An invention for the filtering, sorting and analysis of microseismicity induced during production of fluid resources from their reservoirs which allows direct 4 dimensional measurements of all or many of the components of the permeability fields as well as other petrophysical rock properties important to reservoir analysis and monitoring. The seismicity associated with the permeability field is identified by its spatial and temporal location in two general conoidal volumes (12), symmetrically disposed about the injection point (14) in any well being used for this purpose. The seismicity is generated by fractures hydraulically linked to the injection well and comprises the permeability field associated with that well. Mapping of the permeability field identified by this means can also be used for guiding the placement of subsequent infill, development and injection wells. In addition by permitting the active deformation field to be seen, it allows potential hazards to the field infrastructure to be recognized. By predicting the fluid paths, the invention forms an important adjunct to 4D active seismic analysis which monitors the migration of fluid fronts.
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Method for 4D permeability analysis of geologic fluid reservoirs

This application claims priority from United States Provisional Patent Application No. 60/104,482, filed 10/16/98, and entitled "Method for 4D permeability analysis of geologic fluid reservoirs."

Field of Invention

This invention relates to the measurement of the permeability fields of underground geologic fluid systems and more specifically it uses microseismicity induced by the production process for determining the petrophysical properties of a reservoir in general, its permeability in particular and analyzing its structure.

Background

It is generally known that the earth's crust contains underground fluid reservoirs. These reservoirs form an important natural resource for major components of our economic systems, e.g. oil, gas, water, etc. Recovery of these resources is critically dependent on knowing the "plumbing" of these reservoirs, i.e. the paths through which the fluid moves and by means of which it can be extracted. In a fluid reservoir the "plumbing system" includes a network of interconnected cracks which can be described as "hydraulically linked" i.e. changes in fluid pressure can be transmitted through them.

The character of the hydraulically linked crack network is known as the "reservoir permeability field". By character is meant the shape and distribution of the network and the ease with which fluid moves through it. Determining this character is the focus of much of the effort of fluid resource recovery and exploitation. The reason for this interest is that the spatial geometry of the permeability field and the variation in flow through it, are major factors in identifying the best location for production wells and in the case of hydrocarbons, injector wells in addition to production wells. Injector wells are used to inject fluids that are denser than the hydrocarbons and thus act to "sweep" the less dense fluid that remains after the initial production phase.

To date, determination of the permeability field of fluid reservoirs has been largely restricted to the use of "guess and test" methods using reservoir simulators. A "guess and test" method uses largely inferential and sparse information about the permeability
field to make a best "guess" as to its full three dimensional character. The "guess" is then tested by using measured data on production and injection from the field in question in the model, to test whether the model reproduces the measured data. The efficacy of the "guess and test" methods is poor. It is generally accepted that one of the principal reasons that recovery of resource from hydrocarbon reservoirs averages only about 30 - 35% of the total resource in any given reservoir, is the low quality of permeability information. What is needed is a means of seeing or illuminating the permeability field so that it can be directly measured.

It has been recognized that production from fluid reservoirs can induce seismicity. Attempts have been made to use microseismicity induced by production to identify fracture systems and other possible causes of the earthquakes, e.g. pore collapse, fault reactivation, etc. Efforts at deciphering the information contained in the microseismicity has had limited success. It is believed that the principal reason for this failure has to do with the way earthquake seismologists get their information on the earthquake process (seismogenesis).

An earthquake is a seismic wave that results from the elastic failure of rock. It is the signal or "sound" of that failure. However, elastic failure can result from a variety of natural processes, e.g. folding, faulting under compression/extension, pore collapse, increased fluid pressure, etc. Unfortunately all seismic waves produced by natural causes, no matter what their seismogenesis, are very similar in their appearance or "wave form". This condition makes it virtually impossible to derive the particular process (i.e. folding, faulting, etc.) that produces any given seismic wave by studying the wave itself. Thus the almost exclusive restriction of the analysis of microseismicity to its signal has produced only a limited amount of useful information particularly as far as reservoir characteristics are concerned.

Attempts to distinguish the sets of signals from one another are largely ad hoc. Thus identification of fractures associated with the permeability field is; 1) only inferential; 2) limited to the immediate vicinity of injection wells (i.e. within a few 100 meters). This information is too poor to be usefully extrapolated to the entire reservoir. No attempts to directly measure any other components of the reservoir permeability field using
microseismicity have been made. In terms of structural data, i.e. folding and faulting, microseismicity has been used to successfully locate faults in some cases where apparently only simple faulting is occurring. However regions with more complex deformation result in earthquake data clouds which are either left un-interpreted or only poorly explained.

A recent development that permits the clouds of earthquake data to be much more rigorously interpreted is described by Seeber and Armbruster (1995 The San Andreas Fault system through the Transverse Ranges as illuminated by earthquakes, J. Geophysical Research, 100, 5, 8285-8310). They have developed analysis techniques for earthquake slip planes that allow them to be sorted into structural assemblages. These structural assemblages represent portions of the instantaneous and incremental deformation field. The techniques for analyzing the slip plane data are embodied in a known software application; Seeber and Armbruster's QuakeView.

In addition to the foregoing, the following sets of observations on secondary hydrocarbon recovery, hydraulically conductive fractures and microseismicity, are of particular importance with regard to the background of the present invention.

1. **Rate correlation statistics, maximum compressive directions and rapid response:**

   Heffer et al, (1997, Novel techniques show links between reservoir flow directionality, earth stress, fault structure and geomechanical changes in mature waterfloods, SPE Journal, V. 2, June, pp. 91 -98) show that rate of production correlation's between producer and injection wells is directly related to the orientation of the maximum ambient compressive stress direction. Positive correlation's (i.e. production increases) are observed between injection and production wells where the line connecting the two wells lies within a sector of arc of from 60 to 90 degrees that is bisected by the local maximum compressive stress. Response times between injector and producer wells has "zero" (less than 1 month) time lag over very large distances (> 4.5 kilometers). They note that D'arcyian type diffusive flow cannot explain this phenomena.

2. **Hydraulically conductive fractures are critically stressed:** Barton et al (1995, Fluid flow along potentially active faults in crystalline rock, Geology, V. 23, no. 8, p. 683-686) demonstrate that critically stressed faults and fractures are those with the
highest hydraulic conductivity and that statistically these are conoidally distributed around the maximum stress direction (Barton et al, 1995; figure 3).

3. **Seismicity induced by increased fluid pressure shows rapid response over large distances**: In the earthquake control experiment run at Chevron's Rangely, CO field and reported by Raleigh et al (1976, An experiment in earthquake control at Rangely, Colorado; Science, V. 191, p. 1230 - 1237), microseismicity induced by fluid injection and occurring at distances of up to 3 km from the injection well, were observed to stop within 1 day of lowering fluid pressure at the injection wells.

**Objects and Advantages**

Accordingly, several objects and advantages of my invention are to provide a method of using microseismicity to determine the nature of the interconnected network of openings that define the permeability field of underground reservoirs. By nature is meant the shape of this network, the variation of its shape in space and time, the change in space and time of the rate of movement of the fluid through the network, etc. The invention does this by providing a means of distinguishing microseismicity associated with the permeability field from other types of microseismicity. It also permits determination of the relationship of the microseismicity to other elements of the reservoir geology, e.g. rock type, whether part of a fold or fault, etc. This information can be used as input to reservoir models and other multi-dimensional images for exploration, production and development thereby improving the potential of recovery of fluid resources from the earth's crust.

Other objects are:

1. to provide a means of guiding the placement of subsequent wells for the purposes of infill and/or development and/or injection;
2. to provide a means of determining the orientation of the maximum compressive stress direction using fluid injection;
3. to provide a means of using the information derived from the microseismically produced signal to be used for multi-dimensional analysis of petrophysical properties including direct 4D measurement of components of the permeability field and structural environments;
4. to improve velocity field models;
5. to improve interpretation of geodetic surveys whose aim is identifying subsurface behavior of the crust associated with fluid motion;
6. to provide independent evidence for paths of fluid motion that may be identified by 4D seismic reflection analysis or other means;
7. to provide information on possible hazards to human infrastructure arising from deformation of the earth's crust associated with fluid extraction and injection.

Still further objects and advantages will become apparent from a consideration of the ensuing description and accompanying drawings.

Figure 1 is a perspective view of a conoidal volume of failure containing the microseismicity associated with the hydraulically linked fracture system. The microseismicity is generated by the interaction between increased fluid pressure at the injection well and the ambient stress field.

Figure 2 is an elevation view of Figure 1. The view is parallel to the axes of maximum compressive stress and shows the conoidal volumes in cross section as the two lines that intersect at the point of fluid injection on the well.

Figure 3 is a schematic time/map view of a hypothetical example showing the behavior of hydraulically linked microseismic events generated by increased pore pressure at the injection well. The microseismic events are shown by the projection onto the map of the line of intersection between the slip plane of the microseismic event and a horizontal plane.

Figure 4 is a flowchart of a Seismo-tectonic Reservoir Monitoring system. The flowchart shows how all available geological and geophysical parameters associated with seismogenesis and reservoir characterization are collected, processed and assembled.
Figure 5 is a flowchart showing development phases of a passive seismic monitoring program relative to field development stage and a 4D seismic program.

Figure 6a is a schematic map view of a hypothetical reservoir showing the method by which the STRM system can be used to map the permeability and stress fields as a guide for oil and gas field for development (STRM mapping). It shows the initial injection test results for the discovery well and the location of the first delineation well.

Figure 6b is a schematic map showing the second injection test run at the first delineation well to further STRM map the hypothetical field and to place the second delineation well.

Figure 6c is a schematic map showing the third injection test run at the second delineation well to further STRM map the hypothetical field and to place the third delineation well.

Figure 6d is a schematic map showing the fourth injection test run at the third delineation well to further STRM map the hypothetical field.

Figure 6e is a schematic map shows the placement of a fourth delineation well and its use to further STRM map the hypothetical field.

Figure 6f is a schematic map shows the placement of a fifth delineation well and its use to further STRM map the hypothetical field.

Preferred Embodiment – Description

Microseismicity is the product of a large number of independent parameters. Analysis of multiparametric phenomena requires the ability to control and directly compare the various parameters. It is a basic aspect of this invention to control and compare as many of these parameters as possible. The description of this invention describes the controlling mechanism and the means of systematic collection and assemblage of all parametric data available into a single n-dimensional model. This model allows direct
comparison of one parameter against another in correct spatial and temporal relations and also provides a means for direct measurement and mapping of the entire reservoir permeability field as well as all other seismogenic aspects of the reservoir. This system of data collection, assemblage, analysis and displaying the results as multi-dimensional images, is referred to as Seismo-Tectonic Reservoir Monitoring™ or STRM™.

Figure 1 is a three dimensional schematic showing how an operating injection well can be used to control the seismicity of a hydraulically linked network. The figure shows the geometric relationships between an operating injection well [10] used to control seismicity, the maximum compressive stress direction of an isotropic, homogeneous ambient stress field [11], the two conoidal volumes locating the hydraulically linked microseismicity [12] and a hypothetical passive seismic network [13] that may be connected to a central computer [43]. The conoidal volumes are symmetrically distributed with respect to the injection point of the well [14]. The maximum compressive stress direction locates the cone axes [11]. The apical angle of the cones will always be acute, typically varying from 20 to 45 degrees but may be larger or smaller depending on local conditions. The cone apices are located at or close to the point on the well bore where fluid is being injected [14]. The cone axes have lengths measured in kilometers. The seismometers [15] in the passive seismic network [13] may be located either on the surface and/or in the subsurface. Optionally, instead of connecting the seismometers [15] to a central computer [43], the seismometers could include processors therein for processing and analyzing the data. The connections between the components of the network could be via electrical conductors, optical links, transmitted electromagnetic waves, or any other suitable medium.

Figure 2 is an elevation view made parallel to the maximum compressive stress directions [11]. The intersections of the conoidal volumes with the plane of the elevation are shown by the two lines [12] that intersect at the well injection point [14].

Figure 3 shows how microseismicity illuminating a hydraulically linked fracture network can be identified. The stress field is isotropic and homogeneous. The figure is a schematic map view showing a hypothetical example of the space/time variation of microseismic events hydraulically linked to an injection well [10]. The events are
produced by an increase in fluid pressure at that well [10]. The hydraulically linked
events can be recognized by two characteristics, one spatial and the second temporal:

1. Spatially the events occur within the region bounded by a projection
   of the conoidal volumes [12] of which the maximum compressive stress is
   the cone axis. The map view projection of the maximum compressive stress
direction [11] of the ambient stress field forms the bisector of the angle
   between the projected boundaries of the conoidal volumes [12] containing
   the hydraulically linked events.

2. Temporally, the projections of the strike lines of these events migrate
   away from the injection well in time. The events are grouped into arbitrary
   time units for purposes of illustration only.

Regions of hydraulically linked microseismicity that contain no production wells identify
areas of potential well infill. The axis of the conoidal pattern of seismicity created by
the injection well also locates the direction of the maximum compressive stress axis
and can be used to independently determine the ambient stress field.

For the case of an anisotropic, heterogeneous stress field, the path of the permeability
field microseismicity is determined by the local variation in the maximum stress
direction. The variability of this field can be independently derived from standard
independent means which refers to resolved earthquake focal mechanisms, borehole
breakouts, and so forth, and also by the conoidal pattern of seismicity induced by
injection wells.

Figure 4 is a flowchart of a seismo-tectonic reservoir monitoring system (STRM). The
purpose of this system is the gathering, processing and analysis of all geological and
geophysical data on the reservoir that is available and relevant to the process of
seismogenesis and fluid production and displaying it as a multi-dimensional image.
Once prepared, this information may be applied to determining the permeability field;
identifying potential field infrastructure hazards and improving reservoir modeling. A key
element is that the system allows different geophysical and geological parameters
relating to seismogenesis, reservoir geology and geophysics, to be directly compared to
one another. The microseismicity data provides important quantitative information
critical to the fluid production process that is only indirectly available by other means.
and thus makes a significant improvement in the reservoir monitoring process. Although three velocity models are indicated this is simply the minimum number needed to achieve optimal results. The actual number of models used may be larger or smaller.

The following describes the components of the flowchart:

**3D Structural Data and Velocity Model [10]:** 3D structural data and 3D velocity model(s) are gathered. 3D structural data includes of geometric and kinematic information (e.g. strike and dip of bedding, faults, etc.; stratigraphic boundary locations; movement indicators; etc.). 3D velocity models give the distribution of seismic velocities in the volume of interest. The models are provided by known independent methods embodied by existing software applications (e.g. Velmod, etc.).

**Construct 3D Structural Model box [11]** The structural data gathered in the previous step is processed into a 3D structural model using section construction and validation techniques. These techniques permit physically impossible interpretations to be eliminated from consideration. The section construction and validation techniques are provided by known independent methods embodied by existing software applications (e.g. Paradigm Geophysical's Geosec programs, etc.). The structural model provides the geometry of the finite deformation field. The finite deformation field includes the directions of lines of no finite longitudinal strain, the simple shear directions, the surfaces containing the displacement vectors.

**Initial 3D Structural Model [12]:** The initial 3D structural model is a validated interpretation of the section construction process. It may be brought into concordance with the velocity model or used directly as the 3D finite deformation field.

**Concordant Structural and Velocity Models [13]:** The structural and velocity models are processed by comparing and adjusting them to resolve differences. An example of such differences might be where the structural model shows faulting of units with known velocity contrasts where such contrasts are not reflected in the velocity model. Resolving the problem requires that the input parameters and their method of analysis for the two different models be examined to see if there is sufficient flexibility to bring the two into concordance. This process results in the creation of a concordant velocity model (Model 3).
Velocity Model 3 [14]: The concordant velocity model (Velocity Model 3) is the output of the Concordant structural and velocity model processing. It is used for processing earthquake and seismic reflection data.

Finite Deformation Field [15]: This is either the validated or the adjusted 3D structural model that conforms to the concordant velocity model. The 3D structural model gives the finite deformation field.

Active Deformation Field Analysis [16]: The active deformation field shows the structures that are presently deforming. It is created by the addition of earthquake slip plane assemblages to the finite deformation field model. Geiser and Seeber (1997 Seismo-Tectonic Imaging: A New Time Lapse Reservoir Monitoring Technique.

Applications of Emerging Technologies: Unconventional Methods in Exploration for Petroleum and Natural Gas V. Proceedings, Dallas, Tx; 30–31 October 1997, ISEM, Southern Methodist University, Dallas, Texas, p. 137–152.) have developed a technique, seismo-tectonic imaging and analysis, for imaging the finite deformation field and relating it to the instantaneous and incremental deformation represented by seismogenic activity. The tools for applying this technique are embodied in known software applications (e.g. Paradigm Geophysical’s Geosec programs, Midland Valley’s Move programs).

These analysis tools use a quantitative description of the geometry and kinematics of the rock deformation mechanism to process structural data and image the finite deformation field. This field includes of lines of no finite longitudinal strain, the simple shear directions and the displacement surfaces containing the displacement vectors. Making the assumption of volume constant strain permits the infinitesimal and instantaneous strain field to be located. Given the location of this field it is now possible to place the earthquake slip planes into their proper geological and structural environments. Thus the clouds of earthquake data that were either un-interpretable or only weakly so, can now be much more confidently understood.

Active Deformation Field [17]: The active deformation field is the product of the deformation field analysis. It is displayed as a multidimensional image.

Infrastructure Analysis [18]: An analysis of physical infrastructure is made in the context of the active deformation field to determine which active structures represent potential hazards to the infrastructure. Combining the active deformation field with the
infrastructure in a multidimensional image does this. Thus infrastructure located in close proximity or in the path of tectonically active structures may be considered at risk. Infrastructure Hazard [19]: The output of the infrastructure hazard shows the infrastructure that is at risk from the active deformation field.

Passive Seismic Network; Eq (earthquake) Signal Data [20]: Microseismicity data collected by the Passive Seismic Network. The passive seismic network is the collection of recording devices for detecting and collecting seismic waves generated by earthquake activity.

Eq Signal Data Processing [21]: The raw seismic wave data is treated using filtering algorithms, transform analysis and other such analysis tools, to remove noise and analyze the seismic waveforms. These tools are embodied in known software applications; e.g. Engineering Seismology Group’s Hyperion system.

Filtered Eq Data [22]: The filtered earthquake data is the output of the Eq signal data processing.

Seismic Tomography [23]: The processed earthquake data is treated using tomographic techniques to create a velocity model (Velocity Model 2 [24]). The tomographic tools for creating the velocity models from earthquake data are embodied in known software applications that are widely disseminated in the seismological literature.

Eq Data Processing [24]: Processing of earthquake data uses the concordant velocity model to give resolved [25] and/or unresolved [26] earthquake hypocenter information. The resolved hypocenters provide information on the local variation in the stress field [27] via focal mechanism analysis as well as the location and orientation of earthquake slip planes [28] and the slip direction on those planes. The slip planes are subjected to Slip Plane Processing [29]. Techniques for focal mechanism analysis are widely disseminated throughout the seismological literature.

Resolved [25]: These are resolved hypocenters output from Eq data processing[24]. They provide information on the local stress conditions [27] and earthquake slip plane orientation[28]. Techniques for resolving hypocenters are widely disseminated throughout the seismological literature.

Unresolved [26]: Unresolved hypocenters give only the spatial and temporal location of the earthquake. These data are subject to Time/Space sorting [30].
Stress [27]: Stress is output as a multidimensional image that contains information on the local stress field derived from focal mechanism analysis output from Eq data processing[24].

Slip Planes [28]: Information on earthquake slip planes output from Eq data processing[24].

Slip Plane Processing [29]: Sorting of slip planes into slip plane assemblages illuminating structural elements. Slip plane processing uses known software (e.g. Seeber and Armbruster's "Quakeview") that embodies the sorting and filtering of the earthquake data into structural assemblages in space as well as time.

Slip Plane Assemblages [30]: Slip plane assemblages are output from slip plane processing. Slip plane assemblages are structural elements illuminated by earthquakes. They are output as a multidimensional image.

Time/space Sorting [31]: Time/space sorting of the hypocenter data creates assemblages of hypocenters which are related only by their time/space coordinates, e.g. assemblages with the same time coordinates, same space coordinates, and so forth. Sorting is done by standard sorting routines.

4D Active Seismic Array Seismic data [32]: The 4D active seismic array collects time lapse 3D seismic data in order to detect time/space variation in velocities. This information is used to infer the movement of fluids in the reservoir.

Seismic Data Processing [33]: The concordant velocity model [14] is used to process seismic reflection data collected by 4D Active Seismic Network.

4D Seismic Model [34]: 4D seismic model is the result of processing the time lapse 3D seismic reflection data using the concordant velocity model [14]. The 4D seismic model shows the movement of fluid phases with time.

Independent Stress Field Determination [35]: The determination of the stress field by means other than the STRM process, these means include focal mechanism analysis [27], bore hole breakout, and so forth.

Permeability Field Analysis[36]: Permeability field analysis comprises the processing of geological and geophysical data relevant to the permeability field. The processing of this data uses known software (e.g. Colorado School of Mines Unsert application) as well as the analysis tools of the STRM system.

Permeability Field [37]: The permeability field is a multidimensional image that is the output of the permeability field analysis.
Reservoir Modeling [38]: Reservoir modeling processes the geological and geophysical data input to derive a reservoir model [39]. It uses known software which embody reservoir simulators (e.g. DOE's Boast, Landmark Graphic's, STORM, and so forth.) but in addition includes the finite and active deformation fields, permeability and stress fields from the STRM process and information on fluid motion from 4D seismic model. The output is the reservoir model [39].

Reservoir Model [39]: The reservoir model is a multidimensional image consisting of all the geological, geophysical and petrophysical data deemed relevant to the reservoir properties.

Infill and Injection Plan [40]: The infill and injection plan is derived from the Reservoir modeling and the model so created. It is the plan for locating new reservoir infill and injection wells as well as formulating ideas on how to improve existing wells.

Field Operation Data [41]: Field operation data includes of production, fluid pressure and other information from production field operations. It is used to monitor performance of the STRM system and as input for reservoir modeling [38] and Permeability field analysis [36].

Figure 5 is a diagram of the role that STRM has in the production and development history of the field.

Development Phase: During pre-development, a regional passive seismic network is set up to determine the level of background seismicity and the active deformation field prior to drilling and production operations. Earthquake tomography also provides an independent velocity model used to establish the concordant velocity model (figure 4[14]). The local seismic network that monitors the field is established during development. In addition initial fluid injection tests are run on production wells to map the initial permeability field associated with each well (figure 6a-f), the orientation of the maximum compressive stress axis and as a guide for locating wells during field delineation (figure 6a-f).

Production Phase: During primary production the local and regional passive seismic networks monitor activity. Periodic injection tests track the evolution of the permeability field while ongoing analysis of the active deformation field provides information on the interaction between the regional stress field and changes in the stress state and
tectonics of the field induced by production activities. Further information critical to
understanding and predicting the geomechanics and fluid migration history are also
provided as shown in figure 4.

During secondary and tertiary recovery, the local and regional passive seismic networks
monitor activity. Periodic injection tests track the evolution of the permeability field
while ongoing analysis of the active deformation field provides information on the
interaction between the regional stress field and changes in the stress state and
tectonics of the field induced by production activities. Further information critical to
understanding and predicting the geomechanics and fluid migration history are also
provided as shown in figure 4.

Figure 6a shows the means by which the STRM system is used to map the permeability
and stress fields of a hypothetical reservoir. In this phase an injection test is run in the
discovery well [10]. The STRM passive seismic network records the distribution of
microseismicity resulting from the test and shown as earthquake slip planes. The slip
planes form a conoidal volume indicating the part of the permeability field that is in
communication with the discovery well. The extent and density of the microseismicity
are a function of the permeability field. Regions of greater extent and denser seismicity
may reflect volumes of higher permeability. Regions of lesser extent and more diffuse
seismicity may reflect volumes of lower permeability. The seismicity distribution is used
as a guide to locate the first delineation well [11]. The cone axis of the conoidal volume
of seismicity gives the maximum principal stress direction [12].

Figure 6b shows the placement of the first delineation well [10] within the permeability
field in communication with the discovery well [11]. An injection test is now run in the
The cone axis of this volume [12] gives the orientation of the maximum compressive
stress direction at the delineation well [10]. The new region of the permeability field
located by the injection test in the first delineation well is used to locate the second
delineation well [13].
Figure 6c shows the pattern of seismicity responding to an injection test in the second delineation well [10]. Note that the short extent of the seismicity extending to the right from the second delineation well [10] indicates the presence of a boundary to the permeability field [11]. The cone axis to the seismicity generated by the injection test gives the local orientation of the maximum compressive stress axis [12]. Because the orientation of the stress field at the second delineation well [10] leaves an area unmapped, it is necessary to place a third delineation well [13] in the permeability field imaged by the discovery well [14] in order to run an injection test in this new well [13] to cover the unmapped area.

Figure 6d shows a continuation of the permeability field mapping using the third delineation well [10]. An injection test in this well fills in the information gap between it and the second delineation well [11].

Figure 6e shows the placement of the fourth delineation well [10] in the permeability field revealed by the first delineation well [11] in order to further map the reservoir permeability of the field.

Figure 6f shows the placement of a fifth delineation well [10] between the fourth delineation well [11] and the first delineation well [12] in order to map the permeability field not imaged by the first and fourth wells.

Preferred Embodiment -- Operation

Figure 1 shows the means whereby microseismicity illuminating the hydraulically linked fractures of the permeability field may be recognized. There exist two conoidal volumes [12] sharing a common cone axis [11] and whose apices join at the point of fluid injection [14] of the injection well. The common cone axis [11] is the maximum compressive stress direction of the local ambient stress field. The conoidal volumes contain the set of fractures that are hydraulically linked to the injection well. As fluid pressure is increased, the hydraulically linked fractures fail elastically resulting in a set of earthquakes whose size depends upon that of the rupture. As long as fluid pressure is maintained at the well, the increased fluid pressure will move out from the well (figure 3) creating a migrating front of microseismicity illuminating the reservoir permeability.
field associated with the active injection well. It is believed that maintaining a static fluid pressure may be most effective in revealing the hydraulically linked fractures, however it may also be that pulsing or fluctuating fluid pressure may be desirable or equally as effective under some or all circumstances.

The unique temporal and spatial association of the seismicity associated with the permeability field allows the permeability field to be identified.

1. Spatially it is located within the conoidal volumes ([12] of Figure 1) defined by the ambient maximum compressive stress direction ([11] of Figure 1) and the location of the injection point ([14] of figure 1) on the injection well.

2. Temporally the seismicity is recognized by its rapid outward migration from the active injection well (figure 3). Seismicity migration rates will exceed that of diffusional flow by 3 to 5 orders of magnitude. The onset of the seismicity is set by the initiation of increased fluid pressure at the injection well ([10] of figure 1).

Figure 3 schematically illustrates a hypothetical example of the seismicity motion associated with an injection well.

3. This procedure may be inverted to identify regions of high fluid pressure.

Knowledge about the physical characteristics of the reservoir can be had from the following observations:

1. Speed of migration of seismicity provides information on the average permeability while variation in the rate of migration indicates relative changes in the permeability field.

2. The orientation and location of the earthquake slip planes enables direct measurement of the geometry of the part of the permeability field controlled by fractures.

3. The orientation of the earthquake slip planes relative to the maximum compressive stress directions (e.g. as plotted on a 3 dimensional Mohr diagram) provides information on the rock strength.

4. Seismo-tectonic analysis of the earthquake data provides information on structural controls on the permeability.

5. Continuous monitoring of microseismicity associated with field production provides information about the evolution of the reservoir.
6. Identification of the microseismicity associated with the permeability field acts as a filter for distinguishing other earthquake data sets. It does this by distinguishing their cause from those of the remaining earthquake events.

A model for the operation of the present invention is based upon the well established observation that the earth's lithosphere is everywhere close to critical failure and that small perturbations (on the order of 1 bar or less) are sufficient to cause failure. The reasoning behind the present invention is that the observations made by Raleigh et al (1976) and Heffer et al (1997) demonstrate that there exists a means of rapidly communicating increased fluid pressure over large distances by a non-D'arcyian mechanism. The induced microseismicity of the Rangely experiment had the same position relative to the injection wells and the maximum compressive stress (i.e. within 45 degrees) as do the positive correlating production and injection wells observed by Heffer et al (1997). Shutting in the wells at Rangely also caused seismicity to cease at distances of up to 4 kms from the injection wells within 1 day. Barton et al (1995) indicate that the hydraulically conductive fractures have a conoidal spatial distribution about the maximum compressive stress direction (figure 1 of this invention). The conoidal distribution is also reflected in the geometric relationship between injection and production wells found by Heffer et al (1997). These fractures make angles with the maximum compressive stress direction ranging from about 10 to 45 degrees. Figure 4 from Heffer et al (1997) shows the development of "shear bands" in a coupled "geomechanical-fluid flow" model, which "emanate from the injector within 45 degrees of Shmax (the maximum compressive stress) to provide the main paths of conductivity."

Placing these results in the context of the well established observation that the earth's crust is in a metastable yield condition where stress drops on the order of a few bars or less are associated with microseismicity, indicating that only very small changes in stress state are necessary for failure, leads me to hypothesize the following set of events:

1. It is known that fluid pressure increases are rapidly propagated throughout a system whose components are in fluid communication. I term such a system "hydraulically
linked". The permeability field of a fluid reservoir is an example of a hydraulically
linked system.
2. Fluid pressure increase created at the injection point of an injection well interacting
with the maximum compressive stress direction of the ambient stress field creates
two conoidal volumes of maximum shear stress ([12] figure 1), approximately
symmetric about the maximum compressive stress direction ([11] figure 1).
Fracture planes occupying this volume whose shear strength and orientation are
such that they are critically loaded for failure and hydraulically linked to the injection
well, will respond to the increase in fluid pressure by elastic failure. These failures
will be reflected as small earthquakes illuminating the reservoir permeability field.
3. Thus an increase in fluid pressure at an injection well will cause a wave of
microseismicity to move out from the well in a volume whose geometry is defined by
the ambient stress field. This microseismicity will illuminate the permeability field of
the reservoir associated with the well. Passive seismic monitoring of controlled
increases in fluid pressure at the injection well will allow the spatial and temporal
mapping of this field as well as the determination of other associated petrophysical
properties as discussed elsewhere in this invention.

While I believe that the foregoing is a reasonable physical model to explain the
operation of the invention, I do not wish to be bound by it.

Seismo-Tectonic Reservoir Monitoring System -- Description
Figure 4 is a flowchart showing a Seismo-tectonic Reservoir monitoring system. The
purpose of this system is to allow the various petrophysical properties associated with
seismogenesis to be compared and analyzed. The results of the analysis are output
as velocity models, input for reservoir models and the potential for field infrastructure
hazard.

Seismo-Tectonic Reservoir Monitoring System -- Operation
Starting with the left-hand data box of figure 4, [10]; geometric and kinematic structural
data is assembled along with independently determined velocity models (e.g. from
reflection seismology; Velocity model 1). The structural data is then processed (figure
4, [11]) to produce one or more valid structural models (figure 4, [12]). These models
are then compared and rationalized (figure 4, [13]) with all velocity models available (e.g. Velocity models 1 and 2) to create a concordant velocity model (Velocity model 3). The structural model that emerges (figure 4, [15]) from the comparison is used to define the Finite Deformation Field. The addition of earthquake slip plane data (figure 4, [31]) to the Finite Deformation Field, generates the Active Deformation Field (figure 4,[17]) that used to identify potential Field Infrastructure Hazards (figure 4, [19]).

The Passive Seismic Network; Eq Signal Data (figure 4, [20]) represents the earthquake data collected by the Passive Seismic Network. This data is then prepared for Seismic Tomography and resolution of the hypocentral data by filtering and location of the hypocenters (figure 4, [21]). The application of seismic tomography to the data generates Velocity Model 2 used to generate the concordant Velocity model (Model 3) by resolving differences between the independently derived Structural (figure 4, [11]) and Velocity models.

Once the concordant velocity model is available, it is used to for both reflection seismic (figure 4, [34]) and earthquake data processing (figure 4, [24]). The reflection seismic data is acquired through a 4D Active Seismic Array (figure 4,[33]). The processed reflection data is used to create a 4D seismic model to image fluid front migration.

Earthquake data processing either 1] locates the earthquake hypocenters (figure 4, [27]); or 2] where data permits, resolves the hypocenter data (figure 4, [26]) to generate earthquake slip planes (figure 4, [29]) and stress information (figure 4, [28]). The permeability field (figure 4,[38]) may be defined using either resolved or unresolved hypocenter data. It is identified by its spatial and temporal location relative to the injection well and the maximum compressive stress of the ambient stress field. If unresolved data is used, it is subject to only Time/space sorting (figure 4, [32]). If Resolved data (figure 4, [26]) is used, then it is input for further processing by a filtering and sorting application (figure 4, [30]) that generates structural assemblages of earthquake slip planes (figure 4, [31]). In addition to creating structural assemblages, processing of the earthquake data (figure 4, [30]) also includes assigning temporal and magnitude data to each earthquake slip plane.
The processed earthquake slip plane data is used as input to the Active Deformation Field analysis (figure 4, [16]) and is incorporated into the Permeability Field Analysis (figure 4, [37]) along with the stress data (figure 4, [27], [36]) to generate the Permeability Field model (figure 4, [38]). This data combined with information from the Active Deformation Field and reservoir Field Operations provides input for Reservoir Modeling (figure 4, [39]). Output from the Reservoir Modeling application (Reservoir Model; figure 4, [40]), provides data on Infill and Injection Plans (figure 4, [41]) that are used to guide Field Operations (figure 4, [42]).

Role of STRM in development and production -- Operation

A STRM system has utility throughout the development and production history of a fluid reservoir. The outline of this utility is shown in figure 5. The following discussion describes an idealized sequence. The STRM system can be implemented at any stage in the field history.

Pre-Production Phase

I] Pre-Development: A regional passive seismic network is established which includes the site of the proposed field. The network should cover a region whose dip direction dimensions are at least two wavelengths greater than that of the largest structure which forms the field. This network purpose is to; 1] establish the background microseismicity; 2] if background seismicity is sufficient it can be used for seismotectonic imaging (Geiser, P. A. and Seeber, L.; 1997 Seismo-Tectonic Imaging: A New Time Lapse Reservoir Monitoring Technique. Applications of Emerging Technologies: Unconventional Methods in Exploration for Petroleum and Natural Gas V. Proceedings, Dallas, TX; 30 –31 October 1997, ISEM, Southern Methodist University, Dallas, Texas, p. 137–152.) and to build an independent velocity model. This model can be rationalized with other independently determined velocity models to form a concordant velocity model (figure 4, [14]) for any initial seismic surveys.

II] Field Delineation and Development: The local seismic network is set up over the area proposed for initial development. The parameters that control the spatial distribution and location of the seismometers include;

1. the minimum size of event to be recorded;
2. The nature of the velocity field of the reservoir.
3. The sensitivity of the geophones;
4. nature of the seismic signal filtering algorithms.
As wells are completed fluid injection tests are run on each well in order to establish the initial permeability field associated with each well (figure 6a-f) and delineate the field. A schematic example of this process is shown in figures 6a-f. The initial STRM mapping is done with the discovery well (figure 6a). The permeability distribution revealed by the injection test and STRM mapping is used to locate the next delineation well. An injection test is then done in this well and the permeability field associated with it is revealed and used to plan the location of the next delineation well (figure 6b). This procedure is repeated until the entire reservoir permeability field has been mapped (figures 5c,d,e,f) and the wells located according to the STRM mapping.

Production Phase

I] Primary production: Local network monitors field evolution through periodic injection tests, with 4D seismic to recording the fluid migration history. The regional network is used to monitor any far-field effects that may be produced by production operations.

II] Secondary and Tertiary Recovery: Local network to monitor field evolution through periodic injection tests and use of 4D seismic to record fluid migration history.
Regional network continues to monitor any far-field effects that may be produced by production operations.

Conclusions, Ramifications, and Scope
Accordingly, it can be seen that with the invention described, I have provided a means of direct 4 dimensional measurement and multidimensional imaging of many if not all the components of the permeability field of a fluid reservoir. This process is referred to as STRM mapping. Use of the information provided by STRM mapping can lead to improved efficiency of well placement and field development. In addition the invention forms a powerful synergistic companion to 4D reflection seismic which can monitor the migration history of the fluid phases as predicted by the permeability field given by the STRM system. Further the two systems can potentially be piggy-backed on each other, while holes dedicated to seismometers can be used for supplying additional information (e.g. cross hole tomography, one way travel time for 3D reflection...
seismology) thus resulting in efficiencies of operation. Finally the STRM system provides warning on potential damage to infrastructure and to the reservoir itself arising from the active deformation field.

Although the description above contains many specificities, these should not be construed as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention. Various other embodiments and ramifications are possible within its scope. For example, because the STRM system is essentially an experiment in seismogenesis in which not only is the seismogenic object made visible but it allows the process to be studied in the context of a set of controlled conditions where most of the petrophysical parameters are known. Such information is invaluable for gaining deeper understanding of the seismogenic process. The STRM system is also capable of imaging in terrane that is opaque to reflection seismology and thus has utility in regions where reflection data cannot be acquired. Another example of the scope of the invention is that as a passive system it allows imaging in regions that do not permit active systems to operate e.g. regions that are either environmentally or politically sensitive. Thus the scope of the invention should be determined by the appended claims and their legal equivalents, rather than by the examples given.
I claim:

1. A method for measuring and enhancing the permeability fields of fluid reservoirs during production of fluids from said reservoirs comprising:
   a. establishing a network of earthquake recording devices for acquiring, resolving, analyzing and monitoring earthquake data said network being of predetermined size and location in and around said reservoirs,
   b. causing a fluid pressure wave to be generated through fluid injection in one or a plurality of fluid injection wells in said reservoir at one or a plurality of injection sites, said fluid pressure wave causing failure to occur on fractures comprising the permeability field associated with said wells, with said failure enhancing the permeability on said fractures, with said failure generating earthquake seismic waves recorded by said network;
   c. using said network to image at least one conoidal volume of fractures generating said earthquake seismic waves, with said conoidal volume having an acute apical angle with a cone axis that passes through said injection site or plurality of sites with said conoidal volume showing a temporal migration of the earthquakes away from said injection site or plurality of sites;
   d. using said conoidal volume and said temporal migration of said earthquakes away from said injection location or plurality of locations within said conoidal volume to identify said fractures as those that comprise the permeability field to which said injection well is connected or to which the plurality of said injection wells are connected, whereby said permeability field of a said fluid reservoir is both enhanced and measured in time and space.

2. A set of multidimensional images of the reservoir permeability field prepared by the method of claim 1, in which each image is temporally separated from the preceding one thereby showing the changes of the permeability field with time.

3. The images of claim 2 digitally stored in a memory or contained on maps or other electronic or printed display media.
4. A method for determining the maximum compressive stress direction of the ambient stress field of a fluid reservoir comprising;
   a. steps a, b and c of claim 1;
   b. plotting the orientation of said axis of said conoidal fracture distribution in space, said axis being the maximum compressive stress direction of the ambient stress field in the vicinity of the well or plurality of wells.
   c. repeating steps (a), (b), (c) of claim 1 and step (a) of claim 2 at any or all additional wells in said reservoir;

whereby the maximum compressive stress directions are determined for the reservoir.

5. The set of multidimensional images of the orientation of the maximum compressive stress direction of the ambient stress field determined by the method of claim 4.

6. The images of claim 5 digitally stored in a memory or contained on maps or other electronic or printed display media.

7. The method of claim 1 comprising;
   a. determining the direction of maximum compressive stress direction of the ambient stress field by standard, independent means;
   b. steps (a), (b) and (c) of claim 1;
   c. finding the conoidal volume whose cone axis is parallel to the direction of said maximum compressive stress direction of said ambient stress field, this conoidal volume of said fractures being the set of fractures comprising the permeability field associated with said injection sites or plurality of sites.

whereby said permeability field of a said fluid reservoir is both enhanced and measured in time and space.

8. A set of multidimensional images of the reservoir permeability field prepared by the method of claim 7, in which each image is temporally separated from the preceding one thereby showing the changes of the permeability field with time.
9. The multidimensional images of claim 8 digitally stored in a memory or contained on maps or other electronic or printed display media.

10. A method for multidimensional imaging of the permeability field of a fluid reservoir comprising the steps of:
   a. using the method of claim 1 to identify the fracture system of the permeability field connected to said wells or plurality of wells;
   b. plotting said data collected in step (a) in n dimensional space to locate the well or plurality of wells hydraulically linked to said well or plurality of wells;
   c. using said well or plurality of wells identified in step (b) to run additional injection tests to further map the permeability field in time and space;
   d. combining the information of steps (b) and (c) to continue mapping of the permeability field in said n-dimensional space;
   e. repeating steps (a), (b), (c) and (d) until all wells of the reservoir field have been subjected to this method;

whereby the spatial and temporal characteristics of the reservoir permeability field are determined and mapped.

11. The set of multidimensional images of the spatial and temporal locations of the fractures and their associated permeability values of said permeability field determined by the method of claim 10, each multidimensional image temporally separated from the preceding one.

12. The multidimensional images of claim 11 wherein the permeability field data are digitally stored in a memory or contained on maps or other electronic or printed display media.

13. The method of claim 10 in which the method of claim 7 replaces the method of claim 1 in step (a).

14. The set of multidimensional images of the spatial and temporal locations of the fractures and their associated permeability values of said permeability field
determined by the method of claim 13, each multidimensional image temporarily separated from the preceding one.

15. The multidimensional images of claim 11 digitally stored in a memory or contained on maps or other electronic or printed display media.

16. A method wherein the time and space measurement of said permeability field is used to determine infill, delineation and injection well locations for said reservoir comprising;
   a. superimposing the information of the multidimensional images of claim 11 on a multidimensional image of the volume of the earth's crust containing said reservoir and
   b. using the spatial and temporal distribution of said fractures and their said associated permeability values of said permeability field to guide the spatial distribution and organization of injection, infill and delineation wells relative to the distribution of said fractures and their associated permeability values, whereby the most advantageous placement may made of the infill, delineation and injection wells with respect to the permeability field of the reservoir both in space and time.

17. The method of claim 16, further including;
   a. Drilling a well at a location or a plurality of locations identified in step (b) of claim 16.

18. The method of claim 16 using the images of claim 8 in step (a) of claim 16.

19. The method of claim 18, further including;
   a. drilling a well at a location or a plurality of locations identified in step (b) of claim 16.

20. A method for determining the active deformation field comprising the steps of;
a. gathering and analyzing 3D structural and kinematic data to define the structural components of the finite deformation field, and

b. combining said structural components with the earthquake data of step (a) of claim 1 to sort said earthquake data according to its relationship to the finite deformation field in time and space,

whereby the active structural components of the active deformation field may be determined in time and space.

21. The set of multidimensional images of the spatial and temporal distribution of the active deformation field created by the method of claim 20, each multi-dimensional map temporally separated from the preceding one.

22. The set of multidimensional images of claim 21 digitally stored in memory or contained on maps or other electronic or printed display media.

23. A method for determining the relationship of the active deformation field of a reservoir to the reservoir permeability field comprising;

a. determining the active deformation field using the method of claim 20, and

b. combining set of multidimensional images of claim 11 with the multidimensional images of claim 21;

whereby the multidimensional relationship of the active deformation field to the permeability field may be viewed in time and space.

24. The set of multidimensional images of the relationship of the permeability field to the active deformation field created by the method of claim 23.

25. The multidimensional images of claim 24 digitally stored in a memory or contained on maps or other electronic or printed display media.

26. The method of claim 23 in which the images of claim 14 replace the images of claim 11 in step (b) of claim 23.
27. The set of multidimensional images of the relationship of the permeability field to the active deformation field created by the method of claim 26.

28. The set of multidimensional images of claim 27 digitally stored in a memory or contained on maps or other electronic or printed display media.
Figure 5

Development Phase:
- Initial 2D/3D Seismic Survey
- Regional Seismic Network
  - Determine background seismicity
  - Local Seismic Network
  - Analyze initial permeability

Production Phase:
- 4D Active Seismic Survey
- Local and Regional Networks
  - Monitor production periodic injection tests to check permeability evolution

Field History

Pre Development
- Development

Primary Production
- Secondary/Tertiary Recovery
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01V/00

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

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01V

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<td>US 5 377 104 A (SORRELLS GORDON G ET AL) 27 December 1994 (1994-12-27) column 2, line 59 - column 3, line 23 column 5, line 44 - column 6, line 38 column 9, line 23 - line 50</td>
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Date of the actual completion of the international search
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Date of mailing of the international search report
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European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epc nl, Fax: (+31-70) 340-3016

Authorized officer
Swartjes, H
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