US 20130075086A1

(19) **United States**

(12) **Patent Application Publication**

PRESS

(10) **Pub. No.: US 2013/0075086 A1**

(43) **Pub. Date: Mar. 28, 2013**

(54) USING MICROSEISMIC ACTIVITY TO FACILITATE HYDROCARBON PRODUCTION IN TIGHT SAND AND SHALE RESERVOIRS

(76) Inventor: **Frank PRESS**, Washington, DC (US)

(21) Appl. No.: **13/441,888**

(22) Filed: **Apr. 8, 2012**

Related U.S. Application Data

(60) Provisional application No. 61/539,960, filed on Sep. 27, 2011, provisional application No. 61/544,444, filed on Oct. 7, 2011, provisional application No. 61/549,240, filed on Oct. 20, 2011, provisional application No. 61/556,800, filed on Nov. 7, 2011, provisional application No. 61/579,193, filed on Dec. 22, 2011.

Publication Classification

(51) **Int. Cl.**

E21B 43/26	(2006.01)
E21B 28/00	(2006.01)

(52) **U.S. Cl.**

USPC **166/249**; 166/177.5

(57) ABSTRACT

Naturally occurring microseismic events are monitored and utilized to synergistically augment a hydraulic fracturing process. Such events generally originate from the tidal dilational stress that makes it easier for fractures to open and slip. If the hydraulic fracturing process can be scheduled to occur coincident with elevated levels of naturally occurring microseismic activity, the efficiency of hydraulic fracturing can be increased. Accordingly, the resources consumed and the byproducts produced by the hydraulic fracturing process will be reduced as will be other elements of environmental damage. In like manner, where hydraulic fracturing cannot be used, the natural dilational stress may be synergistically enhanced with induced hydraulic pressures that are below the pressures required for conventional hydraulic fracturing. These periods of elevated microseismic activity may also be predicted based on natural cyclic phenomena, such as peak earth tides, which are known to be correlated with periods of higher microseismic activity.

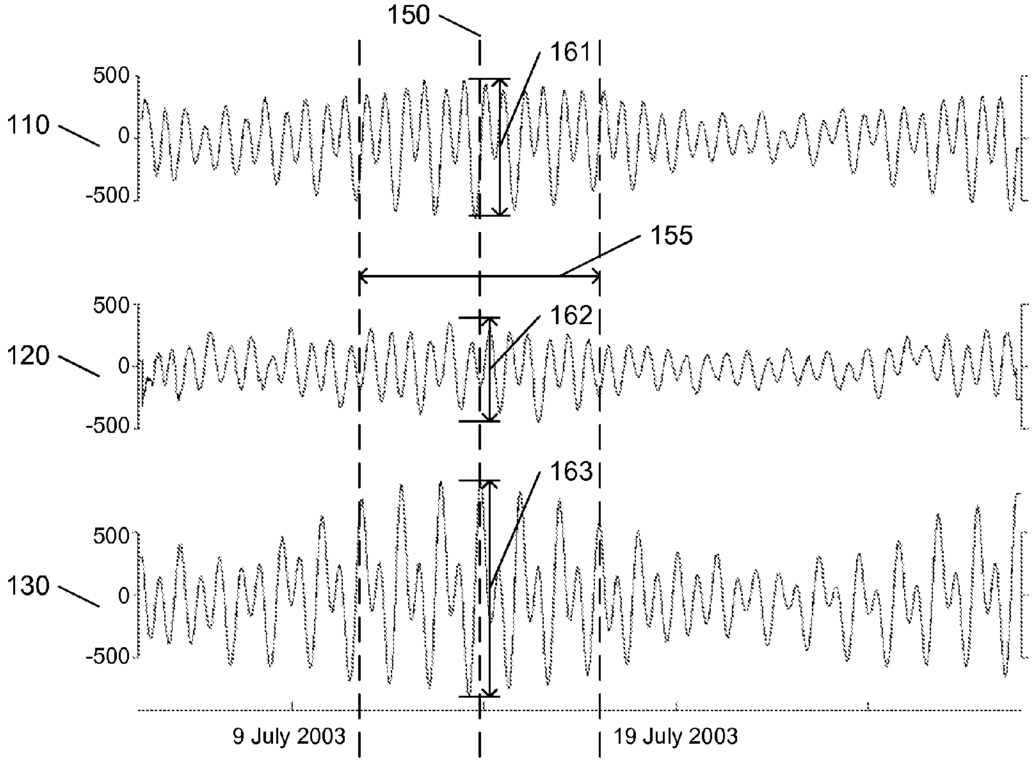
150
161
500
110
0
-500
155
500
162
120
0
-500
163
500
130
0
-500
9 July 2003
19 July 2003

FIG. 1

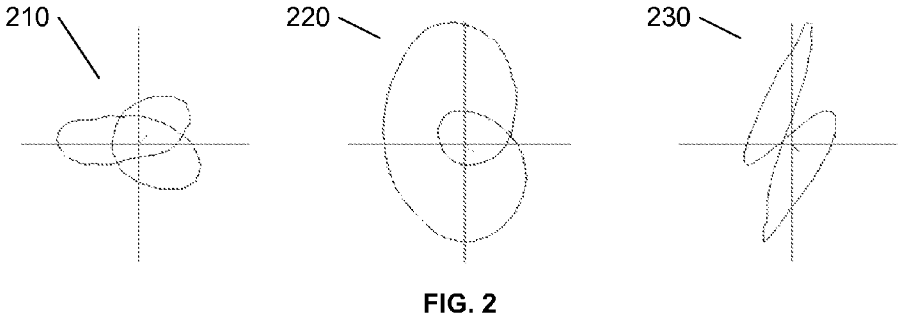
210
220
230

FIG. 2

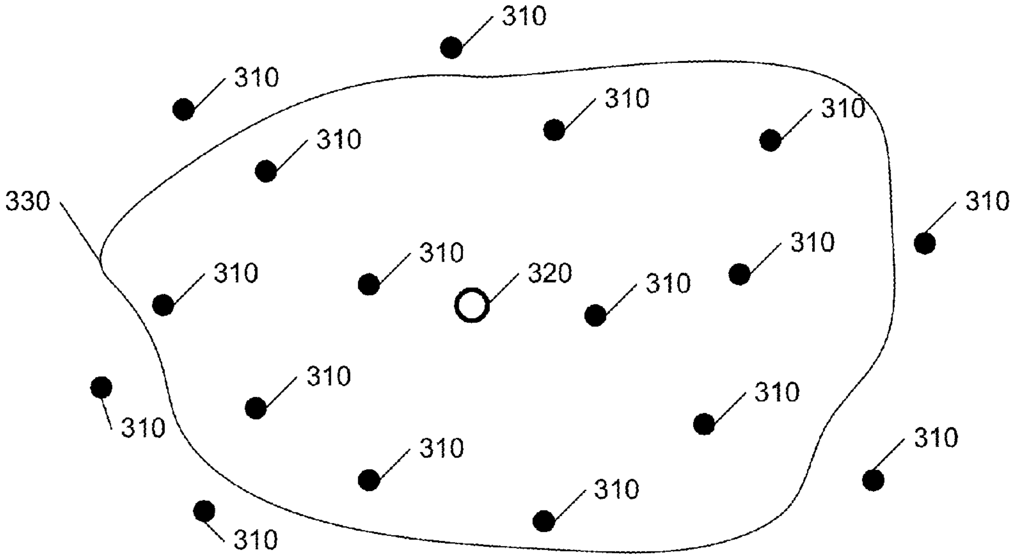

FIG. 3

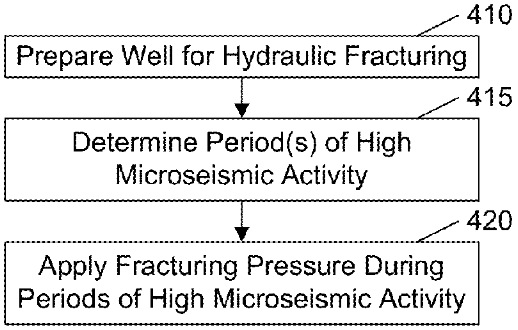

FIG. 4A

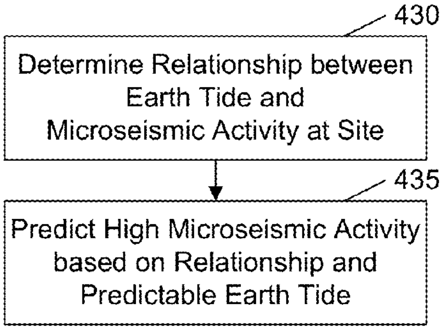

FIG. 4B

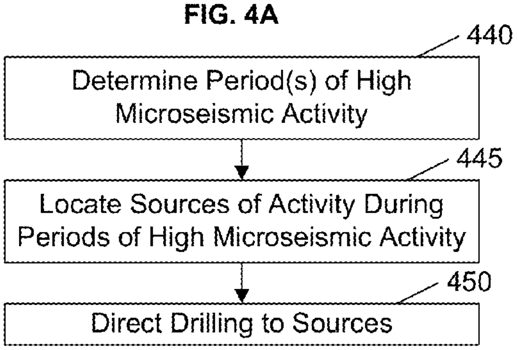

FIG. 4C

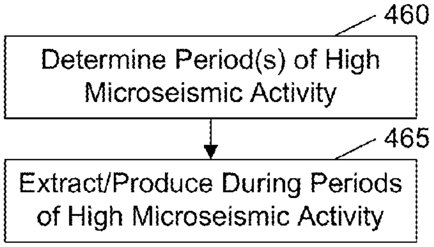

FIG. 4D

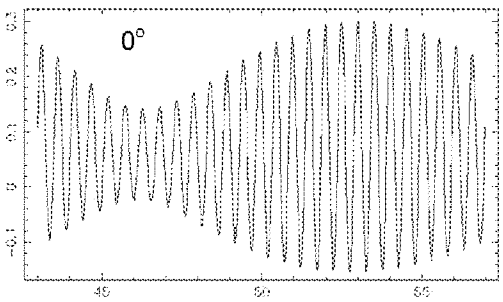

FIG. 5A

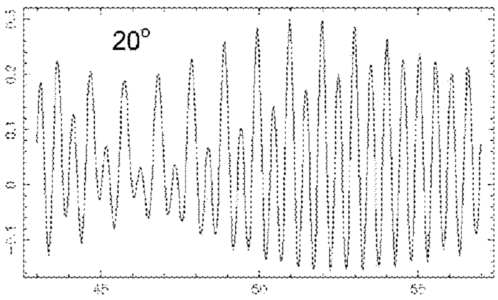

FIG. 5B

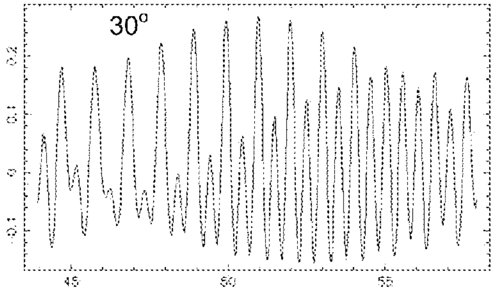

FIG. 5C

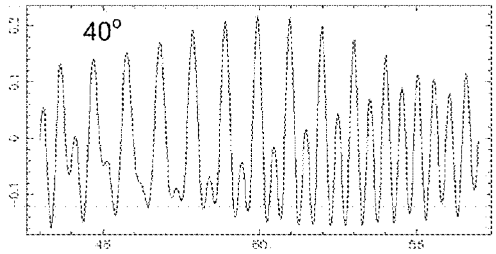

FIG. 5D

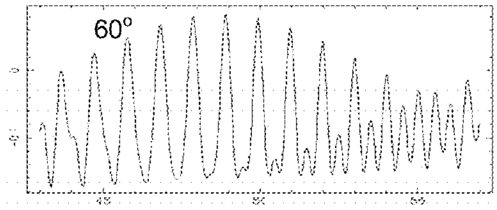

FIG. 5E

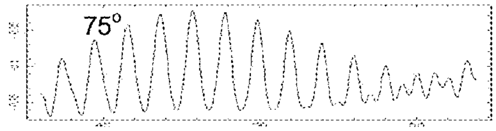

FIG. 5F

USING MICROSEISMIC ACTIVITY TO FACILITATE HYDROCARBON PRODUCTION IN TIGHT SAND AND SHALE RESERVOIRS

[0001] This application claims the benefit of U.S. Provisional Patent Applications 61/539,960, filed 29 Sep. 2011, 61/544,444 filed 7 Oct. 2011, 61/549,240 filed 20 Oct. 2011, 61/556,800 filed 7 Nov. 2011, and 61/579,193 filed 22 Dec. 2011.

BACKGROUND AND SUMMARY OF THE INVENTION

[0002] This invention relates to the field of hydrocarbon production, and in particular to a method and system that uses the detection of microseismic activity in hydrocarbon reservoirs to facilitate hydraulic fracturing, to manage hydrocarbon production, and to replace hydraulic fracturing where desired to reduce environmental damage.

[0003] Hydraulic fracturing (also termed "fracking") is commonly used to extract hydrocarbons (e.g. oil and natural gas) that are captured within subterranean formations. U.S. Pat. No. 4,415,035, "METHOD FOR FRACTURING A PLURALITY OF SUBTERRANEAN FORMATIONS", issued 15 Nov. 1983 to Medlin et al. discloses a common fracturing technique, and is incorporated by reference herein. As disclosed, typically perforations or slots are formed in well casing adjacent a formation to be fractured. Hydraulic fluid is then pumped down the well through the perforations and into contact with the formation. Hydraulic pressure is applied in a sufficient amount to fracture the formation and thereafter fluid is pumped into the fracture to propagate the fracture into the formation. In U.S. Pat. No. 3,028,914, "PRODUCING MULTIPLE FRACTURES IN A CASED WELL", issued 10 Apr. 1962 to Don H. Flickinger, and incorporated by reference herein, there is described a method of producing multiple fractures in a well bore. A first fracture is made and extended into a formation. The same formation, or another formation penetrated by the same well, may then be fractured by plugging the mouth of the first fracture, making a number of perforations concentrated within a short section in the casing, and then injecting fracturing liquid into the well and initiating a second fracture at the location of the second set of perforations.

[0004] The fracturing liquid typically contains sand and other materials, called proppants, that are configured to fill the fractures to prevent their subsequent closure, yet are porous enough to allow the gas or oil to flow through the fractures and into the wellbore after the hydraulic pressure is removed.

[0005] The use of hydraulic fracturing for extracting hydrocarbons continues to increase, due to the development of economically feasible horizontal drilling, pioneered by Mitchell Energy and Development Corporation in the 1980s-1990s. The Potential Gas Committee has estimated that the recoverable reserves of natural gas will last over 100 years at current production levels, an increase of about 40% between 2006 and 2009, due primarily to the determination and/or reclassification of reservoirs as 'technically recoverable' using current and anticipated technologies (Potential Gas Committee, Potential Supply of Natural Gas in the United States, Colorado School of Mines, 2009).

[0006] Oblique drilling may also be used to increase the area of the reservoir accessible by the well, compared to a vertical well, and, for ease of reference, the term 'horizontal well' as used hereinafter is intended to cover any well with a purposely introduced horizontal component, including oblique wells.

[0007] Fractures may also occur naturally; see, for example, "Fluid Flow Among Potentially Active Faults in Crystalline Rock", Barton, C. A. and Zoback, M. D., *Geology* 23, 683-686, 1995. In "Natural Fractures in Shales and Their Importance for Gas Production" by Gale, J. and Holder, J., *Tectonic Studies Group Annual Meeting* 2008, it is reported that natural open fractures tend to be present in widely spaced clusters. When such formations are found, horizontal wells are drilled to intersect the open natural fractures, often obviating the need to apply hydraulic fracturing. Even if the fractures have resealed, the seals are likely to reopen with less hydraulic pressure than unfractured shale.

[0008] Natural fractures, which as used herein includes 'faults', are introduced in rock formations at different times during their geologic history, and Zoback states that they can be mechanically active (can slip and can excite microseismic activity) and are generally hydraulically active (can act as conduits for fluids and gases), and has suggested that the permeability of formations with hydraulically active fractures may be enhanced by intentionally inducing microseismicity at their locale (Reservoir Mechanics, Cambridge University Press, 2007, p 341-342, 360).

[0009] Ecological concerns have been raised with regard to the potential effects of hydraulic fracturing, primarily centered on two aspects: the disposal of the fracturing fluid, and the potential release of toxic chemicals and hydrocarbons, such as methane, into water reservoirs and the atmosphere. The large quantity of water required for hydraulic fracturing is also a concern in some regions. Because of these concerns, and others, hydraulic fracturing has been banned in some locales, and the demand for bans in other locales continues to increase.

[0010] It would be advantageous to reduce the environmental concerns associated with hydraulic fracturing by reducing the resources consumed by hydraulic fracturing as well as the byproducts produced by hydraulic fracturing. It would also be advantageous to provide for this reduction while at the same time reducing the costs associated with hydraulic fracturing.

[0011] These advantages, and others, can be realized by using elevated levels of naturally occurring microseismic events to synergistically augment the hydraulic fracturing process. Such events are generally associated with tidally introduced dilational stresses that make it easier for fractures to open and slip. If the hydraulic fracturing process can be scheduled to occur coincident with naturally occurring high levels of microseismic activity, the intensity of the hydraulic fracturing process can be correspondingly reduced and the efficiency increased. Accordingly, the resources consumed and the byproducts produced by the hydraulic fracturing process will be reduced. In like manner, where hydraulic fracturing cannot be used, the naturally occurring fractures may be synergistically enhanced with induced hydraulic pressures that are below the pressures required for conventional hydraulic fracturing. It is therefore preferable to program the hydraulic fracturing or augmenting processes to occur during periods of peak natural microseismic activity. These periods may be determined based on monitored microseismic activity and/or estimated based on natural cyclic phenomena, such as peak earth tides, which are known to be correlated with periods of higher microseismic activity. These peak periods, which may last several days, are correlated with the occurrence of the new moon or full moon.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The invention is explained in further detail, and by way of example, with reference to the accompanying drawings wherein:

[0013] FIG. **1** illustrates a plot of earth movement caused by earth tide over a one month period.

[0014] FIG. **2** illustrates another view/plot of the earth movement caused by earth tide.

[0015] FIG. **3** illustrates a plurality of microseismic sensors in a region of interest.

[0016] FIGS. **4**A-**4**D illustrate example flow diagrams for the methods of this invention.

[0017] FIGS. **5**A-**5**F illustrate example earth tide vertical movement at various locations.

[0018] Throughout the drawings, the same reference numerals indicate similar or corresponding features or functions. The drawings are included for illustrative purposes and are not intended to limit the scope of the invention.

DETAILED DESCRIPTION

[0019] In the following description, for purposes of explanation rather than limitation, specific details are set forth such as the particular architecture, interfaces, techniques, etc., in order to provide a thorough understanding of the concepts of the invention. However, it will be apparent to those skilled in the art that the present invention may be practiced in other embodiments, which depart from these specific details. In like manner, the text of this description is directed to the example embodiments as illustrated in the Figures, and is not intended to limit the claimed invention beyond the limits expressly included in the claims. For purposes of simplicity and clarity, detailed descriptions of well-known devices, circuits, and methods are omitted so as not to obscure the description of the present invention with unnecessary detail.

[0020] Although major seismic events are relatively rare, microseismic activity (micro-earthquake, tremor, etc.) is a common occurrence. Many thousands of microearthquakes per year have been observed to occur in a single hydrocarbon reservoir. There are many causes of microseismic activity, both natural and man-made. Deep-well drilling and fracturing are common causes of microseismic activity in hydrocarbon reservoirs and surrounding regions. A primary natural source of microseismic activity is the solid earth tide created by the sun and moon. The solid earth tides cause the largest periodic stress variation and the largest periodic microseismicity variation within rock formations.

[0021] Earth tide is the motion of the earth's surface caused primarily by the gravitation attraction of the moon, with the gravitation attraction of the sun increasing or decreasing the lunar effects. The largest earth tide contribution is from the semidiurnal (about 12.4 hours) components, which can be over 50 cm, but there are also significant diurnal components (~20 cm). Due to the fact that the earth, moon, and sun are moving relative to each other, the motion caused by earth tides is horizontal as well as vertical.

[0022] FIGS. **1**A-**1**C illustrate the ground motion at a depth of 840 meters in a deep borehole caused by earth tide at a location in Oklahoma over a period of 23 days, as published by the Oklahoma Geological Survey Observatory. FIG. **1**A illustrates the motion in an east-west direction; FIG. **1**B illustrates the motion in a north-south direction; and FIG. **1**C illustrates the motion in the vertical direction.

[0023] FIGS. **2**A-**2**C illustrate traces of the motion over a period of 25 hours. FIG. **2**A is a view looking down, showing the motion in the horizontal plane; FIGS. **2**B and **2**C are views looking north and east, respectively, showing the vertical motion from two perspectives.

[0024] This continuous and not-insignificant motion induces dilational stress that acts primarily to reduce the pressure in the earth's outer layers that prevents fractures from opening, and it has been shown that a statistically significant correlation exists between earth tides and microseismic events ("On the Correlation Between Earth Tides and Microseismic Activity", Bodri et al. *Physics of the Earth and Planetary Interiors,* v. 55, 126-134 (1989)). In like manner, a statistically significant correlation has been demonstrated between volcanic eruptions and the bimonthly cycle of peak earth tides ("On the Triggering of Volcanic Eruptions by Earth Tides" by F. J. Mauk and M. J. S. Johnston, *Journal of Geophysical Research,* 78, 17, 3356-3362 (1973), and "Tidal Triggering of Earthquakes and Volcanic Events" by Dieter Emter, Springer, Lecture Notes in Earth Sciences, Vol. 66, 293-309, 1997). A strong correlation between earth tides and earthquakes is demonstrated in "Earth Tides Can Trigger Shallow Thrust Fault Earthquakes", Cochran et al. *Science Magazine*, vol. 306, p. 1164-1166, and between earth tides and deep closed well pressures in "The Earth Tide Effects on Petroleum Reservoirs", by Patricia C. Arditty, Thesis, Stanford University (1978).

[0025] Returning to FIG. **1**A, it is clear that, as with ocean tides, the magnitude of the range of the motion **161**, **162**, **163** introduced by earth tides peaks twice a month, at the times of the full moon **150** and the new moon (not illustrated), when the sun, moon, and earth are substantially aligned. These larger semidiurnal swings of tide **161**, **162**, **163** typically occur within a week or so **155** of the full moon **150** and new moon, and results in increased dilational stress during these periods of maximal tidal effects, with accompanying increased microseismic activity. As detailed further below, if the pressures introduced during hydraulic fracturing are introduced in concert with these periods of increased dilational stress, a synergistic combination of forces may be achieved to cause fractures to occur at substantially lower levels of hydraulic pressure.

[0026] This invention is premised on the observation that although microseismic events, by definition, are relative minor geological events, their effect on subterranean structures is often a factor in the occurrence of more significant geological events. That is, for example, although the change in microseismic activity due to the bimonthly variation in earth tides cannot be said to "cause" volcanic activity, the fact that a significant correlation exists between bimonthly earth tides and volcanic activity would suggest that the effects of such microseismic activity is not insubstantial.

[0027] In accordance with one aspect of this invention, natural microseismic activity is monitored, and hydraulic fracturing is performed during periods of predicted high natural microseismic activity. A prediction of the higher natural microseismic activity is used because, as detailed below, the hydraulic fracturing process is typically performed over a period of a few days, and the most synergistic effect is likely to be achieved when higher fracturing pressure is applied when the highest levels of natural microseismic activity are expected to occur.

[0028] Because the pressures introduced by the hydraulic fracturing and the elevated tidal dilatant stress (signaled by the elevated level of natural microseismic activity) act in concert, less hydraulic fracturing pressure will be needed to induce fractures when the intensity of the natural microseismic activity is high. By reducing the intensity of the hydraulic fracturing pressure, a corresponding reduction in the amount of resources required, and a reduction in the amount of byproduct produced, by the hydraulic fracturing process will be achieved.

[0029] FIG. **3** illustrates an example configuration of equipment to achieve a reduction in the intensity of hydraulic fracturing. A plurality of seismic sensors **310** are situated in a region of interest **330** about a well, or future well **320**. These sensors **310** may be surface mounted, or situated in a borehole and include, for example, a three-component borehole seismometer that measures motion in three dimensions (vertical motion, and two orthogonal horizontal motions, e.g. north-south and east-west).

[0030] Deep borehole seismometers are preferred to surface seismometers due to the fact that motion caused by surface activity (traffic and the like) will be attenuated as the depth of the sensor increases, and motion at the relative depth of the target reservoir is of primary interest. In like manner, three-component seismometers are preferred as being able to sense activity in any direction. However, it has been shown that suitable monitoring of microseismic activity may be performed using a network of single dimension (vertical) surface seismographs ("Focal Mechanism Determination Using High Frequency Waveform Matching and Its Application to Small Magnitude Induced Earthquakes", Li et al., *Earth Resources Laboratory Industry Consortia Annual Report,* 2010-05, MIT Press (2010)).

[0031] These seismic sensors **310** are situated in the vicinity of a region believed to contain hydrocarbons situated in a reservoir with low permeability between pockets of the hydrocarbons, such as a reservoir of tight shales or tight sands containing trapped oil or gas. In a typical embodiment, a production well is drilled vertically down to the region of the reservoir, then, in most cases, directed horizontally through the reservoir; a multi-layer casing is then situated or created within the well. Multiple horizontal segments, extending into different parts of the reservoir, may extend from co-located vertical segments, minimizing the surface area consumed by the wells.

[0032] Perforations are created at select location in the horizontal segments of the casing, typically spaced about one hundred feet apart, using, for example, a series of 'perforation guns' that pierce the casing and create crevices in the surrounding material for the proppant filled fluid to flow. These perforated sections are preferably selectively isolated, so that the fracturing process can proceed in a sequential manner.

[0033] During conventional hydraulic fracturing, as mentioned above, a hydraulic mixture of water, sand, and other materials are pumped through the casing of the well and through the perforations under continually increasing pressure. Seismic sensors, such as the seismic sensors **310**, monitor the operation to detect when and where the region surrounding the perforated casing is fractured, and the pumping ceases. The hydraulic pressure at the depth at which the fracturing occurs is determined from the hydraulic "fracture gradient", a factor calculated for each reservoir using corresponding geological information.

[0034] Conventional hydraulic fracturing is performed immediately after the casing is formed and perforated, to minimize the time required to create a productive well, and presumably maximize profit. This presumption may be erroneous, however, in view of the myriad factors associated with hydraulic fracturing, including the energy required to achieve (and often over-achieve) the pressure calculated from the fracture gradient, the resources used during the fracturing process, the disposal of the residual fluid, and so on.

[0035] In accordance with aspects of this invention, as illustrated in FIG. **4**A, the hydraulic fracturing process is scheduled to be synchronized to periods of high microseismic activity. The well is prepared for hydraulic fracturing at **410**, and microseismic activity is monitored at **415** to identify periods of high microseismic activity. This monitoring may be performed before, during, or after the well is prepared for hydraulic fracturing, although it will generally be performed during 'quiet' periods, when noisy drilling operations are not being performed. Based on this monitoring, a pattern of microseismicity can be determined, so that periods of higher levels of microseismic activity can be predicted. Thereafter, at **420**, the hydraulic fracturing operations are performed based on these predicted periods of high microseismic activity.

[0036] It should be noted that the duration and timing of the hydraulic fracturing process will generally be different from the duration and timing of the elevated levels in microseismicity; as the term 'synchronous' is used herein, a 'phase shift' may, and typically will, exist between these two events. For example, the hydraulic fracturing process will preferably start at some point prior to the expected peak in natural microseismicity, because it takes some finite amount of time to build up the hydraulic pressure.

[0037] By synchronizing the hydraulic fracturing process with periods of high microseismic activity, less energy and fewer resources will be required to induce fractures within the formations surrounding the wells. With fewer resources being expended, there will be less residual material for disposal. In addition, better hydraulic fracturing results could be obtained because the elevated tidal dilational stress would simultaneously stimulate natural fractures and open sealed fractures, as well as contribute to the creation of new fractures.

[0038] Recognizing that the major expense in the hydraulic fracturing process is preparing the well, getting the fracturing equipment and materials on site, pumping the chemical and proppant laden fluid, and removing the residuals, the savings in energy and resources consumed and the disposal of residuals can be expected to significantly outweigh the cost of delaying the fracturing to achieve a more efficient fracturing process. In addition to saving these expenses, the reduction in the use of energy and the reduction in the fluid and its residuals, will significantly reduce the ecological impact of this fracturing process.

[0039] Alternatively, instead of introducing an explicit delay between completion of the fracturing setup and the commencement of pumping the fluid and proppant, during which the fracturing equipment is ready for operation and sitting idly on site, the installation schedule can be developed based on a prediction of when the higher microseismic activity will occur, such that the fracturing setup can be scheduled to be completed just prior to this period of predicted higher activity. In this manner, the fracturing operation may be scheduled to include the period of predicted higher activity.

[0040] In addition to a prediction based on on-site monitoring of microseismic activity, a long-term prediction of periods of higher levels of microseismic activity may be used to schedule the hydraulic fracturing process. Such a prediction of higher microseismic activity may be based, for example on the predictable magnitudes of earth tides to facilitate such scheduling. As noted above, it is known that the earth tide peaks twice a month, near new moon and full moon, when the sun and moon are aligned with the earth, and the dilational stress created is likely to increase the magnitude and duration of the resultant microseismic events. Although all of the earth is affected by earth tide, the tidal pattern differs depending upon location, due to the cumulative effect of the lunar, solar, and other components that contribute to the tidal force. These tidal effects are primarily a function of latitude, with minor variations due to longitude.

[0041] FIGS. **5**A-**5**F illustrate the vertical displacement patterns induced by the earth tides at six locations of different latitude for a two week period in February **2012**. As can be seen, these tidal patterns are strongly dependent upon latitude; the largest magnitude of vertical displacements can be expected at a latitude of 23°, corresponding to the tilt of the moon's orbit relative to the earth's equator. The cumulative effect of the tidal components will also vary seasonally, as the tilt of the earth relative to the sun changes.

[0042] Also, as noted above, because these microseismic events result from the increased dilational stresses caused by the tides, there will likely be a phase lag between the peak tides and the increased microseismicity, and the hydraulic fracturing schedule will be adjusted accordingly.

[0043] The particular relationship between earth tides and microseismic activity, such as the lag time between peak tides and peak microseismic activity, may also be dependent upon the structural aspects of the particular reservoir and the effect of ocean tides if the reservoir is within 100 miles of the ocean. As noted above, the predicted earth tides may be used for long-term planning, while on-site monitoring is used to 'fine-tune' the predictions. In accordance with an aspect of this invention, as illustrated in FIG. **4**B, the relationship between the earth tides and the microseismic activity at the reservoir site is determined, at **430**, using, for example, routine correlation techniques. Using this relationship and the predicted earth tides, the periods of high microseismic activity may be determined/predicted, at **435**. Based on this prediction, the timing of the hydraulic fracturing can be scheduled to occur to achieve the aforementioned higher efficiencies in energy consumption and waste disposal, and achieving more productive results from hydraulic fracturing.

[0044] Accordingly, the fracturing setup can be scheduled to be completed just before the determined peak activity periods, based on the predicted earth tides and/or locally monitored microseismic activity, thereby minimizing the likelihood of having to introduce a delay between the completion of the setup and the commencement of the hydraulic fracturing process.

[0045] The monitoring of naturally occurring microseismic activity may also provide other benefits in the exploration for regions suitable for hydraulic fracturing and the identification of target regions for orienting horizontal boreholes.

[0046] By processing the monitored activity from a network of sensors, such as sensors **310**, the location and direction of the existing natural fractures in a region may be determined, and the horizontal drilling can be directed toward regions exhibiting a high degree of natural fractures with knowledge of the orientation of their fracture planes.

[0047] In accordance with an aspect of this invention, as illustrated in FIG. **4**C, because it is known that the dilatant stress produced by earth tides often initiate microseismic activity, monitoring the potential target area for microseismic activity is likely to be productive during periods of high tidal dilatant stress. The cause of such microseismic events will generally be microslips along the fracture planes of natural fractures in the reservoir formations. In a preferred embodiment, at **440**, the period of high microseismic activity is determined, either by contemporaneous monitoring, or by predictions based on the earth tide, as detailed above. At **445**, the network of sensors **310** is configured to monitor microseismic activity during these periods of high microseismic activity. Conventional techniques may be applied to process this data to locate the sources of the microseismic events, and the subsequent horizontal drilling can be directed toward these locations, at **450**.

[0048] In like manner, the monitored microseismic activity may also be used to identify the location of tidally induced microearthquakes and the direction of the corresponding microslip and the orientation of the fracture plane on which it occurred. Knowledge of the location and orientation of the fracture plane and microslip vectors can then be used to guide the direction of horizontal drilling paths, at **450**. Conventional techniques, and in particular those using full waveform inversion rather than P-waves alone, are available for accurately determining the source mechanisms associated with microearthquakes ("Focal mechanism determination of induced microearthquakes in an oil field using full waveforms from shallow and deep seismic networks", J. Li, S. Kuleli, H. Zang, M. N. Toksoz, Geophysics, Vol. 76, No. 6, 2011).

[0049] In addition to monitoring and identifying specific microseismic events caused by tidal stress, the monitoring system may be configured to identify tremors, or continuous vibrations, that may emanate from critically stressed fracture systems. The tidal stress often causes slow slips, or repeated fractional slip failures, which are likely to result in tremors, particularly during peak earth tide periods. Conventional techniques may be applied to locate and identify the source of each tremor, and this information may be used to guide the direction of the horizontal drilling paths.

[0050] In addition to aiding in the exploration and development of new sources of oil and gas, natural microseismic activity may also be used to optimize the production from existing wells. As noted above, the techniques above may be used for locating additional potential sources within an existing region; but additionally, the principles disclosed herein may be applied to enhance the production of existing wells without extending the existing wells.

[0051] As wells age over time, the production efficiency declines because there is less oil or gas remaining in the reservoir to be extracted, and because the initially created fractures may reseal. Additionally, although current proppants are designed to prevent the subsequent closure of created fractures, environmental concerns may eventually result in a limitation or elimination of their use in hydraulic fracturing, thereby increasing the likelihood of created fractures being resealed. Alternatively stated, by providing a process that reopens prior fractures, the use of environmentally unfriendly material as fluids and proppant may be substantially reduced.

[0052] In accordance with an aspect of this invention, when production efficiency drops below a given economically practical threshold, the production schedule is adjusted to reduce overall operational costs. Because microseismic activity increases the likelihood of fractures being reopened, albeit perhaps temporarily, the amount of gas or oil that is accessible by the existing well during periods of high microseismic activity can be expected to be greater than the amount available during periods of low microseismic activity. Accordingly, the costs associated with extracting hydrocarbons during periods of high microseismic activity may be lower than the costs of extraction during periods of low microseismic activity. To increase the economic efficiency of the extraction/production process, the production schedule is adjusted to extract the oil or gas only during these high efficiency periods, as illustrated in FIG. **4**D. Also, the resource may last longer on such an optimized schedule.

[0053] This optimized scheduling of production may be implemented by controlling the extraction process to occur during periods of high microseismic activity. At **460**, the periods of high microseismic activity are identified, based on the monitored microseismic activity at the well site, or based on predictions of high microseismic activity related to earth tides, as detailed above. As noted above, earth tidal stress induces microseismic activity, and the periods of peak microseismic activity occurs bimonthly over a period of several days. Accordingly, the production schedule may be modified to postpone extraction between these peak tidal periods, at **465**.

[0054] Additionally, or alternatively, because the earth tide cycles exhibit a diurnal and semidiurnal cycle, the production schedule may be adjusted on a daily basis based on these cycles. In the above mentioned thesis, "The Earth Tide Effects on Petroleum Reservoirs", by Patricia C. Arditty, it is shown that the pressure variations induced by daily earth tides are a function of the composition of the particular reservoir rock formation, as well as the characteristics of the hydrocarbons being extracted. The particular aspects of such daily scheduling will also be dependent upon the rate/speed of reclosure within the particular well.

[0055] In accordance with aspects of this invention, production efficiency and/or internal well pressure may be determined as a function of time, and the correlation of these measures with the diurnal and semidiurnal earth tide at the well site is determined. When such a correlation exists, the daily production schedule is adjusted to schedule extraction during the phases of the tidal cycle corresponding to the higher efficiency periods. In like manner, if a correlation is determined between the production efficiency (and/or well pressure) and the bimonthly earth tide cycle, the production schedule may be configured to conduct extraction based on this bimonthly cycle. It should be noted that this bimonthly cycle may be somewhat shifted in time from the previously discussed bimonthly periods of high microseismic activity.

[0056] Production efficiency may also be enhanced by introducing hydraulic pressure that stimulates natural fractures and reactivates sealed natural fractures in unproductive tight sands and shales. Rather than introducing a hydraulic pressure that causes hydraulic fracturing, a lower pressure may be introduced with maximum effect during either one of the two bimonthly periods of highest microseismic activity. Even if microseismicity is sparse, the periods of peak tides may be used to schedule the hydraulic pressure periods, because it is known that the dilational stress can be expected to be higher during these tidal peaks. As noted above, the induced microseismic activity in the reactivated fractures together with the microseismic activity in the open natural fractures will generally result in a higher production efficiency of previously unproductive, or low-producing tight sands and shales by reopening fractures that had been sealed over time. The extent of natural fracture activity and sealed fracture reactivation can be followed by monitoring this man-induced microseismic activity while the hydraulic pressure is being introduced and maintained.

[0057] In accordance with an aspect of this invention this increased hydraulic pressure may be introduced during times of maximum microseismicity or maximum earth tides, using only water, or an ecology-friendly mixture, such as sand and water. Such an approach may, for example, be used in environments where hydraulic fracturing is banned based on ecologic concerns with regard to the chemical and proppant laden hydraulic fluids used and their disposal.

[0058] One of skill in the art will recognize that the above techniques for enhancing the naturally occurring microseismic activity without introducing hydraulic fracturing, per se, may be used in any of the above techniques based on the monitoring of microseismic activity. That is, for example, instead of employing hydraulic fracturing, merely enhancing the naturally occurring microseismic activity of natural fractures and reactivated sealed fractures may be sufficient to accomplish the same goals.

[0059] In like manner, one of skill in the art will also recognize that the enhancement of naturally occurring microseismic activity may also result in an acceleration of mechanical activity in natural fractures and the opening of sealed fractures. As such, the ecologic effects of such enhancements are likely to be significantly less than the effects of conventional hydraulic fracturing techniques, and yet may be an acceptable substitute for conventional hydraulic fracturing in environments wherein hydraulic fracturing is banned or otherwise prohibited.

[0060] In each of the above embodiments, the principles of this invention provide enhancements for the creation and exploitation of sources of hydrocarbons that improve the efficiency of conventional hydraulic fracturing techniques. By improving the efficiency, particularly with regard to the energy and resources consumed and the quantity and quality of the residual materials, solutions are provided that are clearly "cleaner than fracking".

[0061] The foregoing merely illustrates the principles of the invention. It will thus be appreciated that those skilled in the art will be able to devise various arrangements which, although not explicitly described or shown herein, embody the principles of the invention and are thus within its spirit and scope. For example, in conventional reservoirs where permeability pre-exists and does not have to be created, production will be best at times of high microseismicity. With regard to environmental concerns, if the hydrocarbon reservoir is near a water reservoir, hydraulic fracturing using diminished pressure, when microseismicity is at high levels, reduces the danger of contamination. These and other system configuration and optimization features will be evident to one of ordinary skill in the art in view of this disclosure, and are included within the scope of the following claims.

[0062] In interpreting these claims, it should be understood that:

- **[0063]** a) the word "comprising" does not exclude the presence of other elements or acts than those listed in a given claim;
- **[0064]** b) the word "a" or "an" preceding an element does not exclude the presence of a plurality of such elements;
- **[0065]** c) any reference signs in the claims do not limit their scope;
- **[0066]** d) several "means" may be represented by the same item or hardware or software implemented structure or function;
- **[0067]** e) any of the disclosed devices or portions thereof may be combined together or separated into further portions unless specifically stated otherwise;
- **[0068]** f) no specific sequence of acts is intended to be required unless specifically indicated; and
- **[0069]** g) the term "plurality of" an element includes two or more of the claimed element, and does not imply any particular range of number of elements; that is, a plurality of elements can be as few as two elements, and can include an immeasurable number of elements.

1. A method comprising:

installing a hydraulic pressure device in a well that is situated in a reservoir;

predicting a period of elevated microseismic activity;

scheduling the hydraulic pressure device to induce fractures in at least a section of the reservoir based on the predicted period of elevated microseismic activity; and

enabling the hydraulic pressure device in accordance with the scheduling to induce the fractures.

2. The method of claim **1**, wherein predicting the period of elevated microseismic activity includes monitoring prior microseismic activity in a vicinity of the reservoir.

3. The method of claim **2**, wherein predicting the period of elevated microseismic activity includes determining a time of maximal earth tide at the reservoir.

4. The method of claim **1**, wherein predicting the period of elevated microseismic activity includes determining a time of maximal earth tide at the reservoir.

5. The method of claim **1**, including:

estimating a minimum fracturing pressure that is sufficient to reliably induce fractures, and

controlling the hydraulic pressure device to apply a maximum pressure that is below the minimum fracturing pressure.

6. The method of claim **5**, wherein the maximum pressure that is applied is substantially lower than the minimum fracturing pressure, so as to assure that new fractures are not created.

7. The method of claim **5**, wherein the minimum fracturing pressure is based on a fracture gradient at the reservoir.

8. The method of claim **5**, including:

determining a minimum quantity of liquid required to achieve the minimum fracturing pressure, and

supplying less than the minimum quantity of liquid to the hydraulic pressure device.

9. The method of claim **5**, wherein the hydraulic pressure device applies the maximum pressure by pumping a liquid into the well, and the liquid comprises only one of: water and a combination of water and sand.

10. The method of claim **1**, including disabling the hydraulic pressure device in accordance with the scheduling.

11. The method of claim **1**, wherein scheduling the hydraulic pressure device includes determining a start time for the enabling of the hydraulic pressure device that is substantially earlier than the predicted period of elevated microseismic activity.

12. The method of claim **1**, wherein the well includes a horizontal segment, and the method includes monitoring microseismic activity in a vicinity of the reservoir and controlling a drilling of the horizontal segment based on the monitored microseismic activity.

13. A system comprising:

a well that is disposed in a reservoir;

a hydraulic pressure device that is disposed in the well and configured to induce fractures in the reservoir; and

a control unit that controls the hydraulic pressure device based on a predicted period of elevated microseismic activity in a vicinity of the reservoir.

14. The system of claim **13**, including one or more monitoring devices that monitor microseismic activity, wherein the predicted period of elevated microseismic activity is based on prior microseismic activity.

15. The system of claim **13**, wherein the one or more monitoring devices include one or more three-component borehole seismographs.

16. The system of claim **13**, wherein the predicted period of elevated microseismic activity is based on a time of maximal earth tide at the reservoir.

17. The system of claim **13**, wherein the well includes a substantially horizontal component, and a vector direction of the horizontal component is based on the monitored microseismic activity.

18. The system of claim **13**, wherein the predicted period of elevated microseismic activity is based on a time of maximal earth tide at the reservoir.

19. The system of claim **18**, wherein the control unit controls the hydraulic pressure device to apply a maximum pressure that is below a minimum fracturing pressure that is sufficient to reliably induce fractures.

20. The system of claim **13**, wherein the control unit controls the hydraulic pressure device to apply a maximum pressure that is below a non-fracturing pressure limit that is determined based on a fracture gradient at the reservoir.

21. The system of claim **20**, wherein the control unit supplies less than a minimum quantity of liquid required to achieve a fracturing pressure based on the fracture gradient to the hydraulic pressure device.

22. The system of claim **13**, wherein the control unit disables the hydraulic pressure device based on predicted periods of lower-than-average microseismic activity.

23. The system of claim **13**, wherein the control unit is configured to establish a start time for the enabling of the hydraulic pressure device that is substantially earlier than the predicted period of elevated microseismic activity.

24. A method comprising:

predicting a period of elevated microseismic activity;

defining a schedule for extracting hydrocarbons from a reservoir based on the periods of elevated microseismic activity; and

selectively enabling and disabling extraction of the hydrocarbons based on the schedule.

25. The method of claim **24**, including applying hydraulic pressure within the reservoir based on the schedule.

26. A method comprising:

predicting a period of elevated microseismic activity at a location;

monitoring the microseismic activity in vicinity of the location during the period of elevated microseismic activity; and

situating drilling equipment in the vicinity of the location based on the monitored microseismic activity.

27. The method of claim **26**, wherein predicting the period of elevated microseismic activity includes determining a time of maximal earth tide at the location.

28. The method of claim **26**, wherein predicting the period of elevated microseismic activity includes monitoring prior microseismic activity in the vicinity of the location.

29. The method of claim **26**, including scheduling operation of the drilling equipment based on the monitored microseismic activity.

30. The method of claim **26**, including determining particular locations for the drilling equipment based on the monitored microseismic activity.

31. The method of claim **26**, including determining a particular horizontal direction for installing horizontal segments of a well.

32. The method of claim **31**, including enabling a hydraulic pressure device to induce fractures at one or more of the horizontal segments of the well.

33. The method of claim **32**, wherein a schedule of enabling the hydraulic pressure device is based on the monitored microseismic activity.

* * * * *