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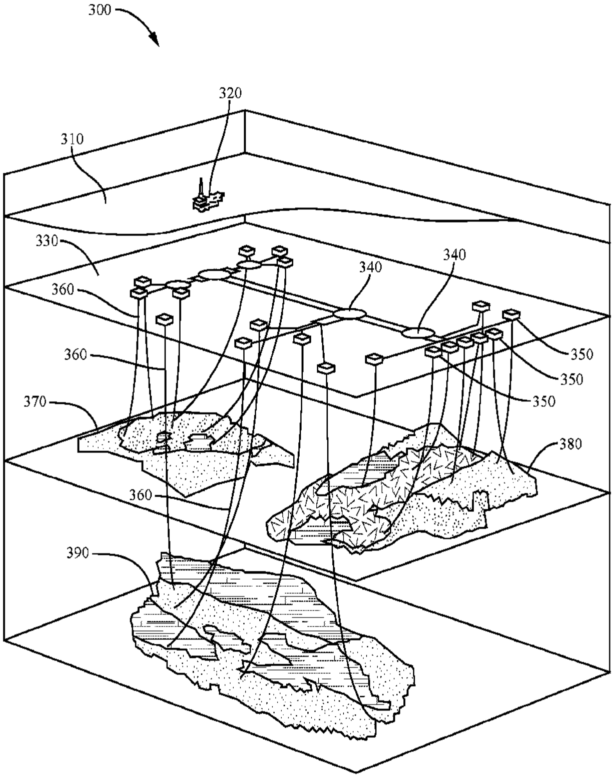
(54) **Titre** : DETECTION PAR FIBRE OPTIQUE MULTI-PARAMETRES POUR L'INGENIERIE DE COMPACTION DE RESERVOIRS

(54) **Title**: MULTI-PARAMETER OPTICAL FIBER SENSING FOR RESERVOIR COMPACTION ENGINEERING



(57) **Abrégé/Abstract**:

A method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi- well hydrocarbon field to continuously update the reservoir model to optimize production efficiency while ensuring well integrity on a field level.

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(54) **Title**: MULTI-PARAMETER OPTICAL FIBER SENSING FOR RESERVOIR COMPACTION ENGINEERING

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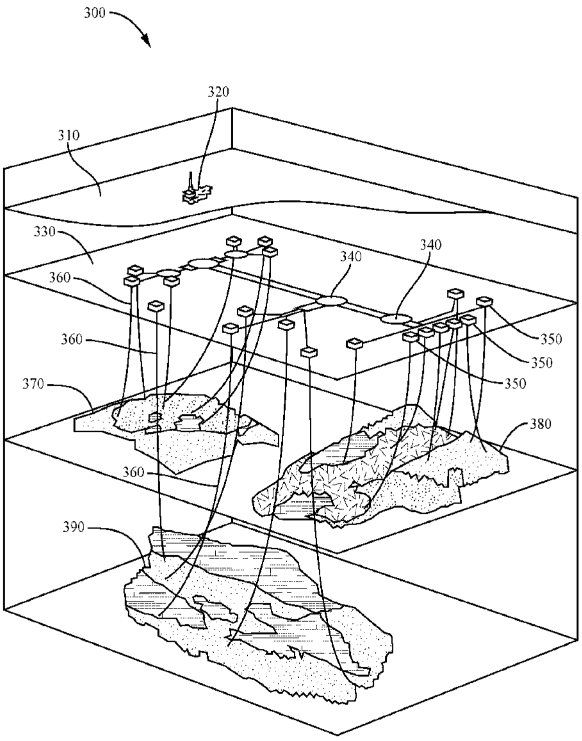

FIG 3

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Title

Multi-Parameter Optical Fiber Sensing for Reservoir Compaction Engineering

Background

This disclosure relates generally to the monitoring of reservoir parameters to anticipate compaction/subsidence on a field level using multi-parameter distributed sensing in multiple wells in a field.

Fiber optic distributed sensing systems were developed in the 1980s to replace older measurement systems composed of multiple individual sensors.

Fiber optic distributed sensing systems are often based on Optical Time-Domain Reflectometry (OTDR) and utilizes techniques originally derived from telecommunications cable testing. Today fiber optic distributed sensing systems provides a cost-effective way of obtaining hundreds, or even thousands, of highly accurate, high-resolution measurements and today find widespread acceptance in industries such as oil and gas, electrical power, and process control.

Subsidence and compaction are two related but distinct processes that can be significant issues in oil and gas reservoirs. There are several well-known cases in the oil and gas industries. Goose Creek field south of Houston was one of the first that received intense study. Subsidence over that field was first noticed in 1918, eventually reaching more than 3 ft [0.9 m] and submerging of the field. The Wilmington field in California, USA, several fields at Lake Maracaibo in Venezuela, and the Groningen field in The Netherlands all had noticeable subsidence that required remediation because the surface above the reservoirs was at or near sea level. The chalk fields in the Norwegian North Sea, notably Ekofisk, Eldfisk and Valhall fields, have compacted, and the resulting subsidence at the mudline generated concern for platform safety. Low-strength carbonate reservoirs in Northwest Java field, Indonesia, and fields offshore Sarawak, Malaysia, have also experienced significant subsidence. The Belridge field in California and neighboring diatomite fields subsided and had numerous well failures.

It is common to use various Enhanced Oil Recovery (EOR) methods to optimize hydrocarbon production, and water flooding is often used to sweep oil and re-pressurize reservoirs. Water saturated chalk compaction strength is lower compared with oil saturated compaction strength, so it is important to understand water front movement in reservoirs from a compaction perspective and also from an ultimate recovery perspective.

There is a need then for deeper insights into the phenomena associated with compaction and subsidence in order to update predictive reservoir models and control or optimize sweep efficiency while ensuring well integrity on a field level.

Summary

In accordance with a general aspect, there is provided a method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi-well hydrocarbon field to continuously update the reservoir model, comprising: a. deploying multi-parameter sensing cables downhole in the wells; b. collecting temperature, strain, acoustic, pressure, and electromagnetic data from the multi-parameter sensing cables; c. collecting micro-deformation data from tilt meters, and/or global positioning satellite and/or Interferometric Synthetic Aperture Radar (InSAR) satellite data; d. analyzing the collected data for fluid movement near the wellbores of the wells; e. using the fluid movement results to update the reservoir compaction and subsidence model; f. calibrating the reservoir compaction and subsidence model against measured strain data; g. updating the reservoir compaction and subsidence model to predict subsidence; and h. updating the production and injection rates in the field to mitigate subsidence as needed.

In accordance with another aspect, there is provided a distributed multi-parameter fiber optic sensing cable enclosed within a cable sheath for simultaneous monitoring of multiple parameters of interest in sub-surface wells comprising: a. multiple fiber optic cables within the sheath; b. some of the multiple fiber optic cables comprising an internal optical fiber surrounded by a fiber cladding material, then a hermetic coating, with an outer coating of a polymeric material; c. wherein the multiple fiber optic cables within the sheath are surrounded by a suitable strain coupling filler material and tightly coupled within the sheath for proper strain transfer.

In accordance with a further aspect, there is provided a distributed multi-parameter fiber optic sensing cable enclosed within a cable sheath for simultaneous monitoring of multiple parameters of interest in sub-surface wells comprising: a. multiple fiber optic cables within the sheath; b. some of the multiple fiber optic cables comprising an internal optical fiber surrounded by a fiber cladding material, with an outer coating of a magnetostrictive material; c. wherein the multiple fiber optic cables within the sheath are surrounded by a suitable strain coupling filler material and tightly coupled within the sheath for proper strain transfer.

Brief Description of the Drawings

Figure 1 illustrates a process flow for monitoring and mitigating subsidence in a field.

Figure 2 illustrates a simple description of fields where the proposal of this application can be used.

Figure 3 illustrates a more complex image of multiple reservoirs where production and injection can be monitored and production rates can be used to mitigate subsidence that could impact seafloor infrastructure including flow lines and pipelines.

Figure 4 illustrates two examples of optical fiber as described in this application.

Figure 5 illustrates another example of a cable construction using multi-parameter optical fibers as described in this application.

Detailed Description

In the following detailed description, reference is made to accompanying drawings that illustrate embodiments of the present disclosure. These embodiments are described in sufficient detail to enable a person of ordinary skill in the art to practice the disclosure without undue experimentation. It should be understood, however, that the embodiments and examples described herein are given by way of illustration only, and not by way of limitation. Various substitutions, modifications, additions, and rearrangements may be made without departing from the spirit of the present disclosure. Therefore, the description that follows is not to be taken in a limited sense, and the scope of the present disclosure will be defined only by the final claims.

The description herein proposes to create a compaction and subsidence model as part of a field development plan and deploy multi-parameter sensing cables and micro-deformation sensors into the field wells as they are drilled and completed, and use them to monitor multiple simultaneous measurements of:

1. Wellbore strain where a strain sensing cable is coupled to the formation. This will allow a better understanding of compaction forces over time as compaction may shear well casing and tubing.
2. Electro Magnetic (EM) sensing for monitoring water flood front movement. Reservoir compaction can then be anticipated before the water front reaches the wellbore and reduces the formation strength around the well. The information from the EM sensors can also be used to change settings of various inflow devices and thereby slow down the approaching water flood front.
3. Distributed Acoustic Sensing (DAS) can be used for 3D/4D seismic profiling and monitor pore pressure changes as water flood fronts

move. DAS can also be used to monitor production in production wells as well as injection profiles in water injection wells.

4. Distributed Temperature Sensing (DTS) to monitor production in production wells as well as injection profiles in water injection wells. A good understanding of what reservoir layers take injected water can then be used to update reservoir models and predict areas of compaction. A correlation to production zones may also indicate communication between reservoir layers.
5. Pressure measurements which can be used to understand communication between wells, and can also be used for pressure build-up tests and to control maximum injection pressure.
6. Micro-deformation sensors like tilt meters may also be used to enhance the system and monitor subsidence above the reservoir and/or small changes to the well-bore deviation.

The multi-parameter cables can be deployed in both vertical and horizontal wells across a given field to monitor reservoir properties related to subsidence.

Referring to Figure 1 the process flow for monitoring and mitigating subsidence in a field can be described beginning in step **110** in which the overall field development plan, including the well locations is used to develop an initial reservoir compaction and subsidence model. As the wells are drilled the multi-parameter sensing cables and micro-deformation sensors are deployed **120** in each of the wells. As production begins the numerous temperature, strain, acoustic, and electromagnetic data is collected **130** and micro-deformation data is collected **140** from tilt meters and/or global positioning satellite (GPS) and/or Interferometric Synthetic Aperture Radar (InSAR) satellite data. Fluid movements are characterized **150** near each of the well bores from each region of the reservoir. This new information is used to then update **160** the reservoir model; the reservoir compaction model is then calibrated with the measured strain data **170** and the updated compaction model is then used to predict **180** subsidence. Finally **190** this information is used to modify both the production and water injection rates in the field development plan to optimize the overall reservoir performance while minimizing the longer-term deleterious effects of compaction and subsidence.

A good understanding of where injection fluids go, where produced fluids come from, and if any of the injected fluids reach producing wells as well as where in the producer wells injected fluids enter combined with far field 3D/4D seismic data and near well bore/far field EM measurements to understand fluid migration will enable the field owner to update reservoir models and anticipate subsidence. This model can then be calibrated with strain data measured in the wellbore, and proactive measures used to minimize the impact of subsidence can then be monitored and controlled.

The reservoir compaction and subsidence model described herein is a complex multivariable computer program model that has instructions that can be carried out on any general purpose computing device that includes but is not limited to circuitry and/or programming for effecting the herein-referenced method aspects; the circuitry and/or programming can be virtually any combination of hardware, software, and/or firmware configured to effect the herein-referenced method aspects depending upon the design choices of the system designer. The general purpose computing device will be referred to herein as a computer device.

The multi-parameter cable can be used for continuous production logging even after compaction starts to deform wellbores whereas conventional through-tubing production logs may not be able to pass through a partially collapsed and/or buckled tubing.

Reservoir compaction is also very common in certain deepwater reservoirs in the Gulf of Mexico which are initially geo pressured to the point where pore pressure supports much of the over burden. These reservoirs initially have very high porosity and permeability, but as pressure depletes, sand grain shifting can result in significant losses in porosity (from as much as 39% to as approximately 25% due to grain shifting) and an associated loss in the effective permeability to oil. The effective permeability to oil is governed by both porosity and water saturation in this case and both change as a result of reservoir compaction of this type. In this situation the initial rock wettability is usually to water, so as oil is produced from the pore space and the reservoir compacts, the bulk volume water on the surface of the sand grains will tend to stay the same and as a result, the water saturation increases significantly when porosity is reduced. The result is a very significant loss in the effective permeability to oil, potentially in the range of 90% loss. Vertical wells or near vertical wells can be highly susceptible to wellbore failure due to compaction in this environment and different means of monitoring compaction have been deployed such as insertion of radioactive tags at each casing joint collar followed by routine logging to measure the change in distance between these points in time and in some cases even sonic image logging to monitor casing deformation over time due to strain and buckling. Both of these solutions require well intervention activities that result in shut-in production on a platform and can have significant cost, especially in an environment where sub-sea wellheads are utilized. Highly deviated or horizontal wells are usually much less susceptible to failure due to reservoir compaction because the wellbore is only exposed to a very small portion of the reservoir in the vertical plane. In this environment, however, non-uniform compaction can be a problem if shale layers are encountered that will not compact. Pipe bending and kinking above or below these interfaces can also pose wellbore integrity issues.

With the use of water injection in many of these reservoirs, the wellbore integrity issues can be compounded by formation fines migration and associated formation plugging and sand production. This can also severely impact well integrity. Water injection wells are also highly subject to failures in this environment due to a host of issues, but often resulting from significant cross flow from high pressured reservoir sections into lower pressured reservoir sections resulting in erosion of the completion, solids production and fill accumulating in the wellbore.

Continuous monitoring of both flow and compaction would enable means of preventing these problems to be deployed early to minimize the well integrity issues and reduce intervention requirements.

Figure 2, shown generally as the numeral **200**, represents a simplified description of possible applications of this methodology. The sensing cables to be described can be deployed in multiple wells and additional micro-deformation sensors can be added. The approach can be used on the sea floor (offshore) or on the surface (onshore). Onshore a production well **240** located on a land surface **210** is extracting hydrocarbons from a deep formation that may have multiple horizontal hydraulic fractures **250**. Nearby a water injection well **220** is used to inject a water flood **230** that drives hydrocarbons toward the production well **240**. Offshore a production platform **260** can be extracting hydrocarbons from a different formation separated by a fault line **255**. An injection well **280** located offshore is creating a water flood **290** for driving hydrocarbons toward production platform **260**. As production progresses and the detection of compaction appears the relative rates of production and water flooding are then varied to minimize the risk of equipment failures due to the stresses of compaction and subsidence. As a general rule as compaction is detected production flow is decreased and water floods increased.

A more complex illustration of possible offshore applications is shown in Figure 3, generally represented by the numeral **300**. In this multilevel representation the sea surface **310** has a production platform **320** connected (not shown) via multiple subsea manifolds **340** to multiple subsea wellheads **350** on the seafloor **330**. These well heads have been drilled further and are thus connected **360** into various rock formations **370**, **380**, **390** for hydrocarbon extraction. Each formation can have multiple geologic structures, with different porosities so that each will have different production performance. In addition compaction and subsidence will vary across the formations during production.

Multi-Parameter Sensing

Deployment of multi-parameter single point sensing systems in wells as single point sensors require cables to be cut at every point where a sensor is inserted. This drives manufacturing complexity, cost and reliability as well as large humps at every point where the single point sensor is inserted. Spooling and handling these single point sensor cables can be complex. The other option is to run multiple cables, one for each individual sensor cable, and that once again drives cost and complexity. Having cables with big sensor lumps or clusters at points along a cable drives deployment complexity as cable stand-offs and centralizers are required to protect the sensors from damage during installation into the bore hole. Dedicated sensor mandrels may also be required and this further drives the cost and complexity. A larger diameter wellbore may also be required to accommodate the larger OD single point sensors, so bore hole stability concerns become important and cost increases significantly when a larger wellbore must be drilled and completed.

The proposal described herein is a distributed multi-parameter fiber optic sensing cable capable of monitoring several parameters of interest in subsurface wells, and in particular subsurface wells related to hydrocarbon production. The cable will be a truly distributed cable with a uniform tubular structure that can easily be cabled and deployed. The preferred size of the tubular cable would be in the range of 1/8"-1/4" where the fibers are tightly coupled to the tubular cable. The cable should be capable of monitoring several or all of the following parameters:

1. Wellbore strain where a strain sensing cable is coupled to the formation. Knowledge of wellbore strain can be used understand compaction related issues where tubulars may buckle, collapse or shear. Wellbore strain can also be used to detect fracture initiation points as the formation opens up when the rock splits open. Strain can also be used to measure frac propagation direction and magnitude from a well being fractured towards a neighboring well instrumented with a strain sensing cable. The strain sensing system may be based upon one or more of several measurement principles like e.g. Brillouin, Rayleigh, Fiber Bragg Gratings or interferometric sensors based on Fabry Perot, Michelson or Mach-Zehnder principles etc. The cable would be a tubular cable of around ¼" OD with good strain coupling from the outer boundary of the cable to the strain sensing fiber(s).

2. Electro Magnetic (EM) sensing for monitoring formation resistivity. Various fluids have different resistivity, and monitoring resistivity can provide an enhanced understanding of subsurface properties related to Hydrocarbon production in sub-surface wells. The EM measurements may be near wellbore measurements when combined with in-well EM emitting sources or far field monitoring when combined with surface/ocean floor/neighboring well emitting sources.

3. Distributed Acoustic Sensing (DAS) based on coherent Rayleigh

scattering can be used for 3D/4D seismic profiling and monitor pore pressure changes as water flood fronts move. DAS can also be used to monitor production in production wells as well as injection profiles in water injection wells. The cable would use a dedicated fiber for monitoring acoustic energy or share a fiber with the EM sensing and/or strain sensing fibers where each of the systems operate at different optical frequencies. The DAS system may use multiple lasers and utilize multiple fibers for monitoring acoustic energy as an option or maximize Signal to Noise Ratio (SNR) in the system. The system may include Fabry-Perot based quasi-distributed sensing systems where the cable may have a fiber with Fiber Bragg Gratings (FBGs) where one or multiple pairs of FBGs form Fabry- Perot cavities with enhanced acoustic sensitivity when compared with Rayleigh based DAS systems.

4. Distributed Temperature Sensing (DTS) can be used to monitor production in production wells as well as injection profiles in water injection wells. A good understanding of what reservoir layers take injected water can then be used to update reservoir models, and DTS data can also be used to calculate how much frac fluid has entered any given perforation or fracture initiation point. The cable would include single and/or multi- mode fibers for DTS, and the system would preferably use a dual wavelength DTS capable of mitigating hydrogen and/or cable manufacturing related optical attenuation.

5. Pressure measurements are useful to understand communication between wells, and can also be used for pressure build-up tests. A pressure/temperature sensor can be placed at the distal end of the cable. Pressure measurements can also be used to monitor and keep injection pressures within desired ranges and also monitor reservoir pressure in production wells.

Figure 4 illustrates two examples of optical fibers as described in this application. In the top illustration of Figure 4 the fiber core **410** is surrounded by a fiber cladding **420**, and then a hermetic coating **430**. The outer coating is a polymeric coating **440**.

In the bottom illustration of Figure 4 an alternative example is a fiber core **450** surrounded by a fiber cladding **460** and a magnetostrictive coating **470**.

Figure 5 is an illustration of a possible cable construction (multiple optical fibers) as described herein. Multiple optical fibers **510** are surrounded by a suitable strain coupling filler material **520** with the entire cable enclosed in a cable sheath **530**.

Many prior art cables used for distributed fiber optic sensing are gel filled loose tube cables with strain isolated fibers floating in the gel. The proposed configuration shown in Figure 5 is aimed at creating a cable where the fibers are tightly coupled in the cable for proper strain transfer. This approach can lead to a reduction in cost and risk and ease deployment while enabling new sensing solutions in the field.

Although certain embodiments and their advantages have been described herein in detail, it should be understood that various changes, substitutions and alterations could be made without departing from the coverage as defined by the appended claims. Moreover, the potential applications of the disclosed techniques is not intended to be limited to the particular embodiments of the processes, machines, manufactures, means, methods and steps described herein. As a person of ordinary skill in the art will readily appreciate from this disclosure, other processes, machines, manufactures, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufactures, means, methods or steps.

Claims

1. A method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi-well hydrocarbon field to continuously update the reservoir model, comprising:
    a. deploying multi-parameter sensing cables downhole in the wells;
    b. collecting temperature, strain, acoustic, pressure, and electromagnetic data from the multi-parameter sensing cables;
    c. collecting micro-deformation data from tilt meters, and/or global positioning satellite and/or Interferometric Synthetic Aperture Radar (InSAR) satellite data;
    d. analyzing the collected data for fluid movement near the wellbores of the wells;
    e. using the fluid movement results to update the reservoir compaction and subsidence model;
    f. calibrating the reservoir compaction and subsidence model against measured strain data;
    g. updating the reservoir compaction and subsidence model to predict subsidence; and
    h. updating the production and injection rates in the field to mitigate subsidence as needed.
2. The method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi-well hydrocarbon field to continuously update the reservoir compaction and subsidence model of claim 1 wherein the reservoir compaction and subsidence model including an overall field and well plan is first developed.
3. The method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a

multi-well hydrocarbon field to continuously update the reservoir compaction and subsidence model of claim 2 wherein the planned wells are drilled based on the overall field and well plan.

4. The method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi-well hydrocarbon field to continuously update the reservoir model, of claim 1 wherein the multi-parameter sensing cables comprise multiple fiber optic fibers, each surrounded by fiber cladding and a coating, with the multiple fiber optic fibers enclosed by a cable sheath to form the sensing cable.

5. The method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi-well hydrocarbon field to continuously update the reservoir model, of claim 1 wherein the multi-parameter sensing cables comprise electromagnetic sensing for monitoring water flood front movement.

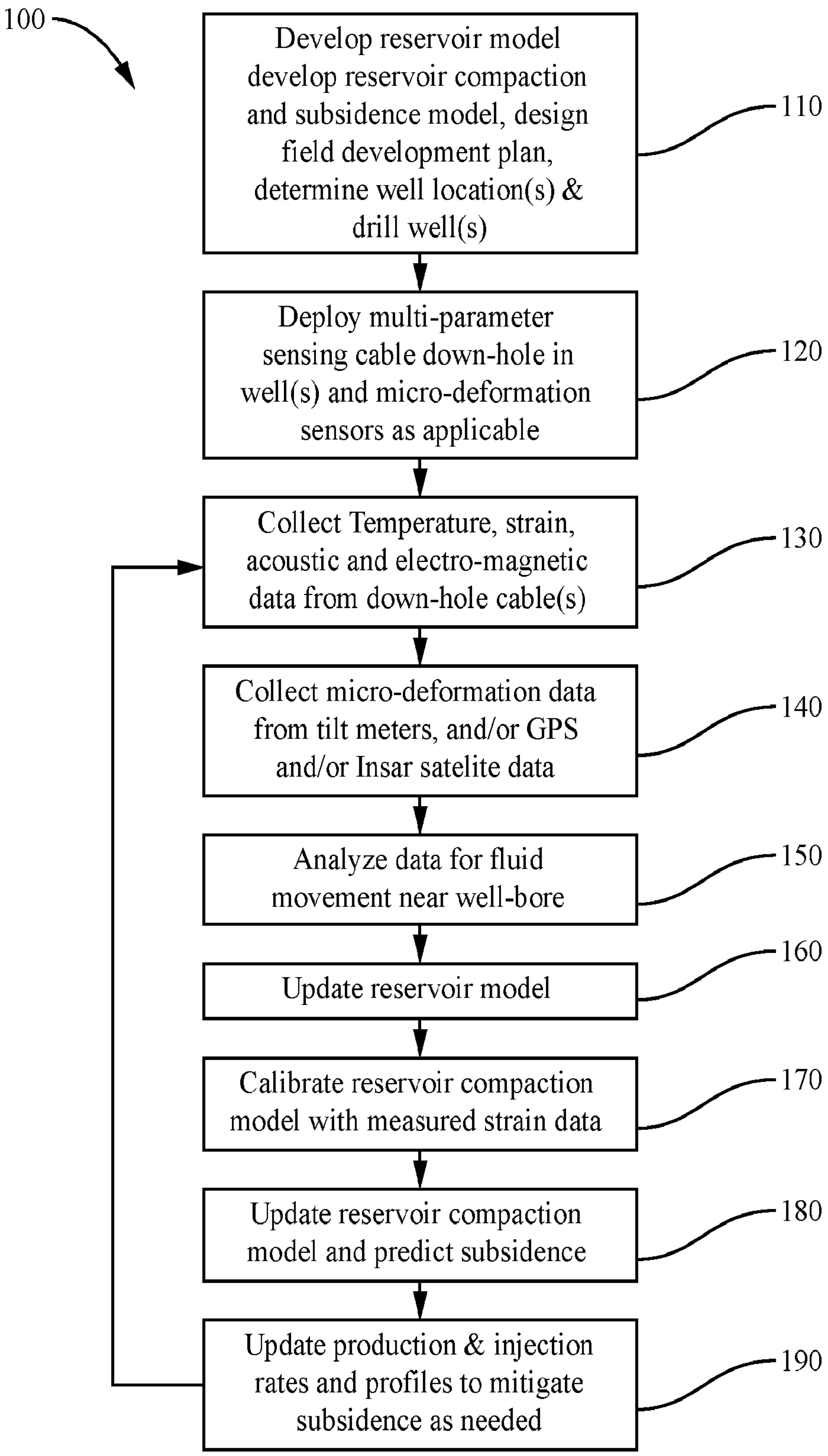
6. The method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi-well hydrocarbon field to continuously update the reservoir model, of claim 1 wherein Distributed Acoustic Sensing (DAS) can be used for 3D/4D seismic profiling and to monitor pore pressure changes as water flood fronts move, monitor production in production wells, and monitor injection profiles in water injection wells.

7. The method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi-well hydrocarbon field to continuously update the reservoir model, of claim 1 wherein Distributed Temperature Sensing (DTS) can be used to monitor production in production wells and injection profiles in water injection wells.

8. The method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi-well hydrocarbon field to continuously update the reservoir

model, of claim 1 wherein wellbore strain sensing cables are coupled to the formation to monitor compaction forces over time.

9. The method for utilizing multi-parameter fiber optic sensing cables in conjunction with a reservoir compaction and subsidence model of a multi-well hydrocarbon field to continuously update the reservoir model, of claim 1 wherein pressure measurements are used to understand communication between wells, and to control maximum injection pressure.
10. A distributed multi-parameter fiber optic sensing cable enclosed within a cable sheath for simultaneous monitoring of multiple parameters of interest in sub-surface wells comprising:
    a. multiple fiber optic cables within the sheath;
    b. some of the multiple fiber optic cables comprising an internal optical fiber surrounded by a fiber cladding material, then a hermetic coating, with an outer coating of a polymeric material;
    c. wherein the multiple fiber optic cables within the sheath are surrounded by a suitable strain coupling filler material and tightly coupled within the sheath for proper strain transfer.
11. A distributed multi-parameter fiber optic sensing cable enclosed within a cable sheath for simultaneous monitoring of multiple parameters of interest in sub-surface wells comprising:
    a. multiple fiber optic cables within the sheath;
    b. some of the multiple fiber optic cables comprising an internal optical fiber surrounded by a fiber cladding material, with an outer coating of a magnetostrictive material;
    c. wherein the multiple fiber optic cables within the sheath are surrounded by a suitable strain coupling filler material and tightly coupled within the sheath for proper strain transfer.


100
Develop reservoir model develop reservoir compaction and subsidence model, design field development plan, determine well location(s) & drill well(s)
110
Deploy multi-parameter sensing cable down-hole in well(s) and micro-deformation sensors as applicable
120
Collect Temperature, strain, acoustic and electro-magnetic data from down-hole cable(s)
130
Collect micro-deformation data from tilt meters, and/or GPS and/or Insar satelite data
140
Analyze data for fluid movement near well-bore
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Update reservoir model
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Calibrate reservoir compaction model with measured strain data
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Update reservoir compaction model and predict subsidence
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Update production & injection rates and profiles to mitigate subsidence as needed
190

FIG 1

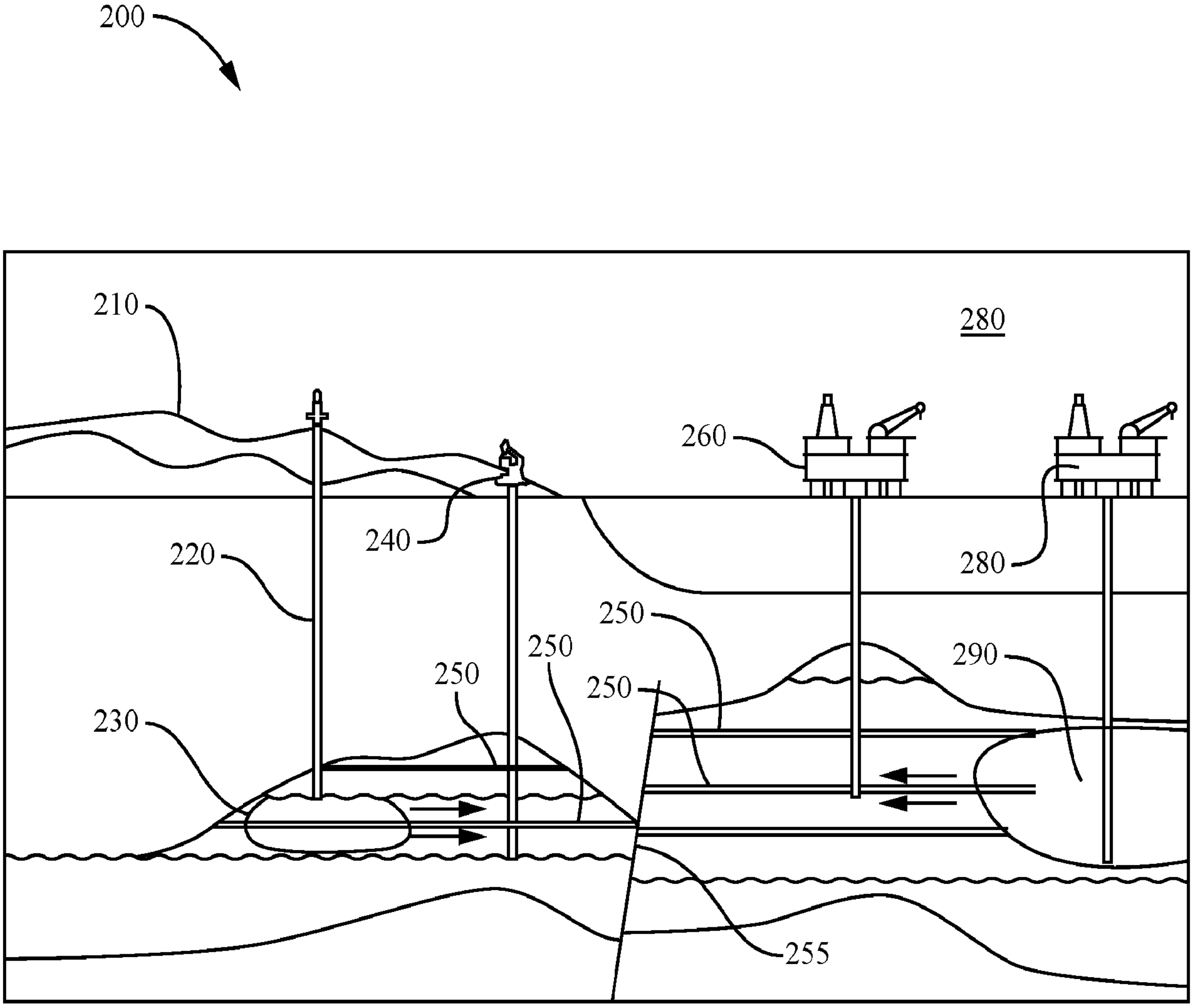


FIG 2

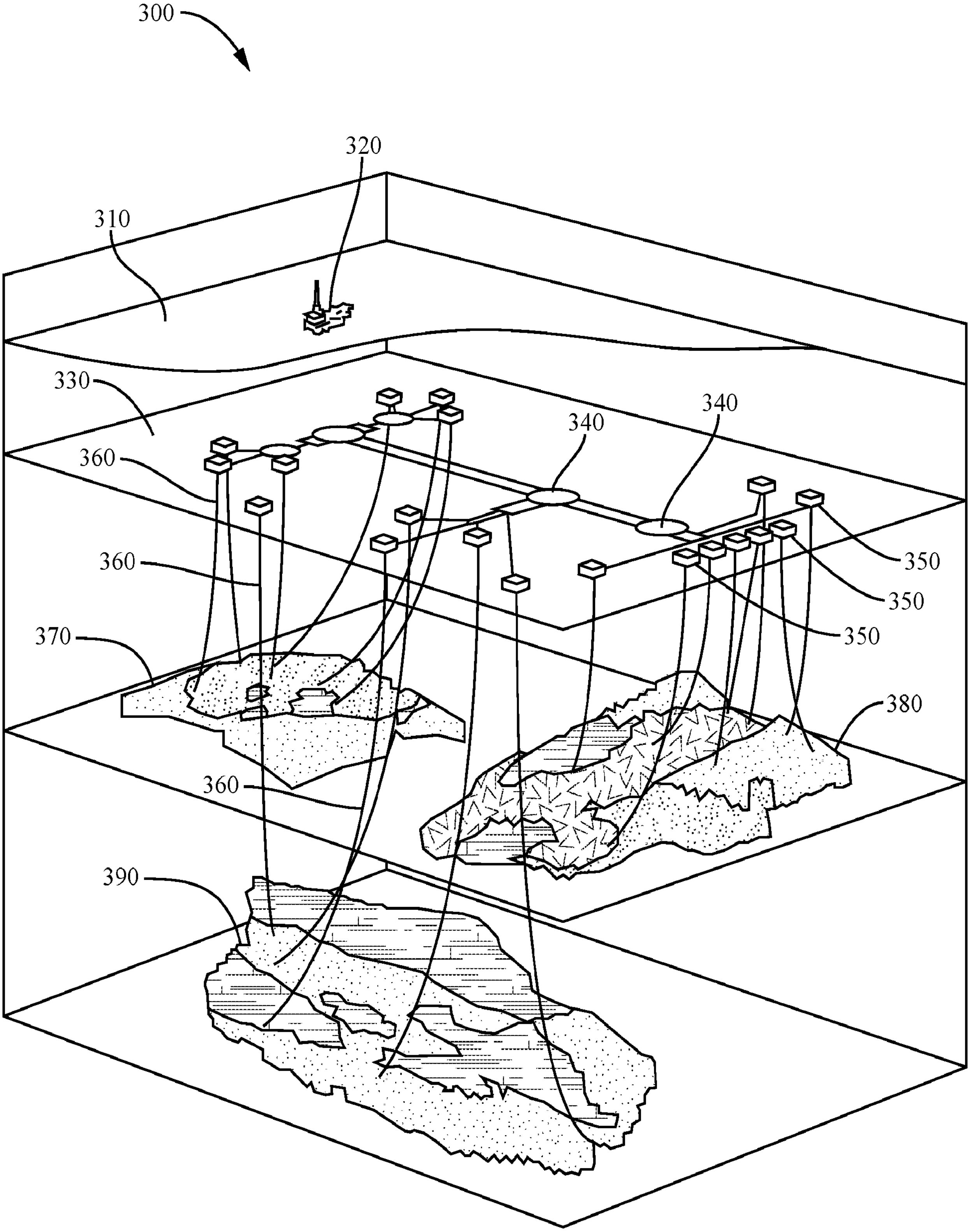


FIG 3

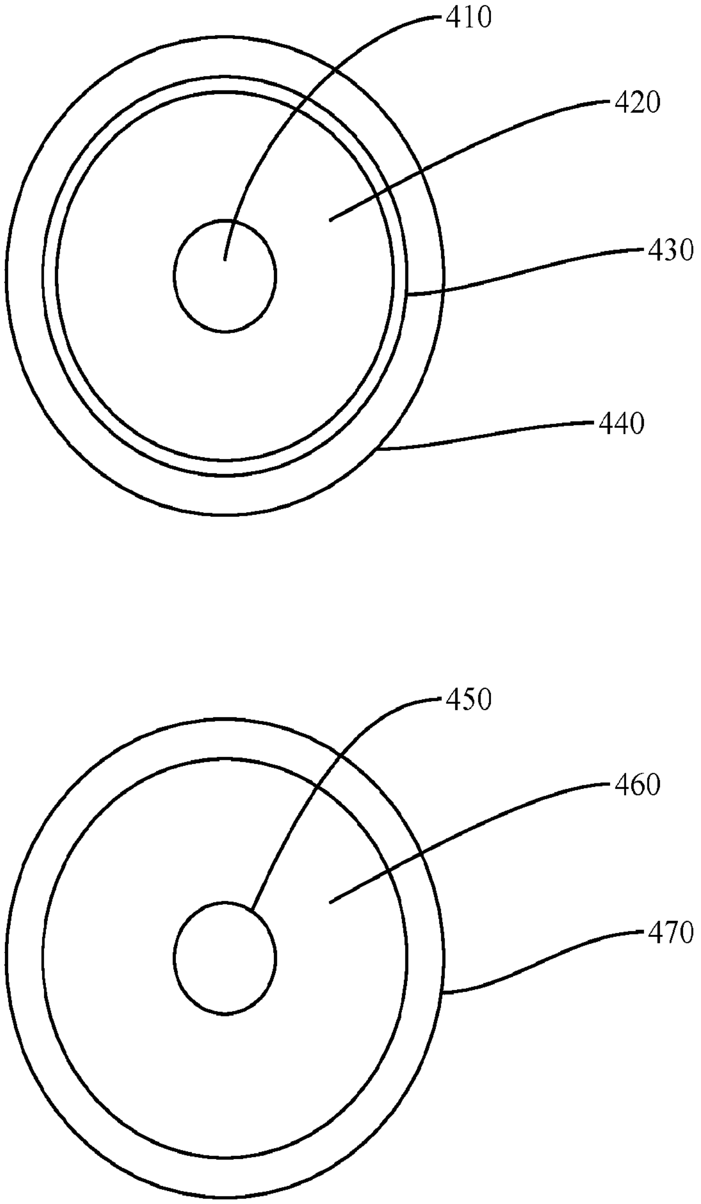


FIG 4

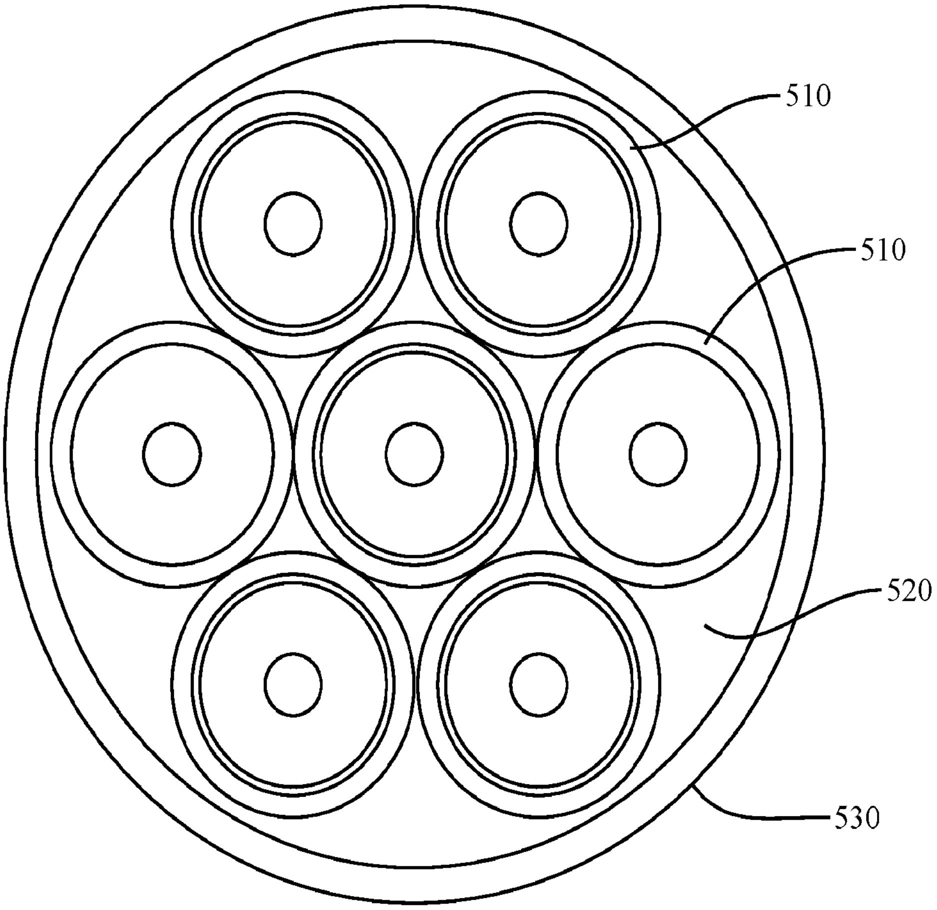
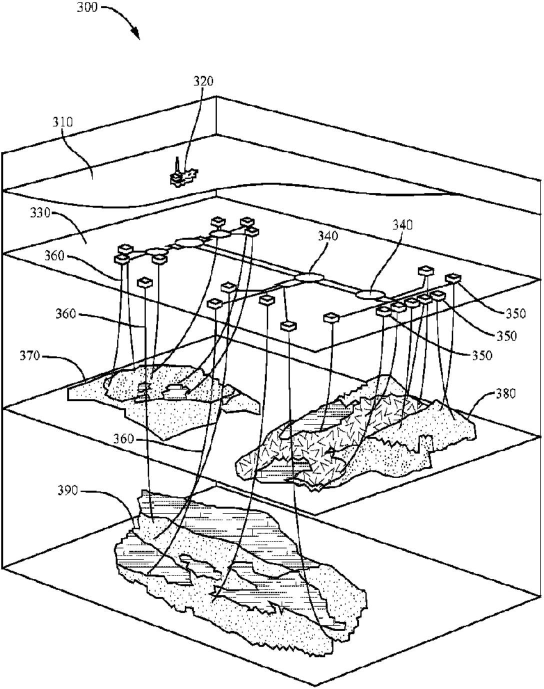


FIG 5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