

Jan. 18, 1966

W. S. CRAKE ETAL

3,229,375

METHOD OF SURVEYING AN INCLINED WELLBORE

Filed July 15, 1963

2 Sheets-Sheet 1

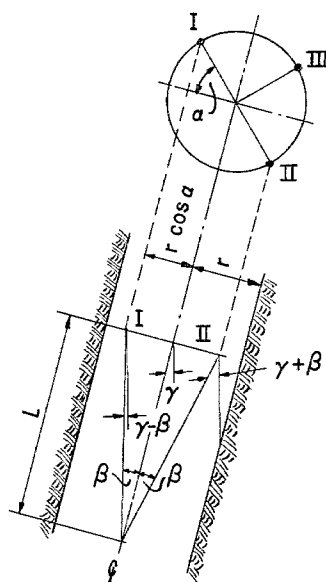
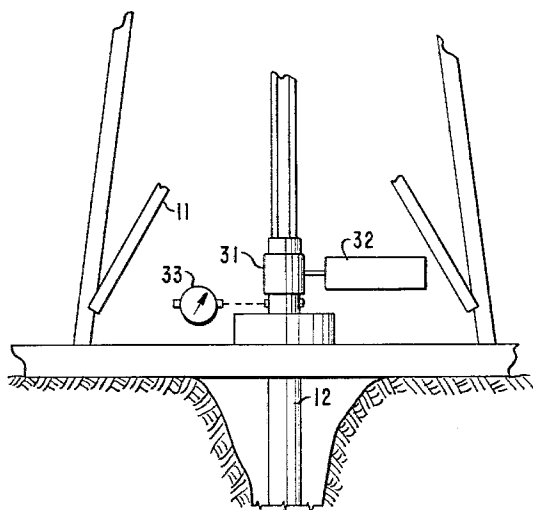


FIG. 2

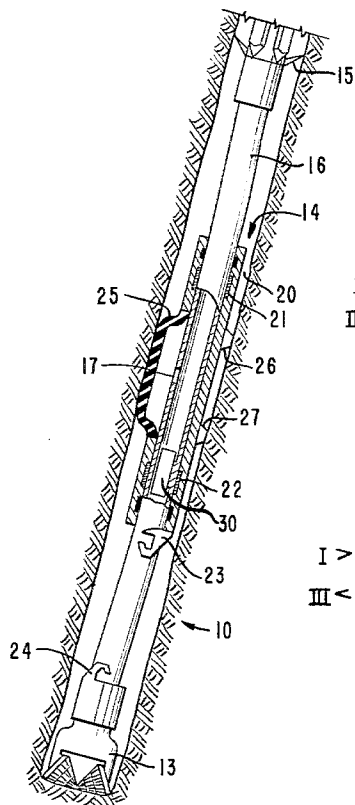


FIG. 1

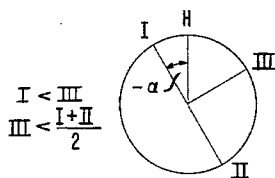


FIG. 3A

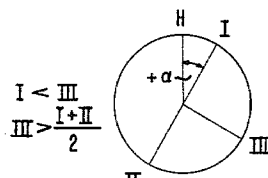


FIG. 3B

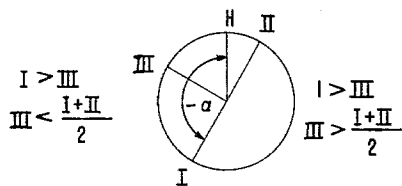


FIG. 3C

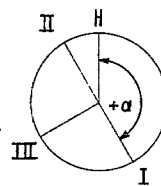


FIG. 3D

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2 Sheets-Sheet 2

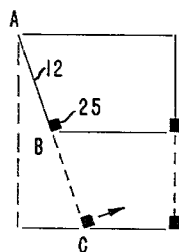


FIG. 5A

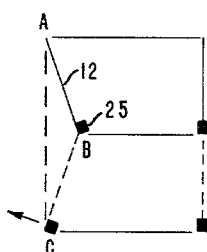


FIG. 5B

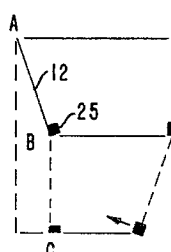


FIG. 5C

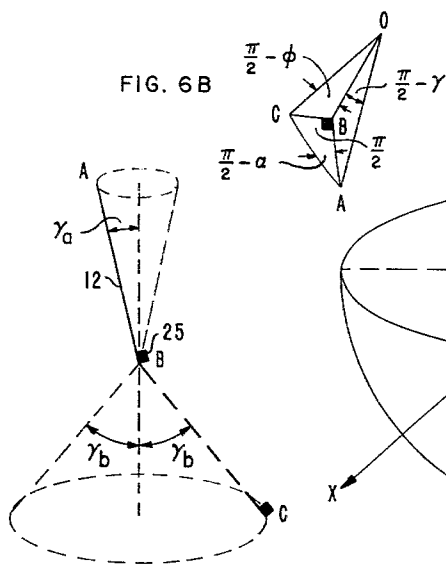


FIG. 4

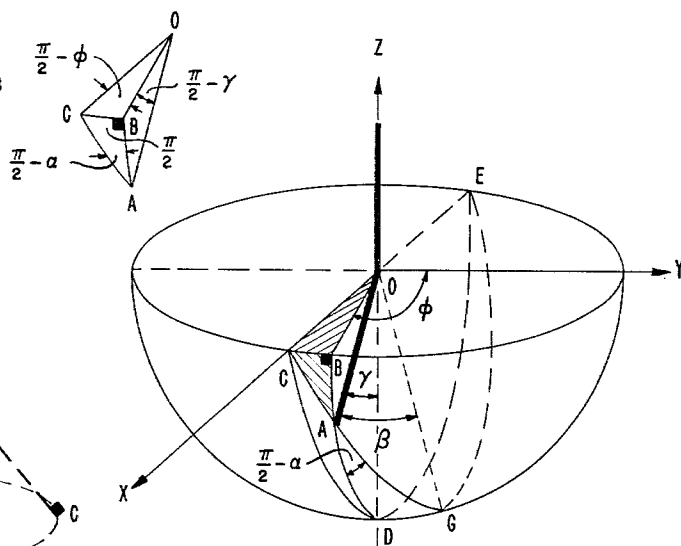


FIG. 6A

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Filed July 15, 1963, Ser. No. 294,955

8 Claims. (Cl. 33—205)

This invention pertains to a method of surveying a wellbore during drilling. More particularly, this invention pertains to a method of determining the orientation of a borehole being drilled with a rotary drill string having mounted thereon a bit guide or eccentric stabilizer.

Wellbores drilled into the earth generally follow a random and crooked course, due to the fact that the drill penetrates layers of rock which are tilted at different angles and have differences in strength from one layer to another. Random, crooked holes are undesirable as they frequently complicate and slow down the drilling operation. For example, if a well is being drilled to a certain depth below the surface where oil, gas or mineral deposits are suspected, and the surface location for the well is directly above that area, it is desirable to drill a straight vertical hole within reasonable limitations so that the bottom portion of the well will penetrate the zone of interest. In other instances, because of surface topography, well sites may be positioned such that a directionally controlled deviated hole is drilled to terminate at or pass through an underground zone of interest which may be a great distance, horizontally as well as vertically, from the surface location. In both examples of drilling wells, that of drilling a reasonable vertical hole and that of drilling a purposely deflected hole which is directionally controlled, the natural, random, meandering tendency of drilled holes must be overcome by some means.

In order to control the direction of the wellbore being drilled, tools for deflecting the drill bit have been developed. An example of such a tool is a resettable eccentric stabilizer which consists basically of a sleeve which is slidably and rotatably mounted on a section of the drill string near the drill bit. An expandable piston, carried by the sleeve, can be set at any desired radial direction, and when expanded it will deflect the drill string and force the drill bit in a direction correlated with the direction of the piston. Although such devices are known in the art, the measurements and procedures necessary in determining the orientation of the wellbore and then properly orienting the directional drilling tool are both time consuming and costly. For example, one of the standard methods has been to run an instrument package of specialized measuring equipment down into the wellbore at frequent intervals by wire line. After the measurements are taken, the instrument package must then be removed from the wellbore before the drilling can commence. Another method which could be used is to permanently mount the specialized measuring equipment in the drill string, and then telemeter the information to the surface. Although this method would appear to solve the problem of reducing the time necessary to make the determinations, in fact, it presents new problems of reliability of the complicated instrument packages and the telemetering of the various information signals to the surface.

It is therefore a primary object of this invention to provide a new and improved method of determining the orientation of a wellbore during drilling.

It is another object of this invention to provide a new and improved method of determining the orientation of a wellbore during a directional drilling operation using conventional measuring equipment.

It is still another object of this invention to provide a new and improved method of determining the orientation of a wellbore being drilled with an eccentric stabilizer type of direction drilling tool which does not require running of special instrument packages down into the wellbore.

It is a further object of this invention to provide a method whereby both the inclination and azimuth of the wellbore being drilled with an eccentric stabilizer type of directional drilling tool may be determined from a plurality of inclination measurements without requiring specialized measuring equipment.

It is still a further object of this invention to provide a method whereby the orientation of the directional drilling tool relative to the high side of the borehole may be determined from the same readings used for the inclination measurements.

Briefly, the above objects of this invention are carried out by maintaining the drill string on either side of an eccentric stabilizer, in a position which is concentric with the wellbore and then displacing the drill string by means of the eccentric stabilizer from its concentric position; and taking an inclination measurement with a conventional inclinometer mounted in the drill string. The drill string is then similarly displaced respectively in directions 90 and 180 degrees from the initial position and an inclinometer reading is taken at each of these latter two locations. The inclination of the wellbore, the initial and final orientation of the eccentric stabilizer relative to the high side of the borehole and the change of azimuth of the wellbore are then determined by utilizing the three inclination measurements and the geometrical relationships existing between the drill string and the wellbore.

These and other objects and advantages of the present invention will be understood from the following description taken with reference to the attached drawings wherein:

FIGURE 1 is a sectional view of an inclined wellbore and the apparatus used in carrying out the invention;

FIGURES 2, 3A, 3B, 3C, and 3D are diagrammatic sketches showing the relationships of the various measurements taken according to the invention;

FIGURE 4 is a diagrammatic sketch showing the relationship in space between the angle of inclination and the azimuth of the borehole.

FIGURES 5A, 5B, and 5C are series of figures showing the relationship between a change in position of the eccentric stabilizer and changes in azimuth for a constant angle of inclination; and,

FIGURES 6A and 6B are diagrammatic sketches showing the relationship between borehole inclination, change of azimuth and orientation of the eccentric stabilizer.

Referring now to FIGURE 1, there is shown a wellbore 10 which is inclined with respect to a vertical axis. Within the wellbore 10 and suspended from a drilling derrick 11 at the surface, is a drill string 12 having at its lower end a drill bit 13. In order to control the direction of the wellbore 10, a bit guide or eccentric stabilizer tool 14 is included in the drill string 12 between the drill bit 13 and a concentric stabilizer 15. With this arrangement the drill string 12 is maintained concentric with the wellbore at the drill bit 13 and at the stabilizer 15.

The bit guide or eccentric stabilizer 14 consists generally of a mandrel 16, which is a length of hollow drill collar having a port 17 in the wall thereof, and a sleeve 20 slidably mounted on the outer surface of the mandrel 16. The sleeve 20 is supported on the mandrel 16 by bearings 21 and 22 and is normally free to rotate about the axis of the mandrel 16. The lower end of the sleeve 20 is provided with a hook 23 which can be locked into a corresponding hook 24 on the mandrel 16 to prevent movement of the sleeve 20 relative to the mandrel 16.

The sleeve 20 is also provided with a piston or expandable member 25, the inner surface of which is in communication with the port 17. When expanded the outer surface of the piston 25 contacts the side of the wellbore 10 and deflects the drill string 12 away from the point of contact. A pair of limiting dogs 26 and 27 are provided on the sleeve 20 to limit the deflection which can be imparted to the drill string.

In order to control the direction of drilling, the sleeve 20 and the mandrel 16 are locked together by means of hooks 23 and 24 and the drill string 12 is lowered until it is almost at the bottom of the well 10. By means of a pump located at the surface (not shown), pressure is then applied to the drilling fluid which passes through the center of the drill string 12 and out through the drill bit 13. Application of the pump pressure to the drilling fluid also applies pressure to the piston 25 via the port 17 causing the piston 25 to expand and deflect the mandrel 16 until the limit dogs 26 and 27 reach the wall of the wellbore 10. Once the piston 25 has been expanded to its maximum amount, the sleeve 20 is prevented from moving either along or about the axis of the mandrel 16 by the friction between the outer surfaces of the piston 25 and limit dogs 26, 27, and the wall of the wellbore 10. The hooks 23 and 24 are then disengaged by left hand rotation of the drill string 12 and the drill bit 13 lowered to the bottom of the well 10 to commence the drilling operation. The drilling is continued until it has progressed a distance sufficient to cause the upper end of the sleeve 20 to reach the top of the mandrel 16. At that time the hooks 23, 24 must be re-engaged and the pump pressure shut off so that the sleeve 20 may be reset at a new location.

In order to determine the inclination of the section of wellbore 10 which has just been drilled and the orientation of the eccentric stabilizer 14, i.e., the position of the piston 25, with respect to the high side of the wellbore 10, so that it can be properly set in order that the drilling may be continued in a desired direction, an inclinometer 30 is provided in the mandrel 16 which transmits a signal proportional to the inclination of the mandrel 16 to the surface by any of the well known methods of telemetering borehole information. No particular type of inclinometer has been shown since wellbore inclinometers which transmit signals to the surface, e.g., by means of vibrations in the drill pipe or by pressure pulses in the drilling fluid, are old and well known in the art. At the surface the signals from the inclinometer 30 are picked up by a transducer 31 which converts the signals to corresponding electrical signals and delivers them to the appropriate measuring, computing and indication circuitry 32 which may, for example, be a properly programmed computer.

When measuring the inclination of a wellbore by means of an inclinometer mounted in the drill string, the angle of inclination of the wellbore is only equal to the angle of inclination of the drill string if the drill string lies along the lower side of the wellbore. These angles, however, are not equal when the inclinometer is located adjacent an eccentric stabilizer. The angle of inclination, however, can be determined from a plurality of readings of the inclinometer as explained below.

Referring now to FIGURE 2, there is shown a diagrammatic sketch of the relationships of the various measurements taken in order to determine the inclination of the borehole. Basically the method consists of lowering the drill string 12 with the mandrel 16 and sleeve 20 locked together by means of hooks 23 and 24 to the desired depth and expanding the piston 25 until it is locked against the wall of the wellbore 10 at some random radial position. The hooks 23 and 24 are then disengaged and the drill bit 13 is lowered to the bottom of wellbore 10. A first inclination measurement is then taken. After the inclination measurement is taken, the hooks 23 and 24 are re-engaged and the pump pressure is removed, thereby freeing the sleeve 20 for rotation with the drill string

12. The drill string 12 is then rotated 180 degrees, the amount of rotation being observed on a meter 33 which is coupled to drill string 12 in any convenient manner. Following the rotation of the drill string 12, the piston 25 is again expanded; the drill bit 13 lowered to the bottom of the well; and, a second inclination reading taken. The inclination of the wellbore 10 is then determined by computing the average value of the two inclination readings.

In the specific example shown in FIGURE 2, the first inclination reading taken at position I determines the angle $(\gamma - \beta)$ where γ is the angle of inclination of the borehole and β is the angle between the centerline of the wellbore and the axis of the section of deflected drill string between the drill bit 13 and the piston 25. The inclination reading at position II determines the angle $(\gamma + \beta)$. The inclination of the wellbore is the average of readings I and II or

$$\gamma = \frac{(\gamma + \beta) + (\gamma - \beta)}{2} = \frac{1}{2}(I + II)$$

At this time it should also be noted that the orientation of the eccentric stabilizer with respect to the high side of the wellbore may also be determined from the same two readings used to determine the inclination. The orientation of the eccentric stabilizer 14 is determined by computing the angle between the initial setting of the piston 25 and the high side of the wellbore. This angle is necessary both in resetting the eccentric stabilizer 14 for directional drilling control and for determining any change in azimuth of the wellbore as will be explained below.

From the two inclination readings, the angle β can be determined from the relationship

$$\beta = \frac{(\gamma + \beta) - (\gamma - \beta)}{2} = \frac{1}{2}(I - II)$$

From an inspection of FIGURE 2 it can be seen that

$$\tan \beta = \frac{r \cos \alpha}{L}$$

wherein r is the effective radius of the wellbore, L is the distance from the drill bit to the eccentric stabilizer and α is the orientation angle, i.e., the angle between a radius of the wellbore through the eccentric stabilizer at position I and a radius of the wellbore on the dip axis and passing through the high side of the wellbore. The angle α is measured from the high side of the wellbore and has a positive sign when measured in clockwise direction. Since L , r and β are all known, the orientation of the eccentric stabilizer can be determined from the relationship

$$\alpha = \cos^{-1} \left(\frac{L}{R} \tan \beta \right)$$

A determination of α by the method, however, will not indicate whether the angle is positive or negative, i.e., whether counterclockwise or clockwise rotation from the initial position (I) is necessary in order to rotate the eccentric stabilizer to the high side of the wellbore accordingly, a third inclination measurement is taken 90 degrees from the initial position. Preferably, as indicated in FIGURES 2 and 3, this third inclination measurement is taken 90 degrees in a clockwise direction from the initial position whereby the sign of the angle α can be determined from the following relationships: α is a negative angle when $III < I + II/2$ and α is a positive angle when $III > I + II/2$, where I, II and III represent the inclination angles measured at position I, I and III, respectively. The various possible angular relationships are shown diagrammatically in FIGURES 3A, 3B, 3C, and 3D wherein H represents the high side of the borehole.

Once the inclination of the section of wellbore 10 has been determined, in order to get a complete picture as to the direction in which the wellbore is progressing, a deter-

mination of the azimuth must be made. Although various special instruments for measuring the borehole azimuth are available, it is possible to determine the change of wellbore azimuth from inclination measurements and the amount of rotation of an eccentric stabilizer as the eccentric stabilizer is lowered from a first location to a second location. If the azimuth direction of the borehole at the first location is known, then the azimuth direction at the second location can easily be determined by adding the change in azimuth to the known azimuth.

Referring now to FIGURE 4, there is shown schematically the orientation of a drill string having an eccentric stabilizer, wherein the position of the piston 25 is diagrammatically shown and, where γ_a represents the inclination at the reference point A and γ_b represents the inclination at point B. In the illustration, a change of inclination is shown from A to B to C but with no change of direction or azimuth. From the inclination readings alone, however, it is known only that BC must lie somewhere on the conical surface indicated in the figure. The method of determining the location of BC on the surface of the cone, and thereby the change in azimuth, from the inclination readings is described below.

When the eccentric stabilizer 14 is ready to be lowered to a new position, the sleeve 20 is locked to the mandrel 16 by the hooks 23 and 24, and the drill string 12 is rotated until the piston 25 is at the high side of the wellbore 10. This can easily be done since the orientation of the eccentric stabilizer had previously been determined as explained above. The angular reading on the meter 33 is then observed. Without rotating the drill string 12, the eccentric stabilizer 14 is lowered to the new location and the new orientation of the eccentric stabilizer is determined. The amount of rotation of the drill string 12 required to rotate the eccentric stabilizer to the high side of the wellbore 10 is indicative of the azimuth change if the drill string is free of torsion. If torsion does exist, a torsion free state can be obtained by vibrating the drill string.

Referring now to FIGURES 5A, 5B, and 5C, there is shown a series of figures illustrating the results of various azimuth changes with no change of inclination. In FIGURES 5A, 5B, and 5C, the drill string is represented first at a reference position AB with the piston 25 (diagrammatically shown) of the eccentric stabilizer tool at the top or high side of the wellbore. As shown in FIGURE 5A, when the drill string is lowered without rotation to position BC, the tool remains on the high side of the hole (indicated by the arrow) for the case of no azimuth change. If there is a change in azimuth of 180 degrees (FIGURE 5B) or 90 degrees (FIGURES 5C) or any other change in azimuth, the drill string must be rotated in order for the tool to be positioned at the high side of the wellbore.

Although the amount of rotation of the drill string 12 necessary to rotate the eccentric stabilizer to the high side of the borehole is indicative of the change in azimuth, due to the geometrical relationships between the drill string and the borehole, the required amount of rotation is, in most instances, not equal to the change in azimuth. The relationship between the wellbore inclination (γ), the change in azimuth (ϕ), and the orientation of the eccentric stabilizer (α) is shown in FIGURE 6A wherein the wellbore is considered to initially lie along the Z axis. At the origin, O, a change in both inclination and azimuth occurs so that the wellbore now lies along OA. The change of hole direction or azimuth (ϕ) is measured from the Y axis in the X-Y plane. If a change in inclination occurs without a change in azimuth, the new line lies in the Y-Z plane, and both ϕ and α are zero. If, however, a change of inclination and direction both occur, the eccentric stabilizer is perpendicular to the CAE plane but the high side of the wellbore is in the DAB plane. The angle between these planes is $\pi/2 - \alpha$. From the spherical triangle OABC, which is shown removed from the main

figure in FIGURE 6B, by Napier's rule for right spherical triangles,

$$\sin\left(\frac{\pi}{2} - \gamma\right) = \tan\left(\frac{\pi}{2} - \phi\right) \tan \alpha$$

or

$$\tan \phi = \frac{\tan \alpha}{\cos \gamma}$$

From this relationship the change in azimuth ϕ can be determined. It should be noted that for wellbores which are only slightly inclined, $\cos \gamma \approx 1$ and $\phi \approx \alpha$.

Once the inclination and the change in azimuth of the section of wellbore which has just been drilled has been ascertained, the proper setting of the eccentric stabilizer to control the direction of the drilling can be determined.

It is to be understood that although the invention has been described using a particular type of bit guide or eccentric stabilizer, that any type of bit guide which functions in a similar manner may be substituted. It is further understood that the method herein described may also be used to survey sections of the wellbore other than the bottom section by merely lowering the drill bit for a suitable distance after the eccentric stabilizer has been set in order to take the inclination measurements, the basic requirement being that the measurements be taken on a deflected section of the drill string which is between two points at which the drill string is concentric with the wellbore.

We claim as our invention:

1. The method of surveying a section of a borehole having a drill string therein comprising:

- (a) laterally displacing a first portion of the drill string relative to a longitudinally spaced portion of the drill string which is concentric with the borehole;
- (b) measuring the inclination of the axis of a section of the drill string which extends from the displaced portion to said concentric portion;
- (c) laterally displacing said first portion of said drill string an equal amount in a direction 180 degrees from the direction of the displacement in step (a);
- (d) measuring the new inclination of the axis of said section of drill string between the displaced portion and said concentric portion; and
- (e) determining the angle of inclination of the axis of the borehole from the two inclination measurements.

2. The method of claim 1 wherein the said angle of inclination of the axis of the borehole is determined by averaging the two said inclination measurements.

3. The method of surveying a section of a borehole having therein a drill string including an eccentric stabilizer mounted from a portion of the drill string which is concentric with the borehole comprising:

- (a) displacing a first portion of said drill string relative to a concentric portion by means of the eccentric stabilizer;
- (b) measuring the inclination of the section of drill string between said concentric portion and said displaced portion;
- (c) rotating said eccentric stabilizer 180 degrees;
- (d) displacing said first portion of said drill string relative to said concentric portion by means of the eccentric stabilizer;
- (e) measuring the new inclination of the section of drill string between said concentric portion and said displaced portion; and,
- (f) determining the inclination of the axis of said borehole by averaging the two said inclination measurements.

4. In a borehole having therein a drill string including an eccentric stabilizer mounted a known distance from a portion of the drill string which is concentric with the

borehole, the method of determining the orientation of the eccentric stabilizer comprising:

- (a) displacing a first portion of said drill string relative to a concentric portion by means of the eccentric stabilizer;
- (b) measuring the inclination of the section of drill string between said concentric portion and said displaced portion;
- (c) rotating said eccentric stabilizer 180 degrees;
- (d) displacing said first portion of said drill string relative to said concentric portion by means of the eccentric stabilizer;
- (e) measuring the new inclination of the section of drill string between said concentric portion and said displaced portion; and,
- (f) determining the orientation of the eccentric stabilizer relative to the high side of the borehole from the relationship

$$\alpha = \cos^{-1} \left(\frac{L}{r} \tan \beta \right)$$

where α is the angle between a radius of the borehole on the dip axis and passing through the high side of the borehole and a radius of the borehole passing through the center of the eccentric stabilizer at its initial position; L is the length of the drill string between the eccentric stabilizer and the concentric portion; r is the effective radius of the borehole; and, β is the angle between the axis of the borehole and the axis of the section of deflected drill string, and is equal to one half the difference between the two inclination measurements.

5. The method of claim 4, including:

- (g) rotating the eccentric stabilizer to a position 90° from the first position;
- (h) displacing said first portion of said drill string relative to said concentric portion by means of the eccentric stabilizer;
- (i) measuring the inclination of the section of drill string between said concentric portion and said displaced portion; whereby the sign of the angle α with respect to the high side of the borehole may be determined from the following relationship when the stabilizer in step (g) is rotated in a positive or clockwise direction relative to the first position: α is a negative angle when $III < I + II/2$; and α is a positive angle when $III > I + II/2$, where I, II, and III represent the angles of inclination measured in steps (b), (e) and (i) respectively.

6. A method of surveying a section of a borehole having a drill string therein comprising:

- (a) laterally displacing a first portion of the drill string

relative to longitudinally spaced portion of the drill string which is concentric with the borehole;

- (b) measuring the inclination of the axis of a section of the drill string which extends from the displaced portion to said concentric portion;
- (c) laterally displacing said first portion of said drill string an equal amount in a direction 180 degrees from the direction of the displacement in step (a);
- (d) measuring the new inclination of the axis of said section of drill string between the displaced portion and said concentric portion; and,
- (e) using said inclination measurements to determine the course of the borehole.

7. The method of surveying a section of a wellbore having therein a drill string including an eccentric stabilizer mounted from a portion of the drill string which is concentric with the borehole comprising:

- (a) at a position of known inclination of the axis of the borehole which position is above said section to be surveyed, rotating the eccentric stabilizer until it is along the dip axis of the wellbore;
- (b) lowering said drill string to a second position which is in the section of the wellbore to be surveyed;
- (c) measuring the angle of inclination of the axis of the wellbore in the section of the wellbore;
- (d) determining the angle between the initial position of the eccentric stabilizer and the dip axis of the wellbore in the said section; and
- (e) determining the change in azimuth of the wellbore from the inclination and the angle between the stabilizer and a radius of the wellbore on the dip axis and passing through the high side of the wellbore in the said section, whereby said change in azimuth is determined from the relationship

$$\tan \theta = \frac{\tan \alpha}{\tan \gamma}$$

wherein θ is the angle through which the azimuth has changed, α is the angle between the initial position of the eccentric stabilizer and the dip axis of the wellbore in the said section and γ is the angle of inclination of the axis of the said section of the wellbore.

8. The method of claim 7 wherein the azimuth of the borehole at said first position is also known and including:

- (f) determining the azimuth of the borehole at said second position by adding the result of step (e) to the known azimuth at said first position.

No references cited.

ISSAC LISANN, *Primary Examiner*.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,229,375

January 18, 1966

Wilfred S. Crake et al.

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 4, line 67 and column 7, line 46, for
"III<I+II/2", each occurrence, read -- III< $\frac{I+II}{2}$ --; column
4, line 68 and column 7, line 47, for "III>I+II/2", each
occurrence, read -- III> $\frac{I+II}{2}$ --.

Signed and sealed this 10th day of January 1967.

(SEAL)

Attest:

ERNEST W. SWIDER

Attesting Officer

EDWARD J. BRENNER

Commissioner of Patents