the field in one of the three core directions. The vector combination or resultant of these three individual voltages is then the direction and strength of the total field component lying in the plane of the triangular core structure. For transmitting this information to the appropriate recorder (either the horizontal recorder 33 or the dip recorder 34, depending on the orientation of the triangular detector unit in frame 18) the outer terminals of the Y-connected coil pairs may be connected by the three leads 131 to a 3-coil Y-connected stator 132 consisting of the coils 133, 134, and 135 oriented 120° apart. As these three voltages and their resultant are of twice the frequency of source 130, the direction of the resultant in stator 132 is indicated by the position of a rotor 136, to which is supplied a current of the same double frequency and proper phase from the source 130 through a frequency-doubling circuit 137. The alignment of rotor 136 is an indication of the resultant field direction, and for transmission to the recorder, for example, recorder 34, it may be made to adjust the contactor 138 of a potentiometer 139 in series with a battery 140, thereby sending to the recorder a direct-current signal over the leads 141 indicative of the magnetic-field dip in the well.

As the magnitude of the resultant voltage in stator 132 is proportional to the total strength of the magnetic field, in the case of this embodiment of the dip detector 24, it may be measured there in place of using the separate detector 25. This may be accomplished, for example, by a suitable pickup coil having its axis oriented by the rotor 136 to a position perpendicular to the resultant field of stator 132.

However, as shown by Figure 6, the exciting coils 123 and 124 of the preferred separate field-strength detector 25 of this embodiment are connected in series opposition and to the source 130. When core 120 is aligned parallel to the average direction of the magnetic field or to its direction at the surface, then the double-frequency unbalance voltage in pickup coil 125 varies in amplitude directly with the field strength. If desired, a rectifier 142 may convert this to a direct-current voltage for recording by the recorder 35.

Source 130 may also supply the exciting voltage for the horizontal-component detector 23 which

is exactly like the detector 24. However, a separate rotor and stator unit is required to analyze the three components of the horizontal flux and transmit an indication of their resultant to the direction recorder 33.

In operation, it is only necessary at the surface to set the detector 23 in a horizontal plane, the detector 24 in the vertical plane which includes the surface field direction, and the field-strength detector core 120 parallel to the surface field. Thereafter the gyro 21 maintains the orientation of frame 18 while the instrument is passed through a well. If desired, the directional logs may be corrected by the output of the detector 25 during the logging run as in the Figure 2 embodiment, or the data from the three detectors may be recorded directly for use in preparing corrected logs later.

An embodiment of my invention directed to the measurement of a directional earth magnetic property different from the remanent magnetism but like in it indicating conditions of deposition of the earth sediments, namely, the property of directional anisotropy of the permeability, is shown in Figures 7 and 8. As the success of this measurement depends to a considerable extent on maintaining concentric the instrument and the walls of the well, it does not appear feasible to measure other components of the permeability than its values in a plane perpendicular to the well axis; that is, the horizontal component in a vertical well.

The apparatus for this measurement consists of a central tube 150 on the axis of the oriented frame 18 adapted to be rotated by the motor 22 through gears 151 and 152. A cross arm 153 is clamped at its center to tube 150 and carries at its extremities the coils 154 and 155, the axes of which lie along cross arm 153. Fastened also to cross arm 153 at its center are the permanent bar magnets 156 and 157 with their axes also aligned parallel to the arm. Magnetic shields 158 and 159 above and below these magnets and coils isolate this section of the apparatus from the remainder of the instrument. Although they are not essential, it is often helpful to balance out the earth's magnetic field at least partially by a plurality of small permanent magnets 160 set in the outer wall of the portion of frame 18 included between shields 158 and 159. The coils 154 and 155 are connected electrically in series and their leads are brought out through the interior of tube 150 to slip rings 162 contacted by brushes 163, whence suitable leads extend to an amplifier and the recording system.

Also mounted on the tube 150 in a position to be shielded from the magnets 156, 157, and 160 is an inductor coil 165 rotatable by tube 150 about the coil diameter. The leads for this coil 165 may also be brought out through the tube 150, slip rings 162 and brushes 163.

The tooth ratio of gear 151 to 152 is preferably 1:2 so that the shaft of motor 22 rotates at exactly twice the speed of tube 150. Coupled directly to motor 22 is a small single-phase alternator 166 which therefore generates a current of twice the frequency of rotation of tube 150.

The circuit connections for this embodiment of my invention are shown in Figure 9. The coils 154 and 155 are connected to a filter 170 which preferably passes only a frequency equal to twice the frequency of rotation of shaft or tube 150, and in particular rejects that frequency equal to the rotation speed. The signal from this filter is then amplified by an amplifier 171 and passed

to one set of input terminals on a phase-meter or bridge 172. The other input to phasemeter 172 is taken from a double-pole double-throw switch 173 which connects either to the inductor 165 or the alternator 166. The output of inductor 165 is preferably fed through a frequency doubler 174. The signal from phasemeter 172 may be transmitted directly to the recorder for recording in correlation with depth, the log then being simply a trace varying according to the phase angle between the two voltages entering meter 172.

The operation of this embodiment of the invention can best be understood from Figures 8 and 10. Let it be assumed that the permeability is a maximum in the direction of the arrows 176 and a minimum in the direction at right angles thereto designated by the arrows 177. Then, as the coils 154 and 155 rotate, along with magnets 156 and 157, some of the flux from the latter will pass through the coils and enter the formations of well 11. Because of the greater permeability in the direction 176, more flux will pass through the coils when cross arm 153 points in this direction and less when it points at right angles, parallel to the arrows 177. These positions of maximum and minimum flux are reached twice for each revolution of the shaft 150, so that the induced voltage due to the permeability effect will have twice the frequency of rotation. On this basis it can be differentiated from the signal due to the rotation of coils 154 and 155 in the unbalanced portion of the earth's magnetic field, which will be the same as the frequency of rotation.

The graphs of Figure 10 will show this even more clearly. Adopting the arrow 178 (Figure 8) as the reference direction, the upper graph shows the assumed variation in permeability around the well 11. It varies from a maximum value of μ_2 at about $\pi/4$ to a minimum of μ_1 at $3\pi/4$, back to a maximum μ_2 at $5\pi/4$ and to a minimum μ_1 again at $7\pi/4$. As the voltage in coils 154 and 155 is proportional to the time rate of change of flux through them passing into the formations from magnets 156 and 157, it is represented by the lower graph, which, it will be observed, is displaced by a phase angle of $\pi/4$ from the permeability graph and has a frequency of twice the frequency of rotation of the coil-magnet structure.

As the direction of the horizontal component of the magnetic field does not vary greatly because it is largely due to induction rather than remanent magnetism, it is used as the reference direction when switch 173 is thrown to the upper position. Alternatively, when switch 173 is in the lower position the output of alternator 166, which has a directional sense because of the orientation of frame 18 by the gyro 21, is used as a reference signal. Either one is adequate to indicate the variations of the direction of anisotropy of the permeability in the different strata of a well.

The logs made in the practice of my invention are useful in many ways, for example, in direct correlation from well to well by the similarities of appearance of the logs, or for the preparation of master logs showing the attitude of the earth's magnetic field at the various times of deposition of the strata. Also, the data will be found highly useful in improving the accuracy of core-orienting procedures which rely on the remanent magnetism of cores for directional orientation.

Although in the case of the remanent mag-

netism it has been proposed to measure more than one component, i. e., the horizontal component and the dip, it will be appreciated that most of the advantages of the invention are retained if logs are made of only one component, such as the direction of the horizontal component.

While the invention has been described in terms of the foregoing specific embodiments thereof, it is obvious that many modifications will occur to those skilled in the well-logging art. The invention should therefore not be considered as limited solely to these specific embodiments but is best defined by the following claims.

I claim:

1. The method of logging wells which comprises the steps of measuring at a plurality of depths within a well the direction of the horizontal component of the earth's magnetism, said magnetism including flux due to both the induced and the remanent fields, measuring at a plurality of depths the dip of said magnetism, and recording separately the variations of said direction and of said dip as functions of depth.

2. The method of logging wells which comprises the steps of producing a first electrical signal varying with the direction of the horizontal component of the magnetic field in a well, said field being the resultant of both the induced and the remanent magnetism, producing a second electrical signal varying with the dip of said magnetic field, producing a third electrical signal varying with the strength of said field, and recording the variations in each of said signals as functions of depth.

3. The method of logging wells which comprises the steps of producing within a well a first electrical signal varying quantitatively with the direction of the horizontal component of a directional earth magnetic property, producing within said well a second electrical signal varying quantitatively with the strength of the magnetic field in the well, and recording the variations of each of said signals as functions of depth.

4. The method of logging wells which comprises the steps of, at the earth's surface, orienting a first elongated ferromagnetic core perpendicular to the earth's magnetic field and in a horizontal plane, orienting a second elongated ferromagnetic core perpendicular to the earth's magnetic field and in a vertical plane, passing said cores through a well while maintaining their orientations, and recording as functions of depth in said well the variations in flux traversing said cores longitudinally.

5. The method of logging wells which comprises the steps of, at the earth's surface, orienting a first elongated ferromagnetic core in a horizontal plane and perpendicular to one of the limiting directions expected of the varying horizontal component of the magnetic field in a well, orienting a second elongated ferromagnetic core in a vertical plane and perpendicular to one of the limiting directions expected of the varying dip of the magnetic field in said well, passing said cores through said well while maintaining their orientations, measuring the strength of the magnetic field in said well, and recording as functions of depth in said well said magnetic-field strength and the variations in magnetic flux traversing each of said cores longitudinally.

6. The method of logging wells which comprises the steps of exposing to the magnetic field of the formations of a well a plurality of saturable ferromagnetic cores arranged as the sides of a

polygon forming a plane of investigation, inducing additional periodic saturating fluxes in said cores, measuring the differences in said saturating fluxes in said cores due to the presence of flux from said formations therein, determining the resultant direction of said differences, measuring the total intensity of the magnetic field in said well formations, and recording as functions of depth in said well the variations of said resultant direction and said total intensity.

7. The method of logging wells which comprises the steps of impressing on the formations of a well at varying depths therein a constant flux while rotating the source of said flux about the axis of said well, intercepting a portion of said flux passing into said formations, producing an electrical signal varying with the amount of intercepted flux around said well, and recording in correlation with depth the variations in phase of that component of said signal having a frequency equal to twice the frequency of rotation of said source.

8. The method of logging wells which comprises the steps of impressing on the formations of a well at varying depths therein a constant flux while rotating the source of said flux about the axis of said well, intercepting a portion of said flux passing into said formations, producing an alternating electrical signal proportional to the variations in said intercepted flux around said well, said signal having a frequency equal to twice the frequency of rotation of said source, producing a second electrical signal by rotation of an inductor in the earth's magnetic field, doubling the frequency of said second signal, and recording the variation in phase between said alternating signal and said doubled second signal as a function of depth in said well.

9. The method of preparing well logs which comprises the steps of measuring as a function of depth in a well the direction of a component of the magnetic field therein, which measurement also varies with the strength of said field, measuring as a function of depth the strength of said field, and plotting in correlation with depth a quantity proportional to the quotient of the direction measurement and the field-strength measurement.

10. The method of preparing well logs which comprises the steps of measuring as functions of depth in a well the directions of a plurality of components of the magnetic field therein, which measurements also vary with the strength of said field, measuring as a function of depth the strength of said field, and plotting in correlation with depth a quantity varying with the quotient of each component direction measurement and the field-strength measurement at the corresponding depth.

11. Apparatus for logging wells comprising an instrument housing adapted for lowering into a well, a reference framework in said housing and movable relative thereto, means for maintaining said framework oriented in a fixed direction, means carried by said framework for producing a first electrical signal varying quantitatively with the direction of a directional magnetic property of well strata, means carried by said framework for producing a second electrical signal varying quantitatively with the strength of the magnetic field in the well strata, and means for recording the variations of each of said signals in correlation with depth in a well.

12. Apparatus for logging wells comprising an instrument housing adapted for lowering into a

well, a reference framework in said housing and movable relative thereto, means for maintaining said framework oriented in a fixed direction, at least one magnetic induction means carried by said framework and capable of varying an electrical signal in accordance with changes in direction of a magnetic-field component in a well, means for producing a second electrical signal varying with the magnetic-field strength in a well, and means for recording the variations of each of said signals in correlation with depth in a well.

13. Apparatus for logging wells comprising an instrument housing adapted for lowering into a well, a reference framework in said housing and movable relative thereto, means for maintaining said framework oriented in a fixed direction, means for producing a first electrical signal varying with the direction of the horizontal component of the earth's magnetic field, means for producing a second electrical signal varying with the dip of the earth's magnetic field, means for producing a third electrical signal varying with the strength of the earth's magnetic field, all of said signal-producing means being carried by said framework, and means for recording the variations of each of said signals in correlation with depth in a well.

14. Apparatus for logging wells comprising an instrument housing adapted for lowering into a well, a reference framework suspended in said housing and rotatable relative thereto, means for maintaining said framework oriented in a fixed direction, a plurality of coplanar saturable ferromagnetic cores mounted in said framework and defining a plane of investigation of a magnetic-field component, said cores being at least partially saturable by flux from the well strata, means on each core for inducing periodically an additional saturating flux therein, a pickup-coil means on said cores connected in opposition in pairs whereby voltages from said additional saturating fluxes tend to cancel out leaving residual voltages varying with the well strata flux in said cores, means for combining said residual voltages to produce a resultant field indicative of the strength and direction of said magnetic-field component, and means for recording variations in the strength and the direction of said component in correlation with depth in a well.

15. Apparatus for logging wells comprising an instrument housing adapted for lowering into a well, a reference framework suspended in said housing and rotatable relative thereto, means for maintaining said framework oriented in a fixed direction, two sets of saturable ferromagnetic cores mounted in said framework, each of said sets comprising a plurality of coplanar elongated cores defining a plane of investigation of a magnetic-field component, one of said sets being horizontal and the other in a vertical plane including the magnetic-field vector at the earth's surface, and each of said cores being at least partially saturable by flux induced therein from the well strata, means for inducing in each core an additional periodic saturating flux, pickup-coil means on said cores responsive to differences in said saturating flux in said cores due to the well strata flux therein, means for deriving from said pickup means resultant fields indicating the direction of the magnetic-field component in the plane of each set of cores, means for measuring the total magnetic-field strength in said well strata, and means for recording said total field strength and the variations in direction of said

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resultant fields for each set of cores in correlation with depth in said well.

16. Apparatus for logging wells comprising an instrument housing adapted for lowering into a well, a reference framework suspended in said housing and rotatable relative thereto, means for maintaining said framework oriented in a fixed direction, rotary means carried by said framework and adapted for rotation about the longitudinal axis of said framework, means on said rotary means for inducing an additional magnetic flux in well strata, pickup means on said rotary means adapted to intercept a portion of the flux passing to the well strata from said flux-inducing means, means for detecting an output from said pickup means having a frequency twice the frequency of rotation of the rotary means, and means for recording the phase of said output in correlation with depth in a well.

17. Apparatus for logging wells comprising an instrument housing adapted to be lowered into a well, rotary means in said housing rotatable about the longitudinal axis thereof, means on said rotary means for inducing an additional magnetic flux in the strata of a well, pickup means on said rotary means adapted to intercept a portion of

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the flux passing to the well strata from said flux-inducing means, means for detecting an output component from said pickup means having a frequency twice the rotational frequency of the rotary means, an inductor coil for producing an alternating voltage by rotation in the earth's magnetic field, and means for recording the phase angle between said pickup output and said alternating voltage in correlation with depth in a well.

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