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(54) Title: MONITORING ACID STIMULATION USING HIGH RESOLUTION DISTRIBUTED TEMPERATURE SENSING

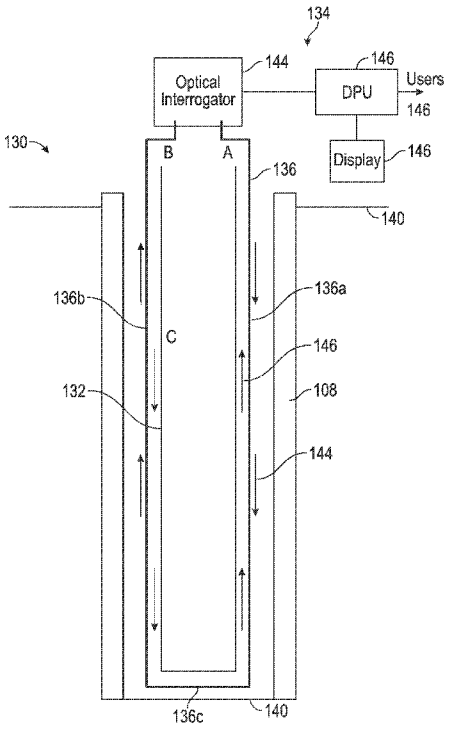


FIG. 2

(57) Abstract: A method, apparatus and computer-readable medium for stimulating a formation is disclosed. A stimulation operation is performed at a selected stimulation zone of the formation using a first value of stimulation parameter. A temperature measurement profile is obtained at the formation during the stimulation operation, wherein the obtained temperature measurement profile is indicative of a parameter related to the stimulation operation. The downhole parameter is determined using the obtained temperature measurements, and stimulation parameter is altered to a second value in real-time based on the determined parameter.

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MONITORING ACID STIMULATION USING HIGH RESOLUTION DISTRIBUTED TEMPERATURE SENSING

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Application No. 14/062561, filed on October 24, 2013, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE DISCLOSURE

1. Field of the Disclosure

[0002] The present application relates to acid stimulation and, in particular, to methods for operating an acid stimulation process using high-resolution distributed temperature obtained in real-time.

2. Description of the Related Art

[0003] Acid stimulation may be used to restore a production well for higher oil/gas recovery, remedy formation damages caused by drilling, completion or clay movement, etc. The performance of an acid stimulation may be optimized by diverting acid accurately and uniformly to a selected perforation interval. In reality, many factors such as the well configuration for the operation, commingled perforation zones, zones having low permeability or low formation pressure, etc., may hinder optimal acid stimulation. Traditionally, an acid stimulation program may be formulated based on the analysis of results of a well diagnosis process conducted prior to stimulation. It is common that various formation features may go undetected, making it difficult to plan the stimulation process. Additionally, such features may be created during the acid stimulation process, thereby changing the feasibility of a stimulation plan based on measurements obtained prior to the stimulation process. Currently changes in the formation properties that occur during the stimulation process cannot be detected until after the monitoring data have been analyzed upon the completion of the stimulation.

SUMMARY OF THE DISCLOSURE

[0004] In one aspect, the present disclosure provides a method of stimulating a formation, the method includes: performing a stimulation operation at a selected stimulation zone of the formation using a first value of stimulation parameter; obtaining a temperature measurement at the formation during the stimulation operation, wherein the obtained temperature measurement is indicative of a parameter related to the stimulation operation;

determining the downhole parameter using the obtained temperature measurements; and altering the stimulation parameter to a second value in real-time based on the determined parameter.

[0005] In another aspect, the present disclosure provides a system for stimulating a formation, the system including: a workstring in a well formed in the formation; a stimulation sub of the work string at a selected zone of the formation configured to perform a stimulation operation; a temperature measurement system disposed along the workstring; and a processor configured to: control the stimulation sub to perform the stimulation operation using a first value of a stimulation parameter, obtain a temperature measurement profile during the stimulation operation from the distributed temperature sensing system, determine a downhole parameter related to the of the stimulation operation from the obtained temperature measurement profile, and alter the stimulation parameter to a second value in real-time based on the determined downhole parameter.

[0006] In yet another aspect, the present disclosure provides a computer-readable medium having stored thereon a set of instructions that when read by a processor enable the processor to perform a method for stimulating a formation. The method includes: performing a stimulation operation using a first value of a stimulation parameter; obtaining a temperature measurement profile related to the stimulation operation during the stimulation operation; determining a downhole parameter related to the of the stimulation operation from the obtained temperature measurement profile; and altering the stimulation parameter to a second value in real-time based on the determined downhole parameter.

[0007] Examples of certain features of the apparatus and method disclosed herein are summarized rather broadly in order that the detailed description thereof that follows may be better understood. There are, of course, additional features of the apparatus and method disclosed hereinafter that will form the subject of the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The present disclosure is best understood with reference to the accompanying figures in which like numerals refer to like elements and in which:

FIG. 1 shows a wellbore system having a distributed temperature sensing system for determining a temperature at a downhole location in an exemplary embodiment of the present disclosure;

FIG. 2 shows an alternate embodiment of a wellbore system suitable for temperature measurements according to the present disclosure;

FIG. 3 shows an exemplary data boundary of a localized two-dimensional subspace of a measurement space;

FIG. 4 shows a schematic diagram of an iterative self-adaptive filtering process of the present disclosure;

FIG. 5 shows an exemplary temperature profile of the present embodiment that illustrates an effect of the existence of a communication channel on a stimulation operation;

FIG. 6 shows a time domain curve for temperature thermal gradient data for the second zone;

FIG. 7 shows a time domain curve for additional zones of the formation in FIG. 5;

FIG. 8 shows a temperature profile showing an effectiveness of two diverting agents during an acid stimulation process;

FIG. 9 shows three stages of an acid stimulation process in a selected zone;

FIG. 10 shows a temperature profile indicative of an integrity of a well and/or a corrosion to a completion string during an acid stimulation process;

FIGS. 11A and 11B illustrate an effectiveness of a stimulation job in various stimulation zones; and

FIGS. 12A-12C illustrate temporal thermal gradient distribution profiles within a range of formation depth at a plurality of times of an acid stimulation process.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0009] FIG. 1 shows a wellbore system 100 having a distributed temperature sensing system 110 for determining a temperature at a downhole location in an exemplary embodiment of the present disclosure. The exemplary wellbore system 100 includes a tubular member 102 disposed in a wellbore 104 formed in a formation 106. The wellbore 104 may be lined with a casing string 108 and the member 102 may be a casing string or disposed inside the casing string 108. In the latter case, the member 102 may be a production tubing, a coiled tubing, or a downhole tool in various embodiments.

[0010] The wellbore system 100 further includes a distributed temperature sensing (DTS) system 110 that is used to obtain a temperature profile along the wellbore 104 over a selected time interval. The DTS system 110 includes fiber optic cable 112 that extends downhole, generally from a surface location. In the embodiment of FIG. 1, fiber optic cable 112 is disposed alongside member 102. In other embodiments, the fiber optic cable 110 may be disposed along the casing string 108 or between the casing string 108 and the formation

106. Thus, the fiber optic cable may be either permanently deployed or may be removable from the wellbore along with the removable member to which it is attached.

[0011] The DTS system 110 includes an optical interrogator 114 which is used to obtain raw temperature measurements from the fiber optic cable 112. The optical interrogator 114 includes a laser light source 118 that generates a short laser pulse that is injected into the fiber optic cable 112 and a digital acquisition unit (DAU) 120 for obtaining optical signals from the fiber optic cable 112 in response to the laser pulse injected therein. The obtained optical signals are indicative of temperature. In one embodiment, Raman scattering in the fiber optic cable 112 occurs while the laser pulse travels along the fiber, resulting in a pair of Stokes and anti-Stokes peaks. The anti-Stokes peak is highly responsive to a change in temperature while the Stokes peak is not. A relative intensity of the two peaks therefore provides a measurement indicative of temperature change. The back-reflected Raman scattering (i.e., the Stokes and anti-Stokes peaks) may thus transmit the temperature information of a virtual sensor while the laser pulse is travelling through the fiber optic cable 112. The location of the virtual sensor is determined by the travel time of the returning optical pulse from the interrogator 114 to the signal detector 120.

[0012] The DAU 120 obtains raw temperature measurement data (raw data) and sends the raw data to a data processing unit (DPU) 116. The DPU 116 performs the various methods disclosed herein for increasing a resolution of temperature measurements, among other things. The DPU 116 may include a processor 122 for performing the various calculations of the methods disclosed herein. The DPU 116 may further comprise a memory device 124 for storing various data such as the raw data from the DAU 120 and various calculated results obtained via the methods disclosed herein. The memory device 124 may further include programs 126 containing a set of instructions that when accessed by the processor 122, cause the processor 122 to perform the methods disclosed herein. The DPU 116 may provide results of the calculations to the memory device 124, display 127 or to one or more users 128. In various embodiments, the DPU 116 may wrap the resulting high-resolution DTS data into a managed data format that may be delivered to the users 128. The DPU 116 may be in proximity to the DAU 120 to reduce data communication times between the DPU 116 and DAU 120. Alternatively, the DPU 116 may be remotely connected to the DAU 120 through a high-speed network.

[0013] The raw data obtained at the DAU 120 may include noises at levels that are in a range from one to several degrees Celsius. Such noises may originate due to attenuation loss, noise in the data acquisition system, environmental temperature variations of the fiber

optic cable, etc. In one embodiment, the present disclosure provides an adaptive filter to reduce those noises to thereby increase a resolution of the temperature measurements. In one embodiment, the temperature resolution of the data after the filtering methods described herein may be greater than the resolution of the raw temperature measurement data. In an exemplary embodiment, a resolution of raw temperature measurement data that is from about 0.5°C to about 1.5°C may be processed using the methods disclosed herein to obtain a post-filtered resolution of about ten millidegrees Celsius. In general, an increase in temperature resolution may be about two orders of magnitude.

[0014] FIG. 2 shows an alternate embodiment of a wellbore system 120 suitable for temperature measurements according to the present disclosure. The alternate wellbore system 120 includes a member 132 having a DTS system 134 attached thereto in which a fiber optic cable 136 of the DTS system 134 is a dual-ended cable. The fiber optic cable 136 has a first leg 136a that extends from a surface location 140 to a bottom location 142 along one side of the member 132 and a second leg 136b that may extend from the bottom location 142 back to the surface location 140 along a same side of the member 132. A third segment 136c of the fiber optic cable 136 may wrap around the bottom of the member 132. Both ends of the fiber optic cable 136 are coupled to the interrogator unit 144. Thus, source laser light generated at the interrogator unit 134 may enter the fiber optic cable at point A and propagate in one direction, referred to herein as a forward direction and indicated by arrows 144, to return to the interrogator unit 134 at point B. Temperature measurements may thus be obtained for the laser light propagating in the forward direction. Alternatively, source laser light may enter the fiber optic cable at point B and propagate in an opposite direction, referred to herein as a backward direction and indicated by arrows 146, to return to the interrogator 134 at point A. Temperature measurements may be obtained for the laser light propagating in the backward direction.

[0015] The raw temperature measurements obtained from the DTS systems of FIGS. 1 and 2 exist in a locally-compact measurement space that is correlative and expandable. A two-dimensional measurement space in time and depth for the temperature measurements may be written as:

$$R(t, z|0 < t < \infty, -\infty < z < \infty) \quad \text{Eq. (1)}$$

for which there exists a subspace

$$R_{i,j}\left(t, z\middle|t_{i-n_t} < t < t_{i+n_t}, z_{j-n_z} < z < z_{j+n_z}\right) \quad \text{Eq. (2)}$$

(also referred to herein as R_{ij}) where $2n_t$ and $2n_z$ are respectively the dimensions for a window defining this subspace within the two-dimensional measurement space.

[0016] FIG. 3 shows an exemplary data boundary of a localized two-dimensional subspace R_{ij} of the measurement space. The data boundary may be related to raw temperature measurement data and may be used in the exemplary filtration method described herein to filter the temperature measurements input into the filter. Signal point 302 is plotted as a function of the variables time (t) and depth (z), with the time plotted along the x-axis and the depth plotted along the y-axis. As shown in FIG. 3, exemplary signal point 302 is located at (i,j). In one aspect, window 304 is drawn around and centered at the exemplary signal point 302 to the selected subspace R_{ij}. The dimension of the window 304 may define parameters of the applied filter. The window 304 has dimensions of $2n_t+1$ along the time axis and $2n_z+1$ along the depth axis and extends from i-n_t to i+n_t along the time axis and from j-n_z to j+n_z along the depth axis. The dimensions of the window 304 may affect a finite impulse response of a filter defined over the measurement subspace.

[0017] If n_t and n_z are of a selected size, for a raw temperature measurement $T_{i+\Delta i,j+\Delta j}$ which falls into the subspace R_{ij}, a Taylor series expansion may be used to correlate measurements for the current window with that of the center point $T_{i,j}$ of the subspace using the following expression:

$$T_{i+\Delta i,j+\Delta j} = T_{i,j} + \left(\frac{\partial T}{\partial t}\right)_{i,j} \Delta i d_t + \left(\frac{\partial T}{\partial z}\right)_{i,j} \Delta j d_z + \left(\frac{\partial^2 T}{\partial t^2}\right)_{i,j} \frac{(\Delta i d_t)^2}{2} + \left(\frac{\partial^2 T}{\partial z^2}\right)_{i,j} \frac{(\Delta j d_z)^2}{2} + \left(\frac{\partial^2 T}{\partial t \partial z}\right)_{i,j} \frac{(\Delta i \Delta j d_t d_z)^2}{2} + \cdots \quad \text{Eq. (3)}$$

where d_t and d_z are respectively the distances along the temporal axis and the spatial axis between two neighboring sensing points within the measurement space, as shown in Figure 3. Eq. (3) defines a multiple term decomposition of the DTS data, wherein the decomposition includes a Taylor series decomposition having terms of selected orders, e.g. first order terms, second order terms, etc. Each term of the Taylor series decomposition generally has an associated physical meaning and provides a different level of resolution to the raw temperature measurement data. The present disclosure employs a non-orthogonal transform of the Taylor series decomposition of Eq. (3) limited to a selected number of these representations. In one embodiment, terms of the Taylor series composition up to the second order are used and terms that are of orders higher than two are not considered. Equation (3) may thus be rewritten as:

$$T_{i+\Delta i,j+\Delta j} = \vec{\boldsymbol{H}}_{i+\Delta i,j+\Delta j} \cdot \vec{\boldsymbol{T}}_{i,j} = \sum_{k=0}^{5} h_{\Delta i,\Delta j}^{k} \mathcal{T}_{i,j}^{k} \quad \text{Eq. (4)}$$

where $\vec{\boldsymbol{H}}_{i,j}$ denotes a non-orthogonal transformation vector, and $\vec{\boldsymbol{T}}_{i,j}$ denotes a vector containing the terms that are to be determined for the giving point (*i,j*). A linear reconstruction of the measurement $T_{i,j}$ in the subspace $R_{i,j}$ may be obtained by maximizing the energy compaction for the given transformation vector or, equivalently, by minimizing an expectation value of a linear estimator function:

$$\sum_{k=0}^{5} E\left[\left\|\Gamma_{i,j}^{k}-\hat{\Gamma}_{i,j}^{k}\right\|^{2}\right] \quad \text{Eq. (5)}$$

where $\hat{\Gamma}_{i,j}^{k}$ is the of $\Gamma_{i,j}^{k}$, and $\Gamma_{i,j}^{k}$ is a collection of the k^{th} term of the decomposition of the temperature measurements in subspace R_{ij}. In particular, $\Gamma_{i,j}^{k}$ are the elements of vector $\mathcal{T}_{i,j}^{k}$, as illustrated with respect to Eq. (8) below.

Referring back to Eq. (5),

$$\Gamma_{i,j}^{k}=\Gamma_{i,j}^{k-1}-\hat{\Gamma}_{i,j}^{k-1} \quad \text{Eq. (6)}$$

where $\Gamma_{i,j}^{0}=\hat{\Gamma}_{i,j}$ is the actual raw temperature measurement ($T_{i,j}$) in the measurement subspace and which may be a function of time and depth. Eq. (6) defines a generally time-consuming approach to the non-orthogonal transform problem, in which a k^{th} representation is progressively obtained using the $(k\text{-}1)^{th}$ representation. However, the present disclosure speeds this process by using a single step approach in which the expectation of the linear estimator function (Eq. (5)) is rewritten as:

$$\sum_{\Delta i=-n_t}^{n_t}\sum_{\Delta j=-n_z}^{n_z}\left(T_{i+\Delta i,j+\Delta j}-\sum_{k=0}^{5}h_{\Delta i,\Delta j}^{k}\mathcal{T}_{i,j}^{k}\right)^{2} \quad \text{Eq. (7)}$$

where $\vec{\mathcal{T}}_{i,j}$ is a vector containing the following physical quantities:

$$\vec{\mathcal{T}}_{i,j}=\left(T_{i,j},\left(\frac{\partial T}{\partial t}\right)_{i,j},\left(\frac{\partial T}{\partial z}\right)_{i,j},\left(\frac{\partial^{2}T}{\partial t^{2}}\right)_{i,j},\left(\frac{\partial^{2}T}{\partial z^{2}}\right)_{i,j},\left(\frac{\partial^{2}T}{\partial t\partial z}\right)_{i,j}\right)^{T} \quad \text{Eq. (8)}$$

By defining a linear transfer function:

$$\mathcal{H}=H(H^{T}H)^{-1}H^{T} \quad \text{Eq. (9)}$$

with

$$H=\begin{pmatrix} h_{-n_t,-n_z}^{0} & \cdots & h_{-n_t,-n_z}^{5} \\ \vdots & \ddots & \vdots \\ h_{n_t,n_z}^{0} & \cdots & h_{n_t,n_z}^{5} \end{pmatrix}, \quad \text{Eq. (10)}$$

we can obtain the following solution:

$$\vec{\mathcal{T}}_{i,j}=\mathcal{H}\Gamma_{i,j} \quad \text{Eq. (11)}$$

[0018] This solution to the Taylor series decomposition may also be viewed as a 2-dimensional filter for digitally filtering the raw temperature measurement data. Since the higher-order terms (i.e., terms of order greater than 2) in the Taylor series decomposition are

not considered, $\mathcal{H}$ in Eq. (9) is only an approximate transfer function in which the approximation error depends on the size of subspace R_{ij}. Therefore, a window size suitable for obtaining selected filtration results may be selected. An iterative self-adaptive algorithm, as shown in FIG. 4 achieves this filtration result to a selected approximation error.

[0019] FIG. 4 shows a schematic diagram 400 of an iterative self-adaptive filtering process of the present disclosure. The iterative filtering process may be used to provide an accuracy or resolution of temperature measurements to within a selected approximation error. The filtering process preserves transition information for the set of continuous temperature measurement data.

[0020] Temperature signal *T(t,z)* 410 represents a raw DTS temperature measurement obtained from a DTS system which is an input signal to the filter system 400. Noise signal *n(t,z)* 412 indicates an unknown noise signal accompanying the temperature measurements 410 and which is also input to the filter system 400. In general, the temperature signal 410 and the noise signal 412 are indistinguishable in DTS systems and thus are input to filter 402 as a single measurement. In addition, noise signal *n(t,z)* 412 is often not constant but changes with changes in environment. Therefore, both temperature signal *T(t,z)* 410 and noise signal *n(t,z)* 412 are dependent on time and depth of the measurement location in the DTS system. Output signal 414 is a filtered output signal and may include multiple terms of the decomposition of Eq. (3), such as for $T_{i,j}, \left(\frac{\partial T}{\partial t}\right)_{i,j}, \left(\frac{\partial T}{\partial z}\right)_{i,j}$, etc.

[0021] In one embodiment, the exemplary filter 402 is a self-adaptive filter using a dynamic window (such as data window 304 in FIG. 3) that may be adjusted to reduce noise in the temperature measurements. The temperature signal 410 and noise signal 412 are fed to filter 402 which provides an approximation to the temperature measurements using the methods disclosed above with respect to Equations (1)-(12). In various embodiments, the approximation may provide values for one or more of terms $T_{i,j}, \left(\frac{\partial T}{\partial t}\right)_{i,j}, \left(\frac{\partial T}{\partial z}\right)_{i,j}$. A criterion 404 may then be applied to the terms output from the filter 402 to determine an effectiveness of the filter 420. In one embodiment, the selected criterion may be a selected resolution of the temperature measurements or a selected resolution for a selected term of the decomposition. If the filtered terms are found to be within the selected resolution, the filtered terms may be accepted as output signals 414. Otherwise, the filter 402 may be updated at updating stage 406. Updating may include, for example, changing the dimensions of the measurements subspace R_{ij}. In various embodiments, this decomposition process represents

DTS measurement data as a Taylor series decomposition that includes terms having various levels of temperature resolution. The first order terms have a resolution that is greater than zero-order terms, the second order terms have a resolution greater than the first order terms, etc. The first order terms, which are thermal derivatives in depth or time and the second order derivatives (i.e., variance with respect to depth, variance with respect to time and variance with respect to depth and time) may reach temperature resolutions up to several hundredths of a degree.

[0022] Although the methods are discussed with respect to temperature measurements, the present disclosure may also be applied to any suitable signal that is a continuous function measured in a two-dimensional measurement space. While the method is described with respect to a Taylor series decomposition (Eq. (3)), other numerical decompositions may be also used in various alternate embodiments.

[0023] The methods described above may be used to create a temperature profile in the form of a temporal thermal gradient (TTG), spatial thermal gradient (STG) as well as thermal divergence data that may be used to view micro-level temperature changes downhole. The thermal gradient and divergence data may display a temperature resolution or sensitivity level up to several hundredths of a degree Celsius. Such resolution may be used to monitor a stimulation operation in real-time. The measurements may be obtained and the temperature profile may be displayed during a stimulation operation i.e. while the stimulation operation is ongoing. The temperature profile may then be used to determine a state of the stimulation operation such as, for example, a detection of a cross-communication channel between stimulation zones, a high-permeability zone or a low pressure zone, a placement of a diverter, an effectiveness of the diverter, an acid injection profile, a corrosion level of a work string and/or a well integrity, a presence and/or location of a water cut zone, and/or an effectiveness of a stimulation procedure. In various embodiments, an operator or processor may use the determined state to select a course of action for the stimulation operation and/or to alter a stimulation parameter of the stimulation operation. For example, the operator may adjust a stimulation parameter, end a stimulation procedure, reschedule a placement of a diverter, change a volume or a concentration of an acid used in the stimulation procedure and add an acid inhibitor to a selected zone, etc. As a result, use of the temperature profiles during the acid stimulation operation reduces uncertainties or "blind spots" in the operation. In general, a real-time change made to the stimulation operation is a change made to the same acid stimulation operation from which the measurements are obtained. Thus, the methods may be used to determine a downhole parameter that may be used to optimize or improve an

acid stimulation process. FIG. 5 shows an exemplary temperature profile 500 of the present embodiment that illustrates an effect of the existence of a communication channel on a stimulation operation. A communication channel, or fracture, may form naturally or may form as a result of a stimulation operation. A stimulation program may not account for a communication channel that forms during the operation, since the communication channel may not be detected in pre-stimulation formation evaluations. The real-time temperature profiles disclosed herein allow an operator to detect the communication channel as it forms during a stimulation operation and to make a real-time adjustment to a parameter or the stimulation operation or to stop the operation altogether.

[0024] The temperature profile 500 displays two perforated zones with the upper zone 510 being the target of acid stimulation. The formation may include additional zones which are not displayed in temperature profile 500. A first zone 510 extends from a depth of approximately 13530 feet to a depth of approximately 14230 ft. A second zone 520 extends from approximately 14300 ft. to approximately 15150 ft. The temperature profile 500 shows wellbore depth along the y-axis and time along the x-axis. The temperature profile 500 is color coded to represent temperature changes in the formation. A red color (such as red color 501) at a selected depth and time indicates an increase in temperature at that selected depth and time. An increase in temperature may be indicative of heating due to a stimulation reaction. A blue color (such as blue color 502) at a selected depth and time indicates a decrease in temperature at the selected depth and time. A decrease in temperature may be indicative of cooling related to an end of a stimulation reaction or a cooling related to introduction of the acid (which is cooler than the formation) into the formation. A green color (such as green color 503) at a selected depth and time indicates a constant temperature at the selected depth and time.

[0025] The first zone 510 is targeted for acid stimulation using acid and diverting agent. However, the second zone 520 appears to show heating and cooling simultaneously with the upper zone 510, thereby strongly suggesting that acid injected in the first zone 510 is being transferred into the second zone 520. Therefore, one may conclude that the first zone 510 and the second zone 520 are connected by a communication channel or fracture.

[0026] FIG. 6 shows a TTG curve 601 from a representative virtual sensor (i.e., fiber optic cable 112) in the second zone 520. Time is shown along the abscissa. The time domain curve 601 shows a heating signal 603 in the second zone 520 in response to acid stimulation corresponding to acid being introduced into the first zone 510. The strong heating signal 603 for second zone 520 indicates that the injected acid from the first zone 510 is being pushed

into the second zone 520, thereby confirming the presence of a communication channel between first zone 510 and second zone 520.

[0027] FIG. 7 shows a time domain TTG curve 701 obtained at the first zone 510 in FIG. 5. Time is shown along the abscissa. Positions 710 and 720 indicate respectively the times at which two upper zones (with respect to the first zone 510) are stimulated. It is clear from time domain curve 701 that no exothermic reaction is occurring in either moment 710 or moment 720. Thus, no acid from the two upper zones have been communicated to the first zone 510. Therefore, it may be concluded that there is no communication channel between zone 520 and the upper zones.

[0028] FIG. 8 shows a temperature profile 800 showing an effectiveness of two diverting agents during an acid stimulation process. The placement and effectiveness of a diverting agent may be observed in real-time. In the temperature profile 800, the introduction of the diverting agent into a selected zone (shown as 'Z's) generates a cooling signal (blue) since the temperature of the diverting agent is normally below that of the formation. The cooling signal may also be a result of the diverting agent cooling an exothermic reaction between an acid and the formation. Acid is injected at a selection zone shown as 'A's. The temperature profile 800 shows that the acid begins at a lower depth (from about 13400 feet to about 13500 feet). Over time, the diverting agent pushes the acid to higher depths in the wellbore (from about 12900 feet to about 13000 feet). The diversion of the acid is indicated by arrow 801. Thus, the effectiveness of the diverting agent may be observed.

[0029] FIG. 9 shows thermal gradient distribution profiles of an acid stimulation process in a selected zone wherein the depth is shown along the x-axis and the gradient is shown along the y-axis. The earliest gradient distribution profile is shown at top and the last gradient distribution profile shown at bottom. The acid stimulation process takes place over a region from about 13,060 to about 13,400 ft. A first stage is represented by a gradient distribution profile 901 and shows acid being injected into the formation. Blue circle 910 indicates that acid has been introduced into the formation and is cooling the formation at the stimulation zone. The second stage is represented by gradient distribution profiles 902 through 904 and shows the progress of the acid stimulation in the formation. At gradient distribution profile 902 (6 minutes after injection), acid reaction is shown beginning along the end regions 911 and 913 while a middle zone 912 is still cooling. Gradient distribution profiles 903 and 904 show acid stimulation reactions taking place throughout the zone. The third stage is represented by gradient distribution profiles 905-908. During the third stage a diverting agent is flooded into the region. The third stage generally begins at about 8 to 9

minutes after the beginning of the second stage (i.e., depth profile 902). The injection of the diverting agent during the third stage has a cooling effect of the reaction, which may be seen in the changes to the temperature gradient. The temperature gradient is generally proportional to an amount of acid consumed by the formation. Therefore, the TTG curves may provide direct information as to the profile of the acid that has been taken.

[0030] FIG. 10 shows a temperature profile 1000 indicative of an integrity of a well and/or a corrosion to a completion string during an acid stimulation process. The color map 100 shows a heating signal 1001 due to exothermal reaction between metal of the completion string and the acid stimulation chemicals. An amount of heating may be determined from the heating signal 1001 and the determined amount of heating and a molar heat of the reaction may be used to determine a degree of the corrosion.

[0031] FIGS. 11A and 11B illustrate an effectiveness of a stimulation job in various stimulation zones. FIG. 11A shows a stimulation process targeted to a zone from 11,600 ft to 12,450 ft. Lower portion 1101 of the depth interval takes a majority of acid, leaving the upper portion 1102 of the perforation interval much less stimulated. The disparity in stimulation may result from a diverter failing to seal off the lower interval 1102, which may be highly permeable. FIG. 11B shows a stimulation process in which a more uniform acid stimulation occurs over the zone 1103 as shown by the red region which extends substantially along the zone.

[0032] FIGS. 12A-12C illustrates thermal gradient distribution profiles 1200 along formation depth at a plurality of times of an acid stimulation process. Plurality of thermal gradient distribution profiles displays temperature representations obtained using the methods disclosed herein. As shown in profile 1200, the depth range covers two isolated perforation zones respectively labeled as Zone 3 and Zone 2. In profile 1202, an acid is injection into the top of the Zone 3 at about 13577 feet. The gradient curve indicated by circle 1220 shows the cooling effect induced by injecting the acid solution into the formation. In profile 1203, the cooling effect occurs over the entirety of Zone 3 as the acid solution fills up the entire zone, as indicated by circle 1222. In profile 1204, an exothermic reaction begins in Zone 3 as indicated by circle 1224. The remainder of Zone 3 shows neither cooling from the injection of the acid solution nor heating due to chemical reactions. Additionally, the cooling is beginning in Zone 2, as indicated by circle 1226, which indicates that a communication channel or fracture exists between Zone 3 and Zone 2.

[0033] FIG. 12B shows thermal gradient distribution profiles 1205-1208 as a continuation of the stimulation process presented in FIG. 12A. In profile 1205, the

exothermic reaction has spread through entire Zone 3 (circle 1228), while acid continues to spread into Zone 2 (circle 1230). As shown in profile 1206, an exothermic reaction (circle 1232) begins in Zone 2, while acid continues to spread throughout Zone 2 (circle 1234). In depth profile 1207. The exothermic reaction begins to diminish as acid is being consumed in the upper portion of Zone 3 (circle 1236) while continuing in the lower portion of Zone 3 (circle 1238). In Zone 2, the acid continues to spread into Zone 2 as indicated by the exothermic reaction signal (circle 1240) and cooling signal induced by liquid penetrating through the formation (circle 1242). In profile 1208, Zone 3 is almost entirely cooling from the acid reaction (circle 1244), while a portion of Zone 2 is experience stimulation (circle 1246).

[0034] FIG. 12C shows thermal gradient distribution profiles 1209-1212 as a continuation of the stimulation process presented in FIG. 12B. In profile 1209, Zone 3 continues to cool (circle 1248) while in Zone 2, cooling begins at an upper portion of Zone 2 (circle 1250) with acid stimulation continuing at lower portions of Zone 2. Profiles 1210, 1211 and 1212 show the progression of the acid stimulation heating (circles 1256, 1260 and 1264) and post-stimulation cooling (circles 1254, 1258 and 1262)

[0035] While the methods disclosed herein have been discussed with respect to vertical wells, the methods may be equally suitable for use in a stimulation process of a horizontal well and/or a deviated well.

[0036] Thus, various downhole parameters may be measured and/or determined using the TTG and STG profiles disclosed herein. These downhole parameters may be used for real-time altering or adjusting of the acid stimulation process. For example, at least a qualitative understanding of permeability or pressure of the formation may be determined by a rate of change of the heating events, etc. Additionally, an acid distribution profile in the wellbore based on locations of the heating and cooling events displayed in an STG. The actual acid distribution profile may be compared with a predetermined or prescheduled acid distribution profile in order to make alterations to the acid stimulation process.

[0037] Therefore in one aspect, the present disclosure provides a method of stimulating a formation. The method includes: performing a stimulation operation at a selected stimulation zone of the formation using a first value of stimulation parameter; obtaining a temperature measurement at the formation during the stimulation operation, wherein the obtained temperature measurement is indicative of a parameter related to the stimulation operation; determining the downhole parameter using the obtained temperature measurements; and altering the stimulation parameter to a second value in real-time based on

the determined parameter. Temperature data may be obtained using a distributed temperature sensing system. A numerical decomposition of the obtained temperature data may be performed within a dynamic window in measurement space of the raw temperature data to obtain decomposition terms of first order and higher. An adaptive filter may be applied to the dynamic window to reduce noise from the decomposition terms of first order and higher, and the temperature profile may be obtained using the filtered decomposition terms of first order and higher. In various embodiments, the temperature profile may display at least one of a temperature divergence and a temperature gradient in the formation. Altering the value of the stimulation parameter in real-time may include altering the parameter before an end of the stimulation operation. The downhole parameter may include: (i) a zone cross-over; (ii) a zone permeability; (iii) a zone formation pressure; (iv) a placement of a diverting agent (v) an effectiveness of a diverting agent; (vi) an acid distribution profile; (vii) a carbonate composition of a formation; and (viii) a property of the formation that affects the stimulation operation, in various embodiments. Obtaining the temperature measurement profile further comprises obtaining a spatio-temporal temperature measurement profile over a selected depth interval of the formation and over a selected time interval.

[0038] In another aspect, the present disclosure provides a system for stimulating a formation, the system including: a work string in a well formed in the formation; a stimulation sub of the work string at a selected zone of the formation configured to perform a stimulation operation; a temperature measurement system disposed along the workstring; and a processor configured to: control the stimulation sub to perform the stimulation operation using a first value of a stimulation parameter, obtain a temperature measurement profile during the stimulation operation from the distributed temperature sensing system, determine a downhole parameter related to the stimulation operation from the obtained temperature measurement profile, and alter the stimulation parameter to a second value in real-time based on the determined downhole parameter. The system may further include a distributed temperature sensing system configured to obtain temperature measurements. The processor performs a numerical decomposition of the obtained temperature data within a dynamic window in measurement space of the raw temperature data to obtain decomposition terms of first order and higher, apply an adaptive filter in the dynamic window to reduce noise from the decomposition terms of first order and higher, and obtain the temperature profile using the filtered decomposition terms of first order and higher. The processor may use the obtained temperature measurement profile to determine at least one of a temperature divergence and a temperature gradient in the formation. The processor may alter the value of

the stimulation parameter in real-time by altering the value of the stimulation parameters before a predetermined end of the stimulation operation. The downhole parameter may include: (i) a connection between zones; (ii) a zone permeability; (iii) a zone formation pressure; (iv) a placement of a diverting agent; (v) an effectiveness of a diverting agent; (vi) an acid stimulation profile; (vii) a carbonate composition of the formation; and (viii) a property of the formation that affects the stimulation operation. The temperature measurement profile may include a spatio-temporal temperature measurement profile over a selected depth interval of the formation and over a selected time interval.

[0039] In yet another aspect, the present disclosure provides a computer-readable medium having stored thereon a set of instructions that when read by a processor enable the processor to perform a method for stimulating a formation. The method includes: performing a stimulation operation using a first value of a stimulation parameter; obtaining a temperature measurement profile related to the stimulation operation during the stimulation operation; determining a downhole parameter related to the stimulation operation from the obtained temperature measurement profile; and altering the stimulation parameter to a second value in real-time based on the determined downhole parameter. Temperature data may be obtained using a distributed temperature sensing system at the formation. The method further includes: performing a numerical decomposition of the obtained temperature data within a dynamic window in measurement space of the raw temperature data to obtain decomposition terms of first order and higher; applying an adaptive filter to the dynamic window to reduce noise from the decomposition terms of first order and higher; and obtaining the temperature profile using the filtered decomposition terms of first order and higher. The method may further include using the obtained temperature measurement profile to determine at least one of a temperature divergence and a temperature gradient in the formation. Altering the stimulation parameter in real-time may include altering the parameter before a predetermined end of the stimulation operation. The downhole parameter may include: (i) a zone cross-over; (ii) a zone permeability; (iii) a zone formation pressure; (iv) a placement of a diverting agent; (v) an effectiveness of a diverting agent; (vi) an acid distributionprofile; (vii) a carbobate composition of a formation; and (viii) a property of the formation that affects the stimulation operation.

[0040] While the foregoing disclosure is directed to the preferred embodiments of the disclosure, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.

CLAIMS

What is claimed is:

1. A method of stimulating a formation, comprising:

performing a stimulation operation at a selected stimulation zone of the formation using a first value of stimulation parameter;

obtaining a temperature measurement profile at the formation during the stimulation operation, wherein the obtained temperature measurement profile is indicative of a parameter related to the stimulation operation;

determining the downhole parameter using the obtained temperature measurement profile; and

altering the stimulation parameter to a second value in real-time based on the determined parameter.

2. The method of claim 1 further comprising obtaining temperature data using a distributed temperature sensing system.

3. The method of claim 3, further comprising performing a numerical decomposition of the obtained temperature data within a dynamic window in measurement space of the raw temperature data to obtain decomposition terms of first order and higher; applying an adaptive filter to the dynamic window to reduce noise from the decomposition terms of first order and higher; and obtaining the temperature profile using the filtered decomposition terms of first order and higher.

4. The method of claim 1, wherein the temperature profile displays at least one of a temperature divergence and a temperature gradient in the formation.

5. The method of claim 1, wherein altering the value of the stimulation parameter in real-time further comprises altering the parameter before an end of the stimulation operation.

6. The method of claim 1, wherein the downhole parameter is at least one: (i) a zone cross-over; (ii) a zone permeability; (iii) a zone formation pressure; (iv) a placement of a diverting agent (v) an effectiveness of a diverting agent; (vi) an acid distribution profile; and (vii) a property of the formation that affects the stimulation operation.

7. The method of claim 1, wherein obtaining the temperature measurement profile further comprises obtaining a spatio-temporal temperature measurement profile over a selected depth interval of the formation and over a selected time interval.

8. A system for stimulating a formation, comprising:

a workstring in a well formed in the formation;

a stimulation sub of the work string at a selected zone of the formation configured to perform a stimulation operation;

a temperature measurement system disposed along the workstring; and

a processor configured to:

control the stimulation sub to perform the stimulation operation using a first value of a stimulation parameter,

obtain a temperature measurement profile during the stimulation operation from the distributed temperature sensing system,

determine a downhole parameter related to the of the stimulation operation from the obtained temperature measurement profile, and

alter the stimulation parameter to a second value in real-time based on the determined downhole parameter.

9. The system of claim 8, wherein the temperature measurement system further comprises a distributed temperature sensing system configured to obtain temperatures measurements.

10. The system of claim 9, wherein the processor is further configured to perform a numerical decomposition of the obtained temperature data within a dynamic window in measurement space of the raw temperature data to obtain decomposition terms of first order and higher, apply an adaptive filter to the dynamic window to reduce noise from the decomposition terms of first order and higher, and obtain the temperature profile using the filtered decomposition terms of first order and higher.

11. The system of claim 9, wherein the processor is further configured to use the obtained temperature measurement profile to determine at least one of a temperature divergence and a temperature gradient in the formation.

12. The system of claim 8, wherein the processor is further configured to alter the value of the stimulation parameter in real-time by altering the value of the stimulation parameter before a predetermined end of the stimulation operation.

13. The system of claim 8, wherein the downhole parameter is at least one: (i) a zone cross-over; (ii) a zone permeability; (iii) a zone formation pressure; (iv) a placement of a diverting agent; (v) an effectiveness of a diverting agent; (vi) an acid distribution profile; and (vii) a property of the formation that affects the stimulation operation.

14. The system of claim 8, wherein the temperature measurement profile further comprises a spatio-temporal temperature measurement profile over a selected depth interval of the formation and over a selected time interval.

15. A computer-readable medium having stored thereon a set of instructions that when read by a processor enable the processor to perform a method for stimulating a formation, the method comprising:

performing a stimulation operation using a first value of a stimulation parameter;

obtaining a temperature measurement profile related to the stimulation operation during the stimulation operation;

determining a downhole parameter related to the of the stimulation operation from the obtained temperature measurement profile; and

altering the stimulation parameter to a second value in real-time based on the determined downhole parameter.

16. The computer-readable medium of claim 15, the method further comprising obtaining temperature data using a distributed temperature sensing system at the formation.

17. The computer-readable medium of claim 16, the method further comprising performing a numerical decomposition of the obtained temperature data within a dynamic window in measurement space of the raw temperature data to obtain decomposition terms of first order and higher; applying an adaptive filter to the dynamic window to reduce noise from the decomposition terms of first order and higher; and obtaining the temperature profile using the filtered decomposition terms of first order and higher.

18. The computer-readable medium of claim 16, the method further comprising using the obtained temperature measurement profile to determine at least one of a temperature divergence and a temperature gradient in the formation.

19. The computer-readable medium of claim 15, wherein altering the stimulation parameter in real-time further comprises altering the parameter before a predetermined end of the stimulation operation.

20. The computer-readable medium of claim 15, wherein the downhole parameter is at least one: (i) a zone cross-over; (ii) a zone permeability; (iii) a zone formation pressure; (iv) a placement of a diverting agent; (v) an effectiveness of a diverting agent; (vi) an acid distribution profile; and (vii) a property of the formation that affects the stimulation operation.

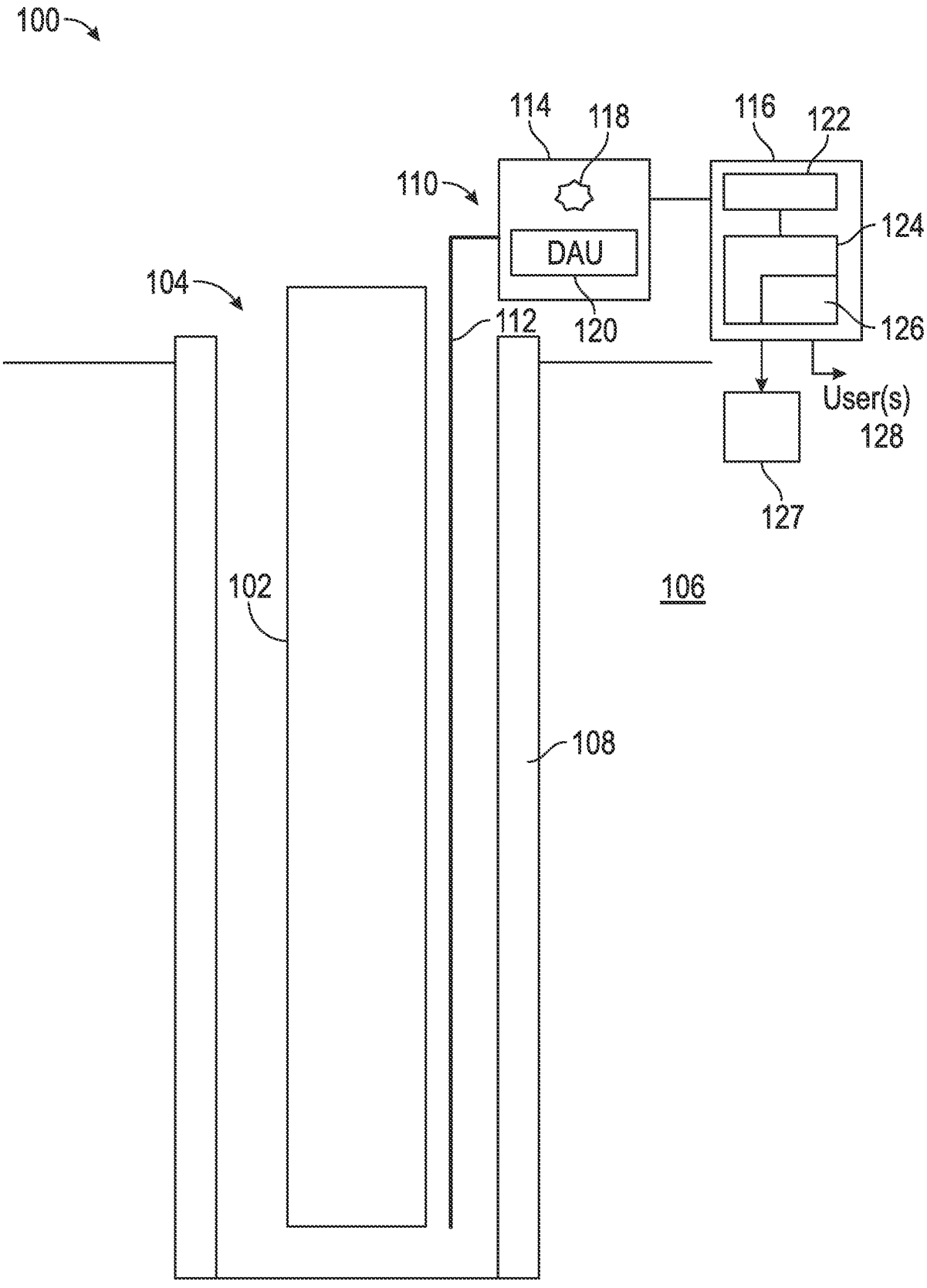

100
114
118
116
122
110
DAU
124
104
112
120
126
User(s)
128
127
102
106
108

FIG. 1

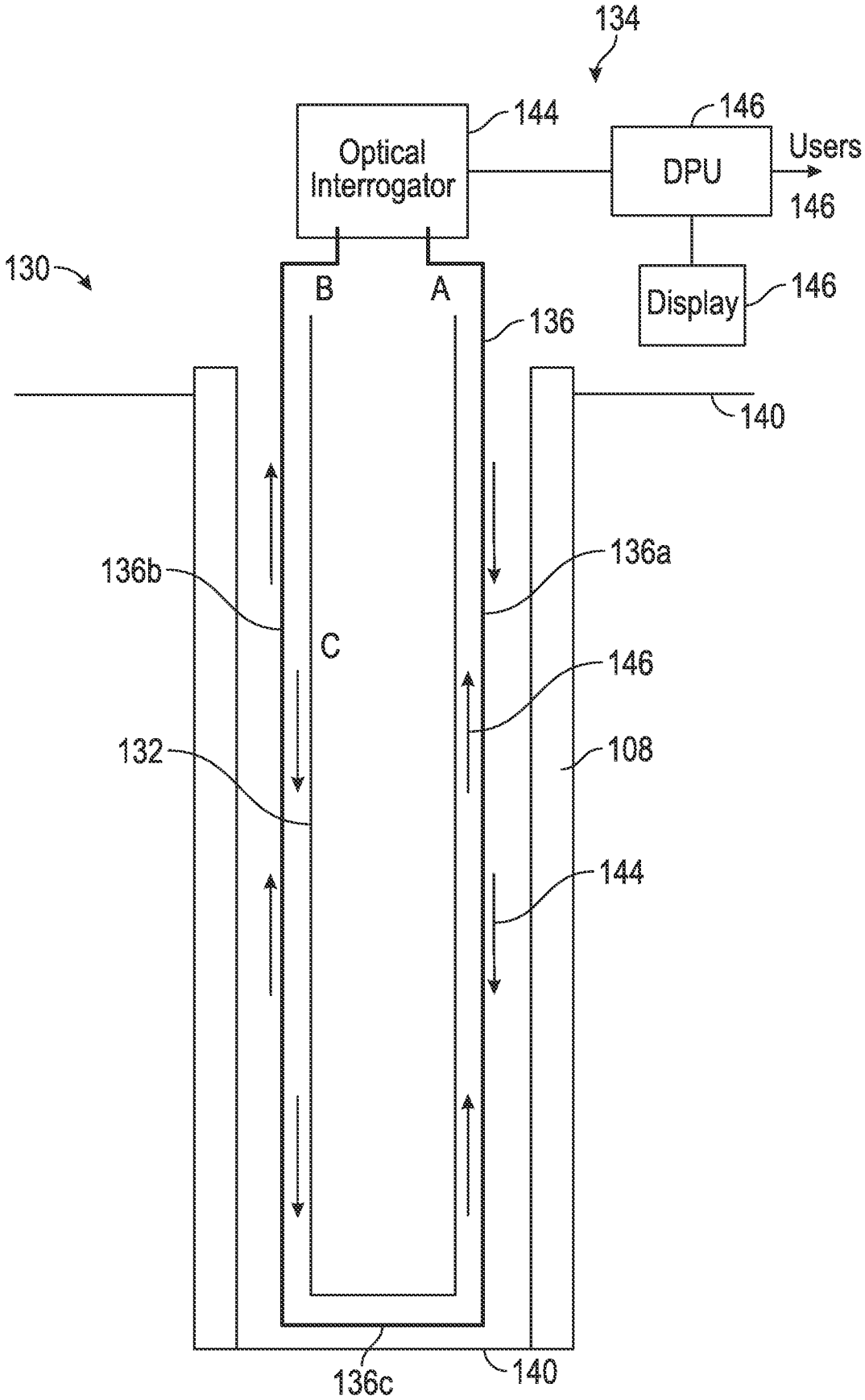

134
144
146
Optical Interrogator
DPU
Users
146
130
B
A
Display
146
136
140
136b
136a
C
146
132
108
144
136c
140

FIG. 2

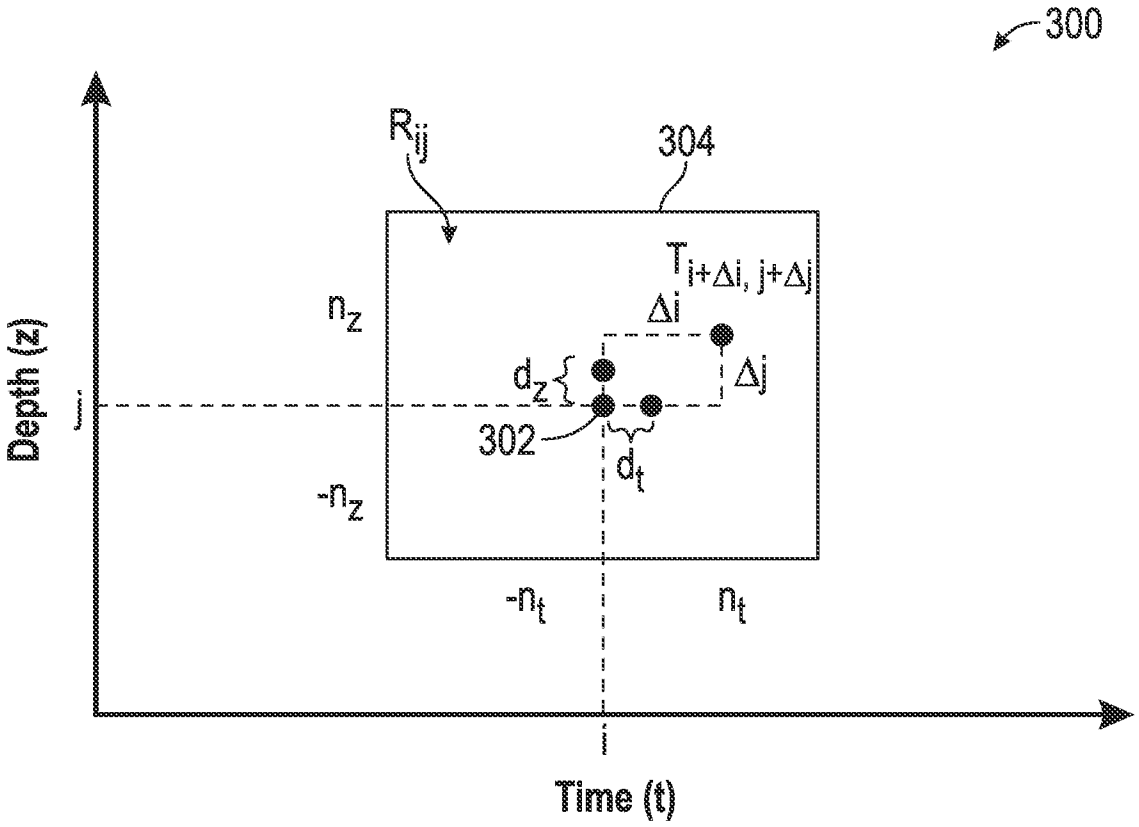

300
R_{ij}
304
$T_{i+\Delta i,\ j+\Delta j}$
n_z
Δi
d_z
Δj
$-n_z$
302
d_t
$-n_t$
n_t
Depth (z)
Time (t)

FIG. 3

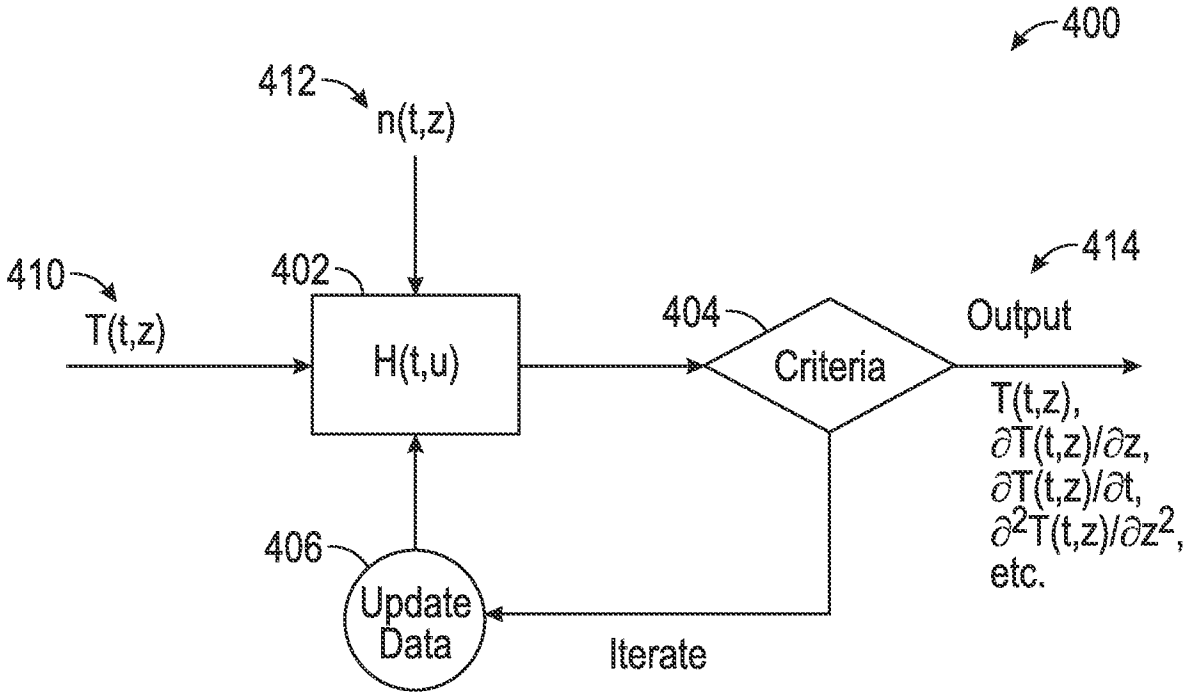

400
412
n(t,z)
410
T(t,z)
402
H(t,u)
404
Criteria
414
Output
T(t,z),
∂T(t,z)/∂z,
∂T(t,z)/∂t,
∂²T(t,z)/∂z²,
etc.
406
Update Data
Iterate

FIG. 4

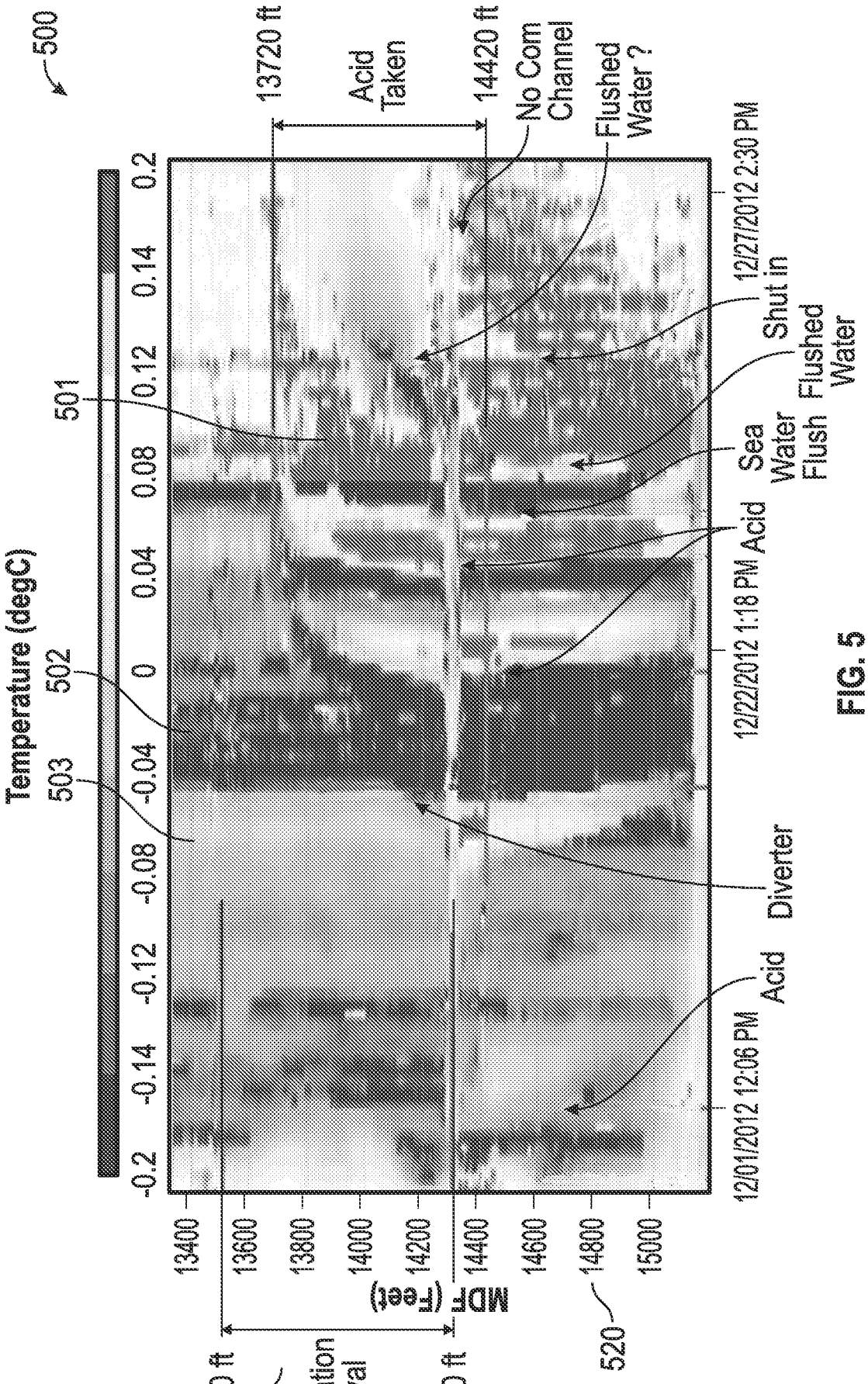

500
Temperature (degC)
-0.2
-0.14
-0.12
-0.08
-0.04
0
0.04
0.08
0.12
0.14
0.2
501
502
503
13400
13600
13800
14000
14200
14400
14600
14800
15000
MD Ft (Feet)
13530 ft
510
Perforation interval
14230 ft
520
13720 ft
14420 ft
Acid Taken
No Com Channel
Flushed Water ?
12/27/2012 2:30 PM
Shut in
Flushed Water
Sea Water Flush
12/22/2012 1:18 PM Acid
Diverter
12/01/2012 12:06 PM
Acid

FIG. 5

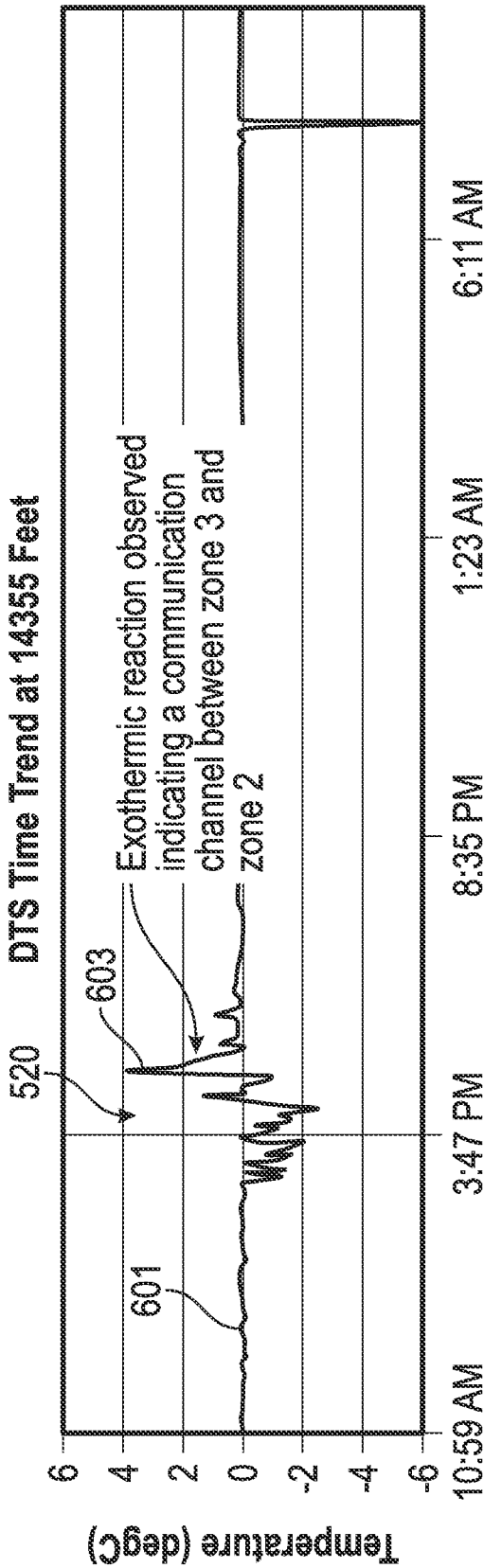

DTS Time Trend at 14355 Feet
520
603
Exothermic reaction observed indicating a communication channel between zone 3 and zone 2
601
Temperature (degC)
6
4
2
0
-2
-4
-6
10:59 AM
3:47 PM
8:35 PM
1:23 AM
6:11 AM

FIG. 6

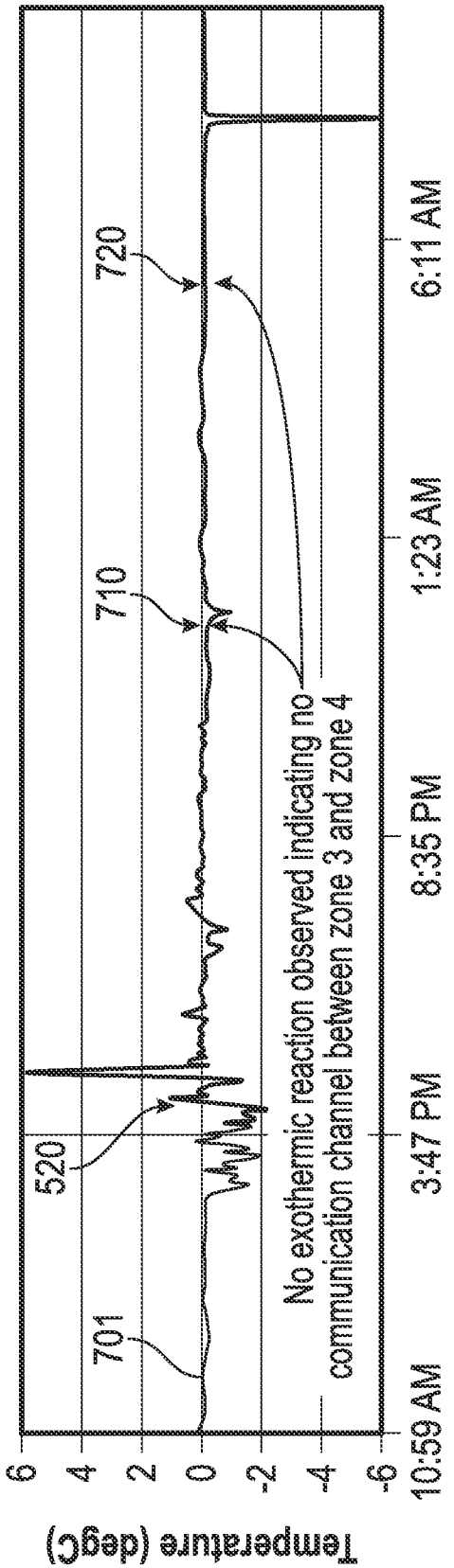
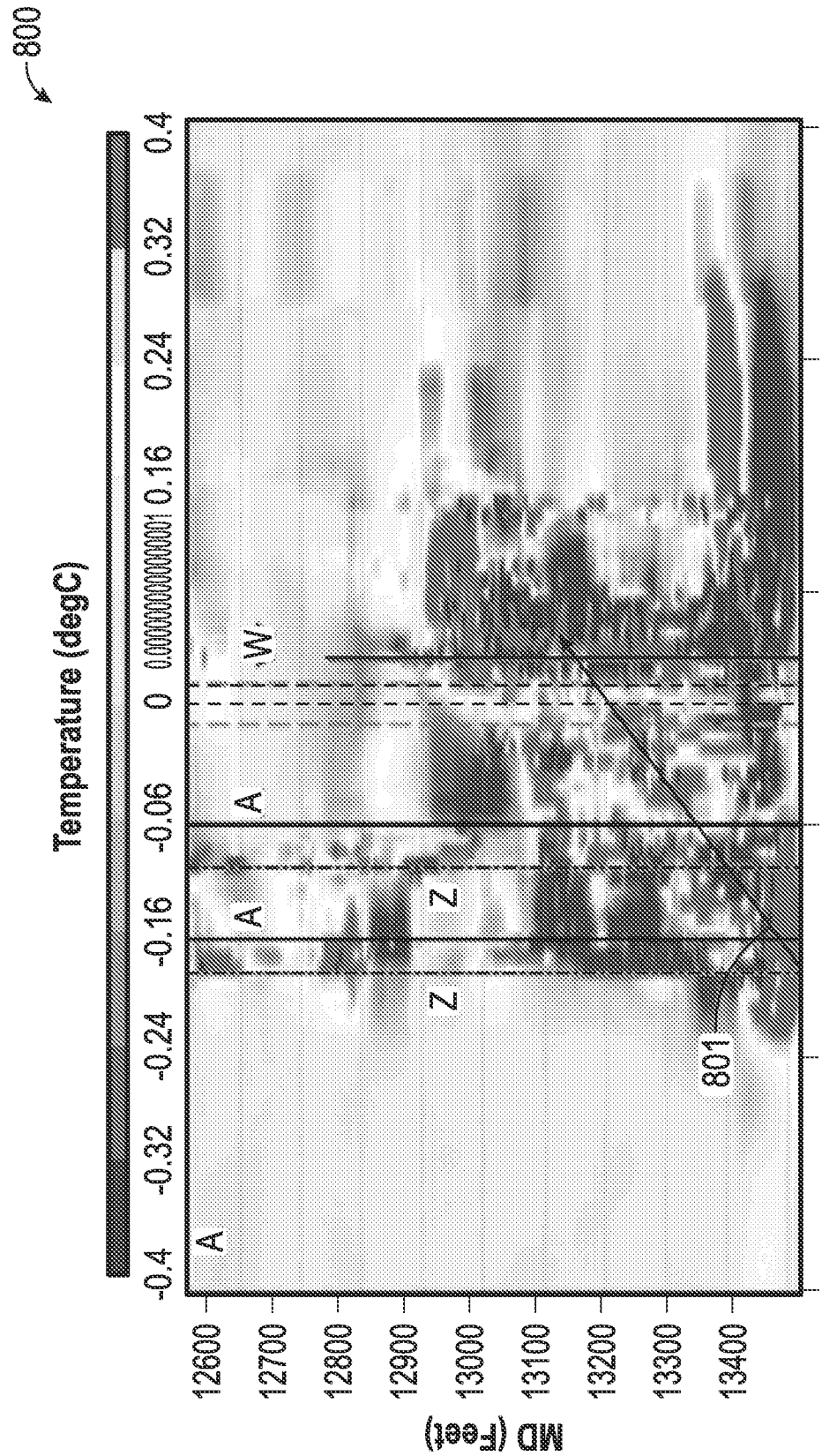

DTS Time Trend at 13772 Feet
720
710
520
701
No exothermic reaction observed indicating no communication channel between zone 3 and zone 4
Temperature (degC)
6
4
2
0
-2
-4
-6
10:59 AM
3:47 PM
8:35 PM
1:23 AM
6:11 AM

FIG. 7



Examplary TSTD color map on a zonal acid stimulation

FIG. 8

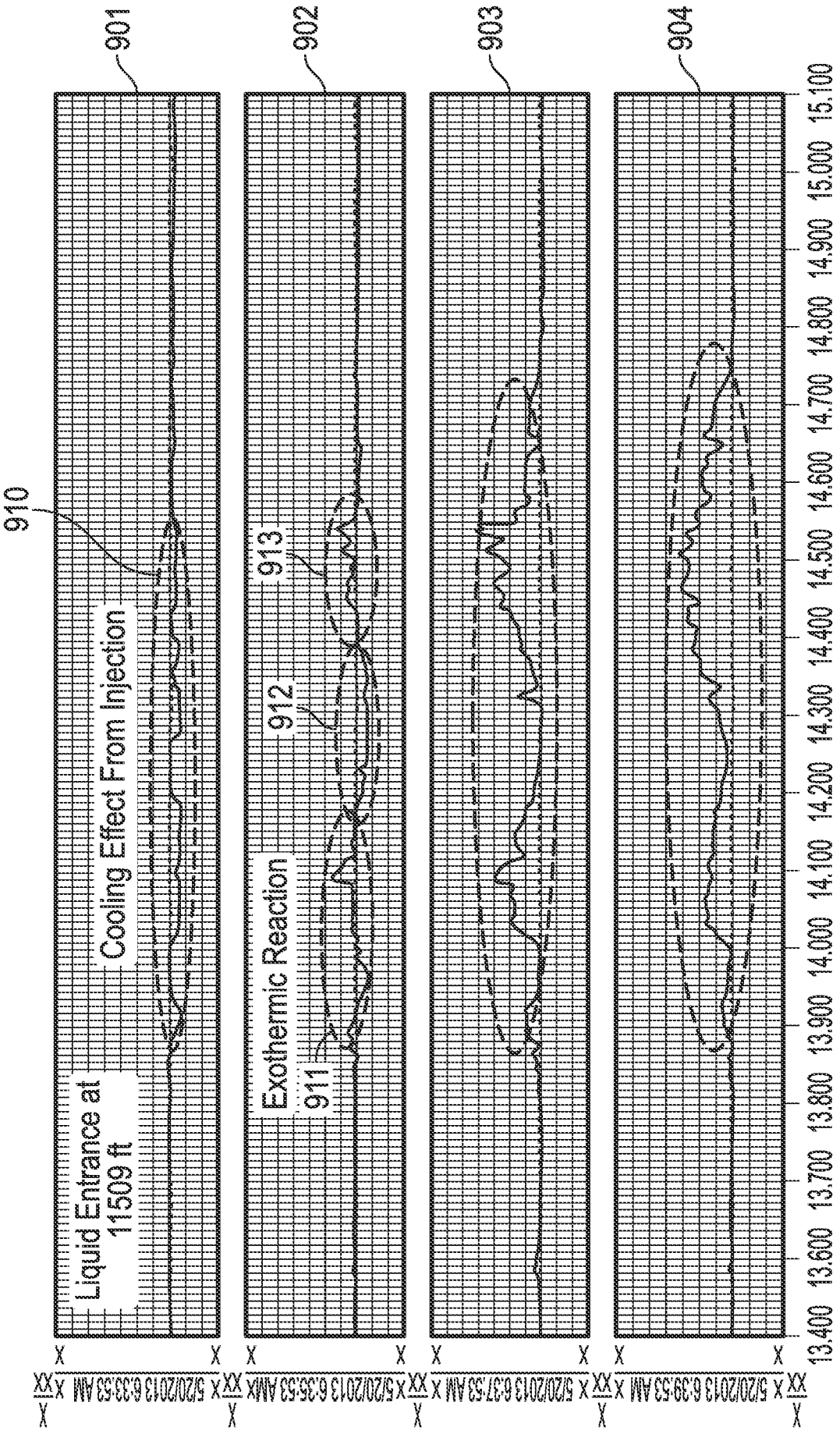

901
902
903
904
910
911
912
913
Liquid Entrance at 11509 ft
Cooling Effect From Injection
Exothermic Reaction
13.400
13.600
13.700
13.800
13.900
14.000
14.100
14.200
14.300
14.400
14.500
14.600
14.700
14.800
14.900
15.000
15.100

FIG. 9

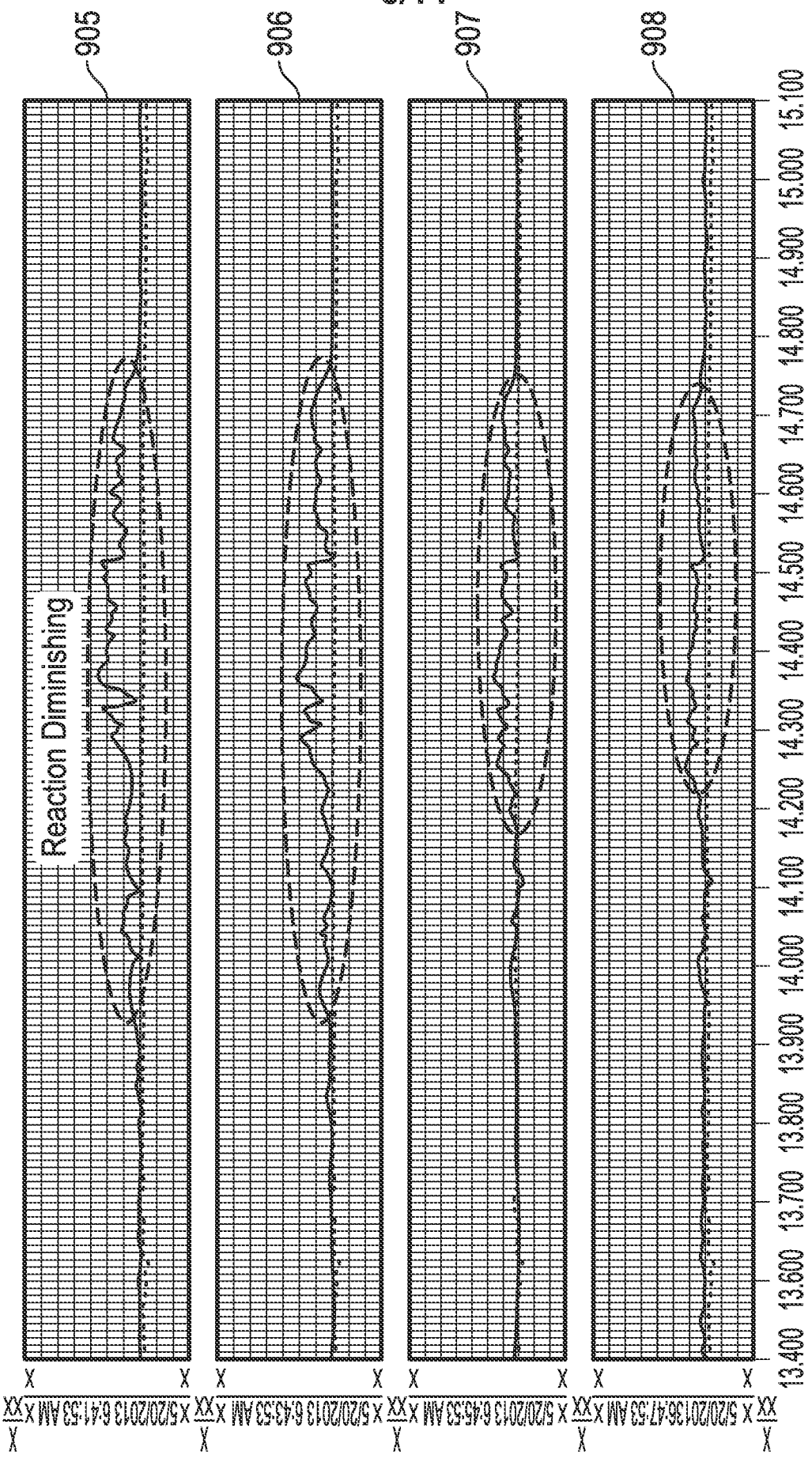
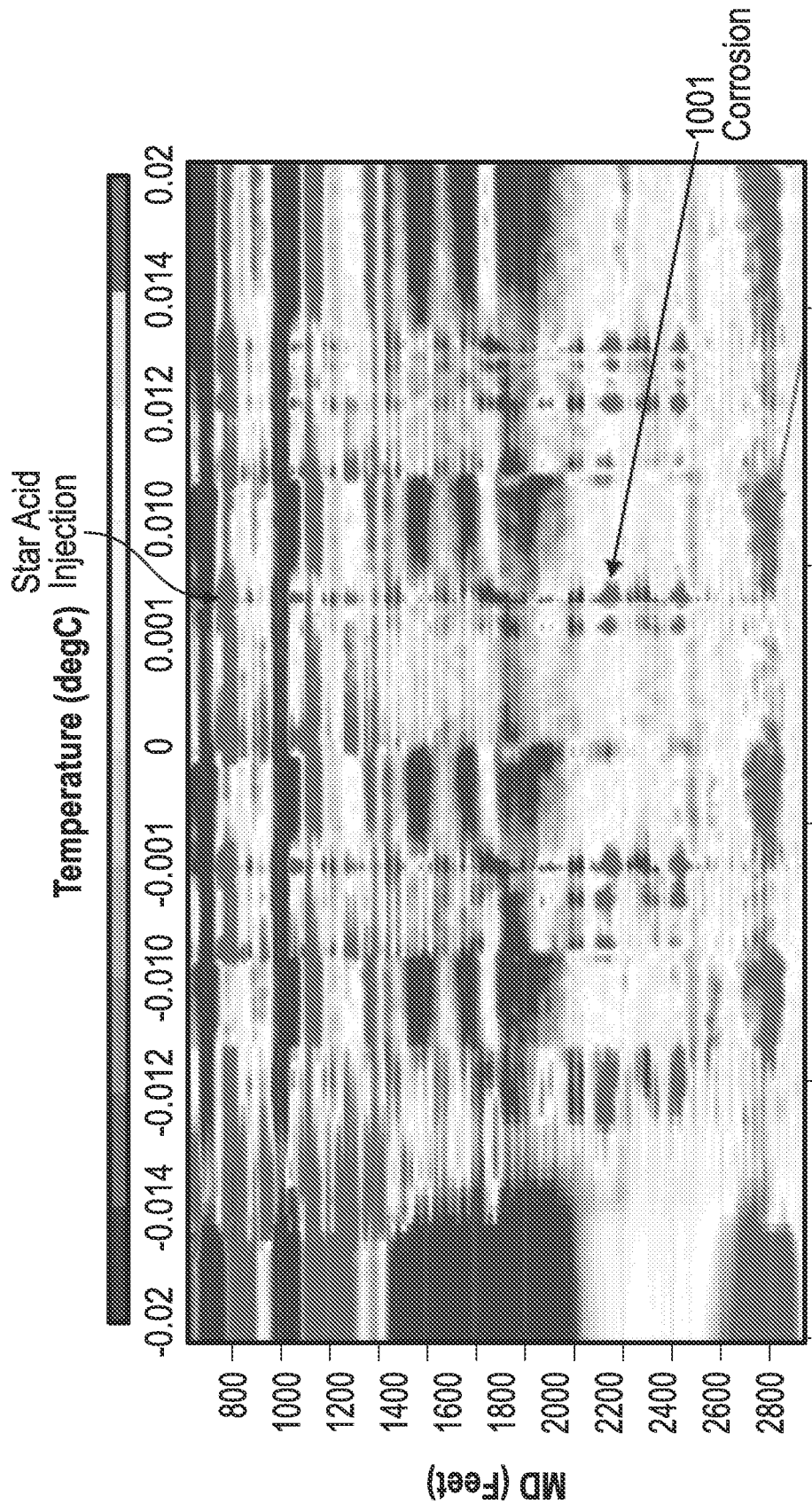
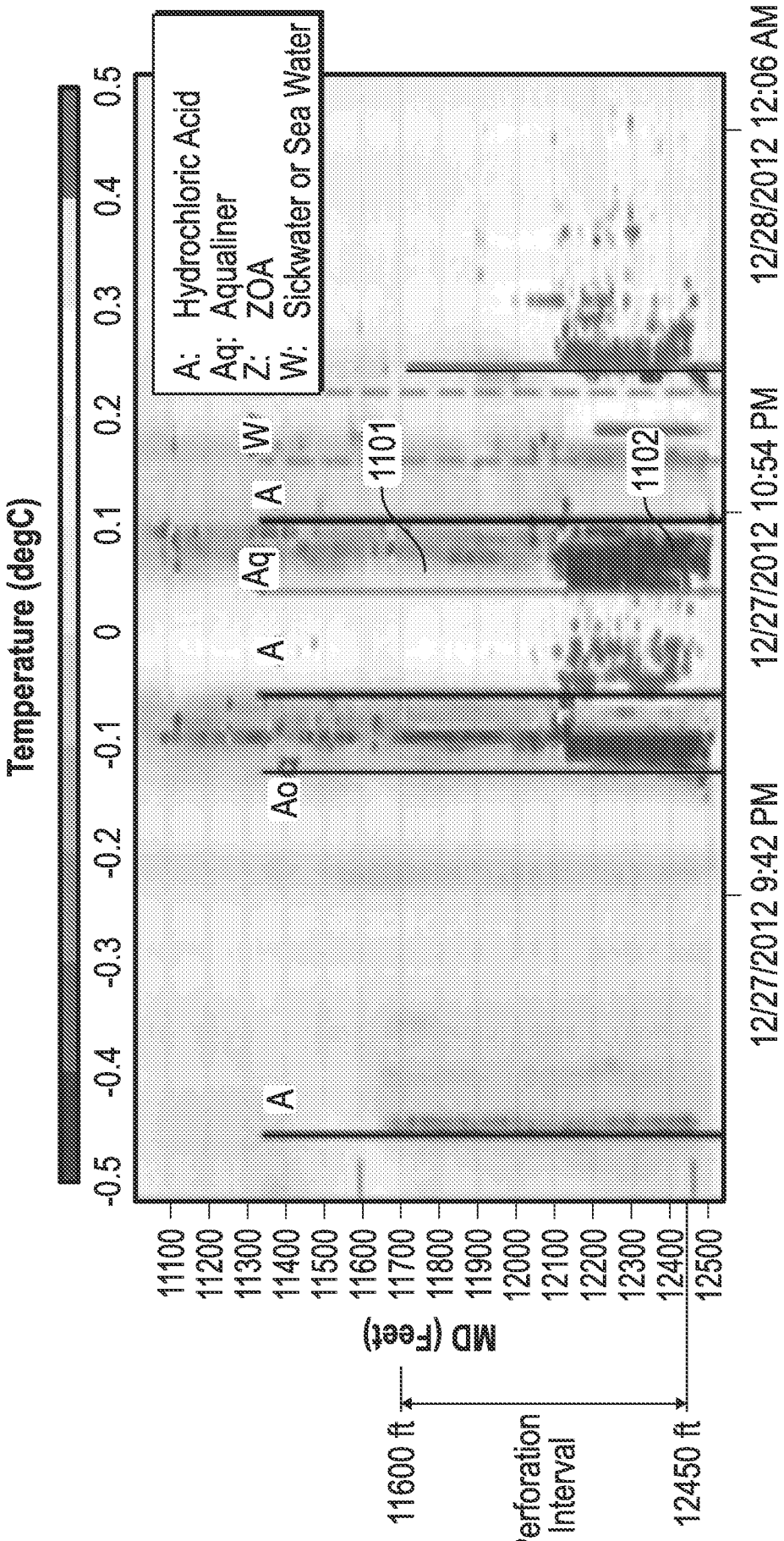


FIG. 9 (Continued)



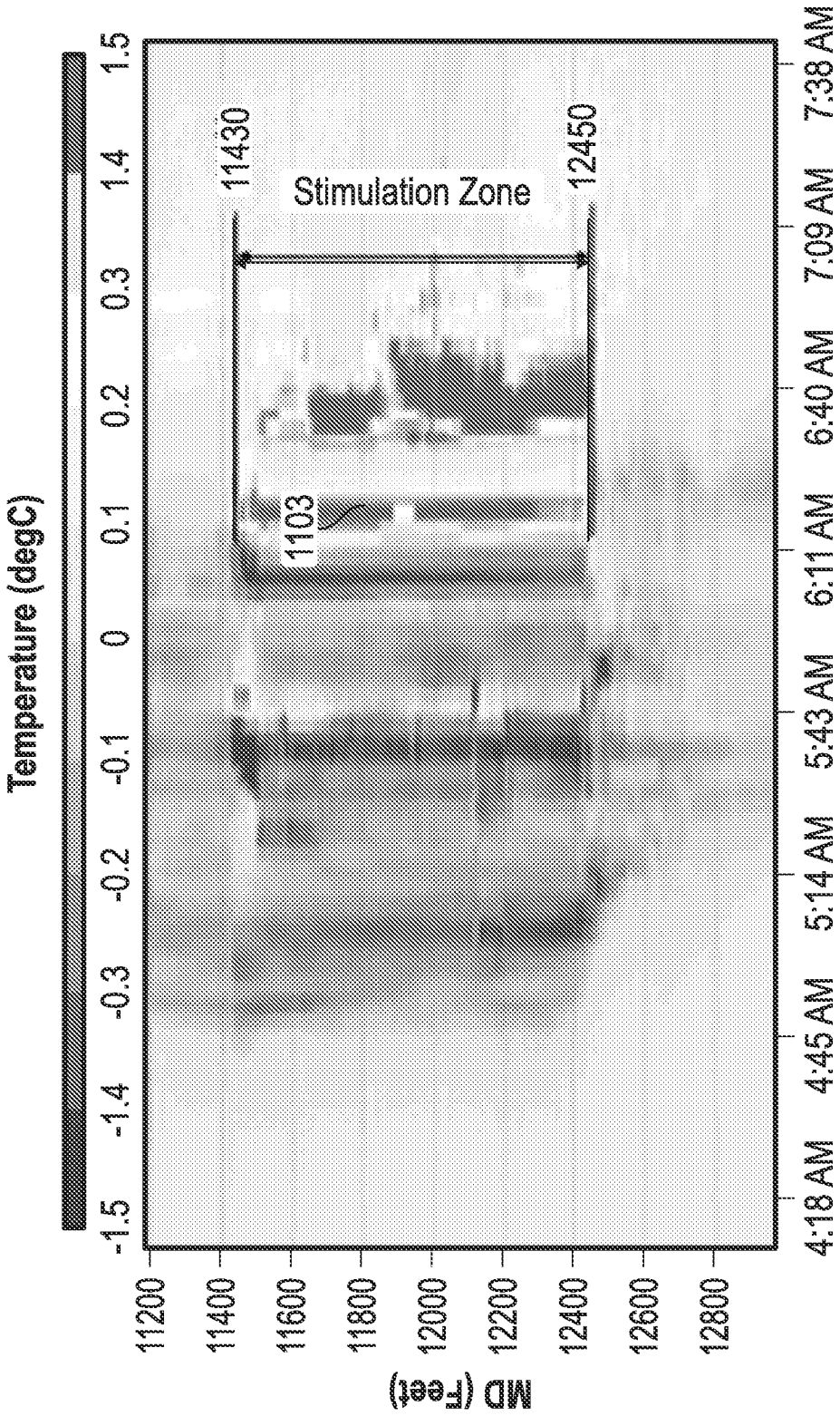
Examplary TTG color map on a zonal acid stimulation

FIG. 10



Examplary TTG color map on a zonal acid stimulation

FIG. 11A



Examplary TTG color map on a zonal acid stimulation

FIG. 11B

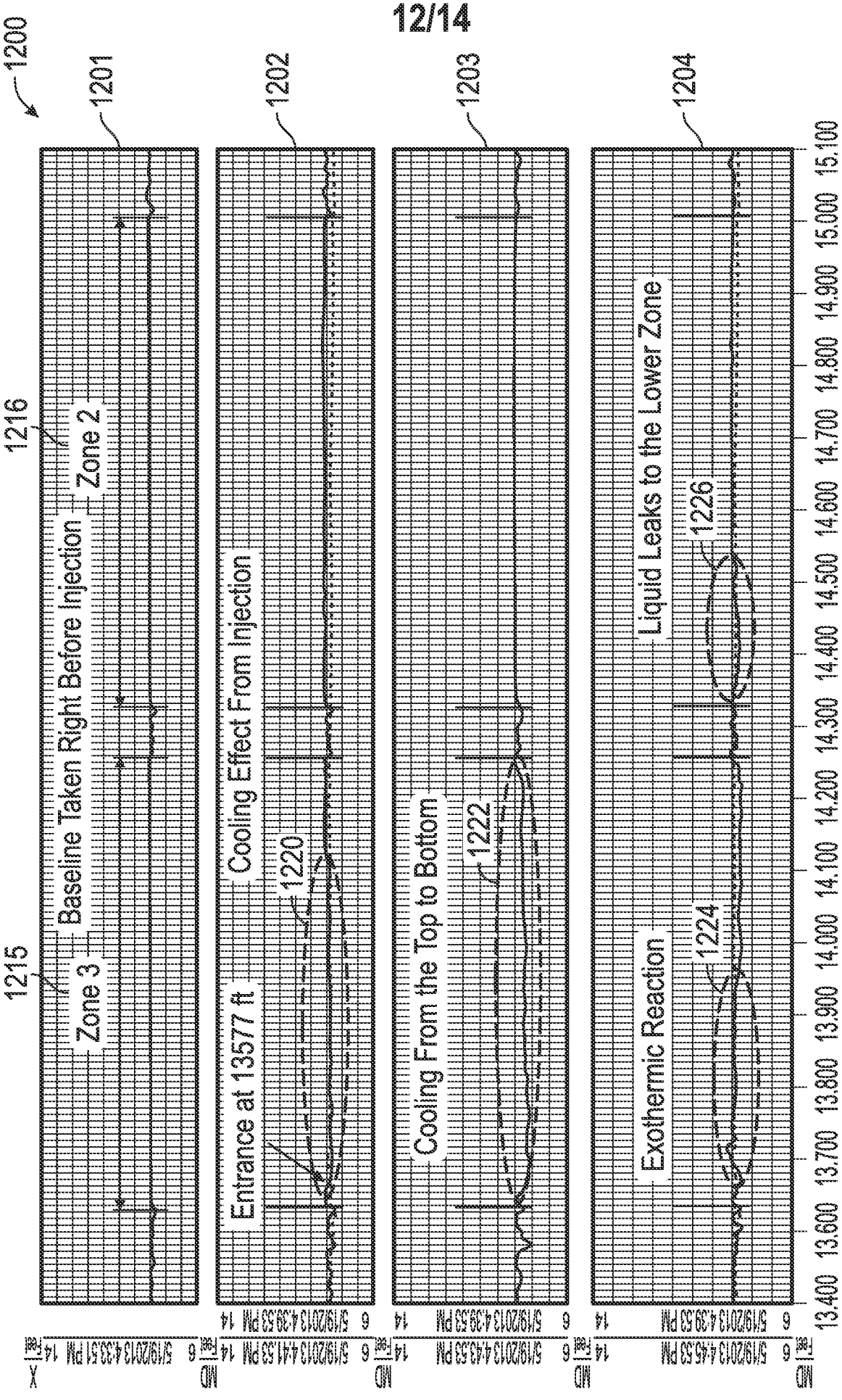

1200
1201
1202
1203
1204
1216
1215
Baseline Taken Right Before Injection
Zone 3
Zone 2
Entrance at 13577 ft
Cooling Effect From Injection
1220
Cooling From the Top to Bottom
1222
Exothermic Reaction
Liquid Leaks to the Lower Zone
1224
1226
13,400
13,600
13,700
13,800
13,900
14,000
14,100
14,200
14,300
14,400
14,500
14,600
14,700
14,800
14,900
15,000
15,100
MD
TIME

FIG. 12A

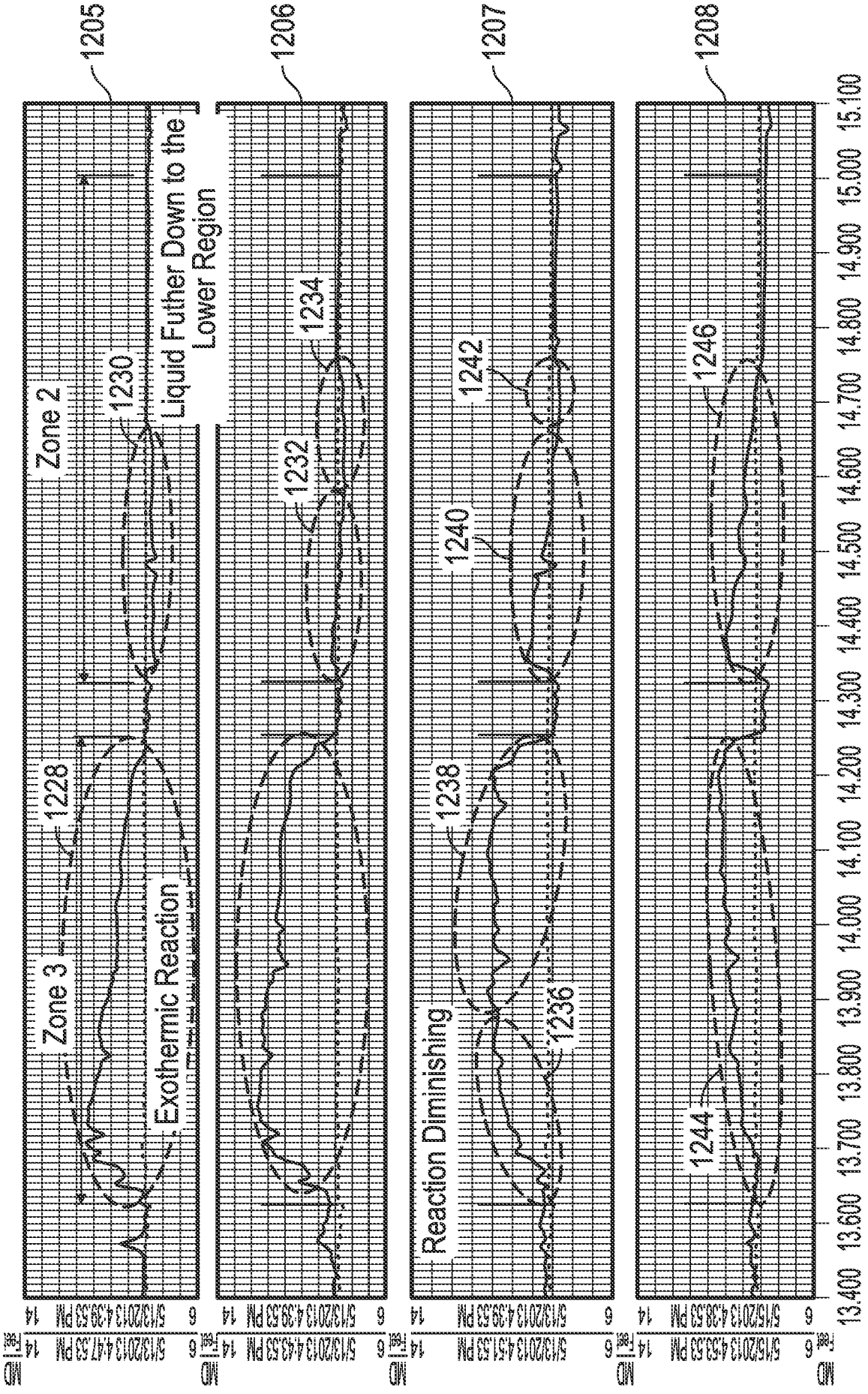

1205
1206
1207
1208
Zone 2
Zone 3
Exothermic Reaction
Liquid Futher Down to the Lower Region
Reaction Diminishing
1228
1230
1232
1234
1236
1238
1240
1242
1244
1246
MD
Feet
13.400
13.600
13.700
13.800
13.900
14.000
14.100
14.200
14.300
14.400
14.500
14.600
14.700
14.800
14.900
15.000
15.100

FIG. 12B

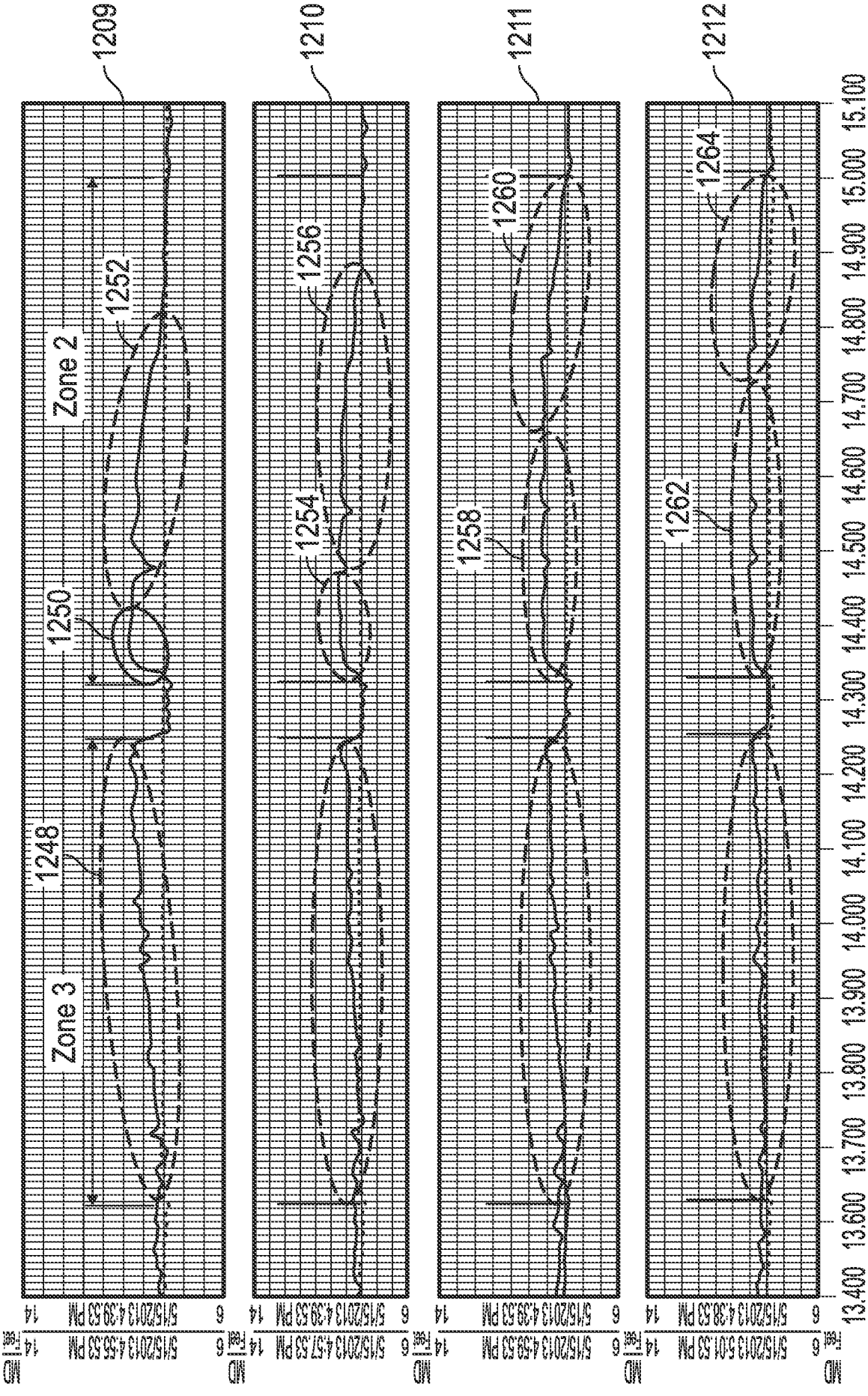

1209
1210
1211
1212
Zone 2
Zone 3
1248
1250
1252
1254
1256
1258
1260
1262
1264
MD
13.400
13.600
13.700
13.800
13.900
14.000
14.100
14.200
14.300
14.400
14.500
14.600
14.700
14.800
14.900
15.000
15.100

FIG. 12C

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/057261

A. CLASSIFICATION OF SUBJECT MATTER

E21B 43/22(2006.01)i, E21B 43/25(2006.01)i, E21B 43/27(2006.01)i

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)
E21B 43/22; E21B 47/00; E21B 47/06; E21B 43/28; E21B 43/25; E21B 43/16; E21B 43/27

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: stimulation, formation, parameter, temperature, downhole, real-time, sensor, string, processor, and well

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012-0012308 A1 (ZIAUDDIN et al.) 19 January 2012 See abstract; paragraphs [0020]-[0021],[0027]-[0035]; claims 1,14; and figures 1-2.	1-2,4-9,11-16,18-20
A		3,10,17
A	US 5431227 A (MONTGOMERY et al.) 11 July 1995 See column 5, lines 6-26; claim 1; and figures 1,7.	1-20
A	WO 02-066789 A1 (SOFITECH N.V. et al.) 29 August 2002 See abstract and claim 1.	1-20
A	US 2010-0006292 A1 (BOLES et al.) 14 January 2010 See paragraph [0081]; claims 1-4; and figures 1-4.	1-20
A	US 2011-0308788 A1 (RAVI et al.) 22 December 2011 See paragraphs [0013]-[0026] and figure 1.	1-20

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* 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	Date of mailing of the international search report
07 January 2015 (07.01.2015)	**07 January 2015 (07.01.2015)**

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701,
Republic of Korea
Facsimile No. +82-42-472-7140

Authorized officer
CHOI, Hyun Goo
Telephone No. +82-42-481-8288

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2014/057261

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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