

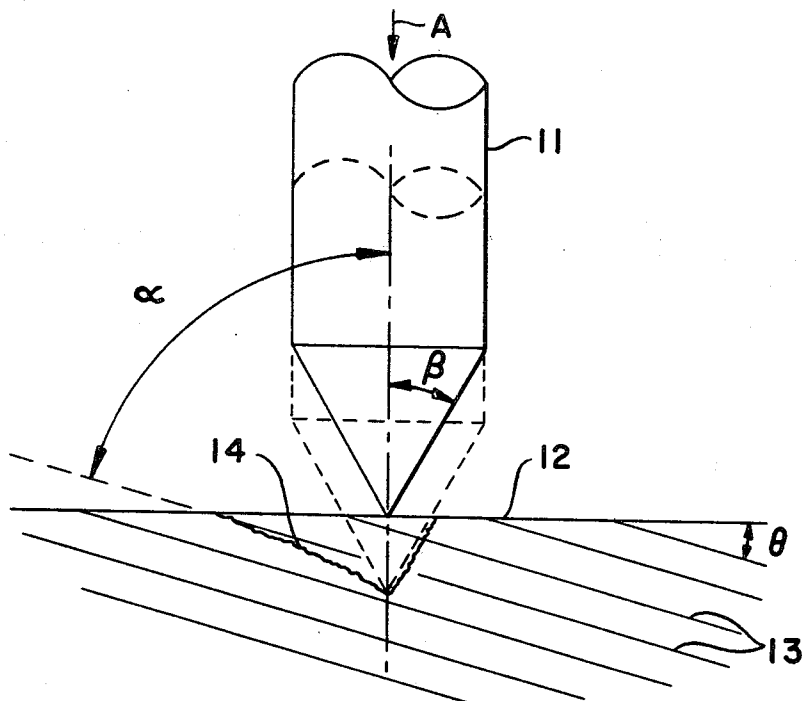
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[45] Patented **Dec. 15, 1970**
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[54] **DEVIATION CONTROL BIT AND METHOD**
7 Claims, 9 Drawing Figs.
[52] **U.S. Cl.**..... **175/61,**
175/378, 175/410
[51] **Int. Cl.**..... **F21b 7/04;**
F21c 1300
[50] **Field of Search**..... **175/331,**
341, 342, 350, 353, 377, 378, 410

ABSTRACT: Method and apparatus for controlling natural hole deviation of a drill string and bit wherein the bit teeth wedges are designed to eliminate or substantially reduce the formation reactive forces that cause the bit to deviate from the vertical as drilling is carried out. Such design permits the use of substantially greater drilling weights than those utilized in prior art systems for a given bit type and formation hardness.



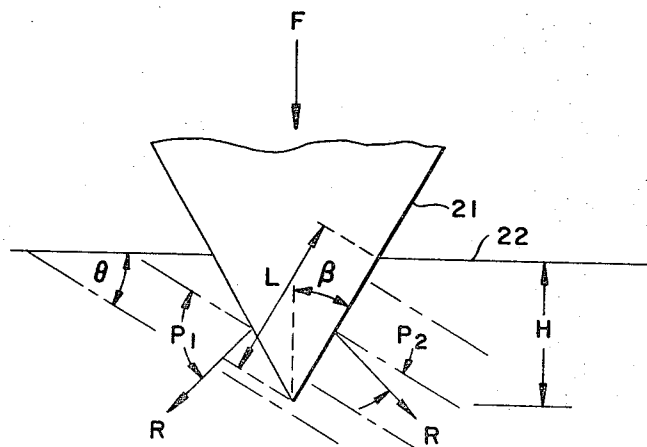


FIG. 2

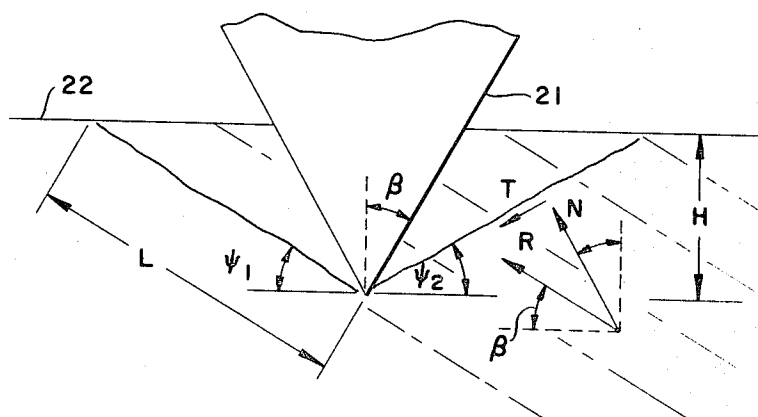


FIG. 3

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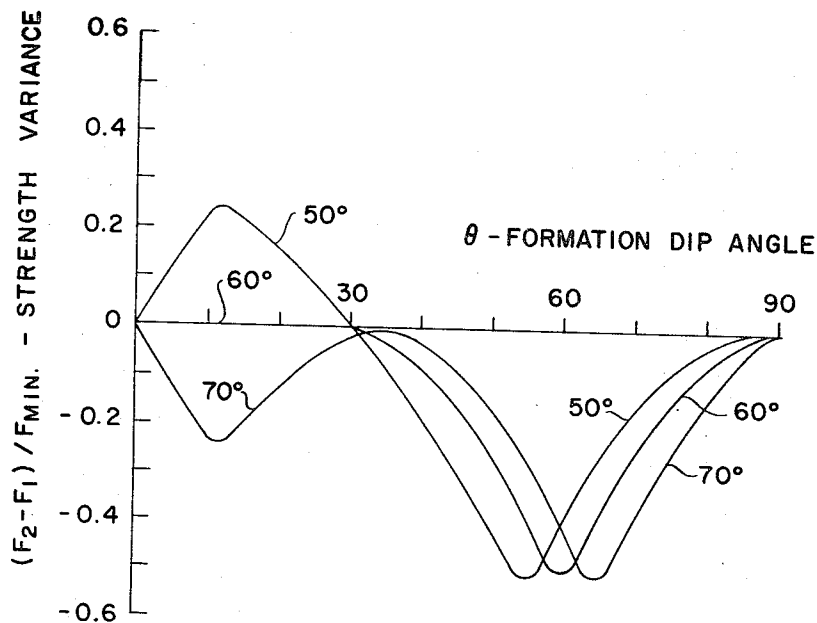


FIG. 5

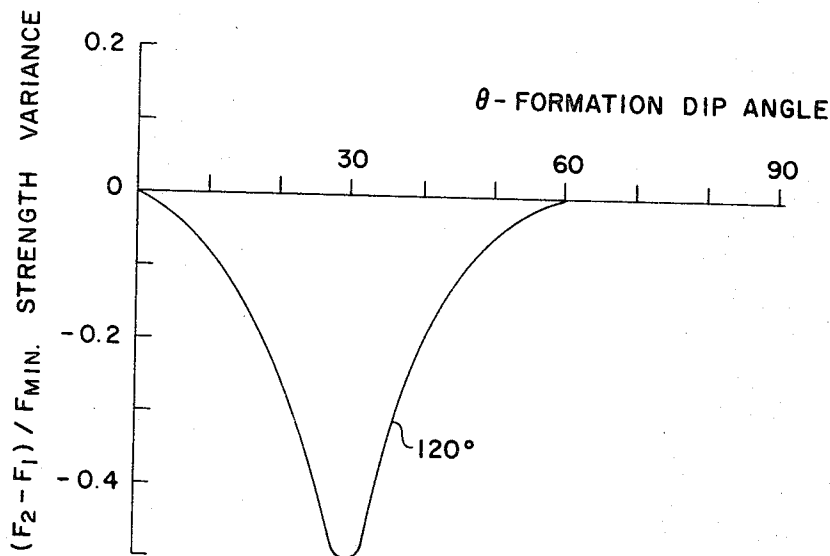


FIG. 6

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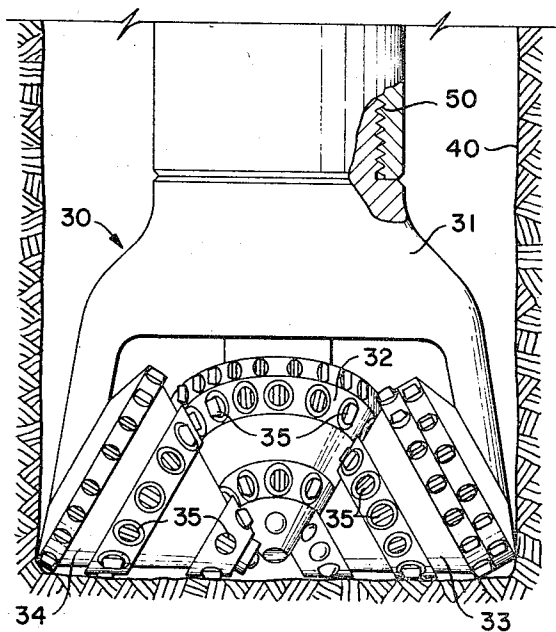


FIG. 7

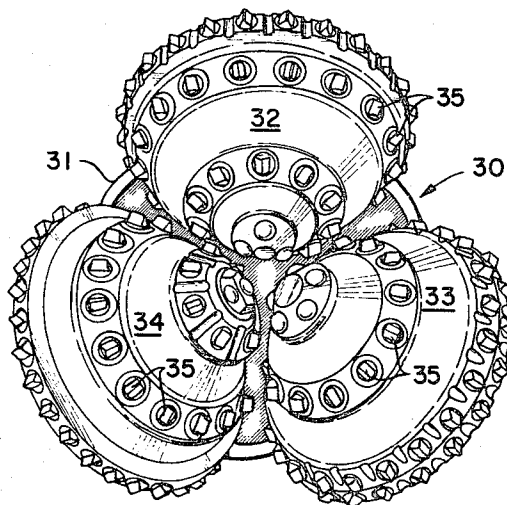


FIG. 8

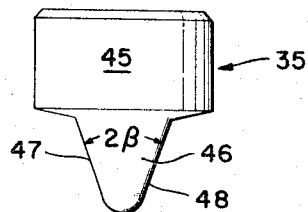


FIG. 9

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DEVIATION CONTROL BIT AND METHOD

The present invention relates to earth boring, and more particularly concerns itself with a method and apparatus for minimizing the formation reactive force acting on a bit wedge-shaped tool so that natural hole deviation (such as may be caused by drilling through dipping, laminated or anisotropic formations) will be reduced or eliminated. Dipping, laminated or anisotropic formations may hereinafter be referred to as "anisotropic formations."

When utilizing conventional rotary drilling techniques and equipment, problems are often encountered as drilling is carried out through anisotropic, dipping, or laminated formations. As the drill bit passes through a formation of this type, each bit tooth or tool, as it strikes the rock, compresses a volume of rock substantially equal to the volume of the tooth penetrating the rock, thereby storing elastic energy in the rock. As a result of the nature of the rock, chips are formed on only one side of the tooth and an imbalance of energy release is created. On the "chip side" of the tooth the energy is responsible for and is released during the initiation and extension of the crack that constitutes the chip. On the opposite side of the tooth, the rock is still in contact with the wedge and a momentary force imbalance is present that imparts a lateral force to the tool. The result of such interaction between the bit teeth and the anisotropic, dipping or laminated formation is that the bit and drill string tend to deviate from the desired direction.

Using currently available bits, the technique used to control or correct natural hole deviation consists of reducing the weight on bit sometimes as much as 90 percent of the optimum drilling weight and maintaining or increasing the rotary speed. This practice accents what is commonly known in the drilling art as the pendulum effect and brings the hole back toward the vertical or other desired drilling direction. An alternative approach for the prevention of undesired bit and drill string deviation is to utilize square drill collars to stiffen the drill string assembly while running lighter bit weights. Both of these prior art approaches are characterized by the fact that much lower drilling rates are obtained with resultant increases in drilling costs per foot of hole.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide a method and apparatus whereby substantially high weight levels may be maintained with respect to a drill string and bit without resulting in deviation of the string and bit even when drilling in anisotropic, dipping or laminated formations.

A further object of the present invention is to provide a method and apparatus whereby formation reaction forces are effectively removed with respect to each bit tooth so that conventional drill string mechanics may be utilized to correct or control deviation of the bit and drill string while drilling in anisotropic, laminated or dipping formations.

A still further object of the present invention is to provide an improved method and apparatus whereby drilling through anisotropic or laminated or dipping formations may be carried out in an economic and efficient manner.

These and other objects have been attained in the present invention by providing a method and apparatus for drilling through anisotropic formations wherein a rotary bit is provided with teeth which are of a configuration adapted to eliminate or substantially reduce the formation reactive forces on the sides of each tooth as drilling is carried out. More particularly, each tooth is in the shape of a wedge having an included angle adapted to create symmetrical chips during the drilling operation. The included angle is in the order of either 60° or 120° with a 60° wedge controlling deviation in areas where the formation dips or is tilted at angles up to 45° and a 120° wedge controlling deviation in areas where the angle of the formation dip exceeds 60°.

DESCRIPTION OF THE DRAWING

The objects of this invention will be understood from the following description taken with reference to the drawing, wherein:

FIG. 1 is a schematic view taken on longitudinal projection of a tool adapted to penetrate an anisotropic, laminated or dipping formation which serves to illustrate the principles underlying the present invention;

FIGS. 2 and 3 are schematic views taken on longitudinal projection of a wedge-shaped drilling bit tooth penetrating an anisotropic rock and serving to illustrate the principles underlying the present invention;

FIGS. 4, 5 and 6 are graphs illustrating certain performance characteristics of selected wedge-shaped tools and incorporating comparative data showing how the method and apparatus according to the present invention result in the elimination of natural hole deviation during the course of drilling activities;

FIG. 7 is a view taken in longitudinal projection of a drill bit constructed in accordance with the present invention;

FIG. 8 is an end view of the drill bit illustrated in FIG. 7 showing the rolling cones of the bit; and

FIG. 9 is an enlarged detail view taken in longitudinal projection of a drill bit tooth incorporating the teachings of the present invention.

Before describing the invention it should be pointed out that the connotation of the terms "optimum" and "equilibrium" drilling conditions, "types" of drill bits, and the procedures for determining combinations of weight on bit, rotary speed, and the like that are involved with respect to a given type of bit and formation hardness, as set forth in the following description, are known to those skilled in the art. The factors involved in such determinations are discussed, for example, in the paper by Lubinski and Woods entitled "Factors Affecting the Angle of Inclination and Dog-Legging in Rotary Bore Holes," found in API Drilling and Production Practice, 1953, page 222.

For the proper understanding of the present invention, the basic principles upon which it is founded will first be discussed. The method and apparatus according to the present invention are based on a theoretical analysis of chip formation in an anisotropic medium as that medium is penetrated by a wedge-shaped tool.

Briefly, the theory states that a chip will be formed on a particular side of the wedge-shaped tool as the tool penetrates an anisotropic formation. Referring now to FIG. 1, a wedge-shaped tool 11 is shown disposed above an anisotropic rock 12 which includes a plurality of bedding or anisotropic planes 13 dipping at an angle θ with respect to the horizontal and at an angle α relative to the longitudinal axis of tool 11. During the course of drilling operations, wedge-shaped tool 11 moves downwardly in the direction of arrow A to the position illustrated by means of the dotted lines so that a hole is formed in anisotropic rock 12 as at 14. Such hole is formed through the creation of individual chips in formation or rock 12 by the tool. The particular side of tool 11 that a chip will be formed on and the force needed to create the chip is a function of the anisotropic strength characteristics of the rock, the angle α between the tool axis and the plane of anisotropy, and the included angle (2β) of the tool. A chip formed to the left of tool 11 as viewed in FIG. 1 will be considered to have been formed on the "updip" side of the tool while a chip formed to the right thereof will be considered "downdip."

This preferred chip formation, either "updip" or "downdip," is the essence of the anisotropic rock's contribution to natural hole deviation. As the tool penetrates the rock, a volume of rock approximately equal to the volume of the penetrating portion of the tool is compressed and elastic energy is stored in the rock. When a chip is formed on only one side of the tool, an imbalance of energy release is created. On the "chip side" the energy is responsible for and is released during the initiation and extension of the crack that constitutes the chip. On the opposite side of the tool, on the other

hand, the rock is still in contact with the wedge and a momentary energy imbalance is present that imparts a force to the tool.

When the wedge-shaped tool in question is a tooth on a conventional rotary drill bit, for example, these unequal reactive forces tend to deviate the entire drill bit and associated drill string away from the desired drilling direction. This is due to the fact that conventional or standard rock bits have wedge-shaped teeth that range from 35° to 45° which, as will be seen below, tend to create a force imbalance through the unequal formation of chips on the sides of the wedge-shaped teeth when drilling through an anisotropic, dipping or laminated formation.

As stated above, deviation of a wedge-shaped tool when penetrating anisotropic rock may be either "updip" or "downdip" depending upon which side of the tool a chip is formed. An appreciation of this phenomenon is important to the proper understanding of the present invention as well as to the development of the subject apparatus and method. For these purposes an analytical analysis has been made of the preferred formation of chips, i.e., either "updip" or "downdip" in an anisotropic formation. FIG. 2 illustrates a physical model utilized in this analysis.

In FIG. 2 a wedge-shaped portion of a tool 21 is shown entering an anisotropic formation or rock 22. The rock 22 is assumed to have been penetrated a distance H by the sharp wedge having an included angle of 2β. The force on the wedge is given by F and the resultant forces acting perpendicular to the two faces of the wedge are given by R. The dip of the bedding plane relative to the normal of the force F is given by θ. The total area of the wedge in contact with the rock is denoted by 2L. Thus:

$$R = \frac{F}{2 \sin \beta} \quad (1)$$

or in terms of stress

$$\sigma_R = \frac{R}{L} = \frac{F}{2 H \tan \beta} \quad (2)$$

The directions of the resultant forces R relative to the bedding plane are defined by the angles ρ₁ (updip) and ρ₂ (downdip), where

$$\rho_1 = |\theta + \beta| \text{ and } \rho_2 = |\theta - \beta| \quad (3)$$

The mathematical model proposed states that when the wedge has penetrated a characteristic distance H, failure may occur on either the updip or downdip side of the wedge or on both sides depending upon the values of θ and β. Failure occurs along planes described by Ψ₁ (updip) and Ψ₂ (downdip) as depicted in FIG. 3. Along the failure plane a modified Mohr-Coulomb failure criterion holds.

Force considerations. The Mohr-Coulomb failure criterion states

$$\tau - \sigma \tan \phi = \tau_0 \quad (4)$$

where τ = shear stress on failure plane, p.s.i.;

σ = normal stress on failure plane, p.s.i.;

tan φ = coefficient of internal friction of the material; and

τ₀ = cohesive strength of the material, p.s.i.

The failure characteristics of anisotropic rocks may be described by a modified Mohr-Coulomb criterion which has the form

$$\tau - \sigma \tan [\phi(\zeta)] = \tau_0(\zeta) \quad (5)$$

where tan [Φ(ζ)] and τ₀(ζ) are empirically determined functions which describe the variations of τ₀ and tan Φ as a function of orientation, ζ. (The angle ζ is the angle between the direction of the maximum compressive load, σ₁, and the bedding plane. In the present model this direction is denoted by ρ₁ and ρ₂.) Experimental evidence indicates the general

forms of τ₀(ζ) and tan [Φ(ζ)] are given by

$$\tau_0(\zeta) = A - B[\cos 2(\alpha - \zeta)]^n \quad (6)$$

$$\phi(\zeta) = \text{Arc tan } \{C - D[\cos 2(\nu - \zeta)]^m\} \quad (7)$$

where

A, B, C, D = empirical constants;

n, m = rock parameter constants;

α = value of ζ where τ₀ is a minimum;

ν = value of ζ where tan σ is a minimum.

Using equations 5, 6, 7 and the geometric consideration depicted in FIG. 3, an expression for the force, F, needed to create a chip can be derived. The forces, T and N, acting on the failure surface defined by ψ in terms of R and F are

$$T = R \cos(\beta + \psi) = \frac{F \cos(\beta + \psi)}{2 \sin \beta} \quad (8)$$

and

$$N = R \sin(\beta + \psi) = \frac{F \sin(\beta + \psi)}{2 \sin \beta} \quad (9)$$

The forces T and N can be converted to the stresses τ and σ by dividing each by "l" (assuming that the wedge is of unit length).

$$l = \frac{H}{\sin \psi} \quad (10)$$

Thus,

$$\tau = \frac{F \cos(\beta + \psi) \sin \psi}{2 H \sin \beta} \quad (11)$$

and

$$\sigma = \frac{F \sin(\beta + \psi) \sin \psi}{2 H \sin \beta} \quad (12)$$

By substituting equation 11 and 12 into equation 5, letting ρ = ζ, and rearranging, we find that

$$\frac{F \sin \psi \cos [\phi(\rho) + \beta + \psi]}{2 H \sin \beta \cos [\phi(\rho)]} = \tau_0(\rho) \quad (13)$$

The relationship between the failure angle ψ, the physical characteristics of the rocks and the geometry of the wedge can be found by differentiating equation 13 with respect to ψ. Such an operation yields

$$\psi = \frac{\pi/2 - \beta - \phi(\rho)}{2} \quad (14)$$

Substituting equation 14 into equation 13, rearranging and generalizing, the force needed to create chipping is found to be

$$F_i = \frac{2 \tau_0(\rho_i) H \sin \beta \cos [\phi(\rho)]}{\sin \left[\frac{\pi/2 - \beta - \phi(\rho_i)}{2} \right] \cos \left[\frac{\pi/2 + \beta + \phi(\rho_i)}{2} \right]} \quad (15)$$

where

i = 1 for updip side of wedge;

i = 2 for downdip side of wedge;

ρ_i is defined by equation (3);

σ(ρ_i) is defined by equation (7); and

τ₀(ρ_i) is defined by equation (6).

For a given H, β and θ, the values F_i can be calculated and the preferred failure or chip formation determined. Failure is assumed to occur at the lower force level.

Referring once again to FIG. 1, by computing the "relative" strength of the rock on both sides of the wedge (as discussed above) as a function of the angle of dip of the bedding planes (θ) and the included angle 2β , equating the two strengths and solving for 2β as a function of θ it is possible to determine unique wedge shapes that eliminate preferred chip formation for various bedding plane dips.

By doing this it becomes apparent that for dip angles ranging from 30° to 45° , depending upon the strength characteristics of the rock, the unique wedge angle to generate symmetrical chips is 2ξ . Where ξ is defined as the particular orientation (angle between bedding plane and the applied force—see above) of the material where the strength of the material is a minimum. Experimental evidence, to date, indicates that ξ is 30° for all rocks exhibiting anisotropic strength characteristics. Thus, for a rather large range of bedding plane dips, a wedge shape of 60° should create symmetrical chips. This will eliminate the force imbalance on the tool that leads to natural hole deviation caused by dipping beds.

FIGS. 4, 5 and 6 illustrate this concept for a hypothetical rock. In all three FIGS. the term $(F_2 - F_1) / F_{min}$ is plotted against θ for various values of 2β , where

F_2 = strength of the rock on the updip side of the wedge;

F_1 = strength of the rock on the downdip side of the wedge; and

F_{min} = minimum of the two values of F_1 and F_2 .

Thus, when $(F_2 - F_1) / F_{min}$ is positive, a chip should be formed on the updip side of the wedge and the "hole" should deviate updip. When the term is negative, the converse occurs. When the term is equal to zero, symmetrical chips are formed when the wedge impacts the rock and the "hole" should drill straight.

In FIG. 4, the characteristics of the range of common wedge angles (35° – 45°) for current tricone roller bits are shown. The FIG. illustrates what has been established in the field, mainly that for dips ranging from 0° to 30° – 45° the hole deviates updip, for greater angles the hole deviates downdip, and for very large dip angles ($>75^\circ$) the deviation problem decreases.

FIG. 5 illustrates the behavior of 50° , 60° and 70° wedges. Two features are important. Note that over the range of θ from 0° to 30° the values of $(F_2 - F_1) / F_{min}$ for the 60° wedge are zero. This indicates that symmetrical chips are being formed.

The other feature of FIG. 5 is the deviation tendency implied in the 70° wedge curve. Theoretically, this indicated that if a hole is drilled with a bit having 70° wedges (or larger), the hole should deviate downdip at all formation dips.

FIG. 6 illustrates the behavior of a 120° wedge. It should be noted that a wedge of this angle should control deviation in areas where the angle of the formation dip exceeds 60° .

In summary, this study indicates that a theoretically designed wedge angle of either 60° or 120° on any cutting or impacting surface of any type of rock bit would control natural hole deviation caused by dipping beds. In particular, the 60° wedge would control updip deviation and the 120° wedge, downdip deviation for formation dips in excess of 60° .

FIGS. 7 and 8 illustrate a rotary drill bit incorporating the teachings of the present invention which is indicated generally by means of reference numeral 30. Drill bit 30 includes a bit body 31 adapted to be attached to a drill string (not shown) by means of screw threads 50 with cone-shaped roller elements 32, 33 and 34 journaled on the bit body by means of suitable conventional axes and load bearings (not illustrated). The roller elements 32, 33 and 34 have disposed in bands or rings about the respective outer peripheries thereof a plurality of bit teeth 35. With particular reference to FIG. 7, drill bit 30 is shown as forming a well bore 40 in the earth. During the course of the drilling operation it is to be understood that the bit is rotated and/or impacted, thus causing cone-shaped roller elements 32, 33 and 34 to turn about their respective axes with bit teeth 35 forming chips in the bottom of the well bore or hole 40.

The bands of bit teeth 35 are disposed about cone-shaped roller elements 32, 33 and 34 in planes extending normal to the rotational axes of the roller elements with the bands or rings of teeth being spaced from each other in an axial direction along the respective cone-shaped roller elements.

Referring briefly to FIG. 9, it may be seen that each bit tooth 35 includes a body portion 45 adapted to be affixed to the cone-shaped roller element and a wedge-shaped tool portion 46 forming substantially flat working surfaces 47 and 48. The included angle between working surfaces 47 and 48 is indicated as 2β , which, based on the foregoing analyses and may be either 60° for use with anisotropic, dipping or laminated formations having dip angles of up to about 45° , or 120° for use in areas where the angle of the formation dip exceeds 60° .

Returning once again to FIGS. 7 and 8, it may be seen that the bit teeth 35 are mounted on cone-shaped roller elements 32, 33 and 34 so that the wedge-shaped tool portions of the teeth contact the bottom of hole 40 as the drill bit rotates. The rings or bands of teeth are disposed in different axial positions about each of the roller elements so that the teeth on the different roller elements do not contact one another as the bit rotates and the cone-shaped roller elements turn. This arrangement further ensures the efficient formation of cuttings along the entire bottom of the bore hole.

When utilizing a bit constructed according to the teachings of the present invention, the drilling through an anisotropic, dipping or laminated formation may be carried out with a combination of weight and rotary speed that is substantially optimum for the type of bit used and the hardness of the formation. The spacing and placement of the wedge-shaped teeth on the bit roller elements may be varied as desired to ensure good indexing and chip-removal effect. Similarly, the height and sharpness of the teeth can be those which are conventional for the bit size and hardness of the earth foundations to be drilled.

Several $12\frac{1}{4}$ inch deviation control bits with 60° teeth have been tested. One such test was conducted in a wildcat well that had a severe deviation problem. Prior to running the deviation control bit, the equilibrium weight on bit to maintain a constant hole angle was determined to be 12,000 pounds for a standard bit. The weight on bit was increased from 12,000 pounds to 20,000 pounds and the hole angle increased from $6\frac{1}{4}^\circ$ to $6\frac{3}{4}^\circ$ in 31 feet with the standard bit. The deviation control bit was then run at weights up to 30,000 pounds and hole angle dropped from $6\frac{3}{4}^\circ$ to 5° in 200 feet, indicating the bit was performing as expected. By virtue of being able to run more weight on bit with the experimental bit and still maintain hole angle control, the drilling rate was increased from an average of 2 to 3 feet per hour to 4 to 6 feet per hour.

Another test was conducted to compare the performance of both standard and the deviation control bits in drilling through nearly 700 feet of top hole 30° dipping shale. Four standard bits were run from 62 feet to 327 feet. For the standard bits, the equilibrium weight on bit for constant hole angle was found to be only 6,000 to 8,000 pounds. The corresponding drilling rates for these low weights were only 7 to 10 feet per hour.

A single deviation control bit was used to drill from 327 feet to 692 feet with weights on bit ranging from 15,000 to 25,000 pounds. The initial hole angle was $1^\circ 49'$ and the final angle was $1^\circ 42'$. The drilling rates for the deviation control bit ranged from 10 to 20 feet per hour. The drilling rates for the deviation control bit were higher than the standard bits due to the greater weight that could be applied and still maintain hole angle control. The increased penetration rates and footage permitted a reduction in drilling costs from \$13 per foot with the standard bits to \$9.40 per foot with the deviation control bit.

I claim:

1. A rotary drill bit adapted for substantially reducing natural hole deviation when drilling a bore hole into a formation having anisotropic strength characteristics, said rotary drill bit comprising:

a bit body adapted to be affixed to a drill string;

a plurality of cone-shaped roller elements rotatably mounted on said bit body; and

a plurality of bit teeth mounted about the outer surfaces of said cone-shaped roller elements, at least a selected number of said bit teeth including a wedge-shaped tool portion forming substantially flat working surfaces converging at an angle selected such that reactive lateral forces on said working surfaces are substantially zero as chips are formed during drilling by the rotary drill bit through the formation.

2. The rotary drill bit according to claim 2 wherein the selected angle formed between said flat working surfaces is substantially 60°.

3. The rotary drill bit according to claim 1 wherein the selected angle formed between said flat working surfaces is substantially 120°.

4. The rotary drill bit according to claim 1 wherein said bit teeth are disposed about the peripheries of said cone-shaped roller elements in bands lying in planes extending normal to the rotational axes of the roller elements with the bands of teeth associated with each roller element being spaced from each other along the rotational axes of the roller element.

5. A method of drilling a substantially straight borehole into an earth formation including bedding planes which dip as high as 30° to 45° with respect to the horizontal, said method comprising:

a rotary cone drill bit having a plurality of teeth arranged on said bit with the effective working surface areas of the teeth being substantially flat areas that form substantially 60° wedges;

affixing said bit to a drill string;

extending said drill bit and drill string to contact said formation;

determining an optimum combination of weight on bit and rotary speed for maximizing the rate of penetration into said formation; and

rotating the drill bit at said preselected optimum rotary

speed while maintaining said optimum weight thereon to drill said substantially straight hole in said formation.

6. A method of drilling a substantially straight borehole into an earth formation including bedding planes which dip at an angle in excess of 60° with respect to the horizontal, said method comprising:

a rotary cone drill bit having a plurality of teeth arranged on said bit with the effective working surface areas of the teeth being substantially flat areas that form substantially 120° wedges;

affixing said bit to a drill string;

extending said drill bit and drill string to contact said formation;

determining an optimum combination of weight on bit and rotary speed for maximizing the rate of penetration into said formation; and

rotating the drill bit at said preselected optimum rotary speed while maintaining said optimum weight thereon to drill said substantially straight hole in said formation.

7. A method of drilling into an earth formation having bedding planes which are dipping with respect to the horizontal, said method comprising the steps of:

determining a wedge shape for a bit tooth including a wedge-shaped tool portion forming substantially flat working surfaces for which wedge shape the reactive lateral forces on said working surfaces are substantially zero when said bit tooth having said wedge shape penetrates said formation;

selecting a bit having teeth of said shape;

affixing said bit to a drill string;

determining an optimum combination of weight on bit and rotary speed for maximizing the rate of penetration into said formation; and rotating said drill string and drill bit at said optimum rotary speed while maintaining said optimum weight on the bit to extend said borehole into said formation.

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