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(54) Downhole directional measurement system

(57) A downhole directional measurement system to determine an inclination angle θ of a wellbore at a point in either a definable vicinity of the wellbore bottom or in a projected path of the wellbore. The system comprises: a first inclinometer (39) for measuring an inclination angle α, and producing an output signal indicative thereof, and a second inclinometer (80) for measuring an inclination angle β, and producing an output signal indicative thereof. The system is capable of determining the inclination angle θ of the wellbore by extrapolation based upon said inclination angle α and said inclination angle β.

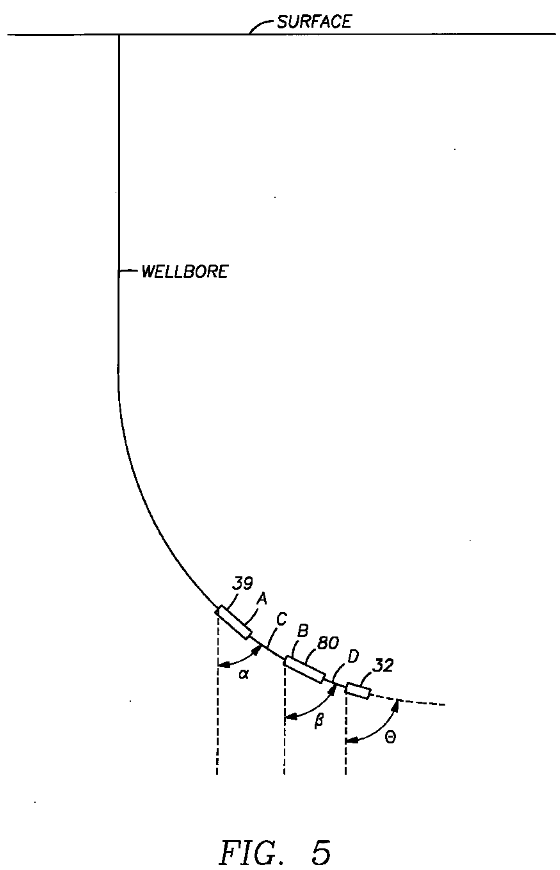

FIG. 5

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Description

The present invention relates to a downhole directional measurement system. More particularly, the invention relates to a system for determining the inclination of a bottom-hole assembly as part of a measurement while drilling ("MWD") system or a logging while drilling ("LWD") system, and to a system for determining the inclination of the hole at the drill bit to permit more precise control of the direction in which the bottom-hole assembly is drilled. Still more particularly, the present invention relates to an MWD system that indirectly determines the inclination of the hole at the drill bit by using measurements from two separate inclinometer sensors positioned at discrete locations in the bottom-hole assembly.

Modern petroleum drilling and production operations demand a great quantity of information relating to parameters and conditions downhole. Such information typically includes the location and orientation of the wellbore and drilling assembly, earth formation properties, and drilling environmental parameters downhole. Directional information relating to surveying the location of the wellbore, and controlling or "steering" the drilling assembly, will be discussed later.

The collection of information relating to formation properties and conditions downhole, commonly referred to as "logging", can be performed by several methods. Oil well logging has been known in the industry for many years as a technique for providing information to a driller regarding the particular earth formation being drilled. In conventional oil well wireline logging, a probe or "sonde" housing formation sensors is lowered into the borehole after some or all of the well has been drilled, and is used to determine certain characteristics of the formations traversed by the borehole. The sonde is supported by a conductive wireline, which attaches to the sonde at the upper end. Power is transmitted to the sensors and instrumentation in the sonde through the conductive wireline. Similarly, the instrumentation in the sonde communicates information to the surface by electrical signals transmitted through the wireline.

More recently, those in the industry have placed an increased emphasis on the collection of data during the drilling process itself. By collecting and processing data during the drilling process, without the necessity of removing or tripping the drilling assembly to insert a wireline logging tool, the driller can make accurate modifications or corrections on-the-fly, as necessary, to optimize performance. Designs for measuring conditions downhole and the movement and location of the drilling assembly, contemporaneously with the drilling of the well, have come to be known as "measurement-while-drilling" techniques, or "MWD." Similar techniques, concentrating more on the measurement of formation parameters, commonly have been referred to as "logging while drilling" techniques, or "LWD." While distinctions between MWD and LWD may exist, the terms MWD and LWD often are used interchangeably. For the purposes of this disclosure, the term MWD will be used with the understanding that this term encompasses both the collection of formation parameters and the collection of information relating to the movement and position of the drilling assembly.

The most common type of MWD sensor is a directional or directional orientation (synonymous terms) sensor. Directional MWD sensors typically comprise a three axis accelerometer and a three axis magnetometer, housed together in the same directional orientation sensor. *See* "State of the Art in MWD," International MWD Society (January 1993). Normally, drill string tubing is made of steel, which is a magnetic material. According to normal practice, and to prevent interference with the magnetometer readings, the sub housing the directional sensors typically comprises a length of tubing made of a non-magnetic material. Normally, the sub containing the directional sensors is positioned a relatively large distance above the drill bit and/or motor. For example, when a motor is used in the bottomhole assembly, the directional sensor typically is located approximately 50 feet or more above the drill bit.

In accordance with known techniques, wellbore directional measurements can be made as follows: a three axis accelerometer measures the earth's gravitational field vector, relative to the tool axis and a point along the circumference of the tool called the tool face scribe line. From this measurement, the inclination of the bottomhole assembly can be determined to provide an indication of the deviation of the wellbore with respect to vertical. The three axis accelerometer also provides a measure of "tool face angle," which is the orientation (rotational about the tool axis) angle between the scribe line and the high side of the wellbore. Additionally, a three axis magnetometer measures the earth's magnetic field vector in a similar manner. From the combined magnetometer and accelerometer data, the azimuth and magnetic tool face angle of the tool may be determined. As one skilled in the art will understand, azimuth is the horizontally projected direction of the wellbore relative to North.

Because the directional sensors typically are mounted a substantial distance above the bit, the inclination measured by the three axis accelerometer in the directional sub may or may not be a fair representation of the inclination at the bit. In certain directional or horizontal wells, the build rate of the well may exceed 10° per 100 feet. Thus, the inclination measured at the directional sensor may not accurately reflect the inclination at the bit. Inclination is an extremely important parameter for the driller to consider when making decisions regarding course changes and corrections, and the like. As a result, there has been a desire in the drilling industry to obtain inclination information nearer the hole bottom (i.e., at the drill bit) in more nearly "real-time." Placing the directional sensor closer to the bottom of the drill string is risky, however, because of the potential problem of magnetic interference to the azimuth sensors caused by components near the bit, such as the downhole motor. Moreover, the use of a downhole motor makes it difficult to recover sensed values from sensors positioned below the motor because of the practical problems related to placement of, and communication with, the sensors. One attempt to obtain more accurate drilling information at or near the bit is found in U.S. Patent No. 5,160,925, the teachings of which are incorporated by reference herein. In that patent, a short hop electromagnetic link is used to permit data sensed below the motor to be transmitted around the motor real-time. While this invention provides a viable solution to the problem, such a system is both complicated and expensive. It would therefore be desirable if an alternative system could be developed to provide information reflecting inclination at the bit which is less expensive and simpler to obtain. Although the advantages of such a system are apparent, to date no such system has been developed except for the solution obtained in U.S. Patent No. 5,160,925.

The present invention solves the shortcomings and deficiencies of the prior art by providing a system for indirectly determining inclination at the bottom of a wellbore. The system includes a standard directional sensor located in its normal position in the wellbore. In addition, a second inclinometer is positioned in the bottom-hole assembly as close to the drill bit as possible. In situations where a motor is used, the second inclinometer is positioned just above the motor.

The second inclinometer provides a second reference point (B) of inclination at a position closer to the bit than the location (A) of the standard inclination measurement. The present invention uses the first and second inclination measurements, together with information regarding the configuration of the bottomhole assembly (BHA), and may also include the use of drilling tendencies to extrapolate the inclination of the wellbore at the drill bit. The term "configuration," when used herein in reference to the bottomhole assembly, includes but is not limited to, the geometry and material properties of the BHA, and also includes stabilization type(s) (gauge, shape, etc.) and point(s) (or position), and bit type and characteristics as well. The first and second inclination measurements provide two points of reference which, taken together with information regarding the configuration of the bottomhole assembly between the inclinometers (segment C) and between the drill bit and second inclinometer (segment D), and other information relating to drilling tendencies, can provide relatively accurate information regarding inclination at the bit, using an appropriate BHA model. The information relating to the configuration of the BHA typically is entered into the surface processor and can be stored in memory for retrieval later. Other parameters also can be used in the BHA model to increase the accuracy with which the wellbore inclination angle at the bit is determined.

The MWD system includes a downhole processor or controller for controlling the operation of the MWD sensors, including the second inclinometer. The downhole processor obtains desired information from the sensors, encodes that information, and transmits that information to the surface processor via a mud pulse signal.

Accordingly, the present invention provides a downhole directional measurement system to determine an inclination angle θ of a wellbore at a point in either a definable vicinity of the wellbore bottom or in a projected path of the wellbore, comprising: a first inclinometer for measuring an inclination angle α, and producing an output signal indicative thereof; a second inclinometer for measuring an inclination angle β, and producing an output signal indicative thereof; wherein said system is capable of determining the inclination angle θ of the wellbore by extrapolation based upon said inclination angle α and said inclination angle β.

The system may form part of an MWD system or a wireline system.

A surface processor is preferably coupled to said first inclinometer and said second inclinometer for receiving said signals therefrom, and for producing the inclination angle θ.

A controller is preferably positioned downhole, which connects electrically to said first and second inclinometers. The controller may selectively activate said inclinometers.

Preferably a mud pulser is connected to said downhole controller for transmitting a mud pulse signal indicative of the output signals from said first and second inclinometers.

The controller may include a memory for storing information relating to the configuration of the bottomhole drilling assembly. The controller can use said configuration information and said output signals from said first and second inclinometer to determine said inclination angle θ.

A stabilizer may also be provided, and said configuration information may include the location and size of said stabilizer. A bend may be provided in said system and said configuration information may include the degree and location of the bend.

Preferably, the system includes a sensor for measuring additional directional information, and providing an output signal indicative thereof. The downhole controller may connect electrically to said sensor and receives said output signal from said sensor.

The controller may use drilling tendency information and said output signals from said first and second inclinometer to determine said inclination angle θ. The drilling tendency information may include weight-on-bit.

Figure 1 is a general illustration of an embodiment of a drilling installation implementing the system of the present invention;

Figure 2 is a front elevation, partially in section, of the bottom hole assembly of Figure 1, constructed in accordance with a preferred embodiment;

Figure 3 is a system block diagram generally depicting the process control and information flow of the system of Figure 1;

Figure 4 is a flow chart depicting a general method of indirectly determining inclination of hole at the drill bit;

Figure 5 is a drawing of a drilling path which illustrates the known quantities used in the BHA model to determine the inclination angle of the wellbore at the drill bit.

During the course of the following description, the terms "upstream" and "downstream" are used to denote the relative position of certain components with respect to the direction of flow of the drilling mud. Thus, where a term is described as upstream from another, it is intended to mean that drilling mud flows first through the first component before flowing through the second component. Similarly, the terms as "above", "upper" and "below" are used to identify the relative position of components in the bottom hole assembly, with respect to the distance to the surface of the well, measured along the borehole path.

In addition, in this application the phrase "inclination angle of the wellbore at the bit" or similar phrases which relate to the inclination angle at the bottom of the wellbore, are used herein to refer to the inclination angle of the wellbore at a point located either in the definable vicinity of the borehole bottom, or in the projected path of the wellbore (which has not yet been drilled). These phrases do not limit the ultimately desired inclination angle to the wellbore inclination angle at the bottom of the wellbore (*i.e.*, the bit location during drilling).

Referring to Figure 1, a typical drilling installation is illustrated which includes a drilling rig 10, constructed at the surface 12 of the well, supporting a drill string 14. The drill string 14 penetrates through a rotary table 16 and into a borehole 18 that is being drilled through earth formations 20. The drill string 14 includes a kelly 22 at its upper end, drill pipe 24 coupled to the kelly 22, and a bottom hole assembly 26 (commonly referred to as a "BHA") coupled to the lower end of the drill pipe 24. The BHA 26 typically includes drill collars 28, directional MWD sensors located in a non-magnetic section 60, other MWD sensors positioned in a separate collar section 55, a downhole motor 40, a drill bit 32 and one or more stabilizer(s) (not shown) for penetrating through earth formations to create the borehole 18. In operation, the kelly 22, the drill pipe 24 and the BHA 26 are rotated by the rotary table 16. The drill collars 28 (which also may be non-magnetic so as not to interfere with the MWD measurements) are used, in accordance with conventional techniques, to add weight to the drill bit 32 and to stiffen the BHA 26, thereby enabling the BHA 26 to transmit weight to the drill bit 32 without buckling. The weight applied through the drill collars 28 to the bit 32 permits the drill bit to penetrate the underground formations.

As the drill bit 32 operates, drilling fluid or mud is pumped from a mud pit 34 at the surface through the kelly hose 37, into the drill pipe, to the drill bit 32, in the direction of arrows 68. After flowing through the drill bit 32, the drilling fluid rises back to the surface, in the direction of arrows 70, through the annular area between the drill pipe 24 and the borehole 18, where it is filtered and returned to the mud pit 34. The drilling fluid is used to lubricate the drill bit 32 and to remove cuttings from the borehole 18. As one skilled in the art will realize, a downhole motor or turbine 40 may be used downhole to rotate the drill bit 32 as an alternative, or in addition to, rotating the drill string from the surface.

As shown in Figures 1 and 2, the BHA 26 typically is defined as all of the downhole components from the top of the drill collars 28, down to and including the drill bit 32, including downhole motor 40. As one skilled in the art will understand, a downhole motor 40 is an optional component which may be omitted from the BHA 26 if desired. In the preferred embodiment, the BHA 26 preferably includes a measurement while drilling system 30 (referred to herein as an "MWD system"), which may be considered part of the drill collar section 28. The MWD system 30 typically includes directional MWD sensors 38, 39 housed in the non-magnetic sub 60 (or drill collar), and can include formation sensors 51, as well. As shown in Figure 3, the formation sensors 51 may include gamma, resistivity, and other sensors (i.e., sonic, density and neutron sensors) in accordance with normal industry practice. In addition, drilling mechanics sensors may be provided, such as weight-on-bit (WOB), torque-on-bit (TOB), shock, vibration, etc. *See generally* "State of the Art in MWD," International MWD Society (January 19, 1993). A downhole controller 65 preferably controls the operation of a signalling unit 35 and orchestrates the operation of the MWD sensors and components. As shown in Figure 2, the controller 65 may be located in sub 60 or elsewhere in the MWD system 30.

Referring to Figures 1, 2 and 3, the downhole data signalling unit 35 preferably is provided as part of the MWD system 30 and is used to transmit sensed values to a surface receiver 105 via a mud pulse acoustic signal. In addition, the downhole system may also include the capability of receiving mud pulse signals from the surface to control the operation or activation of certain MWD sensors or other downhole components. The signalling unit 35 in the preferred embodiment comprises a mud pulser unit housed in a non-magnetic sub in accordance with conventional industry practice.

The downhole controller 65 may include appropriate data encoding circuitry, which produces sequentially encoded digital data signals representative of the measurements obtained by the downhole sensors. In addition, the controller 65 processes the data received from the sensors and produces encoded signals indicative of a portion or all of the received signals for transmission to the surface via a mud pulse signal. The controller 65 also may make decisions based upon the processed data.

Referring to Figure 2, the present invention preferably includes a conventional MWD system 30, which includes at least a directional sensor. In addition to this base MWD system, the present invention adds a second inclinometer 80 that connects electrically and mechanically to the conventional MWD system 30. According to the preferred embodiment, the second inclinometer 80 is positioned in the bottomhole assembly 26 as close as possible to the drill bit 32.

Referring now to Figures 1 and 2, in the preferred implementation, the non-magnetic section 60 contains the directional sensors 38, 39. The directional sensors 38, 39 in sub 60 are selected and adapted as required for the particular drilling operation, to measure such downhole parameters as the inclination and azimuth of the BHA at point A. The directional MWD sensors 38, 39 typically comprise a three axis magnetometer and a three axis accelerometer, preferably housed together in the same sub 60. See "State of the Art in MWD," International MWD Society (January 1993), the teachings of which are incorporated herein.

The non-magnetic section 60 containing the directional sensors is positioned a relatively large distance above the drill bit (approximately 50 feet or more when a motor is used), in accordance with normal practice. The three axis accelerometer 39 measures the earth's gravitational vector, relative to the tool axis and a point along the circumference of the tool called the scribe line. From this measurement, the inclination angle α of the bottomhole assembly at point A can be obtained. The three axis accelerometer also provides a measure of "tool face," which is the angle between the scribe line (which may be located on a particular tool), relative to the high side of the wellbore. The three axis magnetometer 38 measures the earth's magnetic field vector relative to the axis of the tool, and to the same tool face scribe line to thereby determine the magnetic tool face. From combined magnetometer and accelerometer readings, the azimuth of the tool at point A may be determined.

Because the directional sensors 38, 39 typically are mounted a substantial distance above the bit 32, the inclination measured by the three axis accelerometer in the directional MWD system 30 represents the inclination at point A. This inclination may or may not be a fair representation of the inclination at the bit 32. In accordance with the principles of the present invention, directional sensor 80 preferably is provided in the bottomhole assembly 26 below the conventional MWD system 30. If a motor 40 is included in the bottomhole assembly 26, the directional sensor preferably is located directly above the motor 40.

Referring to Figures 2 and 3, the directional sensor 80 preferably comprises a three axis inclinometer for measuring the inclination angle β of the BHA 26 at point B. Alternatively, a single *z* axis inclinometer may be used instead of the three axis inclinometer in horizontal drilling applications (where drilling is being performed between approximately 20° and 160° of inclination). The inclination angle β measured by inclinometer 80 at point B is used in conjunction with the inclination angle α reading from the three axis inclinometer at point A, along with other BHA and drilling tendency information, to indirectly determine the inclination angle θ of the wellbore at the drill bit 32, through the use of an inclination extrapolation model, as described below.

Referring now to Figures 4 and 5, the operation of the present invention will now be described in general terms. In step 202, the downhole controller 65 obtains inclination information from the first inclinometer sensor 39 reflecting the inclination angle α at point A. In step 204, the controller 65 obtains an inclination reading from inclinometer 80 reflecting the inclination angle β at point B. After all necessary and desired sensory information is obtained by the controller 65, the controller preferably sends a mud pulse signal to the surface processor 100 reflecting these values to enable the surface processor to perform steps 206 and 208. Alternatively, downhole controller 65 may perform these steps if the necessary configuration information is available or provided to controller 65.

In step 206, surface processor retrieves information relating to the configuration of BHA 26 at segments C and D. Segment C represents the configuration of BHA 76 between the two inclinometers 39, 80. Segment D represents the configuration of BHA 26 between inclinometer 80 and the bit. After these values are retrieved from memory, or received from an external device or from an operator, the surface processor 100 applies the known data to an appropriate BHA model, which preferably is similar to a conventional program used by most drillers to predict the drilling path of a BHA. *See e.g.* J.S. Williamson, *et al*. "Predicting Bottomhole Assembly Performance," IADC/SPE 14764, presented in Dallas, Texas on February 10-12, 1986, the teaching of which are incorporated by reference. The known values include inclination angle α at point A, inclination angle β at point B, the configuration (including orientation and length) of segments C and D, and other data indicative of drilling tendencies, including weight-on-bit, size and location of stabilizers, and the location and degree of bend angles of bent subs and bent housings. *See* U.S. Patent No. Re. 33,751, the teachings of which are incorporated by reference. From these values, and with the use of an appropriate inclination extrapolation model, the inclination angle θ of the hole at the drill bit can be determined with a reasonable degree of accuracy in step 208.

While a preferred embodiment of the invention has been shown and described, modifications thereof can be made.

Claims

1. A downhole directional measurement system to determine an inclination angle θ of a wellbore at a point in either a definable vicinity of the wellbore bottom or in a projected path of the wellbore, comprising: a first inclinometer (39) for measuring an inclination angle α, and producing an output signal indicative thereof: a second inclinometer (80) for measuring an inclination angle β, and producing an output signal indicative thereof; wherein said system is capable of determining the inclination angle θ of the wellbore by extrapolation based upon said inclination angle α and said inclination angle β.

2. A system according to claim 1, further comprising a surface processor (105) coupled to said first inclinometer (39) and said second inclinometer (80) for receiving said signals therefrom, and for producing the inclination angle θ.

3. A system according to claim 1 or 2, further comprising a controller (65) positioned downhole, which connects electrically to said first (39) and second (80) inclinometers.

4. A system according to claim 3, wherein said controller (65) selectively activates said inclinometers (39,80).

5. A system according to claim 3 or 4, further comprising a mud pulser (35) connected to said downhole controller (65) for transmitting a mud pulse signal indicative of the output signals from said first (39) and second (80) inclinometers.

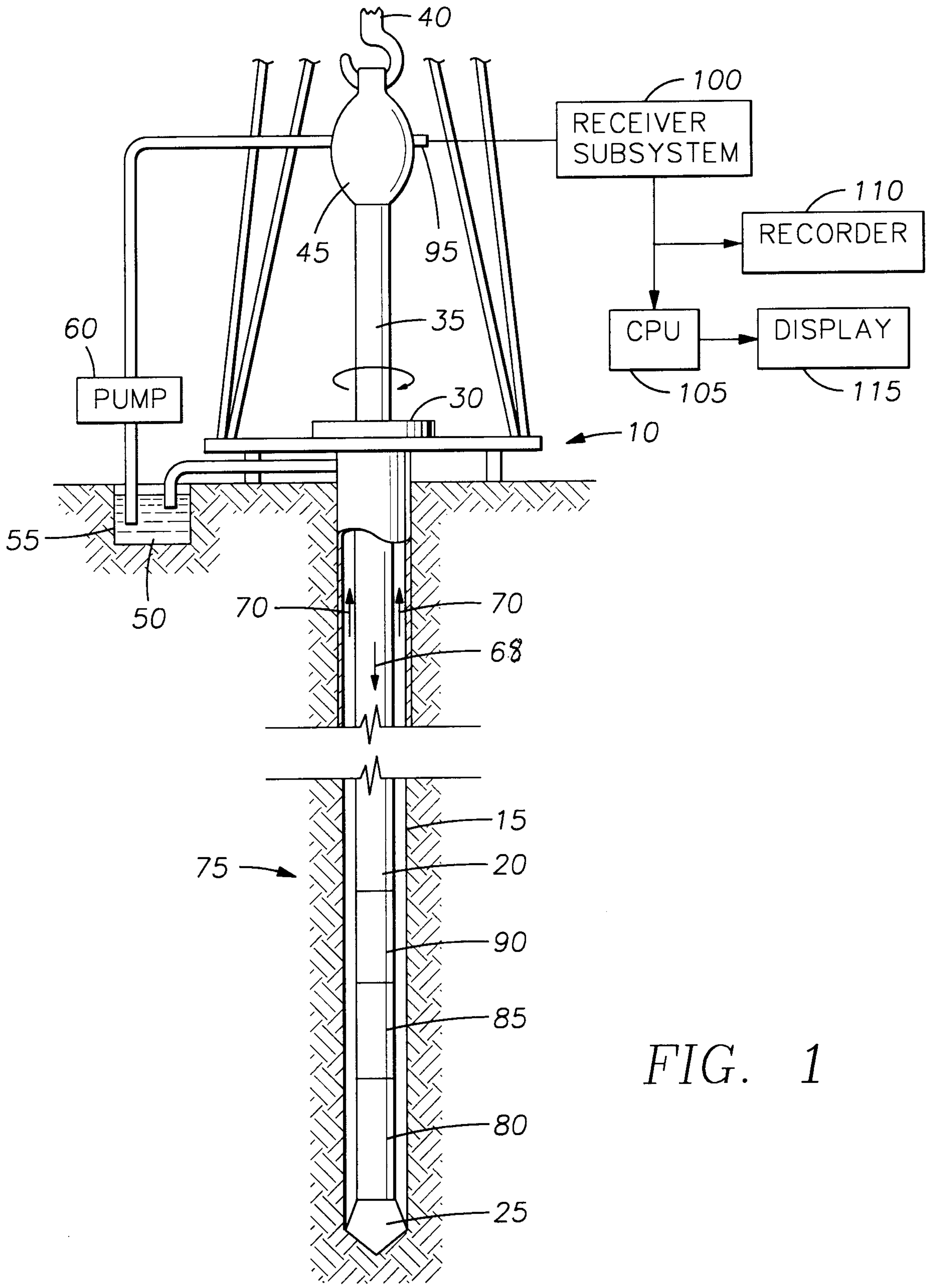
6. A system according to claim 3,4 or 5, wherein said controller (65) includes a memory for storing information relating to the configuration of the bottomhole drilling assembly (26).

7. A system according to claim 6, wherein said controller (65) uses said configuration information and said output signals from said first (39) and second (80) inclinometer to determine said inclination angle θ.

8. A system according to claim 7, further comprising a stabilizer and wherein said configuration information includes the location and size of said stabilizer.

9. A system according to claim 5, wherein said controller (65) uses configuration information and said output signals from said first (39) and second inclinometer (80) to determine said inclination angle θ.

10. A system according to claim 2, further comprising a sensor (38) for measuring additional directional information, and providing an output signal indicative thereof, and wherein said surface processor (105) receives said additional directional information and said output signals from said first (39) and second inclinometers (80) as part of a mud pulse signal and uses these signals in determining said inclination angle θ.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CPU
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FIG. 1

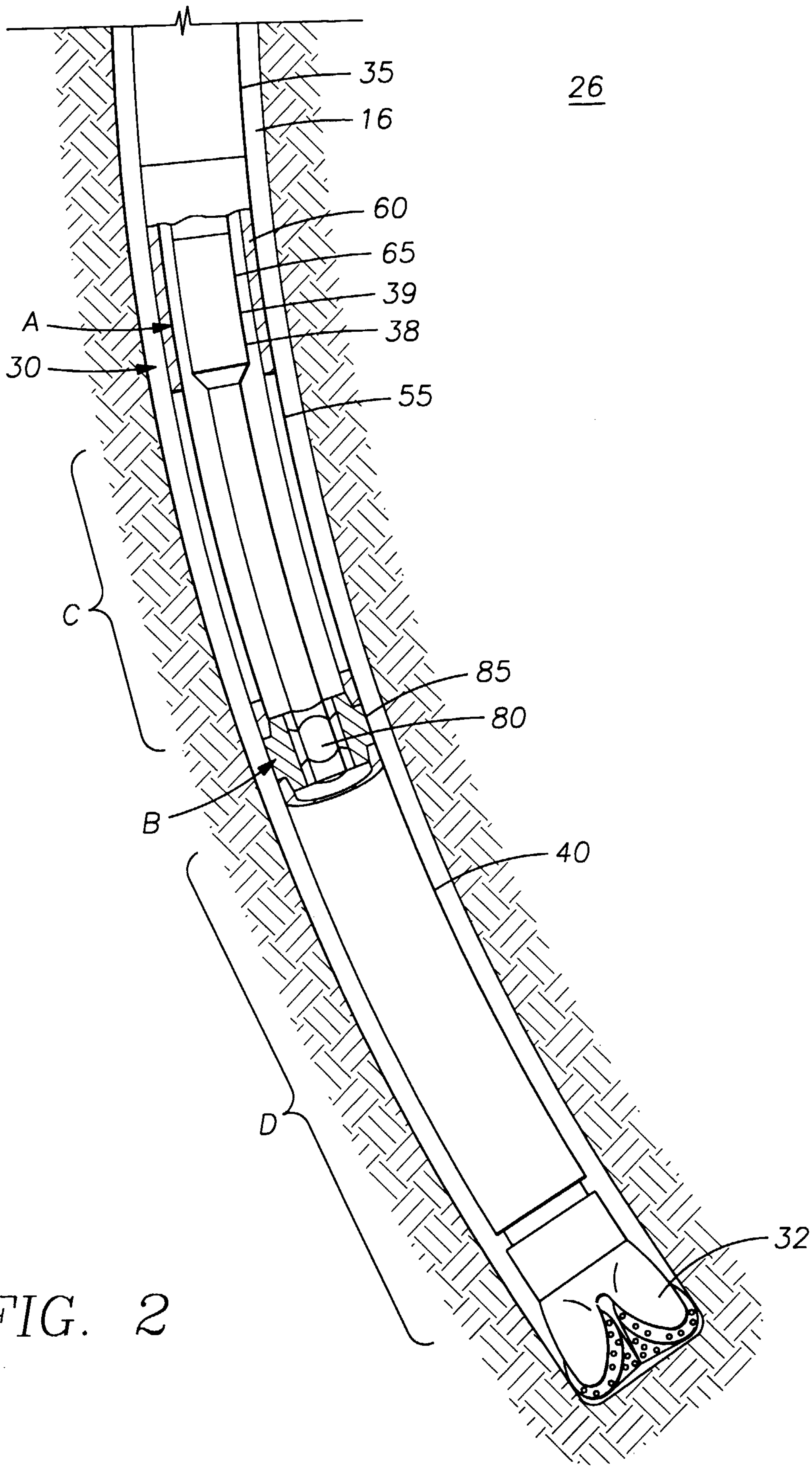

FIG. 2

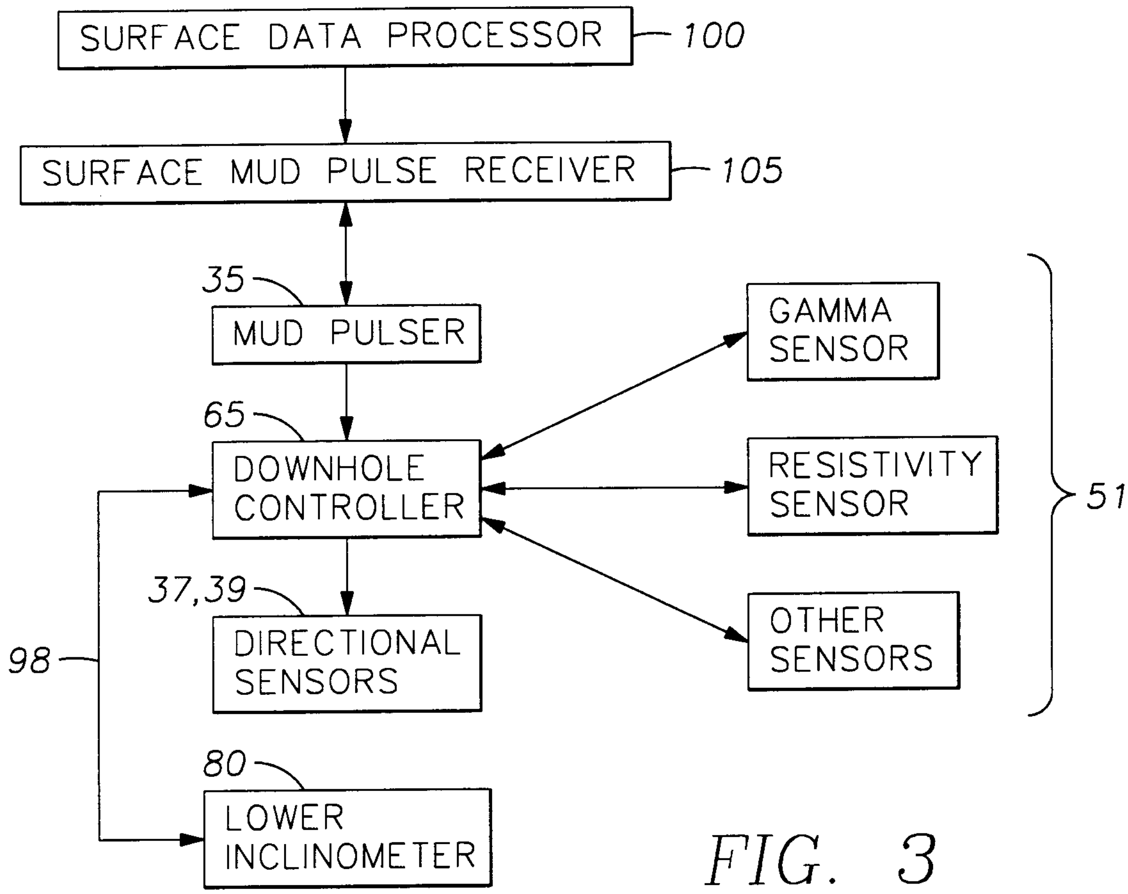
SURFACE DATA PROCESSOR
100
SURFACE MUD PULSE RECEIVER
105
35
MUD PULSER
65
DOWNHOLE CONTROLLER
37,39
DIRECTIONAL SENSORS
80
LOWER INCLINOMETER
98
GAMMA SENSOR
RESISTIVITY SENSOR
OTHER SENSORS
51

FIG. 3

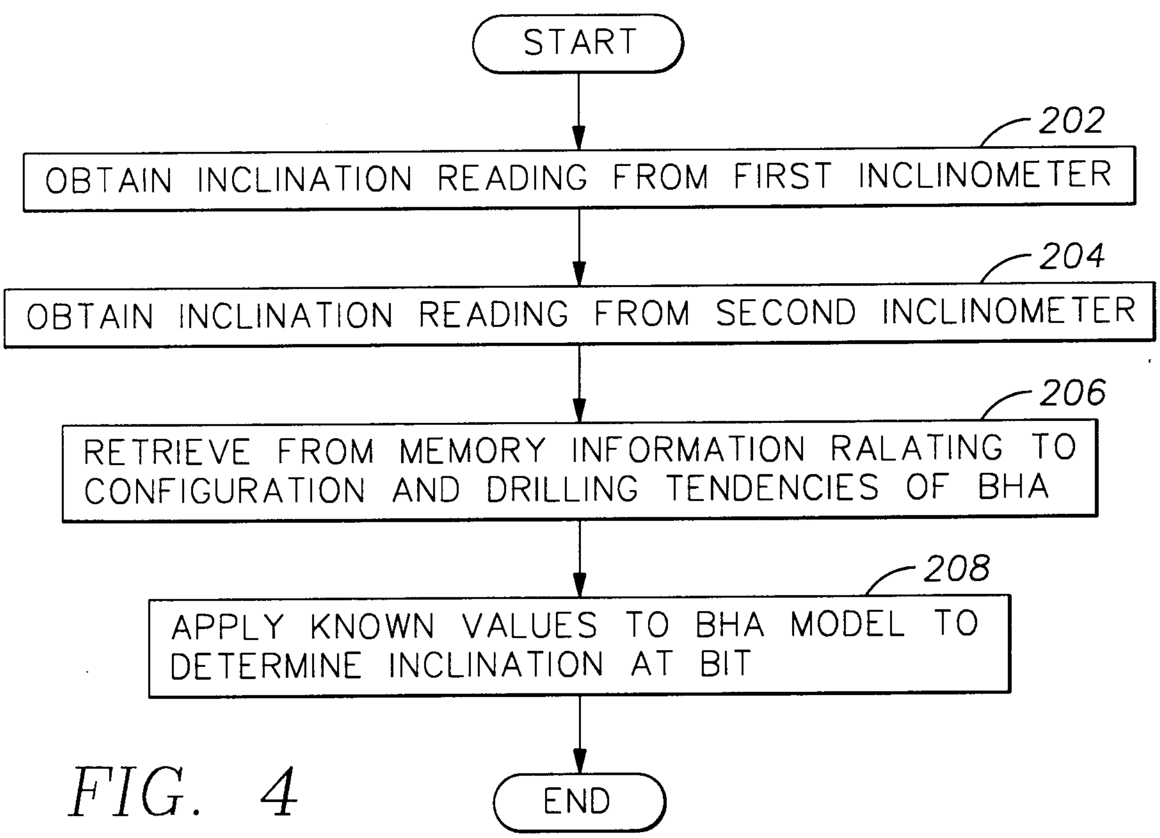
START
202
OBTAIN INCLINATION READING FROM FIRST INCLINOMETER
204
OBTAIN INCLINATION READING FROM SECOND INCLINOMETER
206
RETRIEVE FROM MEMORY INFORMATION RALATING TO CONFIGURATION AND DRILLING TENDENCIES OF BHA
208
APPLY KNOWN VALUES TO BHA MODEL TO DETERMINE INCLINATION AT BIT
END

FIG. 4

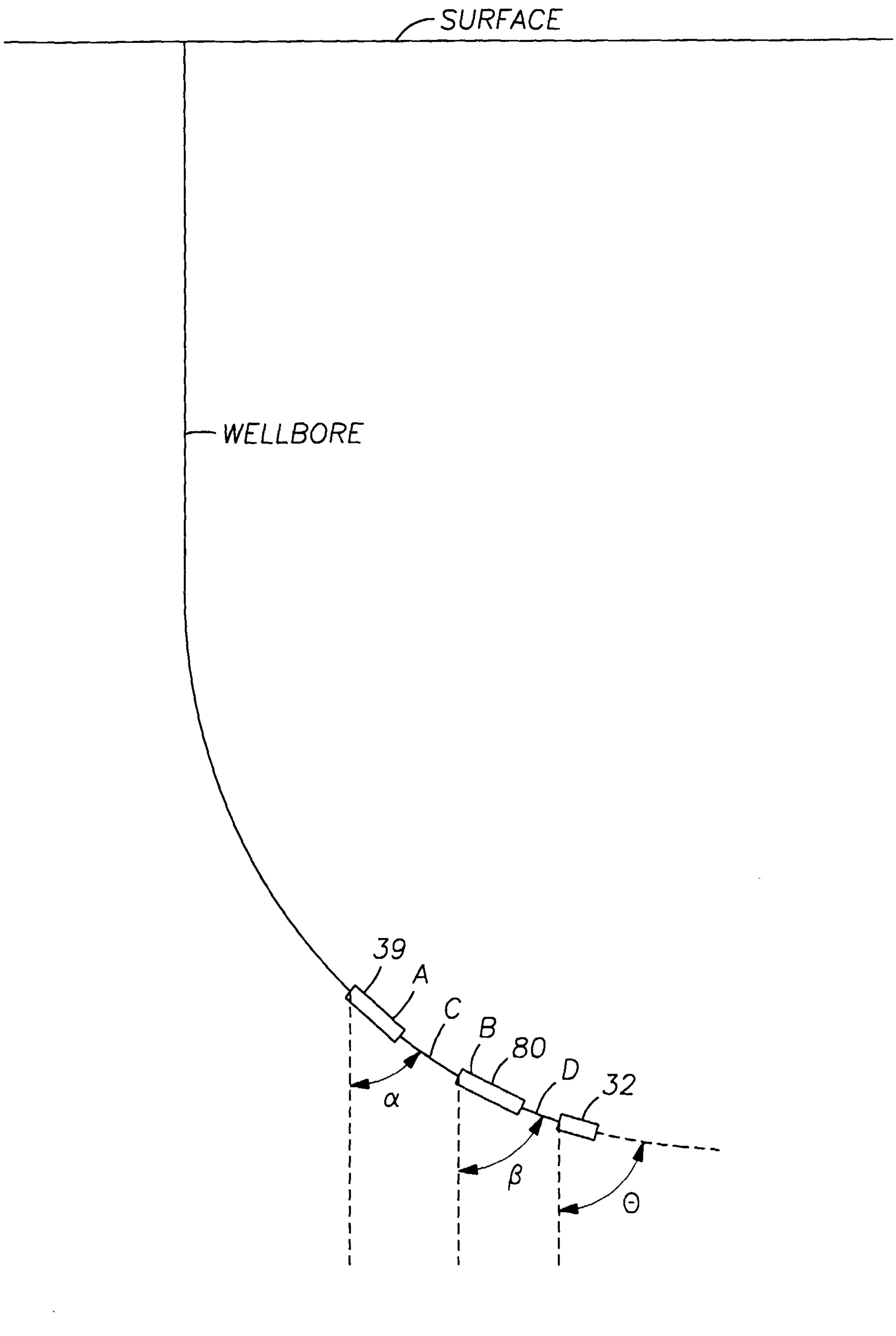

FIG. 5

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 97 30 0746

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	US 5 163 521 A (PUSTANYK RANDAL H ET AL) 17 November 1992 * abstract *	1	E21B47/022
A	GB 2 086 055 A (SUNDSTRAND DATA CONTROL) 6 May 1982 * abstract *	1	
A	SOVIET INVENTIONS ILLUSTRATED Section Ch, Week 8922 12 July 1989 Derwent Publications Ltd., London, GB; Class H01, AN 89-163786 XP002033024 & SU 1 439 223 A (PETROL GAS GEOPHYS) , 3 March 1987 * abstract *	1	
A	SOVIET INVENTIONS ILLUSTRATED Section Ch, Week 8111 22 April 1981 Derwent Publications Ltd., London, GB; Class H01, AN 81-19052D XP002033025 & SU 746 094 A (MOSCOW GUBKIN PETROCHEM) , 27 December 1976 * abstract *	1	TECHNICAL FIELDS SEARCHED (Int.Cl.6) E21B

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	16 June 1997	Hoekstra, F

CATEGORY OF CITED DOCUMENTS

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