Title: ANALYZING MICROSEISMIC DATA FROM A FRACTURE TREATMENT

Abstract: Systems, methods, and software can be used to analyze microseismic data from a fracture treatment. In some aspects, data for a new microseismic event are from a fracture treatment of a subterranean zone. An updated parameter for a fracture plane is calculated. The fracture plane was previously generated based on data for prior microseismic events. The updated parameter calculated is calculated based on the data for the new microseismic event and the data for the prior microseismic events. A graphical representation of the fracture plane is displayed based on the updated parameter.
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Analyzing Microseismic Data from a Fracture Treatment

CROSS-REFERENCE TO RELATED APPLICATIONS


BACKGROUND

[0002] This specification relates to analyzing microseismic data from a fracture treatment. Microseismic data are often acquired in association with hydraulic fracturing treatments applied to a subterranean formation. The hydraulic fracturing treatments are typically applied to induce artificial fractures in the subterranean formation, and to thereby enhance hydrocarbon productivity of the subterranean formation. The pressures generated by the fracture treatment can induce low-amplitude or low-energy seismic events in the subterranean formation, and the events can be detected by sensors and collected for analysis.

SUMMARY

[0003] In one general aspect, microseismic data from a fracture treatment are analyzed. In some instances, the data may be analyzed in real time, for example, during the fracture treatment.

[0004] In some aspects, data for a new microseismic event are collected from a fracture treatment of a subterranean zone. An updated parameter for a fracture plane is calculated. The fracture plane was previously generated based on data for prior microseismic events. The updated parameter calculated is calculated based on the data for the new microseismic event and the data for the prior available microseismic events. A graphical representation of the fracture plane (or a numerical representation of the fracture plane parameters) is displayed based on the updated parameter.

[0005] Implementations may include one or more of the following features. Prior knowledge or estimates of possible fracture planes orientations is used to calculate a
fracture plane parameter. The graphical representation are continuously updated, for example, as long as additional new microseismic events appear in the system input buffer. New microseismic events are collected from the fracture treatment before the fracture treatment begins, during the fracture treatment, after the fracture treatment has terminated, or any combination of these. The updated parameter is calculated and the graphical representation is displayed in real time during the fracture treatment. The fracture plane is selected from multiple fracture planes based on the data for the new microseismic event. The new microseismic event is associated with the selected fracture plane. Displaying a graphical representation of the fracture plane includes updating a graphical representation of the fracture planes in real time during the fracture treatment. Selecting the fracture plane from the fracture planes includes identifying a distance between the new microseismic event and the selected fracture plane and determining that the distance is less than a threshold distance. The threshold value is a static predefined value. The predefined threshold is computed by multiplying a coefficient and the standard deviation or uncertainty of the fracture plane. The coefficient can be a predefined constant value, for example, between 1 and 2, or another value.

[0006] Additionally or alternatively, these and other implementations may include one or more of the following features. Calculating an updated parameter for the fracture plane includes calculating at least one of an updated orientation or an updated area for the fracture plane based on the data for the new microseismic event and the data for the prior microseismic events. Calculating an updated parameter for the fracture plane includes calculating an average distance from the fracture plane for the new microseismic event and the prior microseismic events. The new microseismic event and the prior microseismic events define a set. In response to detecting that the average distance is greater than a predefined threshold distance, an updated average distance is calculated after removing one or more microseismic events from the set.

[0007] Additionally or alternatively, these and other implementations may include one or more of the following features. Calculating an updated parameter for the fracture plane includes calculating an updated area for the fracture plane. The updated area for the fracture plane is compared to a prior area for the fracture plane. The new microseismic event is disassociated from the fracture plane if the updated area for the fracture plane is less than the prior area for the fracture plane. The new microseismic
event is a first new microseismic event. After displaying the graphical representation based on the first new microseismic event, data for a second new microseismic event collected from the fracture treatment is received. A second updated parameter is calculated for the fracture plane based in part on the data for the second new microseismic event. An updated graphical representation of the fracture plane is generated based on the second updated parameter.

[0008] The details of one or more implementations are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

[0009] FIG. 1A is a diagram of an example well system; FIG. 1B is a diagram of the example computing subsystem 110 of FIG. 1A.

[0010] FIGS. 2A and 2B are plots showing example fracture planes.

[0011] FIGS. 3A-3F are plots showing updates for an example fracture plane.

[0012] FIG. 4 is a flow chart of an example technique for analyzing microseismic data.

[0013] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0014] In some aspects of what is described here, fracture parameters, dominant fracture orientations, or other data are identified from microseismic data. In some instances, these or other types of data are dynamically identified, for example, in a real-time fashion during a fracture treatment. For many applications and analysis techniques, an identification of fracture planes from real-time microseismic events is needed, and individual fracture planes can be displayed to show time evolution and geometric elimination, including location, propagation, growth, reduction, or elimination of the fracture planes. Such capabilities can be incorporated into control systems, software, hardware, or other types of tools available to oil and gas field engineers when they analyze potential oil and gas fields, while stimulating hydraulic
fractures and analyzing the resultant signals. Such tools can provide a reliable and direct interface for presenting and visualizing the dynamics of hydraulic fractures, which may assist in analyzing the fracture complexity, fracture network structure, and reservoir geometry. Such tools can assist in evaluating the effectiveness of hydraulic fracturing treatment, for example, by improving, enhancing, or optimizing the fracture density and trace lengths and heights. Such improvements in the fracture treatment applied to the reservoir may enhance production of hydrocarbons or other resources from the reservoir.

[0015] Hydraulic fracture treatments can be applied in any suitable subterranean zone. Hydraulic fracture treatments are often applied in tight formations with low-permeability reservoirs, which may include, for example, low-permeability conventional oil and gas reservoirs, continuous basin-centered resource plays and shale gas reservoirs, or other types of formations. Hydraulic fracturing can induce artificial fractures in the subsurface, which can enhance the hydrocarbon productivity of a reservoir.

[0016] During the application of a hydraulic fracture treatment, the injection of high-pressure fluids can alter stresses, accumulate shear stresses, and cause other effects within the geological subsurface structures. In some instances, microseismic events are associated with hydraulic fractures induced by the fracturing activities. The acoustic energy or sounds associated with rock stresses, deformations, and fracturing can be detected and collected by sensors. In some instances, microseismic events have low-energy (e.g., with the value of the log of the intensity or moment magnitude of less than three), and some uncertainty or accuracy or measurement error is associated with the event locations. The uncertainty can be described, for example, by a prolate spheroid, where the highest likelihood is at the spheroid center and the lowest likelihood is at the edge.

[0017] Microseismic event mapping can be used to geometrically locate the source point of the microseismic events based on the detected compressional and shear waves. The detected compressional and shear waves (e.g., p-waves and s-waves) can yield additional information about microseismic events, including the location of the source point, the event's location and position measurement uncertainty, the event's occurrence time, the event's moment magnitude, the direction of particle motion and energy emission spectrum, and possibly others. The microseismic events can be
monitored in real time, and in some instances, the events are also processed in real
time during the fracture treatment. In some instances, after the fracture treatment, the
microseismic events collected from the treatment are processed together as "post
data."

[0018] Processing microseismic event data collected from a fracture treatment can
include fracture matching (also called fracture mapping). Fracture matching processes
can identify fracture planes in any zone based on microseismic events collected from
the zone. Some example computational algorithms for fracture matching utilize
microseismic event data (e.g., an event's location, an event's location measurement
uncertainty, an event's moment magnitude, etc.) to identify individual fractures that
match the collected set of microseismic events. Some example computational
algorithms can compute statistical properties of fracture patterns. The statistical
properties may include, for example, fracture orientation, fracture orientation trends,
fracture size (e.g., length, height, area, etc.), fracture density, fracture complexity,
fracture network properties, etc. Some computational algorithms account for
uncertainty in the events' location by using multiple realizations of the microseismic
event locations. For example, alternative statistical realizations associated with Monte
Carlo techniques can be used for a defined probability distribution on a spheroid or
another type of distribution.

[0019] Generally, fracture matching algorithms can operate on real-time data, post
data, or any suitable combination of these and other types of data. Some
computational algorithms for fracture matching operate only on post data. Algorithms
operating on post data can be used when any subset or several subsets of microseismic
data to be processed has been collected from the fracture treatment; such algorithms
can access (e.g., as an initial input) the full subset of microseismic events to be
processed. In some implementations, fracture matching algorithms can operate on
real-time data. Such algorithms may be used for real-time automatic fracture matching
during the fracture treatment. Algorithms operating on real-time data can be used
during the fracture treatment, and such algorithms can adapt or dynamically update a
previously-identified fracture model to reflect newly-acquired microseismic events.
For example, once a microseismic event is detected and collected from the treatment
field, a real-time automatic fracture matching algorithm may respond to this new
event by dynamically identifying and extracting fracture planes from the already-
collected microseismic events in a real-time fashion. Some computational algorithms for fracture matching can operate on a combination of post data and real-time data.

[0020] In some cases, fracture mapping algorithms are configured to handle conditions that arise in real-time microseismic data processing. For example, several types of challenges or conditions may occur more predominantly in the real-time context. In some instances, real-time processing techniques can be adapted to account for (or to reduce or avoid) the lower accuracy that is sometimes associated with fractures extracted from data sets lacking a sufficient number of microseismic events or lacking a sufficient number of microseismic events in certain parts of the domain. Some real-time processing techniques can be adapted to produce fracture data that are consistent with the fracture data obtainable from post data processing techniques. For example, some of the example real-time processing techniques described here have produced results that are statistically the same, according to the statistical hypothesis test (t-test and F-test), as results produced by post data processing techniques on the same data.

[0021] In some cases, real-time processing techniques can be adapted to readily (e.g., instantaneously, from a user’s perspective) offer the identified fracture data to users. Such features may allow field engineers or operators to dynamically obtain fracture geometric information and adjust fracture treatment parameters when appropriate (e.g. to improve, enhance, optimize, or otherwise change the treatment). In some instances, fracture planes are dynamically extracted from microseismic data and displayed to field engineers in real time. Real-time processing techniques can exhibit high-speed performance. In some cases, the performance can be enhanced by parallel computing technology, distributed computing technology, parallel threading approaches, fast binary-search algorithms, or a combination of these and other hardware and software solutions that facilitate the real-time operations.

[0022] In some implementations, fracture matching technology can directly present information about fractures planes associated with three-dimensional microseismic events. The fracture planes presented can represent fracture networks that exhibit multiple orientations and activate complex fracture patterns. In some cases, hydraulic fracture parameters are extracted from a cloud of microseismic event data; such parameters may include, for example, fracture orientation trends, fracture density and fracture complexity. The fracture parameter information can be presented to field
engineers or operators, for example, in a tabular, numerical, or graphical interface or an interface that combines tabular, numerical, and graphical elements. The graphical interface can be presented in real time and can exhibit the real-time dynamics of hydraulic fractures. In some instances, this can help field engineers analyze the fracture complexity, the fracture network and reservoir geometry, or it can help them better understand the hydraulic fracturing process as it progresses.

[0023] In some implementations, accuracy confidence values are used to quantify the certainty of the fracture planes extracted from microseismic data. The accuracy confidence values can be used to classify the fractures into confidence levels. For example, three confidence levels (low confidence level, medium confidence level and high confidence level) are appropriate for some contexts, while in other contexts a different number (e.g., two, four, five, etc.) of confidence levels may be appropriate. A fracture plane's accuracy confidence value can be calculated based on any appropriate data. In some implementations, a fracture plane's accuracy confidence value is calculated based on the microseismic events' locations and position uncertainties, individual microseismic events' moment magnitude, distances between individual events and their supporting fracture plane, the number of supporting events associated with the fracture plane, and the weight of variation of the fracture orientation, among others.

[0024] The accuracy confidence values can be computed and the fracture planes can be classified at any appropriate time. In some cases, the accuracy confidence values are computed and the fracture planes are classified in real time during the fracture treatment. The fracture planes can be presented to the user at any appropriate time and in any suitable format. In some instances, the fracture planes are presented graphically in a user interface in real time according to the accuracy confidence values, according to the accuracy confidence levels, or according to any other type of classification. In some instances, users can select individual groups or individual planes (e.g., those with high confidence levels) for viewing or analysis. The fracture planes can be presented to the user in an algebraic format, a numerical format, graphical format, or a combination of these and other formats.

[0025] In some implementations, microseismic events are monitored in real time during the hydraulic fracture treatment. As the events are monitored, they may also be processed in real time, they may be processed later as post data, or they may be
processed using a combination of real time and post data processing. The events may be processed by any suitable technique. In some cases, the events are processed individually, at the time and in the order in which they are received. For example, a system state \( S(M, N - 1) \) can be used to represent the \( M \) number of planes generated from the \( N - 1 \) previous events. The new incoming \( N^{th} \) event can trigger the system \( S(M, N - 1) \). In some cases, upon receiving the the \( N^{th} \) event, a histogram or distribution of orientation ranges is generated. For example, a probability distribution histogram or the Hough transform histogram of the degenerated planes in the strike and dip angle domain can be generated to identify the feasible dominant orientations imbedded in the fractures sets.

[0026] A basic plane can be generated from a subset of microseismic events. For example, any three non-collinear points in space mathematically define a basic plane. The basic plane defined by three non-collinear microseismic events can be represented by the normal vector \((a, b, c)\). The normal vector \((a, b, c)\) may be computed based on the three events’ positions. The basic plane’s orientation can be computed from the normal vector. For example, the dip \( \Theta \) and the strike \( \phi \) can be given by

\[
\Theta = \arctan \frac{\sqrt{a^2 + b^2}}{c}, \quad \phi = \arctan\frac{b}{a}.
\]

The dip angle \( \Theta \) of a fracture plane can represent the angle between the fracture plane and the horizontal plane (e.g., the xy-plane). The strike angle \( \phi \) of a fracture plane can represent the angle between a horizontal reference axis (e.g., the x-axis) and a horizontal line where the fracture plane intersects the horizontal plane. For example, the strike angle can be defined with respect to North or another horizontal reference direction. A fracture plane can be defined by other parameters, including angular parameters other than the strike angle and dip angle.

[0027] In general, \( N \) events can support \( P \) basic planes, where \( P = \frac{N(N - 1)(N - 2)}{6} \). strike and dip angles. A probability histogram can be constructed from the orientation angles. The probability histogram or the enhanced Hough transformation histogram can have any suitable configuration. For example, the histogram configuration can be based on a fixed bin size and a fixed number of bins, natural optimal bin size in the strike and dip angle domain, or other types of bins. The histogram can be based on any suitable number of microseismic events (e.g., tens,
hundreds, thousands, etc.), and any suitable range of orientations. In some cases, multiple discrete bins are defined for the histogram, and each bin represents a discrete range of orientations. A quantity of basic planes in each discrete range can be computed from the basic planes. In some cases, each basic plane's orientation falls within the orientation range associated with one of the bins. For example, for $N$ microseismic events, each of the $P$ basic planes can be assigned to a bin, and the quantity of basic planes assigned to each bin can be computed. The quantity computed for each bin can be any suitable value. For example, the quantity can be a non-normalized number of basic planes, the quantity can be a normalized probability, frequency, or fraction of basic planes, or the quantity can be another type of value that is suitable for a histogram. A histogram can be generated to represent the quantity of basic planes assigned to all of the bins, or to represent the quantity of basic planes assigned to a subset of the bins.

[0028] In some examples, the histogram is presented as a three-dimensional bar chart, a three-dimensional surface map, or another suitable plot in an appropriate coordinate system. The peaks on the histogram plot can indicate dominant fracture orientations. For example, along one axis the histogram may represent strike angles from $0^\circ$ through $360^\circ$ (or another range), and the strike angles can be divided into any suitable number of bins; along another axis the histogram may represent dip angles from $60^\circ$ through $90^\circ$ (or another range), and the dip angles can be divided into any suitable number of bins. The quantity (e.g., probability) for each bin can be represented along a third axis in the histogram. The resulting plot can exhibit local maxima (peaks). Each local maximum (peak) can indicate a respective strike angle and dip angle that represents a dominant fracture orientation. For example, the local maximum of the histogram may indicate that more basic planes are aligned along this direction (or range of directions) than along neighboring directions, and these basic planes are either closely parallel or substantially on the same plane.

[0029] The orientation range represented by each bin in the histogram can be determined by any appropriate technique. In some cases, each bin represents a predetermined range of orientations. For example, the fixed bin size method can be used. In some cases, the range or size for each bin is computed based on the data to be represented by the histogram. For example, the natural optimal bin size method can be used. In some instances, the basic plane orientations are sorted, and clusters of sorted
orientations are identified. For example, all strikes can be sorted in a decreasing or increasing order and then grouped into clusters; similarly, all dip values can be sorted in a decreasing or increasing order and then grouped into clusters. The clusters can be associated with two-dimensional grid, and the number of basic planes in each grid cell can be counted. In some cases, this technique can generate adaptive and dynamic clusters, leading to highly accurate values for the dominant orientations. This technique and associated refinements can be implemented with $N^3 \log(N)$ computational complexity. In some cases, the bin sizes for both the strike and dip are fixed, and each basic plane’s location grid cell can be explicitly determined by the associated strike and dip with $N^3$ computational complexity.

[0030] Fracture planes associated with a set of microseismic events can be extracted from the dominant orientations embedded in the histogram data. Basic planes that support the dominant orientation $(\theta, \phi)$ may be either nearly parallel or on the same plane. Basic planes located within the same plane can be merged together, forming a new fracture plane with stronger support (e.g., representing a larger number of microseismic events). Any suitable technique can be used to merge the fracture planes. In some cases, for each dominant orientation $(\theta, \phi)$, a normal to the plane vector is constructed with components $(\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)$. In some instances, the results are insensitive to the location of the plane, and without loss of generality, the plane can be constructed from this normal vector (e.g., assuming the origin is in the plane). The plane can be described by $x \sin \Theta \cos \phi + y \sin \Theta \sin \phi + z \cos \Theta = 0$. The normal signed distance of each event $(x_o, y_o, z_o)$ from a basic plane to the constructed plane can be represented $d = -(x_o \sin \Theta \cos \phi + y_o \sin \Theta \sin \phi + x_o \cos \Theta)$. In this representation, events with opposite signs of $d$ are located opposite sides of the plane.

[0031] In some cases, microseismic events are grouped into clusters based on their distance from the constructed fracture planes. For example, a cluster of events can contain the group of events closest to a constructed fracture plane. As such, each cluster of microseismic events can support a particular fracture plane. The cluster size refers to the number of the events the cluster contains. In some cases, user input or other program data can designate a minimum number of events in a sustained cluster. The minimum cluster size can depend on the number of microseismic events in the data. In some instances, the minimum cluster size should be larger than or equal three.
For example, clusters having a size larger than or equal to the minimum cluster size can be considered legitimate fracture planes. A fitting algorithm can be applied to the location and location uncertainty values for the events in each cluster to find their corresponding fracture plane.

[0032] Any suitable technique can be used to identify a fracture plane from a set of microseismic events. In some cases, a Chi-square fitting technique is used. Given $K$ observed microseismic events, the locations can be represented $(x_i, y_i, z_i)$, and their measurement uncertainties can be represented $(\sigma_{ix_i}, \sigma_{iy_i}, \sigma_{iz_i})$, where $1 \leq i \leq K$. The parameters of the plane model $z = ax + by + c$ can be calculated, for example, by minimizing the Chi-square merit function

$$\chi^2(a, b, c) = \sum_{i=1}^{K} \frac{(z_i - ax_i - by_i - c)^2}{\sigma_{ix_i}^2 + a^2 \sigma_{ix}^2 + b^2 \sigma_{iy}^2}$$

(2)

The Chi-square merit function can be solved by any suitable technique. In some instances, a solution can be obtained by solving three equations, which are the partial derivatives of $\chi^2(a, b, c)$ with respect to its variables, where each partial derivative is forced to zero. In some instances, there is no analytical solution for this nonlinear mathematical system of equations. Numerical methods (e.g., Newton's numerical method, the Newton-Rafson method, the conjugate gradient method, or another technique) can be applied to solve for the parameters $a$, $b$ and $c$, and the strike and dip angles can be computed (e.g., using equation (1) above). The orientation of the dominant fracture plane computed from the microseismic events can be the same as, or it can be slightly different from, the dominant fracture orientation identified from the histogram.

[0033] In some implementations, an algorithm iterates over all possible dominant orientations to expand all feasible fracture planes. In some cases, the algorithm iterates over a selected subset of possible dominant orientations. The iterations can converge to planes. Some planes may be exactly equal to each other and some may be close to each other. Two planes can be considered "close" to each other, for example, when the average distance of one plane's events from another plane is less than a given threshold. The threshold distance can be designated, for example, as a control
parameter. The algorithm can merge close planes together and the support events of one plane can be associated with the support events of the other merged plane(s).

[0034] In some cases, constraints are imposed on the fracture planes identified from the microseismic data. For example, in some cases, the distance residual of events must be less than a given tolerance distance. The tolerance distance can be designated, for example, as a control parameter. In some instances, the identified fracture planes need to be properly truncated to represent the finite size of fractures. The boundary of truncated planes can be calculated from the support events' position and the events' location measurement uncertainty. The new finite-size fracture planes can be merged with the already-identified fractures.

[0035] In some instances, a new incoming $N^{th}$ microseismic event is associated with the fracture planes already identified based on the previous $N - 1$ microseismic events. Upon associating the new event with an existing fracture, an algorithm can be used to update the existing fracture. For example, updating the fracture may change the fracture's geometry, location, orientation, or other parameters. Upon choosing one of the previously-identified fracture planes, the fracture plane's distance from the new event can be calculated. If the distance is less than or equal to the distance control parameter, the new event can be added to the supporting event set for the fracture plane. If the distance is larger than the distance control parameter, other previously-identified fracture planes can be selected (e.g., iteratively or recursively) until a plane within the threshold distance is found. After the new event is added to a support set for a fracture plane, new strike and dip values can be evaluated and if needed can be re-calculated (e.g., using the Chi-square fitting method, or another statistical or deterministic technique) for the fracture plane. Typically, re-calculating the fracture parameters causes limited change in the orientation due to the conditional control of the distance.

[0036] In some cases, when a new microseismic event is associated with a fracture plane, one or more parameters (e.g., distance residual, area, etc.) can be modified or optimized. The plane's distance residual $r$ can represent the average distance from the supporting events to the plane. If the distance residual is less than the given residual tolerance $T$, the new event can be flagged to the associated events set for the plane. In some cases, an additional process, via which other associated events of the supporting
set are taken-off the list, is launched and is terminated when the distance residual \( r \) falls within the given \( T \). A fracture plane's area can represent the size of the fracture plane. Experience shows that usually a new event causes the fracture plane to propagate in length, grow in height, or both. Thus computational processes can be constrained by a non-decreasing area condition, whereby the new plane's area should grow larger than or remain equal to that of the original plane (rather than shrink) when the new event is added to the plane.

[0037] A fracture plane's orientation can represent the angle of the fracture plane. For example, a normal vector, the strike and dip angles, or other suitable parameters can be used to represent the fracture plane orientation. A change in a fracture plane's orientation (or other changes to a fracture plane) can cause some associated support events to be removed out of the associated events list to the un-associated event list based on their distance from the updated fracture plane. Additionally or alternatively, a change in a fracture plane's orientation can cause some previously-unassociated events to be assigned to the fracture plane based on their proximity to the updated fracture plane. Additionally, some events associated with nearby planes may also be associated with the current plane. If a new event is associated to two fracture planes, the fracture planes may intersect each other. In some cases, intersecting planes can be merged. If the new event does not belong to any existing fracture plane, it can be assigned to the "unassociated events" list.

[0038] The accumulated \( N \) microseismic events can be considered at any point to be a subset of the final post data event set. In such cases, the histogram or distribution of orientations based on the first \( N \) events may be different from the histogram or distribution of orientations constructed from the final post data. Some fracture planes extracted from \( N \) microseismic events may not be accurate, and this inaccuracy can decrease as time increases and more events are accumulated. As an example, accuracy and confidence may be lower at an initial time when the detected fracture planes are associated with microseismic events located close to the wellbore. Such data may indicate fracture planes that are nearly parallel to the wellbore, even if those planes do not represent real fractures.

[0039] Fracture accuracy confidence can be used a measure for the certainty associated with fracture planes identified from microseismic data. In some cases, the
accuracy confidence is identified in real time during the fracture treatment. The accuracy confidence can be determined from any suitable data using any suitable calculations. In some cases, the accuracy confidence value for a fracture plane is influenced by the number of microseismic events associated with the fracture plane. For example, the accuracy confidence value can scale (e.g., linearly, non-linearly, exponentially, polynomially, etc.) with the number of microseismic events according to a function. The number of microseismic events associated with a fracture plane can be incorporated (e.g., as a weight, an exponent, etc.) in an equation for calculating the accuracy confidence. In some instances, a fracture plane has a higher confidence value when the fracture plane is supported by a larger number of microseismic data points (or a lower confidence value when the fracture plane is supported by a smaller number of microseismic data points).

[0040] In some cases, the accuracy confidence value for a fracture plane is influenced by the location uncertainty for the microseismic events associated with the fracture plane. For example, the accuracy confidence value can scale (e.g., linearly, non-linearly, exponentially, polynomially, etc.) with the microseismic event's location uncertainty according to a function. The microseismic event's location uncertainty can be incorporated (e.g., as a weight, an exponent, or any decaying function of the distance, etc.) in an equation for calculating the accuracy confidence. In some instances, a fracture plane has a higher confidence value when the fracture plane is supported by microseismic data points having lower uncertainty (or a lower confidence value when the fracture plane is supported by microseismic data points having higher uncertainty).

[0041] In some cases, the accuracy confidence value for a fracture plane is influenced by the moment magnitude for the microseismic events associated with the fracture plane. For example, the accuracy confidence value can scale (e.g., linearly, non-linearly, exponentially, polynomially, etc.) with the microseismic event's moment magnitude according to a function. The microseismic event's moment magnitude can be incorporated (e.g., as a weight, an exponent, etc.) in an equation for calculating the accuracy confidence. The moment magnitude for a microseismic event can refer to the energy or intensity (sometimes proportional to the square of the amplitude) of the event. For example, the moment magnitude for a microseismic event can be a logarithmic scale value of the energy or intensity, or another type of value.
representing energy intensity. In some instances, a fracture plane has a higher confidence value when the fracture plane is supported by microseismic data points having higher intensity (or a lower confidence value when the fracture plane is supported by microseismic data points having lower intensity).

[0042] In some cases, the accuracy confidence value for a fracture plane is influenced by the distance between the fracture plane and the microseismic events associated with the fracture plane. For example, the accuracy confidence value can scale (e.g., linearly, non-linearly, exponentially, polynomially, etc.) with the average distance between the fracture plane and the microseismic events supporting the fracture plane. The average distance can be incorporated (e.g., as a weight, an exponent, etc.) in an equation for calculating the accuracy confidence. In some instances, a fracture plane has a higher confidence value when the fracture plane is supported by microseismic data points that are, on average, closer to the fracture plane (or a lower confidence value when the fracture plane is supported by microseismic data points that are, on average, farther from the fracture plane).

[0043] In some cases, the accuracy confidence value for a fracture plane is influenced by the fracture plane's orientation with respect to a dominant orientation trend in the microseismic data set. For example, the accuracy confidence value can scale (e.g., linearly, non-linearly, exponentially, polynomially, etc.) with the angular difference between the fracture plane's orientation and a dominant orientation trend in the microseismic data. The orientation angles can include strike, dip or any relevant combination (e.g., a three-dimensional spatial angle). The orientation can be incorporated (e.g., as a weight, an exponent, etc.) in an equation for calculating the accuracy confidence. A microseismic data set can have one dominant orientation trend or it can have multiple dominant orientation trends. Dominant orientation trends can be classified, for example, as primary, secondary, etc. In some instances, a fracture plane has a higher confidence value when the fracture plane is aligned with a dominant orientation trend in the microseismic data set (or a lower confidence value when the fracture plane is deviated from the dominant orientation trend in the microseismic data set).

[0044] A weighting value called the "weight of variation of fracture orientation" can represent the angular difference between the fracture plane's orientation and a dominant orientation trend in the microseismic data. The weight of variation of
fracture orientation can be a scalar value that is a maximum when the fracture plane is aligned with a dominant orientation trend. The weight of variation of fracture orientation can be a minimum for fracture orientations that are maximally separated from a dominant fracture orientation trend. For example, when there is a single dominant fracture orientation trend, the weight of variation of fracture orientation can be zero for fractures that are perpendicular (or normal) to the dominant fracture orientation. As another example, when there are multiple dominant fracture orientation trends, the weight of variation of fracture orientation can be zero for fractures having orientations between the dominant fracture orientations. The weight of variation of the fracture orientation can be the ratio of the calculated plane's orientation and the orientation reflected by the homogeneous case.

The accuracy confidence parameter can be influenced by the supporting microseismic events' location uncertainty, the supporting microseismic events' moment magnitude, distance between the supporting microseismic events and the fracture plane, the number of supporting events associated with the plane, the weight of variation of fracture orientation, other values, or any appropriate combination of one or more of these. In some general models, the confidence increases as moment magnitude is larger, and as the variation of the fracture orientation becomes larger, and the number of supporting events is larger, and their accuracy in their location is
larger, and as the variation of the weight as a function of the distance is larger. These factors can be used as inputs for defining weight in an equation for the accuracy confidence. For example, in some models, the weights are linear or nonlinear functions of these factors and the weight of variation of the fracture orientation may appear with higher weight when influencing the plane's confidence. In some examples, the accuracy confidence is calculated as:

\[
\text{Confidence} = \left( \text{weight of variation of fracture orientation} \right) \times \\
\sum_{i=1}^{\text{number of events}} \left( \text{uncertainty weight} \right) \times \\
\left( \text{moment magnitude weight} \right) \times \\
\left( \text{distance variation weight} \right).
\]

Other equations or algorithms can be used to compute the confidence.

[0047] The identified fracture planes can be classified into confidence levels based on the fracture planes' accuracy confidence values. In some instances, three levels are used: low confidence level, medium confidence level and high confidence level. Any suitable number of confidence levels can be used. In some examples, when a new event is added to the supporting set associated with an existing fracture plane, its associated fracture confidence parameter may increase, which may cause the fracture plane to roll from its current confidence level to a higher one, if it exists. As another example, if a fracture's orientation diverts away from orientation trends exhibited by post microseismic event data, as microseismic events gradually accumulate, a decrease in fracture confidence may be induced, mainly by the weight of variation of fracture orientation, causing the plane to decrease its level to a lower confidence level, if it exists. This may particularly apply to fractures created at the initial time of hydraulic fracturing treatment; it may also apply to other types of fractures in other contexts.

[0048] Users (e.g., field engineers, operational engineers and analysts, and others) can be provided a graphical display of the fracture planes identified from the microseismic data. In some cases, the graphical display allows the user to visualize the identified planes in a real time fashion, in graphical panels presenting the confidence levels. For example, three graphical panels can be used to separately present the low confidence level, medium confidence level and high confidence level fracture planes. In some cases, the lower confidence level fracture planes are created in the initial times of the
fracturing treatment. In some cases, higher confidence level fracture planes propagate in time in the direction nearly perpendicular to the wellbore. As new microseismic events gradually accumulate in time, the graphical display can be updated to enable users to dynamically observe the fracture planes association among confidence levels associated with the graphical panels.

[0049] The confidence level groups can be presented as plots of the fracture planes, or the confidence level groups can be presented in another format. The confidence level groups can be presented algebraically, for example, by showing the algebraic parameters (e.g., parameters for the equation of a plane) of the fracture planes in each group. The confidence level groups can be presented numerically, for example, by showing the numerical parameters (e.g., strike, dip, area, etc.) of the fracture planes in each group. The confidence level groups can be presented in a tabular form, for example, by presenting a table of the algebraic parameters or numerical parameters of the fracture planes in each group. Moreover, a fracture plane can be represented graphically in a three-dimensional space, a two-dimensional space, or another space. For example, a fracture plane can be represented in a rectilinear coordinate system (e.g., x, y, z coordinates) in a polar coordinate system (e.g., r, θ, φ coordinates), or another coordinate system. In some examples, a fracture plane can be represented as a line at the fracture plane's intersection with another plane (e.g., a line in the xy-plane, a line in the xz-plane, a line in the yz-plane, or a line in any arbitrary plane or surface).

[0050] In some instances, a graphical display allows users to track and visualize spatial and temporal evolution of specific fracture planes, including their generation, propagation and growth. For example, a user may observe stages of a specific fracture plane's spatial and temporal evolution such as, for example, initially identifying the fracture plane based on three microseismic events, a new event that changes the plane's orientation, a new event that causes the planes' area to grow (e.g., vertically, horizontally, or both), or other stages in the evolution of a fracture plane. The spatial and temporal evolution of fracture planes may present the travel paths of stimulated fluids and proppants injected into the rock matrix. Visualization of dynamics of fracture planes can help users better understand the hydraulic fracturing process, analyze the fracture complexity more accurately, evaluate the effectiveness of hydraulic fracture, or improve the well performance.
Although this application describes examples involving microseismic event data, the techniques and systems described in this application can be applied to other types of data. For example, the techniques and systems described here can be used to process data sets that include data elements that are unrelated to microseismic events, which may include other types of physical data associated with a subterranean zone. In some aspects, this application provides a framework for processing large volumes of data, and the framework can be adapted for various applications that are not specifically described here. For example, the techniques and systems described here can be used to analyze spatial coordinates, orientation data, or other types of information collected from any source. As an example, soil or rock samples can be collected (e.g., during drilling), and the concentration of a given compound (e.g., a certain "salt") as function of location can be identified. This may help geophysicists and operators evaluate the geo-layers in the ground.

FIG. 1A shows a schematic diagram of an example well system 100 with a computing subsystem 110. The example well system 100 includes a treatment well 102 and an observation well 104. The observation well 104 can be located remotely from the treatment well 102, near the treatment well 102, or at any suitable location. The well system 100 can include one or more additional treatment wells, observation wells, or other types of wells. The computing subsystem 110 can include one or more computing devices or systems located at the treatment well 102, at the observation well 104, or in other locations. The computing subsystem 110 or any of its components can be located apart from the other components shown in FIG. 1A. For example, the computing subsystem 110 can be located at a data processing center, a computing facility, or another suitable location. The well system 100 can include additional or different features, and the features of the well system can be arranged as shown in FIG. 1A or in any other suitable configuration.

The example treatment well 102 includes a well bore 101 in a subterranean zone 121 beneath the surface 106. The subterranean zone 121 can include one or less than one rock formation, or the subterranean zone 121 can include more than one rock formation. In the example shown in FIG. 1A, the subterranean zone 121 includes various subsurface layers 122. The subsurface layers 122 can be defined by geological or other properties of the subterranean zone 121. For example, each of the subsurface layers 122 can correspond to a particular lithology, a particular fluid content, a
particular stress or pressure profile, or any other suitable characteristic. In some
instances, one or more of the subsurface layers 122 can be a fluid reservoir that
contains hydrocarbons or other types of fluids. The subterranean zone 121 may
include any suitable rock formation. For example, one or more of the subsurface
layers 122 can include sandstone, carbonate materials, shale, coal, mudstone, granite,
or other materials.

[0054] The example treatment well 102 includes an injection treatment subsystem
120, which includes instrument trucks 116, pump trucks 114, and other equipment.
The injection treatment subsystem 120 can apply an injection treatment to the
subterranean zone 121 through the well bore 101. The injection treatment can be a
fracture treatment that fractures the subterranean zone 121. For example, the injection
treatment may initiate, propagate, or open fractures in one or more of the subsurface
layers 122. A fracture treatment may include a mini fracture test treatment, a regular
or full fracture treatment, a follow-on fracture treatment, a re-fracture treatment, a
final fracture treatment or another type of fracture treatment.

[0055] The fracture treatment can inject a treatment fluid into the subterranean zone
121 at any suitable fluid pressures and fluid flow rates. Fluids can be injected above,
at or below a fracture initiation pressure, above at or below a fracture closure
pressure, or at any suitable combination of these and other fluid pressures. The
fracture initiation pressure for a formation is the minimum fluid injection pressure that
can initiate or propagate artificial fractures in the formation. Application of a fracture
treatment may or may not initiate or propagate artificial fractures in the formation.
The fracture closure pressure for a formation is the minimum fluid injection pressure
that can dilate existing fractures in the subterranean formation. Application of a
fracture treatment may or may not dilate natural or artificial fractures in the formation.

[0056] A fracture treatment can be applied by any appropriate system, using any
suitable technique. The pump trucks 114 may include mobile vehicles, immobile
installations, skids, hoses, tubes, fluid tanks or reservoirs, pumps, valves, or other
suitable structures and equipment. In some cases, the pump trucks 114 are coupled to
a working string disposed in the well bore 101. During operation, the pump trucks 114
can pump fluid through the working string and into the subterranean zone 121. The
pumped fluid can include a pad, proppants, a flush fluid, additives, or other materials.
A fracture treatment can be applied at a single fluid injection location or at multiple fluid injection locations in a subterranean zone, and the fluid may be injected over a single time period or over multiple different time periods. In some instances, a fracture treatment can use multiple different fluid injection locations in a single well bore, multiple fluid injection locations in multiple different well bores, or any suitable combination. Moreover, the fracture treatment can inject fluid through any suitable type of well bore, such as, for example, vertical well bores, slant well bores, horizontal well bores, curved well bores, or any suitable combination of these and others.

A fracture treatment can be controlled by any appropriate system, using any suitable technique. The instrument trucks 116 can include mobile vehicles, immobile installations, or other suitable structures. The instrument trucks 116 can include an injection control system that monitors and controls the fracture treatment applied by the injection treatment subsystem 120. In some implementations, the injection control system can communicate with other equipment to monitor and control the injection treatment. For example, the instrument trucks 116 may communicate with the pump truck 114, subsurface instruments, and monitoring equipment.

The fracture treatment, as well as other activities and natural phenomena, can generate microseismic events in the subterranean zone 121, and microseismic data can be collected from the subterranean zone 121. For example, the microseismic data can be collected by one or more sensors 112 associated with the observation well 104, or the microseismic data can be collected by other types of systems. The microseismic information detected in the well system 100 can include acoustic signals generated by natural phenomena, acoustic signals associated with a fracture treatment applied through the treatment well 102, or other types of signals. For example, the sensors 112 may detect acoustic signals generated by rock slips, rock movements, rock fractures or other events in the subterranean zone 121. In some instances, the locations of individual microseismic events can be determined based on the microseismic data.

Microseismic events in the subterranean zone 121 may occur, for example, along or near induced hydraulic fractures. The microseismic events may be associated with pre-existing natural fractures or hydraulic fracture planes induced by fracturing activities. In some environments, the majority of detectable microseismic events are
associated with shear-slip rock fracturing. Such events may or may not correspond to induced tensile hydraulic fractures that have significant width generation. The orientation of a fracture can be influenced by the stress regime, the presence of fracture systems that were generated at various times in the past (e.g., under the same or a different stress orientation). In some environments, older fractures can be cemented shut over geologic time, and remain as planes of weakness in the rocks in the subsurface.

[0061] The observation well 104 shown in FIG. 1A includes a well bore 111 in a subterranean region beneath the surface 106. The observation well 104 includes sensors 112 and other equipment that can be used to detect microseismic information. The sensors 112 may include geophones or other types of listening equipment. The sensors 112 can be located at a variety of positions in the well system 100. In FIG. 1A, sensors 112 are installed at the surface 106 and beneath the surface 106 in the well bore 111. Additionally or alternatively, sensors may be positioned in other locations above or below the surface 106, in other locations within the well bore 111, or within another well bore. The observation well 104 may include additional equipment (e.g., working string, packers, casing, or other equipment) not shown in FIG. 1A. In some implementations, microseismic data are detected by sensors installed in the treatment well 102 or at the surface 106, without use of an observation well.

[0062] In some cases, all or part of the computing subsystem 110 can be contained in a technical command center at the well site, in a real-time operations center at a remote location, in another appropriate location, or any suitable combination of these. The well system 100 and the computing subsystem 110 can include or access any suitable communication infrastructure. For example, well system 100 can include multiple separate communication links or a network of interconnected communication links. The communication links can include wired or wireless communications systems. For example, sensors 112 may communicate with the instrument trucks 116 or the computing subsystem 110 through wired or wireless links or networks, or the instrument trucks 116 may communicate with the computing subsystem 110 through wired or wireless links or networks. The communication links can include a public data network, a private data network, satellite links, dedicated communication
channels, telecommunication links, or any suitable combination of these and other communication links.

[0063] The computing subsystem 110 can analyze microseismic data collected in the well system 100. For example, the computing subsystem 110 may analyze microseismic event data from a fracture treatment of a subterranean zone 121. Microseismic data from a fracture treatment can include data collected before, during, or after fluid injection. The computing subsystem 110 can receive the microseismic data at any suitable time. In some instances, the computing subsystem 110 receives the microseismic data in real time (or substantially in real time) during the fracture treatment. For example, the microseismic data may be sent to the computing subsystem 110 immediately upon detection by the sensors 112. In some instances, the computing subsystem 110 receives some or all of the microseismic data after the fracture treatment has been completed. The computing subsystem 110 can receive the microseismic data in any suitable format. For example, the computing subsystem 110 can receive the microseismic data in a format produced by microseismic sensors or detectors, or the computing subsystem 110 can receive the microseismic data after the microseismic data has been formatted, packaged, or otherwise processed. The computing subsystem 110 can receive the microseismic data by any suitable means. For example, the computing subsystem 110 can receive the microseismic data by a wired or wireless communication link, by a wired or wireless network, or by one or more disks or other tangible media.

[0064] The computing subsystem 110 can be used to perform fracture mapping in real time during a fracture treatment. For example, the computing subsystem 110 can receive microseismic data as a time series of individual microseismic events as the fracture treatment is applied. At any given time, the computing subsystem 110 can identify fracture planes based on the microseismic data that has been accumulated thus far. When a new microseismic event is detected, the computing subsystem 110 can updated the previously-generated fracture planes based on the new microseismic event. For example, the computing subsystem 110 can identify a previously-generated fracture plane that is most likely to be associated with the new microseismic event. The previously-generated fracture plane can be identified, for example, based on spatial proximity or other considerations. The new microseismic event can be combined with other microseismic events associated with the previously-generated
fracture plane, and the combined set of microseismic events can be fitted to a plane. Various checks can be performed, for example, to improve the accuracy of the results. In some instances, the updated fracture plane can be displayed to a user in real time, to allow the user to view the growth, propagation, or evolution of fractures in the subterranean zone.

[0065] Some of the techniques and operations described herein may be implemented by a computing subsystem configured to provide the functionality described. In various embodiments, a computing device may include any of various types of devices, including, but not limited to, personal computer systems, desktop computers, laptops, notebooks, mainframe computer systems, handheld computers, workstations, tablets, application servers, storage devices, or any type of computing or electronic device.

[0066] FIG. 1B is a diagram of the example computing subsystem 110 of FIG. 1A. The example computing subsystem 110 can be located at or near one or more wells of the well system 100 or at a remote location. All or part of the computing subsystem 110 may operate independent of the well system 100 or independent of any of the other components shown in FIG. 1A. The example computing subsystem 110 includes a processor 160, a memory 150, and input/output controllers 170 communicably coupled by a bus 165. The memory can include, for example, a random access memory (RAM), a storage device (e.g., a writable read-only memory (ROM) or others), a hard disk, or another type of storage medium. The computing subsystem 110 can be preprogrammed or it can be programmed (and reprogrammed) by loading a program from another source (e.g., from a CD-ROM, from another computer device through a data network, or in another manner). The input/output controller 170 is coupled to input/output devices (e.g., a monitor 175, a mouse, a keyboard, or other input/output devices) and to a communication link 180. The input/output devices receive and transmit data in analog or digital form over communication links such as a serial link, a wireless link (e.g., infrared, radio frequency, or others), a parallel link, or another type of link.

[0067] The communication link 180 can include any type of communication channel, connector, data communication network, or other link. For example, the communication link 180 can include a wireless or a wired network, a Local Area Network (LAN), a Wide Area Network (WAN), a private network, a public network
(such as the Internet), a WiFi network, a network that includes a satellite link, or another type of data communication network.

[0068] The memory 150 can store instructions (e.g., computer code) associated with an operating system, computer applications, and other resources. The memory 150 can also store application data and data objects that can be interpreted by one or more applications or virtual machines running on the computing subsystem 110. As shown in FIG. 1B, the example memory 150 includes microseismic data 151, geological data 152, fracture data 153, other data 155, and applications 156. In some implementations, a memory of a computing device includes additional or different information.

[0069] The microseismic data 151 can include information on the locations of microseisms in a subterranean zone. For example, the microseismic data can include information based on acoustic data detected at the observation well 104, at the surface 106, at the treatment well 102, or at other locations. The microseismic data 151 can include information collected by sensors 112. In some cases, the microseismic data 151 has been combined with other data, reformatted, or otherwise processed. The microseismic event data may include any suitable information relating to microseismic events (locations, magnitudes, uncertainties, times, etc.). The microseismic event data can include data collected from one or more fracture treatments, which may include data collected before, during, or after a fluid injection.

[0070] The geological data 152 can include information on the geological properties of the subterranean zone 121. For example, the geological data 152 may include information on the subsurface layers 122, information on the well bores 101, 111, or information on other attributes of the subterranean zone 121. In some cases, the geological data 152 includes information on the lithology, fluid content, stress profile, pressure profile, spatial extent, or other attributes of one or more rock formations in the subterranean zone. The geological data 152 can include information collected from well logs, rock samples, outcroppings, microseismic imaging, or other data sources.

[0071] The fracture data 153 can include information on fracture planes in a subterranean zone. The fracture data 153 may identify the locations, sizes, shapes, and other properties of fractures in a model of a subterranean zone. The fracture data 153
can include information on natural fractures, hydraulically-induced fractures, or any other type of discontinuity in the subterranean zone 121. The fracture data 153 can include fracture planes calculated from the microseismic data 151. For each fracture plane, the fracture data 153 can include information (e.g., strike angle, dip angle, etc.) identifying an orientation of the fracture, information identifying a shape (e.g., curvature, aperture, etc.) of the fracture, information identifying boundaries of the fracture, or any other suitable information.

[0072] The applications 156 can include software applications, scripts, programs, functions, executables, or other modules that are interpreted or executed by the processor 160. Such applications may include machine-readable instructions for performing one or more of the operations represented in FIG. 4. The applications 156 may include machine-readable instructions for generating a user interface or a plot, such as, for example, those represented in FIGS. 2A, 2B, 3A, 3B, 3C, 3D, 3E, and 3F. The applications 156 can obtain input data, such as microseismic data, geological data, or other types of input data, from the memory 150, from another local source, or from one or more remote sources (e.g., via the communication link 180). The applications 156 can generate output data and store the output data in the memory 150, in another local medium, or in one or more remote devices (e.g., by sending the output data via the communication link 180).

[0073] The processor 160 can execute instructions, for example, to generate output data based on data inputs. For example, the processor 160 can run the applications 156 by executing or interpreting the software, scripts, programs, functions, executables, or other modules contained in the applications 156. The processor 160 may perform one or more of the operations represented in FIG. 4 or generate one or more of the interfaces or plots shown in FIGS. 2A, 2B, 3A, 3B, 3C, 3D, 3E, and 3F. The input data received by the processor 160 or the output data generated by the processor 160 can include any of the microseismic data 151, the geological data 152, the fracture data 153, or the other data 155.

[0074] FIGS. 2A and 2B are plots showing example fracture planes. FIG. 2A includes a plot 200a showing an initial fracture plane 208a, an updated fracture plane 208b, and a microseismic event 206a. The plot 200a shows the effect of updating the parameters of the initial fracture plane 208a based on the new microseismic event
In particular, updating the parameters of the initial fracture plane 208a generates the updated fracture plane 208b.

A fracture plane can be represented in any suitable coordinate system (e.g., spherical coordinates, rectangular coordinates, etc.). The plot 200a shows the fracture planes in a three-dimensional rectilinear coordinate system. In the plot 200a, the coordinate system is represented by the vertical axis 204a and two horizontal axes 204b and 204c. The vertical axis 204a represents a range of depths in a subterranean zone; the horizontal axis 204b represents a range of East-West coordinates; and the horizontal axis 204c represents a range of North-South coordinates (all in units of feet).

The initial fracture plane 208a and the updated fracture plane 208b are both represented by rectangular, two-dimensional bodies extending through three-dimensional space. A fracture plane can have any other suitable geometry, such as, for example, triangular, ellipsoidal, trapezoidal, an irregular geometry, or another type of geometry.

The plot 200a shows one example of how the parameters of a fracture plane can be updated based on a single microseismic event. As shown by comparing the two fracture planes in FIG. 2A, updating the initial fracture plane 208a based on the microseismic event 206a causes the fracture plane to grow in height and length; the updated fracture plane 208b has a greater vertical and horizontal extent than the initial fracture plane 208a. Consequently, the updated fracture plane 208b has a larger area than the initial fracture plane 208a. In some instances, updating a fracture plane changes the fracture plane in another manner.

FIG. 2B includes another plot 200b showing an initial fracture plane 208c, an updated fracture plane 208d, and a microseismic event 206b. The plot 200b shows the effect of updating the parameters of the initial fracture plane 208c based on the new microseismic event 206b. In particular, updating the parameters of the initial fracture plane 208c generates the updated fracture plane 208d.

The plot 200b shows the fracture planes in a three-dimensional rectilinear coordinate system represented by the vertical axis 204d and two horizontal axes 204e and 204f. The axes in the plot 200b represent the same parameters as the axes in the plot 200a, on a different scale. The initial fracture plane 208c and the updated fracture
plane 208d are both represented by rectangular, two-dimensional areas extending in
the three-dimensional coordinate system.

[0080] As shown by comparing the two fracture planes in FIG. 2B, updating the
initial fracture plane 208c based on the microseismic event 206b causes the fracture
plane to rotate to a new orientation. For example, the updated fracture plane 208d has
a different orientation than the initial fracture plane 208c, with respect to the vertical
and horizontal axes in the plot 200b. Accordingly, the updated fracture plane 208d
and the initial fracture plane 208c define normal vectors having different orientations
(i.e., pointing in non-parallel directions in space).

[0081] FIGS. 3A-3F are plots showing updates for an example fracture plane. The
plots show an example time sequence for the fracture plane. FIG. 3A shows a plot
300a of an initial fracture plane 308a; each subsequent plot in the time sequence
shows the fracture plane as updated based on a new microseismic data point. FIG. 3B
shows a plot 300b of a first updated fracture plane 308b; FIG. 3C shows a plot 300c
of a second updated fracture plane 308c; FIG. 3D shows a plot 300d of a third
updated fracture plane 308d; FIG. 3E shows a plot 300e of a fourth updated fracture
plane 308e; and FIG. 3F shows a plot 300f of a fifth updated fracture plane 308f. In
each plot, the previous version of the fracture plane is shown for comparison. The
plots in FIGS. 3A-3F also show the well bore 310 and microseismic events 306.

[0082] Each of the plots 300a, 300b, 300c, 300d, 300e, and 300f shows the respective
fracture planes in a three-dimensional rectilinear coordinate system represented by the
vertical axis 304a and two horizontal axes 304b and 304c. The vertical axis 304a
represents a range of depths in a subterranean zone; the horizontal axis 304b
represents a range of East-West coordinates; and the horizontal axis 304c represents a
range of North-South coordinates (all in units of feet). As shown in the figures, the
axes are scaled for each respective plot. In the examples shown in FIGS. 3A-3F, the
fracture planes are represented by two-dimensional, rectangular areas extending in the
three-dimensional coordinate system. Fracture planes can have other spatial
geometries.

[0083] The initial fracture plane 308a and the updated fracture planes 308b, 308c,
308d, 308e, and 308f represent the growth and evolution of an individual fracture
over time. In the example shown, the initial fracture plane 308a is identified when the
40th microseismic event is received; the 87th microseismic event triggers an update algorithm. For example, the process 430 shown in FIG. 4 (or another process) can be used to update a fracture plane based on a new microseismic event. FIG. 3B shows that updating the fracture plane based on the 87th microseismic event changes the fracture plane's orientation. In particular, updating the initial fracture plane 308a based on the 87th microseismic event causes the fracture plane to rotate to a new orientation, and the first updated fracture plane 308b has a different orientation than the initial fracture plane 308a. The remaining updates shown in FIGS. 3C-3F cause the fracture plane to propagate, and the plots show how the fracture plane's area increases as time progresses.

[0084] FIG. 3C shows an update based on the 89th microseismic event received. Updating the first updated fracture plane 308b based on the 89th microseismic event causes the fracture plane to grow vertically, and the second updated fracture plane 308c is taller than the first updated fracture plane 308b. FIG. 3D shows an update based on the 130th microseismic event received. Updating the second updated fracture plane 308c based on the 130th microseismic event causes the fracture plane to grow vertically, and the third updated fracture plane 308d is taller than the second updated fracture plane 308c. FIG. 3E shows an update based on the 152nd microseismic event received. Updating the third updated fracture plane 308d based on the 152nd microseismic event causes the fracture plane to grow horizontally (toward the left in the figure), and the fourth updated fracture plane 308e is longer than the third updated fracture plane 308d. FIG. 3F shows an update based on the 157th microseismic event received. Updating the third updated fracture plane 308d based on the 157th microseismic event causes the fracture plane to grow horizontally (toward the right in the figure) and vertically, and the fifth updated fracture plane 308f is longer and taller than the fourth updated fracture plane 308e.

[0085] FIG. 4 is a flow chart of an example process 430 for analyzing microseismic data. Some or all of the operations in the process 430 can be implemented by one or more computing devices. In some implementations, the process 430 may include additional, fewer, or different operations performed in the same or a different order. Moreover, one or more of the individual operations or subsets of the operations in the process 430 can be performed in isolation or in other contexts. Output data generated by the process 430, including output generated by intermediate operations, can
include stored, displayed, printed, transmitted, communicated or processed information.

[0086] In some implementations, some or all of the operations in the process 430 are executed in real time during a fracture treatment. An operation can be performed in real time, for example, by performing the operation in response to receiving data (e.g., from a sensor or monitoring system) without substantial delay. An operation can be performed in real time, for example, by performing the operation while monitoring for additional microseismic data from the fracture treatment. Some real time operations can receive an input and produce an output during a fracture treatment; in some instances, the output is made available to a user within a time frame that allows an operator to respond to the output, for example, by modifying the fracture treatment.

[0087] In some cases, some or all of the operations in the process 430 are executed dynamically during a fracture treatment. An operation can be executed dynamically, for example, by iteratively or repeatedly performing the operation based on additional inputs, for example, as the inputs are made available. In some instances, dynamic operations are performed in response to receiving data for a new microseismic event (or in response to receiving data for a certain number of new microseismic events, etc.).

[0088] At 400, microseismic data for a new microseismic event are received. For example, the microseismic data can be obtained by reading the microseismic data from memory, by receiving the microseismic data from a remote device, or in a different manner. The microseismic data may include information on the measured location of the new microseismic event, information on a measured magnitude of the new microseismic event, information on an uncertainty associated with the new microseismic event, or information on a time associated with the new microseismic event, etc. The microseismic data are collected from a fracture treatment. For example, the microseismic event data may include microseismic data collected at an observation well, at a treatment well, at the surface, or at other locations in a well system. Microseismic data from a fracture treatment can include data for microseismic events detected before, during, or after the fracture treatment is applied. For example, in some instances, microseismic monitoring begins before the fracture treatment is applied, ends after the fracture treatment is applied, or both.
At 401, a previously-generated fracture plane is selected. In this example, the fracture plane is "previously-generated" in the sense that it was generated before the data for the new microseismic event was received. In some implementations, parameters of a previously-generated fracture plane are the parameters that were identified from microseismic data collected before the new microseismic event was detected. The prior microseismic event data and the new microseismic event can be part of a microseismic data set from the same fracture treatment of a subterranean zone. In some instance, the prior microseismic event data and the new microseismic event are from different fracture treatments.

Fracture planes (e.g., the previously-generated fracture plane selected at 401) can be identified from microseismic data by any suitable operation, process or algorithm. A fracture plane can be identified by computing the parameters of the fracture plane, for example, from the locations and other parameters of the measured microseismic events. In some cases, the fracture planes are identified in real time during the fracture treatment. Example techniques for identifying fracture planes from microseismic data are described in U.S. Provisional Application Serial No. 61/710,582, filed on October 5, 2012.

In some instances, when the data are received at 400, several fracture planes have already been generated. For example, tens or hundreds of fracture planes may have already been identified from previously-received microseismic data. As such, in some cases, a particular fracture plane is selected from multiple previously-generated fracture planes at 401. For example, the particular fracture plane can be selected from a list of previously-generated fracture planes based on an index, selection criteria, or other information.

At 402, the distance between the new microseismic event and the selected fracture plane is calculated. The distance can be calculated, for example, based on the spatial coordinates of the new microseismic event and the parameters of the selected fracture plane. In some instance, the distance calculation can account for uncertainty in the location of the microseismic event, uncertainty in the location of the fracture plane, or both. Other information can be accounted for in calculating the distance.

At 403, the distance between the new microseismic event and the selected fracture plane is compared to a control parameter. The control parameter can be a
threshold value for determining whether the selected fracture plane is close enough to
the new microseismic event, for example, to consider the new microseismic event as a
supporting event for the selected fracture plane. The control parameter can be a
previously-designated threshold value (e.g., a system constant). The control parameter
can be a dynamically computed value. For example, the control parameter can be
computed based on the parameters of the selected fracture plane, parameters of other
previously-generated fracture planes, or based on other information.

[0094] If the distance between the new microseismic event and the selected fracture
plane is not less than the control parameter, the process 430 progresses to operation
450. At 450, if there are other previously-generated fracture planes that have not been
selected, the process 430 progresses to operation 401. Accordingly, in some cases, the
operations 400, 402, 403, 450, and 401 cause the process 430 to sequentially select
multiple different previously-generated fracture planes.

[0095] The process 430 can use any suitable algorithm or technique to systematically
progress through previously-generated fracture planes. For example, an indexed list of
the previously-generated fracture planes can be created. The list can be sorted, for
example, based on size, confidence, time, or other parameters of the fracture planes,
or the list can be unsorted. A stored index can be used to systematically select a
different previously-generated fracture plane from the list each time operation 401 is
executed.

[0096] In some cases, the previously-generated fracture planes are selected in
sequence until all the previously-generated fracture planes have been selected. At 450,
if all the previously-generated fracture planes have been selected, the new
microseismic event is designated as an unassociated event at 460. As such, the new
microseismic event can be labeled, tagged, or otherwise designated as not supporting
any fracture plane.

[0097] In some cases, the previously-generated fracture planes are selected in
sequence until the distance between a selected fracture plane and the new
microseismic event is less than the control parameter. At 403, if the distance between
the new microseismic event and the selected fracture plane is not less than the control
parameter, the process 430 progresses to operation 415. At 415, the selected fracture
plane is updated based on the new microseismic event. The operations in the dashed
box in FIG. 4 represent an example technique for updating a fracture plane based on a new microseismic event. Other techniques can be used.

[0098] At 404, parameters of the selected fracture plane are computed. In the example shown, the orientation, area, and distance residual of the fracture plane are calculated. The area of the fracture plane indicates the fracture plane's two-dimensional size. The distance residual of a fracture plane indicates the average distance between the fracture plane and the fracture plane's supporting events.

[0099] The orientation of the fracture plane indicates the fracture plane's angle, for example, in a specified coordinate system. The orientation can be specified, for example, by particular values of the dip angle and strike angle. New strike and dip values can be calculated at 404 using a Chi-square fitting technique or other techniques. In some cases, the change in orientation is small, for example, due to the conditional control of the distance.

[0100] The parameters of the selected fracture plane can be calculated based on the new microseismic event and other microseismic events. For example, the other microseismic events can be prior microseismic events that occurred or were detected (or both) before the new microseismic event. In some cases, the other microseismic events are the set of supporting microseismic events that were used to compute the previously-generated fracture plane (i.e., the fracture plane that was selected at 401).

[0101] At 405, the distance residual is compared to a tolerance value. The tolerance value can be a threshold value for determining whether the microseismic events that were used to update the fracture plane are (on average) close enough to the updated fracture plane, for example, to consider the new microseismic event as a supporting event for the updated fracture plane. The tolerance value can be a previously-designated threshold value (e.g., a system constant). The tolerance value can be a dynamically computed value.

[0102] At 405, if the distance residual is less than the control parameter, the process 430 progresses to operation 410. At 410, the updated fracture plane can be stored, and the new microseismic event is associated with the updated fracture plane.

[0103] At 405, if the distance residual is not less than the control parameter, the process 430 progresses to operation 406. At 406, the distance residual can be reduced by disassociating one or more microseismic events from the selected fracture plane.
For example, one or more microseismic events that are the greatest distance from the updated version of the selected fracture plane can be disassociated from the fracture plane.

[0104] At 407, new fracture plane parameters are calculated from the microseismic events remaining after one or more microseismic events were disassociated at 406. If the distance residual has not been reduced or if the distance residual has not been reduced by an acceptable amount (e.g., less than the tolerance value or some other threshold), then the process 430 progresses to operation 460. At 460, the new microseismic event is designated as an unassociated event at 460. As such, the microseismic event can be labeled, tagged, or otherwise designated as not supporting any fracture plane. In some instances, the selected fracture plane can be restored to its previously-generated parameters. In other words, if the new microseismic event is designated as unassociated, the updated parameters for the fracture plane calculated at 404 can be discarded.

[0105] In some cases, the process 430 improves or optimizes the distance residual and area when the selected fracture plane is updated at 415. For example, when the updated fracture plane's distance residual is less than the tolerance value at 405, the new microseismic event becomes associated with the fracture plane at 410. Otherwise, other microseismic events in the supporting set can be disassociated until the distance residual falls within the threshold value. In some cases, the change of the fracture plane's orientation or size causes some microseismic events to be disassociated from the fracture plane. In some cases, the change of the fracture plane's orientation or size causes some microseismic events to be associated to the fracture plane. In some instances, a microseismic event can be associated with multiple fracture planes. The association of a microseismic event with multiple fracture planes can indicate that the fracture planes intersect.

[0106] If the distance residual has been reduced by an acceptable amount at 407, then the process 430 progresses to operation 408. At 408, the area of the updated fracture plane (after disassociating one or more microseismic events at 406) is computed. The area can be the size of the fracture plane generated from the microseismic events still associated with the fracture plane after the events were disassociated at 406. If the size of the fracture plane is not greater than the prior area of the fracture plane, then the process 430 progresses to operation 460 (described above). As such, the check
performed at 408 can ensure that associating the new microseismic event to the fracture plane does not cause the fracture plane to shrink. This check can be performed, for example, to incorporate physical or geological constraints in a fracture matching algorithm. For example, the check can be performed to reflect knowledge that fractures tend to grow (rather than shrink) during a fracture treatment. Experience shows that new microseismic events are typically associated with a fracture propagating in length or growing in height. As such, the non-decreasing area condition can be imposed to ensure that the an updated fracture plane's area is larger than or equal to that of the original plane. Other assumptions are used in some environments.

[0107] At 408, if the size of the fracture plane is greater than the prior area of the fracture plane, then the process 430 progresses to operation 410. At 410, the new microseismic event is associated with the fracture plane. If any microseismic events were disassociated at 406, those microseismic events can be designated as unassociated, or they may be handled in a different manner. Example techniques for handling disassociated microseismic events are described in U.S. Provisional Application Serial No. 61/710,582, filed on October 5, 2012. In some instances, the updated fracture plane parameters (i.e., the fracture plane parameters based on the microseismic events that remain associated after 406) are stored as the updated fracture plane.

[0108] The example process 430 includes checks that can improve the accuracy of a fracture matching algorithm. For example, some or all of the comparisons at 403, 405, 407, and 408 can help to improve confidence that the updated fracture plane corresponds to a physical fracture in the subterranean zone. The comparisons can be adjusted for a particular environment, as appropriate. In some cases, additional or different comparisons can be made. For example, in some cases, an accuracy confidence value is used to determine whether to associated a new microseismic event to a plane. Example techniques for calculating an accuracy confidence value for a fracture plane are described in U.S. Provisional Application Serial No. 61/710,582, filed on October 5, 2012.

[0109] In some implementations, a graphical representation of the updated fracture planes is generated. The graphical representation can be displayed, for example, to present the updated fracture plane in real time during the fracture treatment. The
graphical representation can include a single fracture plane or multiple fracture
planes. The graphical representation can include a three-dimensional representation of
the fracture plane, a three-dimensional representation of the microseismic events
associated with the fracture plane, or a combination of these and other features.
Examples of a graphical representation of a fracture plane are shown in FIGS. 2A, 2B,
3A, 3B, 3C, 3D, 3E, and 3F. Other types of graphical representations can be used.

[0110] The graphical representation can be displayed on a monitor, screen, or other
type of display device. In some instances, the display is updated. For example, the
displayed graphical representation can be updated based on additional microseismic
event data from the fracture treatment. Displaying (and in some cases, updating) the
graphical representation can allow a user to view dynamic behavior associated with a
fracture treatment. In some cases, a fracture plane can be updated as additional
microseismic data is accumulated, and the updates may cause the fracture plane to
grow or change orientation.

[0111] Some embodiments of subject matter and operations described in this
specification can be implemented in digital electronic circuitry, or in computer
software, firmware, or hardware, including the structures disclosed in this
specification and their structural equivalents, or in combinations of one or more of
them. Some embodiments of subject matter described in this specification can be
implemented as one or more computer programs, i.e., one or more modules of
computer program instructions, encoded on computer storage medium for execution
by, or to control the operation of, data processing apparatus. A computer storage
medium can be, or can be included in, a computer-readable storage device, a
computer-readable storage substrate, a random or serial access memory array or
device, or a combination of one or more of them. Moreover, while a computer storage
medium is not a propagated signal, a computer storage medium can be a source or
destination of computer program instructions encoded in an artificially generated
propagated signal. The computer storage medium can also be, or be included in, one
or more separate physical components or media (e.g., multiple CDs, disks, or other
storage devices).

[0112] The term "data processing apparatus" encompasses all kinds of apparatus,
devices, and machines for processing data, including by way of example a
programmable processor, a computer, a system on a chip, or multiple ones, or
combinations, of the foregoing. The apparatus can include special purpose logic
circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application
specific integrated circuit). The apparatus can also include, in addition to hardware,
code that creates an execution environment for the computer program in question,
e.g., code that constitutes processor firmware, a protocol stack, a database
management system, an operating system, a cross-platform runtime environment, a
virtual machine, or a combination of one or more of them. The apparatus and
execution environment can realize various different computing model infrastructures,
such as web services, distributed computing and grid computing infrastructures.

[0113] A computer program (also known as a program, software, software
application, script, or code) can be written in any form of programming language,
including compiled or interpreted languages, declarative or procedural languages. A
computer program may, but need not, correspond to a file in a file system. A program
can be stored in a portion of a file that holds other programs or data (e.g., one or more
scripts stored in a markup language document), in a single file dedicated to the
program in question, or in multiple coordinated files (e.g., files that store one or more
modules, sub programs, or portions of code). A computer program can be deployed to
be executed on one computer or on multiple computers that are located at one site or
distributed across multiple sites and interconnected by a communication network.

[0114] Some of the processes and logic flows described in this specification can be
performed by one or more programmable processors executing one or more computer
programs to perform actions by operating on input data and generating output. The
processes and logic flows can also be performed by, and apparatus can also be
implemented as, special purpose logic circuitry, e.g., an FPGA (field programmable
gate array) or an ASIC (application specific integrated circuit).

[0115] Processors suitable for the execution of a computer program include, by way
of example, both general and special purpose microprocessors, and processors of any
kind of digital computer. Generally, a processor will receive instructions and data
from a read only memory or a random access memory or both. A computer includes a
processor for performing actions in accordance with instructions and one or more
memory devices for storing instructions and data. A computer may also include, or be
operatively coupled to receive data from or transfer data to, or both, one or more mass
storage devices for storing data, e.g., magnetic, magneto optical disks, or optical
disks. However, a computer need not have such devices. Devices suitable for storing computer program instructions and data include all forms of non-volatile memory, media and memory devices, including by way of example semiconductor memory devices (e.g., EPROM, EEPROM, flash memory devices, and others), magnetic disks (e.g., internal hard disks, removable disks, and others), magneto optical disks, and CD-ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

[0116] To provide for interaction with a user, operations can be implemented on a computer having a display device (e.g., a monitor, or another type of display device) for displaying information to the user and a keyboard and a pointing device (e.g., a mouse, a trackball, a tablet, a touch sensitive screen, or another type of pointing device) by which the user can provide input to the computer. Other kinds of devices can be used to provide for interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback, e.g., visual feedback, auditory feedback, or tactile feedback; and input from the user can be received in any form, including acoustic, speech, or tactile input. In addition, a computer can interact with a user by sending documents to and receiving documents from a device that is used by the user; for example, by sending web pages to a web browser on a user's client device in response to requests received from the web browser.

[0117] A client and server are generally remote from each other and typically interact through a communication network. Examples of communication networks include a local area network ("LAN") and a wide area network ("WAN"), an inter-network (e.g., the Internet), a network comprising a satellite link, and peer-to-peer networks (e.g., ad hoc peer-to-peer networks). The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client-server relationship to each other.

[0118] In some aspects of what is described here, dominant orientations embedded in sets of fractures associated with microseismic events can be dynamically identified during a fracture treatment. For example, fracture planes can be extracted from real time microseismic events collected from the field. The fracture planes can be identified based on microseismic event information including: event locations, event location measurement uncertainties, event moment magnitudes, event occurrence
times, and others. At each point in time, data can be associated with previously-computed basic planes, including the microseismic supporting set of events.

[0119] In some aspects of what is described here, a probability histogram or distribution of basic planes can be constructed from the microseismic events collected, and the histogram or distribution can be used for deriving the dominant fracture orientations. Fractures extracted along the dominant orientations can, in some instances, provide an optimal match to the real time microseismic events. The histogram or distribution and the dominant orientations can have non-negligible sensitivity to the new incoming microseismic event. As such, some planes identified during the time microseismic data are assimilated may not be accurate when comparing to the post microseismic event data results. Example techniques for generating, updating, and using histograms based on microseismic data are described in U.S. Provisional Application Serial No. 61/710,582, filed on October 5, 2012.

[0120] In some aspects of what is described here, an accuracy confidence parameter can provide a measure for the accuracy of real-time identified planes. Factors impacting a plane's accuracy confidence can include an event's intrinsic properties, the relationship between support events and the plane, and the weight reflecting the fracture orientation trends of post microseismic event data. In some instances, fracture planes with high confidence at the end of hydraulic fracturing treatment that were identified in real time fashion are consistent with those obtained from the post event data.

[0121] In some aspects, some or all of the features described here can be combined or implemented separately in one or more software programs for real-time automated fracture mapping. The software can be implemented as a computer program product, an installed application, a client-server application, an Internet application, or any other suitable type of software. In some cases, a real-time automated fracture mapping program can dynamically show users spatial and temporal evolution of identified fracture planes in real-time as microseismic events gradually accumulate. The dynamics may include, for example, the generation of new fractures, the propagation and growth of existing fractures, or other dynamics. In some cases, a real-time automated fracture mapping program can provide users the ability to view the real-time identified fracture planes in multiple confidence levels. In some instances, users may observe spatial and temporal evolution of the high confidence level fractures,
which may exhibit the dominant trends of overall microseismic event data. In some cases, a real-time automated fracture mapping program can evaluate fracture accuracy confidence, for example, to measure the certainty of identified fracture planes. The accuracy confidence values may, for example, help users better understand and analyze changes in a probability histogram or orientation distribution, which may continuously vary with the real-time accumulation of microseismic events. In some cases, a real-time automated fracture mapping program can provide results that are consistent with post data fracture mapping. For example, at the end of the hydraulic fracture treatment, the results produced by the real-time automated fracture mapping program can be statistically consistent with those obtained by a post data automated fracture mapping program operating on the same data. Such features may allow field engineers, operators and analysts, to dynamically visualize and monitor spatial and temporal evolution of hydraulic fractures, to analyze the fracture complexity and reservoir geometry, to evaluate the effectiveness of hydraulic fracturing treatment and to improve the well performance.

[0122] While this specification contains many details, these should not be construed as limitations on the scope of what may be claimed, but rather as descriptions of features specific to particular examples. Certain features that are described in this specification in the context of separate implementations can also be combined. Conversely, various features that are described in the context of a single implementation can also be implemented in multiple embodiments separately or in any suitable subcombination.

[0123] A number of embodiments have been described. Nevertheless, it will be understood that various modifications can be made. Accordingly, other embodiments are within the scope of the following claims.
CLAIMS

1. A computer-implemented method for analyzing microseismic data from a fracture treatment, the method comprising:
   receiving data for a new microseismic event associated with a fracture treatment of a subterranean zone;
   calculating, by data processing apparatus, an updated parameter for a fracture plane, the fracture plane being previously-generated based on data for prior microseismic events, the updated parameter calculated based on the data for the new microseismic event and the data for the prior microseismic events; and
   displaying a graphical representation of the fracture plane based on the updated parameter.

2. The method of claim 1, wherein the updated parameter is calculated and the graphical representation is displayed in real time during the fracture treatment.

3. The method of claim 1, further comprising:
   selecting the fracture plane, from a plurality of fracture planes, based on the data for the new microseismic event; and
   associating the new microseismic event with the selected fracture plane.

4. The method of claim 3, wherein displaying a graphical representation of the fracture plane includes updating a graphical representation of the plurality of fracture planes in real time during the fracture treatment.

5. The method of claim 3, wherein selecting the fracture plane from a plurality of fracture planes includes:
   determining a distance between the new microseismic event and the fracture plane; and
   determining that the distance is less than a threshold distance.

6. The method of claim 5, further comprising computing the threshold distance by multiplying a predefined coefficient by the standard deviation of the microseismic events associated with the fracture plane.

7. The method of claim 1, wherein calculating an updated parameter for the fracture plane includes calculating at least one of an updated orientation or an updated
area for the fracture plane based on the data for the new microseismic event and the data for the prior microseismic events.

8. The method of claim 1, wherein calculating an updated parameter for the fracture plane includes calculating an average distance from the fracture plane for the new microseismic event and the prior microseismic events.

9. The method of claim 8, wherein the new microseismic event and the prior microseismic events define a set, and the method further comprises:
   detecting that the average distance is greater than a predefined threshold distance; and
   calculating an updated average distance after removing one or more microseismic events from the set.

10. The method of claim 1, wherein calculating an updated parameter for the fracture plane includes calculating an updated area for the fracture plane, and the method further comprises:
    comparing the updated area for the fracture plane to a prior area for the fracture plane; and
    disassociating the new microseismic event from the fracture plane if the updated area for the fracture plane is less than the prior area for the fracture plane.

11. The method of claim 1, further comprising:
    identifying one or more microseismic events that are farther than a threshold distance from the fracture plane; and
    disassociating the identified microseismic events from the fracture plane.

12. The method of claim 1, wherein the new microseismic event comprises a first new microseismic event, the method further comprising:
    after displaying the graphical representation based on the first new microseismic event, receiving data for a second new microseismic event from the fracture treatment;
    calculating a second updated parameter for the fracture plane based in part on the data for the second new microseismic event; and
    displaying a graphical representation of the fracture plane based on the second updated parameter.
13. A non-transitory computer-readable medium encoded with instructions that, when executed by data processing apparatus, perform operations comprising:

- receiving data for a new microseismic event associated with a fracture treatment of a subterranean zone;
- calculating an updated parameter for a fracture plane, the fracture plane being previously generated based on data for prior microseismic events, the updated parameter calculated based on the data for the new microseismic event and the data for the prior microseismic events; and
- generating a graphical representation of the fracture plane based on the updated parameter.

14. The computer-readable medium of claim 13, wherein the updated parameter is calculated and the graphical representation is generated in real time during the fracture treatment.

15. The computer-readable medium of claim 13, the operations further comprising:

- selecting the fracture plane, from a plurality of fracture planes, based on the data for the new microseismic event; and
- associating the new microseismic event with the selected fracture plane.

16. The computer-readable medium of claim 13, wherein calculating an updated parameter for the fracture plane includes calculating at least one of an updated orientation or an updated area for the fracture plane based on the data for the new microseismic event and the data for the prior microseismic events.

17. The computer-readable medium of claim 13, wherein calculating an updated parameter for the fracture plane includes calculating an average distance from the fracture plane for the new microseismic event and the prior microseismic events.

18. A system comprising:

- data processing apparatus operable to:
  - receive data for a new microseismic event associated with a fracture treatment of a subterranean zone; and
  - calculate an updated parameter for a fracture plane, the fracture plane being previously generated based on data for prior microseismic events, the updated parameter calculated based on the data for the new microseismic event and the data
for the prior microseismic events; and

a display device operable to display a graphical representation of the fracture plane based on the updated parameter.

19. The system of claim 18, further comprising a communication interface operable to receive microseismic event data from one or more sensors associated with the subterranean zone.

20. The system of claim 18, wherein the updated parameter is calculated and the graphical representation is displayed in real time during the fracture treatment.

21. The system of claim 18, wherein the data processing apparatus is further operable to:

- select the fracture plane, from a plurality of fracture planes, based on the data for the new microseismic event; and
- associate the new microseismic event with the selected fracture plane.

22. The system of claim 18, wherein calculating an updated parameter for the fracture plane includes calculating at least one of an updated orientation or an updated area for the fracture plane based on the data for the new microseismic event and the data for the prior microseismic events.
430
400
Receive Data for New Microseismic Event

401
Select a Previously-Generated Plane

460
Designate Event as Unassociated

402
Calculate Distance Between New Event and Selected Plane

450
All Planes Selected?

403
Distance Less than Control Parameter?

404
Yes

405
Residual Less than Tolerance?

406
No

407
Residual Less than Prior Residual?

408
Area Greater than Prior Area?

409
Yes

410
Associate Event with the Plane

415
Update Selected Fracture Plane

416
No

400
Calculate Orientation, Area and Residual

406
Reduce Residual by Disassociating Events

460
Designate Event as Unassociated

FIG. 4
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

G01V 1/40
G01V 1/30

B. FIELDS SEARCHED

G01V E21B

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<td>paragraphs [0051], [0059], [0078], [0095], [0116], [0198] figures 1-3, 5-9</td>
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<td>1-9, 11-22</td>
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Further documents are listed in the continuation of Box C. See patent family annex.

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Bream, Philip
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