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(54) **ELECTROMAGNETIC IMAGING OF PROPPANT IN INDUCED FRACTURES**

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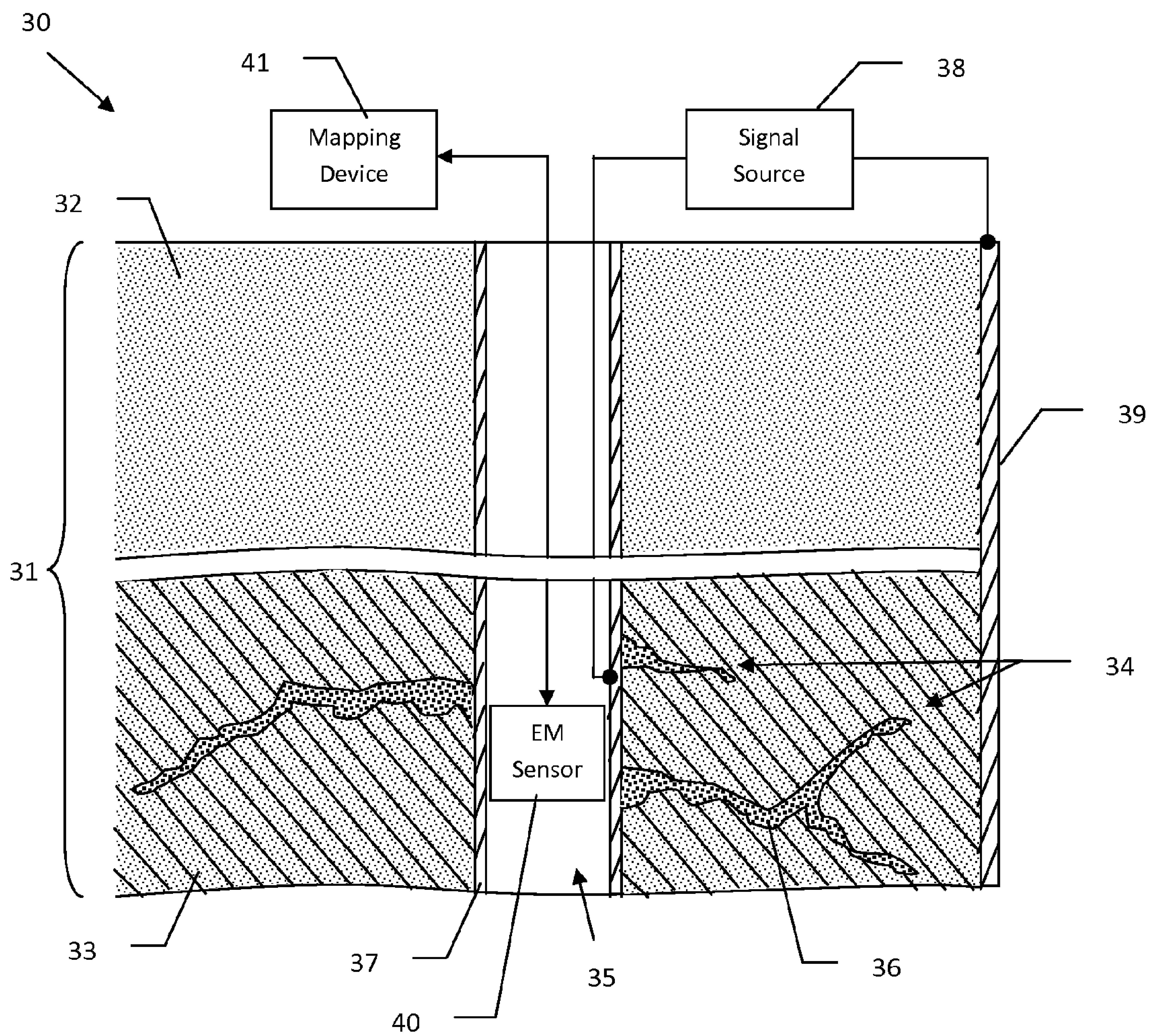
(57) **ABSTRACT**

A method may include forming a borehole in a subterranean formation, lining at least part of the borehole with an electrically conductive casing, and injecting a fracturing fluid, a proppant, and a sensing additive into the borehole to form a propped fracture pattern. The method may further include driving the electrically conductive casing so that the sensing additive generates an electromagnetic (EM) field, sensing the EM field, and mapping the propped fracture pattern based upon the sensed EM field.



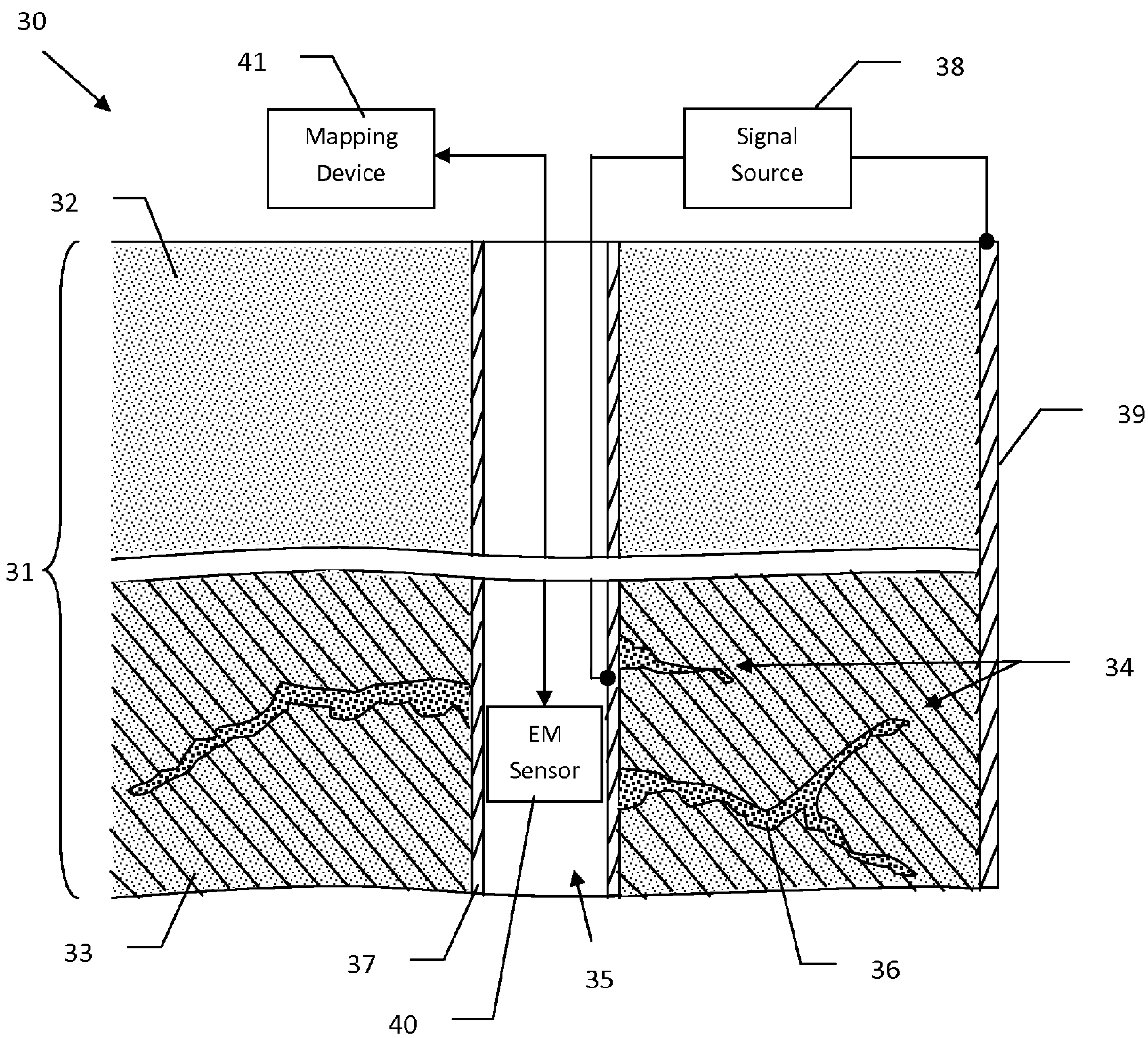

30
41
Mapping Device
Signal Source
38
32
39
31
34
EM Sensor
33
37
35
36
40

FIG. 1

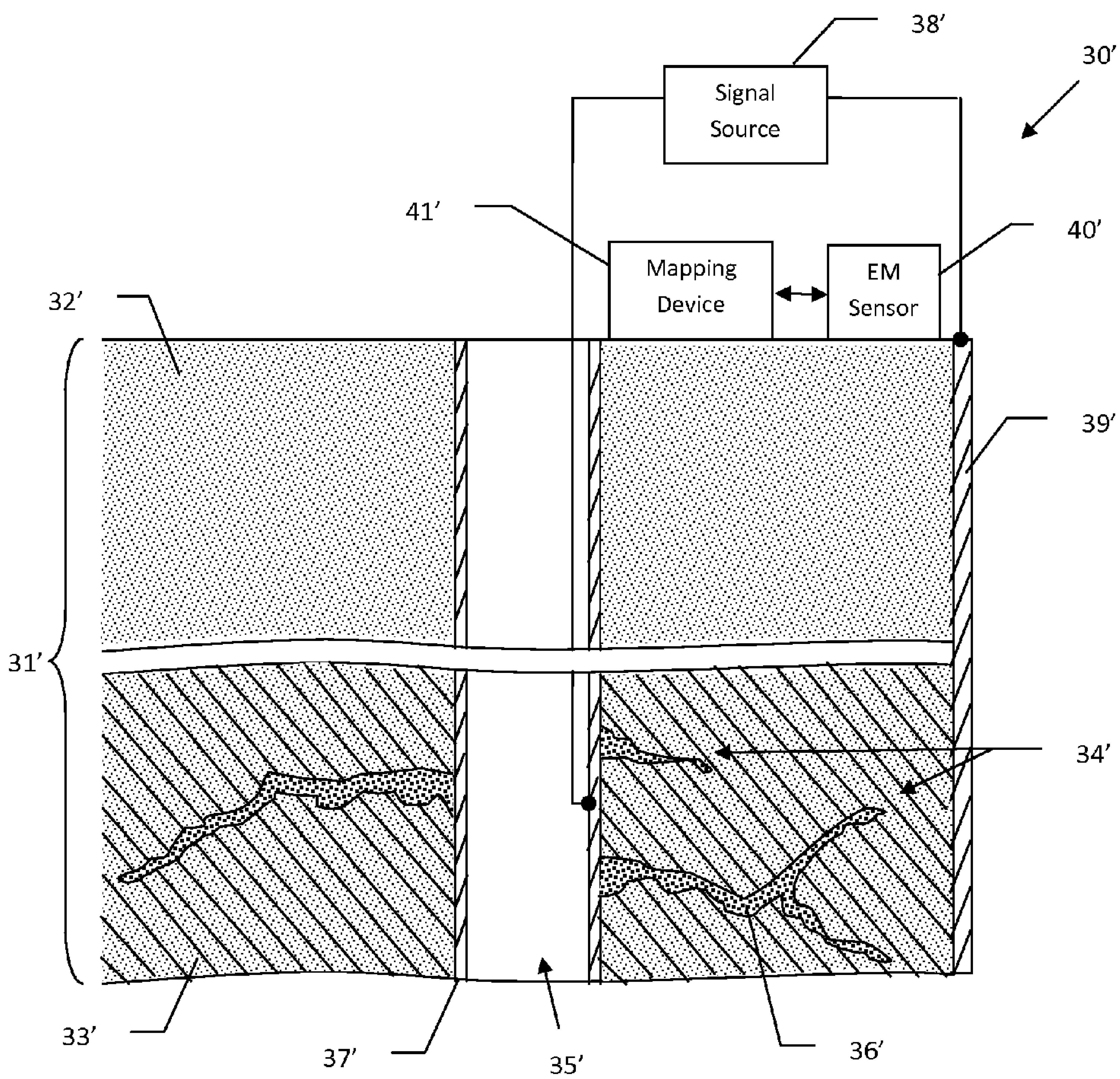

38′
30′
Signal
Source
41′
Mapping
Device
EM
Sensor
40′
32′
39′
31′
34′
33′
37′
35′
36′

FIG. 2

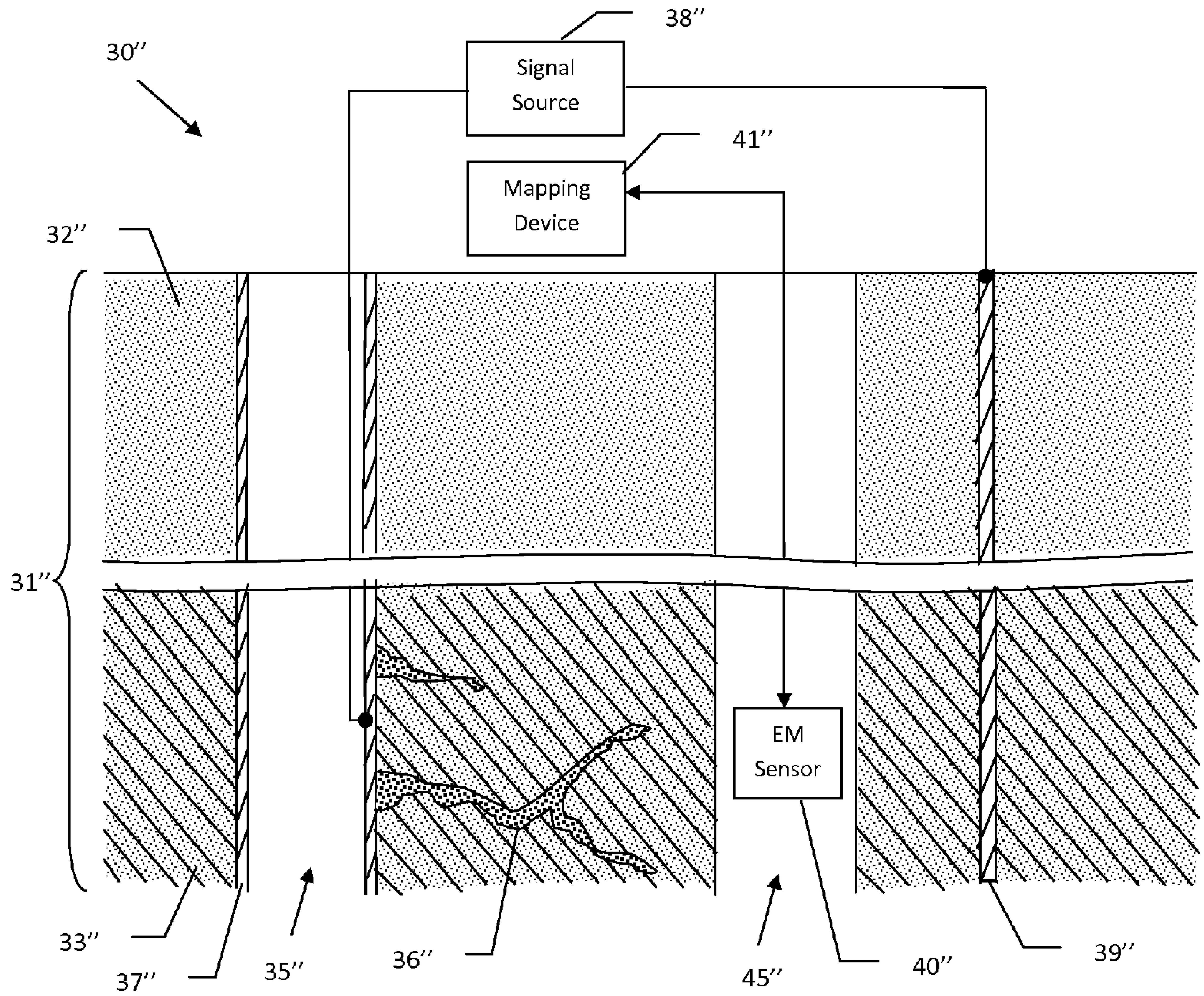

30''
38''
Signal Source
41''
Mapping Device
32''
31''
EM Sensor
33''
37''
35''
36''
45''
40''
39''

FIG. 3

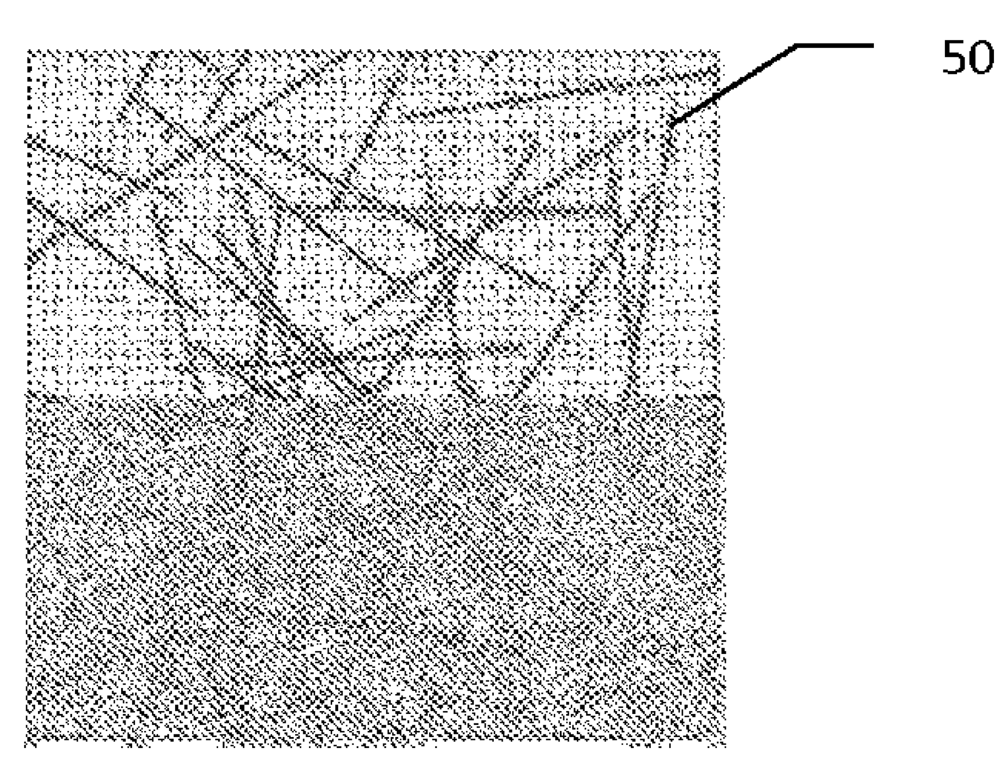

50

FIG. 4

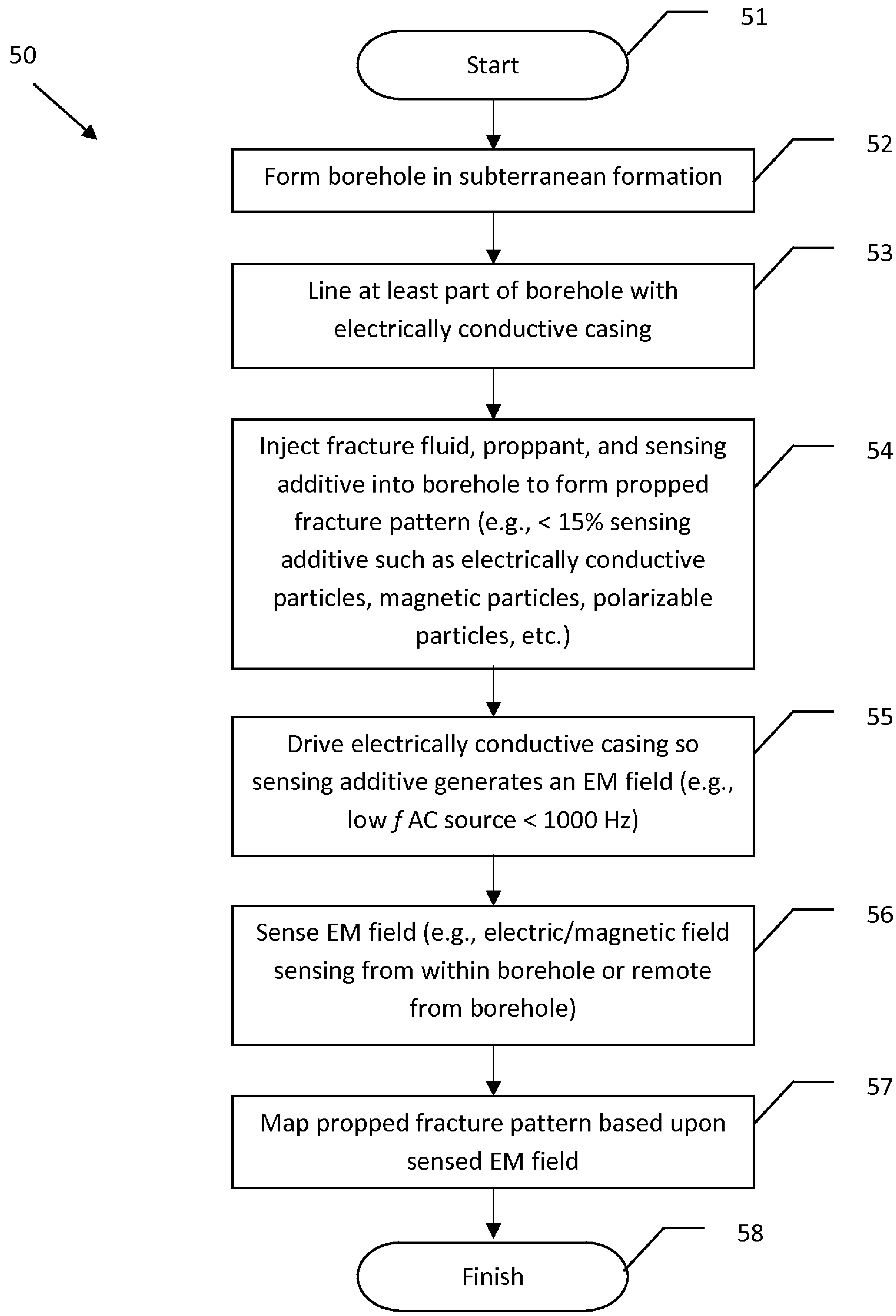

50
51
Start
52
Form borehole in subterranean formation
53
Line at least part of borehole with electrically conductive casing
54
Inject fracture fluid, proppant, and sensing additive into borehole to form propped fracture pattern (e.g., < 15% sensing additive such as electrically conductive particles, magnetic particles, polarizable particles, etc.)
55
Drive electrically conductive casing so sensing additive generates an EM field (e.g., low f AC source < 1000 Hz)
56
Sense EM field (e.g., electric/magnetic field sensing from within borehole or remote from borehole)
57
Map propped fracture pattern based upon sensed EM field
58
Finish

FIG. 5

ELECTROMAGNETIC IMAGING OF PROPPANT IN INDUCED FRACTURES

BACKGROUND

[0001] Hydraulic fracturing, which is also known as "fracking", is a technique used to release a hydrocarbon resource such as oil or natural gas from a subterranean rock formation. During the fracking process, a wellbore is drilled through the top surface layers down to the rock formation where the hydrocarbon resource is located. A hydraulic fluid is then introduced into the wellbore and pressurize to create cracks or fractures through the rock formation, through which the hydrocarbon resource may be extracted through the wellbore.

[0002] To maintain a desired fracture width and help keep the fractures open (or slow their rate of closing), a proppant may be injected into fractures. More particularly, materials such as grains of sand, ceramics, or other particulates are used as proppants to help prevent the fractures from closing when the injection is stopped and the pressure of the fluid is reduced. Different types of proppants may be selected for different depths, since at deeper depths the pressure and stresses on fractures are higher. The propped fractures are sufficiently permeable to allow the flow of the hydrocarbon resource to the wellbore, as well as other fluids that may be introduced into the wellbore during the drilling or fracturing process.

SUMMARY

[0003] This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

[0004] A method is provided herein which may include forming a borehole in a subterranean formation, lining at least part of the borehole with an electrically conductive casing, and injecting a fracturing fluid, a proppant, and a sensing additive into the borehole to form a propped fracture pattern. The method may further include driving the electrically conductive casing so that the sensing additive generates an electromagnetic (EM) field, sensing the EM field, and mapping the propped fracture pattern based upon the sensed EM field.

[0005] A related method is for mapping a propped fracture pattern adjacent a borehole in a subterranean formation, where an electrically conductive casing lines at least part of the borehole, and the propped fracture pattern includes a sensing additive. The method may include driving the electrically conductive casing so that the sensing additive generates an EM field, sensing the EM field, and mapping the propped fracture pattern based upon the sensed EM field.

[0006] A related apparatus may include an electrically conductive casing within a borehole of a subterranean formation having a proppant and a sensing additive within a propped fracture pattern adjacent the borehole. The apparatus may further include a signal source to drive the electrically conductive casing so that the sensing additive generates an EM field (e.g., a secondary EM field), at least one sensor to sense the EM field, and a mapping device coupled to the at least one sensor to map the propped fracture pattern based upon the sensed EM field.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** is a schematic block diagram of an example embodiment of an apparatus for mapping induced fracture patterns in a subterranean formation.

[0008] FIG. **2** is a schematic block diagram of another example embodiment of an apparatus for mapping induced fracture patterns in a subterranean formation.

[0009] FIG. **3** is a schematic block diagram of still another example embodiment of an apparatus for mapping induced fracture patterns in a subterranean formation.

[0010] FIG. **4** is an enlarged view of an example imaging additive for use with the systems of FIGS. **1-3**.

[0011] FIG. **5** is a flow diagram illustrating various fracture pattern mapping method aspects.

DETAILED DESCRIPTION

[0012] The present description is made with reference to the accompanying drawings, in which example embodiments are shown. However, many different embodiments may be used, and thus the description should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete. Like numbers refer to like elements throughout, and prime and multiple prime notation are used to indicate similar elements in different embodiments.

[0013] Referring initially to FIGS. **1** and **5**, an apparatus **30** for imaging an induced fracture pattern in a subterranean formation **31** and related method aspects are first described. A wellbore **35** extends into the subterranean formation **31**, which illustratively includes one or more upper layers **32** (e.g., topsoil, aquifer layer, etc.) and a reservoir layer(s) **33** (e.g., a rock or limestone layer, etc.) where a hydrocarbon resource is located.

[0014] By way of background, induced fractures **34** are being used for developing oil and gas fields in the US and abroad. These fractures **34** provide pathways for fluids (e.g., oil, natural gas, etc.) to flow from the reservoir layers **33** into a wellbore **35** that is drilled into the subterranean formation **31**. The fractures **34** enhance fluid flow in tight, low permeability formations. However, the geometry and characteristics of induced fractures **34** are not always well understood. Of interest to field operators is the determination of what part of the fractured volume has been forced to remain open by an injected proppant **36** within the fractures **34**. A "propped" fracture **34** is considered to represent the portion of the fractured volume that is connecting the reservoir and the wellbore **35**.

[0015] Generally speaking, the apparatus **30** and related method aspects described herein allow for improving the detectability of a propped segment of induced fractures **34** using co-injected contrast or imaging agents or additives, and electromagnetic (EM) methods to image these fractures. The approach involves injecting conductive, dielectric and/or magnetic contrast agents (also referred to as a sensing additive herein) along with proppants such as sand and/or ceramic materials. These contrast agents may be introduced as a mixture with regular proppants, the proppants may be modified to incorporate contrast agents, or a mixture of both may be used. The sensing additive may have similar sizes as the proppant particles so that there is relatively little loss of the proppant/contrast material into the formation. Subsequently, the location and distribution of the sensing additive may be illuminated and interrogated by single well or multi-well EM approaches, as will be discussed further below.

[0016] More particularly, with reference to the flow diagram **50** of FIG. **5**, beginning at Block **51** the borehole **35** is formed (e.g., drilled) in the subterranean formation **31**, at Block **52**, and at least part of the borehole is lined with an electrically conductive casing **37**, at Block **53**. The conductive casing **37** may serve several purposes, such as support during drilling, allowing flowback returns during drilling and cementing of the surface casing, and to help prevent collapse of loose soil near the surface, for example. Typical sizes for a conductive casing may be from about 18 to 30 inches, although other sizes may be used as well. By way of example, the conductive casing **37** may comprise steel, etc.

[0017] After a fracturing fluid is injected into the borehole **35** to induce the fractures **34**, a proppant is injected into the borehole to form a propped fracture pattern, at Block **54**. The fracturing fluid and proppant may be injected through holes in the casing **37**, for example. More particularly, the casing **37** allows the interval in the borehole **35** to be pressure-isolated, and perforations in the casing in the interval of interest allow the fracking fluid and proppant to be introduced at that location. As noted above, the proppant (and/or the fracturing fluid) includes a sensing additive. As a result, the electrically conductive casing **37** may be driven by a signal source **38** so that the sensing additive generates an electromagnetic (EM) field, at Block **55**. That is, the casing **37** essentially provides an antenna to illuminate the sensing additive within the fractures **34**. The EM field generated by the sensing additive may be considered as a total EM field resulting from the primary field from the signal source **38** as well as the secondary field from the target (i.e., sensing additive).

[0018] In the illustrated example, the signal source **38** is coupled to the casing **37** within the wellbore **35** adjacent to the area where the fractures **34** are located. The signal source **38** is also coupled to an electrode **39**, which is positioned in the subterranean formation **31** and spaced apart from the borehole **35**. However, other suitable electrode configurations or placements may be used when driving the casing **37**.

[0019] In the example illustrated in FIG. **1**, one or more EM sensors **40** are positioned in the borehole **35** adjacent the fractures **34** to be imaged. The EM sensor **40** is configured to sense an EM field from the sensing additive when driven by the signal source **38** via the casing **37**, at Block **56**. Example measuring units which may be configured to provide EM sensing through the casing **37** are described in U.S. Pat. No. 4,796,186 to Kaufman and U.S. Pat. No. 4,820,989 to Vail, III, which are hereby incorporated herein in their entireties by reference.

[0020] The system **30** further illustratively includes a mapping device **41** coupled to the EM sensor **40**, which collects the EM field data from the EM sensor and maps the propped fracture pattern based upon the sensed EM field, at Block **57**, which concludes the method illustrated in FIG. **5** (Block **58**). By way of example, the mapping device **41** may be implemented using hardware (e.g., processor, memory, etc.) and associated computer-executable instructions. It should be noted that some or all of the mapping device components may be located remotely from the well site. That is, the data may be collected at the well site for mapping using a mapping device **41** located offsite.

[0021] In other example embodiments, EM sensors may be located remote from the borehole **35**. In another example embodiment illustrated in FIG. **2**, one or more EM sensor devices **40'** may be positioned at the surface of the subterranean formation **31'**, instead of (or in addition to) within the borehole **35'**. In still another example embodiment shown in FIG. **3**, the EM sensor(s) **40"** may be positioned in one or more separate boreholes **45"** spaced apart from the primary borehole **35"**, although an EM sensor may also be positioned within the primary borehole as well. The separate borehole(s) **45"** need not necessarily be lined with a casing.

[0022] With respect to the sensing additive, a relatively small volume fraction of a highly conductive material in the fracture fluid and/or proppant **36** can make the effective conductivity of the fractured regions **34** filled by this proppant relatively high. Generally speaking, the electrical properties of the proppant mixtures are determined by the concentration, shape and distribution of constituents. There is a percolation type behavior when highly conducting material is distributed in a relatively poorly conducting host. That is, the overall conductivity remains low until the highly conducting phase forms a well-connected "percolating" path for conduction.

[0023] In the case of a subterranean formation **31**, the "host" may be the fracture fluid and inert portion part of the proppant, and the highly conducting part may be metallic particles such as aluminum or graphite beads, a conducting polymer, or a conductive material coating on sand/ceramic that can be mixed with the sand. The percolation threshold (f_c) volume fraction depends on the aspect ratio. For spherical grains, theoretical models give f_c to be about 0.28, that is, a relatively large volume fraction of conducting phase is needed. However, this percolating volume fraction may be reduced by using different geometries, such as an elongate or needle-like conductive phase particles **50**, as shown in FIG. **4**. That is, a relatively small volume fraction of needle-shaped conductive particles **50** may form a spanning or a percolating path through the propped fractures **34**. By way of example, such non-spherical sensing co-agents may be included in the proppant mix to enhance the proppant conductivity or polarization at modest concentration levels of less than 15% by volume, and more particularly about 10-15%. Stated alternatively, a proppant to sensing additive volume ration may be greater than about 7 to 1. Example sensing agents may include aluminum, pyrite, magnetite, or graphite, and may be chosen based upon compatibility with chemistry of the fracture fluids. As noted above, inert proppants (e.g., sand, ceramic, etc.) may be coated with conductive or magnetic agents using doped polymers or resins.

[0024] By way of example, proppant sensing additives may be illuminated by various electromagnetic mechanisms. First, if the sensing additive changes the magnetic susceptibility of the propped zone, it can be illuminated with a low frequency magnetic signal (e.g., 20 Hz or less) that couples into the proppant through an enhancement of the magnetic field. Another approach is that electrically conductive sensing additives may be illuminated using a relatively low frequency electrical signal (e.g., 100 Hz or less), or a higher frequency electrical or magnetic source (e.g., 1000 Hz or less). At low frequency, the electrical signals are directly affected, via Ohm-s law, due to the change in electrical conductivity of the propped fracture **34**. At higher frequencies, the electrical or magnetic signals couple electromagnetically into the proppant **36**, causing secondary currents to flow and these currents, in turn, produce secondary EM fields. This affect is analogous to a transformer coupling.

[0025] Another approach is that conductive sensing additives may also be detected from their polarization effect.

More particularly, if the conductors in the proppant are disseminated, the low frequency EM field will polarize the isolated conductive regions. When the external field is removed, the polarized regions will generate their own relaxation field as they return to equilibrium.

[0026] Contrast sensing additives which may be used to enhance the magnetic field include magnetite, illmenite or particles of iron. Conductivity enhancements may be affected by various metallic conductors including pyrite, aluminum, graphite, or a stainless steel coating, etc. Polarizability may be enhanced by discontinuous metallic conductors.

[0027] Generally speaking, imaging of the collected data may be accomplished by fitting the measurements to calculations from a numerical model, typical by an inverse procedure. Here, one may assume a physical property distribution corresponding to the background and fracture properties, and then adjust the model until the measured and calculated data fits within a tolerance. The final model depends on the assumptions made, as well as the data and misfit achieved.

[0028] One imaging model that may be used is a 3D pixelized model. With this model, the formation is divided into pixels within which the physical properties (electrical conductivity or magnetic permeability) are constant. It may be assumed that an initial property distribution is consistent with an extension of the borehole logs, and/or other available data, and adjust the properties of the pixels until a data fit is achieved.

[0029] It should be noted that a rectangular pixelized model may provide a relatively poor representation of a fractured medium, but an "effective medium theory" may be used to give an average physical property distribution within a pixel equivalent to the fracture properties. Within each pixel, the effective medium theory will provide the property values and anisotropy to provide an equivalent response to a fractured medium. The final model does not necessarily correspond to a fracture distribution, but it will provide equivalent EM responses to the fracture model. More particularly, the results of this process will provide property distribution, property anisotropy and overall dimensions of the anomalous propped region from a pixelized inversion.

[0030] Numerical codes which may be used in this approach may be found in Zaslaysky et al., "Hybrid finite-difference integral equation solver for 3D frequency domain anisotropic electromagnetic problems," Geophysics 76, 123-137 (2011); and Li et al., "A compressed implicit Jacobian scheme for 3D electromagnetic data inversion," Geophysics 76, 173-183 (2011), for example, which are hereby incorporated herein in their entireties by reference. Effective medium theory calculations are provided in Choy, "Effective Medium Theory: Principles and Applications," International Series of Monographs on Physics, 1999, for example, which is also incorporated herein in its entirety by reference.

[0031] Another imaging model that may be used is a sheet model. In this approach, it may be assumed that the fractured volume may be approximated by a collection of conductive or magnetized sheets. The orientation, dimensions and number and properties of sheets are determined through an inverse or statistical method. Further details on this approach may be found in Weidelt, "The harmonic and transient electromagnetic response of a thin dipping dike," Geophysics 48, 934-952 (1983), which is hereby incorporated herein in its entirety by reference.

[0032] Many modifications and other embodiments will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that various modifications and embodiments are intended to be included within the scope of the appended claims.

That which is claimed is:

1. A method comprising:

forming a borehole in a subterranean formation;

lining at least part of the borehole with an electrically conductive casing;

injecting a fracturing fluid, a proppant, and a sensing additive into the borehole to form a propped fracture pattern;

driving the electrically conductive casing so that the sensing additive generates an electromagnetic (EM) field;

sensing the EM field; and

mapping the propped fracture pattern based upon the sensed EM field.

2. The method of claim **1** wherein driving comprises driving the electrically conductive casing with an alternating current (AC).

3. The method of claim **2** wherein the AC current has a frequency of less than 100 Hz.

4. The method of claim **2** wherein the AC current has a frequency of less than 1000 Hz.

5. The method of claim **1** wherein sensing comprises sensing from within the borehole.

6. The method of claim **1** wherein sensing comprises sensing remote from the borehole.

7. The method of claim **1** wherein sensing comprises magnetic field sensing.

8. The method of claim **1** wherein sensing comprises electric field sensing.

9. The method of claim **1** wherein the sensing additive comprises at least one of electrically conductive particles, magnetic particles, and polarizable particles.

10. The method of claim **1** wherein the sensing additive comprises particles have an elongate shape.

11. The method of claim **1** wherein a proppant to sensing additive volume ratio is greater than 7 to 1.

12. A method for mapping a propped fracture pattern adjacent a borehole in a subterranean formation, an electrically conductive casing lining at least part of the borehole, and the propped fracture pattern comprising a sensing additive, the method comprising:

driving the electrically conductive casing so that the sensing additive generates an electromagnetic (EM) field;

sensing the EM field; and

mapping the propped fracture pattern based upon the sensed EM field.

13. The method of claim **12** wherein driving comprises driving the electrically conductive casing with an alternating current (AC).

14. The method of claim **12** wherein sensing comprises sensing from within the borehole.

15. The method of claim **12** wherein sensing comprises sensing remote from the borehole.

16. An apparatus comprising:

an electrically conductive casing within a borehole of a subterranean formation having a proppant and a sensing additive within a propped fracture pattern adjacent the borehole;

a signal source to drive the electrically conductive casing so that the sensing additive generates an electromagnetic (EM) field;

at least one sensor to sense the EM field; and

a mapping device coupled to said at least one sensor to map the propped fracture pattern based upon the sensed EM field.

17. The apparatus of claim **16** wherein said signal source comprises an alternating current (AC) source.

18. The apparatus of claim **16** wherein said at least one sensor is to sense the EM field from within the borehole.

19. The apparatus of claim **16** wherein said at least one sensor is to sense the EM field remotely from the borehole.

20. The apparatus of claim **16** wherein said at least one sensor comprises at least one of a magnetic field sensor and an electric field sensor.

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