



(51) International Patent Classification:
E21B 47/00 (2012.01)

(21) International Application Number:
PCT/US2015/024266

(22) International Filing Date:
3 April 2015 (03.04.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/974,744 3 April 2014 (03.04.2014) US

(71) Applicants: GROUNDMETRICS, INC. [US/US]; 4217 Ponderosa Avenue, Suite A, San Diego, CA 92123 (US). SAUDI ARABIAN OIL COMPANY [SA/SA]; 1 Eastern Avenue, Dhahran, 31311 (SA).

(72) Inventors: HIBBS, Andrew, D.; 5574 Avenida Fiesta, La Jolla, CA 92037 (US). MARSALA, Alberto; P.O. Box 8100, Saudi Aramco, Dhahran, 31311 (SA).

(74) Agent: DIEDERIKS, Everett, G.; Diederiks & Whitelaw, PLC, 13885 Hedgewood Dr., Suite 317, Woodbridge, VA 22193 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: MULTI-WELL SURVEYING SYSTEM AND METHOD FOR DETECTING A SUBSURFACE FEATURE

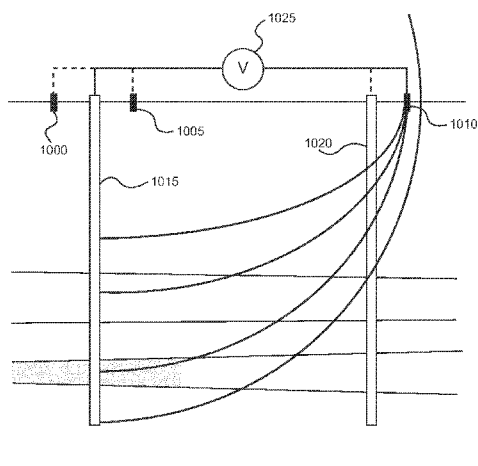


FIG. 3

(57) Abstract: A system is provided that utilizes two or more electrically conductive borehole casings (805, 810; 900, 910) to alternately illuminate the same formation (800; 905) from different lateral locations, and possible different depths. One or more source electrodes (815, 820; 915, 920; 1000, 1005, 1010) are located at the surface for completing the electric current path to the two or more casings (805, 810; 900, 910; 1000, 1005, 1010). A transmitter (1025) is alternately configured to cause a current to flow between each casing (805, 810; 900, 910), and the surface or another casing, or multiple transmitters (1025) could be used at once, operating at different frequencies or within different overlapping temporal intervals, or by some other means of interleaving the transmissions. The resulting data is combined to enhance the vertical or lateral resolution of the measurement at reservoir depth.

MULTI-WELL SURVEYING SYSTEM AND METHOD FOR DETECTING A SUBSURFACE FEATURE

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of U.S. Provisional Application No. 61/974,744, filed April 3, 2014, the entire content of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] The present invention relates to a system and method for probing the subsurface of the Earth using electric currents. More particularly, the invention relates to the discrimination of features at depth within the earth from features close to the surface via an electromagnetic source that injects electrical current into the earth via different, selectable sets of electrodes, in combination with multiple borehole casing.

[0003] The embodiments described herein relate generally to soundings within the Earth based upon electrical fields. As used herein, “earth” or “Earth” generally refers to any region in which a borehole may be located including, for example, the lithosphere. Electromagnetic (EM) geophysical surveys probe electrical resistivity, or equivalently, conductivity, in the ground as a function of depth. Typical targets of interest include ore bodies, hydrocarbons, water, proppants, hydraulic fracture (or fracking) fluids, salts and other substances injected into the ground, and environmental pollutants. Since the resistivities of such targets and the surrounding medium may be quite dissimilar, the targets may be discriminated by measuring their subsurface resistivities when subjected to an electromagnetic field. Using this methodology, the depth, thickness, and lateral extent of materials of interest may be determined and/or monitored.

[0004] The source of the EM field used in a geophysical survey may originate in the natural environment or be manmade. If manmade, the source may produce a primary magnetic field or electrical field that varies in time, and this primary field produces a secondary field in the conducting earth. For example, an electrical field produces electrical currents in the earth that have an associated magnetic field, and a time varying magnetic field induces electrical currents that result in an electrical field. The electrical properties of the earth and rate of change of the field determine the relative magnitudes of the secondary and primary fields. The combination of

primary and secondary fields results in combined electromagnetic interaction with the earth even for a source arranged to produce solely an electrical or magnetic field.

[0005] While the majority of EM geophysical surveys are performed with sensors and EM sources on the surface of the earth, a borehole can provide physical access to the subsurface. Measurement of the electrical or magnetic field within a borehole can be related to the electrical or magnetic field in the earth around the borehole or the fields that would exist in the earth in the absence of the borehole. Similarly, connecting an electrical field or magnetic field source to the earth via a borehole provides a way to produce fields within the earth at desired depths without the attenuation and uncertainties that may result if the source fields originated from a source at the surface of the Earth. A particularly beneficial configuration of borehole EM source is an electrode situated at the top or bottom of a borehole casing and a group or suite of source electrodes, such as six or more electrodes, at the surface approximately arranged in a ring roughly centered on the borehole, or alternatively arranged in a segment of such a ring. In this case, significant electric currents in the ground are caused to flow at depth out to a radial distance from the borehole in the order of the radius of the surface electrode ring.

[0006] The distribution of electric current flow produced by an EM source is determined by the three-dimensional (3-D) resistivity distribution within the earth. The electric current measured at the surface or at depth with a borehole can be used to infer the 3-D resistivity variation over the region where significant current is flowing. The current is typically measured by a suitably calibrated array of electric or magnetic field sensors. The resulting 3-D resistivity variation can be used to project the distribution of ores, hydrocarbons or water or other fluids or materials of interest within the measured volume.

[0007] A common problem in applying this method of subsurface EM imaging is discriminating spatial changes in resistivity at the depth of the formation from those near to the location of the sensors. Recent models of the current flow from a ring (or partial ring) of surface electrodes to a borehole casing show that current flows from the earth into the casing along the entire length of the casing. Thus, significant current flows near the surface of the earth between the source electrodes and the top of the casing. This near-surface current causes a significant interfering measurement artifact for measurement configurations wherein receivers are located at the surface of the earth. The problem is that a resistivity anomaly (i.e., a local change in the earth's resistivity) near the surface causes a much larger change in the EM field at the surface

than an equivalent resistivity change much deeper in the earth. Surface resistivity anomalies can be static over time if they are affected by weather events, for instance rainfall and temperature variations, such as freezing.

[0008] It is possible to isolate the signal produced in the near surface region from that produced at depth. For instance, it is possible to utilize a source configuration that has much higher relative sensitivity to the surface, to provide an independent quantification of the surface signal. This vertical contrast is excellent for removing surface artifacts but, by its very intent, has minimal sensitivity to deeper resistivity changes. However, having contrast to vertical resistivity changes at reservoir depth could be very valuable for imaging layers within a reservoir, for example the location of an oil-to-water contact that is predominantly horizontal, or the profile of an injected CO₂ plume that migrates upwards from a reservoir. With this in mind, there exists a need for a system and method that is preferentially sensitive to resistivity variations at the depth of hydrocarbon or other types of reservoirs. Preferably the method should not attenuate or otherwise reduce the spatial range of the EM survey.

SUMMARY OF THE INVENTION

[0009] The invention relates to improving the overall sensitivity of a combined suite of EM sources to variations in subsurface electrical resistivity deep in the subsurface, for example at a depth greater than 1000 m. More particularly, a system is provided that utilizes two or more electrically conductive borehole casings in combination with one or more source electrodes located at the surface for completing an electric current path to the two or more casings for subsurface surveying purposes. A transmitter is alternately configured to cause a current to flow between each casing, and the surface or another casing, or multiple transmitters could be used at once, operating at different frequencies or within different overlapping temporal intervals, or by some other means of interleaving the transmissions. Accordingly, the system can be employed to alternately illuminate the same formation from different lateral locations, and possible different depths. The resulting data is combined to enhance the vertical or lateral resolution of the measurement at reservoir depth.

[0010] Additional objects, features and advantages of the present invention will become more readily apparent from the following detailed description of preferred embodiments thereof

when taken in conjunction with the drawings wherein like reference numerals refer to corresponding parts in the several views.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Figure 1 is a plan view of multiple cased wells with a fluid volume between them, an inner ring of source electrodes installed around a central well and a separate outer ring of source electrodes at proximate a suite of outer wells;

[0012] Figure 2 is a plan view of a line drive, including one or more first wells arranged along a line, and a line of secondary wells, with surface electrodes located at one of the first wells and near the line of secondary wells;

[0013] Figure 3 illustrates the current paths when a voltage is applied across a casing and a surface electrode at a significant lateral offset from the casing, with the surface electrode in the vicinity of a second casing and the second casing not connected to the transmitter and so not forming part of the source circuit;

[0014] Figure 4 illustrates the current paths when voltage is applied across one or more surface electrodes at the surface near to a casing and at the casing, wherein the configuration enhances the vertical component of current flow;

[0015] Figure 5 illustrates the current paths when the voltage is applied across a casing and a surface electrode at significant lateral offset from a second casing close enough to the first casing to produce a current that separately illuminates the subsurface volume of the first casing; and

[0016] Figure 6 illustrates the current paths between two casings, with one casing being where a fluid volume is primarily located.

DETAILED DESCRIPTION OF THE INVENTION

[0017] Detailed embodiments of the present invention are disclosed herein. However, it is to be understood that the disclosed embodiments are merely exemplary of the invention that may be embodied in various and alternative forms. The figures are not necessarily to scale, and some features may be exaggerated or minimized to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as

limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present invention.

[0018] In the figures of this application, discrete lines are used to illustrate the path of the subsurface current. However, these lines are examples of typical current paths for the configuration of casing and surface electrodes depicted. There are many other current paths in the subsurface, including paths that extend below the bottommost point of a casing and outside the outer area defined by a surface electrode. However, the current in these more extreme paths is much less than in the major regions.

[0019] In the description which follows, like parts may be marked throughout the specification and drawing with the same reference numerals. The foregoing description of the figures is provided for a more complete understanding of the drawings. It should be understood, however, that the embodiments are not limited to the precise arrangements and configurations shown. Although the design and use of various embodiments are discussed in detail below, it should be appreciated that the present invention provides many inventive concepts that may be embodied in a wide variety of contexts. The specific aspects and embodiments discussed herein are merely illustrative of ways to make and use the invention and do not limit the scope of the invention. It would be impossible or impractical to include all of the possible embodiments and contexts of the invention in this disclosure. Upon reading this disclosure, many alternative embodiments of the present invention will be apparent to persons of ordinary skill in the art.

[0020] In general, the invention relates to borehole electromagnetic geophysics, for which the objective is to probe the earth at a considerable distance from a borehole. The invention enables the generation of electromagnetic fields from a borehole that are measured by remote sensors. In practical use, the invention will be used in conjunction with commercially available sensors or array of sensors would be deployed at the earth's surface. A defining feature is that the sensors are outside the borehole, and are separated from the borehole by a distance which in practical cases is at least 50 m. More particularly, a system is provided that utilizes two or more electrically conductive borehole casings to alternately illuminate the same formation from different lateral locations, and possible different depths. One or more source electrodes are located at the surface for completing the electric current path to the two or more casings. A transmitter is alternately configured to cause a current to flow between each casing, and the surface or another casing, or multiple transmitters could be used at once, operating at different

frequencies or within different overlapping temporal intervals, or by some other means of interleaving the transmissions. The resulting data is combined to enhance the vertical or lateral resolution of the measurement at reservoir depth.

[0021] Further, the invention primarily relates to hydrocarbon fields for which multiple wells with electrically conductive casings are located within no more than 5 km of each other. These could be mature fields which have been drilled in a number of locations, possibly to different depths, and thus have two or more existing wells. Further one or more additional wells could be drilled to enhance production, for example water drive, or CO₂ enhanced oil recovery, and these wells could be utilized in the invention. Yet further, all the wells could be new and drilled for new production, for example as in the new production method of hydraulic fracturing unconventional reservoirs.

[0022] A typical pattern of a central well surrounded by one or more outer wells is shown in plan view in Figure 1. An alternate configuration is a line-drive in which one or more injector wells drive hydrocarbons towards a line of one or more producing wells, as illustrated in Figure 2 and discussed in detail below. Typically there is at least one well into which a fluid is injected and one or more wells out of which hydrocarbons are produced. In such a configuration there is an economic benefit and possibly other needs to image the volume of injected fluid, or the volume of displaced fluid, or multiple fluids.

[0023] A particular application of the invention when used with multiple lateral wells is to improve the measurement of fractures caused by the commercial procedure of hydraulic fracturing. Pressure transferred by a fluid is used to create fractures within the subsurface outside the borehole. The pressurizing fluid then flows into those fractures. In this case, the fluid used to create the fracture should be sufficiently electrically conducting to disrupt the path of subsurface electric current in order to produce a measurable signal. One fluid that can be used is water with a high salt concentration. Alternatively, the fluid can contain particles that have measurable electrical properties. Although the method is referred to as fracturing, it is not required that a single fracture be produced or that the fracture region be a thin, narrow separation of the subsurface. Indeed, those skilled in the art consider that, in many instances, a region of damage comprising many intersecting cracks is produced. For the purposes of this invention, a fracture is defined to be any region of subsurface disturbance with at least one very short dimension, either present due to natural process or as a result of a fracturing procedure.

[0024] Turning to Figure 1, there is shown a group of several wells deployed to enhance the production of a volume of fluid 800. A typical pattern involves a central well 805 surrounded by one or more outer wells 810. A similar, alternative configuration is a line-drive in which one or more injector wells 900 drive a fluid 905 (such as hydrocarbons) towards a line of one or more producing wells 910, as illustrated in Figure 2. More generally, there is typically at least one well into which a fluid is injected and one or more wells out of which hydrocarbons are produced. In such a configuration, there is an economic benefit and possibly other needs to image the volume of injected fluid, the volume of displaced fluid or multiple fluids. For the purpose of describing the invention, a scenario is identified in which there is a first well that penetrates a subsurface region, such as a reservoir, in which a fluid is located. This fluid can be produced at the well (*e.g.*, oil, gas, or potable water) or be a fluid injected into the well (*e.g.*, water or CO₂) to support the production of hydrocarbons at another location. In general, the host reservoir will contain fluid or gas, and the fluid depicted at the first well in the illustrations included herein is intended to highlight a specific body of fluid that is injected or desired to be produced. However, is not essential that a fluid be present, and the invention can be applied to image any resistivity anomaly, including a shale bed or ore deposit, or to determine the resistivity of the host rock.

[0025] Figure 1 shows a plan view of central well 805 intercepting fluid 800 and surrounded by a ring of outer wells 810 in an approximately circular configuration centered on the central well 805. There is a suite of inner electrodes 815 located at the surface and all positioned at approximately equal radial distance from central well 805 and approximately equally spaced from one another. There is also an outer suite of electrodes 820 at the surface, also all positioned at approximately equal radial distance from central well 805 but at a radial distance approximately equal to that of the ring of outer wells 810. Electrodes 820 are preferably located just a small offset, such as less than 500 m, preferably less than 300m and most preferably less than 100m, from a respective outer well 810. In a practical embodiment, central well 805 can be an injection well, outer wells 810 can be producing wells, and the fluid that is injected causes increased output of hydrocarbons at the producing wells. Figure 2 shows an embodiment in which one or more injector wells 900 are arranged approximately in a line that is approximately parallel to a line of producing wells 910. For ease of comparison to Figure 1, a single injector well 900 has been illustrated with a suite of inner surface electrodes 915 placed

around it, in a similar manner to central well 805 depicted in Figure 1. Similarly, a suite of surface electrodes 920 is located near to producing wells 910, in an equivalent manner to the central configuration shown in Figure 1. Although, in Figures 1 and 2, suites of surface electrodes have been depicted and discussed as being near to first and secondary wells, a suite can be a single electrode, and it is not essential that each secondary well be paired with an individual surface electrode, as will become apparent below. The separation between the boreholes and injection electrode(s) should be such that a sufficient subsurface current flow can be established between them for a measurable signal change to be produced for the subsurface target of interest. In practice, the electrical resistance between two points within the earth does not increase strongly with the distance between them and, further, the effect of increasing the separation can be compensated for by using a transmitter that can output a higher voltage. In most practical situations where arrays of wells are used for injection and production, the wells are easily close enough to be used as part of the invention. In general, the condition that wells are arranged close enough together to be used as part of the invention is termed that the wells are in range of each other. For commercially available transmitters and state-of-the-art EM sensors, the electrodes and boreholes should be within 5 km of each other, and, more preferably, within 2 km.

[0026] With reference to Figure 3, the basic configuration of a DSEM source is shown schematically for a first well that intercepts a reservoir layer containing a fluid. More specifically, Figure 3 depicts a combination of surface electrodes 1000, 1005 and 1010 and cased boreholes 1015 and 1020 in close proximity. In particular, surface electrode 1010 is used as part of an outer ring and is relatively close to second casing 1020. However, second casing 1020 is not connected to a transmitter 1025 at this time and so does not form part of the source circuit. The idealized current paths for a surface source configuration are significantly disrupted by the presence of a borehole that has an electrically conductive casing as the conducting casing provides a conduit that guides the nominally surface current to a much deeper depth. Therefore, the very high conductivity of the casing relative to the rock advantageously causes significant additional electric current to flow at depth, down to the bottom of the casing. In Figure 3 and other illustrations herein, wherein the boreholes are depicted in an entirely vertical orientation and straight, it should be recognized that the borehole and any casing placed therein can deviate from vertical and even have lateral sections that are horizontal or even fishbone configurations.

Therefore, when the location of a given borehole is specified herein, reference is made to the top of the borehole where it meets the surface of the earth. In addition, an electrode is defined as being “in close proximity”, i.e., “at a borehole”, in accordance with the invention, if the electrode is electrically coupled to the borehole so that more than 50% of the current input into the electrode passes through the outer surface of the borehole and into the earth.

[0027] The casing and surface electrodes are electrically connected to the transmitter via cables. In accordance with the invention, additional connections are provided to other casings and source electrodes as illustrated in Figure 3. At this point, it should be recognized that the transmitter can be located at the surface, though this is not essential. Therefore, although only one electrode and one casing are shown connected in Figure 3, it is within the invention for multiple casings and/or surface electrodes to be connected to the transmitter at the same time. Having multiple connections at once has the benefit of increasing the amount of survey data that can be acquired over a given period of time. Similarly, although only one transmitter is shown connected, it is within the scope of the invention that more than one transmitter be connected at once. If multiple transmitters are connected, they may be operated at the same time or serially. If operated at the same time, the transmitters can be set to produce electric current waveforms of different frequency.

[0028] Further, the casings of boreholes 1015 and 1020 in Figure 3 and subsequent figures are shown to have the depth into the earth, and projected below the reservoir layer by an approximately equal amount. However, it is not essential that the casings extend to the same depth or reach or penetrate a target layer equally. Indeed illuminating the subsurface with casings of different depth has the benefit of offering increased vertical differentiation of one or more target layers.

[0029] A benefit of locating a surface electrode near to a casing is that the surface region illuminated by the current from the surface electrode and the surface region illuminated when the surface electrode is exchanged for the casing near to it, are similar. However, a primary application of this invention is on mature hydrocarbon fields where wells are already drilled, and there may not be a well in a region that later becomes of interest. In such instances it is still useful, and in the scope of the invention, to locate a surface electrode at a region of interest, even if there is no available well casing. Further, it is possible that an additional well may be drilled and cased to provide deep illumination at a desired region.

[0030] Further, although the invention is primarily directed towards using casings via a top electrical connection, it is within the scope of the invention to inject current into a casing at depth. This can be effected by inserting an electrode into the well that couples electrical current from within the casing at depth, for example via current flow through the well fluid or via direct contact to the inside of the casing. The downhole electrode can be located at any depth and connected to the transmitter via a cable to the surface.

[0031] Yet further, although the invention is described for use with electrically conducting casings, it can be used with wells that have some or all sections of their casing made from electrically insulating materials, or wells without casing. The latter application may be particularly beneficial when a slim well is drilled close to a formation specifically for use with the invention and there is no need to case it for production. In the event only part, or none, of the casing is an electrical conductor, then using a downhole electrode is preferable and the subsurface current paths are crowded at the downhole electrode in the well in a similar manner as shown for the current crowding a surface electrode. Similarly, although described as making electrical contact to a casing, electrical contact could be made to any conductor in electrical contact with the casing, such as a collar, well head, or production tubing within the casing. In addition, a fluid can be injected into the casing, with the fluid having electrical properties tailored to improve electrical conduction.

[0032] Based on the above, it should be readily apparent that the system can be employed to alternately illuminate the same formation from different lateral locations, and possible different depths. The resulting data is combined to enhance the vertical or lateral resolution of the measurement at reservoir depth. In connection with alternative data collection arrangements, Figure 4 shows a configuration in which the transmitter is connected across electrodes 1000 and 1005 that are near the top of the well and the casing associated with borehole 1015. Compared to the configuration illustrated in Figure 3, the resulting current paths are predominantly parallel to the axis of the casing and distributed equally as a function of azimuthal angle, referred to as a Vertical Mode. A configuration in which one of the secondary wells is used as the central well of the DSEM configuration is shown in Figure 5. This configuration is the mirror of that in Figure 3, and has the benefit of preferentially illuminating the current flow in the reservoir region based on the fluid around the first well, referred to as an Offset DSEM configuration. A further paradigm subsurface current distribution is produced by connecting a transmitter across first and

secondary wells of boreholes 1015 and 1020 as shown in Figure 6. The produces subsurface current primarily in, or near to the plane of the two wells, referred to as a Casing to Casing DSEM configuration.

[0033] Regardless of the various specific arrangements shown in the figures, it should still be recognized that other paradigm subsurface current distributions can be established between secondary wells and/or outer electrodes, such as a configuration not directly including a first well or the surface electrodes near to it as part of the current path. This can be arranged by connecting the transmitter between outer wells as in Casing to Casing DSEM, between an outer well and outer electrodes as in Standard and Offset DSEM and the Vertical Mode, and between outer electrodes as in a Surface Mode wherein the transmitter is connected between multiple surface electrodes.

[0034] Based on the above, it should be readily apparent that each of the configurations discussed above can be used in multiple ways. With reference to Figures 1 and 2, a first well can be used in conjunction with any of the array of surface electrodes, or any of the secondary wells, and similarly for any of the secondary wells. By such combinations, subsurface current flow can be controllably directed within different regions of the reservoir including preferentially where a fluid is injected and targeted to reach. A restriction on the first well and a secondary well is that the separation between them should be such that a sufficient subsurface current flow can be established between them, for example using the DSEM or Offset DSEM configurations, wherein the surface electrodes are located near to each casing, or the Casing to Casing DSEM configuration. This requirement is met in accordance with the invention by stating that the wells are in range of each other.

[0035] In practice, the electrical resistance between two points within the earth does not strongly increase with distance between them and further the effect of increasing the separation can be compensated by using a transmitter that can output a higher voltage. In most practical situations where arrays of wells are used for injection and production, as in the geometries depicted in Figures 1 and 2, the wells are easily close enough to be used as part of the invention. In situations where it is desired to exploit additional wells which have not been emplaced as part of a pattern, for example, wells drilled over time by different operators of a field, then the wells should be no more than 5 km apart, and preferable no more than 2 km apart.

[0036] It is well known by those skilled in the art that additional sensors may be used to improve the utility of an EM measurement. Electromagnetic signals resulting from the subsurface current are sensed by one or more electromagnetic sensors at or near to the surface. For example, the sensors can be placed on the surface, be buried in shallow pits or be sited in bored holes. Although described with reference to preferred embodiments of the invention, it should be readily understood that various changes and/or modifications can be made to the invention without departing from the spirit thereof. For example, more than one component of the EM field at the surface can be acquired, and both electric field and magnetic fields can be measured. Accordingly, the method described herein may be combined with multiple sensor orientations and different electromagnetic fields. In addition, the electromagnetic signal that is produced by the subsurface current may be primarily characterized by a change in its amplitude, its phase relative to the transmitter, in the distribution of its frequency content, its coherence with other signals, its spatial correlation with other signals, some other property, or a combination of such properties.

CLAIMS

1. A multi-well surveying system for detecting a feature at depth below a surface of the earth comprising:
 - a first borehole including a first well casing;
 - a second borehole including a second well casing, with the second well casing being in range of the first well casing;
 - a suite of electrodes at the surface disposed in close proximity from each of the first and second well casings;
 - a transmitter configured to cause a subsurface current to flow between one or more electrodes of the suite of electrodes and a selective one or more of the first and second well casings; and
 - one or more sensors arranged to detect a signal produced by the subsurface current.
2. The system of claim 1, wherein the subsurface current can be selectively established to flow:
 - a) between the one or more electrodes of the suite and the first well casing;
 - b) between the one or more electrodes of the suite and the second well casing; and
 - c) between the first and second well casings, in order to probe a subsurface formation.
3. The system of claim 1, wherein the first and second well casings are electrically conductive.
4. The system of claim 1, further comprising: multiple additional wells within range of the first well casing.
5. The system of claim 1, wherein the range between the first and second well casings is no more than 5 km.
6. The system of claim 5, wherein the range is no more than 2 km.

7. The system of claim 1, wherein the suite of electrodes constitutes an inner suite arranged about the first borehole and the system further includes an outer suite of electrodes.
8. The system of claim 7, wherein the outer suite of electrodes is located at a small offset from the second well casing and the current can flow between that one or more electrode of the outer suite of electrodes and the first well in order to probe the subsurface formation.
9. The system of claim 7, wherein the small offset is less than 500 m.
10. The system of claims 9, wherein the small offset is less than 100 m.
11. The system of claim 1, wherein the transmitter is connected to a collar, production tubing, a well head, or other electrical conductor associated with first well casing.
12. The system of claim 1, wherein the transmitter is connected to a fluid injected in the first well casing, with the fluid having electrical properties tailored to improve electrical conduction.
13. The system of claim 1, wherein the system can selectively operate in at least two of a Vertical Mode, an Offset DSEM configuration, a Casing to Casing DSEM configuration and a Surface Mode.
14. The system of claim 13, wherein the system can selectively operate in each of the Vertical Mode, Offset DSEM configuration, the Casing to Casing DSEM configuration and the Surface Mode.
15. A method for detecting a feature at depth below a surface of the earth comprising:
causing a subsurface current to flow between one or more electrodes of a suite of electrodes, provided at the surface and disposed in close proximity from each of a first well casing of a first borehole and a second well casing of a second borehole which is in range of the first borehole, and a selective one or more of the first and second well casings; and
detecting a signal produced by the subsurface current by one or more sensors.

16. The method of claim 15, further comprising: selectively establishing the subsurface current to flow:
- a) between the one or more electrodes of the suite and the first well casing;
 - b) between the one or more electrodes of the suite and the second well casing; and
 - c) between the first and second well casings, in order to probe a subsurface formation.
17. The method of claim 15, further comprising: utilizing conductive portions of the first and second well casings in establishing the subsurface current.
18. The method of claim 15, further comprising:
- employing the suite of electrodes as an inner suite arranged about the first borehole;
 - employing an outer suite of electrodes, located at a small offset from the second well casing; and
 - causing the current to flow between one or more electrodes of the outer suite of electrodes and the first well in order to probe the subsurface formation.
19. The method of claim 15, wherein the subsurface current is caused to flow through a collar, production tubing, a well head, or other electrical conductor associated with first well casing.
20. The method of claim 15, wherein the subsurface current is caused to flow through a fluid injected in the first well casing, with the fluid having electrical properties tailored to improve electrical conduction.
21. The method of claim 15, further comprising: selectively operating in at least two of a Vertical Mode, an Offset DSEM configuration, a Casing to Casing DSEM configuration and a Surface Mode.
22. The method of claim 21, further comprising: operating in each of the Vertical Mode, Offset DSEM configuration, the Casing to Casing DSEM configuration and the Surface Mode.

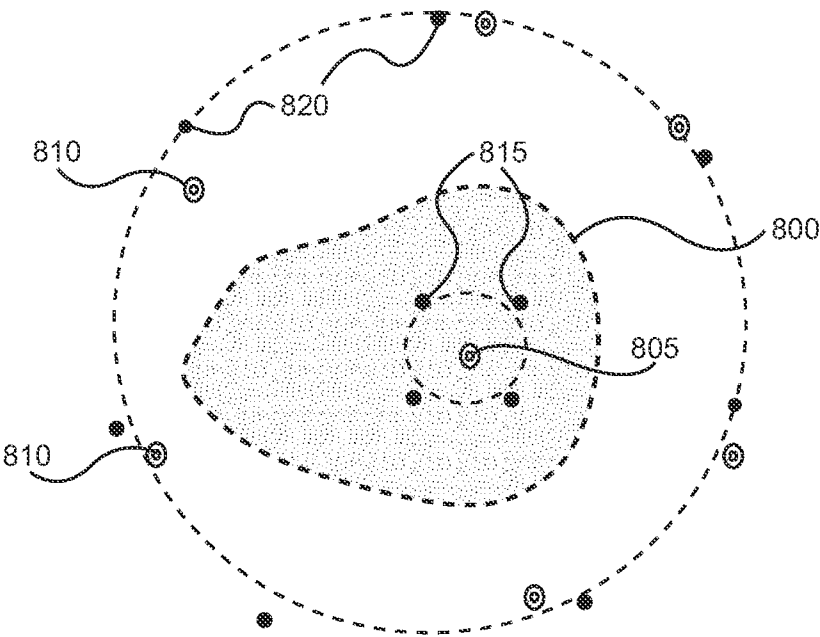


FIG. 1

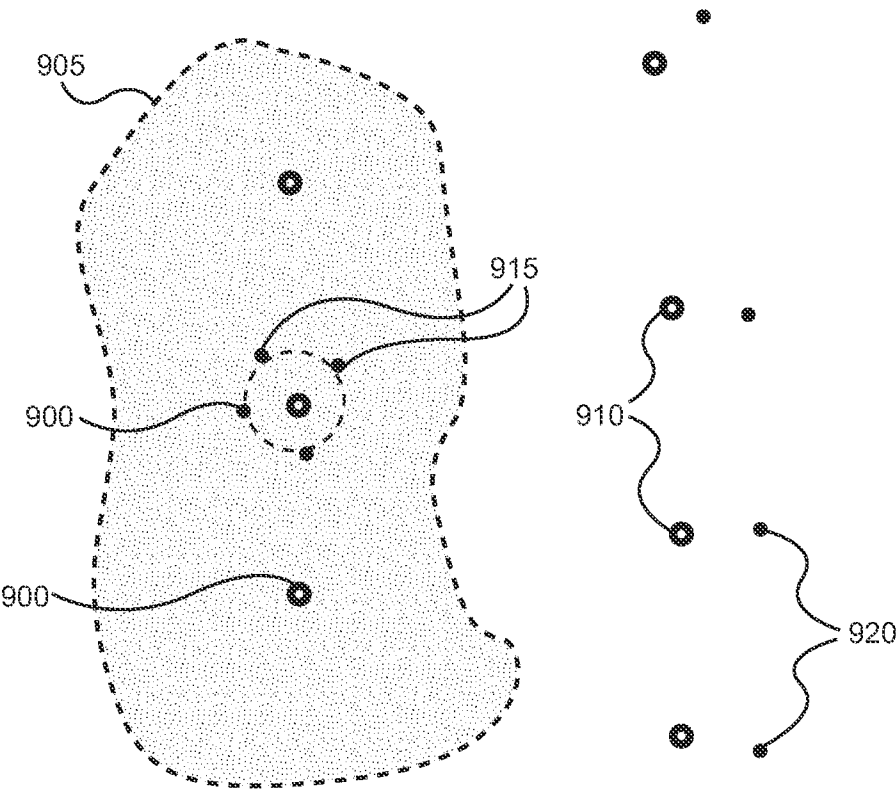


FIG. 2

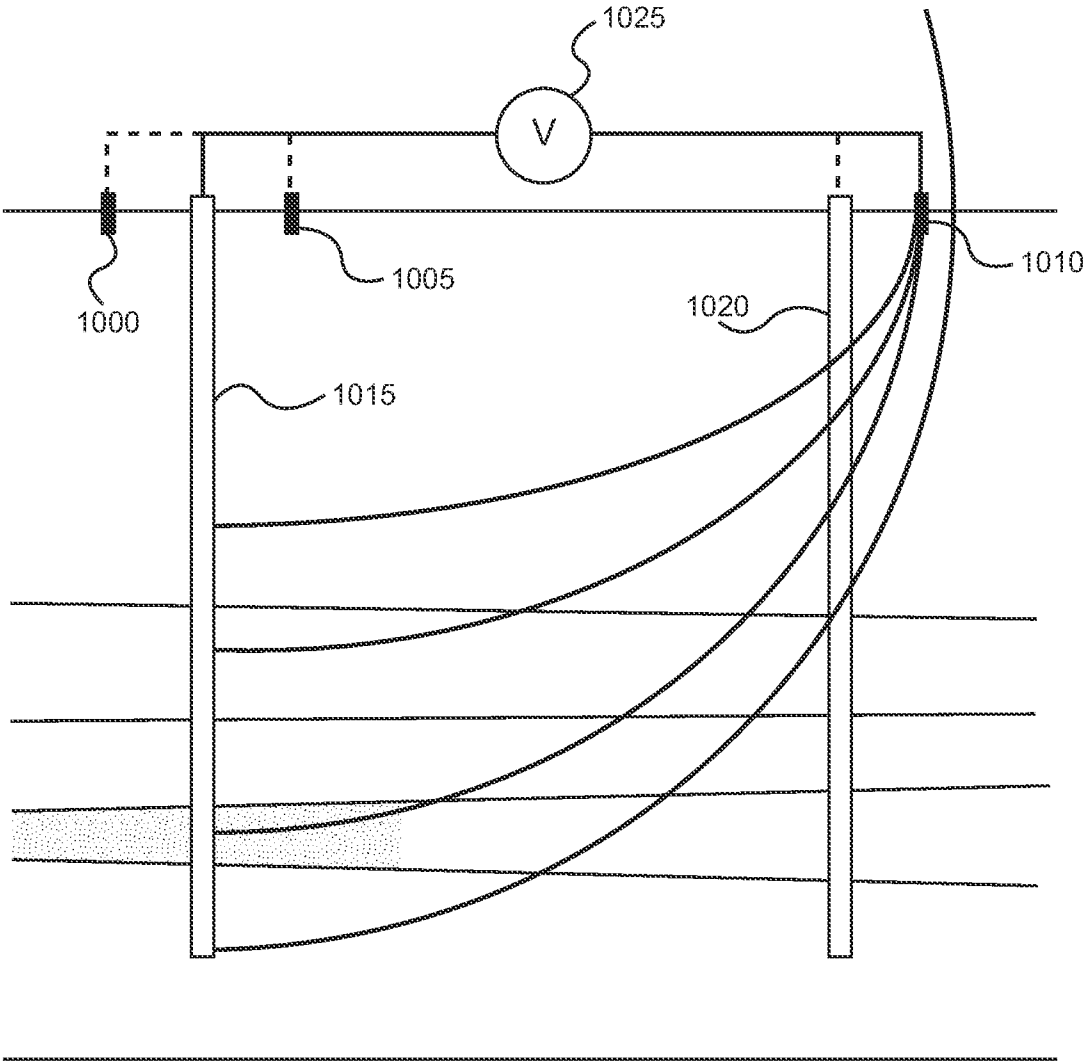


FIG. 3

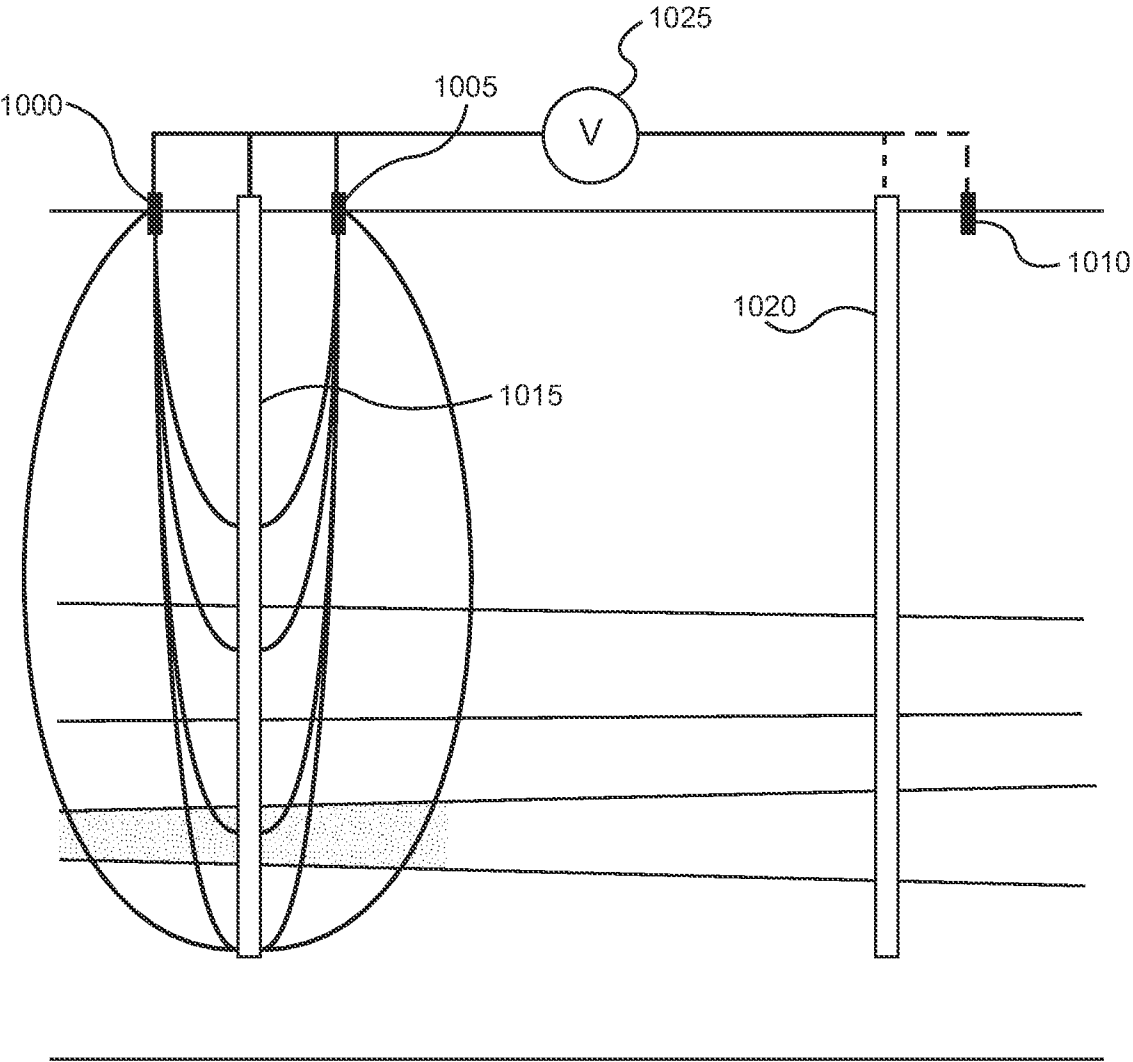


FIG. 4

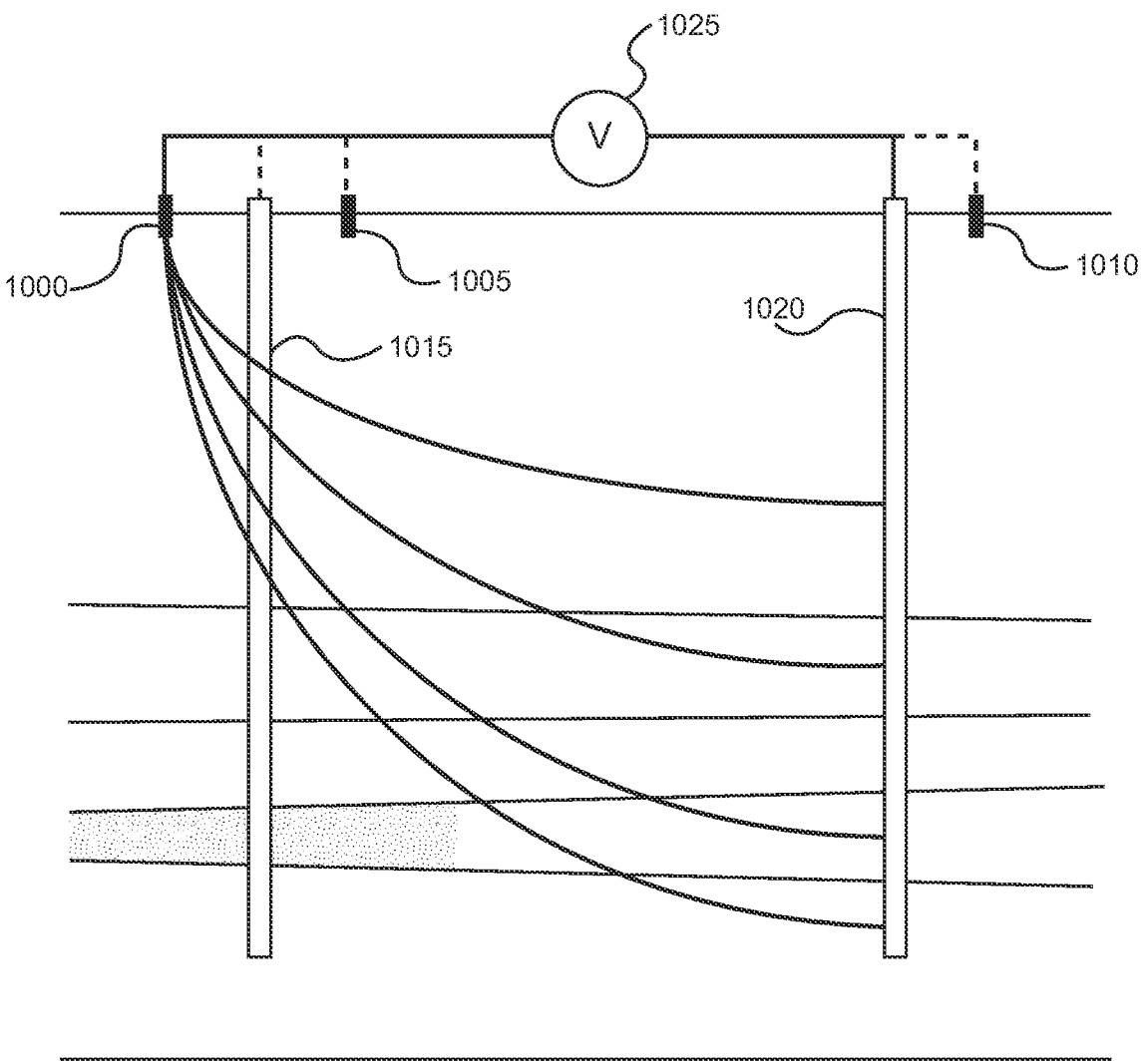


FIG. 5

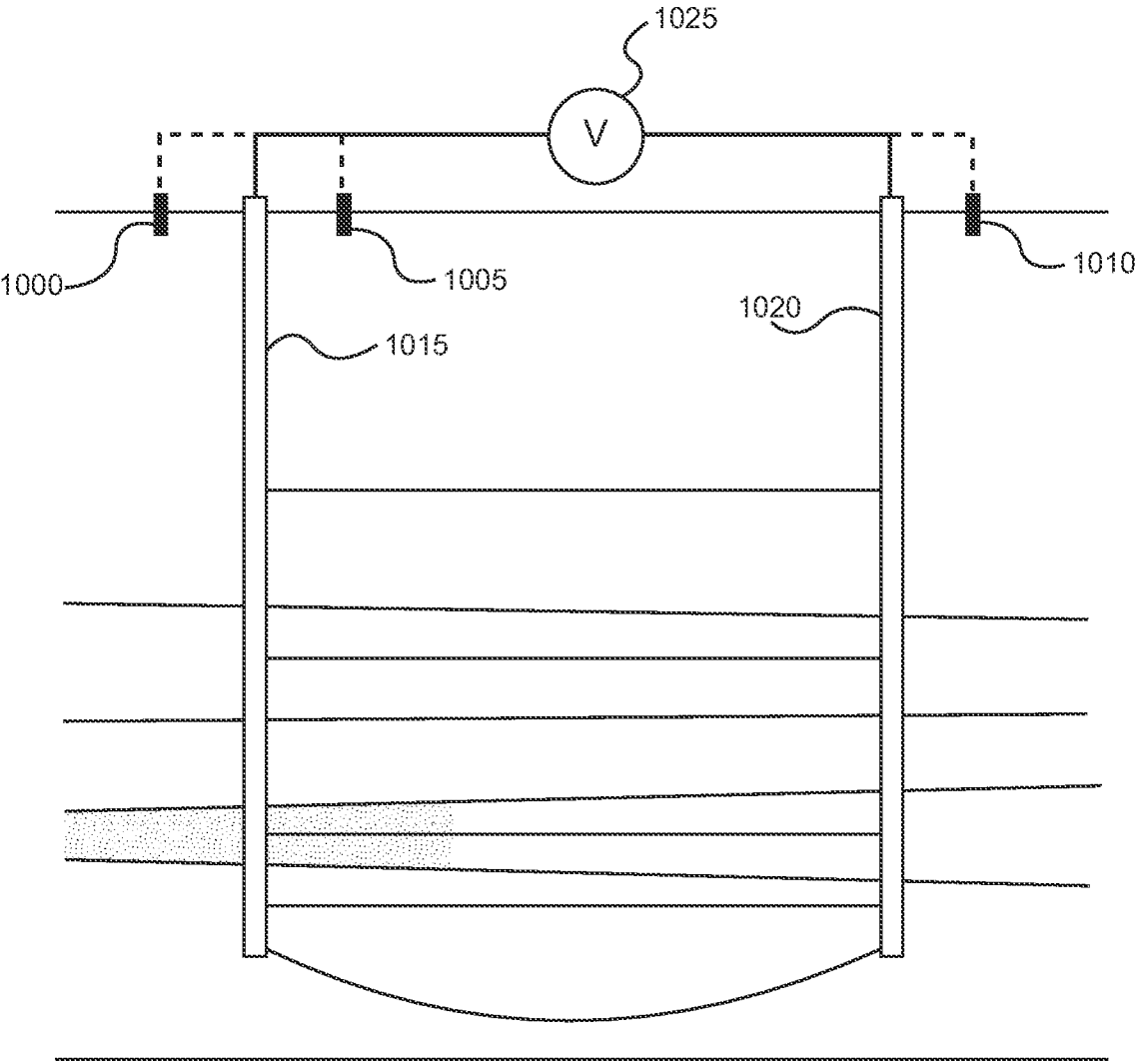


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2015/024266

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - E21B 47/00 (2015.01)

CPC - E21B 47/00 (2015.04)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8) - E21B 17/00, 31/06, 47/00, 47/12, 49/00; G01V 1/00, 1/28, 3/00, 3/08, 3/10, 3/18, 3/20, 3/24 (2015.01)

USPC - 166/66.5, 250.01; 324/323, 324, 338, 347, 354, 355; 340/853.1, 854.3, 854.4; 702/6, 7

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

CPC - E21B 47/00, 47/0001, 47/122, 49/00; G01V 3/00, 3/08, 3/081, 3/088, 3/10, 3/18, 3/20, 3/330, 3/38 (2015.04) (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Orbit, Google Patents, Google Scholar, ProQuest.

Search terms used: well, borehole, sensor, detect, measure, electrode, conduct, transmitter, current, survey, surface, underground, earth.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/0308789 A1 (ZHANG et al.) 22 December 2011 (22.12.2011) entire document	1-22
A	US 5,187,440 A (VAIL) 16 February 1993 (16.02.1993) entire document	1-22
A	WO 2014/039618 A2 (HIBBS et al.) 13 March 2014 (13.03.2014) entire document	1-22
A	US 8,392,119 B2 (ALUMBAUGH et al.) 05 March 2013 (05.03.2014) entire document	1-22
A	US 7,495,446 B2 (LOVELL et al.) 24 February 2009 (04.02.2009) entire document	1-22

☐ Further documents are listed in the continuation of Box C.


* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

09 June 2015

Date of mailing of the international search report

01 JUL 2015

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

Authorized officer:

Blaine R. Copenheaver

PCT Helpdesk: 571-272-4300

PCT OSP: 571-272-7774