Feb. 7, 1967 M. PRATS ETAL 3,302,718

CONSOLIDATION THROUGH LATERAL CHANNELS

Filed Nov. 17, 1964 2 Sheets-Sheet 1

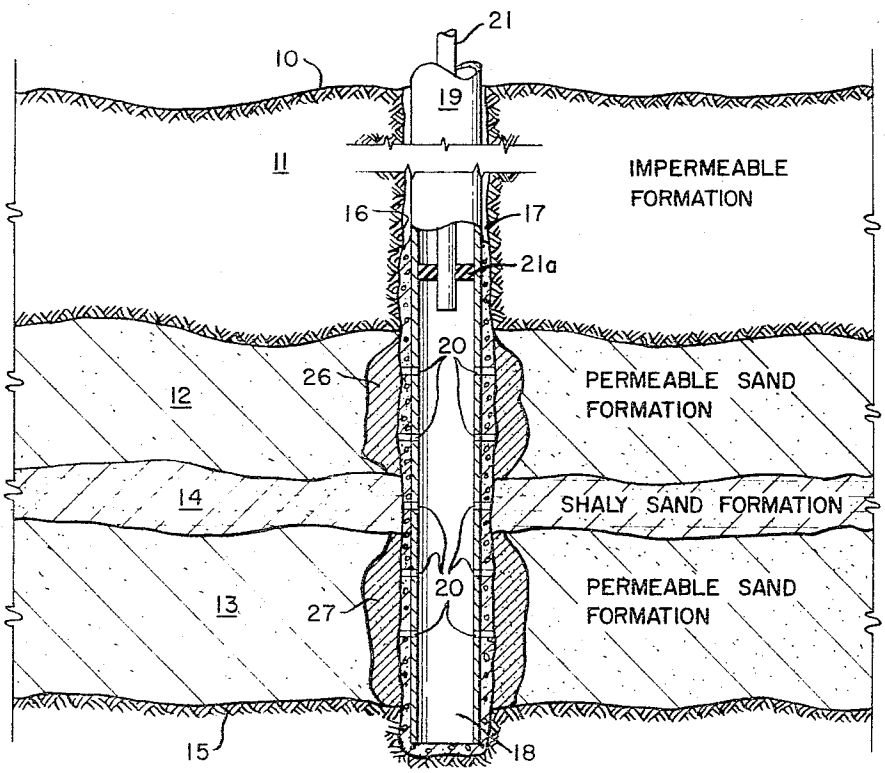


FIG. 1

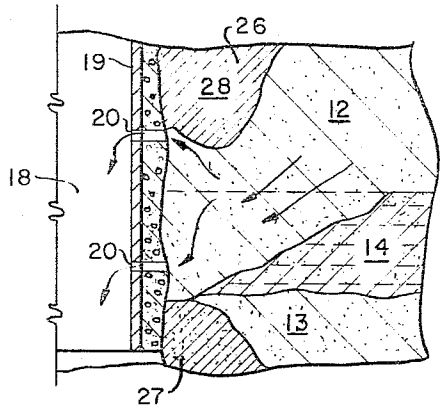


FIG. 2

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CONSOLIDATION THROUGH LATERAL CHANNELS

Filed Nov. 17, 1964 2 Sheets-Sheet 2

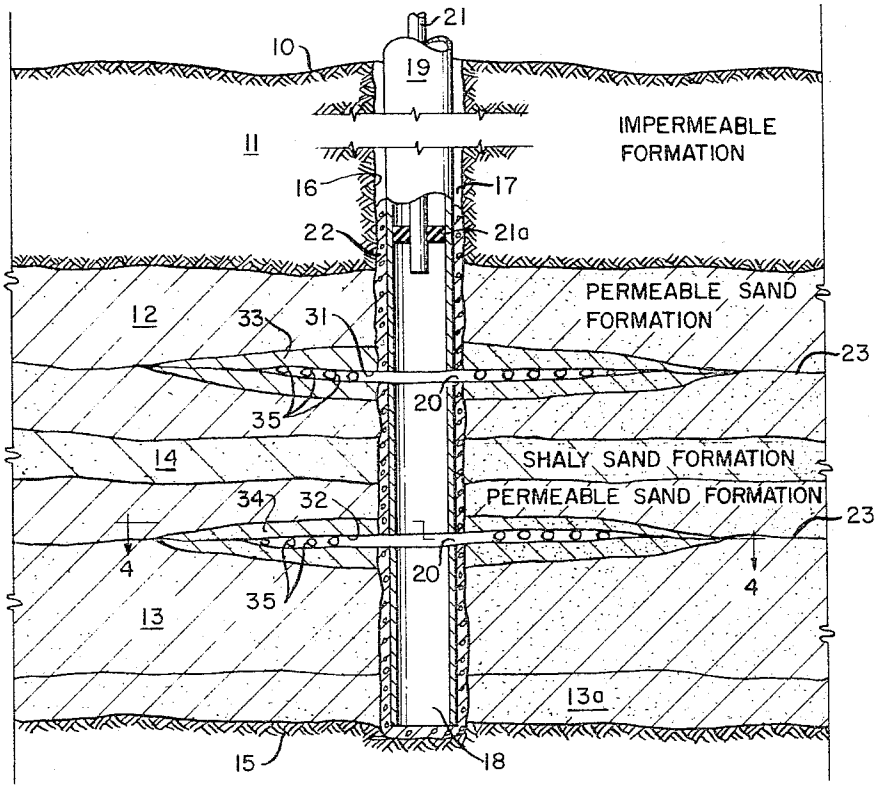


FIG. 3

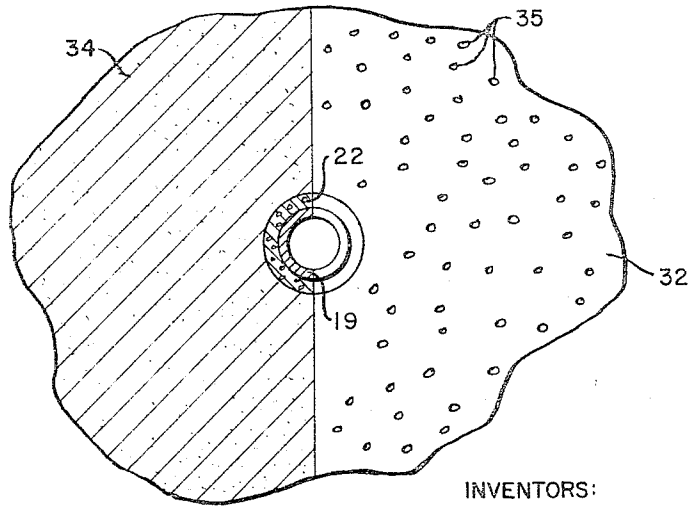


FIG. 4

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CONSOLIDATION THROUGH LATERAL CHANNELS

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Filed Nov. 17, 1964, Ser. No. 411,830
5 Claims. (Cl. 166—33)

This application is a continuation-in-part of copending application Serial No. 169,016, filed January 26, 1962, now abandoned.

The present invention is directed to a method of reducing sand intrusion into petroleum producing wells and more particularly to the prevention of sand intrusion, into producing wells penetrating unconsolidated petroleum producing reservoir formations. More specifically, the invention is related to a method of a layer-by-layer consolidation of a permeable unconsolidated reservoir having a heterogeneous permeability.

Many reservoir formations from which petroleum is produced do not have adequate strength to prevent the erosion of the formation by the flow of fluids through the reservoir to the well bore. These friable or unconsolidated formations are frequently referred to as incompetent formations. In these types of formations, sand intrusion into the producing well has long been a problem and sand carried into the well bore by the fluid flow may completely plug the well. It is further objectionable because the sand will abrade downhole and surface equipment to the point that their service life is manifestly reduced. Further, remedial techniques to remove the sand, such as bailing and the like, are extremely expensive and, if the sand intrusion cannot be stopped the well is often prematurely abandoned.

Long recognized as a serious problem in unconsolidated formations, sand intrusion has been attacked by various methods. One method has been to use a slotted liner or wire wrapped screen in the producing zone of the formation which allows the petroleum fluids to pass through the slots but prevents the sand from entering the cavity of the liner or screen. A somewhat more sophisticated method is to use the slotted liner with a granular pack, often gravel, between the liner and the unconsolidated formation to act as a filter to restrict the inflow of the sand. Such granular materials can be packed around a slotted liner within the casing which is perforated to allow ingress and egress of fluids. Here again the pack acts largely as a filter. A technique very similar to the gravel pack is disclosed in U.S. Patent No. 2,986,538, issued to Nesbitt, which uses a particulate resin coated composition as a packing in the annulus between a perforated casing and a slotted liner which sets into a permeable filter mass limiting the ingress of sand into the slotted liner. The disadvantage of such well lining or gravel packing procedures is that they materially increase the cost and risk of failure, particularly in dual-completion wells in which the upper formation requires sand control. In addition, the use of such procedures generally result in expensive workovers when it becomes apparent that the well needs to be recompleted into a different zone or the liner must be removed or replaced.

Another technique which has been practiced is the injection of a resin capable of setting under the conditions in the formation to bind the sand particles contiguous to the borehole into an integral porous mass. Often the resin used in these types of in situ consolidation of the formation proper are phenol-formaldehyde, epoxy or similar resinous materials.

In general, the consolidation of the entire or major portion of the productive interval of a formation by the injection of a resin is quite expensive, because of the large volume of the resin that is required; although, when the permeability of the treated portion of the reservoir formation is fairly uniform, the injected resinous fluid penetrates fairly uniformly through the formation adjacent to the well bore and gives results which are both effective and durable.

However, in reservoir formations having heterogeneous permeability, the injection of resinous fluids to effect an in situ consolidation are not so successful. In such formations, the injected resinous fluid tends to penetrate the more permeable parts of the formation leaving the less permeable parts unpenetrated. The net result of this non-homogeneous penetration is the excellent consolidation of the more permeable parts of the reservoir with almost no consolidation of the less permeable parts, especially in the vicinity of the borehole. Because of this, when the well is produced, the less permeable and less consolidated portions of the reservoir will tend to wash into the well bore and "sand up" the well. The occurrence of this necessitate expensive workovers for cleaning out the sand and retreating the unconsolidated portions of the reservoir formation.

Accordingly, it is one of the objects of this invention to reduce sand intrusion into petroleum producing wells penetrating permeable, unconsolidated reservoirs of non-homogeneous permeability.

A broader object of the invention is to provide a technique for the elimination of sand intrusion into fluid-producing wells penetrating unconsolidated reservoir formations.

Another object of the invention is to provide an improved, layer-by-layer, method of consolidating permeable, unconsolidated petroleum-producing reservoir formations.

These and other objects of the invention will become apparent from the following description and accompanying illustrations of the invention.

In its broadest aspect, the present invention provides a method of reducing sand intrusion into a fluid-producing well having its borehole extending into a fluid-producing permeable, unconsolidated reservoir formation having non-homogeneous permeability. In practicing the present method, a casing is installed within a borehole that extends into such a reservoir formation. The casing is sealed to the surrounding earth formations along all portions of the reservoir that are encountered by the borehole. A determination is made of the depth boundaries of the layer within the reservoir formation in which the permeability is substantially uniform (and, preferably, is relatively high). The casing and casing sealant are then perforated at at least one point between the depth boundaries of at least one such layer. A fluid consolidating agent that is free of suspended solids is then injected through the perforations and into the pores (or interstices) between the grains of one or more of the layers within which the permeability is substantially uniform. Where the casing is perforated at points adjacent to more than one layer, the fluid consolidating agent is injected into only one layer at a time, unless the permeabilities of more than one layer are substantially equal.

The invention will now be described with reference to the accompanying drawings in which:

FIGURE 1 is a vertical section through a borehole of a petroleum-producing well, illustrating the effect of a conventional consolidation with a resin in a reservoir formation having heterogeneous permeability;

FIGURE 2 is an enlarged view of the bedding planes of heterogeneous permeability in the reservoir formation shown in FIGURE 1, illustrating the effect of the lack of consolidation in the less permeable bedding plane;

FIGURE 3 is a vertical section through a borehole penetrating a reservoir formation having heterogeneous

permeability, corresponding to that of FIGURE 1, in which the employment of the present invention is shown; and

FIGURE 4 is a stepped sectional view taken along line 4—4 of FIGURE 3.

Referring now to FIGURES 1 and 3 of the drawings, numeral **10** designates the top portion of the overburden which includes impermeable strata **11** located above an unconsolidated reservoir formation of heterogeneous permeability. For purposes of illustration the petroleum-producing zone is divided into three strata extending parallel to the bedding planes. These include strata **12** and **13**, which are more permeable than the shaly sand stratum **14**. The three strata are sandwiched between the impermeable overburden stratum **11** and the impermeable underlying stratum **15**. Borehole **16** penetrates the various strata and extends from the surface to the impermeable stratum **15**. The upper portion of the borehole represents an unproductive section **17** which extends through the impermeable overburden stratum **11** with a productive or reservoir section **18** extending through the three interbedded unconsolidated stratum **12**, **13** and **14** to the impermeable underlying stratum **15**. Casing string **19** extends through the unproductive section **17**, the productive section **18** and into the unproductive underlaying stratum **15**. It is sealed to the surrounding earth formations, e.g., by cementing along at least the length of the production section **18** and across the bottom of the borehole. The portion of the casing that is adjacent to productive section **18** is perforated by perforations **20** which provide fluid passageways through the casing and surrounding sealant and into the adjacent earth formations at a suitable density of openings, e.g., one perforation per foot of depth. A production tubing string **21** is supended from the wellhead (not shown) and is extended to a point near the perforations **20** to provide a conduit for producing fluids from or injecting fluid into the reservoir section **18**. The annulus between such a tubing string and the surrounding casing is usually closed off with a tubing string packer such as packer **21***a*.

One conventional method of treating a petroleum producing well is illustrated in FIGURES 1 and 2 to prevent sand intrusion is through the use of a consolidating agent. A formation-penetrating fluid bonding agent such as a liquid epoxy or a phenol-formaldehyde sand consolidating resin formulation is pumped through the tubing string **21** and into the perforated section of the casing **19**. Pressure is applied to the fluid bonding agent to force it out of the borehole and into the permeable, unconsolidated formation. Since we have described a reservoir of heterogeneous permeability, having three layers, **12**, **13** and **14**, of differing permeabilities, the pressure on the fluid bonding agent in the productive section **18** will cause it to be forced into the more permeable strata **12** and **13** with almost no penetration of the less permeable stratum **14**. The net result of this can be seen in FIGURES 1 and 2 where the consolidation occurs in zone **26** and **27** as the result of the penetration of the fluid plastic in these areas. Almost no consolidation occurs in the less permeable stratum **14**.

After a permeable, unconsolidated reservoir formation of heterogeneous permeability, as described above, has been consolidated with a fluid plastic the well is produced. Since production is accomplished by the withdrawal of fluids such as petroleum and water from the formation immediately surrounding the borehole the erosive forces in this area will be severe. Ideally, it would be desirable for all the petroleum and water to be withdrawn through the consolidated zones **26** and **27** into the producing section **18** of the borehole. However, some of the oil will be withdrawn through the less permeable stratum **14** and between the interfaces of the less permeable stratum and the more permeable strata.

The results of petroleum and water flow through the unconsolidated stratum **14** is clearly shown in FIGURE 2 where the flow from the stratum **12** is represented by a series of arrows. This flow tends to wash away the less permeable stratum **14** which is unconsolidated and carry it into the producing section **18** of the borehole "sanding up" the well. As the less permeable stratum **14** washes into the well bore, the flow in this area will be increased since the area now becomes more permeable than the consolidated zones **26** and **27** which manifestly accelerates the sand intrusion into the well. Further, the washing away of the less permeable shaly stratum **14** undercuts the upper consolidated zone **26** which results in a mechanical flexing which tends to break the consolidated zone **26** apart originating with slumping at **28**. Breakage and crumbling of the consolidated zone **26** of course increases the sand intrusion into the borehole.

It should be appreciated that petroleum flow contiguous to the underside of shaly sand strata **14** will also be detrimental, since erosion here will abet the effect described above. Because the problem is adequately illustrated in the description of the fluid flow immediately above the shaly sand strata **14**, it will not be further enlarged by describing the undercutting erosion action.

The present invention is directed to a method of preventing the sand intrusion encountered in a reservoir formation having heterogeneous permeability particularly those having bedding planes along which there are layers of differing degrees of permeability, as exemplified by the above-described reservoir having strata **12**, **13** and **14**. For purposes of illustration in FIGURES 1 and 3, a similar reservoir formation containing three discrete layers (strata) **12**, **13** and **14**, is illustrated for better understanding of the invention. In FIGURE 3, however, the permeable sand formation **13** is shown as containing a lower water-bearing interval **13***a* with the casing string **29** being extended onto a deeper zone. This illustrates a situation which is common in dual-completion wells with the illustrated portion being an upper heterogeneous and unconsolidated reservoir interval. In practical situations clean, distinct layers of uniform but different permeabilities are rare and there can be numerous strata of different degrees of permeability closely interbedded, sometimes without distinct or detectable boundaries. This of course results from the geological condition at the time the reservoir was formed and whether it was subject to water flow, erosion and the like. Thus, the situation in a practical sense is far worse than illustrated in FIGURES 1 and 2 since the gradation in permeability of the various strata will tend to complicate conventional fluid plastic consolidations measurably. It is in such situations that the instant invention will be most effective and it will now be described with reference to the illustrations shown in FIGURES 3 and 4.

The borehole shown in FIGURE 3 is very similar to that shown in FIGURE 1 and like numerals are used to designate corresponding items in the respective figures. In the practice of the invention it is necessary that the casing string **19** traverses the petroleum-producing reservoir zone, between impermeable overburden **11** and petroleum-producing portion of stratum **13** and extends on to a deeper zone. The portion of the casing string which traverses the reservoir zone and, generally, the entire lower portion of the casing string, is sealed in position with a sealing material **30**, such as cement. This sealing material extends the full length of the illustrated productive section **18** of the borehole and isolate the permeable unconsolidated formations from the casing string. In practicing the present invention, it is important that during the drilling and completion of the well, the usual data be collected relative to the nature and location of the earth formations which are encountered by the borehole. In general, this involves the borehole or sidewall coring of the reservoir formations and/or the running of at least some logging tools, such as self potential resistivity or acoustic logs prior to casing the borehole; and, possibly running additional logging tools, such as radio-

activity logs after casing the well. Such data collecting activities are conventional, and the specific procedures for obtaining and utilizing the data are well-known to those skilled in the art.

In connection with the present invention, it is important that determinations be made of the depth of the upper and lower boundaries of at least one uniformly permeable layer within the interval of unconsolidated and heterogeneous earth formations from which fluids are to be produced. As indicated in FIGURE 3, such an interval may contain more than one of such layers, e.g., the permeable sands 12 and 13 above and below the impermeable shaly sand 14.

After the depth boundaries of such a substantially uniformly permeable layer have been determined, the casing string 29, which is fluid tight sealed to the surrounding earth formations through the interval from which fluids are to be produced, is perforated at at least one point between the boundaries of the uniformly permeable layer.

The perforation of such a casing string is a conventional operation for which numerous tools and techniques have been developed. In general, such perforating operations are accomplished by means of perforating guns, shaped charges or casing and cement abrading tools. All of such tools and techniques are designed to open fluid passageways which extend from within the interior of the casing string, through the casing and sealant, and into the surrounding earth formations. In conventional operations, such perforations are often made simultaneously at a plurality of different depths along an extended section of the casing. However, in the present process it is essential that the perforations be made only between the boundaries of a substantially uniformly permeable layer. The conduits in the well are then arranged to provide a fluid passageway that extends from a surface location into fluid communication with only those of the earth formations that constitute one or more substantially uniformly permeable layers.

Referring to FIGURE 3, in consolidating the fluid producing interval 18, after the casing 29 has been installed and the sealant 30 has been allowed to harden, the casing and sealant are perforated to form the channel 31 that extends into sand 12. By a means, such as a conventional technique, the conduits in the well are arranged to convey a fluid consolidating agent that is free of suspended solids (e.g., a liquid epoxy resin formulation) from a surface location to the sand 12. Where, for example, this is the first depth at which a treatment is to be made from within the well, the casing is isolated from the earth formations (by the sealant 22) at all points except those which are penetrated by the channel(s) 31. Therefore, when packer 21*a* is set and fluid is pumped through the tubing string 21, the fluid is injected into and only into the sand 12.

In numerous situations it is desirable to precede the sand consolidation treatment by first fracturing the earth formation from which fluids are to be produced. This is particularly effective in situations in which the regional tectonics are such that fractures 23 tend to form along generally horizontal planes generally paralleling the bedding planes of the earth formations. Horizontal fractures of the type shown in FIGURE 3 are advantageous in providing what amounts to a highly permeable extention of the diameter of the borehole.

In a preferred procedure, where sand 12 is to be fractured, the casing is perforated and the well conduits are arranged as described above. Before the sand consolidating fluid is injected, a liquid in the borehole and tubing string is pressurized to fracture the sand. This creates a fracture extending through the matrix of the sand and allows fluid to flow through the fracture and into the pores of the sand. A propping agent 35, comprising relatively coarse solid particles such as sand, gravel, etc., is suspended in fluid that is forced into the fracture. Such particles are plastered out against the exposed facies of the sand formation and are deposited within the fracture where they maintain a relatively high degree of permeability after the pressure has been reduced below that of the overburden pressure and the walls of the fracture have been allowed to close against the propping agent. The fluid consolidating agent is then pumped through the port 20 and injected into the sand formation in the manner described above.

When the sand consolidating fluid has solidified, the portions of sand 12 that are immediately adjacent to the perforation channels 31 are consolidated; and the consolidation occurs within regions such as those shown in FIGURE 3.

In a preferred procedure for treating the lower permeable sand 13 (which constitutes a second substantially uniformly permeable layer), the tubing string and packer 21 and 21*a* are moved and reset at a depth below that of the perforation channel 31 and above the point between the depth boundaries of sand 13 at which it is desirable to form the perforation channel 32. The lower sand is then fractured and/or consolidated in the manner described above.

As will be apparent to those skilled in the art, an entirely analogous procedure can be followed in consolidating one or more lower unconsolidated and heterogeneous fluid producing intervals that are encountered by the borehole. Also, numerous variations can be made in the perforating and injecting procedures, such as, simultaneously perforating the casing at all of the points that are intermediate between the boundaries of a series of substantially uniformly permeable layers that have been selected as those from which fluids are to be produced and then isolating each level of perforations by means of a straddle packer injection tubing arrangement for the individual sand consolidation treatment of each of the selected layers. In addition, where a pair of substantially uniformly permeable layers have substantially equal permeabilities and are separated by a sufficient depth, they can both be perforated and can be simultaneously consolidated by arranging the well conduits for simultaneously injecting fluid into both of those layers.

Obviously, when using the layer-by-layer consolidation method of this invention it is not possible for the less permeable stratum 14 to break up and flow into the casing string as the result of fluid flow thereinto, as is the case in many other methods of consolidation in such a reservoir. Further, through this technique relatively large disk-shaped collection zones can be consolidated with the minimum amount of chemical required to permeate only the near surface portion of the walls of the collection zones in contrast to the extensive permeation that is required by other methods. In FIGURE 3, the well string 19 and sealant 22 are completely severed and channels are physically cut outwardly into the formation by means of an abrasive fluid or a perforating tool capable of making multiple perforations in a single plane. This is the preferred embodiment of the invention and as can be seen in FIGURE 4 a large disk-shaped consolidated zone of high surface area is formed and enhances the recovery of petroleum from the reservoir.

When this technique has been used to prepare a well penetrating an unconsolidated reservoir formation for production, the petroleum entering the casing string must flow through the consolidated zones 33 and 34 surrounding channels 31 and 32 which contact the casing string 19. Under these circumstances the unconsolidated less permeable strata, such as the shaly sand stratum 14, shown in FIGURE 3, are completely isolated from the interior of the casing string by the consolidated zones. Further, since all portions of the formation which are contacted by each of the channels 31 and 32 have a substantially uniform permeability, the consolidation of zones 33 and 34 is substantially uniform within itself and is unlikely to contain poorly consolidated areas through which sand intrusion can occur. It has been

found that the best results are obtained when channels **31** and **32** are cut along a single plane substantially parallel to bedding plane of the formation and are accurately located between the depth boundaries of the most permeable strata of the reservoir, since this optimizes recovery.

EXAMPLE I

In the drilling and completing of one Gulf Coast well, the data concerning the nature and location of the reservoir formations that were encountered by the borehole indicated the presence of a heterogeneous unconsolidated fluid-containing interval between a depth of 8164 and 8218 feet. This interval included an upper oil-bearing sand and a lower water-bearing sand with a oil-water contact at 8184 feet. The upper sand contained a thin, substantially uniformly permeable, generally horizontal layer at a depth of 8168 feet.

In completing the well, a casing was first cemented throughout the entire fluid-containing interval and was initially perforated only in a substantially single horizontal plane at 8168 feet, using five radially oriented jets disposed in the same plane. The adjacent thin layer was consolidated by subjecting it to a conventional epoxy resin sand consolidation treatment using 320 gallons of the resin. After the resin had hardened, the casing was perforated within a lower oil-bearing sand and the well was completed as a dual-zone production well. A consistent production rate at the 130 barrels of oil per day depth allowable was obtained with no inflow of sand from the consolidated layer within the upper sand.

EXAMPLE II

In another Gulf Coast well, the borehole encountered a heterogeneous unconsolidated oil-bearing sand within a depth interval of from 8188 to 8194 feet. This well was initially completed by cementing a casing along the entire reservoir interval and then perforating it, with about four perforations per foot of depth, and setting a conventional type of screen liner. The so completed well produced about 300,000 barrels of oil, but produced it at declining rates which were interrupted by repeated occurrences of sanding-up. The data obtained on the nature and the location of the earth formations that were encountered by the borehole of this well indicated the presence of a substantially horizontal layer of substantially uniform permeability near the top of the reservoir.

The screen liner was removed and the perforated interval of casing was squeeze-cemented to reseal the casing all along the reservoir interval. The casing was then reperforated at 8185 feet, using four jets that were radially oriented in a single substantially horizontal plane. This selected layer of the fluid-producing interval was subjected to a conventional epoxy resin sand consolidation treatment using only 320 gallons of the resin. An analogous treatment over the entire fluid-producing interval would have required at least 950 gallons of the resin; and, in view of the heterogeneity of the permeability of the reservoir formation, would not have been likely to control the sanding-up problem. The above treatment of the selected layer caused the production rate to increase from a rate of 35 barrels of oil per day (the rate exhibited immediately prior to the treatment) to the maxmium depth allowable of 130 barrels of oil per day. This rate has been maintained consistently with no inflow of sand.

From the foregoing description of the invention it is believed apparent that the inventive method may be practiced with commercially available equipment and commercially available fluid consolidating agents. It should be pointed out that since the invention is intended for the consolidation of incompetent (unconsolidated) formations solid materials in the resinous composition are unacceptable. By permeating the pores of the formation with fluid capable of reacting within the formation to form an intergranular cementing solid, it is necessary to employ a formation-penetrating, grain-bonding agent capable of penetrating into the pores of the formation. In general, such formation-penetrating, grain-bonding agents must be free of any microscopic particles of suspended solids. Although the pores of various relatively highly permeable reservoir formations can be penetrated by colloidal suspensions such as aqueous slurries of starch, carboxy methylated cellulose, etc., many of the tighter reservoir formations can only be penetrated by a clear fluid. The interstice or pores within unconsolidated reservoir formations are generally small enough to screen out the suspended particles of for example a cement slurry and prevent its successful utilization as a formation consolidating agent. Numerous conventional sand consolidating treatments are effected by the injection of a formation-penetrating, grain-bonding agent and are thus suitable for use in the present process. Typical treatments of this type include: injecting fluids containing the components of phenol-formaldehyde, epoxy, or the like resin materials; injecting a fluid containing a solute such as sodium silicate followed by a fluid containing a material capable of precipitating the solute, e.g., a cresol, or the like combination of precipitate-forming materials; injecting a fluid oxidant or a hot gas to cause or accelerate an in situ carbonization of crude oil within the sand; injecting a carbohydrate containing solution such as a sugar solution and then heating the solution permeated formation to thermally coat the carbohydrate; and the like treatments.

Various changes in details of the description and of the described method may be made within the scope of the appended claims without departure from the spirit and scope of this invention.

We claim as our invention:

1. A method of reducing sand intrusion into well boreholes penetrating an unconsolidated, fluid-producing reservoir formation having non-uniform permeability comprising the steps of:

(a) determining the depth boundaries of at least one layer within said reservoir formation in which the permeability is substantially uniform;

(b) casing said borehole and sealing said casing in said reservoir with sealant to the extent of its vertical traverse of said reservoir;

(c) perforating said casing and sealant between said depth boundaries of at least one layer in said reservoir formation in which the permeability is substantially uniform; and

(d) forcing a solids-free, fluid grain-bonding consolidating agent through the resulting perforations into said uniformly permeable layer whereby a layer of substantially uniform permeability is consolidated into a permeable porous mass when said fluid consolidating agent sets.

2. A method according to claim **1** wherein the perforation is accomplished by severing the casing string and sealant between the boundaries of at least one layer in which the permeability is substantially uniform.

3. A method according to claim **1** wherein the layer communicating with the inside of the casing string through the perforation is fractured prior to forcing the solids-free, fluid grain-bonding consolidating agent into said layer.

4. A method according to claim **1** wherein the consolidating agent is a solids-free, liquid resin/curing agent mixture.

5. A method of reducing sand intrusion into well bores penetrating an unconsolidated, fluid-producing reservoir formation having non-uniform permeability comprising the steps of:

(a) determining the depth boundaries of layers within said reservoir formation having substantially uniform permeability;

(b) casing said borehole and sealing said casing in said reservoir with sealant to the extent of its vertical traverse of said reservoir;

(c) perforating said casing string and sealant between the depth boundaries of the more permeable layers having substantially uniform permeability;

(d) fracturing said layers communicating with the inside of said casing string through the resulting perforations;

(e) forcing a solids-free, fluid consolidating agent through said perforations and into the resulting fractured layers whereby these layers are consolidated into a permeable, porous mass when said agent sets; and

(f) producing fluids from said reservoir formation only through the resulting consolidated layers.

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