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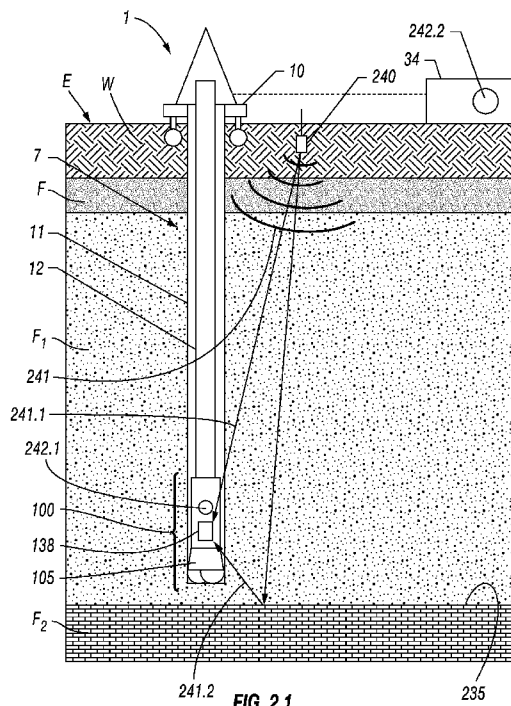
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[Continued on next page]

(54) Title: DOWN HOLE SUBSURFACE WAVE SYSTEM WITH DRILL STRING WAVE DISCRIMINATION AND METHOD OF USING SAME



(57) Abstract: A system, method and tool for measuring subsurface waves from a wellbore is provided comprising a source for propagating at least earth waves and a drilling tool. The drilling tool may include a drill string comprising a number of drill pipe sections positionable in the wellbore and a bottom hole assembly. The bottom hole assembly may include a sensor package containing a strain gauge to determine strain measurements of the drill string and a subsurface sensor to determine subsurface measurements of earth waves passing through the earth and drill string waves passing through the drill string. Embodiments of the system may compare the strain measurements to the subsurface measurements in order to distinguish drill string waves from earth waves.



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DOWN HOLE SUBSURFACE WAVE SYSTEM
WITH DRILL STRING WAVE DISCRIMINATION AND METHOD OF USING SAME

CROSS-REFERENCE TO RELATED APPLICATION

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This application claims benefit of U.S. Non-Provisional Patent App. Serial No. 14/259,093 filed April 22, 2014, which is herein incorporated by reference in its entirety.

BACKGROUND

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The present disclosure relates generally to well site operations. In particular, the present disclosure relates to measuring and/or analyzing subsurface parameters of a down hole formation.

Wellbores are drilled to locate and produce hydrocarbons. A down hole drilling tool with a bit at an end thereof is advanced into the ground to form a wellbore. As the drilling tool is advanced, drilling mud is pumped through the drilling tool and out of the drill bit to cool the drilling tool and carry away cuttings. The fluid exits the drill bit and flows back up to the surface for recirculation through the drilling tool. The drilling mud is also used to form a mudcake to line the wellbore.

During or after a drilling operation, various down hole evaluations may be performed to determine various characteristics of the wellbore and surrounding formations. In some cases, the drilling tool may be provided with devices to test and/or sample the surrounding formation and/or fluid contained therein in reservoirs. In other cases, the drilling tool may be removed and a down hole wireline tool may be deployed into the wellbore to measure formation properties, such as resistivity, gamma ray, density, sonic slowness and/or to test and/or sample the formation. These samples or tests may be used, for example, to determine whether valuable hydrocarbons are present. Production equipment may be positioned in the wellbore to draw located hydrocarbons to the surface.

Formation evaluation may involve drawing fluid from the formation into the drilling tool for testing and/or sampling. Various devices, such as probes or packers, may be extended from the drilling tool to establish fluid communication with the formation surrounding the wellbore and to draw fluid into the drilling tool. Drilling tools may be provided with fluid analyzers and/or sensors to measure subsurface parameters, such as fluid properties. Examples of down hole tools are provided in patent/publication No. US7458252, the entire contents of which are

hereby incorporated by reference. The down hole tool may also be provided with sensors, such as seismic sensors, accelerometers, and strain gauges, for measuring subsurface parameters, such as formation properties. Examples of sensors are provided in patent/publication Nos. 2012/0063263, 2011/0194375, 2010/0296366, 2009/0238043, and 2010/0020636, the entire
5 contents of which are hereby incorporated by reference.

SUMMARY

This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the
10 scope of the claimed subject matter.

Embodiments of the claimed disclosure include a system for measuring subsurface waves from a wellbore comprising a source for propagating at least earth waves and a drilling tool. The drilling tool may include a drill string comprising a plurality of drill pipe positionable in the wellbore and a bottom hole assembly. The bottom hole assembly may include a sensor
15 package containing a strain gauge to determine strain measurements of the drill string and a subsurface sensor to determine subsurface measurements of earth waves passing through the earth and drill string waves passing through the drill string. Embodiments of the system may compare the strain measurements to the subsurface measurements in order to distinguish drill string waves from earth waves.

Another embodiment of the claimed disclosure may include a method of measuring subsurface waves from a wellbore comprising advancing a drilling tool to form the wellbore. The drilling tool may include a drill string and a bottom hole assembly. The bottom hole assembly may further include a sensor package containing a strain gauge and a subsurface sensor. The method may additionally include taking strain measurements of the drill string with
20 the strain gauge and taking subsurface measurements of earth waves passing through the earth and drill string waves passing through the drill string with the subsurface sensor. In addition, the method may include discriminating the drill string waves from the earth waves via comparisons between the strain measurements and the subsurface measurements.

Still another embodiment of the claimed disclosure may include a wellbore tool
30 comprising a strain gauge configured to detect strain signals traveling within the tool and a subsurface wave sensor configured to detect subsurface waves. Noise in a subsurface wave measurement may be reduced by discriminating out the impact of strain signals on the subsurface wave sensor.

Other or alternative features will become apparent from the following description, from the drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Embodiments of the subsurface wave system with drill string wave discrimination and method are described with reference to the following figures. The same numbers are used throughout the figures to reference like features and components.

FIG. 1 illustrates a schematic diagram, including a partially cross-sectional view, of a well site having a down hole drilling tool deployed into a wellbore, the down hole tool
10 comprising a drill string and a bottom hole assembly (BHA) with a sensor package therein for measuring subsurface waves in accordance with various embodiments of the present disclosure;

FIG. 2.1 is another schematic view of the well site and drilling tool of FIG. 1 depicting the sensor package measuring subsurface waves in accordance with embodiments of the present disclosure;

15 FIG. 2.2 depicts the well site and drilling tool of FIG. 2.1 with the sensor package measuring drill string and earth waves in accordance with embodiments of the present disclosure;

FIGS. 3.1 and 3.2 are schematic, cross-sectional views of a portion of the BHA of FIG. 1 depicting the sensor package in accordance with embodiments of the present disclosure;

20 FIG. 3.3 is a cross-sectional view of the portion of FIG. 3.1 taken along line 3.1-3.1;

FIG. 4 is a schematic, cross-sectional view of a geophone in accordance with embodiments of the present disclosure;

FIG. 5 is another view of the well site and drilling tool of FIG. 2.1 depicting forces on the drill string in accordance with embodiments of the present disclosure;

25 FIG. 6 is a graph depicting timing of measured drill string and earth waves in accordance with an embodiment of the present disclosure;

FIGS. 7.1 and 7.2 are graphs depicting geophone amplitude and phase response, respectively, of a geophone in accordance with an embodiment of the present disclosure;

30 FIG. 8 is a graph depicting spacing of measured drill string waves and earth waves in accordance with an embodiment of the present disclosure;

FIG. 9 is a graph depicting a drill string and earth waves as measured by various subsurface sensors in accordance with an embodiment of the present disclosure;

FIG. 10 is a schematic diagram depicting drill string wave elimination in accordance with an embodiment of the present disclosure;

FIG. 11 is a graph depicting temperature effect on a geophone in accordance with an embodiment of the present disclosure;

5 FIGS. 12.1 to 12.3 are a series of graphs of a subsurface section depicting the down hole tool relative to a target estimation over time in accordance with an embodiment of the present disclosure; and

FIG. 13 is a flow chart illustrating a method of sensing subsurface waves in accordance with embodiments of the present disclosure.

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DETAILED DESCRIPTION

The description that follows includes exemplary apparatuses, methods, techniques, and instruction sequences that embody techniques of the disclosed subject matter. However, it is understood that the described embodiments may be practiced without these specific details.

15 The present disclosure relates to a subsurface wave system for measuring properties of a subsurface formation. The earth wave is defined as the acoustic waves propagating in the natural earth, such as P waves or S waves propagating in the ocean, in the earth formation, volcanic rocks, salt domes. The earth wave can be reflected or refracted from various boundaries of earth structures. On the contrary, subsurface waves include earth waves and any
20 acoustic waves propagating the subsurface of the earth, in a hole drilled in the earth, heavy structures deployed in the earth, or any other man made subsurface constructions.

The system includes a down hole drilling tool including a drill string and a bottom hole assembly (BHA) with a sensor package to detect subsurface waves. The sensor package includes a strain gauge sensitive to strain on the drill string and acoustic sensors sensitive to
25 subsurface waves. The acoustic sensors may include, for example, a hydrophone sensitive to pressure of a media (e.g., drilling fluid) where the earthwave propagates, and geophones sensitive to particle velocity of the drill string where the geophones are mounted.

A geophone may be oriented in a direction relative to an axis of the drilling tool such that waves passing through the drill string may be separable from waves passing through the
30 earth without passing through the drill string. The drill string waves (and/or associated noise) may be eliminated (or disregarded) from the earth waves thereby providing measurements of the formation that reduce or exclude the effects or influence of noise propagating through the drilling tool.

‘Formation evaluation’ as used herein relates to the measurement, testing, sampling, and/or other analysis of well site materials and components, such as gases, fluids and/or solids. Such formation evaluation may be performed at a surface and/or a down hole location to provide data, such as subsurface parameters (e.g., temperature, pressure, permeability, porosity, resistivity, gamma ray, density, sonic slowness, etc.), material properties (e.g., viscosity, composition, density, etc.), and the like.

‘Subsurface measurement’ as used herein relates to a type of formation evaluation involving investigation of down hole formations. Subsurface measurement may be performed by seismic and/or acoustic sensors capable of measuring formation properties, such as ground motion and/or earth vibrations. Subsurface sensors, such as geophones, hydrophones, accelerometers, seismometers, seismographs, electronic sensors, amplifiers, recorders, and/or other subsurface measurement and/or sensing devices, may be used to measure parameters involved in subsurface measurement, monitoring and/or analysis.

FIG. 1 illustrates a well site system in which the disclosed subsurface wave system can be employed. The well site system of FIG. 1 may be onshore or offshore. In the well site system of FIG. 1, a wellbore 11 may be formed in earth E by rotary drilling using any suitable technique. The well site system includes a drilling tool 7 that may be suspended within the wellbore 11. The drilling tool 7 includes a drill string 12, a bottom hole assembly (BHA) 100, and a drill bit 105 at a down hole end of the BHA 100.

A surface system of the well site system of FIG. 1 may include a drilling rig 10 (including platform and derrick assembly) positioned over the wellbore 11, the drilling rig 10 including a rotary table 16, kelly 17, hook 18 and rotary swivel 19. The drill string 12 may be rotated by the rotary table 16, energized by any suitable means, which engages the kelly 17 at an upper end of the drill string 12. The drill string 12 may be suspended from the hook 18, attached to a traveling block (not shown), through the kelly 17 and the rotary swivel 19, which permits rotation of the drill string 12 relative to the hook 18. A top drive system could alternatively be used, which may be a top drive system well known to those of ordinary skill in the art.

In the well site system of FIG. 1, the surface system may also include drilling fluid or mud 26 stored in a pit 27 formed at the well site. A pump 29 may deliver the drilling fluid 26 to the interior of the drill string 12 via a standpipe 40, kelly hose 42, and a port in the swivel 19, causing the drilling fluid to flow downwardly through the drill string 12 as indicated by the directional arrow 8. The drilling fluid 26 may exit the drill string 12 via ports in the drill bit 105, and circulate upwardly through the annulus region between the outside of the drill string 12

and the wall of the wellbore 11, as indicated by the directional arrows 9. In this manner, the drilling fluid 26 lubricates the drill bit 105 and carries formation cuttings up to the surface as the fluid 26 is returned to the pit 27 for recirculation.

5 The BHA 100 of the well site system of FIG. 1 may include a measuring-while-drilling (MWD) module 130, a logging-while-drilling (LWD) module 120, and/or a roto-steerable system and motor 150, and the drill bit 105. The MWD module 130 can be housed in a special type of drill pipe, as is known in the art, and can contain one or more devices for measuring characteristics of the drill string 12 and drill bit 105. It will also be understood that more than one MWD can be employed, as generally represented at numeral 130A. As such, references to
10 the MWD module 130 can alternatively mean a module at the position of 130A as well.

The MWD module 130 may also include an apparatus for generating electrical power to the down hole system. Such an electrical generator may include, for example, a mud turbine generator powered by the flow of the drilling fluid, but other power and/or battery systems may be employed additionally or alternatively. In the well site system of FIG. 1, the MWD module
15 130 may include one or more of the following types of measuring devices: a weight-on-bit measuring device, a torque measuring device, temperature measuring device, pressure measuring device, a vibration measuring device, a shock measuring device, a stick slip measuring device, a direction measuring device, and/or an inclination measuring device.

The MWD module 130 transmits drilling data to surface by generating pressure waves
20 in the mud column in the drill pipe. Mud pulse telemetry may be used to send data at a limited data rate, for example, at about one to about ten bits per second. If a higher data rate is desired, electric signals may be sent through wired drill pipe or other telemetry means.

The LWD module 120 can also be housed in a special type of drill pipe, as is known in the art, and can contain one or more known types of logging tools. It will also be understood
25 that more than one LWD module can be employed, as generally represented at numeral 120A. As such, references to the LWD module 120 can alternatively mean a module at the position of 120A as well. The LWD module 120 may include capabilities for measuring, processing, and storing information, as well as sending data to the MWD to telemetry to the surface. The LWD module 120 may be employed to obtain various formation measurements, such as resistivity,
30 sonic, density, resistivity, seismic, etc. Sonic and seismic may differ with regards to frequency, precision, and depth of penetration. Sonic is approximately related to a frequency range of 1 to 25 kilohertz while seismic is approximately related to a frequency range of 1 to 100 Hz.

The BHA 100 may also be provided with a sensor package 138 for measuring subsurface parameters and/or waves about the wellbore 11. The sensor package 138 may be

mounted into one of the drill pipes of the BHA 100. The sensor package 138 may be utilized, for example, to measure subsurface waves, as will be described more fully herein.

Measurements captured by the sensor package 138 may be collected for retrieval at the surface. The surface unit 34 may be provided to communicate with the drilling tool 7 for
5 passage of signals (e.g., data, power, command, etc.) there between. For example, the sensor package 138 and/or the drilling tool 7 may be coupled to the surface unit 34 for passing data thereto.

A surface unit 34 may be implemented using any desired combination of hardware and software. For example, a personal computer platform, workstation platform, etc. may store
10 information, code or data on a computer readable medium, for example, a magnetic or optical hard disk, or random access memory and execute one or more software routines, programs, machine readable code, or instructions to perform the operations described herein. Additionally or alternatively, the surface system processor may utilize dedicated hardware or logic such as, for example, application specific integrated circuits, configured programmable logic controllers,
15 discrete logic, analog circuitry, or passive electrical components to perform the functions or operations described herein.

Still further, the surface unit 34 may be positioned proximate or adjacent to the drilling rig 10. In other words, the surface system processor may be co-located with the drilling rig 10. Alternatively, a part of or the entire surface system processor may be located remotely with
20 respect to the drilling rig 10. The down hole data may be transmitted to surface, for example, using mud pulse telemetry, electro-magnetic telemetry, wired drill pipe, or other forms of telemetry.

In an example using mud pulse telemetry provided by the MWD 130, acoustic signals from mud pulse telemetry may be detected at the standpipe 40 by using at least one pressure
25 transducer 41. The signals from the pressure transducers 41 are sent to the surface unit 34, and the surface unit 34 digitizes the signals and recovers the down hole data. The data rate of the mud pulse telemetry may be at a rate of from about a few to about ten bps. The depth of the bit may be estimated by counting the number of drill pipe sections used to form the drill string, and by the movement of the traveling block (not shown). The surface unit 34 may be used to
30 process the down hole data and to combine the down hole data with bit depth, to generate a log, and/or to transmit data (e.g., to an office via satellite).

FIG. 2.1 depicts an additional schematic view of a well site 1 (which may be the same as the well site of FIG. 1) in which the subject matter of the present disclosure may be implemented. For example, FIG. 2.1 also depicts a source 240 used for generating earth waves

241 for measurement by the sensor package 138. The source 240 may be, in some cases, an air gun in water, explosive charges, or any of a number of methods known to those of skill in the art. As shown, the source 240 is depicted at a surface location, but may be anywhere capable of generating earth waves 241 for measurement by the sensor package 138.

5 For the particular exemplary embodiment shown in FIG. 2.1, the earth waves 241 are generated from the air gun suspended in water region W and pass into earth E in multiple directions radiating from the source 240. The earth waves 241 pass through one or more of the formations F, F1 and F2. A portion of the earth waves 241 may be measurable by the sensor package 138, for example as indicated by the ray paths 241.1 and 241.2. Figure 2.2 shows
10 another version of the well site 1 with wellbore 11 passing through formation F and with the source 240 generating waves 241.3 and 241.1. As shown in FIGS. 2.1 and 2.2, the portion of earth E shown includes a water region W, formations F, F1 and F2. The air gun may be deployed in a water pit prepared on land or in a nearby well. The source can be a seismic vibrator, a thumper truck, dynamite, a piezo electric transducer, a plasma sound source, an
15 electro-magnetic source or a boomer sound source, among others. The source may also be mounted in the drill string. Other variations may be present.

The sensor package 138 includes subsurface sensors (and possibly other types of sensors) for measuring subsurface parameters. Subsurface parameters may include parameters such as travel time from the source 240, slowness, porosity images of reflectors, reflectivity,
20 etc., of the formations and other materials (e.g., fluids, salt dome, volcanic rocks, granite, etc.) in the earth E.

While not shown in this particular view, as described earlier in FIG. 1 other components may be provided in the BHA 100, such as the MWD 130 and LWD 120. Other components may also be provided about the well site 1 for facilitating and/or analyzing the measurements of
25 the sensor package 138. For example, a surface clock 242.2 and/or a down hole clock 242.1 may be provided to determine the timing of various aspects of the operation.

For example, the surface and down hole clocks 242.2, 242.1 detect the timing of the creation of an earth wave from the source 240 and the timing of an arrival of the earth waves at the sensor package 138. The time difference between the surface clock 242.2 and the down
30 hole clock 241.1 is the transit time for the earth wave to directly propagate from source 240 to the sensor package 138 on the ray path 241.1. The surface clock 242.2 and down hole clock 242.1 may be high precision clocks. Drifts in time from various synchronization events may be negligible to determine the transit time from source 240 to sensor package 138. The clocks 242.1, 241.2 may also record various events, such as start and stop of drilling operations, etc.

As shown in FIG. 2.1, earth waves 241 may propagate as earth (or seismic) waves through the earth E to the sensor package 138. The earth E may include subterranean formations (e.g., F1 and F2) and any materials therein, such as a water region W and reflectors 235, located along a boundary between formations F1 and F2. The sensor package 138 may
5 acquire an earth wave traveling from the source 240 directly to the sensor package 138 through the formations (e.g., F, F1, F2) on the ray path 241.1, and/or an earth wave reflected from an acoustic impedance contrast at a reflector 235 located below the sensor package 138 as shown in FIG. 2.1 on the ray path 241.2. In some cases, the reflected earth wave may be reflected from below the drill bit 105.

10 Measurements of the earth waves may be used, for example, to determine the transit time for the earth waves to propagate from the source 240 to the sensor package 138. The transit time and the length of the drill string 12 (or bit depth) may be used, for example, for a time-depth conversion of a subsurface section otherwise displayed in time scale. The reflected earth wave may be used to image reflectors 235 located below the bit 105 to examine the
15 structure of the formation ahead of the drill bit 105.

As shown in FIG. 2.2, earth waves 241 may be emitted from the source 240. In some cases, an earth wave 241 passes through the formation directly to the sensor package 138 as described by the ray path 241.1. While in other cases, an earth wave 241 passes through the formation to the drill string 12 on the ray path 241.3. When the drill string 12 receives an earth
20 wave 241.3 at a critical angle or condition, the earth wave 241.3 may be converted to drill string wave 243 to further propagate down the drill string 12 as shown in FIG. 2.2. Earth waves 241 may pass through the earth E as 'seismic' or 'sonic' waves. While, subsurface waves 243 passing through the drill string 12 as drill string waves are 'acoustic' waves.

Drill string wave 243 may be converted from the earth waves 241 and/or from any other
25 mechanism, such as noises or shocks emanating from work on the rig floor, nearby construction, vehicles passing by, etc. These occurrences may propagate through the drill string 12 as drill string waves 243. Attenuation of drill string waves in the drill string 12 may vary during drilling operations. The attenuation of a drill string wave 243 may be small, for example, about 0.5 dB/kf. Such attenuation may be small as long as the drill string 12 is not in
30 contact with earth E. The drill string wave 243 may attenuate more where the drill string 12 is in high contact with the earth E, such as where the wellbore 11 sharply deviates (not shown). For example, if the BHA 100 enters a tight section of the wellbore 11, for example, a turn or a lateral section, the drill string wave 243 may attenuate further.

The drill string wave 243 may be detected by the sensor package 138 prior to arrival of the earth waves in the ray paths 241.1, 241.2 passing through the earth E without passing through the drill string 12. The earth wave spreads in the earth E and suffers a reduction in amplitude, especially if the sensor package is far from the source; however, the drill string wave may arrive at the sensor package without a corresponding reduction in amplitude. This means that the drill string wave can be relatively strong and overshadow the earth wave. However, in some cases measurements of the drill string wave 243 may be discriminated from earth waves 241 in order to determine the transit time of the earth waves 241.

While FIGS. 1 - 2.2 depict a specific type of down hole drilling tool 7, any down hole tool with a drill pipe may be used, such as a sonic tool, a drill stem tester, or other down hole tool conveyed by a drill pipe. Also, while FIGS. 1 - 2.2 depict one sensor package 138 in a BHA 100 of a down hole drilling tool 7, it will be appreciated that one or more sensor packages 138 and/or other types of sensors may be positioned at various locations about the down hole drilling tool 7 and/or wellbore 11.

FIGS. 3.1 and 3.2 are schematic views of a portion of the BHA 100 depicting the sensor package 138 therein. FIG. 3.3 is a cross-sectional view of the BHA 100 of FIG. 3.1 taken along line 3.3 - 3.3. The BHA 100 includes a drill pipe 343 with a mandrel 345 therein. The sensor package 138 is positioned in the drill pipe 343 and extends into the mandrel 345. Electronics 347 are provided in the mandrel 345 for operation with the sensor package 138, for example, for power and/or communication.

The sensor package 138 may include a strain gauge 348 and at least one acoustic sensor. The acoustic sensor may be, for example, an omni-directional sensor, such as a hydrophone 344 and one or more directional sensor(s), such as geophones or accelerometers (e.g., a set of geophones) 346 as shown in FIGS. 3.1 and 3.2. Other sensors S may also be provided.

The strain gauge 348 may also be directly glued to drill pipe 343 in a pocket of the drill pipe 343 as shown in FIG. 3.2. The strain gauge 348 may be oriented along the axis A of the drill pipe 343. The strain gauge 348 may have an insulating flexible film on which a metallic foil pattern is glued. The resistance of the strain gauge 348 changes as the strain gauge 348 is compressed or elongated. The strain gauge 348 may be more sensitive to strain in the vertical direction than in the horizontal direction. The strain gauge 348 may be firmly attached to the drill pipe 343 by using an adhesive so that the resistance of the strain gauge 348 represents the strain of the drill pipe 343.

Referring still to FIGS. 3.1 - 3.3, the hydrophone 344 is mounted on the drill pipe 343 for exposure to the drilling fluid in the wellbore. The hydrophone 344 extends through the drill

pipe 343 and into the mandrel 345, and operatively connects to the electronics 347 for processing (e.g., signal amplification, digitization, data storage, break time picking and/or sending data to surface).

The set of geophones 346 are positioned in a geophone housing 350 in the drill pipe 343.

5 The set of geophones 346 are positioned so as to move with the drill pipe 343. The strain gauge 348 may be positioned in the geophone housing 350 which is tightly mounted in the drill pipe 343. The motion and strain of the drill pipe 343 may be transmitted to the geophone housing 350 such that the strain gauge 348 may measure the strain in the drill pipe 343 via the location of the strain gauge 348 in the geophone housing 350.

10 The hydrophone 344 and the set of geophones 346 may be used to detect earth waves (e.g., 241.1-241.2 of FIGS. 2.1 and 2.2). The hydrophone 344 is sensitive to pressure of the media (e.g., drilling fluid of FIG. 1) through which the earth waves pass in the paths 241.1, 241.2. The hydrophone 344 responds to pressure of the media. Accordingly, the amplitude of the hydrophone signal is the same for the waves in the paths 241.1, 241.2 propagating in any
15 direction (see, e.g., FIG. 2.1). Since the hydrophone 344 is sensitive to pressure, a hydrophone may sense P-waves, but not S-waves.

Each of the geophones in 346 is sensitive to the particle velocity of the media through which the earth waves in the paths 241.1-241.3 propagate. Propagation of the earth waves may cause particle motion in the media. The direction of the motion is along the axis of propagation
20 for P-wave propagation and perpendicular to the axis of propagation for S-wave propagation.

The set of geophones 346 may include one or more geophones oriented along one or more axes. For example, an X-axis geophone 346.1, a Y-axis geophone 346.2, and a Z-axis geophone 346.3 respectively along the X, Y, and Z coordinate axes, as shown in FIG. 3.1. In another example, the sensor package may include two X-axis geophones 346.1 and one Y-axis
25 geophone 346.2. Each axis of geophones 346.1 - 346.3 may be perpendicular to one another. The Z-axis geophone 346.3 may be mounted along the axis A of the drill pipe 343; the X-axis geophone 346.1 may be in a radial direction; and the Y-axis geophone 346.2 may be in an angular direction as indicated by the XYZ axis. From the three axis data, it is possible to determine the direction of the particle motion caused by the wave propagation. A combination
30 of multi-component geophones is capable of separating P-waves and S-waves.

The set of geophones 346 may be distributed in the drill pipe. FIG. 3.3 shows another embodiment of three geophones mounted in 120 degrees increments along the cylindrical drill pipe 343. Each geophone is tilted from the axis A of the drill pipe. However, it is possible to construct a signal in the Z-axis through a summation of all three geophone signals. Weighted

subtraction of geophones allows construction of X or Y axis signals. More geophones may also be used to detect the rotation of the drill pipe 343 and/or providing a redundancy of the signal measurements. The BHA 100 and the three-component geophone 346 mounted therein respond to the particle velocity of the earth waves propagated in the paths 241.1-241.3.

5 Any-axis geophone capable of measuring the subsurface waves may be used, such as a seismometer type electro-dynamic sensor, geophone accelerometer (GAC), and/or other sensing devices. At least some such geophones may be configured or designed to measure within desired acceleration ranges. Examples of geophones are provided in 2012/0063263, 2011/0194375, 2010/0296366, 2009/0238043, and 2010/0020636, previously incorporated by
10 reference herein, and may be commercially available from SCHLUMBERGER TECHNOLOGY CORPORATION™ (see www.slb.com).

The strain gauge 348 is sensitive to strain at a wide frequency range, such as direct current (DC). The hydrophone 344 is sensitive to pressure at a wide frequency range, but not DC. The low frequency response of the geophone 346 is limited by its natural frequency, which
15 may be from about 5 Hz to about 30 Hz. The amplitude of the measured signal at low frequencies may be reduced, and phase rotated around the natural frequency. The signal measured by the geophone 346 is not the same as the shape of propagating waves and is different from a hydrophone 344.

The signals captured by the sensor package 138 may be wired to the electronics 347 for
20 amplification, digitization, and/or communication. The digitized signals are time stamped by using the high precision down hole clock 242.1. The down hole clock 242.1 may be positioned in the electronics 347. The electronics 347 may also be provided, for example, with a central processing unit (CPU). In some cases, the electronics 347 may pick a down hole break time of the captured data and send the down hole break time to the surface via telemetry (e.g., MWD
25 130 of FIG. 1) for surface retrieval. The surface unit 34 may be provided to communicate with the sensor package 138 and/or the drilling tool 7 for passage of signals there between. For example, the sensor package 138 and/or BHA 100 may be coupled to the surface unit 34 for passing data there between. The electronics 347 may be configured to send full, raw, subsurface data to the surface, for example, if wired drill pipe is available.

30 FIG. 4 is a cross-sectional view of a geophone 446 which may be used as any of the geophones herein. The geophone 446 includes a moving coil 452 mounted on a bobbin 453, a magnet 454 with north (N) and south (S) poles, a pair of pole pieces 456, 458 with suspension springs 460, 462 and a housing 464 as shown in the figure. The pole pieces 456, 458 and housing 464 are made of magnetically permeable material and form a magnetic field in which

the moving coil 452 is suspended. In the example shown in FIG. 4, the moving coil 452, bobbin 453, and suspension springs 460, 462 collectively form the effective moving mass portion (m) of the geophone 446.

As shown in the illustrative embodiment of FIG. 4, the moving coil 452 is suspended in a magnetic flux field ϕ by means of the spring (or pair of springs) 460, 462. The moving coil 452 may try to stay in the same position, while the housing of the geophone 464 is moved in response to external vibrations. The field ϕ is generated through the geophone 446. The relative movement of the moving coil 452 creates electrical signals. The signals are divided by the resistance of the moving coil 452 and the shunt resistor 467. The resulting signal may be passed to the electronics 347 (FIGS. 3.1-3.3) for acquisition and/or to the MWD 130 and surface unit 34 (as shown, for example, in FIGS. 1 - 2.2) for data collection and analysis.

As illustrated, a magnetic flux from the field ϕ passes out one winding from inside to outside from the north N of the magnet 454 through the pole piece 456. The magnetic flux passes into the other winding from outside to inside and goes back to the south S of the magnet 454 via the pole piece 458. The pole pieces 456, 458 and the housing 464 are made of magnetically permeable material and form a magnetic flux in the gap in which the moving coil 452 is suspended. In a particular embodiment as shown, the coil windings 452 are connected in series to form a continuous coil. The windings may be disposed about the bobbin 453 in opposite directions, so that the two windings generate voltages in a common direction. The windings of the moving coil 452 are commonly mounted and move together. The output of the moving coil 452 is shunted by the shunt resistor R_s to flow a current i into the moving coil 452 to dampen or prevent the motion of the moving coil 452. A total damping factor may be tuned to be near about 70% by adjusting the shunt resistor R_s .

FIG. 5 shows another view of the well site 1 of FIG. 2.2 depicting forces on a portion of the drill string 12. A short section of drill pipe 566 of the drill string 12 is shown with compressive forces F_c caused by the drill string wave 243 is applied thereto. As the drill string wave 243 propagates through the drill pipe 566 and compressive forces F_c are applied to the drill pipe section 566, the drill pipe section 566 deforms to the outer surface deformed position as depicted by imaginary lines 566.1. The propagation of the drill string wave through the outer surface drill pipe 566 causes particle motions as indicated by the arrows 568.1, 568.2.

The particle motion along an outer surface of the drill pipe 566 may have a large amplitude along axial arrow 568.1 in a direction parallel to axis A of the drill string 12. There may also be particle motion with a reduced amplitude along radial arrow 568.2 in radial direction, for example, where there is a discontinuity, such as a hole or upset. The periodical

nature of drill pipe upsets may cause a passband and stopband nature, and drill string waves at some frequencies may not propagate. The first stop band may present at around about 250 Hz for multiple connections of 10 m drill pipe joints.

The velocity of the drill string waves may be reduced from the sound velocity in steel.

5 The reduction may depend on the weight and the grade of the drill pipe 566 (e.g., about 4500 ~ about 4800 m/s). Assuming a homogeneous drill pipe 566, there may be no particle motion in an angular direction.

The drill string wave 243 may be measurable, for example, along the A axis by the Z-axis geophone 346.3, slightly along the x axis by the x-axis geophone 346.1, and possibly in

10 small amounts in y-axis geophone 346.2 (see, e.g., Fig. 3.1 and 3.2). Measurements may be determined based on the selected configuration of hydrophones 344 and geophones 346.1-346.3.

The hydrophone 344 may not be sensitive to the motion of the drill pipe 566, for example, such as in cases using an acceleration cancelling design for the hydrophone 344. A

15 hydrophone 344 has its own mass. If a hydrophone 344 is accelerated, the mass may try to stay in the same position through inertia and the hydrophone 344 may internally deform. This strain on the hydrophone 344 appears as a signal. The multiple elements of hydrophone 344 may be arranged so that their combined output is insensitive to the motion, sometime referred to as an acceleration cancelling design, and may be described together with pressure sensitivity. Where

20 the hydrophone 344 is firmly attached to the drill pipe 566, the particle motion of the drill pipe 566 transmits acceleration through the drill pipe 566 as an electric signal. Optionally, the electrical signal output may be reduced by the arrangement of acceleration cancelling.

In some applications, down hole acquisition may begin each time the drilling is momentarily stopped, such as for example, to add or remove a stand of drill pipe to the drill

25 string. During this time, the surface unit 34 may fire the source 240 and record the time of firing from the surface clock 242.2.

In some cases, the sensor package 138 starts acquisition after the drilling stops. The microprocessor of the sensor package 138 may be used to search for a first break in the operation. The sensor package 138 can time stamp the occurrence of the first break by using the

30 down hole clock 242.1 and transmits the break time via telemetry (e.g., mud pulse telemetry). The difference between the source firing time and the down hole first break time corresponds to the transit time for the earth wave propagated from the source 240 to the sensor package 138 on the ray path 241.1. The sensor package 138 may also send waveforms occurring in a limited

time window selected so as to include the occurrence of the first break. The first break waveforms may be used as a form of quality control to confirm the break time picking.

In other applications, the source may be fired continuously while drilling is in progress. In these cases, a sensor package 138 may continuously acquire the earth waves, such as in the case of using a sonic tool. The source 240 may be mounted in the same drill string 12 as the sensor package 138. The source 240 and the sensor package 138 may share the same down hole clock 138 to establish the firing timing and first break time. A source 240 mounted on the drill pipe may generate earth waves in the earth and drill string waves 243 in the drill string 12. The sensor package 138 receives both earth waves coming back from the earth and drill string waves propagated in the drill string 12.

In still other applications, a sonic tool deployed with a drill stem tester. The source 240 can also use another down hole clock 242.1 if the source is far from the first down hole clock or if the source 240 is in an adjacent well.

The surface unit 34 may include an interface unit 538 to communicate with or to receive down hole measurements from the BHA 100 via MWD 130 telemetry (and/or other down hole components), a monitoring unit 536 to acquire signals from various sensors about the well site (e.g., sensors mounted on the rig to compute the bit depth), a surface high precision clock 242.2, a data processing unit 541, and a data storage unit 539.

The surface unit 34 may also include a subsurface unit to receive, process, analyze, report, control, and/or otherwise perform functions associated with the measurements. The subsurface unit may include a sensor tool 537.1, which may include a geophone tool and/or a hydrophone tool for collecting and processing measurements from the geophone and hydrophones, a strain gauge tool 537.2 for collecting and processing measurements from the strain gauge, and a source tool 537.3 to fire the source 240 and acquire reference signals from a source sensor 247. The source sensor 247 may be mounted on or nearby the source 240 in order to measure the timing of wave generation.

The surface unit 34 may also be provided with other devices, such as a satellite communication unit, displays, printing device for logs and reports, power supplies, and other devices for collecting, analyzing, processing and outputting of data and/or analysis generated therefrom, and for providing power and communication signals as needed. Various software and/or hardware facilities and/or devices may also be provided as needed to facilitate measurement, communication, analysis, and/or other functions.

While the figures herein depict specific exemplary configurations of a sensor package 138, geophones 346, hydrophones 344 and/or strain gauges 348, various combinations of

seismic, acoustic, strain, and/or other sensors may be provided. For example, certain configurations of one or more sensor packages 138 with one or more of the various sensors may be provided about one or more of the drilling tools to take the desired measurements in a desired orientation. One or more additional sensors capable of measuring other down hole parameters may also be provided.

In some operations, acquisition may be executed, for example, during the adding of a joint or a stand of drill pipe to form the drill string 12. The source 240 is fired from surface aside or at an offset distance from the drill string 12. Energy radially spreads from the source 240 in subsurface earth waves 241 in various directions, such as paths 241.1-241.3. A portion of the energy from the earth waves are coupled to the drill string 12 near the surface and are converted to a subsurface drill string wave 243 that propagates along the drill string 12 to arrive at the sensor package 138 in the BHA 100. This energy may be detected and measured by sensors located in sensor package 138. Alternatively, a portion of the earth waves passes through the formation on ray paths 241.1 and 241.2 (as earth waves) and arrive at the sensor package 138 without passing through the drill string 12.

Since the drill string wave 243 travels at a similar or slightly reduced velocity from the sound velocity in steel, the drill string wave 243 may appear at the sensor package 138 before the earth waves that arrive directly through the formation via ray path 241.1. The drill string arrival time T_s for the drill string wave 243 may be a function of various factors, including but not limited to the offset of the source 240, water velocity, and the length of the drill string 12, among others. The arrival down hole break time T_f for earth waves 241.1 propagated in the earth may also be a function of various factors, including but not limited to the offset of the source 240, water depth, sensor depth, well trajectory, water velocity and formation velocity.

In some situations, the drill string wave 243 may arrive at the sensor package 138 earlier than the earth wave 241.1. However, if the source offset is large and well deviation toward the source 240 is large, the arrival of the drill string wave 243 may be the same or later than the arrival of the earth waves from the ray paths 241.1, 241.2 to the sensor package 138.

Clocks 242.1, 242.2 may be used to help resolve timing issues, such as the down hole break time and the firing time of the source 240 at the well site. The difference between these two times is the transit time for the earth waves to propagate from the surface to the down hole location of the sensors. This transit time and bit depth information may be used to locate the bit 105 on a surface subsurface section displayed using a time scale. Drillers can determine the approximate depth of the bit 105 from the length of the BHA 100 and number of joints (or sections) making up the drill pipe. However, it is difficult to know where the bit 105 is relative

to formation reflectors 235. The reflectors 235 may also be displayed on a subsurface section plotted in time scale.

The transit time and depth information may be used to convert a time scale to a depth scale. For example, the down hole break time T_f of earth wave 241.1 and the reflected earth wave 241.2 that is reflected from reflectors 235 below the drill bit 105 (e.g., where the next portion of the formation is going to be drilled) may be used to understand the transit time T_t from the source 240 directly to the sensor package 138. The earth wave 241.1 that passes through the formation may be used for the purposes of mapping subsurface formations.

However, in some cases, it may be difficult to discern whether an earth wave on ray path 241.1, or a drill string wave 243 is being measured. In some cases, measurements of the drill string wave 243 may differ from the earth wave on ray path 241.1. By analyzing the various subsurface waves, the drill string wave 243 and the timing of the various events, it may be possible to discern the various waves and/or to eliminate the effects of a drill string wave 243 on the various measurements.

For example, if a drill string wave 243 arrives earlier than an earth wave traveling on ray path 241.1, a micro-processor may inappropriately select the drill string wave 243 instead of the earth wave on ray path 241.1 to determine transit time T_t . If so, the selected transit time T_t measurement may not reflect the travel time through the formation (for example, T_s may be selected rather than T_f and the wrong value may be chosen for analysis). In some cases, the system may be configured to transmit waveforms that surround and include the break time pick in case the break time is required to be re-picked at the surface. Of course, the formation arrival can be outside of the window of the waveform transmission.

In another example, if the drill string wave 243 overlaps with the earth waves on ray paths 241.1, 241.2, the break time T_f of the earth waves may be difficult to detect. If drill string wave 243 arrival is later than the direct arrival of earth waves on ray paths 241.1, 241.2, the drill string arrival 243 may not interfere with picking the break time. However, in some cases vertical seismic profiling (VSP) for imaging below the bit may be difficult.

FIG. 6 depicts a graph 600 of a simulated acquisition for a drilling operation, such as shown in FIG. 5. The graph plots time T (x-axis) versus depth D (y-axis) for subsurface waves 670.1-670.8 as measured by the sensor package 138 of the BHA 100 at difference depths within the wellbore. As shown by this diagram, a drill string wave 243 interferes with the earth waves 241. In this example, since the drill string wave 243 originated from the same source 240 as the earth wave 241, the arrival time is synchronized or corresponds to the arrival time of the earth waves 241. Alternatively, if the drill string wave 243 is caused by any other mechanism, such

as work on rig floor, construction or vehicles passing nearby the rig, for example, the arrival time may be more random. Further, if such drill string wave 243 is generated and arrives continuously, the drill string wave 243 may contaminate all the subsurface signals and reduces signal-to-noise ratio in the acquisition.

5 To correct or improve the measured subsurface waves 670.1-670.8, the drill string wave 243 may be removed to isolate the earth waves 241. This may be done by analyzing the signals of the measurements taken by the various sensors in the sensor package 138. The analysis may take into consideration, for example, that the magnitude of the drill string wave 243 is large in the z-axis geophone 346.3 and reduced in the x-axis geophone 346.1. In addition, the amplitude
10 of the drill string wave 243 may depend on the hydrophone design, and even further, the drill string wave 243 may exist in an angular irregularity of the wall thickness of the drill pipe, among other factors. As shown in FIGS. 3.1 and 3.2 for example, the strain gauge 342 may be useful to detect the drill string wave 243 in the absence of earth waves 241, and then allowing for the and subtraction of the drill string wave 243 from the hydrophone 344 and geophone 346
15 data.

A wave equation in the drill pipe is described as follows:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \quad \text{Equation (1)}$$

where u is the particle displacement of the media (e.g., drill pipe 566 of FIG. 5) and x is the coordinate along the direction of drill string wave propagation, c is the velocity of drill string
20 wave propagation and t is time. A general solution is:

$$u = a \sin(kx - \omega t) \quad \text{Equation (2)}$$

where a is the amplitude of the particle displacement, ω is the angular frequency and k is the wave number. The velocity c, frequency ω , and wave number k are related as follows:

$$c = \frac{\omega}{k} \quad \text{Equation (3)}$$

25 A strain gauge is sensitive to the strain of the media (e.g., drill pipe). The strain may be obtained by taking a spatial derivative of Equation (2) as follows:

$$\frac{\partial u}{\partial x} = ak \cos(kx - \omega t) \quad \text{Equation (4)}$$

The transfer function of a strain gauge may be the sensitivity. Although the electronics, such as a DC block filter and a low pass filter may change the amplitude and phase of the
30 measuring signal, the effects may be ignored where the effects are assumed to be the same for the hydrophone and the geophone if the same electronics are used for the geophone and

hydrophone channels. The effect of the transfer function of the electronics may be cancelled when eliminating the drill string wave 243. For simplicity, by ignoring the electronic effects, the signals from the strain gauge may be written as follows:

$$e_s = S_s \frac{\partial u}{\partial x} \quad \text{Equation (5)}$$

5 where S_s is the sensitivity of the strain gauge, and u is the media displacement.

The particle velocity v is the time derivative of Equation (2), which may be described as follows:

$$v = \frac{\partial u}{\partial t} = -a\omega \cos(kx - \omega t) \quad \text{Equation (6)}$$

10 Thus, the particle velocity may be found from the measurement of the drill string wave 243 based on the following:

$$v = -\frac{c}{S_s} e_s \quad \text{Equation (7)}$$

Where the geophone mounted in parallel to the drill string (e.g., Z-axis geophone 346.3 of Fig. 3.1), the geophone may be used to obtain the particle velocity. This geophone outputs a signal and drill string wave 243 as:

$$15 \quad e_g = e_{gw} + F_g(v) \quad \text{Equation (8)}$$

where e_{gw} is the signal and F_g is the function to convert the input velocity signal to an electric output.

20 The transfer function of a geophone (e.g., geophone 446 of FIG. 4) may be frequency dependent. The natural frequency of a geophone may be, for example, from about 10 Hz to about 30 Hz depending on the application and the energy of the drill string wave that exists above and below the natural frequency.

The geophone may have a damping factor associated with the movement of the coil along the springs. The total damping factor of the geophone may defined as:

$$D = D_0 + \frac{S_0^2}{2m\omega_0(r + R_s)} \quad \text{Equation (9)}$$

$$25 \quad \omega_0 = 2\pi f_0 \quad \text{Equation (10)}$$

where ω_0 is the angular natural frequency of geophone that is equal to $2\pi f_0$, f_0 is the natural frequency of the geophone, S_0 is the open circuit sensitivity, D_0 is the open circuit damping, m is the moving mass of the moving coil, and r is the DC resistance of the moving coil.

Assume u is the displacement of the media (e.g., the drill pipe), a is the amplitude, ω is the frequency, and t is time. For a given particle displacement, the displacement may be described as follows:

$$u = a \sin(\omega t) \quad \text{Equation (11)}$$

5 A geophone generates electric signal (or amplitude) eg as:

$$e_s = \frac{a \omega S_0 \left(\frac{\omega}{\omega_0} \right)^2}{\sqrt{\left(1 - \frac{\omega^2}{\omega_0^2} \right)^2 + \left(2D \frac{\omega}{\omega_0} \right)^2}} \cos(\omega t - \varphi) \quad \text{Equation (12)}$$

where the phase delay φ is:

$$\tan(\varphi) = \frac{2D \frac{\omega}{\omega_0}}{1 - \frac{\omega^2}{\omega_0^2}} \quad \text{Equation (13)}$$

10 Since the output of the geophone is shunted by R_s , the output signal (or amplitude) e_o is reduced to the following:

$$e_o = e_s \frac{R_s}{r + R_s} \quad \text{Equation (14)}$$

Assume geophone response parameters as set forth in Table 1 below:

	Geophone
f_0 [Hz]	10
S_0 [V/(m/s)]	40
D_0 [-]	0.3
r [Ω]	400
m [kg]	0.01

and further assume damping adjustments as set forth in Table 2 below:

	Case 1	Case 2	Case 3
R_s [Ω]	12000	2800	1400
D [-]	0.40	0.70	1.00
S [V/(m/s)]	38.7	33.7	29.9

The amplitude (see Equations 12 and 14) and phase (see Equation 13) responses of the geophone (Table 1) for different damping conditions (Table 2) are shown in FIGS. 7.1 and 7.2. FIG. 7.1 is a graph 700.1 of the geophone amplitude response. The graph 700.1 depicts frequency f_r (x-axis) versus amplitude AMP (y-axis) at various total damping factors D of Table 2 above. As demonstrated by the resulting response lines 772.1 - 772.3, the amplitude of the response reduces as the total damping factor D is increased.

FIG. 7.2 is a graph 700.2 of a geophone phase response. The graph 700.2 depicts frequency f_r (x-axis) versus phase response ϕ (y-axis) at various total damping factors D of Table 2 above. As demonstrated by the resulting response lines 774.1 - 774.3, the phase of the response remains relatively consistent at higher frequencies, but opposite from the movement of media where the geophone is placed. If the media moves up, the case of the geophone moves with the media while the moving coil stays in relatively the same position. This means that the movement of the moving coil is down relative to the case or media. The phase rotates by 90 degrees at near the natural frequency and the phase is reversed at below the natural frequency.

The hydrophone of the sensor package (e.g., 344 of Fig. 3.1) is sensitive to pressure. The hydrophone may also be sensitive to motion, for example, depending on how the hydrophone is mounted. If the hydrophone is not mounted in an acceleration cancelling fashion, the hydrophone outputs both earth wave signals and drill string signals according to the following:

$$e_h = e_{hw} + S_a \alpha \quad \text{Equation (15)}$$

Where e_h is the output signal from the hydrophone, e_{hw} is the earth wave signal, α is the acceleration of particle motion in the drill pipe and S_a is the acceleration sensitivity of the hydrophone. The acceleration α may be found from the strain gauge signal by differentiating the strain gauge signal as follows:

$$\alpha = \frac{\partial v}{\partial t} = -\frac{c}{S_s} \frac{de_s}{dt} \quad \text{Equation (16)}$$

Since the acceleration may be found from the strain gauge measurement, the noise due to the drill string wave can be removed from the hydrophone signal.

In the explanation above, the sensitivity of the strain gauge and the acceleration sensitivities of a hydrophone may be assumed to be just single numbers. In some cases, these sensitivities may be frequency dependent. Since the hydrophone is a high impedance sensor, the wiring may have additional stray capacitance and leakage causing low frequency roll off. The deviation of sensor performance from theory may cause errors in eliminating the drill string wave.

The components of electronics may also have their own tolerances. In addition, the responses of an X-axis geophone and a Y-axis geophone (e.g., 346.1 and 346.2 of FIG. 3.1) to the drill string wave may not simply be theoretically derived. The sensitivity estimation may have an error of about 5% in each sensor, leaving approximately 10% of the noise that cannot be removed.

The sensors may be calibrated and a transfer function determined for each sensor and electric channel. Calibration does not include any assumptions, but includes noise that can be reduced by averaging the measurements.

FIG. 8 is a graph 800 showing an example calibration during acquisition. The graph 800 is similar to the graph 500 of FIG. 5, except that in this case, the set of waveforms of an acoustic sensor, such as a hydrophone 344 or geophone(s) 346 is selected for all of the sensors in which the drill string wave 243 does not interfere with the earth wave traveled in the ray path 241.1. The graph plots time T (x-axis) versus depth D (y-axis) for subsurface waves 870.1 - 870.8 as measured by the sensor package 138 of the BHA 100.

FIG.9 shows a graph 900 depicting the simulated waveforms of a drill string wave 243 and an earth wave on ray path 241.1. For this simulation, it is assumed that: 1) the strain gauge is only sensitive to the strain in the drill pipe, 2) geophone parameters are $f_0=15\text{Hz}$, $D=0.7$, sensitive to the particle motion of the drill string, and sensitive to both the drill string wave 243 and the earth wave 241.1; and 3) the hydrophone is sensitive to the acceleration of the drill string wave 243 and pressure of the earth wave on ray path 241.1. For this simulation, it is also assumed that the energy of the drill string wave 243 and the earth wave on ray path 241.1 is between about 0.5 Hz and about 75.0 Hz. Amplitudes of the signals from the sensors are normalized for a visual comparison.

The graph 900 plots time T (x-axis) versus the sensor channel C (y-axis). The graph 900 depicts measurements of the various signals detected by the strain gauge as indicated by line 976.1, the geophone as indicated by line 976.2, and the hydrophone as indicated by line 976.3. The graph 900 also depicts a disruption 978.1 caused by the drill string wave 243, and a disruption 978.2 caused by the earth wave on ray path 241.1.

A window 980 may be provided for discriminating (or identifying) the drill string wave 243. The signals are acquired by the electronics 347 in the drill pipe 343 (FIG.3.1). The microprocessor in the electronics picks the break times of the geophone signal and/or hydrophone signal. The microprocessor checks the strain gauge signal to see if the strain gauge 348 picked the drill string wave 243 (event 978.1). If so, the microprocessor understands this is the drill string wave 243, and not the earth wave. The microprocessor then looks for another

break after the drill string wave 243. If the microprocessor does not observe a drill string wave 243 in the strain gauge 348 (event 978.2) at the time an event is recorded by the other sensors, the microprocessor thinks this is the proper break time and sends the down hole break time to the subsurface unit 537 via telemetry to surface (FIG. 5) . This base method may be used to
 5 eliminate the influence of the drill string wave 243, even in cases where the drill string wave 243 arrives at the sensor package 138 earlier than the earth waves.

Another method may be needed if the drill string wave 243 is interfering with the earth waves. If the drill string wave 243 interferes with the earth waves, the waveform data in the small window may be transferred to the surface for quality control. The down hole electronics
 10 may also send to the surface short waveform data for the drill string wave 243. The transfer function may be pre-determined in the absence of earth waves. The window 980 may also be provided for calculating the transfer functions. In some cases, the window 980 may be selected to cover only the drill string wave 243 as shown. A fast Fourier transform frs, frg and frh for signals es, eg, eh, from the strain gauge, geophones, and hydrophone, respectively, may be
 15 taken as follows:

$$fr_s = fft(e_s) \quad \text{Equation (17)}$$

$$fr_g = fft(e_g) \quad \text{Equation (18)}$$

$$fr_h = fft(e_h) \quad \text{Equation (19)}$$

The transfer functions from the strain gauge signal can be calculated for the geophone,
 20 Tsg and the hydrophone, Tsh as follows:

$$T_{sg} = \frac{fr_g}{fr_s} \quad \text{Equation (20)}$$

$$T_{sh} = \frac{fr_h}{fr_s} \quad \text{Equation (21)}$$

The drill string wave 243 in the geophone and the hydrophone may be estimated from the strain gauge as follows:

$$e_{sg} = real\{iffi(T_{sg} \bullet fft(s_s))\} \quad \text{Equation (22)}$$

$$e_{sh} = real\{iffi(T_{sh} \bullet fft(s_s))\} \quad \text{Equation (23)}$$

The transfer functions from the strain gauge to a geophone and a hydrophone Tsg and Tsh are predetermined in the absence of earth waves. If the drill string wave 243 interferes with the earth waves, the down hole electronics 347 sends short waveforms to the surface that
 30 include the drill string wave 243. The appearance of a drill string wave 243 in a geophone 346

and a hydrophone 344 are estimated by using the strain gauge signal es by using Equations (22) and (23). The drill string waves 243 that appear in the geophone 346 are eliminated by subtracting esg. The drill string waves 243 that appear in the hydrophone 344 are removed by subtracting esh.

5 As shown by this example, drill string wave elimination may be performed in the frequency domain. In another example, deconvolution may be used in the time domain. An impulse response function can also be found to transform a strain gauge signal for a geophone 346 and a hydrophone 344. The impulse response function can be applied in a finite impulse response (FIR) filter fashion to the strain gauge 346 signals in the time domain. If the
10 theoretical function is known, such as for a geophone, the theoretical transfer function can also be used instead of deriving the function from a measurement.

The filter function for a geophone can be obtained from an electric circuit. For $f_0=15\text{Hz}$ and $D=0.7$, the geophone filter function, F_g may be the same as the second order Butterworth filter. The transformation from a strain gauge signal e to a geophone signal g can be executed
15 by an infinite impulse response (IIR) filter as follows:

$$g_i = F_g(e) = \frac{S}{S_s} (b_1 e_i + b_1 e_{i-1} + b_3 e_{i-2} - a_2 g_{i-1} - a_3 g_{i-2}) \quad \text{Equation (24)}$$

where $b_1=0.9355$, $b_2=-1.8711$, $b_3=0.9355$, $a_2=-1.8669$, and $a_3=0.8752$ for $\delta t = 1\text{ms}$. S is the output sensitivity (Equation 11, 13) with shunt resistor R_s .

The time derivative to compute acceleration can be performed in the numerical
20 computation as follows:

$$\frac{de_i}{dt} = \frac{e_{i+1} - e_{i-1}}{2\Delta t} \quad \text{Equation (25)}$$

where Δt is the sampling interval of the ADC. From Equation 16 and Equation 25, the hydrophone signal, h for acceleration sensitivity may be computed as follows:

$$h_i = F_h(e) = \frac{S_h c}{2S_s \Delta t} (e_{i+1} - e_{i-1}) \quad \text{Equation (26)}$$

25 The time domain computation may use the filter function for any length of the data and for computation in real time. The filters can be updated by modifying response parameters, such as the natural frequency or damping factor of the geophones. In some cases, uncertain parameters may be modeled, such as stray capacitance for the hydrophone response.

The influence of the drill string wave 243 in the geophone 346 and the hydrophone 344
30 data can be removed by subtracting the estimated drill string wave signals obtained from the strain gauge 348 as shown in the diagram in FIG.10. FIG. 10 depicts the signals and the data

generated by sensor package 138 and electronics 347 of the BHA 100/drill pipe 343 and processed through the surface unit 34/subsurface unit 537. Signals 1085.1-1085.3 are respectively generated in the sensor package 138 from the geophone 346, the strain gauge 348 and the hydrophone 344. The signals are passed through a DC block filter 1086, a high cut
5 filter 1088, and an analog to digital converter (ADC) 1090 of the electronics 347. The signals 1085.1-1085.3 are then converted by the electronics 347 to reflect geophone, strain gauge and hydrophone data 1085.1'-1085.3', respectively.

The appearance of the drill string signal in the geophone data is estimated from the strain gauge signal and/or data 1085.2 by using the transfer function Tsg (Equation (20)) or the
10 filter function Fg (Equation (24)) as indicated by box 1093.1. Box 1093.2 estimates that the drill string waves appear in the hydrophone signal by using the transfer function Tsh of Equation (21) or the filter function Fh of Equation (26).

Box 1092.1 subtracts the estimated drill string waves 243 from the geophone signal and/or data 1085.1' and box 1092.2 subtracts the estimated drill string waves 243 that appear in
15 the hydrophone data 1085.3'. A clean geophone signal 1094.1 and a clean hydrophone signal and/or data 1094.2 may be generated from the drill string wave 243 cancellation of box 1092.1 and 1092.2.

The current block diagram shows that the signals are digitized down hole and the BHA 100 sends a set of short waveforms of geophone, hydrophone and strain gauge data 1085.1'-
20 1085.3' to the surface covering the time period around and including the first break. The surface unit 34 applies drill string wave discrimination (e.g., cancellation) based on the most popular technology of MWD telemetry. The discrimination can also be performed down hole. The down hole CPU searches events in the strain gauge signal 1085.2 and discriminates the estimated drill string waves from the geophone signal 1085.1 and hydrophone signal 1085.3,
25 whenever the CPU identifies a strain gauge signal event. If high speed telemetry is available, such as may be the case with wired or fiber optic drill pipe, all the data can be sent to surface and the discrimination can be executed by analyzing at the results. The residuals of the discrimination may be further reduced by tuning the parameters for the transfer functions or the filters 1086, 1088.

30 Once the transfer functions are determined, the transfer functions may be unique to the particular tool or configuration. In some cases, the transfer functions can be temperature dependent. FIG. 11 is a graph 1100 depicting how geophone response parameters change with temperature. Graph 1100 plots temperature Temp (x-axis) versus a normalized parameter NP (y-axis) for a geophone. Normalized first order f0, second order D0 and second order S0

polynomials are plotted to demonstrate the temperature effects on the geophone response parameters.

The natural frequency f_0 , the open circuit sensitivity S_0 and the open circuit damping D_0 may be normalized by the values at 25 degree Celsius. Since the DC resistance of the moving coil r is a function of temperature T , the temperature of the working geophone is found by knowing the DC resistance at 25 degree Celsius. For copper magnet wire, the resistance of the coil is from the industrial standard as follows:

$$\frac{r}{r_{25}} = 1 + 0.00393(T - 25)$$

Equation (27)

The change in the response parameters of a geophone relative to temperature changes affects output signals as described by Equation (12) in which the total damping factor described by Equation (9) also changes. If the amplitude of a geophone signal is reduced by 5%, then drill string wave cancellation can result in 5% of over correction. For this case, 5% of the drill string wave 243 may remain as noise. To improve the correspondence of the generated drill string wave, the transfer function or the filter function from the strain gauge to a geophone may be updated according to the temperature of the geophone. The temperature of the geophone may be estimated and evaluated by measuring the DC resistance of the moving coil as shown by Equation (27). The responses of the strain gauge 348 and the hydrophone 344 are not frequency dependent, but their sensitivity may change in relation to temperature. The temperature dependencies of sensitivities of the strain gauge 348 and the hydrophone 344 may be predetermined and adjusted according to the measured or estimated temperature in order for a more precise subtraction of drill string waves.

Based on the sensitivities of the various sensors, multiple combinations of calculations may be used to selectively remove biases that may be present in one or more of the sensors. In addition, the sensor may be oriented and/or configured to eliminate certain sensitivities and/or the effects of any forces on the system.

Measured data may be collected, analyzed and/or processed. The data may also be used to display the estimated drill string position 1212 on subsurface images 1200.1-1300.3 of the reflectors, such as those depicted in FIG. 12. The length of the drill string 1212 may be converted to transit time by using two way travel time. This transit time and bit depth information may be used to estimate the location of the bit 1205 on a surface subsurface section displayed in a time scale. The depth of the bit may be estimated from the length of the BHA and number of joints of drill pipe. In some cases, it may be difficult to know where the bit 1205 is relative to the reflectors displayed on a subsurface section, since the subsurface section is

plotted in a time scale. However, transit time and depth may be used to convert a time scale to depth scale.

FIG. 12 shows three subsurface sections 1200.1-1200.3 with a drill string 1212 in different drilling stages for an example of the application. After the initial spud of the well is drilled, as shown in subsurface section 1200.1, the depth of a target reflector T is estimated at 3352m based on a pre-drilled velocity model used to generate the subsurface sections from the seismic data. The short drill string 1212 is shown in a bold back line with the bit 1205 at a distance D1 from surface.

As the drilling progresses to the next subsurface section 1200.2, the bit 1205 depth D2 is at 2911m, and the target reflector T is updated to indicate the target reflector T' at 3248m. The transit time from the surface to the bottom of the drill string may be measured, with the location below the bit 1205 still in the form of a prediction.

In subsurface section 1200.3, the bit 1205 intersects the updated target T' at a depth DT of 3202m. In this example, the target reflector T' is about 150m shallower than initially estimated. If the drilling had continued to the initial target depth T of 3352m, as shown in subsurface section 1200.1, problems such as a blowout may have occurred.

FIG. 13 refers generally to an exemplary method 1300 for sensing subsurface parameters. The boxes are not necessarily in order and in some cases, multiple occurrences or rearrangement may be done as needed. In this example, one action is advancing a drilling tool into the earth to form a wellbore, as shown in box 1395. As previously explained, the drilling tool may comprise a drill string and a bottom hole assembly (BHA). The BHA may further include a plurality of drill pipe, and a sensor package positionable in the drill pipe. Embodiments of the sensor package may include a strain gauge and at least one subsurface sensor. The method includes propagating with a source at least one subsurface wave through the earth and to the sensor package, as shown in box 1396.

While connecting a drill pipe, box 1397 indicates taking strain measurements of the drill pipe with the strain gauge and taking subsurface measurements of the subsurface waves propagated by a source. The subsurface waves are measured by the subsurface sensor after having passed through the earth to the sensor package. The subsurface waves include drill string waves passing through the drill string and earth waves passing outside of the drill string and traveling through the earth. The drill string waves are discriminated from the earth waves by selectively comparing the strain measurements with the subsurface measurements, as seen in box 1398. In some embodiments and as shown in box 1399, the drilling advancement is adjusted based on the wellbore parameters and measurements determined by the sensors.

In operation, the selectively comparing (from box 1398) may involve comparing the strain measurements with the acoustic measurements as shown in FIG. 9. The break time may be determined as the time in which the acoustic sensors measure a subsurface wave, but the strain gauge does not. Referring again generally to FIG. 9, in this example the time occurs at time 500 ms (outside of the window 980). The break time may then be sent to the surface to estimate a transit time (e.g., the travel time for the direct wave 241 to move from the source 240 to the sensor package 138 on the ray path 241.1) by comparing the break time as measured by the down hole clock 242.1 and the firing of the source as measured by the surface clock 242.2, and as shown in FIG. 5.

The length of the drill string 12 is converted to a time scale to show the current estimated location of the drill string (the drill bit 105) relative to the target reflector in the time scale subsurface image. Alternatively, the relative location of the target reflect to the drill may use a time scale subsurface image converted to depth by using the two way time. In some cases, the target reflector T may be on top of an over pressure zone and drilling into the over pressure zone may unexpectedly cause disaster in the drilling operation (e.g., such as a uncontrolled blow out of the well). The time-depth conversion may be repeated as the drilling progresses until the drill bit is close to the target T. Keep in mind that the target T may be updated to T' to reflect the increasing accuracy as the bit approaches the target area, thereby reducing the travel time of the ray paths.

The break time (FIG. 9) determined by the down hole clock 242.1 may be sent to surface and compared with the surface break time for the source that originated the subsurface wave by using the surface clock 242.2 (FIG. 5). The comparison is used to determine the transit time (e.g., the time the earthwave takes to propagate from the surface to down hole). Time depth conversion can then locate the bit relative to the target reflector T on the various subsurface sections 1200.1-1200.3 (FIG.12).

The method may involve various aspects of drilling, surface activities, and down hole operations. The subsurface wave operation may involve drilling the wellbore by advancing a BHA of the down hole drilling tool into the wellbore via a drill string formed by connecting stands of pipe thereto. When drilling stops, the drill string may be pulled and placed in the slip at the rotary table (see, e.g., FIG. 1). The top drive may then be disconnected to add pipe. The drill string may be lifted to remove the slip and lower the drill string to resume drilling. Mud may be circulated and the drilling operation commenced. In some cases, the drill string may be removed to change a drill bit and/or a BHA.

The subsurface wave operation may also involve surface activities, such as firing a source (e.g., 240 of FIGS.2.1-3.2). The firing may be repeated and continue at intervals. The timing of the source generating the subsurface waves may be determined by using the surface clock. The down hole break time may be determined by the down hole clock. In some
5 embodiments the down hole break time is transmitted to surface. The firing may be stopped and the data received by the drilling tool upon resumption of drilling operations. The transit time from generation to reception of waves generated by the firing may be determined as the difference between the surface break and the down hole break. The location of the bit may also be determined based on the selection. After the measurements are gathered, the BHA may be
10 tripped out to download the data and process images generated there from.

The operation may also involve down hole operations. The down hole operations may involve digitizing signals from the sensors, detecting a first break in the signals (or the arrival of the subsurface waves). The down hole operations may also involve capturing traces from before the first break and for about three to six seconds. The break time may be determined
15 based on the down hole clock. The collected data may be stored. The break time may be sent to the surface. The method may be performed in a desired order, and repeated as desired.

Plural instances may be provided for components, operations or structures described herein as a single instance. In general, structures and functionality presented as separate components in the exemplary configurations may be implemented as a combined structure or
20 component. Similarly, structures and functionality presented as a single component may be implemented as separate components. These and other variations, modifications, additions, and improvements may fall within the scope of the inventive subject matter.

Although only a few example embodiments have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the example
25 embodiments without materially departing from this invention. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims. In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural equivalents in that
30 a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures. It is the express intention of the applicant not to invoke 35 U.S.C. § 112, paragraph 6 for any limitations of any of the claims herein, except for those in which the claim expressly uses the words 'means for' together with an associated function.

CLAIMS

What is claimed is:

1. A system for measuring subsurface waves from a wellbore, the system comprising:
a source for propagating at least earth waves;
5 a drilling tool comprising:
a drill string comprising a plurality of drill pipe positionable in the wellbore; and
a bottom hole assembly comprising:
a sensor package comprising:
a strain gauge to determine strain measurements of the drill string;
10 and
a subsurface sensor to determine subsurface measurements of
earth waves passing through the earth and drill string waves passing
through the drill string; and
wherein the strain measurements are compared with the subsurface measurements to
15 distinguish the drill string waves from the earth waves.
2. The system of Claim 1, further comprising a subsurface unit comprising a strain gauge
tool to receive the strain gauge measurements and a subsurface sensor tool to receive the
subsurface measurements.
3. The system of Claim 2 wherein the comparison between the subsurface measurements
20 and the strain measurements occur down hole.
4. The system of Claim 1, wherein the subsurface sensor comprises;
at least one of a hydrophone or a geophone; and
the subsurface measurements comprises at least a corresponding one of a
hydrophone measurement or a geophone measurement.
- 25 5. The system of Claim 4, further comprising a subsurface unit comprising at least one of a
corresponding hydrophone tool to receive the hydrophone measurements or a geophone tool to
receive the geophone measurements.
6. The system of Claim 5 wherein the comparison between the strain measurements and
the at least one of the corresponding hydrophone measurements or the geophone measurements
30 occurs down hole.
7. The system of Claim 1, wherein the source comprises an air gun.
8. The system of Claim 1 further comprising a source sensor operatively connected to the
source.
9. The system of Claim 1, further comprising a surface clock and a down hole clock.

10. The system of Claim 1, further comprising a down hole sensor, the down hole sensor measuring at least one down hole parameter comprising a temperature, a pressure or a density.
11. The system of Claim 1, wherein the drilling tool comprises one of a drilling tool or a drill stem tester.
- 5 12. A method of measuring subsurface waves from a wellbore comprising:
advancing a drilling tool to form the wellbore, the drilling tool comprising a drill string,
and a bottom hole assembly comprising a sensor package comprising a strain
gauge and a subsurface sensor;
taking strain measurements of the drill string with the strain gauge and taking subsurface
10 measurements of earth waves passing through the earth and drill string waves
passing through the drill string with the subsurface sensor; and
discriminating the drill string waves from the earth waves via comparisons between the
strain measurements and the subsurface measurements.
13. The method of Claim 12, further comprising determining a down hole break time for the
15 earth wave when the subsurface measurement records the earth wave but the strain gauge does
not.
14. The method of Claim 13, further comprising determining a transit time for the earth
wave by differencing the down hole break time with a surface break time established at an
activation of a source.
- 20 15. The method of Claim 12, further comprising activating a source during an addition or
subtraction of a drill pipe section to the drill string.
16. The method of Claim 12, further comprising determining wellbore parameters via a
down hole sensor.
17. A wellbore tool comprising:
25 a strain gauge configured to detect strain signals traveling within the tool;
a subsurface wave sensor configured to detect subsurface waves;
wherein noise in a subsurface wave measurement is reduced by discriminating out the
impact of strain signals on the subsurface wave sensor.
18. The tool of Claim 17, wherein the subsurface wave sensor is at least one of a
30 hydrophone or a geophone.
19. The tool of Claim 17, wherein the subsurface waves comprise earth waves traveling
through earth and drill string waves traveling through the tool, and wherein the strain signals are
drill string waves.

20. The tool of Claim 17, wherein the wellbore tool further comprises a down hole clock for determining a down hole break time.

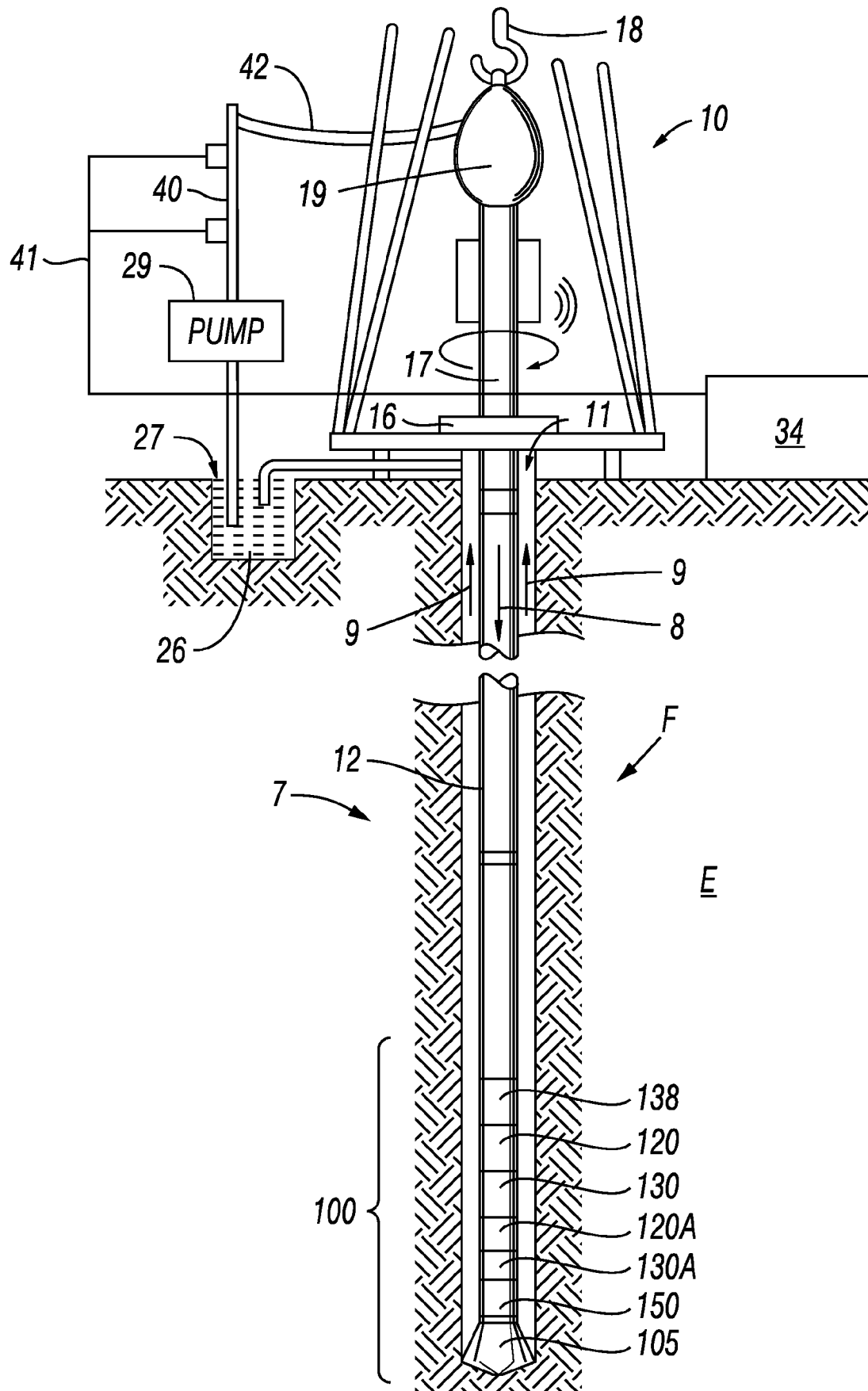


FIG. 1

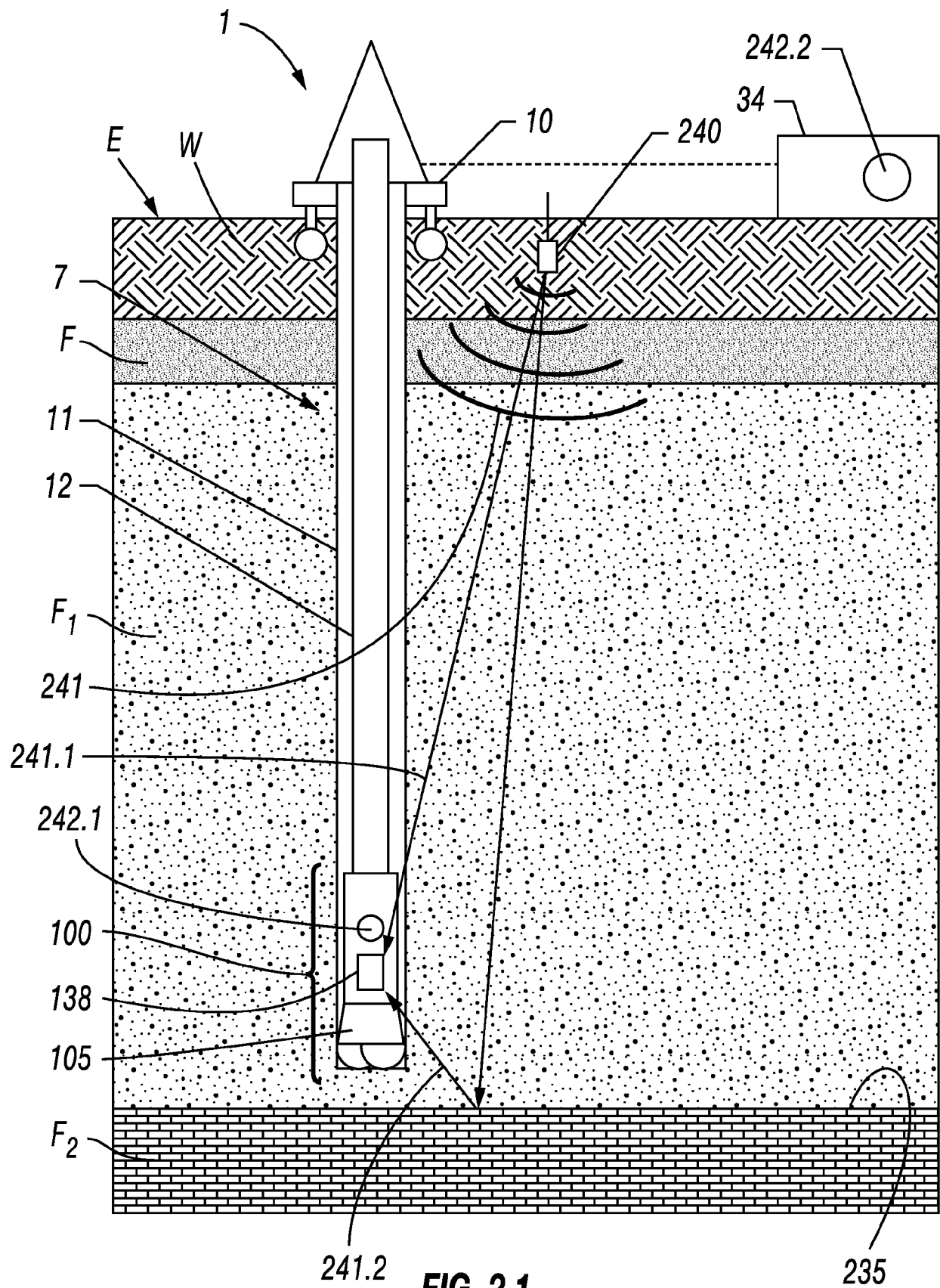


FIG. 2.1

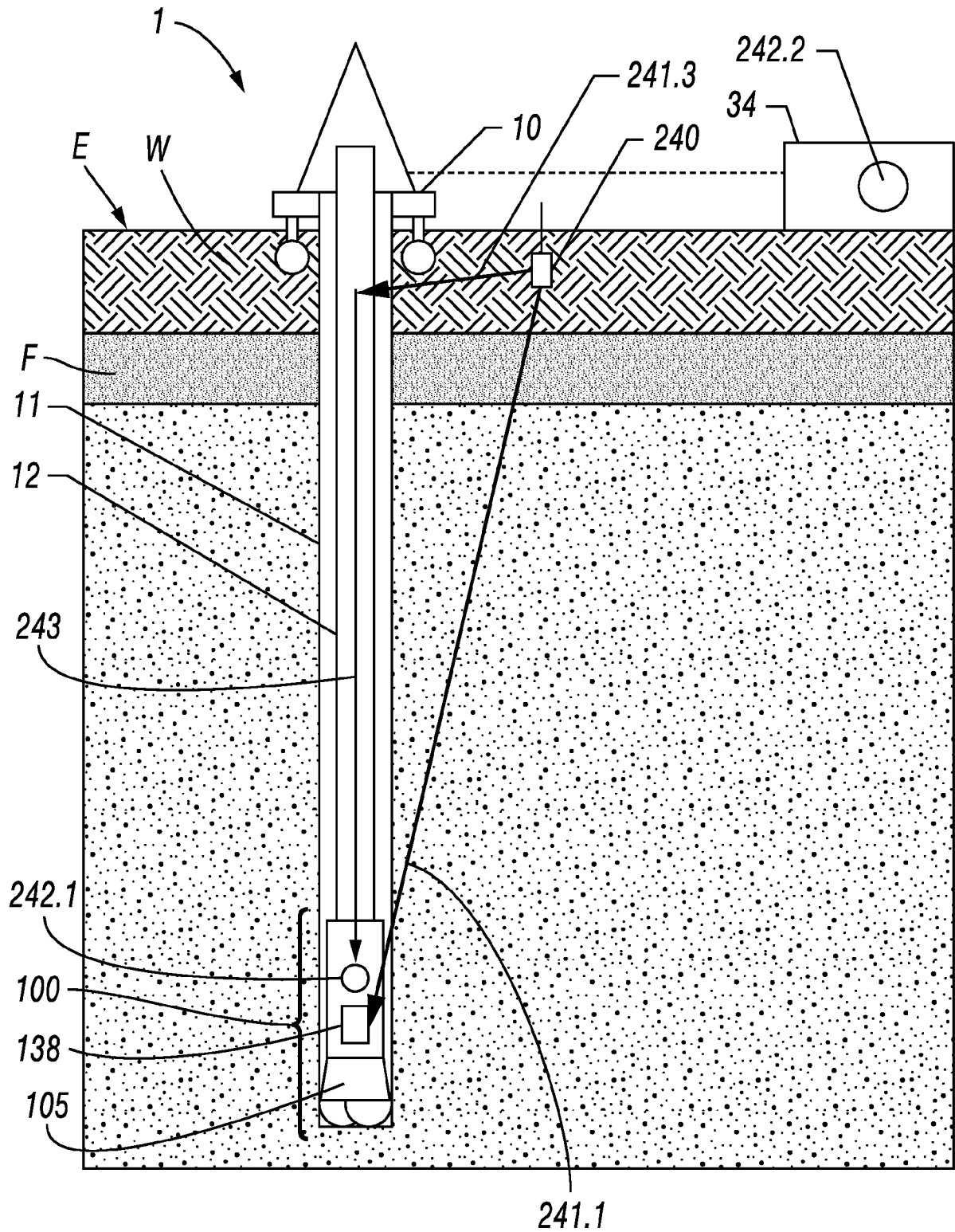


FIG. 2.2

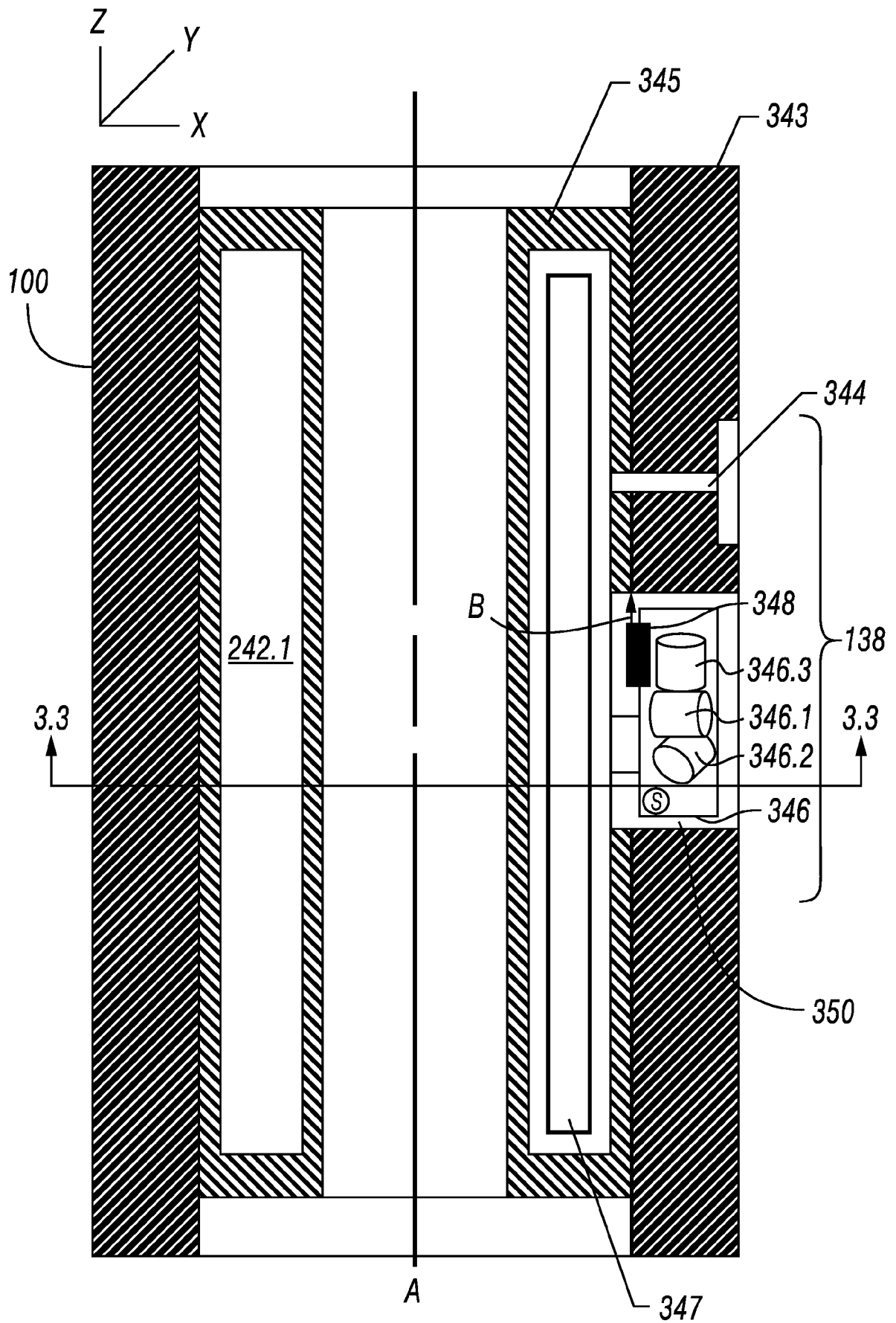
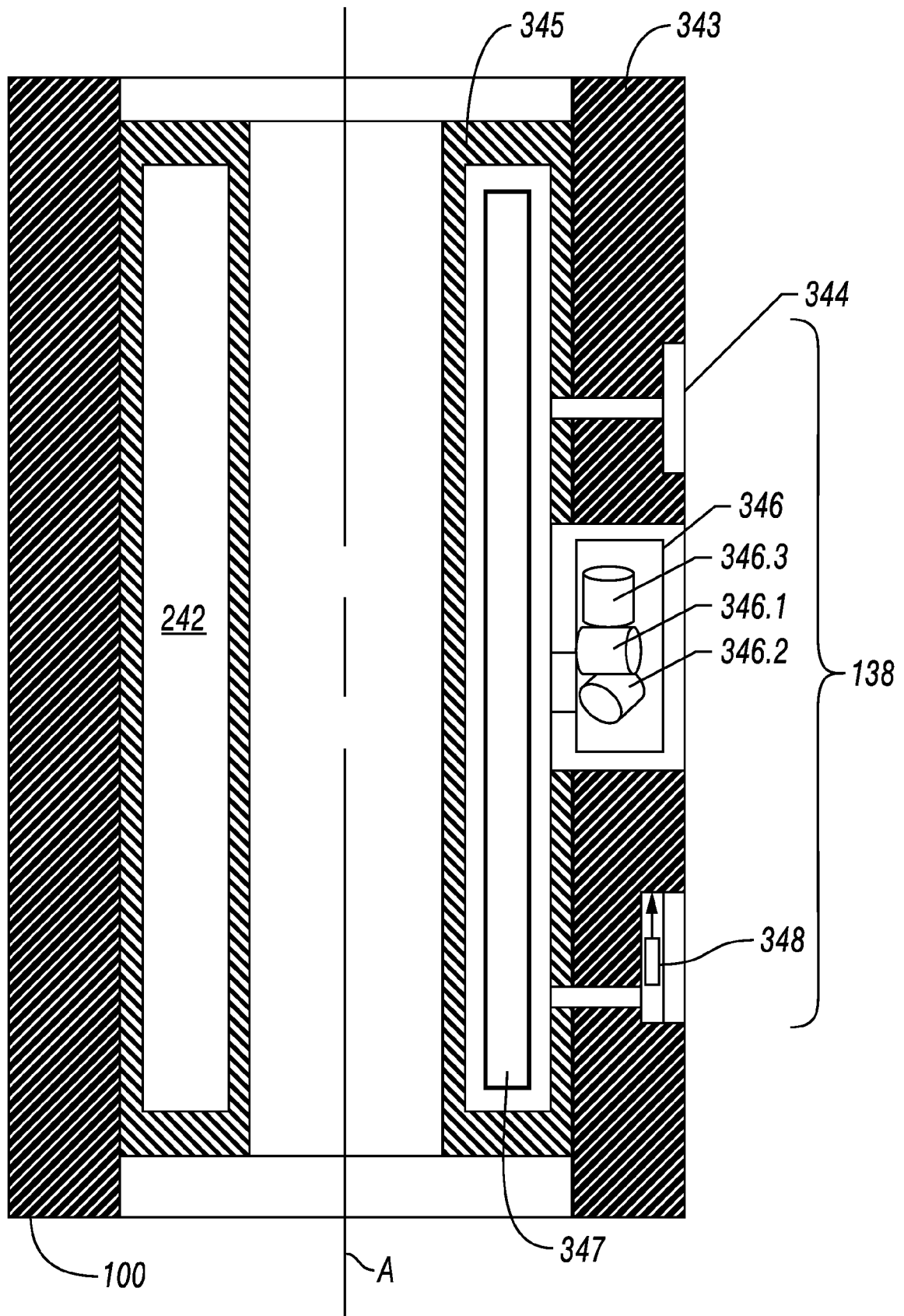


FIG. 3.1

**FIG. 3.2**

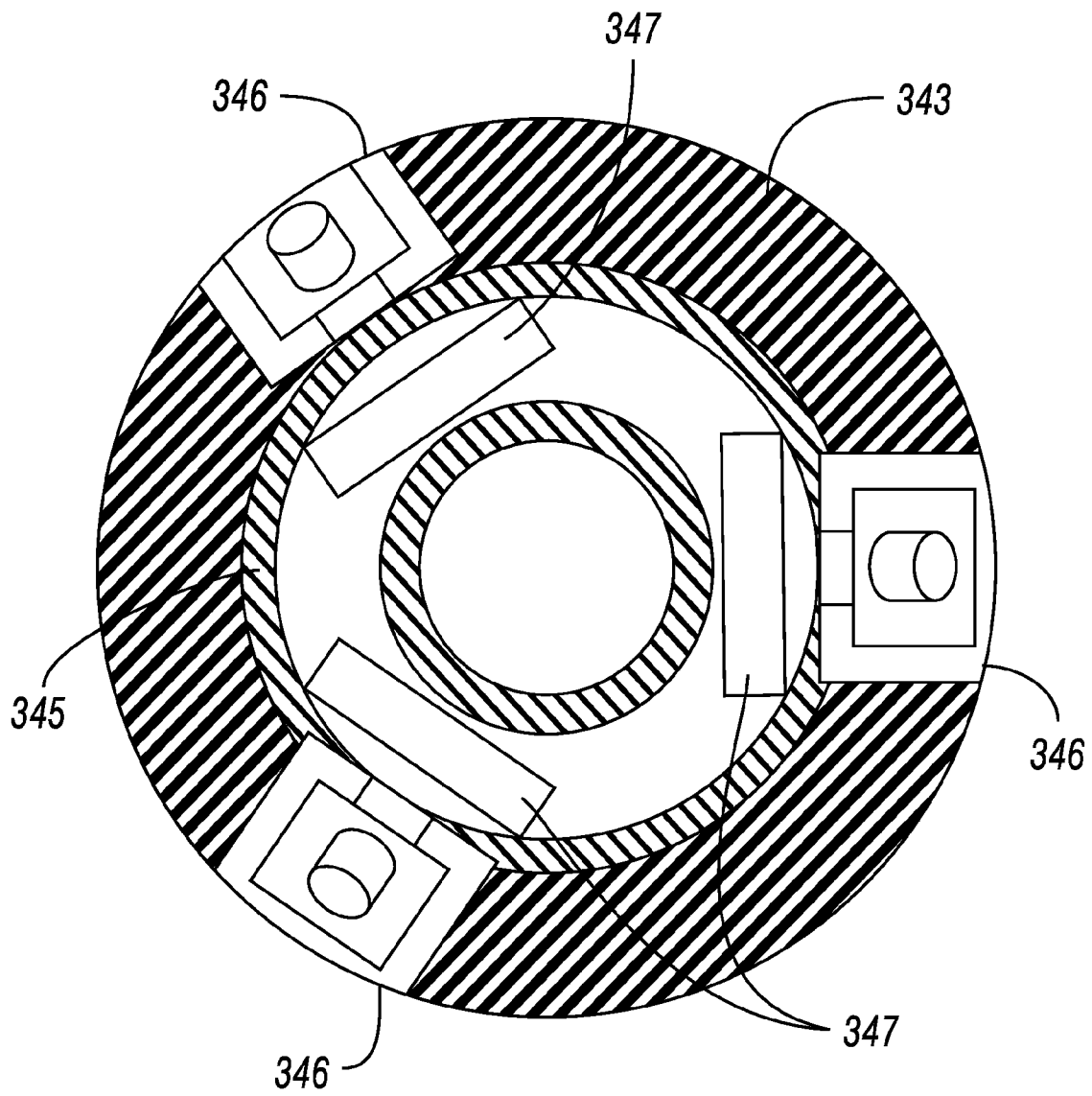


FIG. 3.3

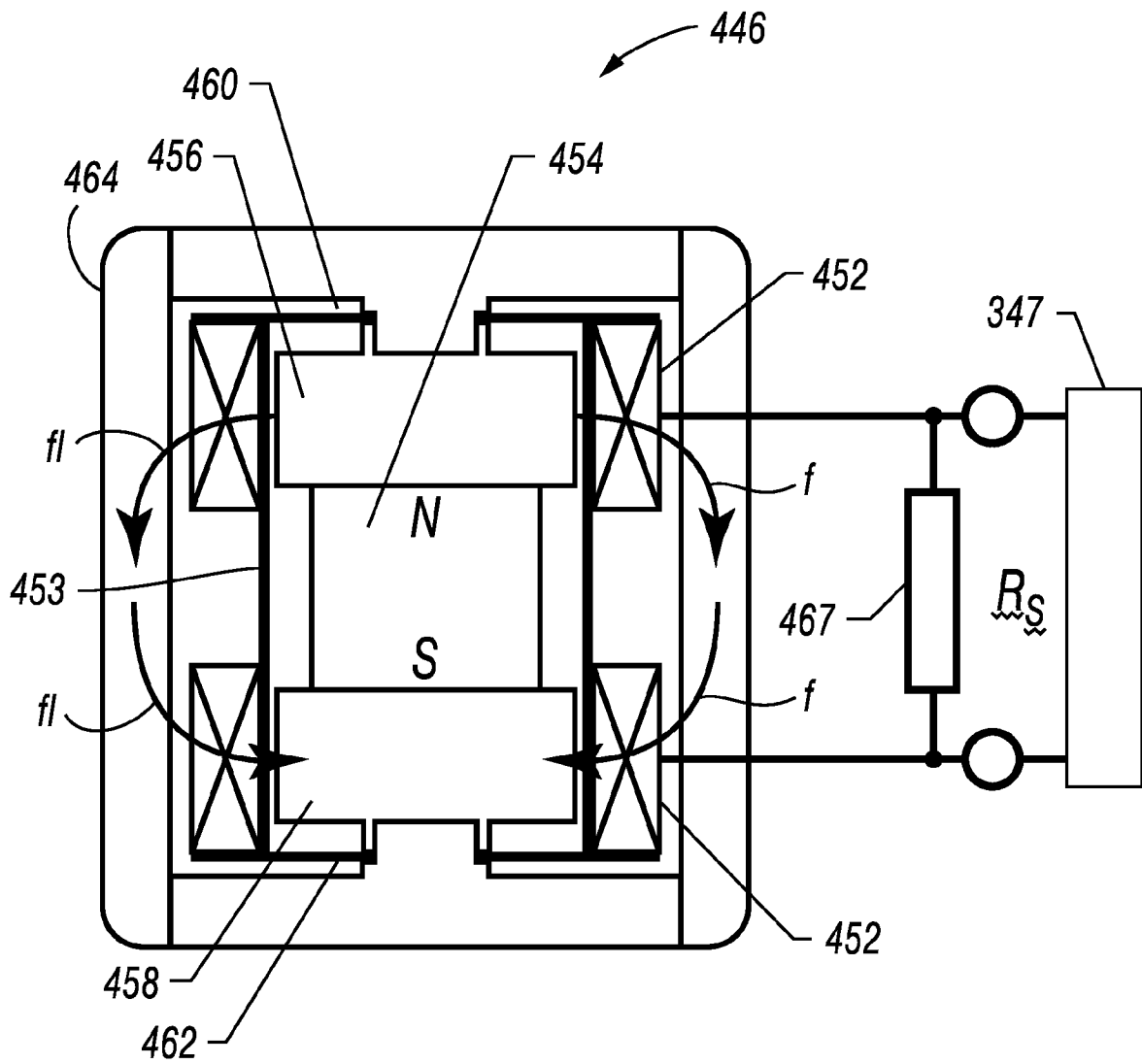


FIG. 4

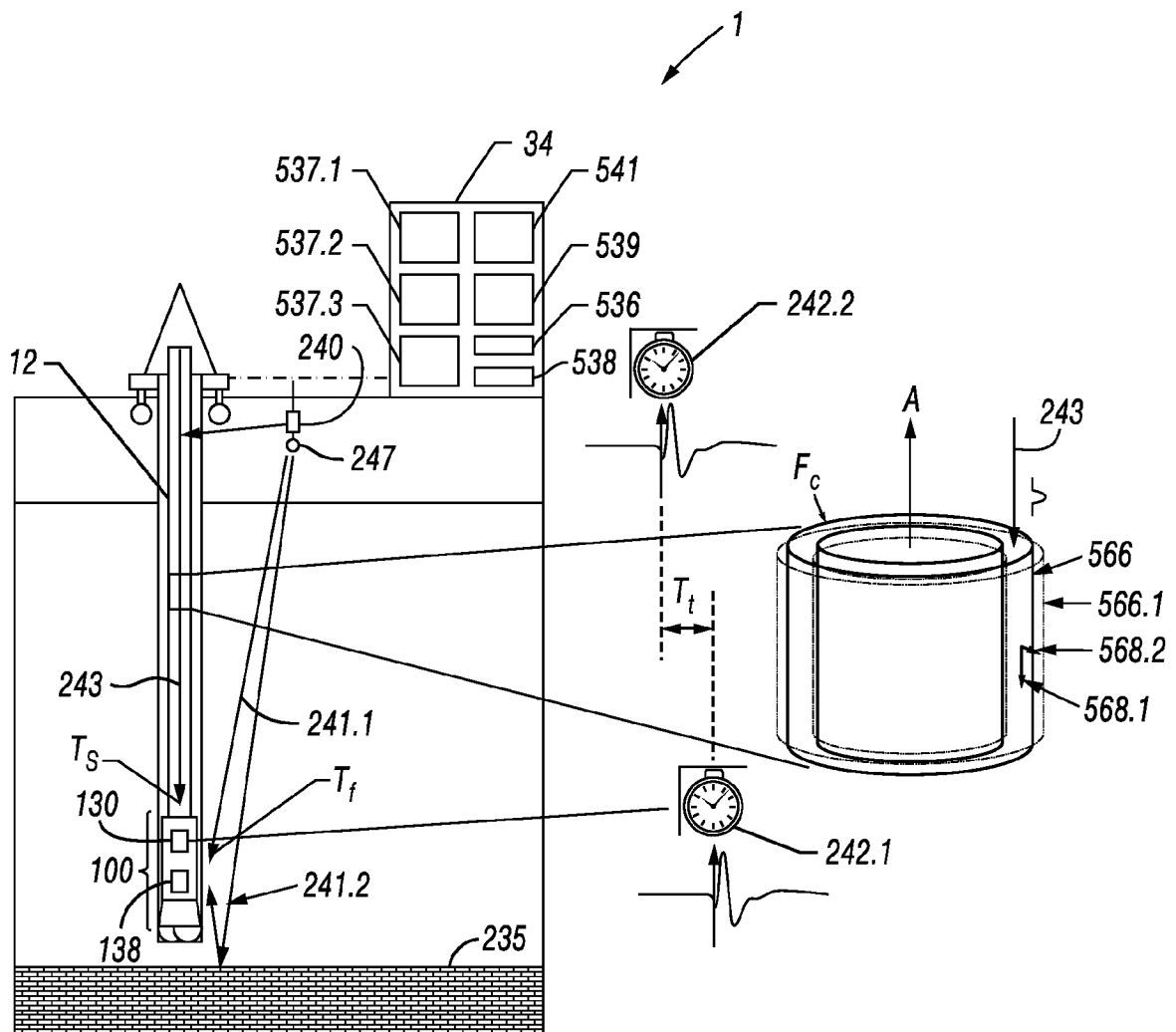
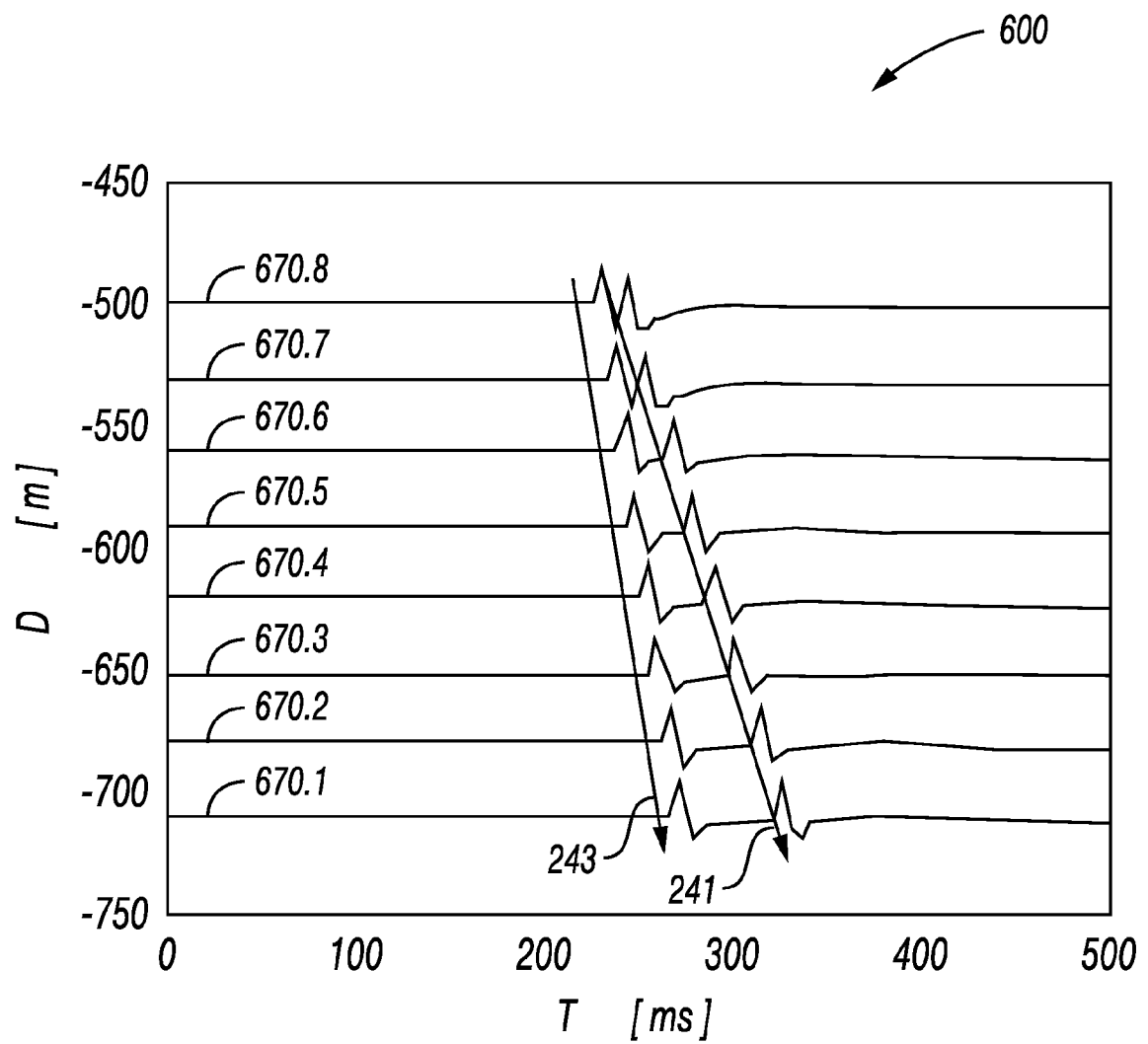
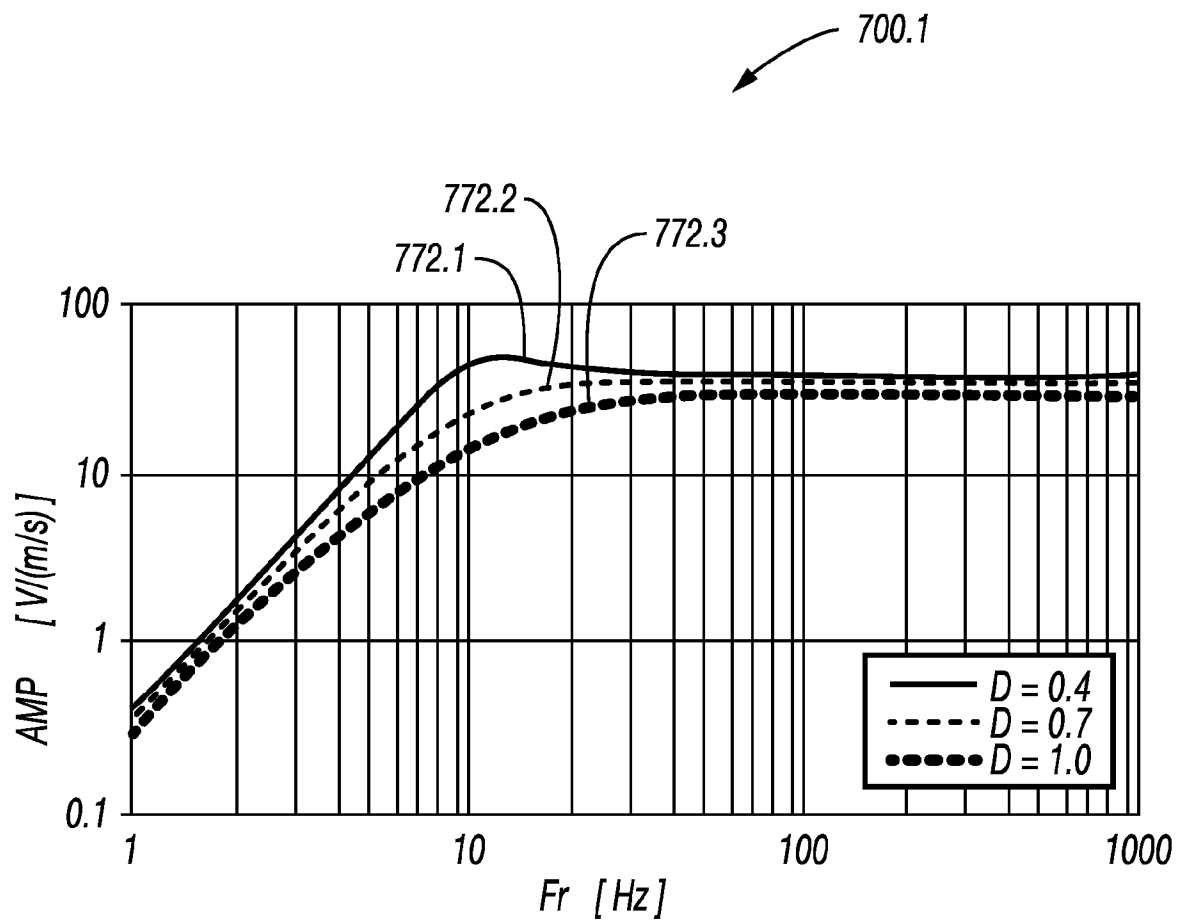
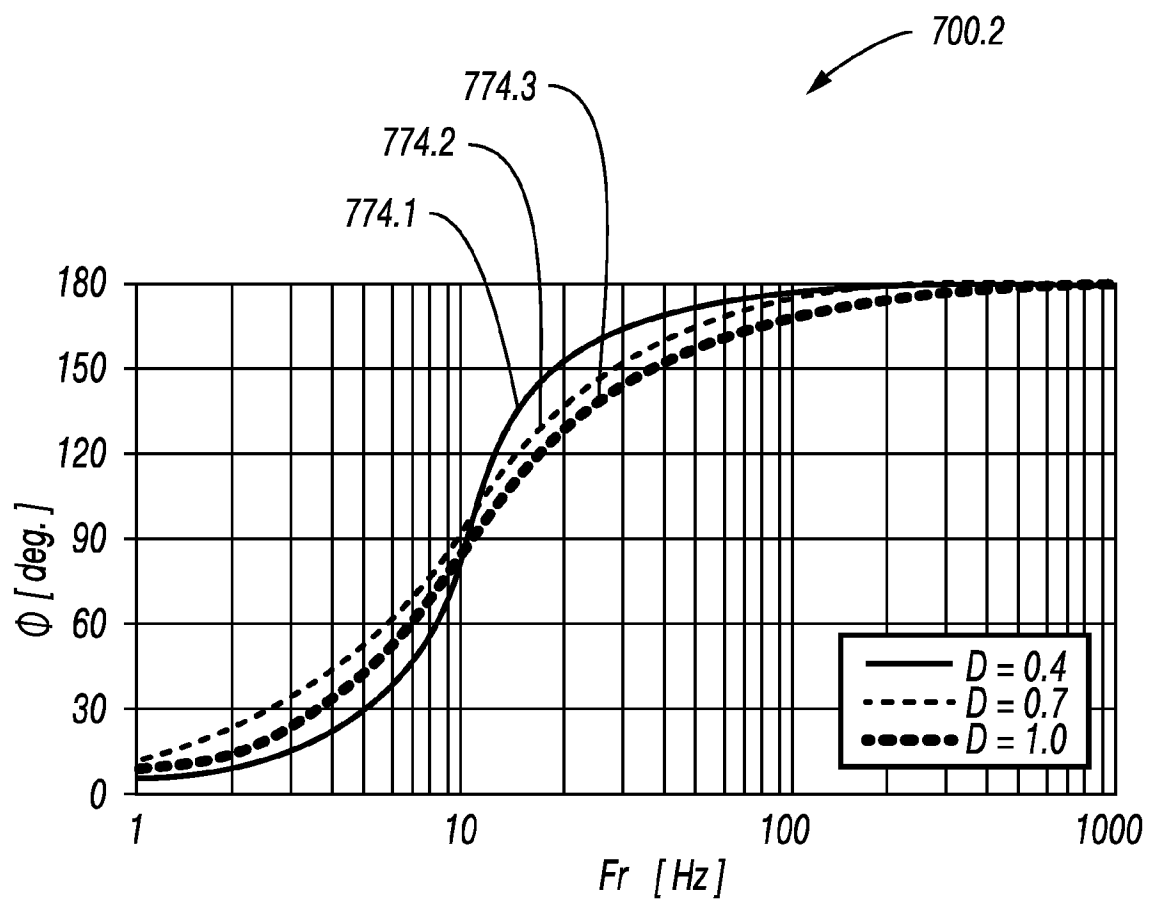
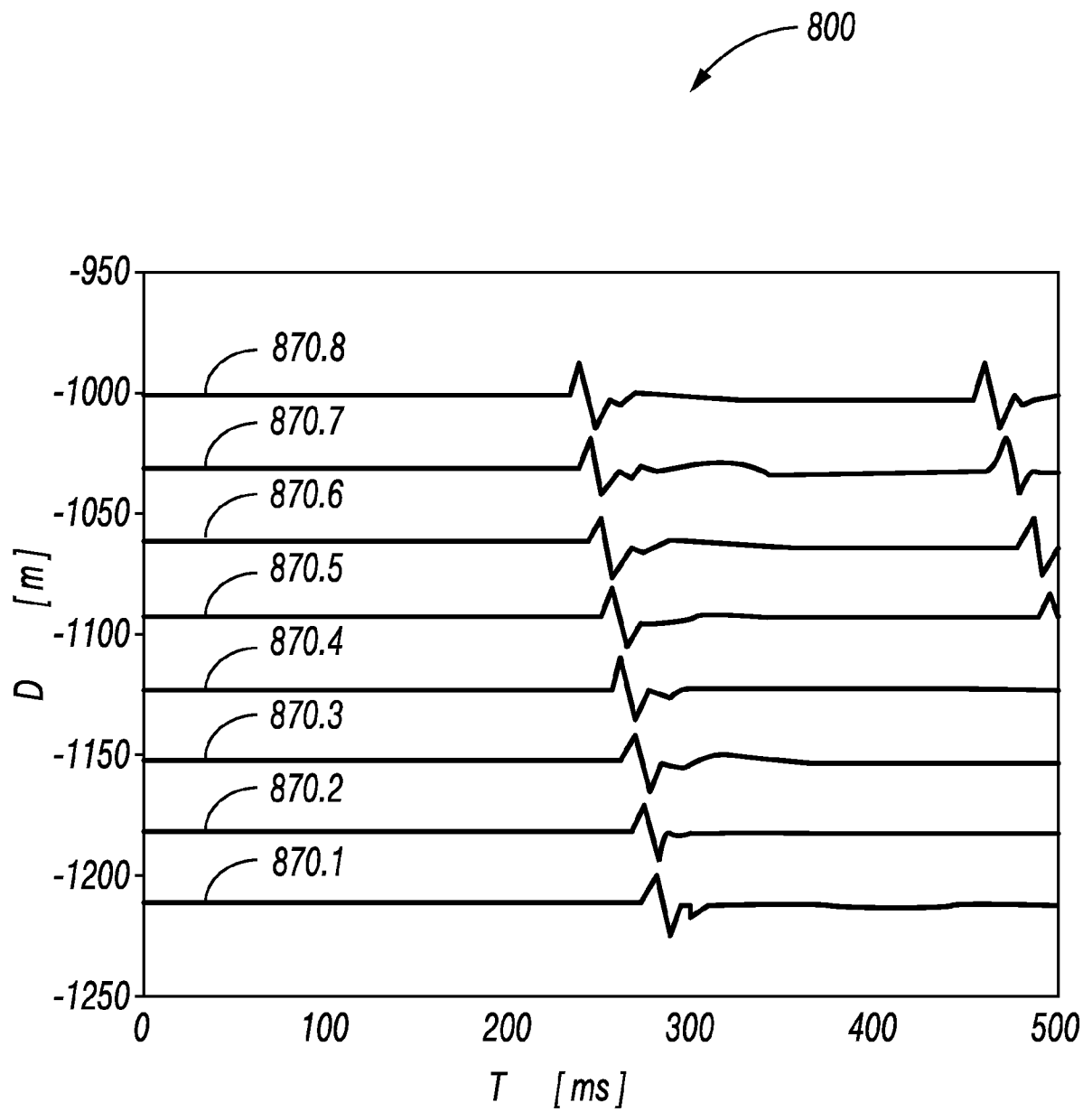


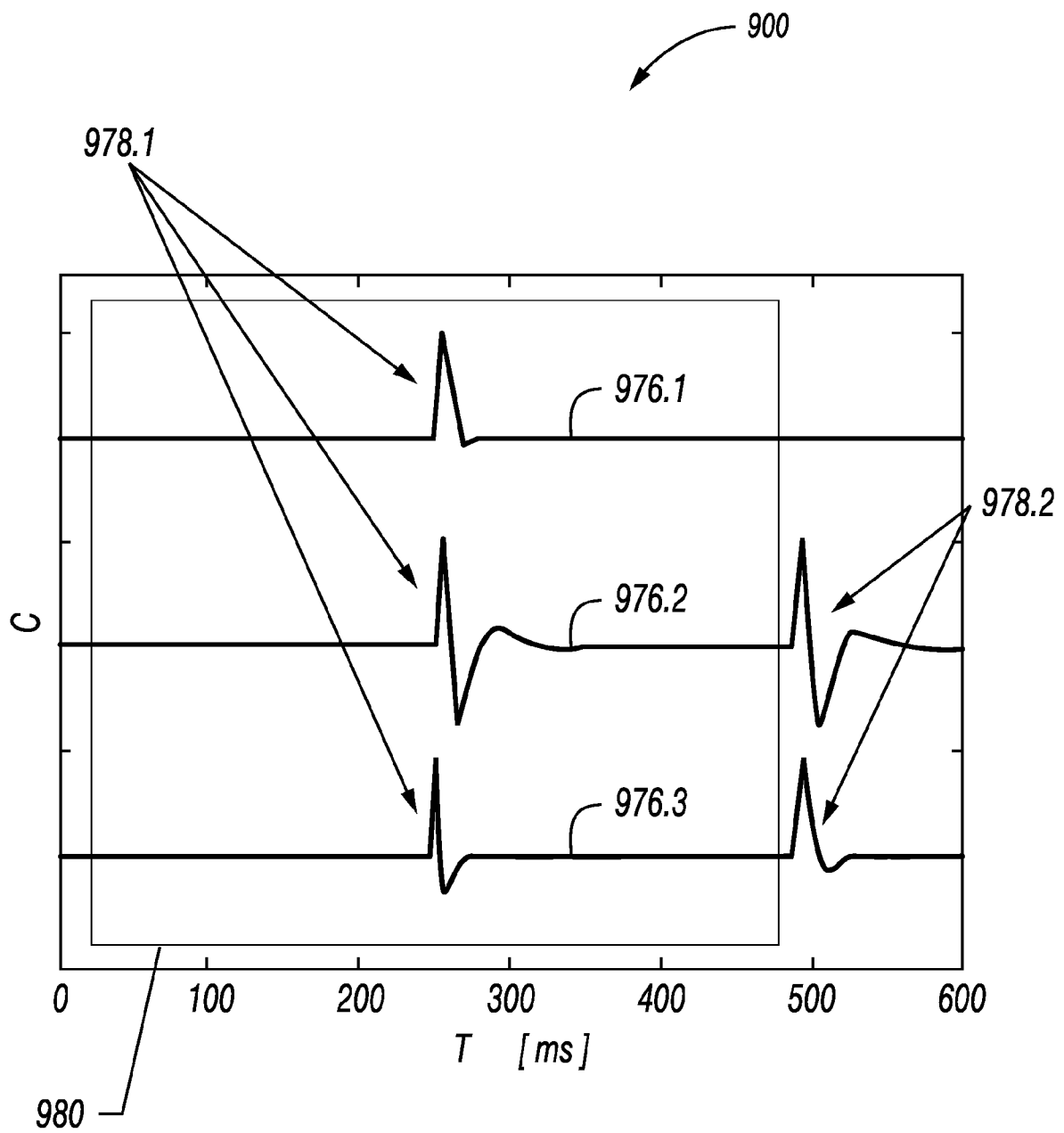
FIG. 5

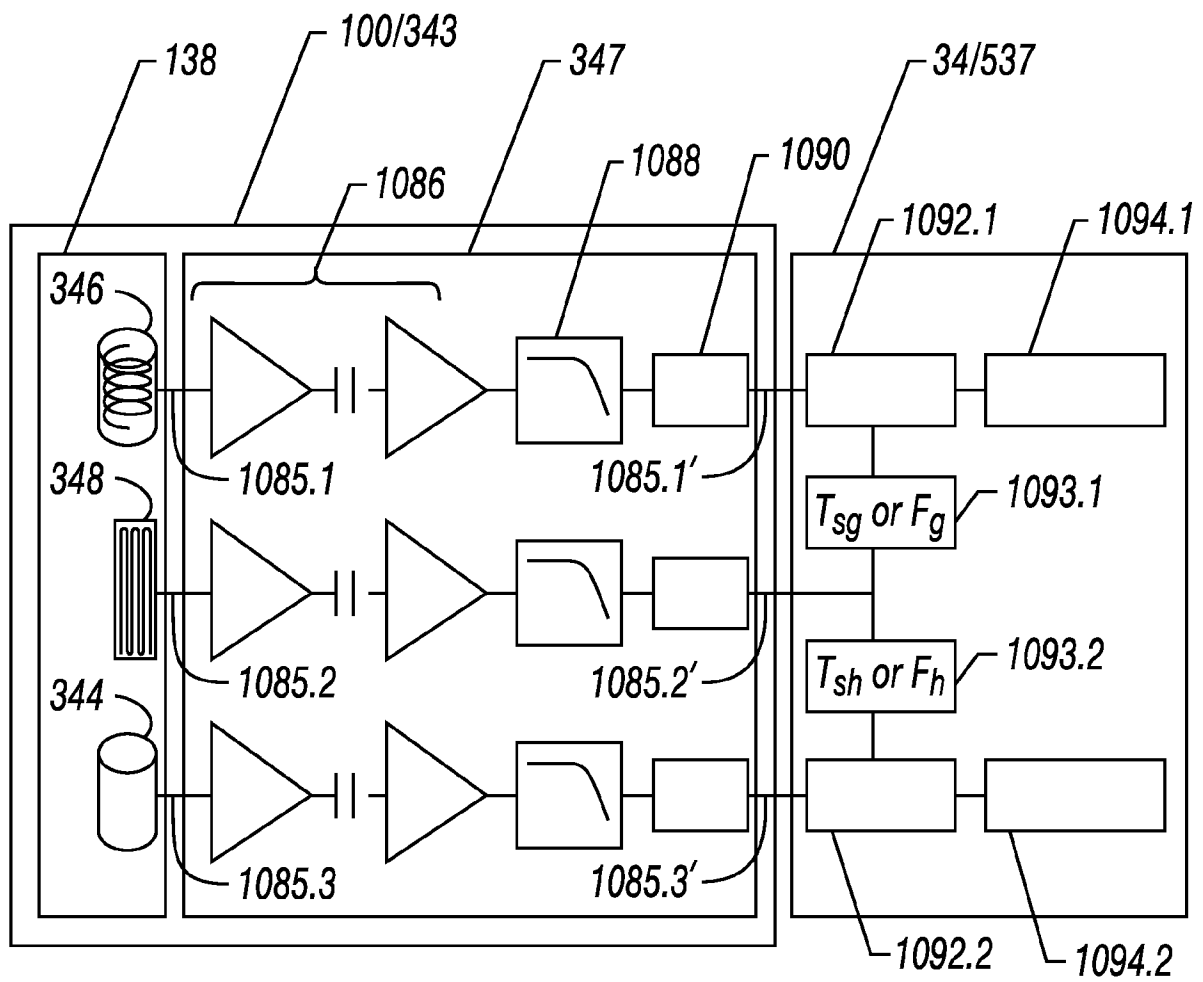
**FIG. 6**

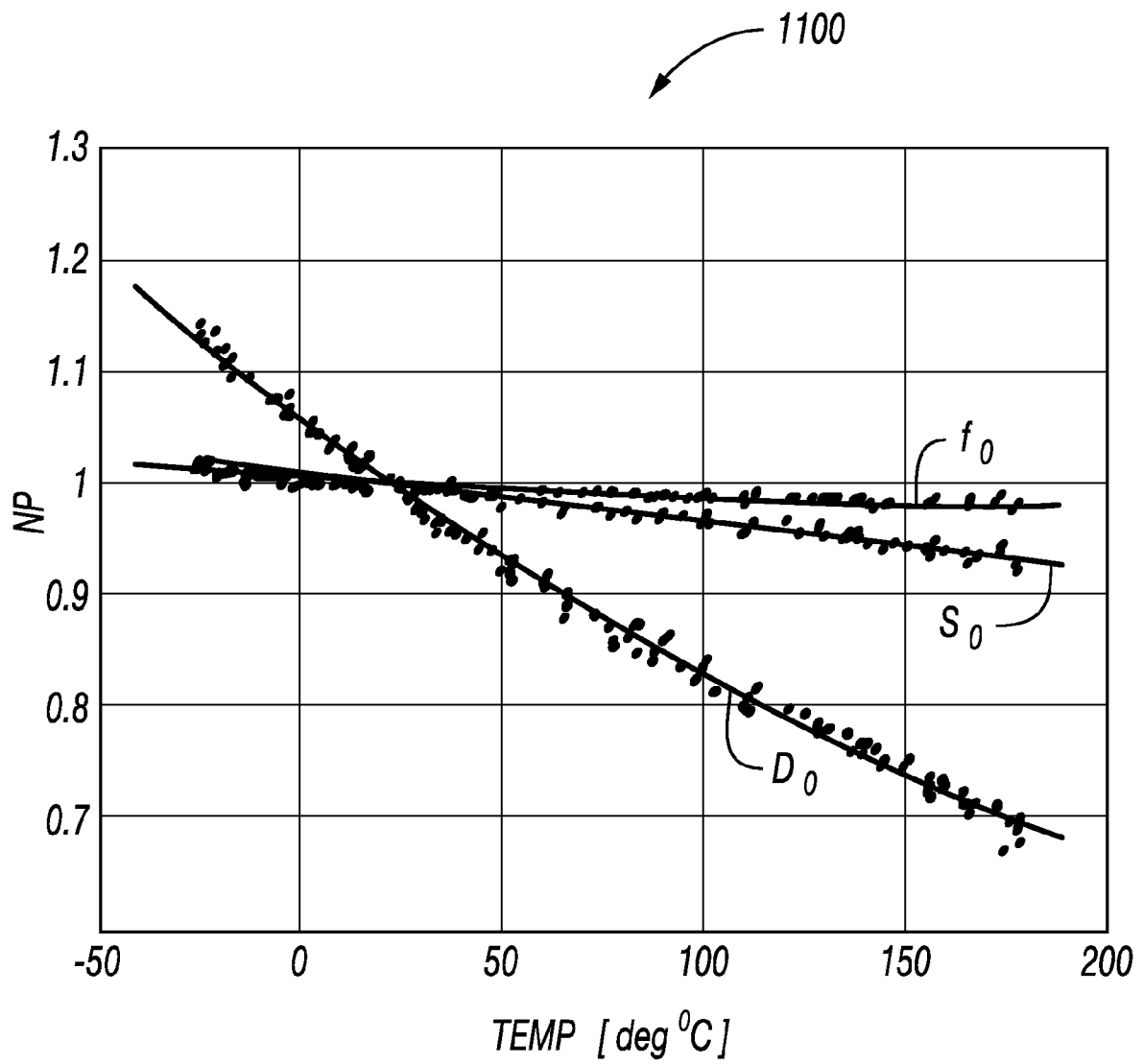
**FIG. 7.1**

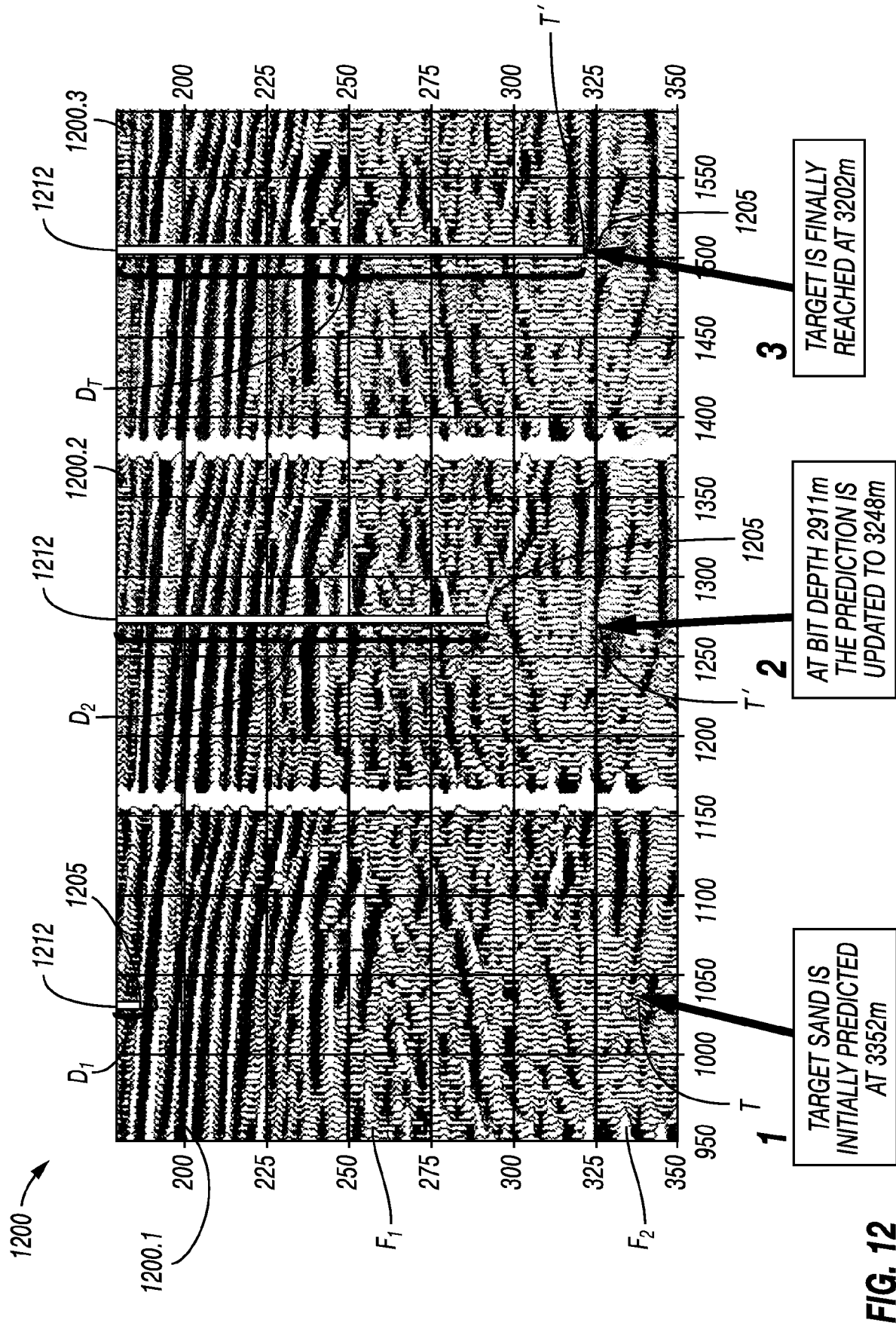
**FIG. 7.2**

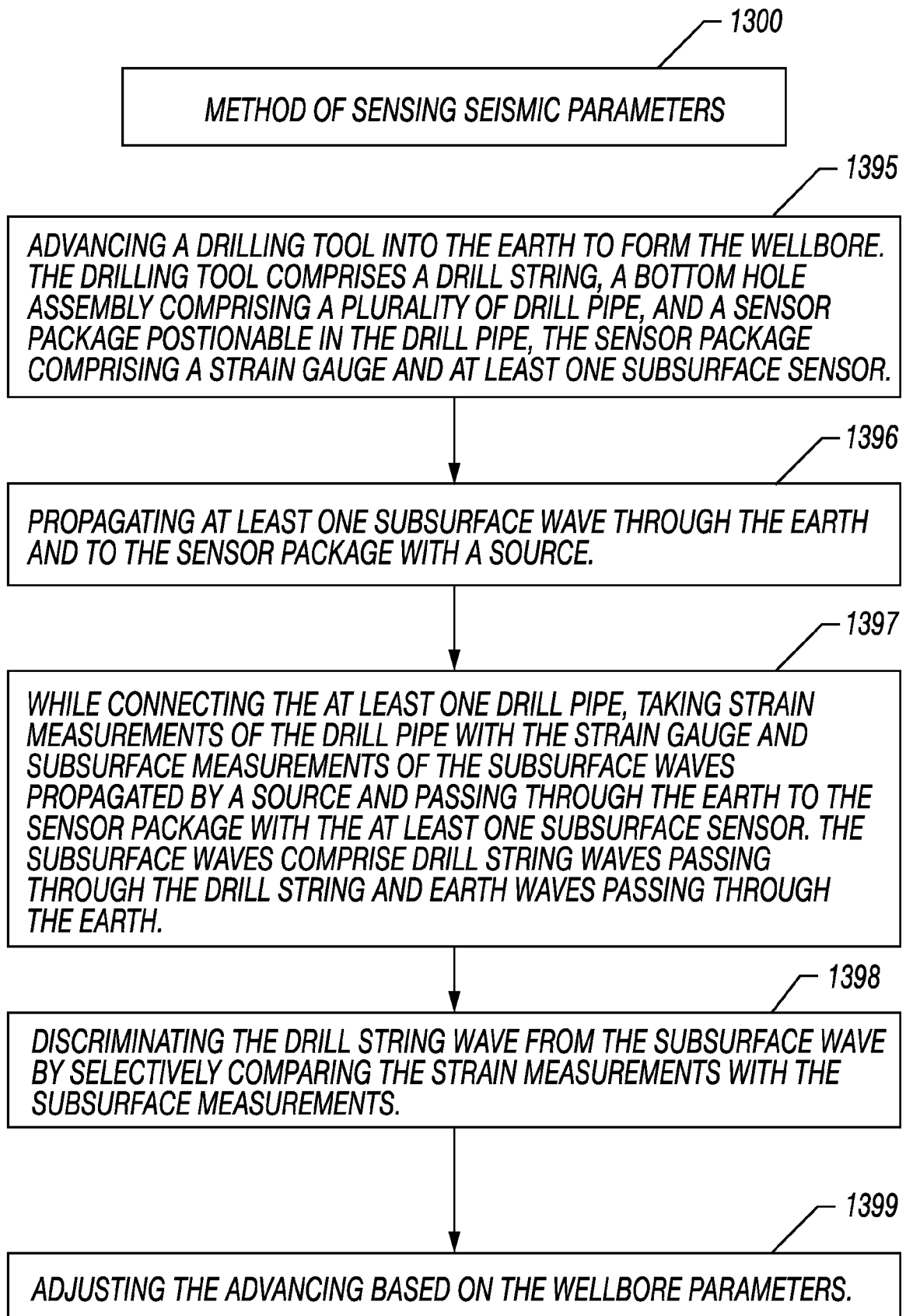
**FIG. 8**

**FIG. 9**

**FIG. 10**

**FIG. 11**



**FIG. 13**

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/027013**A. CLASSIFICATION OF SUBJECT MATTER****E21B 47/00(2006.01)i, G01V 1/40(2006.01)i, G01V 1/50(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B 47/00; G01V 1/24; E21B 7/128; G01V 3/00; G01V 1/40; G01V 1/18; G01V 1/50

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: earth wave, sensor package, strain gauge, subsurface sensor, drill string wave, hydrophone, geophone, surface clock, and down hole clock

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2008-0217057 A1 (HALL et al.) 11 September 2008 See paragraphs [0016], [0019]-[0022], [0026], [0029], [0034], [0039] and figures 1, 3, 6, 8.	1-20
Y	WO 2013-185225 A1 (KOBOLD SERVICES INC.) 19 December 2013 See page 4, lines 10-18; page 7, lines 10-22; page 13, lines 3-16; page 15, lines 5-20 and figures 1A-3C.	1-20
A	US 5818352 A (MCCLURE, PAUL ANTHONY) 06 October 1998 See column 5, lines 5-24 and figure 2.	1-20
A	US 2005-0052949 A1 (GASTON et al.) 10 March 2005 See paragraphs [0023]-[0030] and figures 2-5.	1-20
A	US 8640790 B2 (MACDOUGALL et al.) 04 February 2014 See column 7, line 59 - column 8, line 23; column 16, line 53 - column 17, line 49 and figures 1-3, 9.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

23 July 2015 (23.07.2015)

Date of mailing of the international search report

23 July 2015 (23.07.2015)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/027013

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