US 20060201713A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2006/0201713 A1

(43) Pub. Date: Sep. 14, 2006

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(54) DEVIATED DRILLING METHOD FOR WATER PRODUCTION

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(21) Appl. No.: 11/116,715

(22) Filed: Apr. 28, 2005

Related U.S. Application Data

(60) Provisional application No. 60/566,551, filed on Apr. 29, 2004.

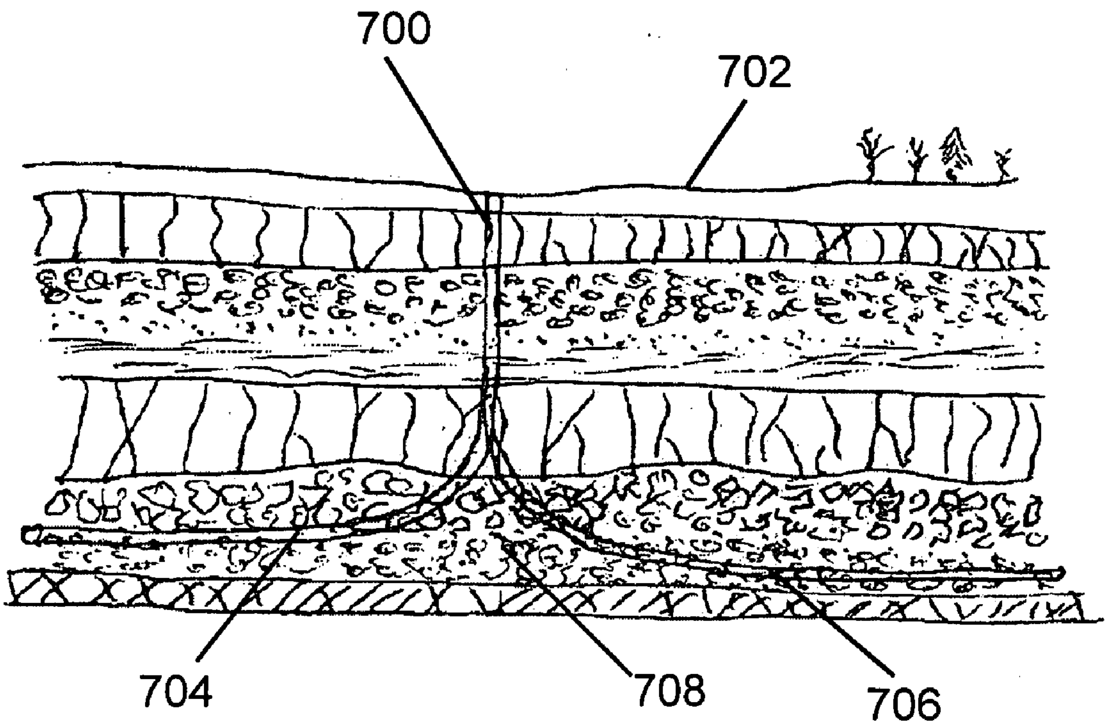
Publication Classification

(51) Int. Cl.
E21B 7/04 (2006.01)

(52) U.S. Cl. 175/61; 166/50

(57) ABSTRACT

Method for drilling horizontal or deviated water wells through hard and fragmented rock formations that are prone to caving, such as Hawaiian basalts. The method may be used to drill into basal aquifers directly underlain by salt water, compartmented aquifers, and perched aquifers. The method uses deviated drilling and may use formation pre-grouting, casing drilling, and/or percussion drilling, and a percussion drilling tool may be combined with a casing drill string.



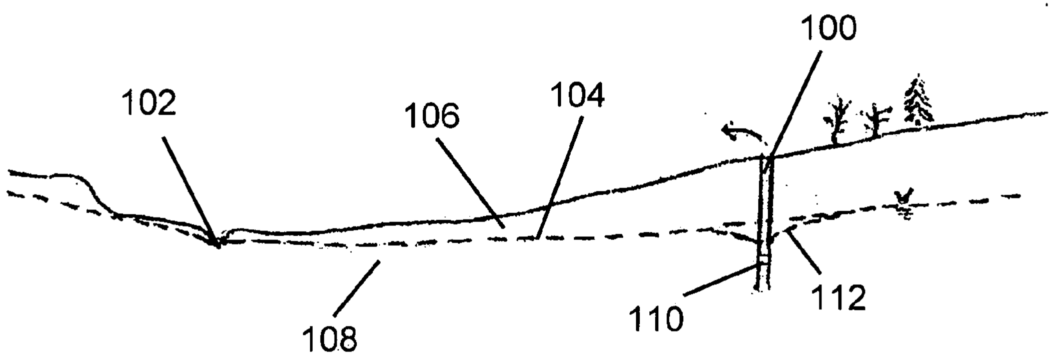


Fig. 1 (prior art)

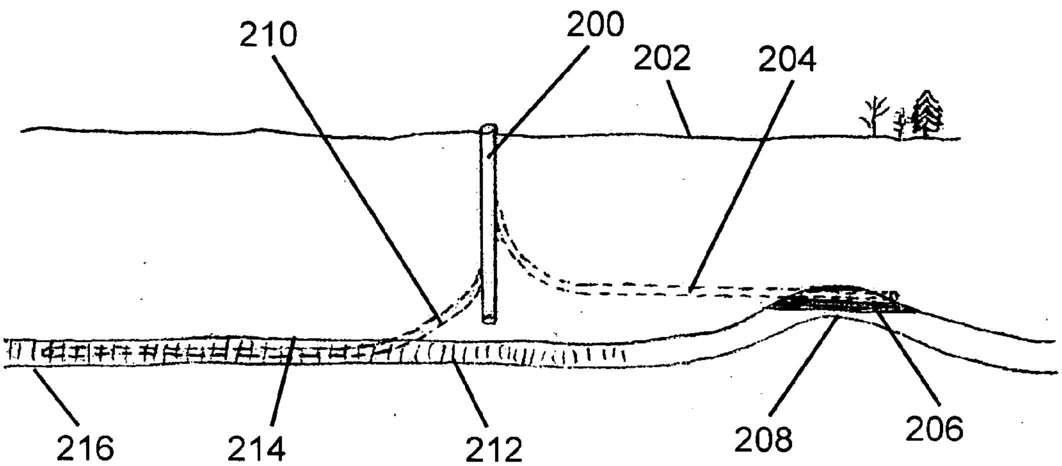


Fig. 2 (prior art)

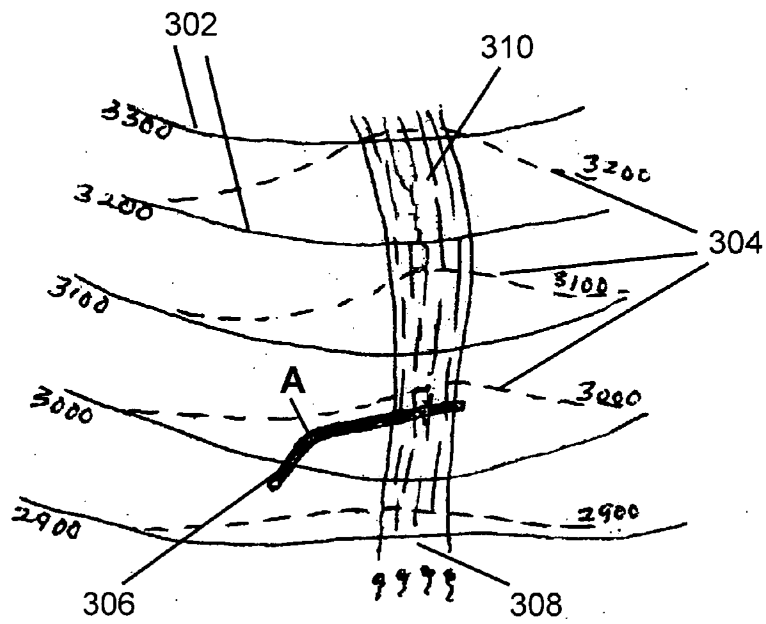


Fig. 3 (prior art)

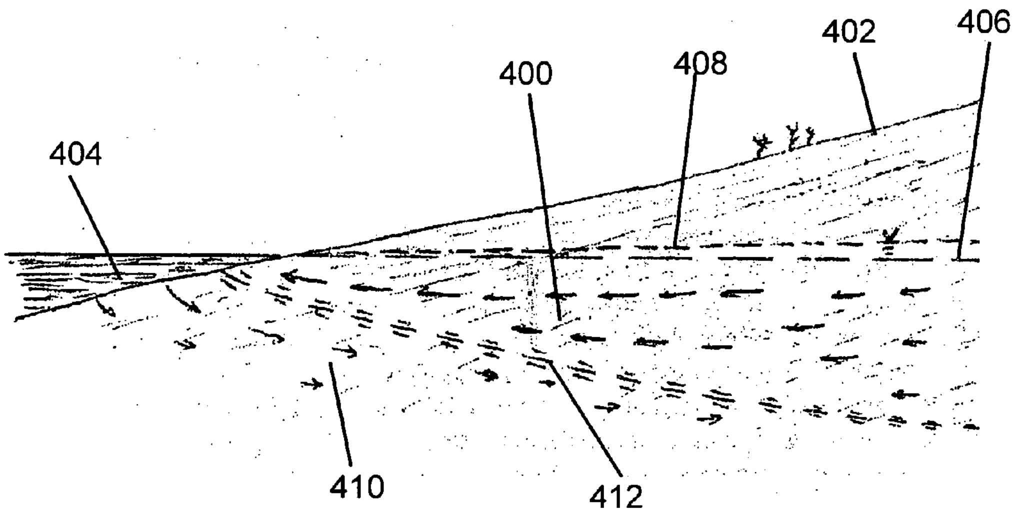


Fig. 4

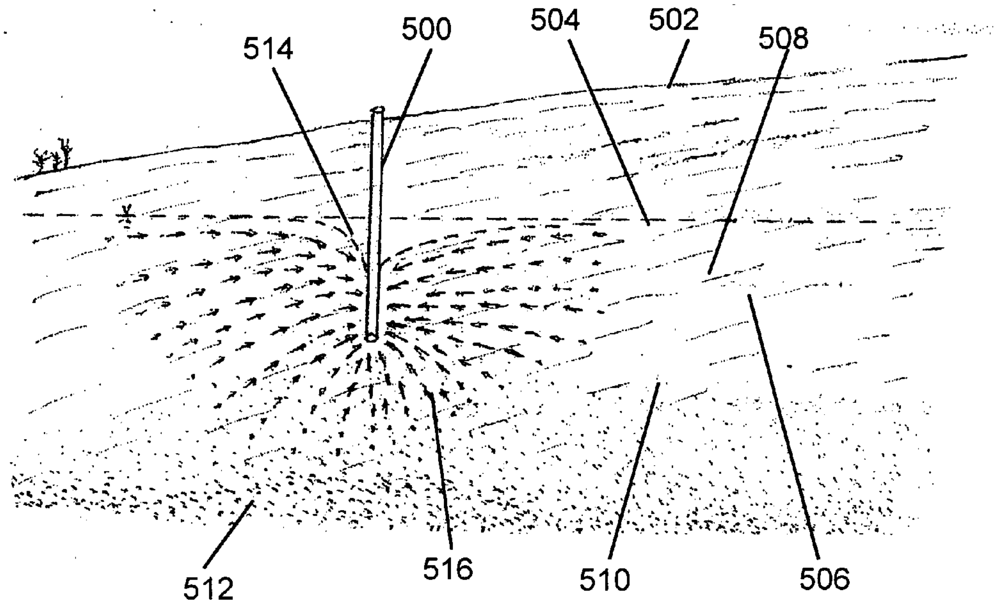


Fig. 5 (prior art)

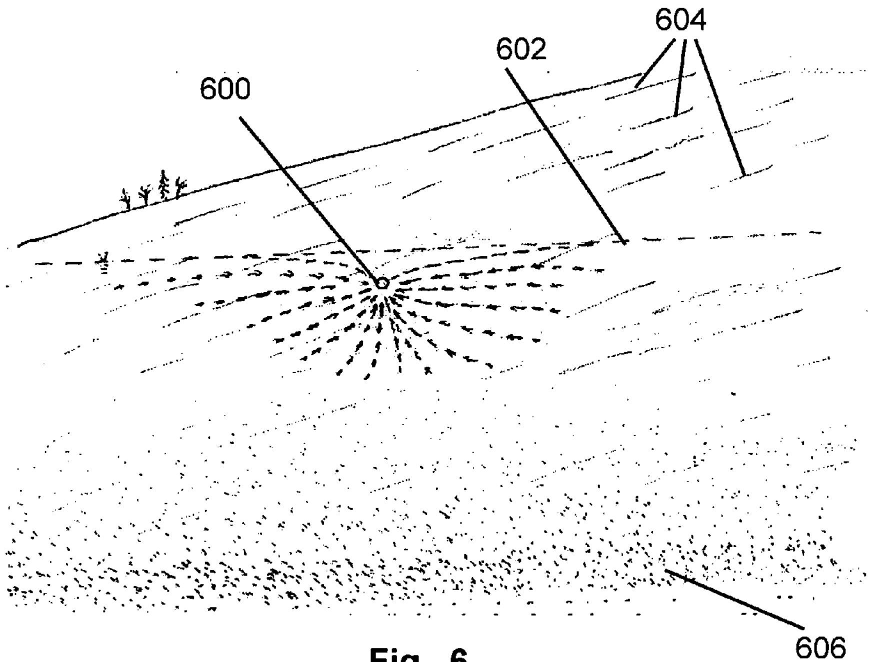


Fig. 6

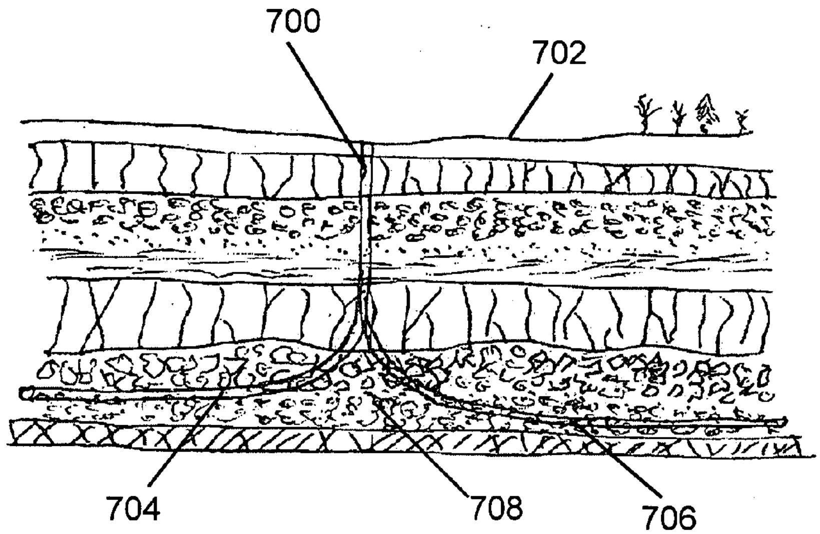


Fig. 7

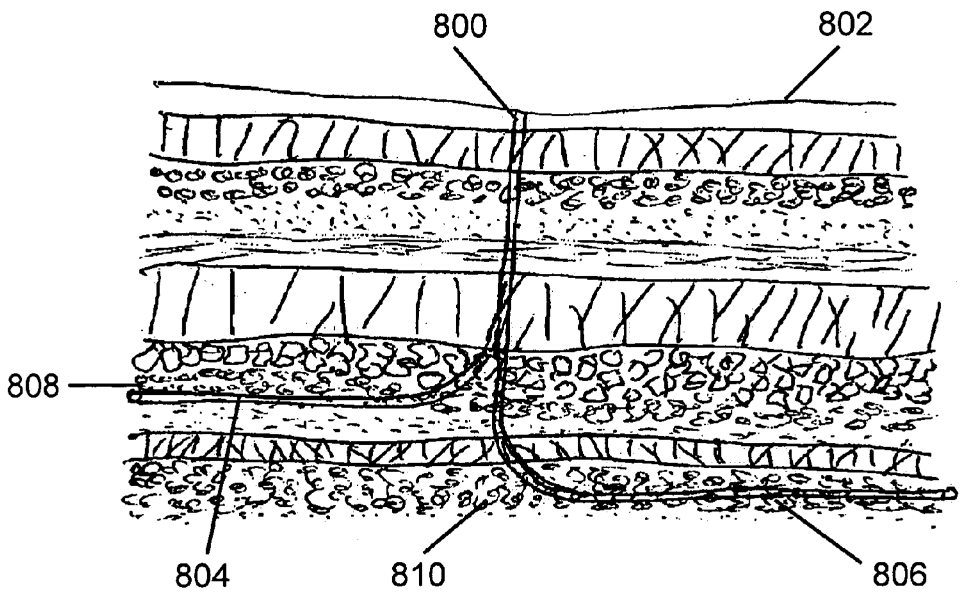


Fig. 8

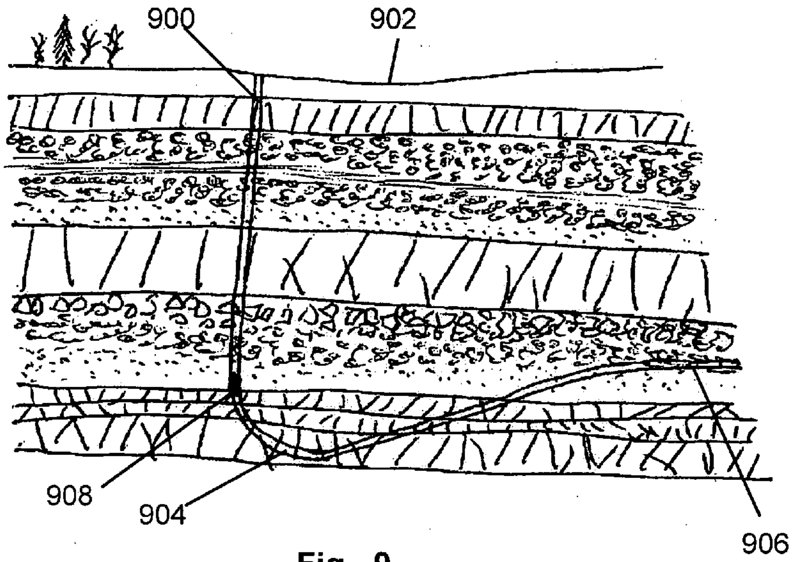


Fig. 9

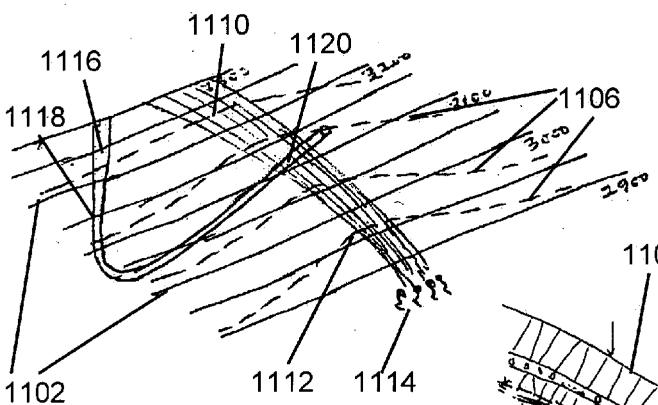


Fig. 11a

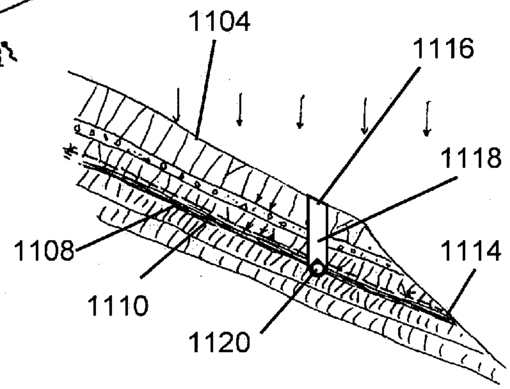


Fig. 11b

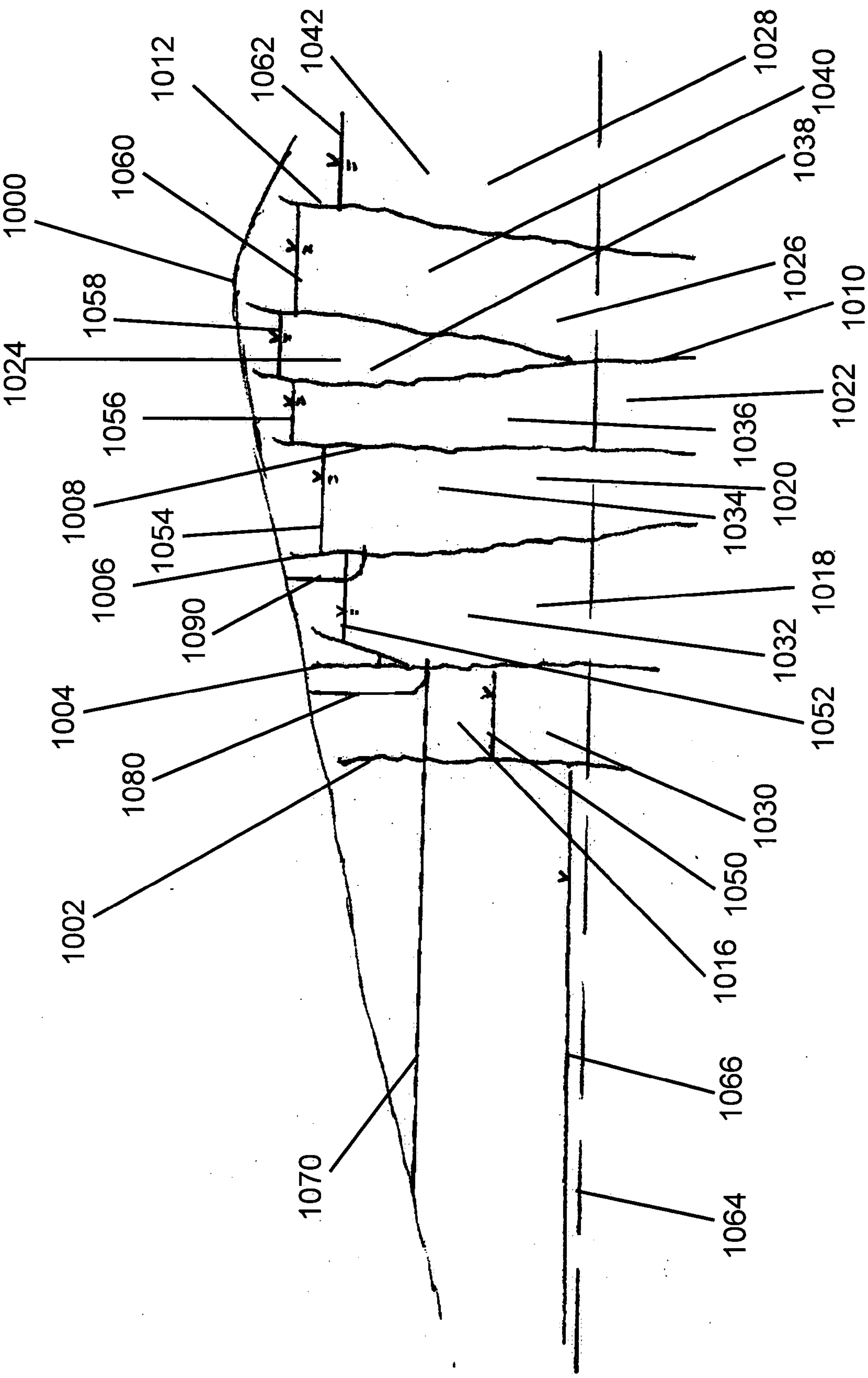


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Fig. 10

DEVIATED DRILLING METHOD FOR WATER PRODUCTION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is related to U.S. Provisional Application Ser. No. 60/566,551, filed on Apr. 29, 2004, entitled "An Application of Deviated Drilling by the Casing Drilling Method or Other Methods for the Construction of Horizontal Wells to Produce Groundwater from the Freshwater Lens of the Hawaiian Basal Aquifers, Dike-Compartmented Aquifers and Perched Aquifers," which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] The present invention relates generally to a method for drilling horizontal or deviated water wells through hard rock formations that are prone to caving, and more specifically to a method for drilling horizontal or deviated water wells using casing drilling and/or percussion drilling.

BACKGROUND OF THE INVENTION

[0003] At shallow depths, pore spaces in rocks and soil are filled with air or a combination of air and water. The water table is the level at which groundwater saturates the pore spaces of rocks and soils, extending to a depth where the rock porosity vanishes or the rock is molten. Voids in the unsaturated zone are at atmospheric pressure down to the water table, and meteoric water that percolates downward through the unsaturated zone recharges the groundwater by flowing across the water table. In such mountainous areas as the Hawaiian Islands, most of the groundwater flow collects in upgradient areas of great precipitation, so the water table is nearly a flow line, inclined at a very small angle, about 0.05 degrees to the horizon. In some localized situations, "perched" groundwater is underlain by an impermeable layer, below which the soil or rock is unsaturated with water.

[0004] **FIG. 1** illustrates a common water table condition. Well **100** is drilled vertically from a position on the ground that is somewhat higher than streambed **102**. Water table **104**, marking the boundary between unsaturated zone **106** and water-saturated zone **108**, rises gradually underneath the valley walls as the distance from streambed **102** increases. Pump **110** is positioned within well **100** at a depth that is initially below water table **104**. As water is pumped to the surface through well **100**, the portion of the subsurface rock or soil adjacent well **100** becomes unsaturated with water, locally lowering or downwardly "coning" the water table, as indicated at **112**. For this reason, water wells are usually designed to produce water from a depth significantly lower than the water table, thereby facilitating sufficient drawdown to generate production and prolonging the time it takes to reach meta-stable conditions.

[0005] Typically, the economical and practical method of groundwater production from water table aquifers is by pumping the water from vertical or nearly vertical wells drilled to depths that penetrate below the water table, as shown in the sketch section of **FIG. 1**. Lowering the water level in a well causes the groundwater to flow through the pores in the rock and into the well to replenish it continuously.

[0006] In recent years, the petroleum industry has used deviated and horizontal wells increasingly to produce hydrocarbons. Usually, these wells originate at the surface as vertical or near-vertical wells, and at some point below the surface, the drilling trajectory curves to a shallower angle or even a horizontal trajectory. Although a horizontal well is more expensive to drill than a vertical well in some circumstances, the potential hydrocarbon recovery from a horizontal well is significantly greater than from a vertical well, and fewer wells need to be drilled. In recent years, methods and equipment have been developed to control the drilling trajectory so the deviated or horizontal portion of the well traverses the desired section of rock. In particular, steerable drill bits have been developed, with the ability to control the angle from vertical as well as the compass direction in which the drilling progresses. For some applications, particularly offshore drilling, a single vertical shaft is drilled from the surface, and multiple deviated well bores are drilled outwards from the vertical shaft, using a technique called "whipstocking." Such radial arrangements of deviated bores originating from a single vertical section have been used to penetrate specific subsurface targets, such as oil-bearing sands and remote geologic structures.

[0007] **FIG. 2** illustrates two circumstances, in which deviated drilling has been used for hydrocarbon production. A vertical well section **200** descends from the ground surface **202**. Deviated well bore **204** branches off of vertical section **200** to intersect an oil-bearing zone **206** near the top of a nearby subsurface geological structure **208**. A second deviated well bore **210** branches off of vertical section **200** in a different radial direction to traverse a substantially horizontal sandstone reservoir **212** confined between impermeable shale beds **214** and **216**.

[0008] Recently, Tesco Corporation of Calgary, Alberta, Canada, developed a new method of deviated drilling referred to as casing drilling. In the casing drilling method, the bit is attached to the end of the casing, which is rotated from the surface. The bit can be detached and retrieved via a wireline for replacement while leaving the casing in place to support the walls of the well bore. Casing drilling facilitates penetration and retention of an intact bore through subsurface formations that are otherwise difficult to support. To date, casing drilling has produced more than a million feet of hole, mainly for oil and gas exploration and production.

[0009] Groundwater is generally produced from much shallower wells than hydrocarbons. The shallow water wells are generally much less expensive to drill than hydrocarbon wells, and groundwater production typically uses vertical wells. However, in situations where a fresh water lens overlies salt water within a coastal aquifer, vertical water wells may penetrate too deeply into the freshwater lens, eventually leading to upward coning and production of the underlying salt waters. When produced salt concentrations exceed drinking water or irrigation water standards, the well and, perhaps, the aquifer are abandoned.

[0010] It has long been recognized that a horizontal well or tunnel emplaced a small distance below the water table can skim the fresh water from a large area of such an aquifer, significantly prolonging the useful lifetime of the well by delaying the time when salt water contamination would end further production. However, because deviated drilling is considerably more costly than vertical well drilling, until now the method has been used rarely for water wells. Deviated drilling techniques developed for petroleum exploitation have been applied for water production in some settings, such as in sedimentary rocks of the Persian Gulf, the Ogallala aquifer underlying a large part of the high plains of the United States, and the Austin Chalk formation in Texas.

[0011] There are three different hydrogeological settings in Hawaii in which substantially horizontal bores have been used to produce groundwater. The basal aquifer, a lens of freshwater floating at near sea-level upon saline water connected to the sea, has been tapped via wells on the islands of Maui (the "Maui wells") and Oahu that were drilled or driven horizontally from near the bottom of vertical shafts. These wells are shafts that were hand-excavated to positions below the water table. Some of the wells have been copious producers for nearly 100 years.

[0012] At higher elevations, typically in central parts of each Hawaiian volcano, compartmented aquifers are contained within systems of vertical basalt dikes. Also occurring at higher elevations are perched aquifers, where buried clay soil or impermeable ash beds form aquicludes. Percolating rain water also provides the water supply for the compartmented and perched aquifers. In the case of the perched aquifers, inclined strata or ancient soil layers with low water permeability deflect some of the vertically percolating rain water on its way down to the basal aquifer, and the perched water may emerge at the surface as springs. Unsaturated ground occurs between the aquiclude and the next underlying water table, often the lowest or "basal" aquifer. In some cases, vertical wells have inadvertently pierced aquicludes below perched water bodies, causing water to leak across the aquicludes and decreasing the amount of water flowing in the perched aquifer.

[0013] In Hawaii, both the compartmented aquifers and the perched aquifers can feed springs where the water spills into incised valleys. The early ranchers and planters recognized the nature of the spring water sources, and in some of the deeply-incised valleys of Oahu and west Maui, they were able to drive tunnels to intersect one or more dikes at levels below the water table, facilitating drawdown and the use of the reservoir capacity to sustain flow in irrigation ditches feeding the cane-fields. To tap perched aquifers, their strategy was to search for places where soils mantled ancient valley bottoms, with a trough in the soil layer channeling the perched waters towards the outcrop. **FIG. 3** illustrates the approach followed by the ranchers. Topographic contours are indicated with solid lines **302**, and the contours of a buried impermeable soil layer **304** are indicated with dashed lines. The ranchers dug a tunnel **306** into the mountain near and above a spring **308** until the soil layer **304** was encountered at point A and then turned the tunnel parallel to the contour of the soil layer, following it into the thalweg of the ancient valley, where saturated ground lay deepest, to find a perched aquifer **310**. These early Hawaiian horizontal tunnels or well bores were driven by hand mining or rotary drilling directly from nearby, steeply sloping canyon walls or from large-diameter vertical shafts. Some of these older horizontal bores are also copious producers.

[0014] In recent decades, the high cost of mining has precluded additional tunnel construction for water resources of the compartmented and perched aquifers, so essentially all new water sources have been developed by drilling vertical wells to the basal aquifer. Even in steep terrain, vertical wells have been more practical to drill than horizontal wells, because gravity aids in the vertical drilling process, while horizontal wells require special drilling technology and equipment and are, therefore, more expensive. Further, the rock formations in Hawaii are notoriously difficult to drill using rotary drill bits, such as are generally used to drill horizontal wells. No new horizontal bores of this type have been excavated in nearly 100 years, due to both the high cost of hand tunneling and to a lack of favorable sites. Thus, there is a need for a method of drilling into compartmented and perched aquifers.

[0015] Some Hawaiian basal aquifers are currently in danger of eventual abandonment due to gradually increasing salinities of waters produced through the numerous vertical wells. There is a need for a method for producing water in volcanic terrain that is less prone to coning of salt water. There also is a need for a method for producing water from rock formations that are difficult to drill using conventional rotary drill bits. There is an additional need for a method for drilling deviated and horizontal well bores in such rock formations. There is a further need for a method for drilling deviated or horizontal wells originating from a vertical section of well to provide easier access to aquifers that occur as lenses above salt water or that are compartmented or perched. There is yet another need for a method of drilling wells into aquifers in a manner that maximizes water production and/or prolongs the useful lifetime of the well and the aquifer.

SUMMARY OF THE INVENTION

[0016] It is an object of the present invention to provide a method for producing water in volcanic terrain that is less prone than previous methods to coning of salt water.

[0017] It is another object of the present invention to provide a method for producing water from rock formations that are difficult to drill using conventional rotary drill bits.

[0018] It is yet another object of the present invention to provide a method for drilling deviated and horizontal well bores in rock formations that are difficult to drill using conventional rotary drilling methods.

[0019] It is a still further object of the present invention to provide a method for drilling deviated or horizontal wells originating from a vertical section of well to provide easier access to aquifers that occur as lenses above salt water or that are compartmented or perched.

[0020] It is yet a further object of the present invention to provide a method of drilling wells into aquifers in a manner that maximizes water production and/or prolongs the useful lifetime of the well and the aquifer.

[0021] To achieve the foregoing and other objects and in accordance with the purpose of the present invention broadly described herein, one embodiment of this invention comprises a method for drilling a deviated water well in a subsurface formation having interbedded hard and fragmented rocks and that is prone to caving, where the formation has a subterranean aquifer below a water table. The formation may comprise volcanic rocks or interbeds of rocks selected from lava flows, clinker, and pyroclastics. The method comprises the steps of drilling a vertical section of a well downward from the earth's surface, causing the drilling direction to deviate from vertical in a predetermined path to intersect the aquifer, and continuing to drill in a substantially horizontal path through the aquifer at a predetermined depth below the water table. Either or both of the causing step and the continuing step may comprise using a casing drilling method. Either or both of the causing step and the continuing step may comprise using a drilling tool selected from rotary bits and percussion tools. If the percussion tool is used, it may be combinable with casing used in a casing drilling method. Optionally, the method may further comprise the step of pre-grouting a portion of the formation by injecting cementitious material prior to drilling through the portion.

[0022] The aquifer may be a basal aquifer directly underlain by salt water and occurring within and across dipping strata, and the substantially horizontal path may be oriented substantially parallel to the strike of the strata. The basal aquifer may be directly underlain by salt water and occur within rocks comprising basalt lava, pyroclastics, coral, sediments, or combinations thereof. The continuing step may comprise drilling in a substantially horizontal path near the top of the aquifer. Alternatively, the aquifer may be a dike-compartmented aquifer or a perched aquifer.

[0023] The method may comprise an additional step of forming a portion of the well between the vertical section and the substantially horizontal path, with the portion being lower than the substantially horizontal path and forming a J-shaped trap into which a pump can be positioned vertically. Also, the method may comprise an additional step of using the well for a purpose selected from water production, subsurface exploration, geothermal heat production, and pressure control.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] These and other features, aspects, and advantages of the present invention will become better understood with reference to the following description, appended claims, and accompanying drawings, where:

[0025] **FIG. 1** is a vertical section through the ground showing common water table conditions for prior art water well production;

[0026] **FIG. 2** is a vertical section through the ground showing circumstances where prior art horizontal deviated drilling has been used for oil and gas production;

[0027] **FIG. 3** is a plan view of a prior art tunnel into a perched aquifer;

[0028] **FIG. 4** is a vertical section through the ground showing typical water table conditions beneath Hawaiian volcanic terrains;

[0029] **FIG. 5** is a vertical section through the ground showing asymmetric flow into a prior art vertical well in dipping volcanic strata;

[0030] **FIG. 6** is a vertical section through the ground showing asymmetric flow into a horizontal well placed in accordance with the method of the present invention;

[0031] **FIG. 7** is a vertical section through the ground showing two horizontal bores extending in opposite directions along the strike of the beds within a single interbed in accordance with the present invention;

[0032] **FIG. 8** is a vertical section through the ground showing multiple horizontal bores branching from a single vertical shaft and extending into different interbeds in accordance with the present invention;

[0033] **FIG. 9**. is a vertical section through the ground showing a "J" shaped trap to accommodate a submersible pump between the vertical and horizontal sections of a well drilled in accordance with the present invention;

[0034] **FIG. 10** is a vertical section through the ground showing dike-compartmented groundwater bodies and deviated wells situated in accordance with the present invention to tap the groundwater bodies; and

[0035] **FIG. 11*a*** is a contour map showing a deviated well in accordance with the present invention that crosses a perched aquifer, and **FIG. 11*b*** is a vertical section through the ground showing the well of **FIG. 11*a***.

DETAILED DESCRIPTION OF THE INVENTION

[0036] Maintaining potable water supplies to a burgeoning population is widely recognized as a problem. The present invention provides a solution to this problem and comprises a method for producing water from aquifers via deviated or horizontal well bores. This solution is particularly suitable for water production in volcanic and other terrains where subsurface rock types and bedding characteristics make conventional rotary drilling methods, including rotary drilling methods that have been used for deviated and horizontal well bores in sedimentary rocks, difficult. The method in accordance with the present invention can be used to produce water from different types of aquifers, including but not limited to basal aquifers of fresh water floating on salt water, compartmented aquifers formed between dikes, and perched aquifers floored by aquicludes such as impermeable strata and ancient, buried soil layers. These types of aquifers, described in more detail below, are all known to exist in Hawaii, and similar aquifers also occur in other locations. In accordance with the present invention; deviated drilling techniques developed in the oil industry can be adapted to offer practical means of constructing horizontal wells in such terrains, including Hawaii. Horizontal or nearly horizontal deviated water wells can yield more potable water or yield potable water for a greater number of years of pumping than can, or do, the currently used vertical drilled wells in bedded basalt formations of the Hawaiian Islands.

[0037] The Hawaiian Islands are volcanic in origin, and throughout the islands, stratified lava flows slope towards the sea. In basaltic volcanic areas, such as Hawaii, lava flows dip toward the sea at a relatively shallow angle, often about 10 to 13 degrees. The lava flows are hard but fractured rocks, interbedded with pyroclastic granular strata, including ash, clinker, breccia, and agglomerate, most of which contain and transmit much more water than do the lavas. Near the coastline, coral may also occur in interbeds. In addition to water flow along interbeds between lavas, a smaller flow component is approximately normal to the lava beds via fractures in the beds. Although abundant rainfall, about 300 to 400 inches per year, falls on the mountains, there is little runoff, because most of the precipitation percolates through an extensive unsaturated zone to the water table not far above sea level, recharging what is called the "basal" aquifer.

[0038] The basal aquifer in Hawaii is vital to the island economy, serving most of the needs of agriculture and domestic consumption through pumped wells, some of which yield over a million gallons per day. Even though the volcano summits are thousands of feet above sea level, most of the demand for water is near the coast at altitudes of a few hundred feet or less. Thus, most water wells in the islands, including nearly all of the municipal wells, are also located near the coast.

[0039] In very permeable rocks and soils such as those typical of Hawaii, the water table of the basal aquifer is nearly flat, sloping gently less than one degree towards the groundwater discharge areas. **FIG. 4** illustrates the nature of the basal aquifer **400**. The ground surface **402** slopes gently toward the sea **404**, and the long dashed line **406** indicates sea level. The basal fresh-water aquifer **400** has water table **408**, and it has limited volume in this coastal environment because it is underlain by saline water **410**. The higher density of salt water (about 2% greater at 19,600 mg/l of NaCl in solution) compared to fresh water has, over eons of time, caused the salt water to invade the volcanic rock formations, so that it underlies the fresh water floating upon it, as shown in **FIG. 4**. Rather than a sharp interface between fresh and salt water, the short dashed lines **412** approximate a zone of salinity transition, grading from fresh above, to brackish, then to saline with depth. Small hydraulic gradients of the water table slope are sufficient to drive to the sea the large volume of fresh water that recharges the groundwater. The hydraulic gradient causes both the fresh and mixed waters to flow seaward, partially compensated by a landward movement of salt water to replace the salt, depicted by the arrows in **FIG. 4**.

[0040] The level at which half seawater composition is found can be predicted by the Ghyben-Herzberg relationship, which balances a static salt-water column against a taller but lighter fresh-water column. This indicates that the theoretical 9,800 mg/l isochlor (line of equal chlorine content) is to be found at about 40 feet below sea level for each foot that the water table lies above sea level. Thus if a well is drilled 300 feet to the water table, penetrating it say 10 feet above sea level, water with less than 9,800 mg/l salt may extend about 400 feet below sea level. But in these pervious volcanic rocks, the transition zone is typically many feet thick, thus the useable fresh water (<250 mg/l salt) occupies a body shaped like a part of a lens, in most places little more than 100 feet thick, underlain by salty water. Wells cannot safely penetrate the full thickness of the lens of useful quality water without risking upward coning of brackish water whose production contaminates the fresh water in the well bore.

[0041] Not shown in **FIG. 4** is the typical profile of valleys eroded into the flanks of the volcanoes, providing access to drill sites closer to the water table. Most municipal wells in Hawaii take advantage of valleys to gain proximity to the water table. Near the coasts, where nearly all the people live and where agriculture abounds, the water table of the basal aquifer is only a few feet or tens of feet above sea level. Consequently, typical well depths of 200-300 feet are required to reach the fresh water, and nearly all drilling has been for vertical wells. A horizontal well, even if drilled from within a canyon and able to drain via gravity, would be significantly longer and thus more costly to drill.

[0042] One embodiment of the method of the present invention, with deviated wells sunk to basal, salt-supported aquifers, is intended to mitigate the salt water contamination that may occur to vertical wells sunk deeper into the basal aquifer. When a vertical well is pumped for some time, it perturbs the natural gradients to induce flow towards the well, as illustrated in **FIG. 5**. Vertical well **500** extends from the ground surface **502** past water table **504** into basal aquifer **506**. Below the fresh water zone **508** of the aquifer lie brackish water **510** and saline water **512**. Adjacent to well **500**, downward flow of fresh water from above the producing section of the well causes the water table to have a cone-shaped depression **514** around the well, and upward flow of salty water from beneath the well causes formation of an upwardly pointing cone **516** of saline water around the bottom of the well **500**. The longer pumping persists, the greater the yield of salt to the well, and the average water salinity, after mixing in the well bore and pipelines, gradually increases. When the salt concentration of the mixed water reaches about 250 mg/l NaCl, it is no longer deemed potable, whereupon the well, and ultimately a portion of the aquifer, may have to be abandoned.

[0043] In accordance with the present invention, a deviated or horizontal water well can be drilled into an aquifer containing a fresh water lens floating on salt water, such as can be found beneath the coastal reaches of the Hawaiian Islands or any other coastal aquifer connected to the sea. Many advantages would be derived from a horizontal or near-horizontal well or system of horizontal or near-horizontal wells to produce groundwater from the freshwater lens that floats upon salt waters. Referring to **FIG. 6**, a horizontal well **600** can be practically situated a few feet below the original water table **602** to create a different, more sustainable and thus more beneficial groundwater flow pattern than does a vertical well. Well **600**, viewed in cross section as a circle, extends substantially horizontally in and out of the page, substantially parallel to the strike of lava beds **604**. With its horizontal orientation near the top of the aquifer, well **600** is much slower to yield contaminated water than the typical vertical production well that extends more deeply into the aquifer. Because horizontal wells such as well **600** skim fresh water from near the water table **602**, the upward coning of salt water **606** can be avoided. Thus, well **600** can facilitate continued-production of potable quality water for several times as many years as will a vertical well. Wells such as well **600** can extend for many hundreds of feet along and just beneath the water table so as to yield large discharges.

[0044] Just how perfectly the horizontal well system performs depends not only upon its placement, but also on the formation properties, which are currently ill-defined. With some measures of apparent hydraulic conductivities, K, based on vertical well production versus drawdown data, some cultured guesses can be made about the future behavior of horizontal wells. The formation is doubtless very anisotropic, with greatest hydraulic conductivity (K) values parallel to bedding, least normal to bedding. Since the current vertical wells are nearly normal to the lavas, the apparent K is roughly the geometric mean of K in the down-dip (slope) direction and K along strike (contour).

Probably the former exceeds the latter, since some stream channels formed between eruptions, leaving buried agglomerate-filled conduits, and many open lava tubes formed along that same up-and-down-slope direction.

[0045] Conductivity normal to the lavas is uncertain but finite because flow occurs parallel to the water table, cutting the bedding at an acute angle, as seen in **FIG. 4**. All three principle conductivities would need to be measured to facilitate design and to predict accurately the performance of horizontal wells. To maximize yields, the best orientation for a horizontal well is along the strike of the lava beds, since it would have apparent conductivity that is the geometric mean of K downdip and K normal.

[0046] Suppose, for example, that $K_d=7\ K_s=49\ K_n$, where the subscripts d, s and n represent the downdip, strike and normal directions, respectively. In that hypothetical case, a horizontal well following the strike direction would manifest the apparent $K=(K_n\ K_d)^{1/2}=7\ K_n$, whereas a vertical well reflects an apparent $K=(K_s K_d)^{1/2}=7\ 18.5\ K_n$. Thus a 100-foot vertical well would yield 2.65 as much per unit length as does a strike-well, or the same as a 265 foot long horizontal strike well.

[0047] Thus, it is desirable to drill horizontal wells that tap the basal aquifers approximately along the strike of the dipping lava beds, as shown in **FIGS. 6-8** to greatly enhance the life of basal aquifers of fresh water floating on salt water. The wells can be initiated as substantially vertical wells descending from the surface and then deviated to horizontal or near-horizontal at a depth slightly below the water table. Using whipstocking methods known in the oil and gas industry, multiple horizontal bores can be drilled from a single vertical section. For example, as shown in **FIG. 7**, a vertical well **700** can descend from the surface **702**, with two horizontal bores **704** and **706** extending approximately horizontally in opposite directions along the strike of the beds or within or nearly within a single interbed, **708**. Alternatively, as shown in **FIG. 8**, a single vertical well **800** could be drilled downward from the surface **802**, and horizontal bores **804** and **806** could be placed in different interbeds **808** and **810**, respectively. It should be noted that more than two horizontal or nearly horizontal sections could extend from a single vertical section of a well, and a horizontal section could be inclined approximately parallel to the water table but at other angles to the strike of the beds (not shown).

[0048] Normally, a submersible pump is used to raise water to the surface. Most submersible pumps are designed to operate in a vertical orientation. The water provides cooling as well as helping to maintain suction. If a submersible pump is operated horizontally or on an incline, it will soon fail because the bearings are designed for operation in a vertical orientation. As shown in **FIG. 9**, well **900** extends vertically downward from the surface **902**, and a portion **904** of the well adjacent to the vertical section forms a "J" shaped trap below the horizontal section **906** of the well bore. A pump **908** is positioned in the trap at an elevation lower than that of horizontal section **906** and with a vertical orientation. Thus, trap **904** ensures that the pump **908** will remain submerged.

[0049] Compared to conventional production via vertical drilled wells, greater aquifer longevity is predicted if groundwater production is done through horizontal wells skimming the freshest water from the uppermost portion of a freshwater lens floating upon salt water in coastal environments such as the Hawaiian Islands. Not only is the distance between the well and the underlying zone of transition to brackish and saline waters greater in the case of horizontal wells compared to vertical wells, but the speed of movement is minimized by the comparatively low conductivity of the formations in the direction normal to the slightly-inclined bedded lavas and interbeds.

[0050] Because horizontal wells may be drilled many hundreds of feet, and occasionally a thousand feet or more at depths just a few feet below the original water table, their yields may exceed those of vertical wells limited by the thickness of the freshwater lens, leading to more efficient well field arrangements for aquifer management. Thus, horizontal drilling technology, similar to what has been used in the United States, the North Sea, the Middle East, North Africa and elsewhere, can be imported from the oil industry to the Hawaiian Islands and other coastal environments where salt water underlies thin basal fresh-water aquifers. A particularly applicable subset of the horizontal drilling technology is that of casing or liner drilling, which can help solve the prevalent problems of hole support and permanence commonly encountered in the Hawaiian basalt formations.

[0051] It may be desirable to pre-grout the subsurface formation to consolidate loose or broken rocks and reduce the risk of drilling difficulties or failures. A small-diameter pilot bore is drilled, and a cementitious material is injected through the pilot bore. Then a larger diameter bore is drilled concentric with the pilot bore.

[0052] A greater proportion of the infiltrating rainwater that recharges the Hawaiian basalt basal aquifers will be recoverable if horizontal wells are employed, rather than a greater number of vertical wells, and less water will be wasted to the sea. This will be commensurate with the greater longevity of such aquifers produced to horizontal wells instead of the current system of vertical wells. In areas already limited by the apparent need to conserve the fresh groundwater threatened by slowly-rising salinities observed in well-waters, horizontal wells can optimize resource development and utilization, making more potable water available for current and future use.

[0053] Besides the basal aquifer, found near sea level under all Hawaiian coasts and extending some miles inland, there are other occurrences of water in the subsurface that are commonly exploited. These are also favorable targets for deviated drilling in accordance with the present invention.

[0054] Near the center of a volcano, steeply dipping to vertical dikes of basalt form during the volcano-building as molten lava rises through deep cracks in the interior of the volcano, fills the cracks, and then solidifies. Solidifying at depth and under high pressure in the mountain, the basalt dikes are generally massive and non-vesicular (i.e., free of gas bubbles), so they tend to have low permeability. However, fractures that form as the lava cools can act as minor conduits for water leakage across the dikes. The dikes generally act as impermeable underground dams to hold water, giving rise to elevated water bodies. The water table in each compartment depends upon the amount of recharge and the leakage through boundary dikes. If the water tables of adjacent compartments are different, water can leak from the compartment with the higher water table into the adjacent compartment with a lower water table, until the rate of recharge and the rate of leakage are balanced. Generally, the water tables step up to higher and higher levels as one approaches the summit of the volcano, and in some cases, the elevation differences in the water tables can be as great as thousands of feet. Electrical soundings have shown fresh water extending to great depths within such compartments. It is believed that salt water occurs at some depth below these compartmented aquifers, perhaps as deep as 40,000 feet. However, no one has drilled to confirm the limits of the fresh-water bodies, and they are probably far below any vertical drilling capabilities.

[0055] The nature of dike-compartmented groundwater bodies can be understood with reference to **FIG. 10**. Volcano **1000** includes a number of approximately vertical and relatively water-impermeable dikes **1002**, **1004**, **1006**, **1008**, **1010**, and **1012**. Compartments **1016**, **1018**, **1020**, **1022**, **1024**, **1026**, and **1028** are formed between dikes **1002**, **1004**, **1006**, **1008**, **1010**, and **1012**, respectively. Each compartment partially encloses an aquifer **1030**, **1032**, **1034**, **1036**, **1038**, **1040** or **1042**. The aquifers have stepped water tables **1050**, **1052**, **1054**, **1056**, **1058**, **1060**, and **1062**, all of which are significantly higher than sea level **1064** and the water table **1066** of the basal aquifer.

[0056] The water bodies contained within the dike systems, such as the system illustrated in **FIG. 10**, may discharge to springs and streams high on mountainsides. Until now, these water sources have been accessible at springs or via tunneling from deep valleys, such as those leading into the West Maui mountains and the other dissected older volcanoes on the islands of Oahu and Kauai. Generally, horizontal tunneling or drilling into the dike-compartmented water bodies from younger volcanoes, such as Haleakala or Mauna Kea, has been impractical or impossible, due to the long horizontal distances from portal sites to the water bodies. Horizontal conduit **1070** in **FIG. 10** illustrates this problem.

[0057] As shown in **FIG. 10**, deviated wells in accordance with the present invention, such as wells **1080** and **1090**, provide the decided advantage of shortening the distance from the surface to a point of dike penetration below a compartment's water table. Well **1080** originates at the surface above the dike-bounded compartment **1016**, descends vertically through the unsaturated zone in compartment **1016** to a depth below water table **1052**, and then changes direction to a horizontal or near-horizontal path and penetrates dike **1004** to access water in compartment **1018**. The vertical section of well **1080** is significantly shorter than a horizontal conduit such as conduit **1070**. Alternatively, a single well, such as well **1090**, may collect water from multiple aquifers, such as aquifers **1032** and **1034**. Well **1090** descends vertically through compartment **1018** to a depth below the water table **1052** in compartment **1018** and also below water table **1054** in compartment **1020**. Well **1090** then deviates and passes through dike **1006** to collect water from both aquifers.

[0058] The method of the present invention provides many more opportunities to tap compartmented water bodies since wells that start vertically, reach the desired level, and then deviate to a shallow or horizontal attitude can be used wherever high-level water table conditions and the dikes that support them can be found. Although dikes often do not surface through recent lava flows on undissected slopes of young volcanoes, geophysical sounding methods can determine the presence of the dikes and the water levels between them.

[0059] Production from deviated compartment wells may require pumping. To facilitate use of a submersible pump, it may be desirable to design the well with a nearly horizontal section that slopes upward away from the vertical section of the well, creating a trap that remains filled with water such as is shown in **FIG. 9**. The water produced by a deviated well into a compartmented dike system may be used locally near the production site, or it may delivered to a high-level distribution system such as municipal water works.

[0060] Another type of aquifer found in many places, including Hawaii, is a perched aquifer. Perched aquifers occur when infiltrating ground water collects above a buried aquiclude, or impermeable layer, such as an ancient soil horizon, a layer of clay, or a bed of consolidated volcanic ash. **FIG. 11** illustrates a perched aquifer similar to that shown in **FIG. 3**. Solid lines **1102** indicate contours of surface **1104**, and dashed lines **1106** indicate contours on a buried soil layer **1108**. Aquifer **1110** is formed by precipitation percolating downward from the surface **1104** and collecting in the subsurface depression or thalweg **1112** formed by the soil layer **1108**. Aquifer **1110** intersects the surface to form spring **1114**. Well **1116** originates at the surface at an elevation somewhat higher than spring **1114** and has a vertical section **1118** descending from the surface **1104** to the buried soil layer, and a substantially horizontal section **1120** that follows the contour of the soil layer into the aquifer **1110** perched on thalweg **1112**. Because deviated drilling can mimic the previously used water-tunneling technique by following a soil layer, it may be possible to tap perched water bodies identified by the presence of a spring or by other means, such as geophysical surveying. By diverting the ground water flow into a well, such as well **1116**, it may be possible by pumping to produce the full capacity of a perched aquifer, such as aquifer **1110**, into a pipeline. In this case, any springs fed by the aquifer, such as spring **1114**, would be dried up.

[0061] Both of these types of high-altitude aquifers, dike compartmented groundwater bodies and perched water bodies, may prove to be the most common future applications of deviated drilling in Hawaii. Production via horizontal or deviated wells may provide a steady flow of a few gallons per minute (gpm), sufficient to provide water for residential subdivisions, in locations where vertical wells cannot be drilled. Such deviated or horizontal wells may be more economical than pipeline deliveries from scarce municipal supplies.

[0062] At low elevations, where only the basal aquifer offers prospects for subdivision water supplies, large capacity vertical wells that are deviated to horizontal and extend approximately parallel to the water table may provide discharges of 1000 gallons per minute (gpm) or more, sufficient to produce municipal water supplies. These less numerous wells may ultimately prove to be of great importance to the local population and government, because they will help maximize yields from the basal aquifer while preserving water quality and aquifer life.

[0063] In addition to providing water supplies, deviated and/or horizontal wells may have applications of a geotechnical nature. These applications include subsurface geological exploration, geothermal production, and controlling water levels or water pressure in any aquifer best accessed by horizontal wells.

[0064] Well drilling is difficult in Hawaii, because the basalt lavas and their interbedded clinker zones and pyroclastics of all grain sizes create caving conditions, where the boreholes collapse. Indeed, even some vertical wells have been abandoned during construction or stopped short of their intended depths due to caving. Horizontal holes are even more difficult to drill, because dislodged rocks fall into the bore. Any motion of a detached fragment during or after passage of the drill bit may bind against the drill string or casing string and interfere with rotation or advance of the string. Consequently, horizontal drilling, either direct or deviated, has rarely been attempted through the Hawaiian basalt sequences. Tunneling, used in the past to create horizontal bores, has a much greater cost per foot than drilling.

[0065] Recently, Tesco Corp. of Calgary, Alberta, developed casing drilling, where a drill bit, usually of the rotary type, is attached to the end of a casing string and rotated from the surface. The bit is detached and retrieved by wireline for replacement while leaving the casing in place to support the ground. To date, the method has been used to drill more than a million feet of hole, mainly for oil and gas exploration and production. Not only does the casing drilling method minimize trip time for replacing worn drill bits, but it also facilitates penetration and retention of an intact bore through ground that is otherwise difficult to support. Typically, a hole is started with a large size casing, such as 12⅞ inch diameter, so that progressively smaller telescoping sizes may be inserted to prolong the hole when and if casing becomes stuck or resists turning. Reaming is also conducted to enlarge casing in the hole to facilitate passage of additional casing. These techniques may be applicable and beneficial in water-well drilling through loose or broken ground, such as prevails in Hawaiian volcanics. Casing drilling of deviated wells may solve the problems of hole support inherent to such formations as occur in Hawaii, and especially for horizontal bores.

[0066] Percussion drilling, with penetration rates of tens of feet per hour, is more efficient for cutting through the tough basalt lava flows than is rotary drilling that produces penetration rates of a few inches per hour. Steerable percussion drilling, using an air-driven down-hole hammer, may be used for deviated and horizontal drilling through formations such as those found in Hawaii. The percussion drilling tool may be attached to a casing drilling string in a manner similar to that used for attaching rotary drill bits to casing. Alternatively, a conventionally percussion-drilled pilot hole may be followed by a casing-drive reamer to set casing behind the hammer drill. Either method of advancement, rotary or percussion, may thus be adapted to the construction of horizontal wells in the Hawaiian basalt formations.

[0067] Another notable adaptation that may prove valuable for water production is the "whipstocking" or deviation of several holes from the same vertical starter well, as is known in the oil and gas industry.

[0068] In addition to increasing or prolonging water production from individual wells, horizontal or deviated drilling in accordance with the present invention may enhance the value of land in areas that can be serviced by horizontal wells.

[0069] The foregoing description is considered as illustrative only of the principles of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and process shown and described above. Accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

1. A method for drilling a deviated water well in a subsurface formation having interbedded hard and fragmented rocks and that is prone to caving, said formation having a subterranean aquifer below a water table, comprising the steps of:

drilling a first section of a well in a direction from the earth's surface, the direction selected from downward, laterally, and combinations thereof;

causing the drilling direction to deviate from the direction of said first section in a predetermined path to intersect the aquifer; and

continuing to drill in a path extending into the aquifer at a predetermined depth below the water table.

2. The method of claim 1, wherein at least one of said causing step and said continuing step comprises using a casing drilling method.

3. The method of claim 1, wherein at least one of said causing step and said continuing step comprises using a drilling tool selected from rotary bits and percussion tools.

4. The method of claim 1, wherein at least one of said causing step and said continuing step comprises using a percussion tool that is combinable with casing used in a casing drilling method.

5. The method of claim 1, further comprising the step of pre-grouting a portion of the formation by injecting cementitious material prior to drilling through said portion.

6. The method of claim 1, wherein the aquifer is a basal aquifer directly underlain by salt water and occurring within and across dipping strata, and said path extends into the aquifer substantially horizontally and is oriented substantially parallel to the strike of the strata.

7. The method of claim 1, wherein said aquifer is a basal aquifer directly underlain by salt water and occurring within rocks comprising basalt lava, pyroclastics, coral, sediments, or combinations thereof.

8. The method of claim 1, wherein the aquifer is a basal aquifer directly underlain by salt water, and said continuing step comprises drilling in a substantially horizontal path near the top of said aquifer.

9. The method of claim 1, wherein the aquifer is selected from a dike-compartmented aquifers and perched aquifers.

10. (canceled)

11. The method of claim 1, further comprising the step of using said well for a purpose selected from water production, subsurface exploration, geothermal energy production, and pressure control.

12. The method of claim 1, further comprising the step of drilling a second section between said first section and said path, said portion being lower than said path and forming a J-shaped trap into which a pump can be positioned vertically.

13. The method of claim 1, wherein said formation comprises volcanic rocks.

14. The method of claim 1, wherein said formation comprises interbeds of rocks selected from lava flows, clinker, and pyroclastics.

15. A deviated water well, comprising:

a first section extending downward from the surface; and

a second section extending in a different direction into an aquifer below a water table in a subsurface formation, wherein the formation includes interbedded hard and fragmented rocks and is prone to caving.

16. The well of claim 15, further comprising a J-shaped section between said first and second sections.

17. The well of claim 15, wherein the subsurface formation comprises rocks selected from basalt lava, pyroclastics, coral, sediments, and combinations thereof.

18. The well of claim 15, wherein said aquifer is selected from basal aquifers underlain by brackish or salt water, dike-compartmented aquifers, and perched aquifers.

19. The well of claim 15, wherein said subsurface formation comprises dipping beds and said substantially horizontal section is oriented substantially parallel to the strike of the beds.

20. The well of claim 15, further comprising a plurality of additional sections extending in different directions into the aquifer.

21. The well of claim 15, further comprising a plurality of additional sections extending in different directions into a plurality of aquifers.

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