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(54) **MICROHYDRAULIC FRACTURING WITH DOWNHOLE ACOUSTIC MEASUREMENT**

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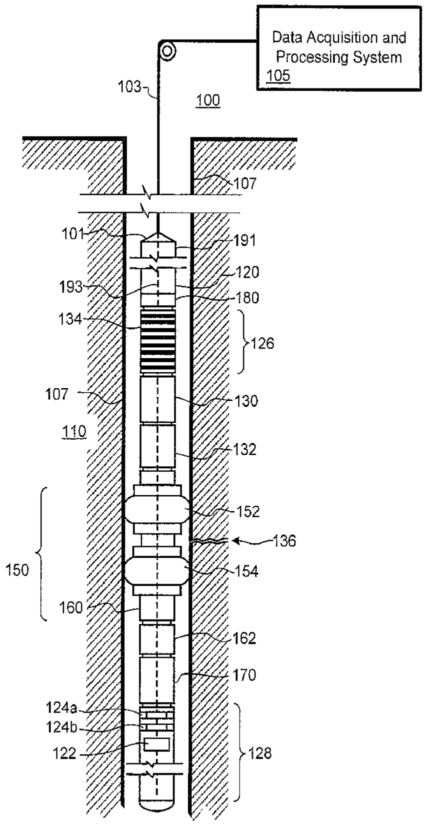
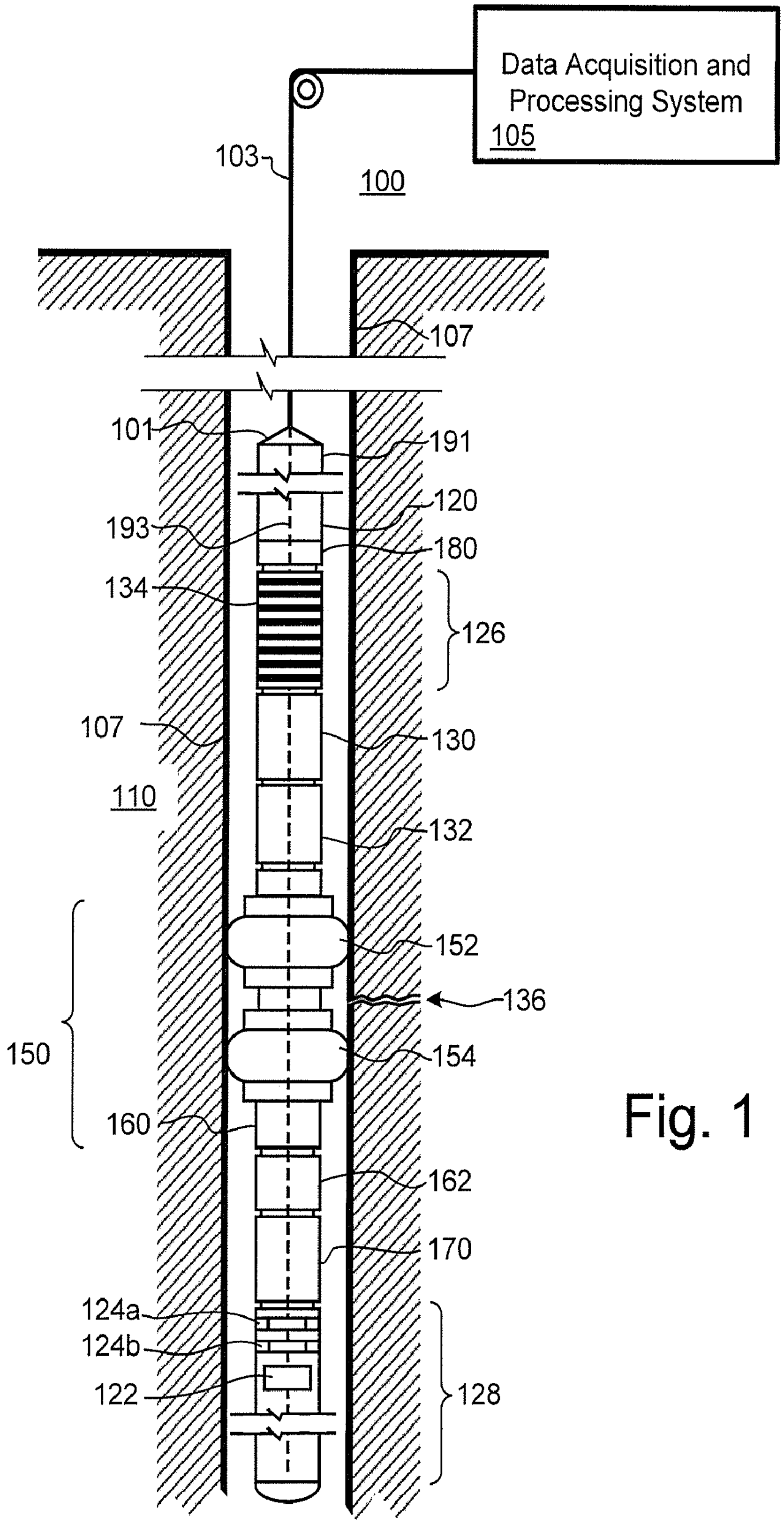
(57) **ABSTRACT**

Methods and related systems are described for measuring acoustic signals in a borehole during a fracturing operation. The system includes a downhole toolstring designed and adapted for deployment in a borehole formed within a subterranean rock formation. A downhole rock fracturing tool opens and propagates a fracture in the subterranean rock formation. Dipole and/or quadrupole acoustic sources transmit acoustic energy into the subterranean rock formation. A receiver array measures acoustic energy traveling through the subterranean rock formation before, during and after the fracture induction. Geophones mounted on extendable arms can be used to measure shear wave acoustic energy travelling in the rock formation. The toolstring can be constructed such that the sources and receivers straddle the fracture zone during the fracturing. Alternatively, the sources or the receivers can co-located axially with the fracture zone, or the toolstring can be repositioned following fracturing such that the fracture zone is between the acoustic sources and receivers.

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193
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124a
124b
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128

Fig. 1

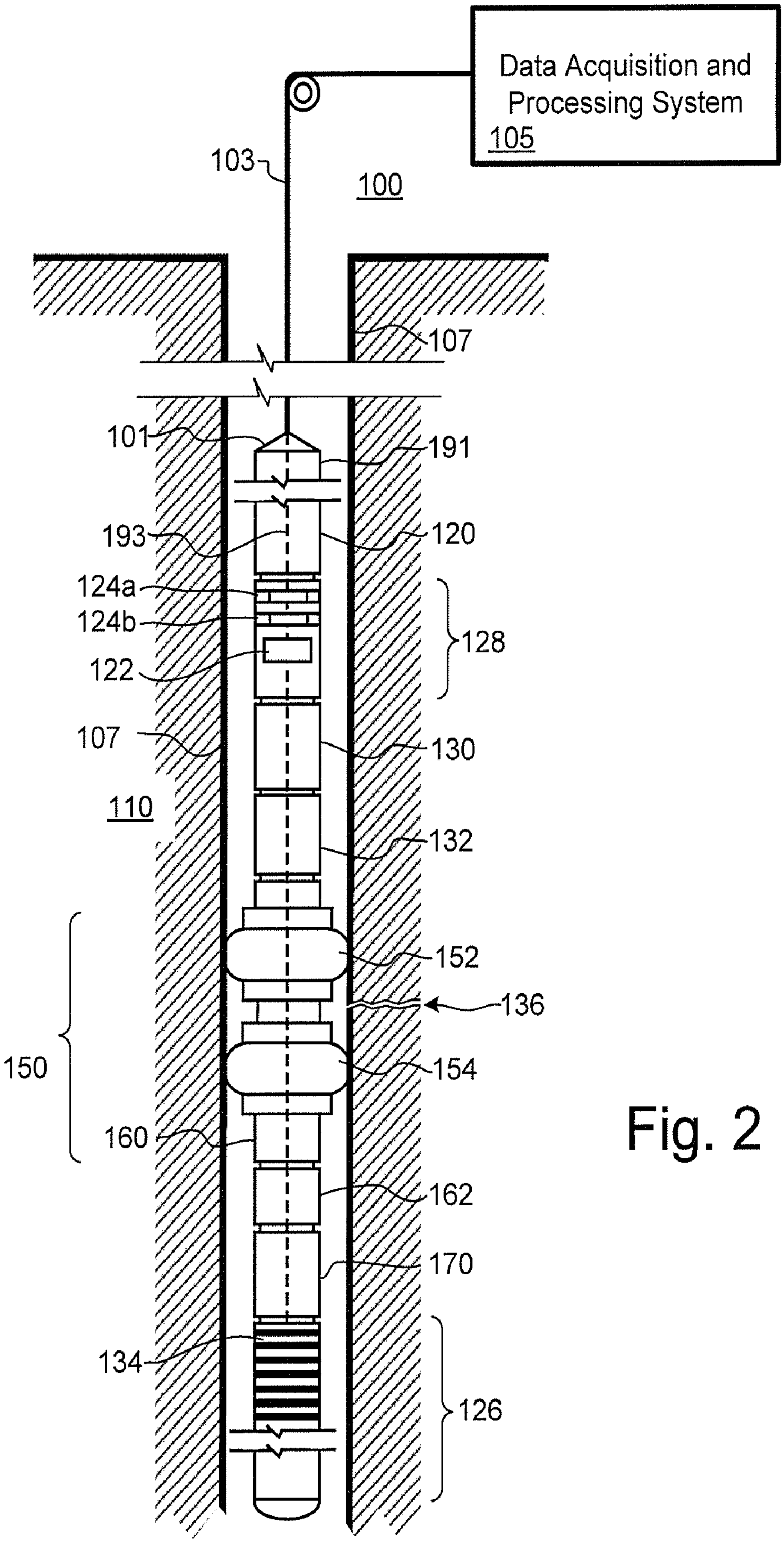
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Fig. 2

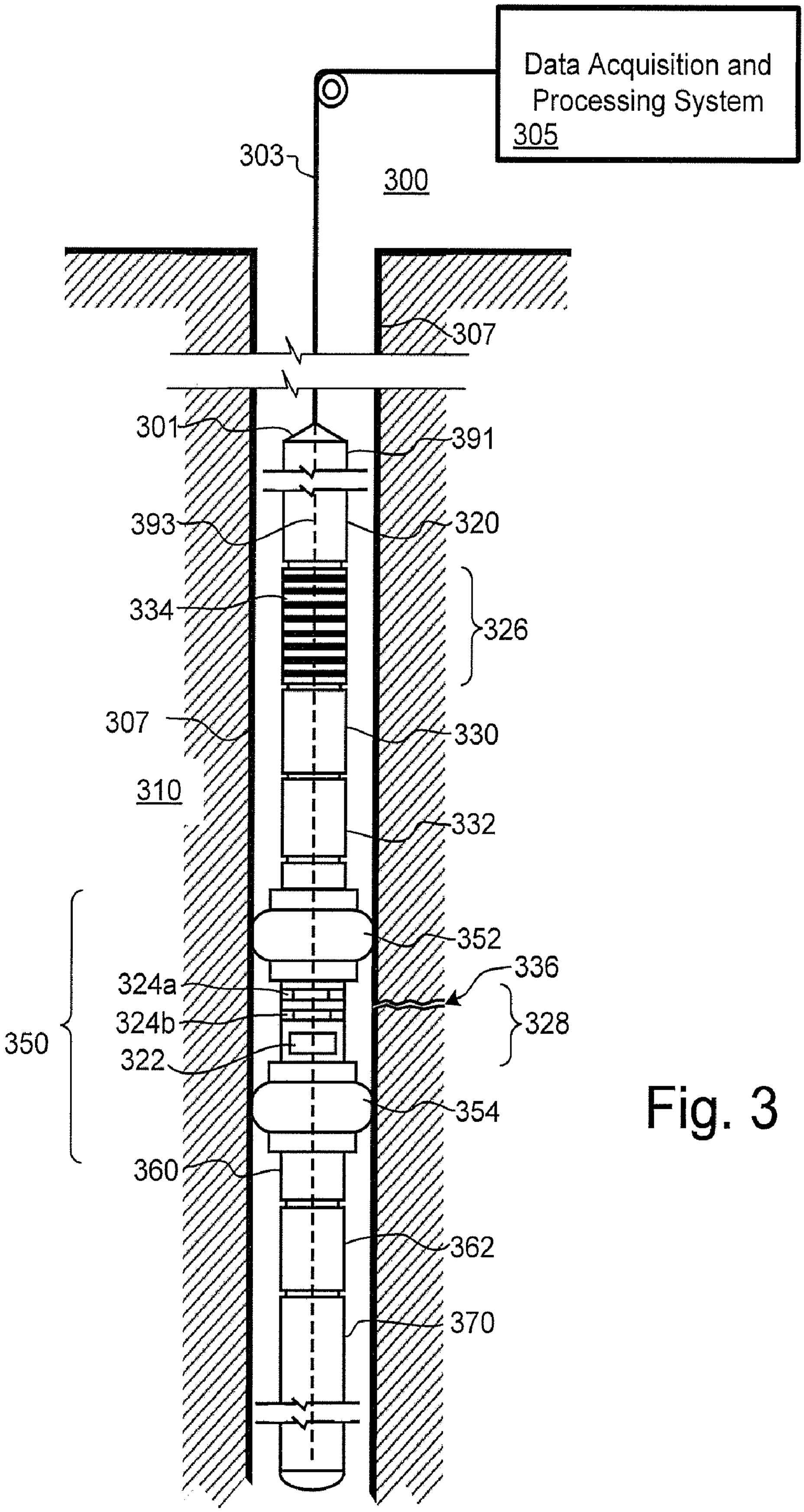
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Fig. 3

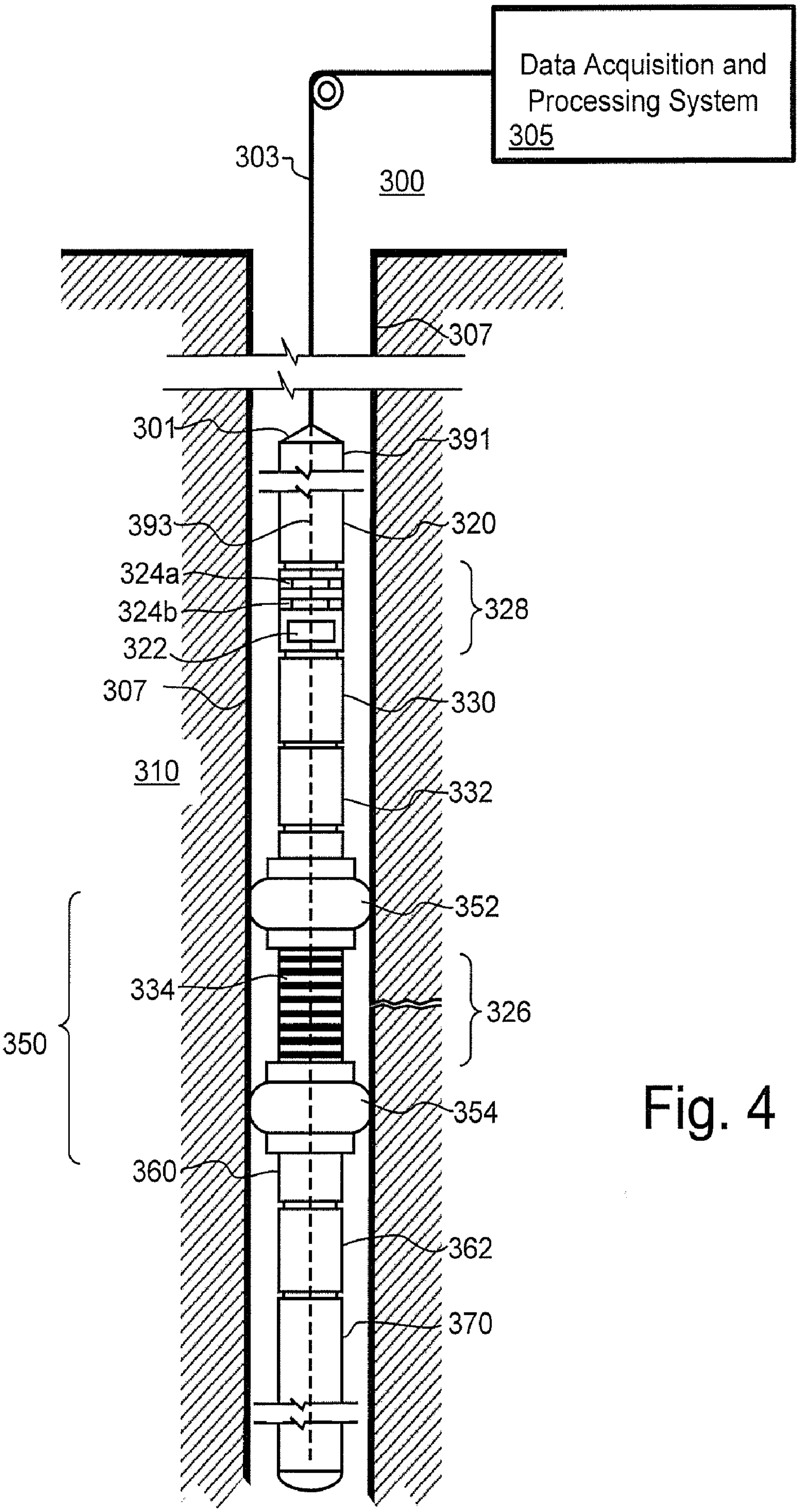
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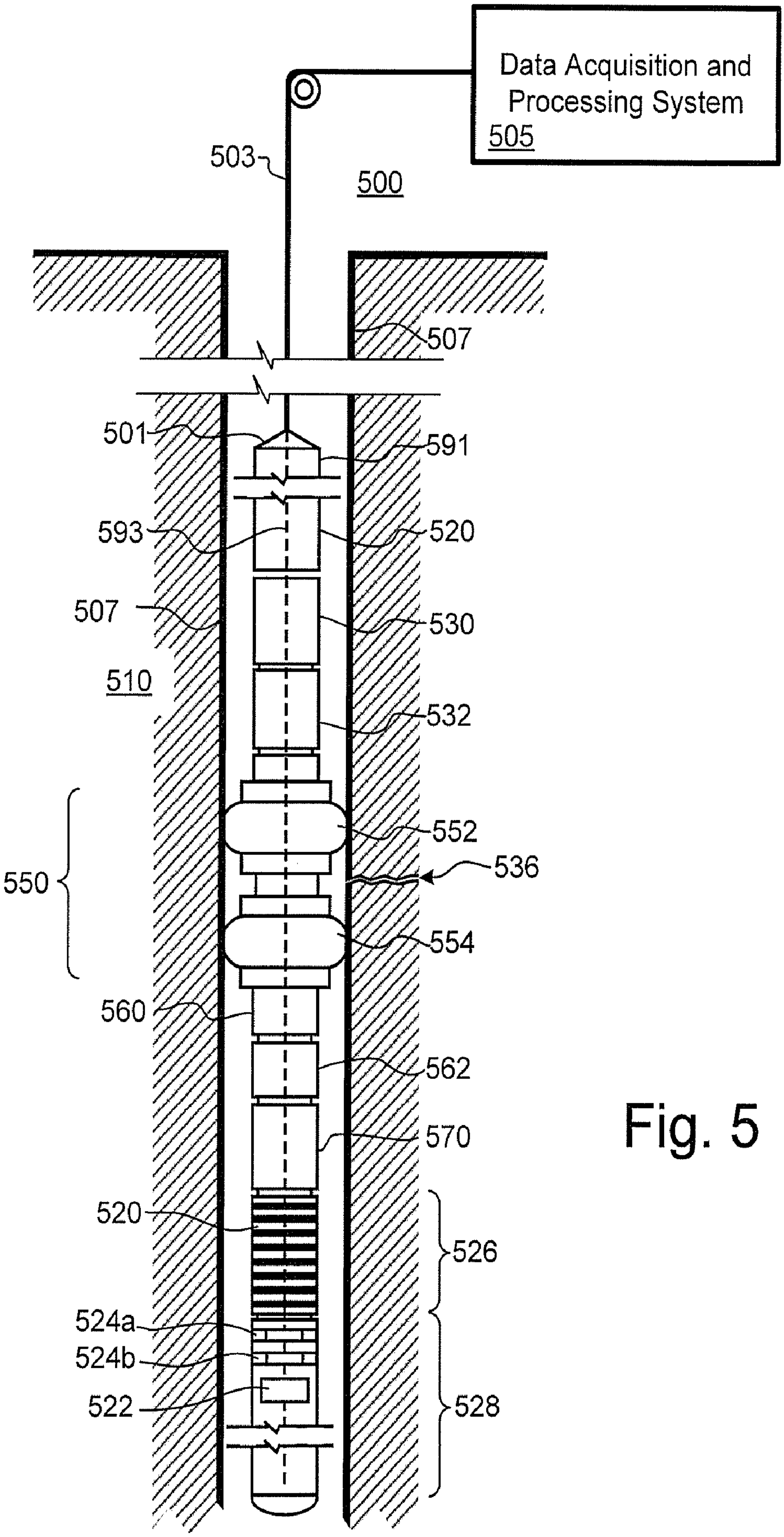
Fig. 4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524b
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Fig. 5

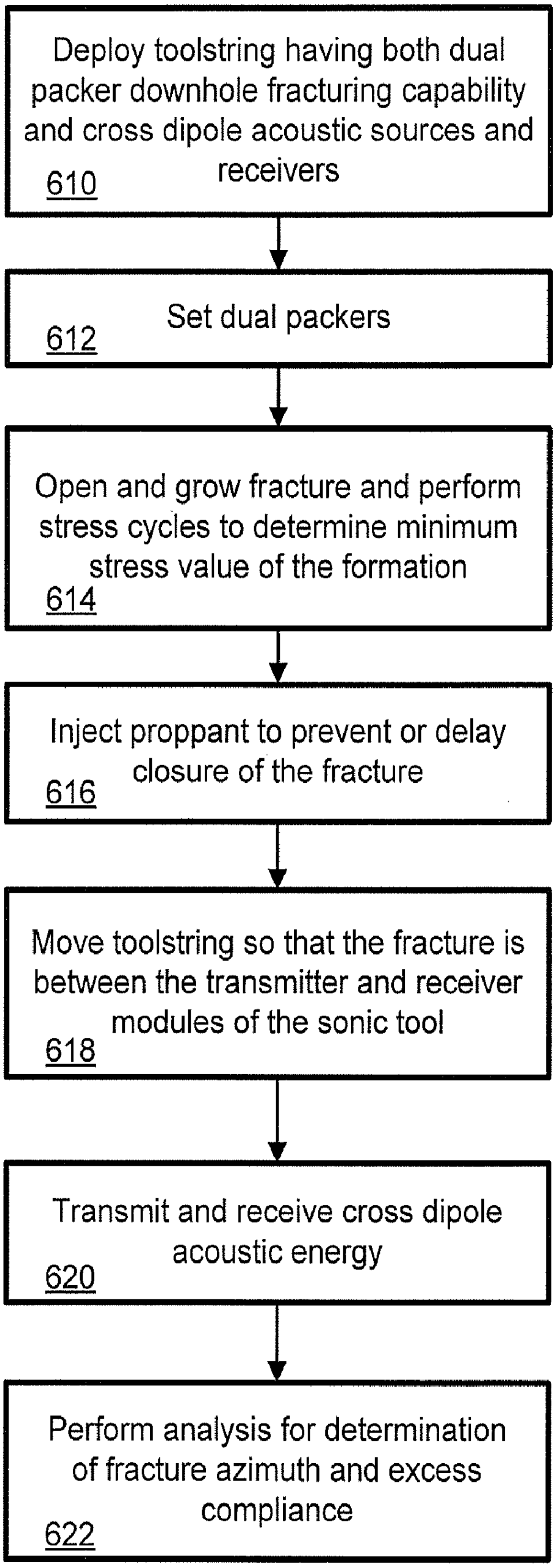

Deploy toolstring having both dual packer downhole fracturing capability and cross dipole acoustic sources and receivers
610
Set dual packers
612
Open and grow fracture and perform stress cycles to determine minimum stress value of the formation
614
Inject proppant to prevent or delay closure of the fracture
616
Move toolstring so that the fracture is between the transmitter and receiver modules of the sonic tool
618
Transmit and receive cross dipole acoustic energy
620
Perform analysis for determination of fracture azimuth and excess compliance
622

Fig. 6

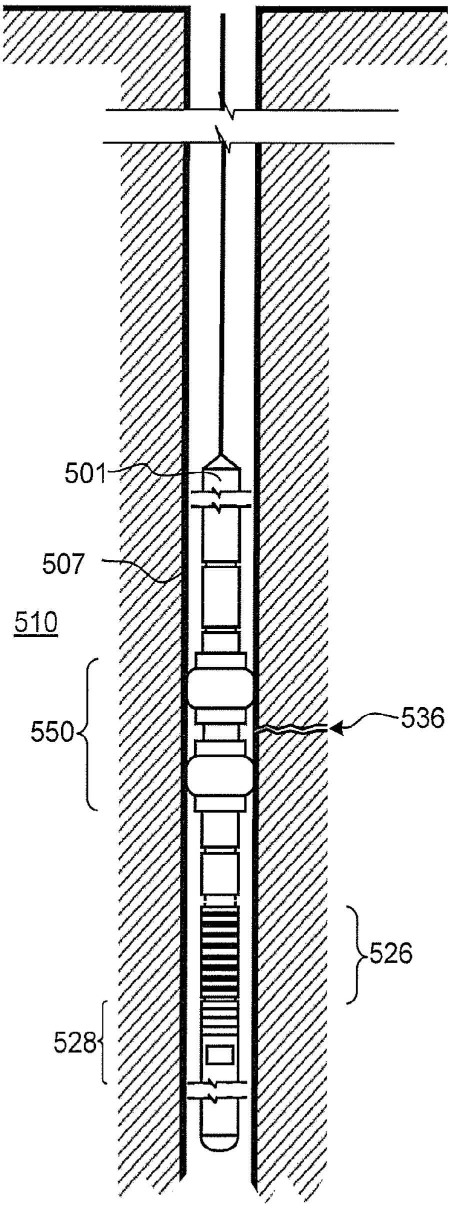


Fig. 7a

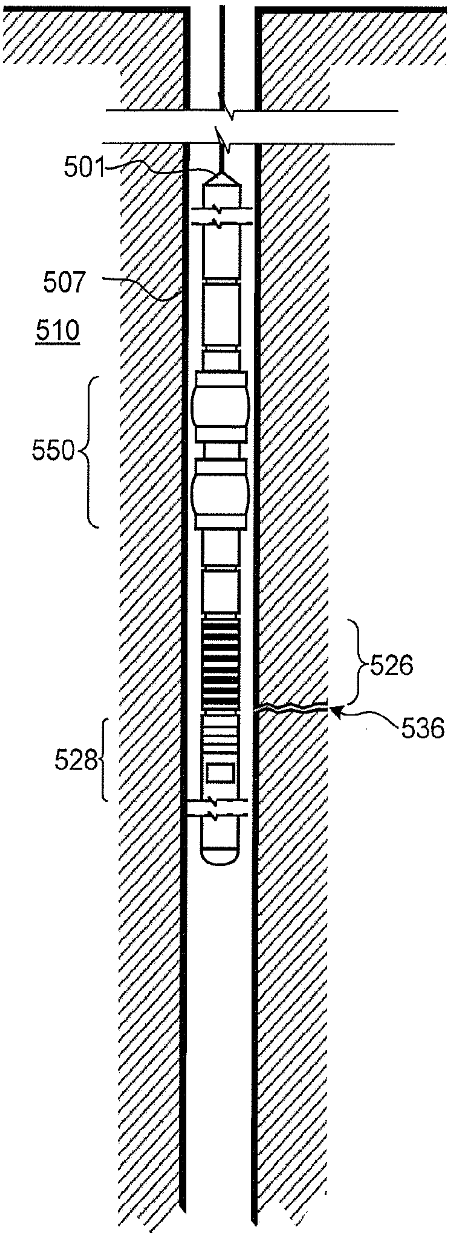
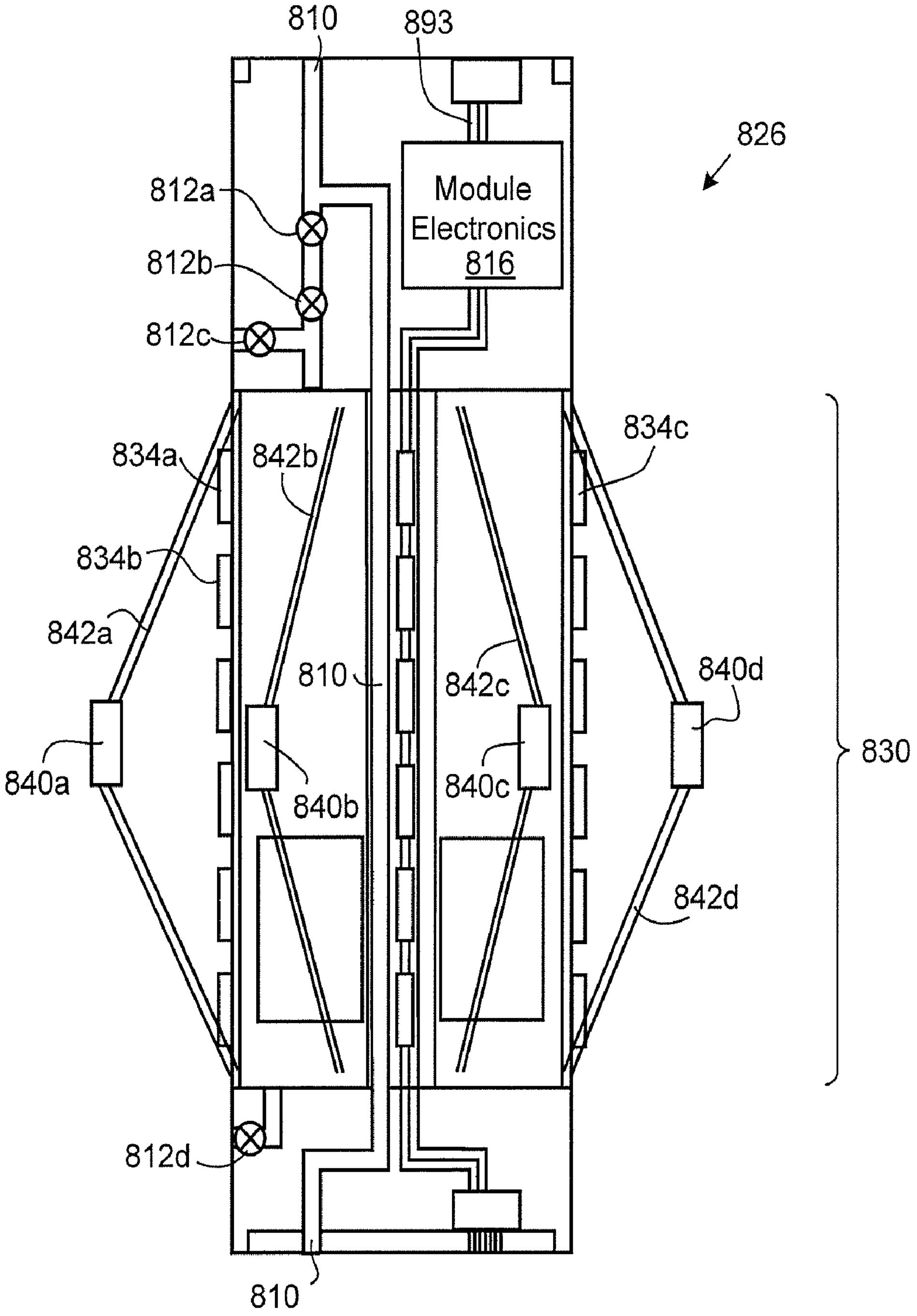


Fig. 7b


810
893
826
812a
Module
Electronics
816
812b
812c
834a
842b
834c
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840d
830
840a
840b
840c
842d
812d
810

Fig. 8

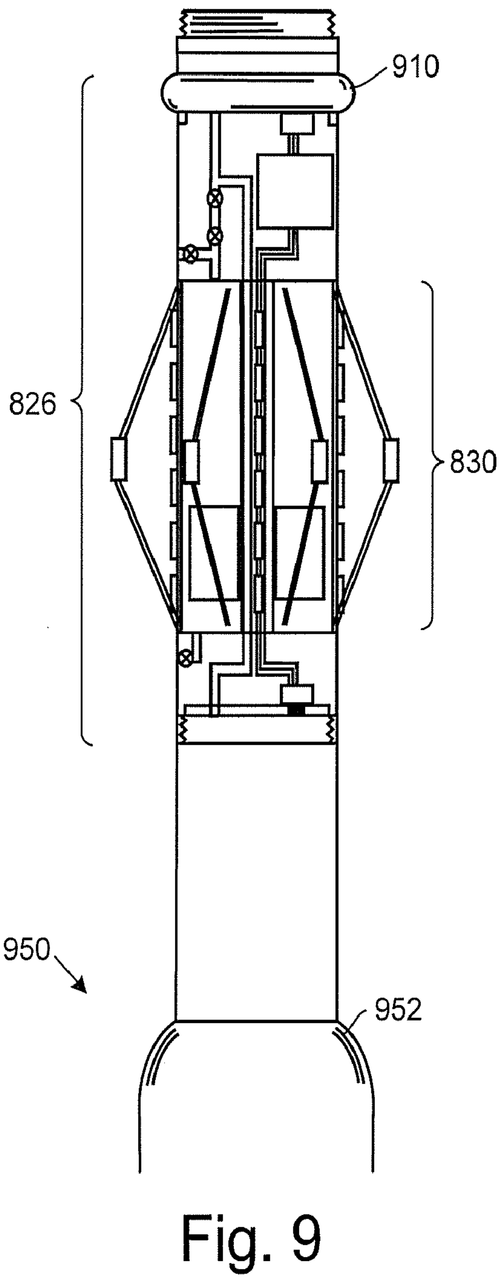

Fig. 9

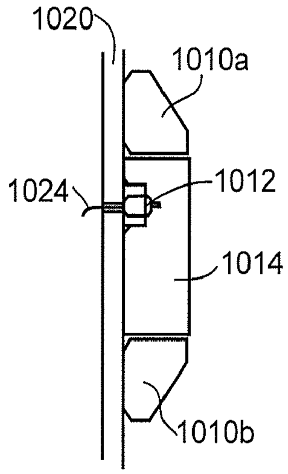

Fig. 10

# MICROHYDRAULIC FRACTURING WITH DOWNHOLE ACOUSTIC MEASUREMENT

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This patent application is a continuation-in-part of International Patent Application PCT/US08/87970, filed Dec. 21, 2007, which is incorporated by reference herein.

## BACKGROUND OF THE INVENTION

**[0002]** 1. Field of the Invention

**[0003]** This patent specification relates to downhole acoustic measurements in connection with downhole fluid sampling and testing. More particularly, this patent specification relates to systems and methods for making and analyzing acoustic measurements in combination with a downhole hydraulic fracturing tool system.

**[0004]** 2. Background of the Invention

**[0005]** In the oilfield service industry, characterizing commercially viable reservoirs of hydrocarbons is a main objective of well logging services. Downhole sampling and testing tools such as the Modular Dynamic Formation Tester (MDT) from Schlumberger are used during the well logging phase to gain a more direct assessment of the production characteristics of the accumulation. In one common configuration, the MDT is arranged with dual packers set against the borehole wall, thereby creating an isolated fluid interval in the annulus bounded by the tool outer surface, the borehole wall, and the two inflatable packers. Additional modules within the MDT enable controlled changes in pressure and flow in the interval.

**[0006]** In some types of testing operations, rapid changes in pressure sometimes occur. For example, in a microhydraulic fracturing test, the interval is pressurized by pumping fluid into the annulus until a tensile fracture begins. The initiation is recorded by a breakdown on a pressure-vs-time record sampled at about one sample per second. It is desirable to evaluate these rapid changes in greater detail. Further detail of acoustic measurements during microhydraulic fracturing testing and in connection with other downhole sampling and testing tool systems is disclosed in International Patent Application PCT/US08/87970, filed Dec. 21, 2007 which is incorporated by reference herein. It is desirable to farther improve the evaluations of the formation when performing microhydraulic fracturing testing.

## SUMMARY OF THE INVENTION

**[0007]** According to embodiments, system for measuring acoustic signals in a borehole during a fracturing operation is provided. The system includes a downhole toolstring designed and adapted for deployment in a borehole formed within a subterranean rock formation. A downhole rock fracturing tool forms part of the toolstring, and is designed and adapted to open and propagate a fracture in the subterranean rock formation. One or more acoustic sources are mounted to the toolstring, and are designed and adapted to transmit acoustic energy into the subterranean rock formation. One or more acoustic sensors are also mounted to the toolstring, and are designed and adapted to measure part of the acoustic energy traveling through the subterranean rock formation.

**[0008]** According to embodiments, a method for measuring acoustic signals in a borehole during a fracturing operation is provided. The method includes positioning a downhole toolstring in a borehole formed within a subterranean rock formation; inducing fracturing in rock formation using a rock fracturing tool forming part of the toolstring; transmitting acoustic energy into the rock formation using one or more acoustic sources mounted to the toolstring; and measuring acoustic energy traveling through the rock formation using one or more acoustic sensors mounted to the toolstring.

**[0009]** Further features and advantages of the invention will become more readily apparent from the following detailed description when taken in conjunction with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0010]** The present invention is further described in the detailed description which follows, in reference to the noted plurality of drawings by way of non-limiting examples of exemplary embodiments of the present invention, in which like reference numerals represent similar parts throughout the several views of the drawings, and wherein:

**[0011]** FIG. **1** shows a downhole system for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling tool, according to embodiments;

**[0012]** FIG. **2** shows a downhole system for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling tool, according to embodiments;

**[0013]** FIG. **3** shows a downhole system for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling tool, according to other embodiments;

**[0014]** FIG. **4** shows a downhole system for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling tool, according to further embodiments;

**[0015]** FIG. **5** shows a downhole system for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling tool, according to yet further embodiments;

**[0016]** FIG. **6** is a flow chart showing steps in running an system as shown in FIG. **5**, according to embodiments;

**[0017]** FIGS. **7***a* and **7***b* show repositioning of a downhole system such as shown in FIG. **5**, according to some embodiments;

**[0018]** FIG. **8** shows further detail of a receiver module for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling tool, according to some embodiments;

**[0019]** FIG. **9** shows the receiver module of FIG. **8** mounted within a microhydraulic fracturing and fluid sampling tool, according to embodiments; and

**[0020]** FIG. **10** shows further detail of an acoustic sensor mounted on a receiver module, according to some embodiments.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

**[0021]** The particulars shown herein are by way of example and for purposes of illustrative discussion of the embodiments of the present invention only and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the present invention. In this regard, no attempt is made to show structural details of the present invention in more detail than is necessary for the fundamental understanding of the present invention, the description taken with the drawings making apparent to those skilled in the art how the several forms of the present invention may be embodied in practice. Further, like reference numbers and designations in the various drawings indicated like elements.

**[0022]** It has been found that by making and properly recording acoustic and/or micro-acoustic frequency measurements, in-situ evaluations of rock mechanical properties and environmental stress can be performed. For example, by monitoring changes in the rock's acoustic response before, during and/or after the creation of a mini-hydraulic fracture, such evaluations can be made. According to embodiments, evaluating minimum stress direction stress and estimation of hydraulic fracture compliance by detecting changes in acoustic propagation can be accomplished using a combination of the mini-hydraulic fracturing tool such as Schlumberger's MDT tool, and an acoustic tool having cross dipole sources and receivers, such as Schlumberger's Sonic Scanner tool. In addition, the combination of known stress test procedures and an acoustic monitoring device can be used to get a more accurate closure pressure time to estimate the magnitude of the minimum stress.

**[0023]** When a fracture in a rock formation is induced by hydraulic fracturing (or drilling) process, the fracture azimuth is related to stress directions. Acoustic tool such as Schlumberger's Sonic Scanner tool can be used to detect fracture azimuth by looking for changes in cross-dipole shear anisotropy due to the induced or natural fracture. See, e.g. Prioul, R., C., Signer, A., Boyd, A., Donald, R., Koepsell, T., Bratton, D., Heliot, X., Zhan, 2007, "Discrimination of fracture and stress effects using image and sonic logs hydraulic fracturing design," The Leading Edge, September 2007; and Prioul, R., A., Donald, R., Koepsell, Z. El Marzouki, T., Bratton, 2007, "Forward modeling of fracture-induced sonic anisotropy using a combination of borehole image and sonic logs," Geophysics, Vol. 72, pp. E135-E147, both of which are incorporated by reference herein. Furthermore, acoustic data from a tool such as Schlumberger's Sonic Scanner can be used to estimate the fracture compliance property required to assess area of fracture and farther geomechanical analysis. See, e.g. U.S. Pat. No. 7,457,194; and Prioul, R., J. Jocker, P. Montaggioni, L. Escare, "Fracture compliance estimation using a combination of image and sonic logs," SEG 2008, both of which are incorporated by reference herein.

**[0024]** According to embodiments, the ability is provided to detect mechanical and acoustic changes depending on the stress state and the fracture adding excess compliance to the rock system at the time the log is run (after the pressure has returned to equilibrium). According to some embodiments, the effect is enhanced, and hence, the measurement made more robust, by making the acoustic measurements while the fracture is still held open by the annular pressure in the MDT interval. According to other embodiments, the acoustic measurements are made while the fracture is held open by a proppant material that is significantly compliant in shear. Moreover, by measuring the acoustic response before and during fracture opening, the data can be analyzed to determine complex fracture trajectories and estimate hydraulic fracture compliances. For instance, early in the fracture growth the hoop stress dominates and the fracture growth is responsive to hoop stress geometries. The corresponding interpretation determines the direction and geometry of the fracture subject to this near wellbore condition. As the fracture continues to grow, differential analysis of the acoustic signature coupled with previous determinations of the characteristics of the (growing) fracture enables the evolution of the fracture to be determined.

**[0025]** Various embodiments are described herein, with many having the following components in common:

**[0026]** 1. A cross-dipole transmitter (e.g. a vibration-generating device capable of creating vibration with mirror-antisymmetry with respect to either of two mutually orthogonal axial planes) such as the transmitter section of Schlumberger's Sonic Scanner tool;

**[0027]** 2. A fracturing device (FD), such as the dual-packer MDT tool from Schlumberger, capable of generating, in an axisymmetric way, pressure sufficient to initiate and grow a fracture in an isolated interval of borehole; and

**[0028]** 3. A cross-dipole receiver (e.g. a vibration-sensing device capable of detecting vibration with mirror-antisymmetry with respect to either of two mutually orthogonal axial planes) such as the receiver section of Schlumberger's Sonic Scanner tool.

**[0029]** FIG. **1** shows a downhole system for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling tool, according to embodiments. Wireline logging system **100** is shown including multiple tools for taking geophysical measurements. Wireline **103** is a power and data transmission cable that connects the tools to a data acquisition and processing system **105** on the surface. The tools connected to the wireline **103** are lowered into a well borehole **107** to obtain measurements of geophysical properties for the surrounding subterranean rock formation **110**. The wireline **103** supports tools by supplying power to the tool string **101**. Furthermore, the wireline **103** provides a communication medium to send signals to the tools and to receive data from the tools.

**[0030]** The tools, sometimes referred to as modules are typically connected via a tool bus **193** to telemetry unit **191** which is turn is connects to the wireline **103** for receiving and transmitting data and control signals between the tools and the surface data acquisition and processing system **105**. Commonly, the tools are lowered to a particular depth of interest in the borehole and are then retrieved by reeling-in by the data acquisition and processing system **105**. For sampling and testing operations, such as Schlumberger's MDT tool, the tool is positioned at location and data is collected while the tool is stationary and sent via wireline **103** to data acquisition and processing system **105** at the surface, usually contained inside a logging truck or logging unit (not shown).

**[0031]** Electronic power module **120** converts AC power from the surface to provide DC power for all modules in the tool string **101**. Pump out module **130** is used to pump unwanted fluid, for example mud filtrate, from the formation to the borehole, so that representative samples can be taken from formation **110**. Pump out module **130** can also be used to pump fluid from the borehole into the flowline for inflating packers in module containing inflatable packers. Pump out module **130** can also be configured to transfer fluid from one part element of the tool string to another. Hydraulic module **132** contains an electric motor and hydraulic pump to provide hydraulic power as may be needed by certain modules. The tool string **101** can also include other sensor such as a strain gauge and a high resolution CQG gauge. Examples of a fluid sampling system using probes and packers are depicted in U.S. Pat. Nos. 4,936,139 and 4,860,581 where are incorporated by reference herein.

**[0032]** Dual-packer module **150** includes an upper inflatable packer element **152**, lower packer element **154**, valve body **160** and electronics **162**. Inflatable packer elements **152** and **154** seal against the borehole wall **107** to isolate an interval of the borehole. Pumpout Module **130** inflates the packers with wellbore fluid. The length of the test interval (i.e., the distance between the packers) about 3.2 ft (0.98 m) and can be extended by inserting spacers between the packer elements. The area of the isolated interval of the borehole is about many orders of magnitude larger than the area of the borehole wall isolated by a probe. Dual-packer module **150** can be used to perform micro-hydraulic fracturing that can be pressure tested to determine the minimum in situ stress magnitude. A fracture, such as fracture **136**, is created by pumping wellbore fluid into the interval between the inflatable packer elements. Below dual-packer module **150** are one or more sample chamber units **170** for holding fluid samples collected downhole.

**[0033]** According to embodiments, tool string **101** is provided with one or more acoustic transmitters and receivers for making acoustic measurements in connection with downhole fluid sampling and or testing. Transmitter module **128** can be a transmitter section of a wireline deployable sonic tool such as from the Sonic Scanner Tool from Schlumberger. Transmitter module **128** includes one or more monopole acoustic transmitters **122** that can produce strong pressure pulses or "clicks" generating clear P- and S-waves, from low frequency Stoneley mode to high frequency energy useful for some types of evaluations. Transmitter module **128** also includes two dipole transmitters **124*a*** and **124*b***, which essentially are shaking devices, each consisting of an electromagnetic motor mounted in a cylinder suspended in the tool housing. The dipole sources generate a high-pressure dipole signal without inducing significant vibration in the tool housing. The dipole sources **124*a*** and **124*b*** are oriented orthogonally with respect to each other, such that one vibrates in line with the tool reference axis and the other at 90 degrees to the axis. The dipole sources generate strong flexural modes that propagate up and down the borehole and also into the formation to different depths that depend on their frequencies. According to embodiments, the dipole sources **124*a*** and **124*b*** are designed generate frequencies in a sweep from about 300 Hz to 8 kHz.

**[0034]** According to some embodiments, the transducer elements of sources **124*a*** and **124*b*** are arcuate shaped and are designed an arranged such that they can be excited separately in a selected pattern to effectively excite other acoustic modes, such as quadrupole and higher-order modes. According to some embodiments, for example, each source **124*a*** and **124*b*** includes four-quadrant arcuate shaped members which are operated to generate quadrupole mode acoustic energy into the wellbore and rock formation. For further description of suitable transducer elements including arcuate shaped transducers for generating monopole, dipole, quadrupole and high-order modes, see e.g. U.S. Pat. No. 7,460,435, U.S. Pat. No. 7,364,007, and U.S. Patent Application Publication No. 2006/0254767, each of which are incorporated by reference herein.

**[0035]** The receiver module **126** is a multi-pole receiver unit such as the receiver section of the Sonic Scanner Tool from Schlumberger. Receiver module **126** includes a number, for example **13**, of axial receiver stations **134** in a 6 foot (1.8 meter) receiver array. Each receiver station includes eight azimuthally distributed acoustic receivers, placed every 45 degrees for a total of **104** sensors on module **126**. The receiver module is preferably constructed using a central mandrel having a mass-spring structure. For further details of a suitable acoustic transmitter and receiver modules having mass-spring structure and a central mandrel, see e.g. U.S. Pat. No. 7,336,562, and Franco et. al. "Sonic Investigations In and Around the Borehole," Oilfield Review, Spring 2006, pp. 16-45, each of which are incorporated herein by reference.

**[0036]** According to some embodiments, a geopositioning and inclinometry tool **180** is also included in toolstring **101**. Tool **180** includes both a three-axis inclinometer and a three-axis magnetometer to make measurement for determining tool orientation in terms of three parameters: tool deviation, tool azimuth an relative bearing. According to some embodiments, a tool such as Schlumberger's General Purpose Inclinometry Tool (GPIT) is used for tool **180**. The measurements from tool **180** can be used for orientation of the acoustic sensors. Although not shown, it is understood that a geopositioning and inclinometry tool such as described herein can be included in the embodiments described with respect to FIGS. **2-5** below.

**[0037]** Note that unlike many commercially used acoustic tools such as Schlumberger's Sonic Scanner Tool, the transmitter module **128** does not have to be synchronized with the receiver module **126**. Additionally, as long as the orientation of the transceiver module **128** is not changed during the measurement procedure, the tool orientation need to be controlled or known. Preferably, the orientation of the receiver module **126** is known, and the receiver module **126** is capable of listening continuously or repeatedly with a substantial duty cycle. Also, according to some embodiments, the source time signature is controlled and known with enough precision to allow the received signal to be stacked for noise reduction and processed to determine relative orientation of the source and receiver dipoles. It has been found to be sufficient, for example, to have alternating pulses in the two dipole orientations repeated continuously with a precisely known delay between successive pulses. According to alternative embodiments, m-sequences, sweeps, or chirps are used.

**[0038]** According to some embodiments, source dipoles can be denoted SA and SB. Receiver dipoles can be denoted Ra, Rb, and are not assumed to be parallel with SA, SB. The source firing schedule should alternate long (for example, **10** second) repetitions of SA and SB, followed by interleaved repetitions with a precisely controlled delay. Since the source firing schedule is known, the long states (LSA, LSB) can be known and separated timewise. Receiver states Ra and Rb are separate channels in the recording. Thus the total recorded signal during the long states can be partitioned into four distinct components LSARa, LSARb, LSBRa, LSBRb. Signal energy (sum of squared signal amplitude) from these components are then analyzed using known methods (for example, the Alford Rotation method) to determine rotation unit vectors to be used to minimize cross-energy.

**[0039]** If the initial state of the rock is Transversely Isotropic with its symmetry axis aligned to the borehole, this minimization will only depend on the relative angle between source and receiver rotations, which will be a measure of the orientation of the source. In an orthorhombic initial state (as can be expected with unequal horizontal stresses), the minimum will only be achieved when the receivers are rotated to align to the orthorhombic stress symmetry planes and the sources are rotated to align with the receivers.

**[0040]** After rotation, the received signal in the interleaved data will show delays between repetitions that are slightly large when alternating from slow to fast directions and slightly small when alternating from fast to slow and hence can be used to determine which are the fast and slow shear directions. Without a time synchronization between source and receiver, absolute traveltime will not be directly measureable. However, since velocity across the receiver array can be measured, equations requiring a reference traveltime can use a reference traveltime obtained by dividing the known Transmitter/Receiver spacing by this measured velocity at the receiver. Note that the determination of relative source orientation need only be performed once.

**[0041]** As the fracture is created and grown, the azimuthal anisotropy becomes larger both in the energy difference and time difference between fast and slow directions. Time-lapse processing, in which baseline waveforms are subtracted to enhance the ability to see slight changes or drifts, are useful here. Time reference for this subtraction may be obtained either by aligning on some detected feature in the waveforms, or by maximizing cross-correlation, or by relying upon the known, precise repetition rate of the source.

**[0042]** FIG. **2** shows a downhole system for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling, according to embodiments. The system of FIG. **2** is very similar to that of FIG. **1** with like reference numbers used for the same modules. However in the embodiment of FIG. **2** the positions of the transmitter module **128** and the receiver module **126** on toolstring **101** are switched such that the transmitter module **128** is located above the dual packer module **150** and the receiver module **126** is located below dual packer module **150**.

**[0043]** FIG. **3** shows a downhole system for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling tool, according to other embodiments. Similar to the systems shown in FIGS. **1-2**, wireline logging system **300** includes multiple tools for taking geophysical measurements. Wireline **303** is a power and data transmission cable that connects the tools to a data acquisition and processing system **305** on the surface. The tools connected to the wireline **303** are lowered into a well borehole **307** to obtain measurements of geophysical properties for the surrounding subterranean rock formation **310**. The wireline **303** supports tools by supplying power to the tool string **301**. Furthermore, the wireline **303** provides a communication medium to send signals to the tools and to receive data from the tools.

**[0044]** The tools are connected via a tool bus **393** to telemetry unit **391** which is turn is connects to the wireline **303** for receiving and transmitting data and control signals between the tools and the surface data acquisition and processing system **305**. The tool is positioned at a location and data is collected while the tool is stationary and sent via wireline **303** to data acquisition and processing system **305** at the surface, usually contained inside a logging truck or logging unit (not shown). Similar to the system shown in FIG. **1**, electronic power module **320**, pump out module **330**, and hydraulic module **332** are provided.

**[0045]** Tool string **301** also includes a receiver module **326**, which is similar to module **126** shown and described with respect to FIG. **1**. Receiver module **326** includes a number, for example 13, of axial receiver stations **334** in a 6 foot (1.8 meter) receiver array, and each receiver station includes eight azimuthally distributed acoustic receivers, placed every 45 degrees.

**[0046]** Dual-packer module **350** includes an upper inflatable packer element **352**, lower packer element **354**, valve body **360** and electronics **362**. Inflatable packer elements **352** and **354** seal against the borehole wall **307** to isolate an interval of the borehole. Pumpout Module **330** inflates the packers with wellbore fluid. Dual-packer module **350** can be used to perform micro-hydraulic fracturing that can be pressure tested to determine the minimum in situ stress magnitude. A fracture, such as fracture **336** is created by pumping wellbore fluid into the interval between the inflatable packer elements. The packer module **350** includes an autonomous acoustic source **328**. Source **328** is similar to transmitter module **128** shown and described with respect to FIG. **1**, and includes one or more monopole acoustic transmitters **322** as well as two multi-pole (e.g. dipole or quadrupole) transmitters **324***a* and **324***b*. According to embodiments, source **328** is autonomous and is programmed to fire on a precise regular schedule while using measuring the acoustic response using receiver module **326**. These acoustic measurements are carried out preferably before, during and after the formation of fracture **336**. Below dual-packer module **350** are one or more sample chamber units **370** for holding fluid samples collected downhole.

**[0047]** FIG. **4** shows a downhole system for making acoustic measurements with downhole microhydraulic fracturing and fluid sampling, according to further embodiments. The system of FIG. **4** is very similar to that of FIG. **3** with like reference numbers used for the same modules. However in the embodiment of FIG. **4** the positions of the source **328** and the receiver module **326** on toolstring **301** are switched such that source **328** is located above the dual packer module **350** and the receiver module **326** is located between the packers of dual packer module **350**.

**[0048]** FIG. **5** shows a downhole system for making acoustic measurements with downhole microhydraulic fracturing and fluid sampling, according to yet further embodiments. Similar to the systems shown in FIGS. **1-4**, wireline logging system **500** includes multiple tools for taking geophysical measurements. Wireline **503** connects the tools to a data acquisition and processing system **505** on the surface. The tools connected to the wireline **503** are lowered into a well borehole **507** to obtain measurements of geophysical properties for the surrounding subterranean rock formation **510**. The wireline **503** supports tools by supplying power to the tool string **501**, and provides a communication medium to send signals to the tools and to receive data from the tools. The tools are connected via a tool bus **593** to telemetry unit **591** which is turn is connects to the wireline **503**. The tool is positioned at a location and data is collected while the tool is stationary and sent via wireline **503** to data acquisition and processing system **505** at the surface. Similar to the systems shown in FIGS. **1-4**, electronic power module **520**, pump out module **530**, and hydraulic module **532** are provided.

**[0049]** Dual-packer module **550** includes an upper inflatable packer element **552**, lower packer element **554**, valve body **560** and electronics **562**. Inflatable packer elements **552** and **554** seal against the borehole wall **507** to isolate an interval of the borehole. Pumpout Module **530** inflates the packers with wellbore fluid. Dual-packer module **550** can be used to perform micro-hydraulic fracturing that can be pressure tested to determine the minimum in situ stress magnitude. A fracture, such as fracture **536** is created by pumping wellbore fluid into the interval between the inflatable packer elements. Below dual-packer module **550** are one or more sample chamber units **570** which can be used for holding fluid samples collected downhole. According to some embodiments, sample chamber units **570** can also be used to hold proppant material which is pumped into the packed-off interval and into the fracture **536**, as will be described in further detail herein.

**[0050]** Tool string **501** also includes a receiver module **526**, which is similar to module **126** shown and described with respect to FIG. **1**. Receiver module **526** includes a number, for example **13**, of axial receiver stations **534** in a 6 foot (1.8 meter) receiver array, and each receiver station includes eight azimuthally distributed acoustic receivers, placed every 45 degrees. Tool string **501** also includes a transmitter module **528** is similar to transmitter module **128** shown and described with respect to FIG. **1**. Transmitter module **528** includes one or more monopole acoustic transmitters **522** as well as two multi-pole (e.g. dipole or quadrupole) transmitters **524***a* and **524***b*.

**[0051]** According to some embodiments, stored in one or more of the sample chamber units **570** is a proppant material that is significantly compliant in shear and which can decay with time over a relatively short period.

**[0052]** Examples of a suitable proppant material include: (1) calcined calcium carbonate, which can be dissolved using mild acid; (2) polylactic, polyglycolic acid beads or the like in water, which dissolve at various rates as temperature increases; (3) crystalline sodium chloride in a sodium chloride solution, which can be dissolved by "flowing back" or circulating pure water; and (4) magnesium oxide which can be dissolved by circulating an ammonium chloride solution. According to other embodiments, the fracture **536** is propagated with a resinous material such as polyurethane, epoxy or other curing polymeric material that forms a solid mass after a predetermined time.

**[0053]** FIG. **6** is a flow chart showing steps in running an system as shown in FIG. **5**, according to embodiments. In step **610**, a toolstring having both dual packer downhole fracturing capability and cross dipole acoustic sources and receivers, such as shown in FIG. **5**, deployed downhole. In step **612**, the dual packers are set. In step **614**, the rock fracturing is initiated. After opening and growing the fracture with the fracturing tool module, stress cycles are performed to determine minimum stress value of the formation (i.e. until the fracture exits the hoop stress region and fully enters the far field stress region). In step **616**, proppant material is injected into the fracture to prevent or delay the fracture closure.

**[0054]** In step **618**, the tool combination is shifted so that the fracture is between the transmitter and receiver sections of the sonic tool. In step **620**, the sonic tool transmitters generate dipole acoustic energy and the sonic tool receivers measure the response. In step **622**, an analysis is performed for determination of fracture azimuth and excess compliance. The analysis can be as described, for example, in: Prioul, R., A., Donald, R., Koepsell, Z. El Marzouki, T., Bratton, 2007, Forward modeling of fracture-induced sonic anisotropy using a combination of borehole image and sonic logs, Geophysics, Vol. 72, pp. E135-E147; and Prioul, R., J. Jocker, P. Montaggioni, L. Escare (2008), Fracture compliance estimation using a combination of image and sonic logs, SEG 2008, which is incorporated by reference herein.

**[0055]** According to some embodiments, time-lapse processing, in which baseline waveforms are subtracted to enhance the ability to see slight changes or drifts, and to make evaluations of rock properties at locations further from the borehole than would be possible without such subtraction techniques. Time reference for this subtraction may be obtained either by aligning on some detected feature in the waveforms, or by maximizing cross-correlation, or by relying upon the known, precise repetition rate of the source. For further detail in analyzing the sonic and ultrasonic waveforms, see, U.S. Pat. No. 5,859,811, which is incorporated by reference herein

**[0056]** FIGS. **7***a* and **7***b* show repositioning of a downhole system such as shown in FIG. **5**, according to some embodiments. In FIG. **7***a*, toolstring **501** is positioned such that dual packer module **550** is able to isolate an annular region and create fracture **536**. As described herein, a proppant material is injected into fracture **536** such that the fracture remains open long enough for the toolstring to be repositioned and for acoustic measurements to be made. In FIG. **7***b*, The toolstring **501** is shown repositioned such that the induced fracture **536** is between acoustic transmitter module **528** and acoustic receiver module **526**.

**[0057]** FIG. **8** shows further detail of a receiver module for making acoustic measurements with a downhole microhydraulic fracturing and fluid sampling tool, according to some embodiments. Receiver module **826** includes sensor section **830**. Sensor section **830** includes a number of sensors, including acoustic sensors and 3-axis geophones. A number of acoustic sensors, for example, sensors **834***a* and **834***b* are mounted on the surface of sensor section **830**. In this example, four azimuthally spaced acoustic sensors are mounted in each station, and there are six stations for a total of 24 acoustic sensors on sensor section **830**. Six geophones are also included in sensor section **830**, four geophones are shown in the view of FIG. **8**, namely geophones **840***a*, **840***b*, **840***c* and **840***d*. Each geophone is mounted on an extendable arm so as to be in contact with the borehole wall during measurement. The extendable arms are similar to those used on centralizer arms commonly used in downhole tools. Geophones **840***a*, **840***b*, **840***c* and **840***d* are shown mounted on arms **842***a*, **842***b*, **842***c* and **842***d*, respectively. Each of the geophones are 3-axis and by contacting the borehole wall, they allow for recording of both compressional and shear components of the incident acoustic waves. According to some embodiments, the geophones are also capable of receiving micro-acoustic emissions at ultrasonic frequency.

**[0058]** Flowline **810** allows for fluid communication between other modules of the microhydraulic fracturing and fluid sampling tool which may be located both above and below receiver module **826** as described elsewhere herein. Valves **812***a*, **812***b*, **812***c* and **812***d* may be manual or automatically closed depending on the hydraulic layout of the tool system. Control signals to and data from both the acoustic sensors and geophones on sensor section **830** are sent and received from module electronics **816**. Module electronics **816**, in turn, sends and receives data with the rest of the tool system and with the surface via tool bus **893**.

**[0059]** FIG. **9** shows the receiver module of FIG. **8** mounted within a microhydraulic fracturing and fluid sampling tool, according to embodiments. In the example shown, receiver module **826** is mounted immediately above dual packer module **950** and below other modules such as a pump out module and/or a hydraulic module (not shown) as described in FIG. **1**. According to some embodiments, a bumper guard **910** is provided to protect the sensors on sensor section **830**. The bumper guard **910** is useful, for example, in cases where extendable arms are not used in connection with geophones. Note although the receiver module **830** is shown immediately above the dual packer module **950** in FIG. **8**, the receiver module as described in FIGS. **8** and **9** can be used in other positions and incorporated into other modules as shown and described with respect to FIGS. **1-5** herein.

**[0060]** FIG. **10** shows further detail of an acoustic sensor mounted on a receiver module, according to some embodiments. A sonic detector **1012** is shown mounted on tool housing wall **1020**. A detector housing **1014** surrounds the detector **1012**, which receives control signals and sends data via wire **1024** passing through a small hole in housing **1020**. Additionally, guards **1010***a* and **1010***b* are provided to protect the detector from mechanical damage in the downhole environment.

**[0061]** Whereas many alterations and modifications of the present invention will no doubt become apparent to a person of ordinary skill in the art after having read the foregoing description, it is to be understood that the particular embodiments shown and described by way of illustration are in no way intended to be considered limiting. Further, the invention has been described with reference to particular preferred embodiments, but variations within the spirit and scope of the invention will occur to those skilled in the art. It is noted that the foregoing examples have been provided merely for the purpose of explanation and are in no way to be construed as limiting of the present invention. While the present invention has been described with reference to exemplary embodiments, it is understood that the words, which have been used herein, are words of description and illustration, rather than words of limitation. Changes may be made, within the purview of the appended claims, as presently stated and as amended, without departing from the scope and spirit of the present invention in its aspects. Although the present invention has been described herein with reference to particular means, materials and embodiments, the present invention is not intended to be limited to the particulars disclosed herein; rather, the present invention extends to all functionally equivalent structures, methods and uses, such as are within the scope of the appended claims.

What is claimed is:

**1**. A system for measuring acoustic signals in a borehole during a fracturing operation:

- a downhole toolstring designed and adapted for deployment in a borehole formed within a subterranean rock formation;
- a downhole rock fracturing tool forming part of the toolstring, designed and adapted to open and propagate a fracture in the subterranean rock formation;
- one or more acoustic sources mounted to the toolstring, designed and adapted to transmit acoustic energy into the subterranean rock formation; and
- one or more sensors mounted to the toolstring, designed and adapted to measure part of the acoustic energy traveling through the subterranean rock formation.

**2**. A system according to claim **1** wherein the downhole rock fracturing tool comprises a downhole pumping system mounted to the toolstring and adapted to pump fluid into an annular region defined by at least the toolstring and a wall of the borehole

**3**. A system according to claim **1** wherein the one or more acoustic sources include two multi-pole sources each capable of generating a multi-pole acoustic signal.

**4**. A system according to claim **3** wherein the two multi-pole sources are dipole sources and are mounted such that they are oriented orthogonally with respect to each other.

**5**. A system according to claim **3** wherein the two multi-pole sources are quadrupole acoustic sources.

**6**. A system according to claim **1** wherein the one or more sensors includes one or more geophones mounted to the toolstring, designed and adapted to measure part of the acoustic energy traveling through the subterranean rock formation.

**7**. A system according to claim **6** wherein each geophone is a 3-axis geophone and is mounted on an extendable member such that the geophone can be in direct communication with the borehole wall and shear components of the acoustic energy traveling in the rock formation can be measured.

**8**. A system according to claim **1** wherein the one or more sensors include acoustic sensors that make up an acoustic receiver array including a plurality of receiver stations spaced apart along the axis of the downhole toolstring, and each receiver station including a plurality of azimuthally distributed acoustic sensors at substantially the same axial position.

**9**. A system according to claim **1** wherein the rock fracturing tool and the one or more acoustic sources and sensors are arranged along the axis of the toolstring such that axial positions of the one or more sources are on one side of the location of the rock to be fractured and the axial positions of the one or more receivers are on the other side.

**10**. A system according to claim **1** wherein the one or more sources and the rock fracturing tool are arranged on the toolstring such that the axial positions of the one or more sources and the axial position of the rock to be fractured is substantially the same.

**11**. A system according to claim **1** wherein the one or more sources and the rock fracturing tool are arranged on the toolstring such that the axial positions of the one or more receivers and the axial position of the rock to be fractured is substantially the same.

**12**. A system according to claim **1** wherein the fracturing tool, sources and receivers are arranged on the toolstring such that following an induced fracturing of rock, the toolstring can be repositioned so that the induced fracture is between the source and receiver.

**13**. A system according to claim **13** wherein the fracturing tool includes a pumping system adapted to inject proppant material into the induced fracture such that closure of the induced fracture is prevented or delayed.

**14**. A system according to claim **14** wherein the proppant material includes one or more materials selected from the group consisting of calcined calcium carbonate, polyester beads, crystalline sodium chloride, and magnesium oxide.

**15**. A system according to claim **14** wherein the fracture is propagated with a resinous material that forms a solid mass after a predetermined time.

**16**. A system according to claim **1** further comprising a processor adapted to evaluate one or more properties of the rock formation, and the evaluation is based at least in part on the acoustic energy traveling through the rock formation as measured by the one or more sensors.

**17**. A system according to claim **17** wherein the one or more properties includes direction and speed of sonic propagation within the rock formation.

**18**. A system according to claim **17** wherein the one or more properties includes far field stress and/or fracture properties.

**19**. A system according to claim **17** wherein the one or more properties are for locations having a distance from the borehole wall of greater than the diameter of the borehole.

**20**. A system according to claim **17** wherein processor is programmed to combine data based on measurements of acoustic energy after an induced rock fracture with reference data based on measurements of acoustic energy prior to and/or during the induction of rock fracturing.

**21**. A system according to claim **1** wherein the rock fracturing tool comprises a first and second member designed and positioned to seal the region between the toolstring and a wall of the borehole such that an annular region is defined by the tool housing, the borehole wall, and the first and second members.

**22**. A system according to claim **22** wherein the first and second members are expandable packers attached to the tool and making contact with the borehole wall when deployed.

**23**. A system according to claim **23** wherein the one or more sensors are positioned on the toolstring so as to be in primary acoustic communication with locations other than the annular region.

**24**. A system according to claim **23** wherein the one or more receivers are positioned on the toolstring so as to be in primary acoustic communication with locations other than the annular region.

**25**. A system according to claim **1** further comprising an orientation tool for making measurements such that measurements from the one or more sensors can be oriented.

**26**. A method for measuring acoustic signals in a borehole during a fracturing operation, comprising:

positioning a downhole toolstring in a borehole formed within a subterranean rock formation;

inducing fracturing in rock formation using a rock fracturing tool forming part of the toolstring;

transmitting acoustic energy into the rock formation using one or more acoustic sources mounted to the toolstring; and

measuring acoustic energy traveling through the rock formation using one or more sensors mounted to the toolstring.

**27**. A method according to claim **27** wherein the one or more acoustic sources are multi-pole acoustic sources, and the acoustic energy transmitted includes multi-pole acoustic energy.

**28**. A method according to claim **28** wherein the one or more multi-pole acoustic sources include two orthogonally oriented dipole sources and the transmitted acoustic energy includes dipole acoustic energy.

**29**. A method according to claim **28** wherein the one or more multi-pole acoustic sources include one or more quadrupole acoustic sources and the transmitted acoustic energy includes quadrupole acoustic energy.

**30**. A method according to claim **27** wherein the one or more sensors include a plurality of acoustic sensors arranged on the toolstring so as to be capable of detecting multi-pole acoustic energy.

**31**. A method according to claim **27** wherein the one or more sensors include one or more geophones.

**32**. A method according to claim **32** wherein each of the geophones is a 3-axis geophone mounted on a extendable member such that the geophone can be in direct communication with the borehole wall, and wherein the measuring includes measuring shear components of the acoustic energy traveling in the rock formation.

**33**. A method according to claim **27** wherein the rock fracturing tool and the one or more acoustic sources and sensors are arranged along the axis of the toolstring such that axial positions of the one or more sources are on one side of the location of the induced rock fracture and the axial positions of the one or more receivers are on the other side.

**34**. A method according to claim **27** wherein the one or more sources and the rock fracturing tool are arranged on the toolstring such that the that axial positions of the one or more sources and the axial position of the induced rock fracture is substantially the same.

**35**. A method according to claim **27** wherein the one or more sources and the rock fracturing tool are arranged on the toolstring such that the that axial positions of the one or more receivers and the axial position of the induced rock fracture is substantially the same.

**36**. A method according to claim **27** further comprising repositioning the toolstring after inducing the fracturing such that the induced fracture is between the source and receiver.

**37**. A method according to claim **37** further comprising injecting proppant material into the induced fracture such that closure of the induced fracture is prevented or delayed.

**38**. A method according to claim **38** wherein the proppant material includes one or more materials selected from the group consisting of calcined calcium carbonate, polyester beads, crystalline sodium chloride, and magnesium oxide.

**39**. A method according to claim **39** wherein the inducing fracturing includes propagating the fracture with a resinous material that forms a solid mass after a predetermined time.

**40**. A method according to claim **27** further comprising evaluating one or more properties of the rock formation based at least in part on the measuring of acoustic energy.

**41**. A method according to claim **41** wherein the one or more properties includes direction and speed of sonic propagation within the rock formation.

**42**. A method according to claim **41** wherein the one or more properties includes far field stress and/or fracture properties.

**43**. A method according to claim **41** wherein the evaluating comprises combining data based on measurements of acoustic energy after the induced fracturing with reference data based on measurements of acoustic energy prior to and/or during the induced fracturing.

**44**. A method according to claim **29** wherein the transmitting comprises repeatedly generating alternating pulses from each of the two dipole sources with a predetermined delay between successive pulses.

**45**. A method according to claim **27** wherein the fracturing induction comprises sealing an annular region that is a volume bounded by a first sealing member, a second sealing member, the outer surface of the toolstring, and the borehole wall.

**46**. A method according to claim **46** wherein the fracturing further comprises pumping fluid into the annular region so as to significantly increase the fluid pressure in the annular region thereby inducing the fracture.

**47**. A method according to claim **46** wherein the one or more sensors are positioned on the toolstring so as to be in primary acoustic communication with locations other than the annular region.

**48**. A method according to claim **46** wherein the one or more receivers are positioned on the toolstring so as to be in primary acoustic communication with locations other than the annular region.

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