GROUNDWATER DIRECTION DETERMINATION

Filed April 25, 1957

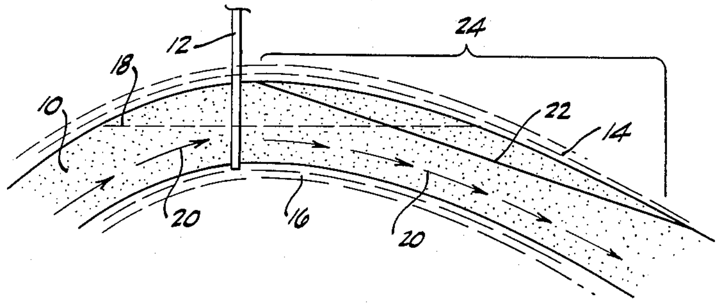


FIG. 1.

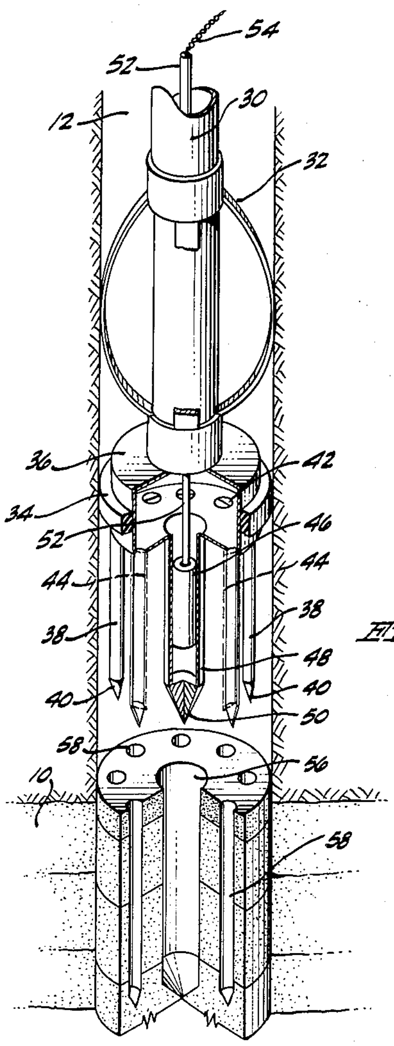


FIG. 2.

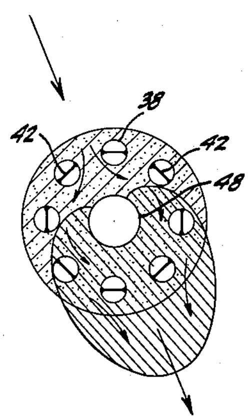


FIG. 3a.

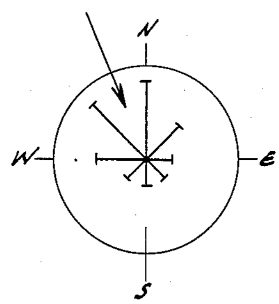
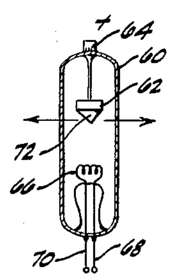


FIG. 3b.

FIG. 4.



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GROUNDWATER DIRECTION DETERMINATION

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This invention relates to underground geophysical exploration by means of bores drilled into the earth's crust and particularly relates to an improved method for the detection of the direction of flow of underground fluids through fluid permeable underground formations in connection with geophysical exploration for crude oil and gas deposits and the like.

Crude petroleum and gas are frequently found trapped in arching geological structures known as anticlines. Fluids are contained in the porous and permeable rock layer such as sandstone which arches upwardly underneath an overlying layer of impermeable rock. Any gas which may be present usually exists as a cap at the top and a layer of petroleum saturates the permeable formation immediately below the gas cap. Further down in the formation is the groundwater or brine also usually present with the gas and the oil. Frequently the anticlinal structures have plural arches connected to each other in a series which generally slope from one end to the other of the series. In other words, the peaks of each of the connected anticlines in a given direction may be successively higher or lower in a given direction with a general change in height that may vary on the order of 100 to 800 feet per mile.

In such sloped structures the groundwater tends to flow, having a source perhaps in a mountainous region at the high end from which water drains through the anticlinal structure toward a sink of one sort or another at the lower end. The net movement of the groundwater through the permeable rock below the oil and gas layers trapped beneath each anticline exerts hydrodynamic forces on the oil and tends to move it in a direction of the groundwater flow down the structure from the position at which it would otherwise be expected just beneath the arch. For this reason wildcat well bores drilled in unproven territories into an anticline crest, which is located by any of the many well-known geophysical exploration methods, frequently will exhibit traces of oil and gas but no sufficient amount to constitute commercial production. There are otherwise no other available criteria to determine the most likely direction to drill the next well into the deposit of oil and gas possibly displaced by these forces. The flow velocities are of the order of 0.1 inch per day and the pressure gradient associated with this flow is of the order of 3×10^{-6} pounds per square inch per foot. Obviously these minute velocities and pressure gradients are immeasurable by any of the conventional means under well bore conditions.

The present invention is therefore directed to a method for determining the flow direction of such underground fluids by placement of a fluid having a different "opacity" to radiation than the normal well fluid, and the detection of its movement photographically in and near the well bore.

It is therefore a primary object of this invention to provide a method for the determination of the direction and approximate flow rate of underground fluid flow which moves through underground permeable strata.

It is an additional object to determine the appropriate location for additional wildcat well bores on the basis of a determination of the flow direction of groundwater located in permeable strata penetrated by a previous well bore.

It is a specific object of this invention to improve the efficiency of the discovery of crude petroleum and other valuable materials by means of wildcat wells through the selection of additional well sites after a determination of the direction of groundwater flow in a previously drilled well bore.

Other objects and advantages of the present invention will become apparent to those skilled in the art as the description and illustration thereof proceed.

Briefly the present invention comprises a method and apparatus for the determination of the direction of underground fluid flow such as groundwater for example, in the permeable strata penetrated by a wildcat well bore by detecting the direction of the migration of a radiation opacity modified fluid which has previously been introduced into the bore opposite the strata in question. Several radiation detectors, such as for example photographic films in suitable holders, are disposed peripherally and substantially in a circle around the wall of the borehole at known azimuth positions. A radiation source is centrally introduced into the bore surrounded by the film holders and substantially at the borehole axis. These elements, the radiation source and the radiation detectors, are submerged in and separated from each other by a fluid-permeable solid medium, e.g., the radiation detectors are disposed in bores drilled beyond the bottom of the borehole in the fluid-permeable stratum or in a sand pack within the bore itself. The groundwater flows at its normal rate through the fluid-permeable material and at least partially displaces the radiation opacity modifier material from the bore off into the adjacent permeable strata in the direction of groundwater flow. At this time the detectors are exposed in a manner suitable to the type of radiation source employed. For example, an X-ray source is activated electrically from the surface, or a radioactivity source is inserted centrally within a ring of film holders for a brief period and then removed.

With X-ray radiation and an X-ray absorber as the opacity modifier fluid, those detectors located upstream toward the apparent source of groundwater flow are more heavily exposed than those located downstream toward the groundwater sink, due to the fact that groundwater flow has caused migration of the absorber in the downstream direction. With a neutron source of radiation and a modifier containing little or no hydrogen, it is the water which acts as the absorber and so those films located upstream toward the apparent source are least exposed. In either case, after elapse of a relatively short length of time, the direction of groundwater flow may be indicated by comparing the degree of exposure of the various detectors disposed around the source of the radiation.

The period of delay between the time of placement of the absorber fluid and the detectors and the exposure of the latter in a manner suggested varies between about one and about 20 days depending upon the actual groundwater flow rate, the diameter of the bore, and other geometrical considerations. Suitable indications however of the groundwater flow direction may be obtained by exposure of the detectors after an elapse of between about 2 and about 7 days from the placement of the absorber fluid and the detectors.

In the process of the present invention several types of radiation sources may be employed. In one modification an X-ray or Coolidge tube is located centrally within the well bore and is surrounded at a distance by a plurality of vertically elongated photographic film holders placed in known positions azimuthally from the X-ray source. The tube is connected by means of suitable electrical connections to associated power equipment at the surface of the earth whereby the filament of the tube is heated and at a predetermined time the high voltage is supplied to generate the X-ray radiation whereby the surrounding films are exposed to varying degrees.

In another modification the peripheral series of vertically elongated film holders are disposed in the same general positions as previously described, and after a suitable delay a radioactive material in a suitable "transparent" container is projected centrally within the series of film holders and allowed to remain for a sufficient time to expose the films. After this time the radioactive material is removed followed by removal of the films.

In both of the foregoing cases the annular region included between the film holders and the source of high energy particles is supplied with a fluid radiation opacity modifier whose physical and chemical properties render it opaque to the particular type of radiation employed to expose the film. The selection of suitable fluids for this purpose depends of course upon the nature of the radiation used. For gamma ray or X-ray radiation absorption fluids such as methyl iodide, iodobenzene, tetraethyllead, saturated solutions of sodium iodide, etc. may be employed. For neutron radiation by a neutron source such as radium-beryllium, suitable modifier liquids are those miscible in water but containing a minimum of hydrogen atoms such as heptachlorobutyric acid. It is "transparent" to neutron fluxes. The neutron backscattering and associated radiations expose the film and is measured and plotted on polar coordinates.

In another preferred modification, other forms of radiation detectors may be placed at each of the several positions at the outside of the annular test zone surrounding the radiation source. A Geiger-Müller tube for example may be substituted for each of the photographic films described above and connected by cables to suitable surface recording equipment. In this manner constant watch on the displacement of the modifier fluid by the ground fluid flow may be maintained.

The process and apparatus of the present invention will be more readily understood by reference to the accompanying drawings in which:

Figure 1 is an elevation view in cross section of a typical anticline formation in which lateral groundwater flow has displaced the trapped petroleum deposit,

Figure 2 is an isometric view of the bottom of the borehole and showing the equipment used therein to accomplish the aforementioned objects according to this invention,

Figures 3A and 3B are schematic diagrams illustrating respectively the groundwater flow displacement of the radiation absorption fluid and a polar coordinate plot showing the degree of exposure of the films from which the groundwater flow direction can be determined, and

Figure 4 is a cross section view of an X-ray tube adapted to omnidirectional X-ray radiation.

Referring now more particularly to Figure 1, an arching structure **10** of permeable rock is penetrated by well bore **12**. This arching structure is known as an anticline and is overlain by one or more layers of fluid impermeable rock **14** and underlain by other nonfluid-containing layers **16**. The specific gravity of petroleum gas and oil is nearly always less than that of the brine which constitutes the groundwater frequently associated with it. Accordingly these hydrocarbon materials migrate upwardly and tend to collect in anticlinal traps such as that shown in this figure. Because of the fluid impermeable stratum **14** the accumulation of petroleum ordinarily exists above broken line **18**. In the absence of groundwater flow this line **18**, which constitutes the lower extremity of the petroleum deposit, will be substantially level or horizontal. When however the groundwater flows in the direction indicated by arrows **20**, the hydrodynamic effect of such flow is to displace the petroleum deposit to the right in permeable stratum **10** so that it occupies the position indicated between line **22** and the lower surface of impermeable stratum **14**.

There are many geophysical methods for locating the approximate position of an anticlinal structure. Once the approximate location is determined, the site for drilling well bore **12** is readily picked. If the petroleum deposit were undisplaced, then well bore **12** would be expected to produce commercial quantities of petroleum. However, with the deposit displaced into a position embraced in bracket **24**, well bore **12** drilled at approximately the crest of the anticline will show little more than traces of oil and gas. The present invention is directed to the use of well bore **12** to determine the direction of groundwater flow and the most likely direction of displacement of the gas and oil so that a logical direction for drilling further wells may be picked with the first well as a reference point.

Referring now more particularly to Figure 2, an isometric view of the bottom of the borehole **12** is shown including permeable stratum **10**. Tubing string **30** is provided with tubing centralizer means **32** and packer **34** disposed immediately above the dependent film holders and radiation source. The purpose of the packer is to prevent interference with the normal groundwater flow by flow of these fluids into or from the borehole. If desired, a packer both above and below the annular test zone may be used.

Dependent from supporting head **36** disposed at the lower end of tubing string **30** is a plurality of film holders **38** arranged generally in a circle near the borehole walls and provided at their lower ends with conical or other shaped points **40**. In each of the film holders **38** is disposed an elongated film strip of photographic film. The upper edge **42** of these strips appears in the drawing at the rear of housing **36**. The broken lines associated with film holders **38** in the foreground of Figure 2 and which are shown in section indicate also the position of the film holders and the film **44**. It should be noted that the surface of the film is disposed at right angles to or facing the centrally located radiation source **46**.

Centrally dependent from housing **36** essentially along the borehole axis is radiation source enclosure **48** provided with a conical or otherwise pointed lower end **50**. The radiation source **46** is connected by means **52** which extends upwardly through casing **30** to the surface. When the radiation source comprises an X-ray tube, support means **52** contains electrical cable **54** by means of which the tube is activated from the surface. This cable contains a high voltage anode lead and a pair of low voltage filament heating leads including a ground return by means of which the tube is operated. When the radiation source **46** comprises a radioactive material, the cable **54** is unnecessary and **52** comprises a support rod by means of which the radiation source is raised and lowered relative to the surrounding film holders.

Referring now particularly to the lower portion of Figure 2, a series of longitudinal openings are shown in the fluid-permeable solid material at the bottom of the bore. These include a central opening or radiation zone **56** into which the radiation source enclosure **48** is extended, and a plurality of surrounding openings or detection zones **58** into which the film holder or other detector enclosures extend.

These longitudinal openings may be drilled into the fluid-permeable formation from the bottom of the borehole at suitable locations so that the elongated radiation source and film holder enclosures will readily extend into them. In another modification these openings comprise the positions in a sand pack, or other body of fluid-permeable solids placed in the borehole opposite the fluid-permeable strata after the borehole has been drilled therethrough. In this latter modification supporting head **36** is moved downwardly by means of tubing string **30** and the film holder and radiation source enclosures with their pointed lower ends are forced downwardly into the sand pack forming therein elongated openings **56** and **58** as indicated in Figure 2 and forming the annular-shaped fluid-permeable solid test zone between the central radiation source and the surrounding film holders.

In either case, a fluid radiation absorber is employed. With the sand pack, the fluid radiation opacity modifier is mixed with the sand and placed by conventional sand pack placement means in the borehole opposite the permeable strata through which the groundwater flows. When the elongated openings are drilled into the fluid-permeable strata, the fluid radiation absorbing medium is injected into the openings, and particularly the film holder openings **58**. After injection of the film holder enclosures **38**, their respective positions in relation to the geographical azimuth are determined by conventional methods and equipment, not shown, such as are widely employed in orienting whipstocks, side-wall core samplers, etc. Suitable methods and equipment of this character are described in the "Composite Catalog of Oil Field Equipment and Services," 20th edition (1954–1955) at pages 1433 and 1436. Packer 34 is set and the groundwater flow proceeds whereby partial displacement of the fluid radiation opacity modifier is effected. After a suitable delay the films are exposed by any of the means referred to previously and then supporting enclosure or head **36** is withdrawn from the hole for recovery of the exposed film and analysis of the exposure data.

Referring now more particularly to Figure 3A, a transverse cross section view in schematic form of the fluid-permeable solid annular test zone enclosing the film holders **38** and the radiation source **48** is shown. Here the upper edges **42** of the film strips and their position with respect to the location of the radiation source are clearly indicated. The wide-spaced cross hatching in the annular space indicates the cross section of the fluid-permeable solids through which the groundwater flows. The narrow-spaced cross hatching indicates the region into which the radiation modifier fluid has migrated after a delay of about 6 days under the influence of groundwater flow in a direction from NNW to SSE. It is to be noted that the modifier fluid has been swept entirely away from between radiation source **48** and those two of the film holders **38** which, by means referred to above or their equivalent, have previously been determined to be located to the north and to the northwest of the bore hole. It is further noted that the modifier fluid has been partially removed from between radiation source **48** and two more of the film holders, namely those to the west and to the northeast. The remaining film holders are still affected to a considerable extent by means of the modifier fluid and accordingly the degree of exposure of these films is considerably different.

Referring now more particularly to Figure 3B, a polar coordinate plot showing the degree of exposure of each film strip as a function of its azimuthal position and the variation in radiation opacity along different radii are shown when the radiation opacity modifier fluid is a radiation absorber, i.e. is opaque to the radiation. The northern and northwestern films are indicated as being most highly exposed, the northeastern and western films are shown with a reduced exposure, and the remaining films are shown with the least exposure. From these data it is readily determined that the displacement of the radiation absorption fluid has occurred to the greatest extent to the south and southeast, and accordingly it is ascertained that the groundwater flow causing this displacement is in a direction from the NNW to the SSE.

Referring now more particularly to Figure 4, a simplified cross sectional view of an X-ray tube adapted to omnidirectional X-ray radiation is shown. An essentially cylindrical envelope **60** encloses anode **62** provided with high voltage connection **64**. Spaced apart therefrom is an electron emitting filament **66** electrically heated by a current flow applied thereto by means of connections **68** and **70**. Because of conical portion **72** of anode **62** disposed facing filament **66** and provided with an approximately 90° apex angle, the resulting X-ray radiation is omnidirectional in a transverse plane passing through envelope **60**. When such a tube is located centrally as the radiation source an approximately equal amount of radiation is directed toward each of the surrounding plurality of film holders.

Preferably the relative exposure of each of the film holders is determined with reference to a blank exposure in which film holders are exposed without the modifier medium and with the X-ray tube or radiation source located in the same relative positions. The exposure in the well bore is then effected and plotted in Figure 3B in terms of relative exposure whereby non-uniformity of radiation from the X-ray tube may be eliminated. The same relative determination is highly preferred with respect to the radioactive sources to avoid possible non-uniformity of radiation in different directions.

In one preferred modification using the elongated films, the films are exposed at one end immediately after placement of the opacity modifier, and then the other ends of the films are exposed later after the effects of groundwater flow have progressed.

The structural materials for the radiation enclosure **48** and the film holders **38** are selected on the basis of the type of radiation to be employed and they of course must be transparent or at least substantially transparent to the particular radiation used. With respect to X-ray or gamma ray radiation, suitable materials of construction for these enclosures include the materials having very low atomic numbers, such as aluminum, or plastics of carbon, hydrogen, and oxygen. With beta radiation suitable structural materials include any material, provided the mass of such material in the path of the radiation is kept at a minimum possible value. With neutron radiation the materials may be selected from the well known materials having low neutron capture cross sections, such as aluminum, zirconium, etc.

The extent of the delay period between the time of placement of the absorption fluid and the exposure of the film is somewhat variable depending upon the intensity and nature of the radiation, the distances involved between the radiation source and the film holder, the efficiency of absorption of the radiation absorption fluid, the sensitivity of the film, the velocity of groundwater or other fluid flow whose direction is to be determined, and other considerations. In a general way however delays of between about one and about 20 days ordinarily will be satisfactory for nearly all applications. With 35 kv. X-rays, a methyl iodide absorption medium saturating the interstices of a quartz sand pack, with ordinary X-ray film disposed 2.5 inches radially apart from the X-ray tube, and a flow rate of about 0.1 inch per day, a delay of about 8 days will in nearly all cases indicate a high exposure on at least one of the plurality of films and from which the groundwater flow direction may be determined.

The number of film holders disposed around the radiation source is at least three, and preferably six or eight or more such holders are provided in a circle just in from the borehole wall in known azimuthal positions.

From the data determined according to the method of the present invention and applying known geometric and hydrodynamic relations, the change of the detected variable with time also serves to give an indication of the flow rate of the groundwater through the region of the intersection of the permeable strata and the borehole. With groundwater flows which are relatively rapid, the return of the sand pack condition to the norm corresponding to the presence of groundwater in the sand pack is relatively rapid. In the opposite case when this flow is relatively slow the change in sand pack condition, with respect to the measured variable, is relatively slow. Knowing the required time for this variation, one may readily estimate the flow velocities.

It is apparent from the practice of the present invention as described above that the location of nearby deposits of gas and oil and other valuable fluids found in underground permeable strata, has been improved. It is contemplated in the practice of this invention that the usual geophysical methods will be applied in locating the anticlinal type of structure or other characteristic types of structures in which such valuable fluids are found. It is further contemplated that at least one wildcat well bore will be drilled into this structure so as to expose the permeable strata and render the path of groundwater flow accessible for analysis. The present invention is intended to be used in this analysis, specifically to determine the direction of groundwater flow past the well bore in those cases where traces of valuable fluids have been found in the bore in order to indicate the most likely direction which the main body of these valuable fluids have been displaced by the groundwater flow.

A particular embodiment of the present invention has been hereinabove described in considerable detail by way of illustration. It should be understood that various other modifications and adaptations thereof may be made by those skilled in this particular art without departing from the spirit and scope of this invention as set forth in the appended claims.

We claim:

1. The method for determining the direction of flow of connate fluids flowing essentially laterally through a subterranean stratum penetrated by a well bore which comprises positioning a source of radiation centrally within said well bore opposite said stratum; positioning a plurality of radiation detectors within said well bore opposite said stratum, said detectors being positioned substantially symmetrically around said source of radiation at substantially uniform radial distances therefrom and being separated from said source of radiation and from each other by a fluid-permeable solid; introducing into said fluid-permeable solid a fluid having an opacity to said radiation different from that of said connate fluids; positioning at least one packer into said well bore to isolate said stratum from the remainder of the bore; permitting said connate fluids to resume their natural course of flow through said stratum; and subsequently measuring the amount of radiation detected by each of said detectors.

2. A method according to claim 1 in combination with the step of measuring the radiation detected by each of said detectors prior to permitting said connate fluids to resume their natural course of flow through said stratum.

3. A method according to claim 1 wherein the said fluid-permeable solid which is interposed between said radiation detectors and said source of radiation is a fluid-permeable mass of granular solids introduced into the bore hole from the earth's surface.

4. The method of determining the direction of flow of connate fluids flowing essentially laterally through a subterranean stratum which comprises (1) drilling a well bore of relatively large diameter to the vicinity of the upper horizon of said stratum; (2) extending said well bore into said stratum, said well bore extension being of reduced diameter; (3) drilling a plurality of secondary bores into said stratum, said secondary bores being located substantially symmetrically around said well bore extension and radially spaced therefrom at substantially uniform distances; (4) positioning a source of radiation within said well bore extension; (5) positioning a plurality of radiation detectors within each of said secondary bores; (6) introducing into the annular portion of said stratum which lies between said well bore extension and said secondary bores a fluid having an opacity to said radiation different from that of said connate fluids; (7) setting at least one packer within said well bore to isolate said stratum from the remainder of the bore; (8) permitting said connate fluids to resume their natural course of flow through said stratum; and (9) subsequently measuring the amount of radiation detected by each of said detectors.

5. A method in accordance with claim 4 in combination with the step of measuring the radiation detected by each of said detectors immediately prior to permitting said connate fluids to resume their natural course of flow through said stratum.

6. The method of determining the direction of flow of connate fluids flowing essentially laterally through a subterranean stratum which comprises (1) drilling a well bore into said stratum; (2) positioning within said well bore and opposite said stratum a fluid-permeable mass of granular solids; (3) positioning a source of radiation within said solid mass substantially coaxially therewith; (4) positioning a plurality of radiation detectors within said solid mass substantially symmetrically around the periphery thereof; (5) introducing into said solid mass a fluid having an opacity to said radiation different from that of said connate fluids; (6) setting at least one packer within said well bore to isolate said stratum from the remainder of the bore; (7) permitting said connate fluids to resume their natural course of flow through said stratum; and (8) subsequently measuring the amount of radiation detected by each of said detectors.

7. A method in accordance with claim 6 in combination with the step of measuring the radiation detected by each of said detectors immediately prior to permitting said connate fluids to resume their natural course of flow through said stratum.

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