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SYSTEM AND METHOD FOR AUTOMATIC DETECTION OF MICROSEISMIC REFLECTIONS IN DISTRIBUTED ACOUSTIC SENSING DATA

Abstract

A method is described for automatically detecting shear-wave (S-wave) microseismic reflections using distributed acoustic sensing (DAS). The method includes obtaining raw DAS data; performing passive seismic event detection and phase picking; extracting a passive seismic event based on the passive seismic event phase picks to generate a seismic S-wave event gather; reducing noise in the raw DAS data; using the passive seismic S-wave event gather and the passive seismic event phases to identify an apex of a passive seismic S-wave event in the denoised DAS dataset and dividing it into two portions based on the apex; dip filtering the two portions to remove the direct arrival of the passive seismic S-wave events to generate a dip-filtered gather; and generating an S-wave microseismic reflection gather based on the dip-filtered gather.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS
[0001] Not applicable.
STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT
[0002] Not applicable.
TECHNICAL FIELD
[0003] The disclosed embodiments relate generally to techniques for seismic data processing. In particular, the disclosed embodiments relate to automatic detection of microseismic shear wave (S-wave) events in distributed acoustic sensing (DAS) data.
BACKGROUND
[0004] Seismic exploration involves surveying subterranean geological media for hydrocarbon deposits. A survey typically involves deploying seismic sources and seismic sensors at predetermined locations. The sources generate seismic waves, which propagate into the geological medium creating pressure changes and vibrations. Variations in physical properties of the geological medium give rise to changes in certain properties of the seismic waves, such as their direction of propagation and other properties. Alternatively, rather than having active seismic sources to generate seismic waves, a passive seismic survey may use ambient seismic sources such as but not limited to earthquakes, rock fracturing, and/or environmental sources (e.g., vehicle traffic, ocean waves, and the like). When these ambient seismic sources are weak, such as rock fracturing, they may be considered microseismic sources emitting microseismic energy.
[0005] Portions of the seismic waves reach the seismic sensors. Some seismic sensors are sensitive to pressure changes (e.g., hydrophones), others to particle motion (e.g., geophones), and industrial surveys may deploy one type of sensor or both. In response to the detected seismic waves, the sensors generate corresponding electrical signals, known as traces, and record them in storage media as seismic data. Seismic data will include a plurality of “shots” (individual instances of the seismic source being activated), each of which are associated with a plurality of traces recorded at the plurality of sensors.
[0006] An alternative seismic sensor may include fiber-optic cables. Fiber-optic cables may be deployed in a borehole drilled through the earth's subsurface, along the earth's surface, on a seabed, and the like. FIG. **1** illustrates a fiber-optic cable **12** attached to an interrogator **10**. A laser pulse **14** propagates through the fiber-optic cable **12**, shown as light stream **16**. The light stream **16** sends information to interrogator **10**. An acoustic signal **18** encountering the fiber-optic cable **12** is recorded as a change in strain or strain-rate along the cable and may be considered to be a seismic event.
[0007] Seismic data is processed to create seismic images that can be interpreted to identify subsurface geologic features including hydrocarbon deposits. The ability to define the location of rock and fluid property changes in the subsurface is crucial to our ability to make the most appropriate choices for purchasing materials, operating safely, and successfully completing projects. Project cost is dependent upon accurate prediction of the position of physical boundaries within the Earth. Decisions include, but are not limited to, budgetary planning, obtaining mineral and lease rights, signing well commitments, permitting rig locations, designing well paths and

drilling strategy, preventing subsurface integrity issues by planning proper casing and cementation strategies, and selecting and purchasing appropriate completion and production equipment.
[0008] There exists a need for methods of processing DAS data in order to identify microseismic reflections.

SUMMARY
[0009] In accordance with some embodiments, a method of automatically detecting shear-wave (S-wave) microseismic reflections using distributed acoustic sensing (DAS) is disclosed. The method includes obtaining raw DAS data collected for a subsurface volume of interest; performing passive seismic event detection and phase picking on the raw DAS data to identify passive seismic events and passive seismic event phases; extracting a passive seismic event based on the passive seismic event phase picks to generate a seismic S-wave event gather; reducing noise in the raw DAS data to generate a denoised DAS dataset; using the passive seismic S-wave event gather and the passive seismic event phases to identify an apex of a passive seismic S-wave event in the denoised DAS dataset and dividing the passive seismic S-wave event in the denoised DAS dataset into two portions based on the apex; identifying a dip of a direct arrival of the passive seismic S-wave event gather in each of the two portions; dip filtering the two portions to remove the direct arrival of the passive seismic S-wave events to generate a dip-filtered gather; generating an S-wave microseismic reflection gather based on the dip-filtered gather; and displaying the S-wave microseismic reflection gather on a graphical display.
[0010] In another aspect of the present invention, to address the aforementioned problems, some embodiments provide a non-transitory computer readable storage medium storing one or more programs. The one or more programs comprise instructions, which when executed by a computer system with one or more processors and memory, cause the computer system to perform any of the methods provided herein.
[0011] In yet another aspect of the present invention, to address the aforementioned problems, some embodiments provide a computer system. The computer system includes one or more processors, memory, and one or more programs. The one or more programs are stored in memory and configured to be executed by the one or more processors. The one or more programs include an operating system and instructions that when executed by the one or more processors cause the computer system to perform any of the methods provided herein.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0012] FIG. **1** is a simple diagram of a distributed acoustic sensing (DAS) system;
[0013] FIG. **2** illustrates an example system for identifying and displaying S-wave reflections from DAS data;
[0014] FIG. **3** illustrates an example method for identifying and displaying S-wave reflections from DAS data; and
[0015] FIG. **4** illustrates example steps of a method for identifying and displaying S-wave reflections from DAS data;
[0016] FIG. **5** shows a result of a method for identifying and displaying S-wave reflections from DAS data;
[0017] FIG. **6** shows a result of a method for identifying and displaying S-wave reflections from DAS data; and
[0018] FIG. **7** shows a result of a method for identifying and displaying S-wave reflections from DAS data.
[0019] Like reference numerals refer to corresponding parts throughout the drawings.
DETAILED DESCRIPTION OF EMBODIMENTS

[0020] Described below are methods, systems, and computer readable storage media that provide a manner of detecting microseismic shear wave (S-wave) reflections in distributed acoustic sensing (DAS) data. These embodiments are designed to identify microseismic reflections automatically without the need for manual picking, making them more efficient and accurate than conventional methods.
[0021] Reference will now be made in detail to various embodiments, examples of which are illustrated in the accompanying drawings. In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the present disclosure and the embodiments described herein. However, embodiments described herein may be practiced without these specific details. In other instances, well-known methods, procedures, components, and mechanical apparatus have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.
[0022] The methods and systems of the present disclosure may be implemented by a system and/or in a system, such as a system **20** shown in FIG. **2**. The system **20** may include one or more of a processor **21**, an interface **22** (e.g., bus, wireless interface), an electronic storage **23**, a graphical display **24**, and/or other components. The processor **21** is configured to receive raw distributed acoustic data (DAS) data and produce images of microseismic reflections.
[0023] The electronic storage **23** may be configured to include electronic storage medium that electronically stores information. The electronic storage **23** may store software algorithms, information determined by the processor **21**, information received remotely, and/or other information that enables the system **20** to function properly. For example, the electronic storage **23** may store information relating to input DAS data, and/or other information. For example, the electronic storage **23** may store information relating to output S-wave reflections, and/or other information. The electronic storage media of the electronic storage **23** may be provided integrally (i.e., substantially non-removable) with one or more components of the system **20** and/or as removable storage that is connectable to one or more components of the system **20** via, for example, a port (e.g., a USB port, a Firewire port, etc.) or a drive (e.g., a disk drive, etc.). The electronic storage **23** may include one or more of optically readable storage media (e.g., optical disks, etc.), magnetically readable storage media (e.g., magnetic tape, magnetic hard drive, floppy drive, etc.), electrical charge-based storage media (e.g., EPROM, EEPROM, RAM, etc.), solid-state storage media (e.g., flash drive, etc.), and/or other electronically readable storage media. The electronic storage **23** may include one or more non-transitory computer readable storage medium storing one or more programs. The electronic storage **23** may be a separate component within the system **20**, or the electronic storage **23** may be provided integrally with one or more other components of the system **20** (e.g., the processor **21**). Although the electronic storage **23** is shown in FIG. **2** as a single entity, this is for illustrative purposes only. In some implementations, the electronic storage **23** may comprise a plurality of storage units. These storage units may be physically located within the same device, or the electronic storage **23** may represent storage functionality of a plurality of devices operating in coordination.
[0024] The graphical display **24** may refer to an electronic device that provides visual presentation of information. The graphical display **24** may include a color display and/or a non-color display. The graphical display **24** may be configured to visually present information. The graphical display **24** may present information using/within one or more graphical user interfaces. For example, the graphical display **24** may present information relating to DAS data, S-wave reflections, and/or other information.
[0025] The processor **21** may be configured to provide information processing capabilities in the system **20**. As such, the processor **21** may comprise one or more of a digital processor, an analog processor, a digital circuit designed to process information, a central processing unit, a graphics processing unit, a microcontroller, an analog circuit designed to process information, a state machine, and/or other mechanisms for electronically processing information. The processor **21** may

be configured to execute one or more machine-readable instructions **100** to facilitate identification of S-wave reflections in DAS data. The machine-readable instructions **100** may include one or more computer program components. The machine-readable instructions **100** may include an event detection component **102**, a S-wave selection component **104**, a denoising component **106**, a S-wave processing component **108**, a S-wave reflection component **110**, and/or other computer program components.

[0026] It should be appreciated that although computer program components are illustrated in FIG. **2** as being co-located within a single processing unit, one or more of computer program components may be located remotely from the other computer program components. While computer program components are described as performing or being configured to perform operations, computer program components may comprise instructions which may program processor **21** and/or system **20** to perform the operation.

[0027] While computer program components are described herein as being implemented via processor **21** through machine-readable instructions **100**, this is merely for ease of reference and is not meant to be limiting. In some implementations, one or more functions of computer program components described herein may be implemented via hardware (e.g., dedicated chip, field-programmable gate array) rather than software. One or more functions of computer program components described herein may be software-implemented, hardware-implemented, or software and hardware-implemented.

[0028] Referring again to machine-readable instructions **100**, the event detection component **102** may be configured to identify passive seismic events using unsupervised machine learning techniques to associate picks from multiple sensors to the same passive seismic event. An example of an appropriate unsupervised machine learning technique is density-based clustering. It may use a convolutional neural network trained to pick the arrival times of primary (P) and shear(S) waves from the DAS data, such as PhaseNet.

[0029] The S-wave selection component **104** may be configured to select passive S-waves based on phase picks. These are used to separate the two main dips of the seismic events.

[0030] The denoising component **106** may be configured to improve the signal-to-noise ratio of the DAS data.

[0031] The S-wave processing component **108** may be configured to process the data based on the selected S-waves.

[0032] The S-wave reflection component **110** may be configured to output the S-wave reflections.

[0033] The description of the functionality provided by the different computer program components described herein is for illustrative purposes, and is not intended to be limiting, as any of computer program components may provide more or less functionality than is described. For example, one or more of computer program components may be eliminated, and some or all of its functionality may be provided by other computer program components. As another example, processor **21** may be configured to execute one or more additional computer program components that may perform some or all of the functionality attributed to one or more of computer program components described herein.

[0034] FIG. **3** illustrates an example process **300** for identifying S-wave microseismic reflections from DAS data. At step **30**, the raw DAS data is obtained via fiber-optic cable. Raw DAS data may contain passive seismic events that travel directly from microseismic sources to the fiber-optic receivers as well as events that reflect from geologic interfaces in the geologic features near the fiber-optic cable. For example, the seismic energy may reflect off of fractures in the geologic formation.

[0035] At step **31**, the process performs passive seismic event detection and phase picking in the raw DAS data. This may be done, by way of example and not limitation, using appropriate unsupervised machine learning techniques such as density-based clustering. It may use a convolutional neural network trained to pick the arrival times of primary (P) and shear(S) waves from the DAS data, such as PhaseNet. PhaseNet is a deep-neural-network-based phase picking algorithm designed to pick initial seismic phases from the raw data. This step then applies an unsupervised learning method for data clustering to group the associated P-and S-wave phases from the same seismic event. Clustering removes the false detections by neglecting the initial P-or S-wave arrivals which do not have their associated counterparts. The timing when microseismic events occurred in the continuous DAS recording will be identified after imposing additional physical constraints on picks after clustering.

[0036] At step **32**, the process identifies passive seismic S-waves. Based on the timing determined from phases pickings in step **31**, an individual gather of microseismic event which contains both P- and S-waves is extracted from the raw data for reflection detection.

[0037] At step **33**, the signal-to-noise ratio of the raw DAS data is improved via denoising. The denoising technique, for example non-local mean filter, is used to further suppress the random noises in the extracted raw microseismic event. The denoised data will be used as the input in step **34**.

[0038] At step **34**, the apex of each S-wave event is found based on the phase picks. When the apex is identified, the event can be separated to left and right parts. The separation is conducted using the denoised data which contains less random noises. The left and right parts have two main dips based on the direct arrival of the S-wave. Based on the dips identified, the denoised DAS data from step **33** is dip filtered at step **35**. By filtering out the two main dips, any conflicting dips become visible. The conflicting dips are the reflections.

[0039] At step **36**, the S-wave reflections that were made visible in step **35** are output. They may be displayed on a graphical user interface and/or stored in electronic storage. In an embodiment, the S-wave reflections may be transformed into the frequency-wavenumber (f-k) domain and displayed on the graphical user interface and/or stored in electronic storage. These S-wave reflections may be used to characterize fractures in the geologic formations. This is of particular use in unconventional reservoirs such as shale and other tight rocks (rocks with minimal permeability). The identified S-wave reflections can be mapped from time domain to space domain. These reflections in space domain helps characterizing the fracture geometry (fracture height or width) between the microseismic sources and the fiber at the time of microseismic events.

[0040] FIG. **4** illustrates steps of process **300** using both raw (before panels on left) and denoised (after panels on right) DAS data. The top two panels show the raw DAS data. The middle two panels show the S-wave reflections after the direct S-wave arrivals have been dip-filtered out. The bottom two panels show the S-wave reflections in the frequency-wavenumber (f-k) domain. Note that the S-wave reflections are much clearer (in both x-t and f-k domains) when derived from the denoised data.

[0041] FIG. **5**, FIG. **6**, and FIG. **7** all show examples of process **300**. In each of these, the top “Before” panels show the S-wave arrivals divided into the left and right sides, as done in step **34** of process **300**. The “After” panels show the S-wave reflections that can be seen after the dip filtering has removed the direct arrivals.

[0042] While particular embodiments are described above, it will be understood it is not intended to limit the invention to these particular embodiments. On the contrary, the invention includes alternatives, modifications and equivalents that are within the spirit and scope of the appended claims. Numerous specific details are set forth in order to provide a thorough understanding of the subject matter presented herein. But it will be apparent to one of ordinary skill in the art that the subject matter may be practiced without these specific details. In other instances, well-known methods, procedures, components, and circuits have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.

[0043] The terminology used in the description of the invention herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used in the description of the invention and the appended claims, the singular forms “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term “and/or” as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items. It will be further understood that the terms “includes,” “including,” “comprises,” and/or “comprising,” when used in this specification, specify the presence of stated features, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, operations, elements, components, and/or groups thereof.

[0044] As used herein, the term “if” may be construed to mean “when” or “upon” or “in response to determining” or “in accordance with a determination” or “in response to detecting,” that a stated condition precedent is true, depending on the context. Similarly, the phrase “if it is determined [that a stated condition precedent is true]” or “if [a stated condition precedent is true]” or “when [a stated condition precedent is true]” may be construed to mean “upon determining” or “in response to determining” or “in accordance with a determination” or “upon detecting” or “in response to detecting” that the stated condition precedent is true, depending on the context.

[0045] Although some of the various drawings illustrate a number of logical stages in a particular order, stages that are not order dependent may be reordered and other stages may be combined or broken out. While some reordering or other groupings are specifically mentioned, others will be obvious to those of ordinary skill in the art and so do not present an exhaustive list of alternatives. Moreover, it should be recognized that the stages could be implemented in hardware, firmware, software or any combination thereof.

[0046] The foregoing description, for purpose of explanation, has been described with reference to specific embodiments. However, the illustrative discussions above are not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated.

Claims

1. A computer-implemented method for automatically detecting shear-wave (S-wave) microseismic reflections using distributed acoustic sensing (DAS), comprising: a. obtaining raw DAS data collected for a subsurface volume of interest; b. performing passive seismic event detection and phase picking on the raw DAS data to identify passive seismic events and passive seismic event phases; c. extracting a passive seismic event based on the passive seismic event phase picks to generate a seismic S-wave event gather; d. reducing noise in the raw DAS data to generate a denoised DAS dataset; e. using the passive seismic S-wave event gather and the passive seismic event phases to identify an apex of a passive seismic S-wave event in the denoised DAS dataset and dividing the passive seismic S-wave event in the denoised DAS dataset into two portions based on the apex; f. identifying a dip of a direct arrival of the passive seismic S-wave event gather in each of the two portions; g. dip filtering the two portions to remove the direct arrival of the passive seismic S-wave events to generate a dip-filtered gather; h. generating an S-wave microseismic reflection gather based on the dip-filtered gather; and i. displaying the S-wave microseismic reflection gather on a graphical display.

2. The method of claim 1 wherein the passive seismic event detection and phase picking is performed by an unsupervised machine learning algorithm.

3. The method of claim 2 wherein the unsupervised machine learning algorithm includes density-based clustering.

4. The method of claim 1 further comprising using the S-wave microseismic reflection gather to characterize fractures in the subsurface volume of interest.

5. A computer system, comprising: one or more processors; memory; and one or more programs, wherein the one or more programs are stored in the memory and configured to be executed by the one or more processors, the one or more programs including instructions that when executed by the one or more processors cause the system to automatically detect shear-wave (S-wave) microseismic reflections using distributed acoustic sensing (DAS) by: a. obtaining raw DAS data collected for a subsurface volume of interest; b. performing passive seismic event detection and phase picking on the raw DAS data to identify passive seismic events and passive seismic event phases; c. extracting a passive seismic event based on the passive seismic event phase picks to generate a seismic S-wave event gather; d. reducing noise in the raw DAS data to generate a denoised DAS dataset; e. using the passive seismic S-wave event gather and the passive seismic event phases to identify an apex of a passive seismic S-wave event in the denoised DAS dataset and dividing the passive seismic S-wave event in the denoised DAS dataset into two portions based on the apex; f. identifying a dip of a direct arrival of the passive seismic S-wave event gather in each of the two portions; g. dip filtering the two portions to remove the direct arrival of the passive seismic S-wave events to generate a dip-filtered gather; h. generating an S-wave microseismic reflection gather based on the dip-filtered gather; and i. displaying the S-wave microseismic reflection gather on a graphical display.
6. The system of claim 5 wherein the passive seismic event detection and phase picking is performed by an unsupervised machine learning algorithm.
7. The system of claim 6 wherein the unsupervised machine learning algorithm includes density-based clustering.
8. The system of claim 5 further comprising one or more programs including instructions that when executed by the one or more processors cause the system to use the S-wave microseismic reflection gather to characterize fractures in the subsurface volume of interest.
9. A non-transitory computer readable storage medium storing one or more programs, the one or more programs comprising instructions, which when executed by an electronic device with one or more processors and memory, cause the device to automatically detect shear-wave (S-wave) microseismic reflections using distributed acoustic sensing (DAS) by: a. obtaining raw DAS data collected for a subsurface volume of interest; b. performing passive seismic event detection and phase picking on the raw DAS data to identify passive seismic events and passive seismic event phases; c. extracting a passive seismic event based on the passive seismic event phase picks to generate a seismic S-wave event gather; d. reducing noise in the raw DAS data to generate a denoised DAS dataset; e. using the passive seismic S-wave event gather and the passive seismic event phases to identify an apex of a passive seismic S-wave event in the denoised DAS dataset and dividing the passive seismic S-wave event in the denoised DAS dataset into two portions based on the apex; f. identifying a dip of a direct arrival of the passive seismic S-wave event gather in each of the two portions; g. dip filtering the two portions to remove the direct arrival of the passive seismic S-wave events to generate a dip-filtered gather; h. generating an S-wave microseismic reflection gather based on the dip-filtered gather; and i. displaying the S-wave microseismic reflection gather on a graphical display.
10. The non-transitory computer readable storage medium of claim 9 wherein the passive seismic event detection and phase picking is performed by an unsupervised machine learning algorithm.
11. The non-transitory computer readable storage medium of claim 10 wherein the unsupervised machine learning algorithm includes density-based clustering.
12. The non-transitory computer readable storage medium of claim 9 wherein the one or more programs further comprising instructions that when executed by the one or more processors cause the device to use the S-wave microseismic reflection gather to characterize fractures in the subsurface volume of interest.