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(71) Applicant: **Camco International (UK) Limited**
Stonehouse, Gloucestershire GL10 3RQ (GB)

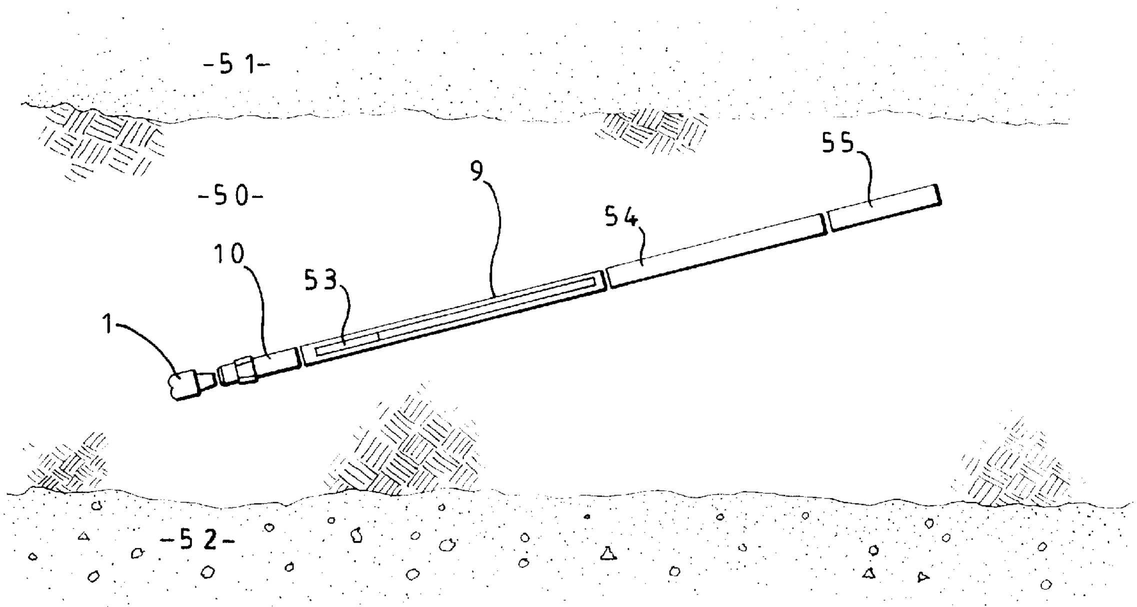
(72) Inventor: **Barr, John Denzil**
Cheltenham, Gloucestershire (GB)

(74) Representative: **Carter, Gerald et al**
Arthur R. Davies & Co.
27 Imperial Square
Cheltenham, Gloucestershire GL50 1RQ (GB)

(54) Steerable rotary drilling system

(57) A steerable rotary drilling system comprises a bottom hole assembly which includes a drill bit (1) and a bias unit (10) which is rotatable with the drill bit and includes peripheral actuators (13) which are displaceable laterally as the bias unit rotates to impart a lateral bias to the drill bit. A roll stabilised control unit (9) controls the displacement of the actuators (13) so as to control the direction of drilling. The bottom hole assembly also includes at least one geophysical sensor (53) which is responsive to a characteristic of the subsurface formation (51, 52) in the vicinity of the bottom hole assembly. The sensor (53) provides an output signal corresponding to the current value ofthe characteristic, and means are provided for automatically modifying the operation of the control unit (9), and hence operation of the rotatable bias unit (10), in response to said output signal, so that the direction in which the drill bit (1) is steered is influenced by the characteristic of the surrounding formation.

FIG 4



Description

The invention relates to steerable rotary drilling systems and provides, in particular, methods and apparatus for use with such systems for the acquisition of geophysical data concerning the nature and characteristics of the subsurface formation being drilled, and the use of such data as an input parameter for control of the direction of drilling.

As is well known, when drilling holes in subsurface formations, it is desirable to be able to vary and control the direction of drilling, for example to direct the borehole towards a desired target, or to control the direction generally horizontally within the payzone once the target has been reached.

Hitherto, fully controllable directional drilling has normally required the drill bit to be rotated by a downhole motor. The drill bit may, for example, be coupled to the motor by a double tilt unit whereby the central axis of the drill bit is inclined to the axis of the motor. During normal drilling the effect of this inclination is nullified by continual rotation ofthe drill string, and hence the motor casing, as the bit is rotated by the motor. When variation of the direction of drilling is required, the rotation of the drill bit is stopped with the bit tilted in the required direction. Continued rotation of the drill bit by the motor then causes the bit to drill in that direction.

Although such arrangements can, under favourable conditions, allow accurately controlled directional drilling to be achieved, there are reasons why rotary drilling is sometimes to be preferred, particularly in long reach drilling, rotary drilling being a system in which a bottom hole assembly, including the drill bit, is connected to a drill string which is rotatably driven from the drilling platform at the surface. Various systems have been proposed for achieving fully steerable rotary drilling.

The present invention relates to steerable rotary drilling systems of the kind where the bottom hole assembly includes a drill bit, a bias unit rotatable with the drill bit and including one or more actuators which are displaceable laterally as the bias unit rotates to impart a lateral bias to the drill bit, and a control unit to control the displacement of the actuators and thereby control the direction of drilling.

One form of steerable rotary drilling system ofthis kind is described and claimed, for example, in British Patent Specification No. 2259316. One form of control unit for use in such a system is described and claimed in British Patent Specification No. 2257182.

In the course of operating a steerable rotary drilling system it is necessary to obtain data concerning the operating parameters of the bottom hole assembly. For example, it may be required to obtain information concerning the status of the equipment including the control unit and bias unit, or information concerning the command status, that is to say the instructions which the control unit is giving to the bias unit. Furthermore, it is usually also required to obtain survey information regarding the azimuth and inclination of part of the bottom hole assembly, or the roll angle of the control unit. For example, the bottom hole assembly may include sensors such as inclinometers and/or magnetometers which supply calibrated survey data. Finally, it may able desirable to obtain data regarding the characteristics of the formation through which the bottom hole assembly is passing. Thus, the bottom hole assembly may include sensors, such as gamma ray detectors, neutron formation sensors or resistivity sensors.

U.S. Patents Nos. 5325714, 5467832 and 5448227 disclose arrangements for formation evaluation in the course of drilling using a downhole motor assembly, and U.S. 5419405 discloses detection of a subterranean target when rotary drilling using a non-rotating controllable stabiliser downhole to control the direction of drilling.

In existing arrangements the data derived from the downhole surveying, geophysical and other sensors are normally transmitted to the surface and are taken into account by an operator who controls the direction of drilling by means of signals sent downhole from the surface. However, U.S. 5419405 also discloses the use of an output signal from the means for detecting a subterranean target as an input parameter to means for automatically controlling the direction of drilling.

The present invention relates to the use of formation evaluation data in a steerable rotary drilling system of the kind first referred to.

According to a first aspect of the invention there is provided a steerable rotary drilling system where the bottom hole assembly includes a drill bit, a bias unit rotatable with the drill bit and including one or more actuators which are displaceable laterally as the bias unit rotates to impart a lateral bias to the drill bit, and a control unit to control the displacement of said actuator and thereby control the direction of drilling, the bottom hole assembly further including at least one geophysical sensor responsive to a characteristic of formation or formations in the vicinity of the bottom hole assembly, said sensor providing an output signal corresponding to the current value of said characteristic, and means for automatically modifying the operation of the control unit, and hence operation of the rotatable bias unit, in response to said output signal.

Thus, according to the invention, the path of the borehole drilled by the bit may be automatically and accurately controlled to be the optimum path given the nature of the surrounding formation. For example, it frequently occurs that the borehole is required to extend generally horizontally through a comparatively shallow reservoir of hydrocarbon-bearing formation. The formation evaluation sensors may then locate the upper and lower boundaries of the formation and the input to the control unit may then be used automatically to maintain the drill bit at an optimum level between the upper and/or lower boundaries, as will be described.

Said means for automatically modifying the operation of the control unit are preferably located in the bottom hole assembly. For example said means may be located in the control unit itself. Such arrangement enables the control loop to be closed downhole thus avoiding the necessity and difficulties of frequent transmission of the formation evaluation data to the surface so that the appropriate control signals may then be transmitted downhole from the surface. Closing the control loop downhole enables the data to be sampled, and control signals generated, at higher frequencies than is the case where the data signals have to be sent to the surface, resulting in better, smoother control of the direction of drilling. However, in the case where the control loop is closed downhole, it may well be desirable for information also to be transmitted to the surface occasionally, using any of the well known current methods of data transmission, so that the automatic operation and steering of the bottom hole assembly can be monitored and operator-controlled corrections made if necessary.

In any of the arrangements according to the invention one or more of the geophysical sensors may also be located in the control unit itself. Alternatively, one or more of the sensors may be located elsewhere in the bottom hole assembly, data from said sensors being transmitted to the control unit by a short range downhole transmission system of any of the kinds currently employed.

Although the invention relates to any steerable rotary drilling system having a rotatable bias unit, as first referred to, the bias unit is preferably a synchronous modulated bias unit where the control unit may cause the actuators to be displaced in synchronism with rotation of the bias unit, and in selected phase relation thereto, whereby, as the bit and bias unit rotate, the or each actuator is displaced outwardly at the same selected rotational position so as to bias the bias unit and drill bit laterally and thereby control the direction of drilling.

The control unit may comprise an instrument carrier which can be roll stabilised so as to remain substantially non-rotating in space, the direction of bias of the bias unit being determined by the rotational orientation of the instrument carrier. Alternatively, the control unit may be strapped-down, i.e. rotatable with the bias unit.

According to another aspect of the present invention, there is provided a steerable rotary drilling system where the bottom hole assembly includes a drill bit, a bias unit rotatable with the drill bit and including one or more actuators which are displaceable laterally as the bias unit rotates to impart a lateral bias to the drill bit, and a control unit to control the displacement of said actuator and thereby control the direction of drilling, the bottom hole assembly including at least one geophysical sensor responsive to a characteristic of formation in the vicinity of the bottom hole assembly, said sensor providing an output signal corresponding to the current value of said characteristic, and being located in the control unit.

In any of the arrangements according to the present invention, the geophysical sensor may be a gamma sensor adapted to detect natural gamma ray emissions from the formation. As is well known, the formation, usually shale, above a target hydrocarbon-bearing formation will normally have a relatively high level of natural radioactivity which will be detected by the gamma sensor. The output signal from the gamma sensor may thus be used to obtain information about the position of the borehole in relation to the upper boundary of the hydrocarbon-bearing formation and to control the path of the borehole so as to maintain it in the upper region of the formation.

Alternatively, the gamma sensor may comprise a gamma ray source and detector so that gamma rays from the source are reflected from the surrounding formation and are received by the detector, the attenuation of the gamma rays then being a measure of the density of the formation. Such an arrangement is described in US 5134285.

Similarly the geophysical sensors may include a neutron emission source and a detector for measuring the porosity of the formation as described in U.S. 5144126. In this case, high energy neutrons from the emission source pass into the formation and the depletion of the neutron energy, measured by the detector, is an indication of the amount of hydrogen in the formation, which in turn is an indication of its porosity.

The geophysical sensors may also include an electrical resistivity sensor as described, for example, in U. S. 5001675. In this case an electro-magnetic wave is emitted from a suitable transmitter and the returning signals received by a detector enable the resistivity of the surrounding formation to be determined.

Another form of sensor is a sonic sensor which measures the velocity of a sound wave propagated through the formation, to derive information concerning its density and elasticity.

Another type of sonic sensor comprises a sound wave emitter and a detector to sense the sound waves reflected from the surrounding formation, such arrangement being used to locate boundaries in the formation from which the sound waves are reflected.

The following is a description of embodiments of the invention, reference being made to the accompanying drawings in which:

Figure 1 is a diagrammatic sectional representation of a deep hole drilling installation,

Figure 2 is a part-longitudinal section, part side elevation of a modulated bias unit according to the present invention,

Figure 3 is a diagrammatic longitudinal section through a control unit for the bias unit to Figures 1 and 2, and

Figure 4 is a diagrammatic representation of a bottom hole assembly of a drilling system in accordance with the present invention.

Figure 1 shows diagrammatically a typical rotary drilling installation of a kind in which the present invention may be employed.

As is well known, the bottom hole assembly includes a drill bit 1, and is connected to the lower end of a drill string 2 which is rotatably driven from the surface by a rotary table 3 on a drilling platform 4. The rotary table is driven by a drive motor indicated diagrammatically at 5 and raising and lowering of the drill string, and application of weight-on-bit, is under the control of draw works indicated diagrammatically at 6.

The bottom hole assembly includes a modulated bias unit 10 to which the drill bit 1 is connected and a roll stabilised control unit 9 which controls operation of the bias unit 10 in accordance with an on-board computer program, and/or in accordance with signals transmitted to the control unit from the surface. The bias unit 10 can be controlled to apply a lateral bias to the drill bit 1 in a desired direction so as to control the direction of drilling.

Referring to Figure 2, the bias unit 10 comprises an elongate main body structure provided at its upper end with a threaded pin 11 for connecting the unit to a drill collar, incorporating the roll stabilised control unit 9, which is in turn connected to the lower end of the drill string. The lower end 12 of the body structure is formed with a socket to receive the threaded pin ofthe rotary drill bit. The drill bit may be of any rotary type.

There are provided around the periphery of the bias unit, towards its lower end, three equally spaced hydraulic actuators 13. Each hydraulic actuator 13 is supplied with drilling fluid under pressure through a respective passage 14 under the control of a rotatable disc control valve 15 located in a cavity 16 in the body structure of the bias unit. Drilling fluid delivered under pressure downwardly through the interior of the drill string, in the normal manner, passes into a central passage 17 in the upper part of the bias unit, through a filter 18 consisting of closely spaced longitudinal wires, and through an inlet 19 into the upper end of a vertical multiple choke unit 20 through which the drilling fluid is delivered downwardly at an appropriate pressure to the cavity 16.

The disc control valve 15 is controlled by an axial shaft 21 which is connected by a coupling 22 to the output shaft of the roll stabilised control unit 9.

The roll stabilised control unit maintains the shaft 21 substantially stationary at a rotational orientation which is selected, either from the surface or by a downhole computer program, according to the direction in which the drill bit is to be steered. As the bias unit rotates around the stationary shaft 21 the disc valve 15 operates to deliver drilling fluid under pressure to the three hydraulic actuators 13 in succession. The hydraulic actuators are thus operated in succession as the bias unit rotates, each in the same rotational position so as to displace the bias unit laterally in a selected direction. The selected rotational position of the shaft 21 in space thus determines the direction in which the bias unit is actually displaced and hence the direction in which the drill bit is steered.

Figure 3 shows diagrammatically, in greater detail, one form of roll stabilised control unit for controlling a bias unit of the kind shown in Figure 2. Other forms of roll stabilised control unit are described in British Patent Specification No. 2257182, and in co-pending Application No. 9503828.7

Referring to Figure 3, the support for the control unit comprises a tubular drill collar 23 forming part of the drill string. The control unit comprises an elongate generally cylindrical hollow instrument carrier 24 mounted in bearings 25, 26 supported within the drill collar 23, for rotation relative to the drill collar 23 about the central longitudinal axis thereof. The carrier has one or more internal compartments which contain an instrument package 27 comprising sensors for sensing the rotation and orientation of the control unit, and associated equipment for processing signals from the sensors and controlling the rotation of the carrier.

At the lower end of the control unit a multi-bladed impeller 28 is rotatably mounted on the carrier 24. The impeller comprises a cylindrical sleeve 29 which encircles the carrier and is mounted in bearings 30 thereon. The blades 31 of the impeller are rigidly mounted on the lower end of the sleeve 29. During drilling operations the drill string, including the drill collar 23, will normally rotate clockwise, as indicated by the arrow 32, and the impeller 28 is so designed that it tends to be rotated anticlockwise as a result of the flow of drilling fluid down the interior of the collar 23 and across the impeller blades 31.

The impeller 28 is coupled to the instrument carrier 24, by an electrical torquer-generator. The sleeve 29 contains around its inner periphery a pole structure comprising an array of permanent magnets 33 cooperating with an armature 34 fixed within the carrier 24. The magnet/armature arrangement serves as a variable drive coupling between the impeller 28 and the carrier 24.

A second impeller 38 is mounted adjacent the upper end of the carrier 24. The second impeller is, like the first impeller 28, also coupled to the carrier 24 in such a manner that the torque it imparts to the carrier can be varied. The upper impeller 38 is generally similar in construction to the lower impeller 28 and comprises a cylindrical sleeve 39 which encircles the carrier casing and is mounted in bearings 40 thereon. The blades 41 of the impeller are rigidly mounted on the upper end of the sleeve 39. However, the blades of the upper impeller are so designed that the impeller tends to be rotated clockwise as a result of the flow of drilling fluid down the interior of the collar 23 and across the impeller blades 41.

Like the impeller 28, the impeller 38 is coupled the carrier 24 by an electrical torquer-generator. The sleeve 39 contains around its inner periphery an array of permanent magnets 42 cooperating with an armature 43 fixed within the carrier 24. The magnet/armature arrangement serves as a variable drive coupling between the impeller 38 and the carrier.

As the drill collar 23 rotates during drilling, the main bearings 25, 26 and the disc valve 15 of the bias unit apply a clockwise input torque to the carrier 24 and a further clockwise torque is applied by the upper impeller 38 through the torquer-generator 42,43 and its bearings 40. These clockwise torques are opposed by an anticlockwise torque applied to the carrier by the lower impeller 28. The torque applied to the carrier 24 by each impeller may be varied by varying the electrical load on each generator constituted by the magnets 33 or 42 and the armature 34 or 43. This variable load is applied by generator load control units under the control of a microprocessor in the instrument package 27. During steered drilling there are fed to the processor an input signal indicative of the required rotational orientation (roll angle) of the carrier 24, and feedback signals from roll sensors included in the instrument package 27. The input signal may be transmitted to the control unit from the surface, or may be derived from a downhole program defining the desired path of the borehole being drilled in accordance with survey and geophysical data derived downhole.

The processor is pre-programmed to process the feedback signal which is indicative of the rotational orientation of the carrier 24 in space, and the input signal which is indicative of the desired rotational orientation of the carrier, and to feed a resultant output signal to generator load control units. During steered drilling, the output signal is such as to cause the generator load control units to apply to the torquer-generators 33, 34 and 42,43 electrical loads of such magnitude that the net anticlockwise torque applied to the carrier 24 by the two torquer-generators opposes and balances the other clockwise torques applied to the carrier, such as the bearing torque, so as to maintain the carrier non-rotating in space, and at the rotational orientation demanded by the input signal.

The output from the control unit 9 is provided by the rotational orientation of the carrier itself and the carrier is thus mechanically connected by a single control shaft 35 to the input shaft 21 of the bias unit 10 shown in Figure 2.

Figure 4 shows diagrammatically the bottom hole assembly of one form of drilling system in accordance with the present invention, the bottom hole assembly being shown located in a comparatively narrow horizontal band 50 of hydrocarbon-bearing formation bounded by upper and lower layers of different formation 51 and 52.

In accordance with the present invention, the control unit 9 for the bias unit 10 incorporates a gamma detector 53, the gamma detector being located at the lower end of the control unit 9 so as to be as close as possible to the drill bit 1. The gamma detector may be a directional or non-directional sensor. It may be responsive to the natural radioactivity of the formation in the vicinity of the drill bit or it may include a gamma ray emission device, the detector measuring the attenuation of the returning gamma radiation. As is well known, the gamma sensor can detect the presence and location of a layer of shale 51 forming the upper boundary of the hydrocarbon-bearing layer 50.

In accordance with the present invention, the gamma sensor 53 produces an output signal indicative of the location of the upper boundary layer 51 which is transmitted to the control unit 9. The control unit 9 incorporates means to modify the rotational orientation of the control unit so as to modify the bias imparted to the drill bit 1 by the bias unit 10, as previously described, so as to steer the bit and maintain it at a desired distance from the boundary layer 51. As is well known, it is desirable for the borehole to extend through the upper part of the hydrocarbon-bearing formation 50 and the present invention enables this to be achieved automatically.

Since the gamma sensor 53 is located in the control unit itself, as is also the means for modifying the operation of the control unit, there is no problem in transmission of data signals from the gamma sensor 53 to the control unit as might be the case if the gamma sensor were located elsewhere in the bottom hole assembly. Although the control unit 9 may be capable of roll stabilisation as previously described, it will be appreciated that for the purposes of the present invention it could equally well be a strapped-down control unit rotating with the bias unit 10.

However, the present invention does not exclude arrangements where one or more of the geophysical sensors are located elsewhere in the bottom hole assembly. By way of example, Figure 4 illustrates the location of a resistivity sensor 54 above the control unit 9 and rotatable with the drill string. The resistivity sensor 54 may be a directional or non-directional sensor. In this case, and particularly when the control unit 9 is roll stabilisable, short range telemetry, of any of the well known kinds, such as mud pulse telemetry or magnetic or electro-magnetic telemetry, may be used to transmit data signals from the resistivity sensor 54 to the control unit 9 so that operation of the control unit is automatically modified in accordance with the information from the resistivity sensor 54 to steer the drill bit 1 in an appropriate path.

In the arrangement of Figure 4 any other form of geophysical sensor may also be located at any appropriate position in the bottom hole assembly, including geophysical sensors of any ofthe kinds previously referred to, and data signals from such sensors used automatically to modify operation of the control unit 9 so as to steer the drill bit in the appropriate direction according to the detected characteristics of the surrounding formation.

Instead of such data signals from the sensors being transmitted directly to the control unit, as described above, they may be transmitted, again using any of the well-known methods of short range telemetry, to an intermediate downhole station, located elsewhere in the bottom hole assembly, which processes the signals and then transmits appropriate control signals to the control unit.

Although it is preferable for the control loop to be closed downhole, the invention does not exclude arrangements where the control loop includes a surface station. In this case data signals from the geophysical sensors may be passed, by suitable short range telemetry, to a telemetry transmitter 55 incorporated in the bottom hole assembly. Corresponding signals are then sent to a surface station by the unit 55, e.g. using mud pulse telemetry. The surface unit then processes the signals and transmits appropriate control signals back downhole to the control unit 9. Such arrangement has the advantage that although the drill bit may still be steered automatically in accordance with the geophysical and other data, operator-controlled signals can be introduced into the loop to modify the direction of drilling in accordance with other requirements.

The location of a directional gamma detector 53 in the control unit 9 may provide additional advantage in the case where the control unit is capable of roll stabilisation and/or controlled rotation. A directional gamma detector is screened on one side so as to detect gamma radiation from only a limited region of the formation. In previous arrangements where the detector is simply mounted on a collar to rotate with the drill string, the detector must be actuated in synchronism with rotation of the drill string, so as to be facing in the required direction each time a gamma radiation reading is taken. However it is found that, for effective operation of the gamma detector, the rate of rotation of the drill string must be considerably reduced below its normal drilling speed while gamma readings are being taken, and this interferes with normal drilling. However, if the gamma detector is mounted in the control unit, the control unit may be temporarily roll stabilised with the detector facing in the required direction, or may be rotated at any desired slow speed, while the drill string continues to rotate at its normal drilling speed. Gamma readings may therefore be taken without interfering with drilling.

Claims

1. A steerable rotary drilling system comprising a bottom hole assembly which includes a drill bit (1), a bias unit (10) rotatable with the drill bit and including at least one actuator (13) which is displaceable laterally as the bias unit rotates to impart a lateral bias to the drill bit, and a control unit (9) to control the displacement of said actuator and thereby control the direction of drilling, characterised in that the bottom hole assembly further includes at least one geophysical sensor (53) responsive to a characteristic ofa subsurface formation in the vicinity of the bottom hole assembly, said sensor (53) providing an output signal corresponding to the current value of said characteristic, and means for automatically modifying the operation of the control unit (9), and hence operation of the rotatable bias unit, in response to said output signal.

2. A drilling system according to Claim 1, wherein said means for automatically modifying the operation of the control unit (9) are also located in the bottom hole assembly.

3. A drilling system according to Claim 2, wherein said means for automatically modifying the operation of the control unit are located in the control unit (9).

4. A drilling system according to any of the preceding claims, wherein at least one geophysical sensor (53) is located in the control unit.

5. A drilling system according to any of the preceding claims, wherein at least one geophysical sensor (54) is located in the bottom hole assembly, at a location spaced from the control unit (9), and data from said sensor is transmitted to the control unit by a short range downhole transmission system (55).

6. A drilling system according to any of the preceding claims, wherein the bias unit (10) is a synchronous modulated bias unit where the control unit (9) may cause the actuators (13) to be displaced in synchronism with rotation of the bias unit, and in selected phase relation thereto, whereby, as the bit and bias unit rotate, each actuator (13) is displaced outwardly at the same selected rotational position so as to bias the bias unit and drill bit laterally and thereby control the direction of drilling.

7. A drilling system according to any of the preceding claims, wherein the control unit (9) comprises an instrument carrier (24) which can be roll stabilised so as to remain substantially non-rotating in space, the direction of bias of the bias unit (10) being determined by the rotational orientation of the instrument carrier.

8. A drilling system according to any of Claims 1 to 6, wherein the control unit (9) is rotatable with the bias unit.

9. A steerable rotary drilling system comprising a bottom hole assembly which includes a drill bit (1), a bias unit (10) rotatable with the drill bit and including at least one actuator (13) which is displaceable laterally as the bias unit rotates to impart a lateral bias to the drill bit, and a control unit (9) to control the displacement of said actuator and thereby control the direction of drilling, characterised in that the bottom hole assembly includes at least one geophysical sensor (53) responsive to a characteristic of a subsurface formation in the vicinity of the bottom hole assembly, said sensor providing an output sig-

nal corresponding to the current value of said characteristic, and being located in the control unit (9).

10. A drilling system according to any of the preceding claims, wherein at least one geophysical sensor is a gamma sensor (53) adapted to detect natural gamma ray emissions from the formation.

11. A drilling system according to any of Claims 1 to 9, wherein at least one geophysical sensor (53) comprises a gamma ray source and detector so orientated that, in use, gamma rays from the source are reflected from the surrounding formation and are received by the detector, the attenuation of the gamma rays then being a measure of the density of the formation.

12. A drilling system according to any of the preceding claims, wherein at least one geophysical sensor includes a neutron emission source and a detector for measuring the porosity of the formation, high energy neutrons from the emission source, in use, passing into the formation and the depletion of the neutron energy, measured by the detector, is an indication of the porosity of the formation.

13. A drilling system according to any of the preceding claims, wherein at least one geophysical sensor is an electrical resistivity sensor (54) wherein, in use, an electro-magnetic wave is emitted from a transmitter and the returning signals are received by a detector to enable the resistivity of the surrounding formation to be determined.

14. A drilling system according to any of the preceding claims, wherein at least one geophysical sensor is a sonic sensor which measures the velocity of a sound wave propagated through the formation, to derive information concerning its density and elasticity.

15. A drilling system according to any of the preceding claims, wherein at least one geophysical sensor comprises a sound wave emitter and a detector to sense the sound waves reflected from the surrounding formation, thereby to locate boundaries in the formation from which the sound waves are reflected.

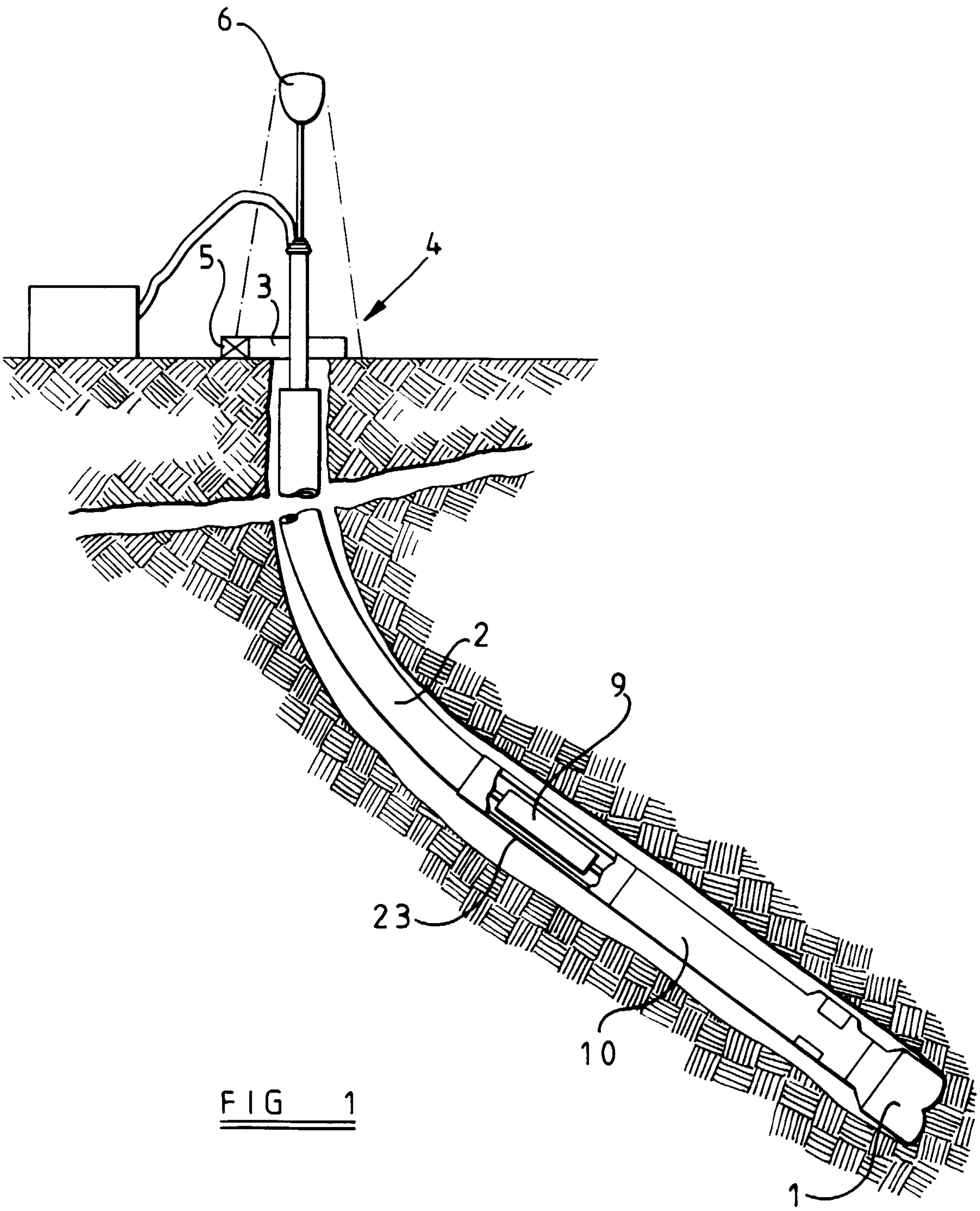


FIG 1

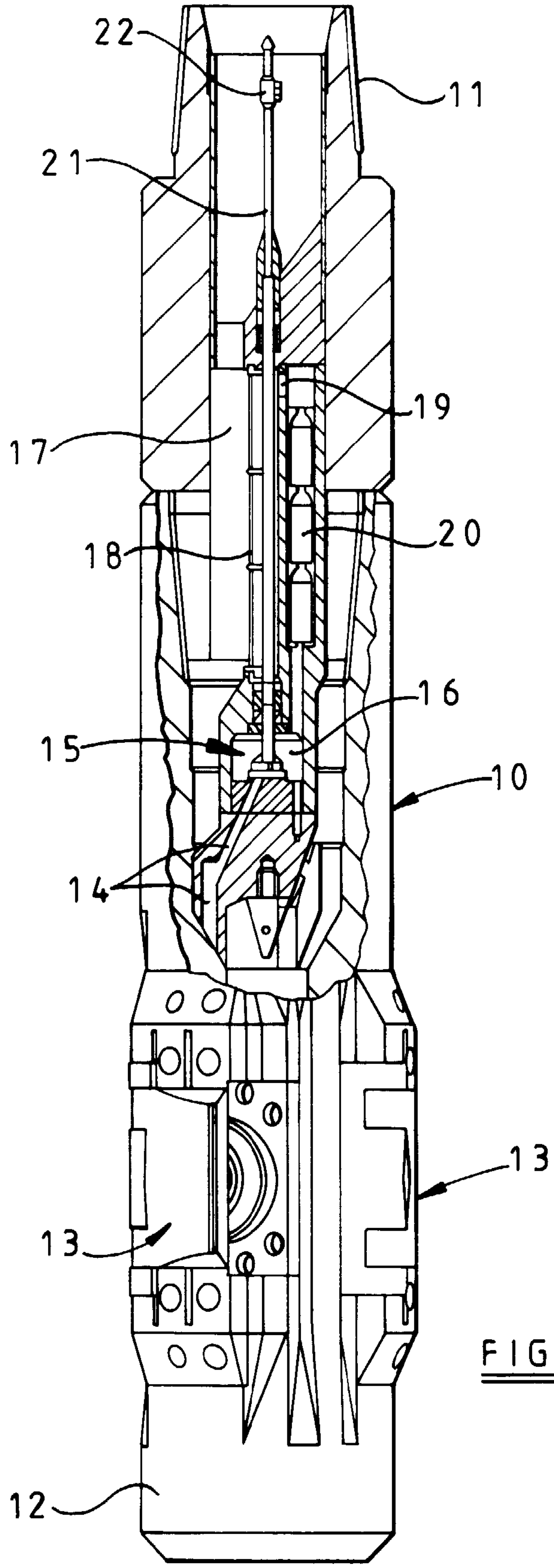


FIG 2

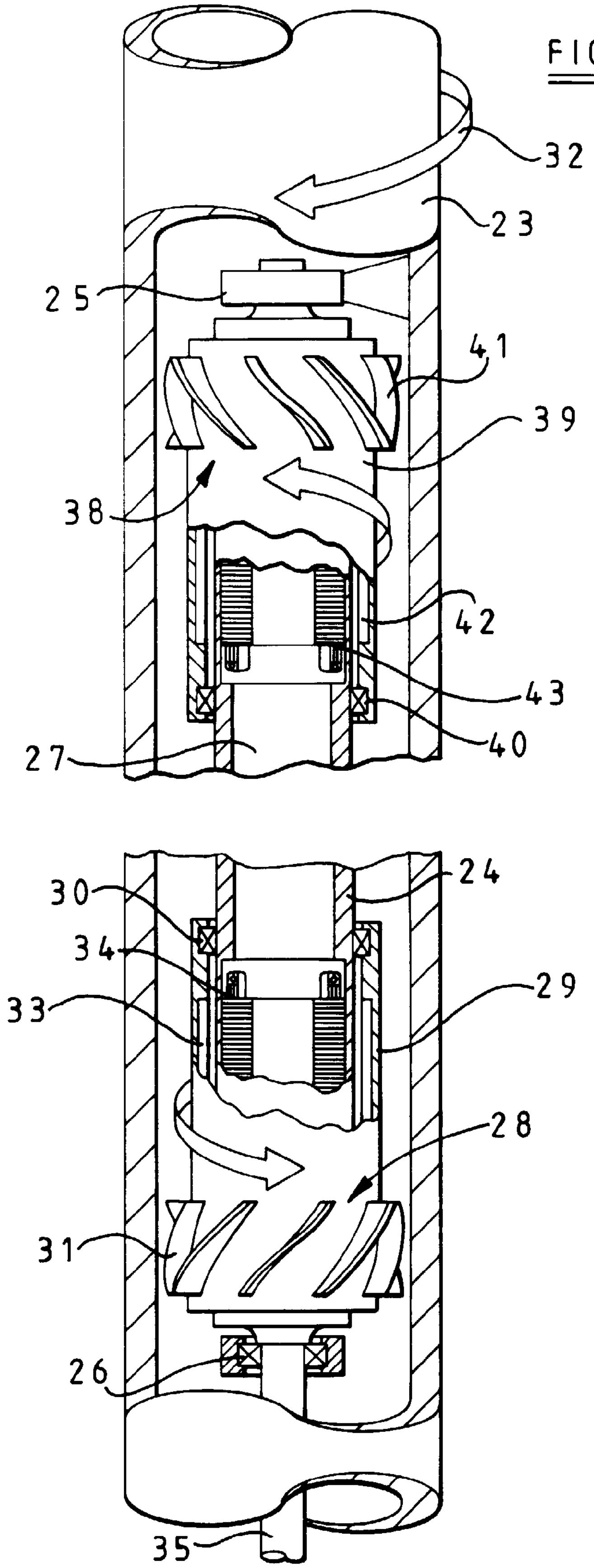


FIG 3

FIG 4