

Dec. 9, 1941.

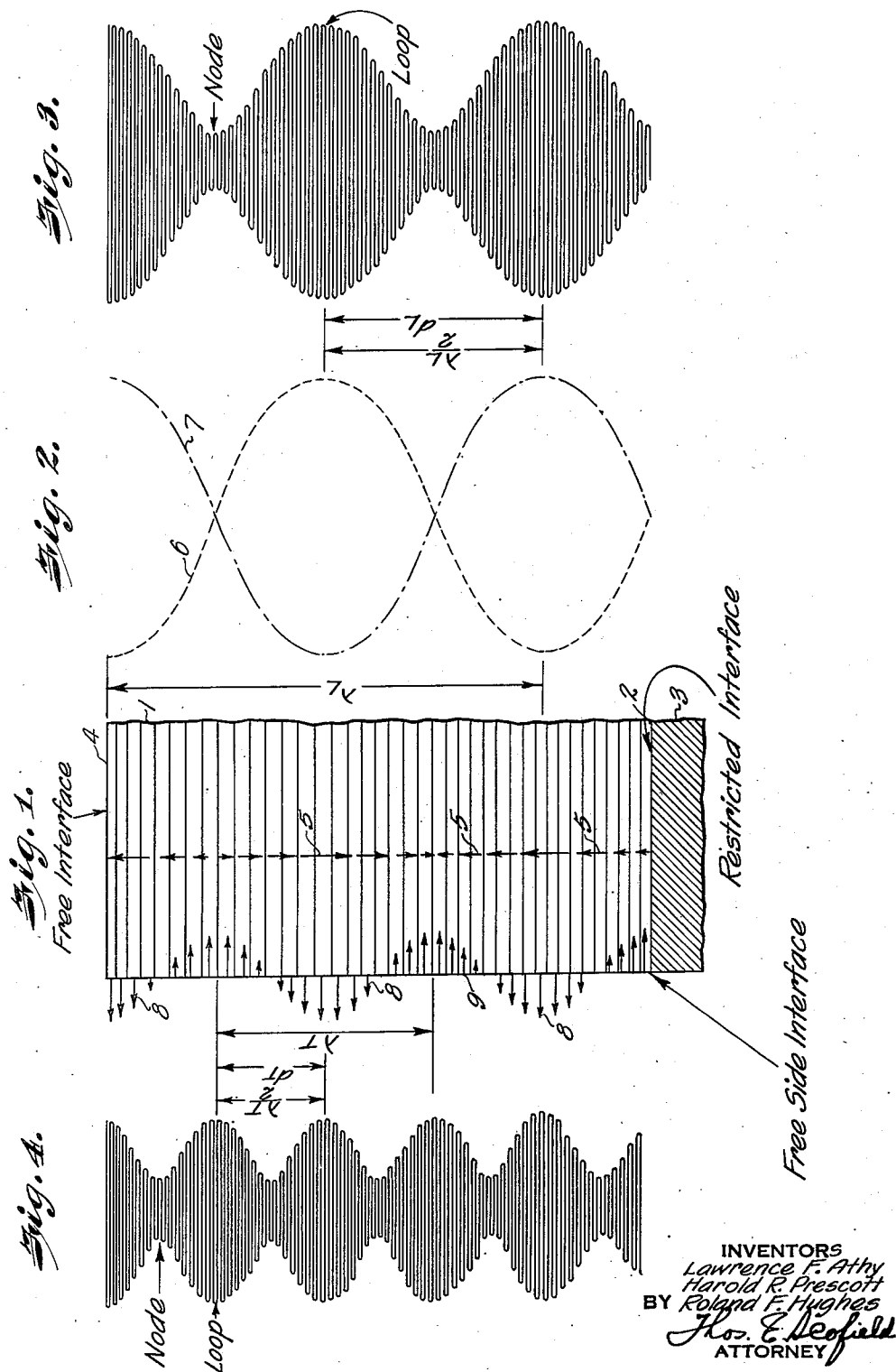
L. F. ATHY ET AL

2,265,768

METHOD OF LOGGING BORE HOLES

Filed July 20, 1940

6 Sheets-Sheet 1



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METHOD OF LOGGING BORE HOLES

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6 Sheets-Sheet 2

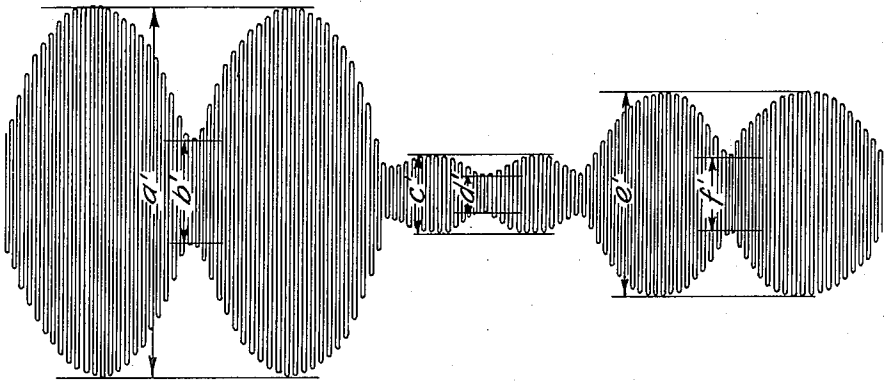


Fig. 7.

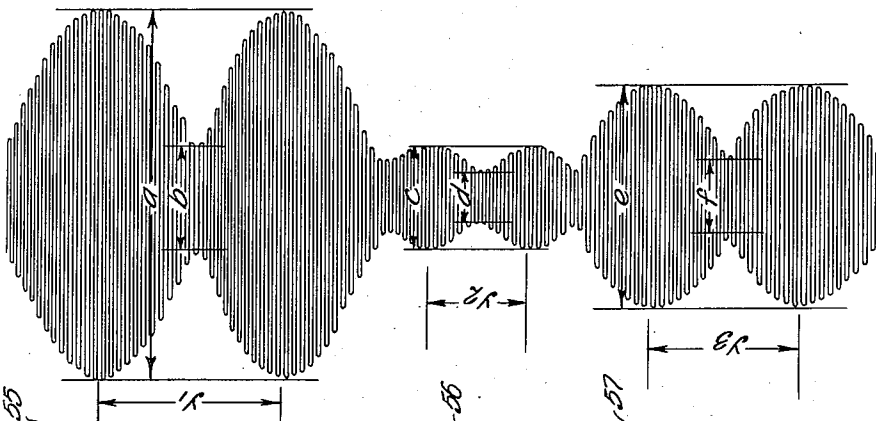


Fig. 6.

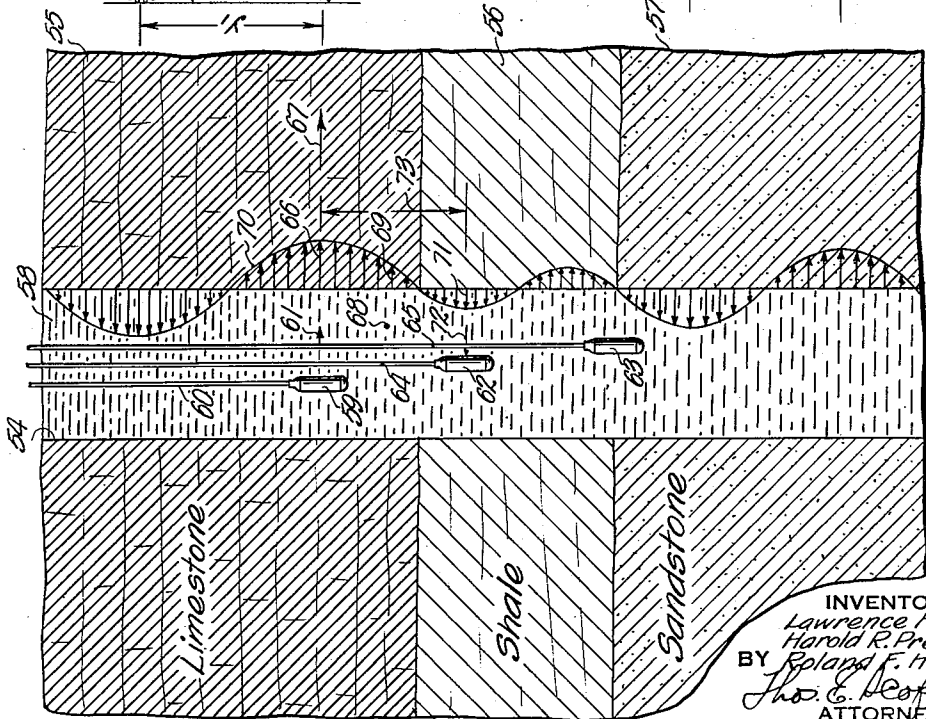


Fig. 5.

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6 Sheets-Sheet 3

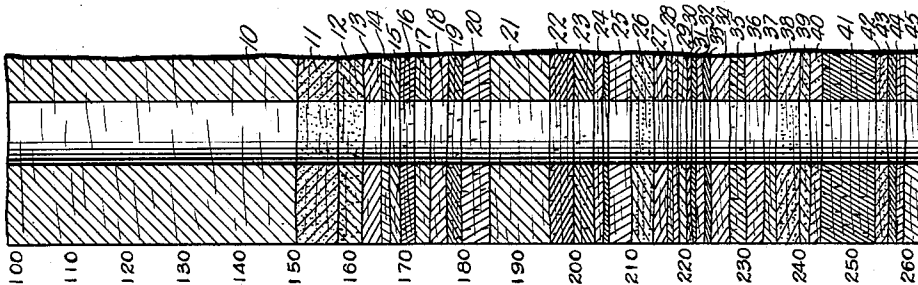


Fig. 8.

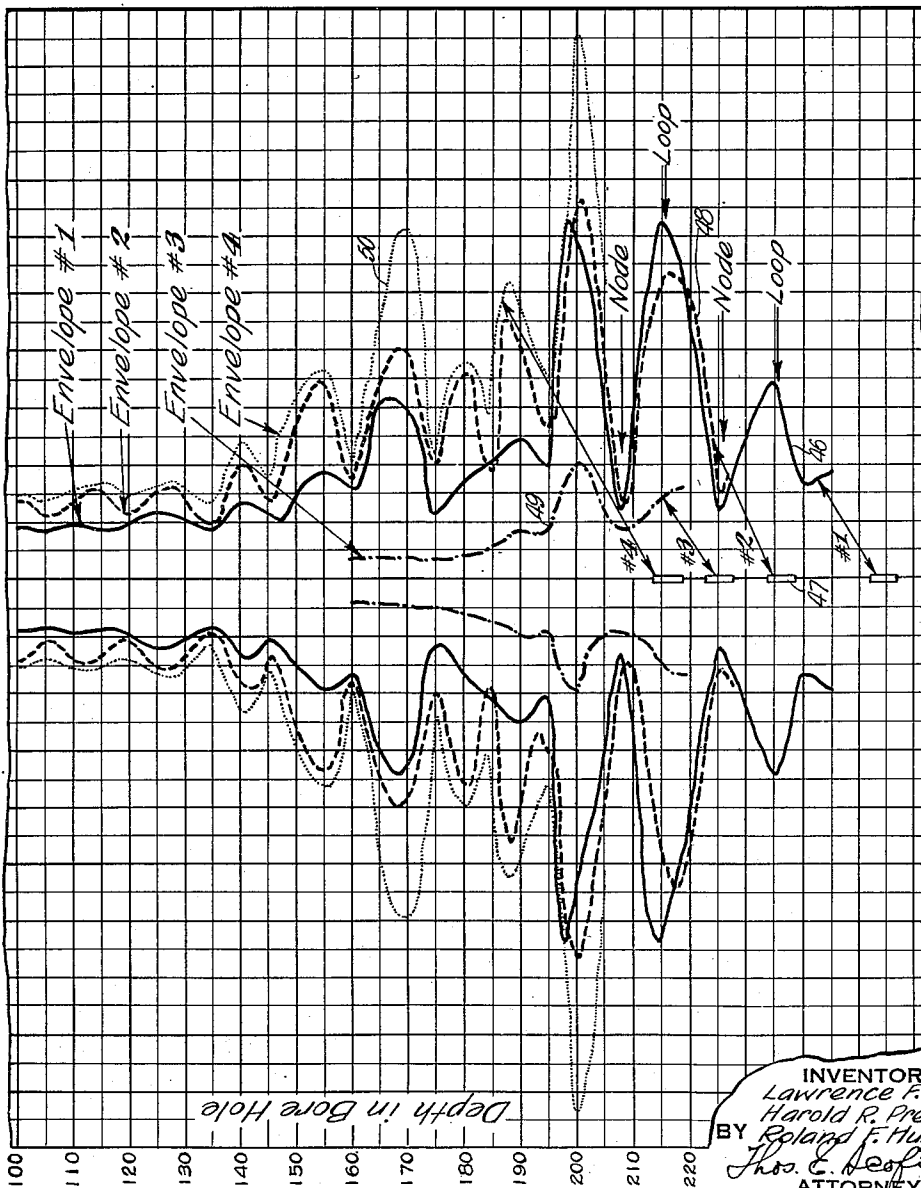


Fig. 9.

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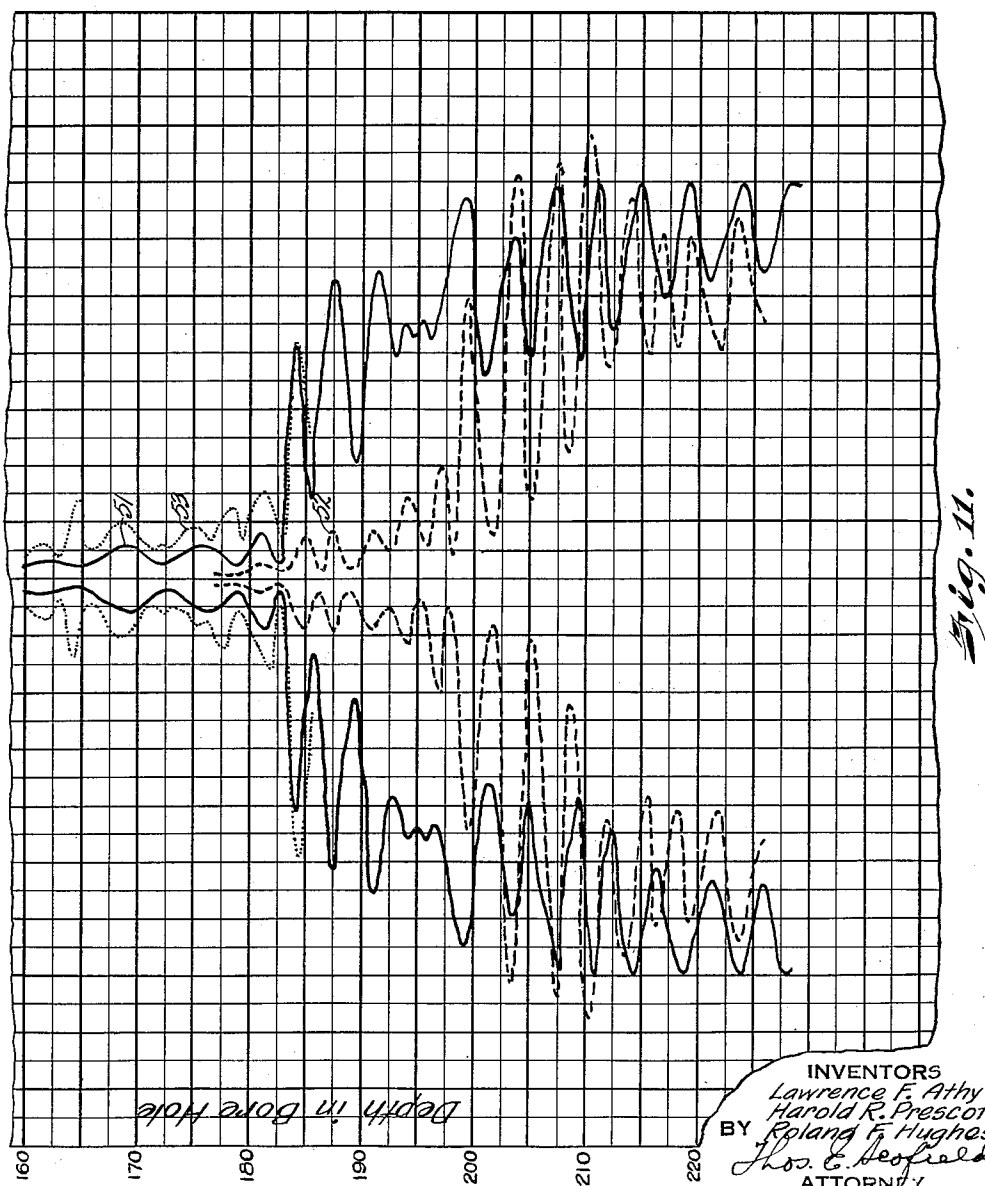
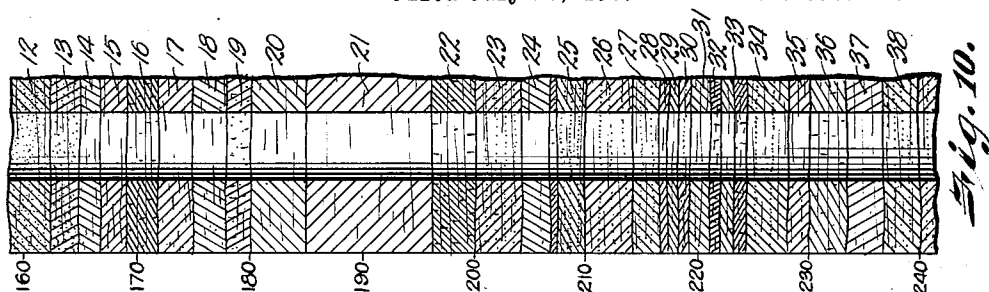
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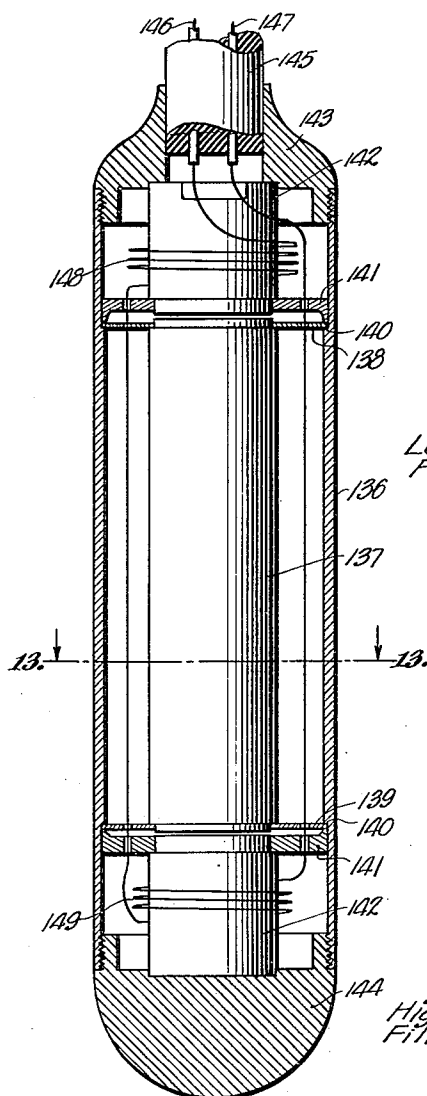


Fig. 12.

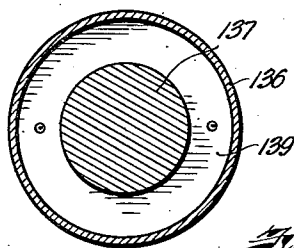


Fig. 13.

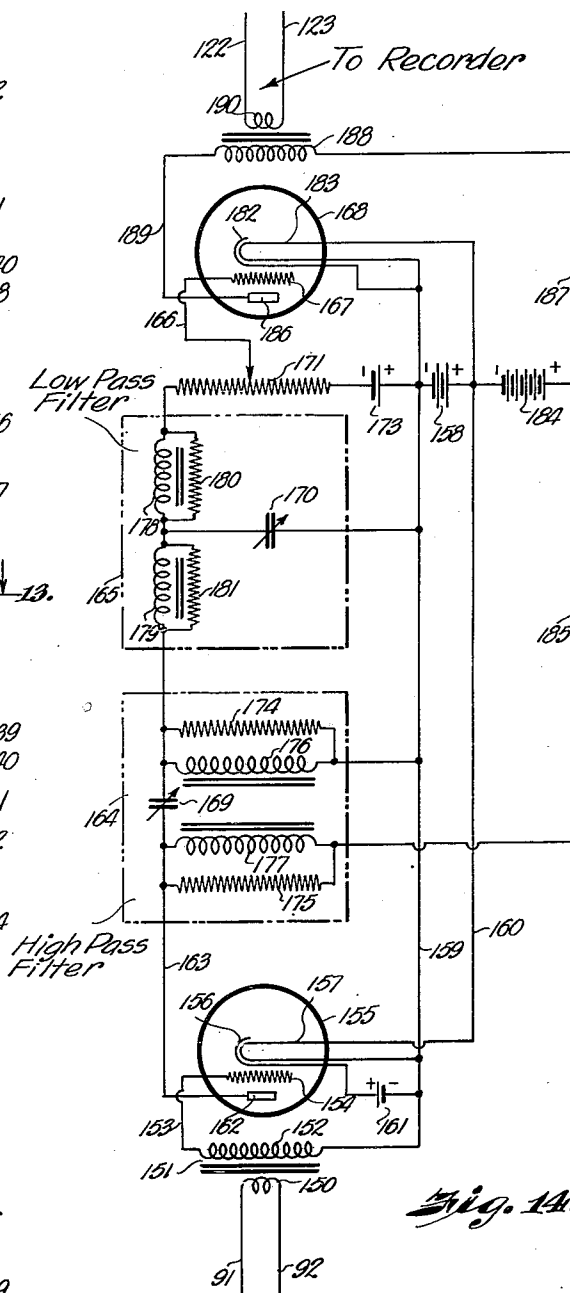


Fig. 14.

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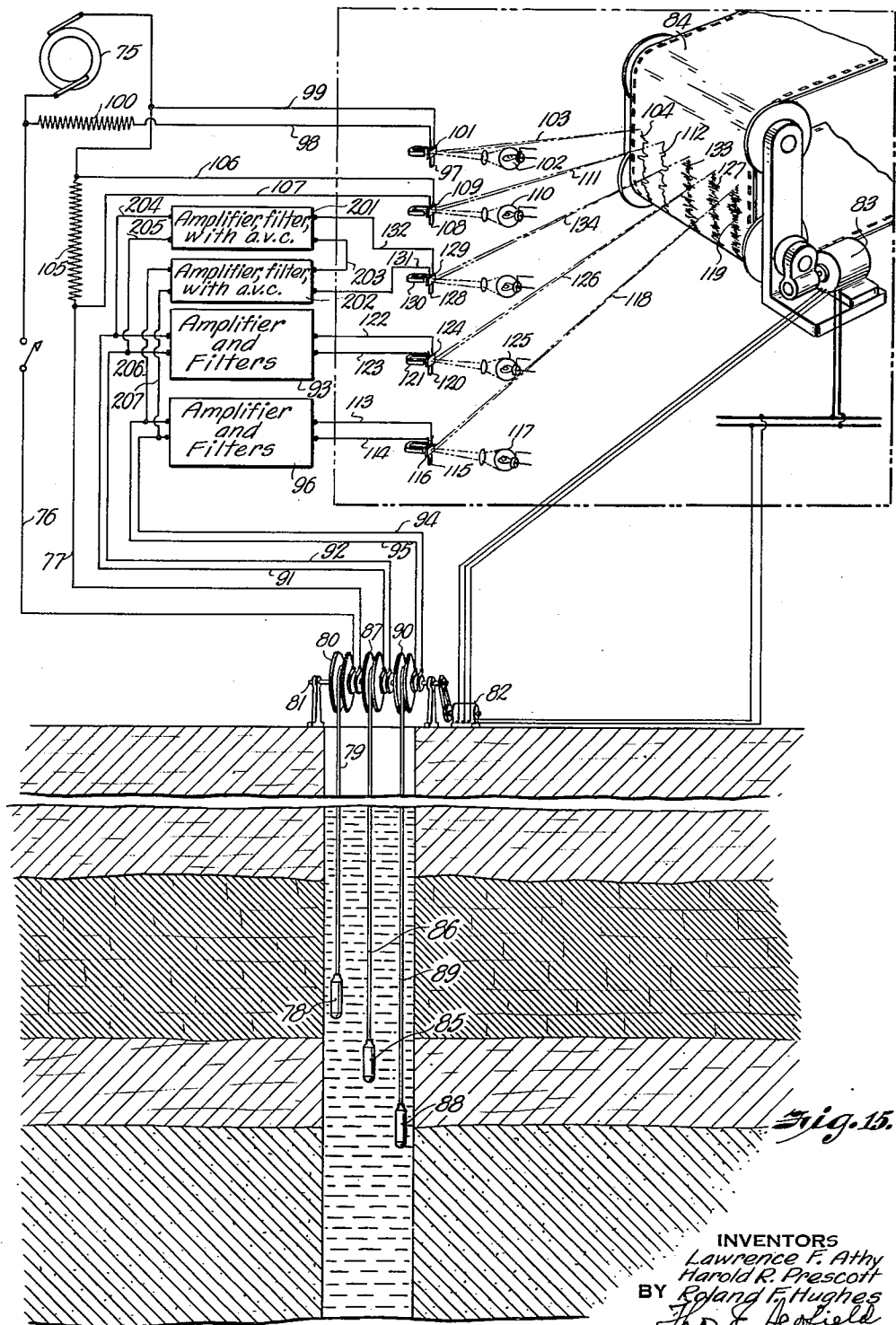
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METHOD OF LOGGING BORE HOLES

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6 Sheets-Sheet 6



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UNITED STATES PATENT OFFICE

2,265,768

METHOD OF LOGGING BORE HOLES

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Application July 20, 1940, Serial No. 346,608

19 Claims. (Cl. 181—0.5)

Our invention relates to a method of logging bore holes.

This application is a continuation in part of our co-pending applications, Serial Nos. 202,483, filed April 16, 1938, Patent No. 2,207,281, July 9, 1940, and 202,741 filed April 18, 1938.

More or less parallel beds of rock materials are pierced by bore holes drilled for exploratory purposes in seeking oil or gas. It is essential to prospectors to be able to recognize certain identifying characteristics of the beds penetrated in order that the geological structure of the buried formations may be accurately determined. This geological structure is a guide in seeking accumulations of oil, gas, or other valuable deposits. By recognizing and logging a sequence of identifying characteristics with respect to depth or sea level elevation in individual bore holes, it is possible to determine the relative structural attitude and position of the various rock formations contributing to these recognizable characteristics.

In geological explorations, core drilling has been resorted to in order to determine the characteristics of the beds penetrated. A record or log is kept showing the different formations traversed. This log is obtained by sampling the drill cuttings to determine their variation in mineral content or rock type. It is a common practice to sample the drill cuttings taken from bore holes and from a careful study of these cuttings to determine their variation of mineral content or rock type with depth or elevation and thereby provide a subsurface map of the structure of said buried formations. Commonly, holes are drilled to relatively shallow depths solely for purposes of determining the structure of the subsurface. In many areas it is impossible or difficult to correlate cuttings from one well with those of another, thereby rendering structural determination by this method ineffective. Sometimes actual cores or chunk samples of the various formations penetrated by the drill are taken in order that the beds may be recognized and correlated. This procedure is slow and expensive, and frequently necessitates deep drilling in order to penetrate recognizable marker beds which may be correlated from hole to hole.

One object of our invention is to provide a novel method and apparatus for logging bore holes, using standing waves.

Another object of our invention is to provide a method of logging bore holes by resonance methods in which the velocity of motion causing resonance may be logged, independent of phase velocity.

Another object of our invention is to provide a method of logging damping of resonance phenomena in various strata in the bore hole.

Another object of our invention is to provide a method which may be used simultaneously with the impedance method disclosed in our co-pending application, Serial No. 202,741.

Another object of our invention is to provide a method of logging resonance phenomena simultaneously with the phenomena disclosed in our co-pending application, Serial No. 202,741, and with the phase velocity method disclosed in our co-pending application, Serial No. 202,483.

Another object of our invention is to provide a method of logging bore holes utilizing transverse waves in addition to compressional or longitudinal waves.

Other and further objects of our invention will appear from the following description.

In the accompanying drawings which form part of the instant specification and are to be read in conjunction therewith and in which like reference numerals are used to indicate like parts in the various views;

Figure 1 is a diagrammatic view used in connection with the explanation of the theory of standing waves.

Figure 2 is a schematic view representing the instantaneous picture of the direction and magnitude of compressional or longitudinal waves in one position and a position one half wave length later in time.

Figure 3 is a schematic view of a log strip of amplitude of longitudinal waves placed opposite the position from which it was obtained.

Figure 4 is a diagrammatic view of a log strip of amplitude of transverse waves placed opposite the position from which it was obtained.

Figure 5 is a diagrammatic sectional view of a bore hole with an emitter and two receptors.

Figure 6 is a diagrammatic view of a log strip made by the upper receptor, the log strip being placed opposite the position from which it was obtained.

Figure 7 is a schematic view of a log strip of amplitudes received at the lower receptor, the log strip being placed opposite the position from which it was obtained.

Figure 8 is a cross sectional view of a bore hole taken between the depths of 100 feet and 260 feet.

Figure 9 is a drawing of envelopes of energy or amplitude logs made with the emitter at various positions in the bore hole.

Figure 10 is a cross sectional view of a bore

hole between the depths of 160 feet and 240 feet.

Figure 11 shows a plurality of superimposed reproductions of envelopes of energy or amplitude received in the bore hole shown in Figure 10 under varying conditions.

Figure 12 is a schematic cross sectional view of one form of emitter and receptor capable of use in carrying out our invention.

Figure 13 is a sectional view taken on the line 13—13 of Figure 12.

Figure 14 is a schematic view showing an amplifier capable of use in carrying out the method of our invention.

Figure 15 is a schematic view of a bore hole fitted with apparatus capable of carrying out the method of our invention.

Referring now to Figure 1, a slab 1 represents isotropic material having good elasticity with a lower interface 2 bonded to a firm foundation 3 such that it is greatly restricted and having a free interface 4 at the top. It will be clear that, since the bottom is restricted, the motion at the restricted interface will be at a minimum and that, since the top interface 4 is free, that this surface will have maximum motion.

If a motion of proper frequency is impressed upon the slab 1 it will resonate. The waves in slab 1 will be of complex nature, consisting of a longitudinal or compressional component, and of a transverse component—also possibly of other more complex components. The arrows 5 represent an instantaneous picture of a direction and magnitude of the compressional or longitudinal waves. This picture may be represented by the sine curve 6. The sine curve 7 represents the instantaneous picture of longitudinal waves one half wave length later in time from the situation shown by curve 6. The wave length of motion of the longitudinal waves is shown in Figure 2 by a symbol λ_L .

If a system responsive to longitudinal waves is lowered through the slab 1, the log strip shown in Figure 3 will be obtained in which the distance d_L between nodes or loops is one half the wave length, that is

$$\frac{\lambda_L}{2}$$

Regardless of the position at which excitation energy of a constant frequency is delivered to the slab 1 or the position at which the energy is received, the position of the nodes and loops will remain fixed. The position of the nodes and loops should not be confused with their magnitude. While the position of the nodes and loops will remain fixed, the magnitude of the nodes and loops will depend upon the position at which excitation takes place. If the slab is excited at a node, the magnitude will be small. If the slab is excited at a loop, the magnitude will be large.

The velocity of the longitudinal waves, V_L may be represented by the expression:

$$V_L = \lambda_L f = 2d_L f$$

The velocity, V_L will be referred to as the "resonance" longitudinal velocity to distinguish it from the "phase" velocity described in our co-pending application Serial No. 202,483.

The transverse component of the wave in slab 1 travels in a direction at right angles to the direction of motion of the individual particles of slab 1 as indicated by the arrows 5 in Figure 1. The velocity of the transverse wave is lower than that of the longitudinal wave. This fact is well known. The arrows 8 drawn on Figure 1

in a direction at right angles to the arrows 5 represent the instantaneous motion of these transverse waves. The wave length λ_T of the transverse wave motion is less than the wave length λ_L of the longitudinal wave motion. If a system responsive to transverse waves is lowered along the lateral interface, the log strip shown in Figure 4 will be obtained in which the distance d_T between nodes or between loops is one half the wave length,

$$\frac{\lambda_T}{2}$$

The velocity of the transverse waves, V_T may be represented by the expression: $V_T = \lambda_T f = 2d_T f$.

The velocity of the transverse waves V_T will be referred to as the "resonance" transverse velocity.

If a bore hole passes through the slab 1, and a responsive system is lowered into it changed conditions exist because the system is in contact with the bore hole fluid instead of the material of slab 1. Because it has no shear rigidity, the bore hole fluid itself cannot sustain the transverse wave. However, the energy of the transverse wave, or more complex wave, which exists in the slab near the walls of the bore hole can be transferred to the responsive means through the short fluid path between the walls of the hole and the responsive means. In this short fluid path the energy undoubtedly is transferred as a compression wave. Hereafter we shall present experimental proof that the energy of such a transverse wave, or more complex wave, actually is transferred in this manner and that the characteristics observed are different from the characteristics of longitudinal waves. Hence we say that the case discussed for transverse waves approaches the case wherein the material is pierced by a bore hole, as must be actually done.

In an actual case, where a bore hole pierces various geological strata of non-isotropic media, of various thicknesses, various hardnesses, and various velocities, the theoretical case shown in Figure 1 does not strictly apply for the reason that there are no completely free interfaces and no completely restricted interfaces. However, it is to be observed that the walls of the bore hole, although in contact with the bore hole fluid, give a fairly good case approaching the free side interface. A strict and comprehensive theoretical treatment of the various phenomena involving compressional waves, transverse waves, reflections from interfaces, reflections from walls of the bore hole, and involving multiple reflections including various paths involved, is very difficult and quite beyond the scope of this specification.

In spite of the fact that the theoretical case of Figure 1 does not strictly apply, the fundamental ideas there represented are useful and we have found that a close approximation to the theoretical phenomena is observed under the complicated conditions in a bore hole.

Referring now to Figure 8, we have shown a section of an actual bore hole between 100 feet and 260 feet. The layer 10 comprises chiefly dark maroon calcareous clay shale containing some sharp limestone fragments. The layer 11 was very fine grained sandstone with paper-thin laminations of maroon clay shale. The layer 12 comprised fine to medium grained sandstone with paper-thin laminations of gray shale. The sandstone was somewhat calcareous. The layer 13 was of dark gray to gray shale, some of which was slightly calcareous. The layer 14 was dark

gray and gray to greenish gray shale. The layer 15 comprised greenish gray calcareous shale, grading to mottled brown and greenish gray calcareous shale. The layer 16 is composed of a light gray to white, finely crystalline limestone. The layer 17 comprised mottled brown and ochre to greenish gray shale. The layer 18 was composed of gray, slightly calcareous fossiliferous shale, grading to mottled gray and greenish gray calcareous shale. The stratum 19 was composed of finely laminated, light green calcareous shale and crystalline limestone, grading to dark gray, calcareous shale having thin streaks of sandstone. The layer 20 is finely laminated, dark gray shale and buff to white finely crystalline shaley limestone grading to gray, greenish, calcareous shale. The stratum 21 is maroon, slightly calcareous shale with occasional limestone concretions.

The layer 22 is composed of grayish green calcareous shale, grading to light gray, finely crystalline marl, which was very fossiliferous grading to finely, then coarsely crystalline limestone containing some shale fragments. The layer 23 was lavender, maroon and ochre, varicolored finely crystalline shaley limestone. The layer 24 was composed of maroon shale. The stratum 25 was varicolored shale interbedded with thin layers of fine grained sandstone grading to fine grained calcareous sandstone interbedded with varicolored shale grading to white, fine to medium grained, slightly calcareous sandstone. The stratum 26 was composed of greenish gray fossiliferous shale interbedded with thin layers of fine grained sandstone. The layer 27 was composed of gray to greenish shale with occasional interbedded thin layers of sandstone. The layer 28 was gray shale, very fossiliferous in its nature. The layer 29 was composed of greenish gray shale, somewhat carbonaceous and containing streaks of sandstone. The layer 30 was composed of gray calcareous fossiliferous shale. The layer 31 was composed of gray, medium crystalline fossiliferous limestone, shaley in the middle part. The layer 32 was gray to greenish gray shale with occasional thin layers of sandstone. The layer 33 comprised gray limestone grading to gray calcareous, fossiliferous shale. The layer 34 was gray shale with occasional thin sandstone streaks. The layer 35 comprised gray medium crystalline shaley fossiliferous limestone, grading to shale. The layer 36 was gray fossiliferous shale, grading to gray medium crystalline shaley limestone. The stratum 37 was interbedded gray shale and limestone, grading to resinous gray, medium crystalline fossiliferous limestone. The layer 38 was fine to medium grained angular sandstone, very porous in its nature, grading to white fine to medium grained, slightly calcareous sandstone. The layer 39 was fine grained, calcareous sandstone, slightly carbonaceous with shale grading to dark gray shale interbedded with thin sandstone streaks. The layer 40 was composed of gray medium crystalline limestone, somewhat shaley and grading to same with streaks of dark gray shale. The layer 41 was gray, finely crystalline, fossiliferous limestone, some shaley, fusulinidae abundant. The layer 42 was gray shale interbedded with hard gray, fine grained calcareous limestone, grading to gray shale with occasional limestone streaks. The layer 43 was gray, finely crystalline, fossiliferous limestone, interbedded with gray shale. The layer 44 was gray, carbonaceous shale. The layer 45 was composed of maroon shale mottled to light gray.

To determine the various phenomena for an actual case, test logs were obtained in the bore hole shown in Figure 8.

Figure 9 shows a superimposed reproduction of the envelopes of the amplitude received in the bore hole 8. A frequency of 100 cycles was used for this series of tests.

First an emitter of continuous 100 cycle energy was lowered to a depth of 254 feet and held constant for the test. A receptor responsive to 100 cycle energy was raised from the starting point 245 feet and a continuous log strip of amplitude of motion obtained as it traversed the bore hole. A reproduction of the envelope is represented by the curve 46 in Figure 9.

Next, the transmitter was raised to position #2, indicated by the reference numeral 47 in Figure 9 and held fixed for the second test. It is to be observed that, at 237 feet, a loop occurred as shown by envelope 46.

For the second test, the receptor was started at 225 feet and a continuous log of the amplitude of motion was obtained as it traversed the bore hole. A reproduction of this envelope is shown in Figure 9 by the curve 48.

Next the transmitter was raised to 225 feet at position #3 and held fixed for the third test. It is to be observed that, at 225 feet a node occurred as shown by both envelopes 46 and 48. For this third test, the receptor was started at 220 feet and a continuous log strip of the amplitude of motion was obtained as it traversed the bore hole. A reproduction of this envelope is shown by the curve 49. It will be observed that the level of the amplitude received was greatly lessened when the transmitter was placed at the node.

In the fourth test, the transmitter was moved to position #4 in Figure 9, where a loop occurred. For the fourth test, the receptor started at 205 feet and a continuous log strip of the amplitude of motion was obtained as the receptor traversed the bore hole section. A reproduction of the envelope is shown in Figure 9 as envelope 50.

It will be observed that, while the transmitter was held at the loop at 217 feet, the amplitude received as indicated by envelope 50 was large overall. The four envelopes thus obtained are superimposed in Figure 9 and the following facts will be appreciated:

1. Regardless of the position of the transmitter or of the receptor, the position of the nodes and loops remain substantially fixed in the bore hole so long as the frequency is held constant.

2. The overall amplitude of motion in the bore hole will be less when the transmitter is placed at a node and greater when it is placed at a loop.

3. The distance between nodes or the distance between loops in slow velocity material is less than in high velocity material. This is apparent by comparing Figures 8 and 9, Figure 9 being placed opposite the layers in Figure 8, which produce the nodes and loops.

4. The ratio of amplitude between loops and nodes is greater in lime sections than in shale sections; that is, there is less damping in lime sections than there is in shale sections.

5. Nodes and loops of standing waves are clearly set up throughout the various strata tested at the one frequency of 100 cycles. This is true, even though theoretical reasons indicate that a given strata with its own elasticity, density, and dimensions, should respond more prominently at a given frequency only.

To determine for an actual case in a bore hole what effect a change in frequency has, a second

series of tests were conducted in the same bore hole, a section of which between 160 feet and 240 feet is reproduced on a somewhat larger scale in Figure 10. The reference numerals indicate the same layers described in connection with Figure 8.

Figure 11 is a superimposed reproduction of envelopes of the individual test records made in a similar fashion to that described for Figure 9, employing a frequency of 480 cycles per second. Envelope 51 is a reproduction of the amplitude received at receptor with the transmitter moving and the receptor held fixed at 260 feet. Envelope 52 is a reproduction of the amplitude received at receptor with transmitter held fixed at 230 feet. Envelope 53 is a reproduction of amplitude received at receptor with transmitter or emitter held fixed at 190 feet with the receptor moving.

In all curves, the depth scale refers to position of the removing element.

It will be apparent from the curves that the facts observed from the curves shown in Figure 9 still hold true and that a further fact is apparent namely that the distance between nodes or the distance between loops lessens as the frequency increases.

It will be clear to those skilled in the art that the theoretical considerations discussed with respect to Figures 1 to 4 in conjunction with the actual phenomena observed, as shown in Figures 8, 9, 10 and 11, conclusively demonstrate that the resonance effect or standing waves, with their characteristics, may be used to indicate the physical properties of strata pierced by bore holes, thus enabling us to correlate bore holes in a simple, convenient, accurate and expeditious manner.

When carrying out our invention in practice, by means of our resonance method, it is desirable to have several nodes and loops in the thinnest strata which it is planned to log and identify. Sometimes this involves the use of fairly high frequencies in the order of 1,000 to 2,000 cycles per second, if the waves utilized have the velocity of compressional or longitudinal waves.

Since transverse waves have less velocity than longitudinal waves, a transmitter and receptor system responsive to and arranged to utilize the transverse waves, may employ lower frequencies and still have as many nodes and loops as desired in the thinnest strata it is planned to log.

From actual observations in the bore hole shown in Figures 8 and 10, we have found in the shale sections of the bore hole that the transverse waves have a velocity of about one-half that of the longitudinal waves. Accordingly, apparatus may be employed having a range of 500 to 1,000 cycles per second, thus simplifying the problem over the use of apparatus in a 1,000 to 2,000 cycle range.

There is another important advantage gained from the employment of transverse waves. With compressional waves, the bore hole fluid conducts the waves regularly "in parallel" with the conduction of those waves through the strata themselves. Although it is true that the cross section of the hole is small compared with the cross sections of the various strata which conduct the waves, still it is highly desirable to minimize this conductivity, if possible, if proper relationship is to appear on the log strip between strata traversed.

It is well known that transverse waves cannot, theoretically, travel in fluid because of the lack of rigidity of fluids to shear forces. This means

that, if transverse waves are utilized, they will have passed through the strata surrounding the borehole rather than through the borehole fluid. The use of transverse waves is, in the practical case, an appreciable help in this respect, though not a complete cure, for the reason that complex conditions exist in a bore hole, with the interface at the walls and various interfaces between strata, all of which tends to translate transverse wave motion into components, some of which can travel in the fluid.

In our preferred apparatus for carrying out our invention, the transmitter delivers harmonic energy to the stratum opposite the transmitter through the medium of the bore hole fluid. The construction of an emitter discourages harmonic vertical compressional waves in the fluid in favor of lateral harmonic waves in the strata. Transverse waves having nodes and loops are set up near the walls of the bore hole and extending back into the virgin strata. The transverse waves, after traveling through the strata intervening between the stratum opposite the emitter and the stratum opposite the receptor, exhibit characteristics opposite the receptor which are an index of the strata through which they traveled. The transverse wave motion at the bore hole interface sets up wave motion in the fluid. The receptor will respond to the fluid motion set up from the stratum opposite the receptor. In this manner, a large portion of the energy which arrives at the receptor to which it is responsive has traveled through geological strata and not the bore hole fluid.

This will be more clearly understood by reference to Figures 5, 6, and 7. In Figure 5, the bore hole 54 passes through a limestone stratum 55, a shale stratum 56 and a sandstone stratum 57, and contains a bore hole fluid 58. An emitter 59 is supplied a harmonic potential at a fixed frequency through a cable 60 so that the emitter 59 will emit harmonic vibrations. The construction of the emitter is such that the vibrations travel principally in a lateral direction as indicated by the arrow 61. At suitable distances below the emitter 59 are positioned receptors 62 and 63. These receptors are responsive to vibrations which come to them in a lateral direction from the stratum opposite them through the bore hole fluid. The receptors are such that vibratory energy is converted into electrical energy, in sympathy therewith, which energy is conducted respectively by cables 64 and 65 to suitable amplifying, filtering and recording apparatus, which will be hereinafter more fully described.

An instantaneous conception of the compressional wave which the transmitter delivers to the fluid is indicated by the arrow 61. When this compressional wave strikes the bore hole interface, a small part of the energy will be reflected laterally but a large part will enter the limestone stratum 55 as indicated by the arrow 66. Later in time the compressional wave has traveled laterally in the limestone stratum as indicated by the arrow 67.

Referring again to the lateral compressional wave 61, although it does transmit compressional movement as indicated by arrows 66 and 67, a particle of water at position indicated by the reference numeral 68 cannot obtain any lateral motion from the wave 61 for the reason that there is no rigidity in the fluid to this shear force at 61, as will be understood by those skilled in the art.

However, after a compressional wave force, as indicated by the arrow 61, has been established in the limestone stratum 55, which does have a rigidity to shear forces, a different situation exists. When a compressional wave exists in the stratum as indicated by the arrow 66, the rigidity to shear causes a component indicated by the arrow 69 to move in sympathy with the compressional wave indicated by the arrow 66.

This sets up a wave motion which travels outwardly at right angles to the compressional wave at 66 and 67. This right angle wave is called the transverse wave and travels at less velocity than the compressional wave. These transverse waves exist back within the virgin part of the stratum as a result of the compressional wave at 66 and 67 passing out laterally. One place at which the transverse waves express themselves is as shown by the curve 70 which is an envelope of the instantaneous picture of the motion at and near the bore wall interface.

We have already shown that the fluid itself will not carry transverse motion to the receptor from the lateral compressional wave 61. Now if the transmitter is designed such that very little compressional waves are set up or if the receptor is made such that it is substantially non-responsive to vertical compressional waves which do travel in the fluid, and if the supporting cables 60, 64 and 65 are designed to carry very little energy from the transmitter to the receptor, then the only waves to which the receptor can respond are those in the stratum directly opposite the receptor.

Referring again to Figure 5, the transverse wave motion in the shale stratum 56 is represented by an arrow 71. This motion causes a compressional wave in the fluid represented by the arrow 72 which carries to the receptor 62. The receptor is designed to be primarily responsive to the movement represented by the arrow 72.

From the foregoing, it will be clear that the characteristics of the wave motion arriving at the receptor 62 have been primarily influenced by the section represented by the reference numeral 73 in Figure 5, for the reason that the distance between the transmitter 59 and the receptor 62 is large compared to the fluid path from the wall of the bore hole to the transmitter or receptor.

As the assembly comprising the transmitter and receptors is lifted or lowered, the receptors 62 and 63 will receive the nodes and loops existing opposite respective receptors. Figure 6 shows a log strip of the amplitude arriving at receptor 62 and Figure 7 is a log strip of the amplitude of energy arriving at receptor 63.

In general, it will be necessary to use an amplifier having a somewhat greater gain for amplifying the energy received by receptor 63 than that for amplifying the energy received by receptor 62 in order to obtain sufficient amplitude dimensions for proper recording.

We find that, for the frequency range between 100 and 1,000 cycles per second, in which we prefer to operate, that limestone carries the wave energy at these frequencies quite well. Sandstone is not quite so good a conductor of energy of this range, while shale is a poor conductor of energy lying within this range.

Referring to Figure 6, we find that the amplitude a is the largest, the amplitude e somewhat less, and the amplitude c appreciably smaller. Likewise, referring to the log strip shown in

Figure 7, we find that the amplitude a' is the largest, the amplitude e' somewhat less, and the amplitude c' appreciably smaller.

As indicated above, the "resonance" velocity of the transverse waves can be computed from a knowledge of the distance between nodes or between loops; that is y_1 being the greatest has the greatest "resonance" velocity; y_3 is less than y_1 and has an intermediate "resonance" velocity, while y_2 indicates the smallest "resonance" velocity.

It will be observed that limestone, sandstone and shale are respectively materials of decreasing hardness and would, therefore, be expected to have decreasing "resonance" velocity, the harder material having the greater "resonance" velocity.

The log strips, Figure 6 and Figure 7 yield other useful and pertinent information regarding the strata traversed. The ratio of a to b , that is, the ratio between the amplitude of the loop and the amplitude of a node for limestone is greatest, showing the least damping of the resonance phenomena. The ratio of the amplitude of the loop e to the node f is intermediate for sandstone, showing intermediate damping. The ratio of the loop c to the node d for shale is still less, indicating maximum damping.

Since the receptor 63 is a greater distance from the transmitter 59 than the receptor 62, data becomes available to determine the rate of amplitude decay, that is attenuation of the wave motion with distance. In other words, the ratio of a to c from the log strip in Figure 6, may be compared with the ratio of a' to c' from the log strip shown in Figure 7 to obtain an index of attenuation of amplitude with distance.

As has been pointed out above, it is desirable to use a frequency sufficiently high to obtain enough nodes and loops in the thinnest strata to be located and identified to avoid confusing a node between two large loops as a thin bed of shale having poor conductivity to the transverse waves.

To prove experimentally the feasibility of employing transverse waves in bore holes, a series of tests were carried out.

We first determined the velocity of the longitudinal or compressional waves by the use of explosives. Explosives were detonated at various places in the bore hole and the first arrival impact of the longitudinal wave was recorded at receptors variously spaced in the bore hole. In this manner, we found that the velocity of compressional waves in the shale section of the bore hole was about 6,700 feet per second, while the velocity of the compressional waves in the limestone sections was higher.

Referring now to Figure 9, where a frequency of 100 cycles was used, we found a distance of about 15 feet between nodes (or loops) in the shale section lying between 110 feet and 140 feet. Using the formula outlined above; we find that, $V = 2\pi \text{ distance between nodes} \times f = 2 \times 15 \times 100 = 3,000$ feet per second. This velocity is definitely not that of the compressional waves but is reasonable for transverse waves. In a log obtained by using a frequency of 480 cycles in the shale section lying between 110 and 140 feet we found that the distance between loops was about 3 feet. Applying the formula above, we obtain, $V = 2 \times 3 \times 480 = 2,880$ feet per second.

The above substantiates the fact that the waves producing the energy were not longitudinal.

Further work was done in the same shale section with a frequency of 750 cycles per second. The spacing of the loops was found to be in the

order of 2 feet. Applying the formula, we obtain, $V=2 \times 2 \times 750=3,000$ feet per second.

Here we obtain another confirmation of the fact that transverse waves are utilized.

In another test, one receptor was held fixed in the bore hole at 150 feet which was the bottom of the shale section. A transmitter and a receptor with a spacing of $11\frac{1}{2}$ feet between them were moved as a unit up the bore hole as the record was taken. Connected with each receptor was an amplifier system, such as shown in our application Serial No. 202,483, capable of holding the output amplitude substantially constant regardless of variation of amplitude received at the receptors. The output of the two amplifiers was connected to a single oscillograph element in such manner that the amplitude of the resulting trace indicated phase changes. That is, the maximum required points occur when the motions at the receptors are in phase, and minimum when the motions of the receptors are out of phase. This is fully described in our co-pending application, Serial No. 202,483.

It will be clear that the distance between two maximum or between two minimum points is one wave length of the motion involved. We found this wave length to be 6.1 feet, which corresponds to a velocity of, $V_T=6.1 \times 480=2,928$ feet per second.

The above test gives additional confirmation that the waves recorded were transverse waves.

Since the wave length in the shale section at 480 cycles is 6 feet, the distance between loops should be 3 feet at this frequency. This we found to be the case.

Further actual log strips were taken in adjacent bore holes in which the geological logs were well identified. A frequency of about 750 cycles was employed. An emitter and two receptors such as shown in Figure 15 were used in each bore hole.

Referring now to Figure 15, an alternating current generator 75 supplies electric current at a constant frequency. This frequency is impressed by conductors 76 and 77 upon the emitter 78 through a cable 79 and suitable brushes. The cable 79 is normally wound about a reel 80 mounted on a shaft 81 and rotated by suitable means. A self-synchronous motor 82 is driven by the shaft 81 and is interconnected with a second self-synchronous motor 83 which drives a photosensitive strip 84 as a function of the movement of the emitter 78. A receptor 85 is supported by a cable 86 wound about a reel 87. The reel 87 is secured to the shaft 81 so that it turns with the reel 80 in such fashion that a predetermined spacing is maintained between 78 and 85. Similarly, the receptor 88 is supported by a cable 89 wound about a reel 90, mounted on the shaft 81 for movement along with reels 80 and 87. The receptors 85 and 88 will be more fully described hereinafter and are adapted to convert wave motion into electrical energy which is conducted through the cables. Through suitable brushes the output of the receptor 85 is impressed through conductors 91 and 92 upon the amplification and filter channel indicated diagrammatically by the reference numeral 93. In similar manner, the output of the receptor 88 is impressed by conductors 94 and 95 upon the amplification and filter channel 96. The instantaneous voltage of the alternating current generator 75 is impressed across the galvanometer loop 97 by conductors 98 and 99 through a resistance 100. A mirror 101 carried by the loop 97 is adapted to reflect a light beam from the

incandescent lamp 102 along the path 103 to form the trace 104 which is a trace of the voltage produced by the generator 75. A resistance 105 is placed in one of the leads going to the emitter. Conductors 106 and 107 across this resistance are connected to a galvanometer loop 108. The voltage drop across the resistance 105 will be a function of the current so that the current passing through the galvanometer loop 108 will be a function of the current flowing to the emitter. Galvanometer loop 108 carries a mirror 109 adapted to reflect light from incandescent lamp 110 along the path 111 to form the trace 112 which is a trace of the current delivered to the emitter 78. The motion received by receptor 88 is converted by the receptor into electrical impulses in sympathy with the motion received, and these electrical impulses are transmitted through cable 89 which is wound on drum 90, through suitable brushes, through conductors 94 and 95, through the amplifier and filter assembly 96, through conductors 113 and 114 to the galvanometer wire 115. The galvanometer wire carries a mirror 116, upon which is focused a light beam from incandescent light 117. This light beam is reflected by the mirror 116 along the path 118 upon photosensitive strip 84, and produces trace 119. Similarly, the output of the amplifier 93, which amplifies electrical impulses generated by receptor 85, is impressed upon galvanometer loop 120, positioned within the field of permanent magnet 121 through conductors 122 and 123. The galvanometer element 120 carries a mirror 124 upon which is focused light from incandescent lamp 125 for reflection along the path 126 upon the photosensitive strip 84 to produce trace 127. The trace 127 is produced by the wave motion at receptor 85. The trace 119 is produced by the wave motion at receptor 88.

In order to provide means for indicating the relative phase changes of the harmonic motion received at receptors 85 and 88, we provide an arrangement in which two additional amplifiers 201 and 202 have their output terminals connected through conductors 131, 132 and 203 in series with a single oscillograph element 128 carrying mirror 129 and positioned in the field of magnet 130. Amplifier 201 is connected in parallel with amplifier 93 by conductors 203 and 205 which are joined to conductors 91 and 92 respectively so that it receives the same electrical impulses from receptor 85 as it received by amplifier 93. However, amplifier 201 has incorporated in it an arrangement to provide automatic volume control so that the amplitude of output from amplifier 201 will be maintained substantially constant although the amplitude of electrical impulses from receptor 85 may vary within wide limits. Likewise amplifier 202 is connected in parallel with amplifier 96 by means of conductors 206 and 207 so that it receives the same electrical impulses from receptor 88 as are received by amplifier 96. Also, amplifier 202 provides automatic volume control in the same manner as described for amplifier 201. The output of amplifier 201 is adjusted to be equal in amplitude to the output of amplifier 202; however the phase difference between the output of amplifiers 201 and 202 will be the same as the phase difference between the electrical impulses from receptors 85 and 88. If the electrical impulses from receptors 85 and 88 are in phase with each other the output from amplifiers 201 and 202 will add, making the amplitude of oscillograph trace 133 a maximum value. If the electrical impulses from

receptors 88 and 88 are out of phase with each other the output from amplifiers 201 and 202 will cancel, resulting in a minimum width of oscillograph trace 133. Thus trace 133 affords a measure of the phase relationship between the two wave motions recorded individually as traces 119 and 127. This method is covered in co-pending application 202,483. It is not necessarily limited to recording the phase relationship between the electrical impulses from the two receptors, but may also be used to record the phase relationship between the electrical impulses and a constant frequency such as that of generator 75.

In our recording system, we therefore obtain the following traces:

Trace 104 which is the impressed harmonic voltage.

Trace 112 which is the impressed harmonic current.

Trace 119 which is the wave motion received at one receptor.

Trace 123 which is the wave motion received at another receptor.

Trace 133 which is the phase relationship of the wave motions of traces 119 and 127.

From what has been said hereinabove, it will be clear to those skilled in the art that the following results are obtained:

a. From the general appearance of traces 127 and 119, the logs taken in the various bore holes can be readily correlated.

b. The nodes and loops may be readily seen throughout the length of the log in all of the strata.

c. The level of amplitude of the wave motions is lowest in shale and most in limestone. (This can be checked quite readily by observing the impedance changes as portrayed by traces 104 and 112. The energy required to vibrate the emitter in the region of hard material will be greater than that required to vibrate the emitter in the region of softer material. This gives an additional check.)

d. The distance between loops in the shale sections may be as small as two feet when a frequency of 750 cycles is used, while the distance between loops (or nodes) in the limestone sections may be three feet or more, indicating the higher velocity of the limey portions.

e. The ratio of amplitude of loops and amplitude of nodes (damping) is greatest in shale and least in lime.

f. In addition to the specific characteristics that can be readily described and identified, the overall characteristics of amplitude, standing waves and ratio of amplitudes gives a general character difficult to describe but which carries over from one bore hole to the next, enabling ready correlation of bore holes.

g. The filters permitting passage of wave motion of predetermined frequency only, remove nearly all visible extraneous disturbances caused by the motion of the receptors during the making of a continuous record strip.

h. The phenomena described in the instant case, that is, the use of resonance methods and standing waves, may be plotted simultaneously with energy characteristics and phase characteristics as disclosed in Figure 15, giving a record or log of a bore hole which enables substantially certain identification of respective layers and positive correlation.

In some instances, phase velocities of layers may be the same. Resonance velocities might be the same. Energy conductivity might be the

same and damping might be the same, though other factors may be different. The simultaneous recording of resonance velocity, phase velocity, energy conductivity and damping, as is shown in Figure 15, gives a very complete story of the various characteristics of the layers enabling bore hole logging to be practiced with a degree of certainty heretofore unknown.

In our method, we may log the same hole several times using different frequencies. Though we generally prefer a frequency range between 500 and 1,000 cycles per second for transverse waves, our method is not limited to these frequencies.

Any suitable emitter or receptor may be employed. A preferred type is shown in Figure 12 and Figure 13, in which the housing 136 is a cylindrical tube in which a permanent magnet 137 is held in neutral position by flexible diaphragms 138 and 139. The diaphragms are seated on peripheral shoulders 140 by non-magnetic pressure disks 141. The pressure disks in turn are held in position by core pieces 142 which are, in turn, held in position by upper threaded closure member 143 and lower threaded closure member 144, respectively. The conductor cable 145 is arranged to completely close and seal the passage in the upper closure member 143 and carries conductors 146 and 147. The conductors are connected to an upper coil 148 and a lower coil 149.

When harmonic vibrations are received by the case or housing 136, the air gaps between the permanent magnet 137 and the magnetic cores 142 are varied in sympathy with the harmonic vibrations received. The variation of the air gaps induces electrical potentials in the coils 148 and 149.

Since we, in the instant case, are interested in lateral motions, the case 137 is sufficiently flexible to permit the diaphragms 138 and 139 to deform the case harmonically in a lateral direction as the magnet vibrates when the arrangement shown in Figure 12 is used as an emitter. It is understood, of course, that, if harmonic potential is furnished to the conductors 146 and 147, the permanent magnet 137 will vibrate in a vertical direction, deforming the flexible diaphragms 138 and 139, thus setting up the ripples in the case 136. These ripples will have a large lateral component. It is also desirable to increase the mass of the case system such that the ratio of its mass to the magnet is large. It will be noted that the closures 143 and 144 are quite heavy. The provision of a large mass of the case system to the magnet mass discourages vertical movement of the case, thus tending to suppress vertical vibrations in favor of lateral ones. This principle is useful for both transmitter and receptor.

When the arrangement is used as a receptor, the impression of lateral energy on the case will cause ripples in the case which, in turn, produces a harmonic vibration of the permanent magnet supported by the flexible diaphragms 138 and 139. These harmonic motions set up induced currents in sympathy with the harmonic motions received which are conducted to the amplifier and filter and thence to the recorder.

We have found that a transmitter and receptor such as shown in Figure 12 is satisfactory for a frequency range from 50 cycles to a thousand cycles for both transmitter and receptor.

We prefer, when logging at a fixed frequency, to tune the transmitter to this frequency by adjustment of material and dimensions of the flexible diaphragms 138 and 139 and to operate

without any damping fluid or damping medium inside of the case 136. This permits the delivery of maximum motion output with a minimum of electrical power input when using the device as an emitter.

In the case of receptors, however, we prefer to use a damping fluid to obtain the order of 25 per cent to 100 per cent critically damped. This prevents a small change in frequency, near that of the resonance frequency used, from producing a large change of phase of the electrical output of the receptor.

Referring now to Figure 14, the electrical energy generated by the receptors is conducted by conductors such as 91 and 92 from a receptor directly across the primary winding 150 of the input transformer 151. The winding has a low impedance to match the impedance of the receptor and to minimize induced voltage in the conductors from the source system conductors. The secondary winding 152 of the input transformer, one end of which is connected by conductor 153 to the grid 154 of the thermionic tube 155, provides a step up for the voltage received by the receptor. The cathode 156 of the tube 155 is provided with a filament heater 157, which is furnished energy by an "A" battery 158 through leads 159 and 160. The cathode 156 is biased by a "C" battery 161. The plate 162 of the thermionic tube 155 is connected by conductor 163 to impress the output of tube 155 through a high pass filter 164 and a low pass filter 165, the filtered energy passing through conductor 166 to the grid 167 of thermionic tube 168. The condenser 169 of the high pass filter 164 is adjusted to reject frequencies below those of the predetermined frequency generated by the generator 75 (Figure 15). The condenser 170 of the low pass filter is adjusted to reject frequencies higher than those which it is desired to receive. The volume control comprising the resistance 171 and the variable arm 166 adjusts the overall gain. The grid 167 of the thermionic tube 168 is biased by a "C" battery 173. The resistances 174 and 175 are connected across reactances 176 and 177 of the high pass filter while the reactances 178 and 179 of the low pass filter are shunted by resistances 180 and 181. These resistances suitably damp the electrical network in order to prevent self-oscillation. This damping is desirable when transient impulses are received in order that the impulses will be amplified with reasonable faithfulness. The cathode 182 of the thermionic tube 168 is provided with a filament heater 183 which is supplied with energy from the "A" battery 158. Plate voltage is supplied from the "B" battery 184, the positive terminal thereof being connected to the plate 162 of the thermionic tube 155 by conductor 185, reactance 177 and conductor 163. The positive terminal of the "B" battery 184 is connected to the plate 186 of the thermionic tube 168 through conductor 187, the primary winding 188 of the output transformer and conductor 189. The secondary winding 190 of the output transformer is connected by leads 122 and 123 to the oscillograph element 120 as shown in Figure 15. The amplifier and filter assembly 96 in Figure 15 is similar to that just described. The amplifier and filter assemblies 201 and 202 in Figure 15 are also similar to those just described, and in addition have incorporated in them an arrangement for providing automatic volume control. Such an arrangement is shown in co-pending application 202,483, Figure 4.

While we have described one form of amplifier and filter, it is to be understood that any suitable form of amplifier may be employed and, if desired, an amplitude limiter or volume control arrangement may be used to give a predetermined amplitude of the standing waves on the record. A suitable arrangement is shown in our co-pending application, Serial No. 202,483, in which a portion of the output energy is rectified and used to charge a condenser which is shunted by a variable high resistance. The charge in the condenser is led to the grid of the input tube so that the amplification factor of the channel will vary as a function of the voltage of the output, the variable resistance across the condenser giving the time factor during which biasing of the input tube is effective.

It will be seen that we have accomplished the objects of our invention. We have provided a method for logging bore holes using resonance methods or standing waves. We have provided a method of logging bore holes wherein the velocity of motion causing resonance may be logged independent of phase velocity. Our method provides a means of logging the damping of resonance phenomena in various strata traversed. Our method is such that we utilize transverse waves which may be used simultaneously with compressional or longitudinal waves to facilitate logging.

We have provided a method in which various spacings may be used between emitter and receptors to bring out more clearly the characteristics desired.

It will be understood that certain features and subcombinations are of utility and may be employed without reference to other features and sub-combinations. This is contemplated by and is within the scope of our claims. It is further obvious that various changes may be made in details within the scope of our claims without departing from the spirit of our invention. It is, therefore, to be understood that our invention is not to be limited to the specific details shown and described.

Having thus described our invention, we claim:

1. A method of logging bore holes including the steps of generating a harmonic potential, impressing said potential upon a vibratory means adapted to respond thereto to create standing waves in the strata traversed, lowering said vibratory means into a bore hole the log of which is being made, measuring changes of impedance in said vibratory means caused by the counter effects of motions created as said vibratory means is lowered into the bore hole, and plotting impedance changes to determine the character of the standing waves created.

2. A method of logging bore holes including the steps of generating harmonic potential, impressing said harmonic potential upon a vibratory means adapted to respond thereto and to create standing waves of transverse motion in the strata traversed, lowering said vibratory means into the bore hole the log of which is being made, measuring changes of impedance in said vibratory means caused by the counter effects of motions created as said vibratory means is lowered into the bore hole, and plotting impedance changes on the bore hole log to determine the character of the standing waves created.

3. A method of logging bore holes including the steps of generating a harmonic potential of predetermined frequency, impressing said potential upon a vibratory means adapted to respond there-

to and to create longitudinal waves, lowering said vibratory means into said bore hole the log of which is to be made and permitting said longitudinal waves to pass through the adjacent stratum whereby to create standing waves in the strata traversed, measuring changes of impedance in said vibratory means as it is lowered into the bore hole, plotting impedance changes to obtain a desired bore hole log showing the character of the standing waves created, changing the frequency of the harmonic potential impressed upon said vibratory means and repeating the above steps to obtain a plurality of logs showing the characteristics of standing waves created at a plurality of frequencies.

4. A method of logging bore holes including the steps of generating a harmonic potential of predetermined frequency, impressing said potential upon a vibratory means adapted to respond thereto and to create standing waves in the strata traversed, lowering said vibratory means into the bore hole in predetermined fixed relation to means responsive to transverse vibratory energy, recording the motion received by said responsive means and plotting said motion against depth to obtain a bore hole log of the standing waves created.

5. A method as in claim 4 in which the steps are repeated with a different predetermined frequency to obtain a plurality of logs at different frequencies.

6. A method of logging bore holes including the steps of generating a harmonic potential of predetermined frequency, impressing said harmonic potential upon a vibratory means adapted to respond thereto, lowering said vibratory means into a bore hole to create standing waves within the strata pierced by the bore hole, simultaneously lowering energy responsive means into the bore hole a predetermined distance from said vibratory means, said energy responsive means being adapted to receive transverse motion, converting transverse motion received by said energy responsive means into electrical potentials in sympathy therewith and recording said potentials against depth to obtain a log of resonance velocity characteristics of the standing waves plotted against depth.

7. A method of logging bore holes including the steps of generating a harmonic potential of predetermined frequency, impressing said harmonic potential upon vibratory means, lowering said vibratory means into a bore hole to create standing waves in the strata, simultaneously lowering a plurality of energy responsive means into said bore hole at different predetermined distances from said vibratory means, said energy responsive means being adapted to receive transverse motions in the strata traversed, converting the respective transverse motions into electrical potentials in sympathy therewith, recording said potentials as a function of depth to obtain a bore hole log.

8. A method of logging bore holes including the steps of creating a harmonic potential of predetermined frequency, impressing said harmonic potential upon a vibratory means, lowering said vibratory means into a bore hole to create standing waves of motion in the strata adjacent said vibratory means, receiving transverse motions thus generated at a plurality of points within the bore hole at different predetermined distances from said vibratory means, converting said transverse motions into respective electrical potentials in sympathy therewith, recording said potentials

whereby the attenuation between wave motion traveling from said vibratory means to the remote energy responsive means and that traveling to the proximate energy responsive means may be determined.

9. A method of logging bore holes including the steps of creating a harmonic potential of predetermined frequency, impressing said harmonic potential upon vibratory means responsive thereto, lowering said vibratory means into the bore hole to create standing waves in the strata adjacent said vibratory means, said frequency being such that standing waves will be created in the thinnest stratum to be identified, receiving vibratory motions within the bore hole at a plurality of points therewithin, converting said motions into harmonic potentials in sympathy therewith and recording said potentials as a function of depth to determine the characteristics of the standing waves created within the bore hole.

10. A method of logging bore holes including the steps of generating a harmonic potential of predetermined frequency, impressing said harmonic potential upon a vibratory means responsive thereto, lowering said vibratory means into the bore hole to create standing waves within the bore hole, simultaneously lowering means responsive to transverse energy into said bore hole a predetermined distance from said vibratory means, receiving transverse motion at said responsive means, converting said transverse motion into electrical potential in sympathy therewith, rejecting frequencies higher and lower than the predetermined frequency, amplifying and recording the resultant electrical potential as a function of depth to obtain a log of the standing waves created.

11. A method of logging bore holes including the steps of creating standing waves in the strata in which the bore hole is formed, receiving standing waves within the bore hole, and recording the standing wave motion along the bore hole.

12. A method of logging bore holes including the steps of creating standing waves of transverse motion in the material of the strata in which the bore hole is formed, receiving said standing wave transverse motion along the bore hole, and recording said motion.

13. A method of logging bore holes including the steps of creating a harmonic potential of predetermined frequency, impressing said harmonic potential upon a vibratory means, lowering said vibratory means into a bore hole to create standing waves of motion in the strata adjacent said vibratory means, receiving transverse motions thus generated at a plurality of points within the bore hole at different predetermined distances from said vibratory means, converting said transverse motions into respective electrical potentials in sympathy therewith, recording said potentials whereby the damping between wave motion traveling from said vibratory means to the remote energy responsive means and that traveling to the proximate energy responsive means may be determined.

14. A method of logging bore holes including the steps of creating a harmonic potential of predetermined frequency, impressing said harmonic potential upon a vibratory means, lowering said vibratory means into a bore hole to create standing waves of motion in the strata adjacent said vibratory means, receiving transverse motions thus generated at a plurality of points within the bore hole at different predeter-

mined distances from said vibratory means, converting said transverse motions into respective electrical potentials in sympathy therewith, recording said potentials whereby the resonance velocity of the wave motion traveling from the vibratory means to the remote energy responsive means and that traveling to the proximate energy responsive means may be determined.

15. A method of logging bore holes, including the steps of generating a harmonic potential of predetermined frequency, impressing said harmonic potential upon a vibratory means adapted to respond thereto, lowering said vibratory means into a bore hole to create standing waves within the strata pierced by the bore hole, simultaneously lowering a plurality of energy responsive means in fixed relation to each other and at a predetermined distance from said vibratory means into said bore hole, said energy responsive means being adapted to receive transverse motion, converting transverse motion received by said energy responsive means into electrical potentials in sympathy therewith, and recording said potentials against depth to obtain a log of variations of characteristics of waves through the path of lowering of said energy responsive means.

16. A method of logging bore holes including the steps of creating a harmonic potential of predetermined frequency, impressing said harmonic potential upon a vibratory means, lowering said vibratory means into said bore hole to create standing waves of motion in the strata, simultaneously lowering a plurality of energy responsive means in fixed predetermined relation to said vibratory means and each other, receiving transverse motions thus generated at said energy responsive means, converting said transverse motions into electrical potentials in sympathy therewith, recording said potentials to obtain the attenuation of wave motions traveling the path to the remote energy responsive means as compared with the wave motion traveling the path to proximate energy responsive means.

17. A method as in claim 16, in which said predetermined frequency is selected to obtain standing waves in the thinnest stratum to be identified and in which the potentials at the receptors will enable the characteristics of the standing waves received, the phase velocities received, and the characteristics of the stratum conductivity to wave motion to be identified.

18. A method of logging bore holes, including the steps of generating a harmonic potential of predetermined frequency, impressing said harmonic potential upon a vibratory means adapted to respond thereto, lowering said vibratory means into a bore hole to create standing waves within the strata pierced by the bore hole, simultaneously lowering energy responsive means into the bore hole at a predetermined distance from said vibratory means, said energy responsive means being adapted to receive transverse motion, converting transverse motion received by said energy responsive means into an electrical potential in sympathy therewith and recording said electrical potential against depth to obtain a log of the damping characteristics of the standing waves plotted against depth.

19. A method of logging bore holes, including the steps of generating a harmonic potential of predetermined frequency, impressing said harmonic potential upon a vibratory means, lowering said vibratory means into a bore hole containing fluid, said vibratory means radiating a periodic disturbance at right angles to the direction of travel during said lowering step, transmitting said disturbance through said fluid in the bore hole to the strata adjacent thereto thereby creating standing waves in said strata, simultaneously lowering means responsive to vibratory energy of transverse motion, creating electrical potentials in sympathy with said waves of transverse motion and recording said potentials as a function of depth.

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