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SUMMARY

Characterizing subsurface structures is crucial for used fuel disposition. It is necessary to apply the-state-of-art geophysical techniques to ensure safe and cost-effective used fuel disposition. This report summarizes the most up-to-date geophysical techniques to achieve this goal, particularly for fault and fracture characterization. These techniques include non-invasive methods that are suitable for the early stage of site characterization, and invasive methods that can be applied when the sites are under development. These methods can provide subsurface mechanical and electrical properties, which can help determine surface structures and rock types. Particularly, these methods can determine various parameters of fault and fracture zones, such as the location, dip, width, and activeness.

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USED FUEL DISPOSITION CAMPAIGN
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1 Introduction

The Used Fuel Disposition Campaign (UFDC) has identified the need to improve and integrate geophysical techniques for characterizing the subsurface characteristics of an area or region to support site screening, selection and characterization (Nutt, 2011). Geophysical techniques can complement existing geologic data and have been used by many countries in the early stages of site screening and selection as a relatively cost-effective and non-invasive method for characterizing large areas of the subsurface. Features that are important to detect in the early stages of site screening, selection and characterization include faults, fractures, presence of fluids and lithologic heterogeneities within the subsurface stratigraphy such as interlayers of different rock types.

This report reviews geophysical methods for detecting and characterizing fault and fracture zones in the subsurface. The methods reviewed include the state-of-the-art seismic and electrical techniques, and other novel techniques such as nanotracers and interwell correlation to understand fluid flow and fracture parameters within rocks.

In the early stage of site characterization when no boreholes are available, characterization techniques that only need to collect data on the surface are preferred. These techniques include seismic methods such as seismic imaging, and seismic full-waveform inversion, and electronic resistivity methods such as electronic resistivity tomography and ground penetrating radar. If there are active geological faults around a site being investigated, natural microearthquake imaging can be used to infer the locations of the faults. Generally, seismic methods have a higher resolution than the electrical methods. Therefore, they can be used as a major tool to characterize the site. Seismic imaging is a good choice to detect the locations of fault and fracture zones and layer interfaces. Seismic illumination analysis can be used to understand the illumination of seismic waves within geologic structures in the deep region. Based on the results of the locations of faults, fractures and layer interfaces, seismic full-waveform inversion can be used to gain quantitative information on subsurface structures. On the other hand, electronic resistivity methods provide independent information of the subsurface. The faults, fractures and layer interfaces often generate signals detectable by electronic resistivity methods. Thus, the electronic resistivity tomography should be able to reconstruct those subsurface features, which can be used as a comparison to results obtained using seismic methods. Ground penetrating radar uses very high-frequency signals. Consequently, the signals only propagate to a depth of tens of feet, although the method is able to obtain a high-resolution image. The result of ground penetrating radar serves as a good *a priori* information for seismic imaging and full-waveform inversion, which can image a much deeper region than the ground radar penetration.

When well drilling is conducted, the methods that require data collected in boreholes can be applied. If water circulation is involved in the site development, the techniques of detecting hydraulic fracturing should be used, such as microseismic imaging and tiltmeter mapping. The activity of hydraulic fracturing will create valuable signals for microseismic imaging and tiltmeter mapping. At this stage, well logging will provide in-situ information about subsurface structures, which will improve the results of seismic imaging and full-waveform inversion. Other methods, vertical seismic profiling, effective stress tensor, in-situ state of stress, nanosensors and interwall correlation, can all be used to evaluate underground geophysical parameters. Most of these methods aim at determining the parameters and activeness of the faults and fractures, which is the most crucial information about a geological site. The widths of the faults and fractures detectable by these methods vary from micrometers to kilometer. The range of detection of these methods is as deep as the boleholes, and covers all the area in between the boleholes. In summary, these methods can provide comprehensive information of fault and fracture zones at a geological site.

2 Seismic methods

Seismic methods probe underground structures using records of ground movements, which are generated by explosion, vibrators, earthquakes and other natural phenomena such as hurricanes and ocean waves. Explosion and vibrators here refer to controlled seismic sources. Controlled seismic sources are widely used in site characterization because they are objective-oriented, and can be designed according to the specific problem to achieve a highest-possible resolution. Naturally generated ground movements helps detect long wavelength characters of fault and fraction zones, but they can hardly be directly used to detect detailed characters for the following two reasons. First, the signals they generate are limited to the low frequency range (< 1 Hz). High-frequency signals are needed to uncover the short wavelength information of subsurface structures. Second, natural phenomenon cannot be controlled. It is difficult to predict when and where they happen. However, some triggered natural seismic sources can be useful for inspecting fault and fraction zones, such as microseismic sources. Microseismic sources are natural sources triggered by human activities like fluid injection for geologic carbon storage. When microseismic events occur around the site to be characterized, they may provide valuable information about the fault and fraction zones at the site.

2.1 Elastic-wave reverse-time migration

Description:

Reverse-time migration becomes a feasible tool in seismic imaging with increasing computing power. The goal of migration is to reconstruct the locations and strengths of subsurface reflectors. Reverse-time migration solves the full-wave equation to backpropagate seismic data into the imaging domain to reconstruct subsurface structures [1].

Elastic-wave reverse-time migration (ERTM) with a wavefield-separation imaging condition has the potential to imaging steep faults [2, 3]. Figure 1 shows a numerical example to demonstrate that the technique can produce a high-resolution image of a vertical fault zone, which is difficult to image using conventional seismic migration methods.

Objective:

Elastic-wave reverse-time migration with a wavefield-separation imaging condition is a promising tool for detect fault zones, particularly for steep faults that are almost impossible to be imaged using conventional seismic migration methods. The detection depth of this method can be several kilometers.

Pros:

Compared with conventional imaging methods, elastic-wave reverse-time migration improves our capability to detect fault and fracture zones.

Cons:

This method can produce a high-resolution reflectivity image, but cannot provide quantitative geophysical properties within fault zones, such as wavespeeds and elastic moduli. The computational cost of this method is higher than conventional seismic migration methods such as Kirchhoff and wave-equation migration methods.

2.2 Seismic illumination analysis

Description:
In a complex geological structure, dim regions of seismic-wave illumination may exist. This phenomenon can be caused by many factors, such as limited acquisition geometry, complex overburden structures, and dip angles of reflectors [4]. This phenomenon can happen to steep faults, where little seismic energy can be reflected back to the surface. Seismic illumination analysis is developed to improve migration images in regions with weak seismic illumination (Fig. 2).

Objectives:
Seismic-wave illumination analysis based on various methods, such as the wave-equation illumination analysis method, can be used to optimize acquisition-survey designs, evaluate the image quality, and improve seismic images such as those of steep faults. The detection depth of this method can be several kilometers.

Pros:
Seismic illumination analysis is target oriented. The analysis can adopt wave-equation-based propagators to calculate wave propagation, and can extract angle-related information from the wavefields. This method can improve images of complex regions, and enhance images of fault zones.

Cons:
Seismic illumination analysis can improve subsurface imaging, but cannot provide quantitative information of fault and fracture zones.

2.3 Diffraction imaging

Description:
Diffraction is defined as the transmission of wave energy along nongeometric ray paths [5]. Diffracted energy is much smaller than reflected energy. As a result, diffracted events are usually ignored in seismic imaging, or treated as noise. Actually, diffraction events contain information that characterizes small-size geological objects such as faults or fractures [6]. Therefore, diffracted energy can be used to image small-size geological objects that are difficult to be resolved by imaging methods using reflected events (Fig.3).

To utilize diffracted energy that has small magnitudes, wave separation has to be conducted to remove the larger-magnitude reflected energy. Many approaches are intended for reflection and diffraction energy separation, such as using moveout properties of seismic waves, or using plane-wave constant p sections, or in dip angle domain [6].

Objectives:
Diffraction imaging aims to utilize small-magnitude diffracted energy to characterize small-size geological objects such as faults or fractures.

Pros:
Compared with imaging methods using reflected wave, diffraction imaging has the potential of imaging small-scale elements of subsurface structures.

Cons:
Diffracted energy is one or even two orders of magnitude smaller than reflected energy. Therefore, one difficulty is the separation of the wavefields.

2.4 Full-waveform inversion

Description:
Full-waveform inversion is becoming a promising tool for quantitatively reconstructing subsurface seismic velocity distributions. Full-waveform inversion is the state-of-the-art of all methods that aim to obtain the underground information. This method utilizes all the information contained in seismic data. Full-waveform inversion was introduced decades ago [7], but had not been widely applied at that time because of the limited computing power, even though the resolve power of this method is appealing. With the exponentially increasing computing power, full-waveform inversion is back to researchers' attention. Moreover, recent developments on the source encoding technique greatly reduce the computational cost, which makes full-waveform inversion feasible for practical applications.

However, full-waveform inversion methods need to be further improved practical applications. For example, when applying conventional full-waveform inversion, one difficulty is that the deep region of a model usually cannot be reconstructed as well as the shallow region. Therefore, the faults, especially deep faults, are hardly resolved clearly. This is because the locations of seismic sources and receivers are confined in the shallow region during active seismic reflection surveys. As a result, the seismic energy is dominant in the shallow part of the model. Using a new full-waveform inversion method with wave-energy-weight gradients, the image of the deep part of the model is significantly improved, and the fault zones can be clearly resolved [8, 9]. This improvement has been demonstrated using synthetic data as shown in Fig. 4.

Objective:
Full-waveform inversion has great potential to determine locations of fault zones and geophysical properties within the fault zones. The detection depth of this method can be several kilometers.

Pros:
Full-waveform inversion has a great resolving power. This method reconstructs not only locations of fault and fraction zones, but also quantitative geophysical properties within the fault and fracture zones.

Cons:
Although full-waveform inversion can provides high-resolution and quantitative images, its computational cost is much higher than seismic migration methods. Three-dimensional full-waveform inversion requires a super computer to solve a realistic problem. Moreover, even though theoretically full-waveform inversion should be able to find the best model that fits data, in practice the inversion may encounter many local minima, which means that the inversion result is better than the initial model but may not be the best possible model.

2.5 Vertical seismic profiling

Vertical seismic profiling acquires seismic data using sources on the surface and receivers within a well. Typically, vertical seismic profiling can acquire seismic data with twice of the frequency of surface seismic reflection data, and consequently improve the imaging resolution.

2.5.1 Using Stoneley waves

Description:
Stoneley waves are interface waves with the largest amplitudes confined to the neighborhood of a plane interface of two elastic media. They can exist at a solid-fluid interface, but can exist at a solid-solid interface only where the shear-wave velocities in the two media are nearly equal [10]. Stoneley waves are a major source of noise in vertical seismic profiles. Strong Stoneley waves are observed at depths where

fractures intersect the borehole. Therefore, Stoneley waves can be used as an indicator of the presence of fracture. Geophysical model can be estimated to predict the amplitude of those Stoneley waves. Furthermore, the Stoneley waves can be presented as a function of certain parameters of fractures, namely, the fracture aperture, the orientation, and the degree of stiffness and roughness of the fracture [11].

Objectives:
Stoneley wave is used to detect and determine the characters of the fractures, such as aperture (width), orientation, stiffness, and roughness. The frequency of seismic waves used in this method is tens to hundreds of Hz. The size of the aperture can be as low as 10^{-6} meters. The detection depth can be as low as the depth of data collection. The application of this method at mirror lake (New Hampshire) detected fractures at depth 44 meters [11].

Pros:
This method can detect fractures with aperture in the size of 10^{-6} meters, which is impossible for other seismic imaging method. Furthermore, this method can find out not only the aperture and orientation of fractures, but also the stiffness and roughness of fractures. The stiffness and roughness of the fracture are difficult to be obtained by other seismic methods.

Cons:
First, this method can only detect fractures that intersect boreholes. Therefore the inspection is restricted within the areas around boreholes. Second, the Stoneley waves can only be generated in certain media configuration, which limits the usage of this method.

2.5.2 Using tube waves

Description:
In a borehole, tube wave is a kind of surface wave that propagates along the axis of the hole. The energy of these waves is confined to the vicinity of the borehole. Such waves exhibit dispersion with phase velocity increasing with the wavelength. At wavelength shorter than the borehole radius, they approach Rayleigh waves. The phase velocity reaches the shear velocity at wavelengths of about three times of the radius [10]. A vertical seismic profiling survey using a hydrophone array provides ideal data for tube wave recording and analysis. The application of the method to a vertical seismic profiling experiment conducted at Kent Cliffs, New York and Hamilton, Massachusetts showed a good consistence with the results obtained by other methods [12].

Objectives:
Tube waves are used to detect and characterize fractures that intersect a borehole. The dip of the fracture plane can be determined the dip of the fracture plane by using the amplitude ratio of the SV-generated tube wave to the P-generated tube wave. The dip strike of the fracture plane and hydraulic conductivity can be achieved if hydrophone VSP data are collected from several surface source locations. The frequency of seismic waves used in this method is tens to hundreds of Hz. The detection depth can be as low as the depth of data collection.

Pros:
This method has the potential to provide detailed characterization of a fracture, such as the dip and strike of a fracture plane and hydraulic conductivity. The hydraulic conductivity is hard to be achieved by other seismic imaging methods.

Cons:

Similar to the method using Stoneley waves, this method using tube waves can only detect fractures that intersect boreholes. Thus, only the areas around boreholes can be investigated. The dispersion relation requires the frequency band of the recording is sufficiently broad.

2.6 Effective stiffness tensor

Description:
The linear-slip theory suggests fractures can be treated as displacement discontinuities with the jump in displacement proportional to the traction and excess fracture stiffness. The stiffness tensor of the effective anisotropic medium containing one or more systems of aligned fractures can be obtained by adding the stiffness of each fracture set to the background stiffness (Fig.5).

“The number of uniquely resolvable fracture systems depends on the anisotropy of the host rock and the rheology and orientation of the fractures. It is possible to characterize fewer vertical fracture sets than dipping ones, even though in the latter case the fracture dip has to be found from the data. For the simplest, rotationally invariant fractures embedded in either isotropic or transversely isotropic with a vertical symmetry axis (VTI) host rock, the stiffness tensor can be inverted for up to two vertical or four dipping fracture sets. In contrast, only one fracture set of the most general (microcorrugated) type, regardless of its orientation, is constrained by the effective stiffnesses. These results can be used to guide the development of seismic fracture-characterization algorithms that should address important practical issues of data acquisition, processing, and inversion for particular fracture models.” [13]

Objectives:
This method can estimate the stiffness of multiple fracture sets embedded in isotropic or transversely isotropic with a vertical symmetry axis host rock. The maximum number of fracture sets can be determined by this method is two.

Pros:
This method can utilize surface seismic and vertical seismic profiling data. The simplicity and generality of the linear-slip theory make this method attractive for seismic inversion.

Cons:
There are limitations of the linear-slip theory such as neglecting the interaction among fracture sets. Also, the main underlying assumption of this method is that the estimate of the complete effective stiffness tensor can be obtained, which is not always true since real data sets have a limited offset and azimuth range.

2.7 Induced microseismic imaging

Description:
Microseisms are defined as a continuous background noise level caused by all sources of rapid deformational energy [5]. Well completions and re-completions account for many of the hydraulic-fracture operations, and therefore constitute a large potential application of microseismic/microearthquake imaging techniques [14]. Microseismic events that occur repeatedly on the same fault plane or along adjacent, similarly-oriented fault planes will produce similar waveforms at a given receiver. Thus, high-precision fracture images can be obtained by locating events relative to a master event location [14] (Fig.6).

Objectives:

Microseismic/microearthquake imaging can be used for monitoring fractures. The resolvable fracture length of microseismic data of Stage 2 Cotton Valley is 150 feet, and the resolvable horizontal linear feature is less than 10 feet along the width and depth dimensions [14].

Pros:
Microseismic imaging can obtain the size of fractures, and can monitor the propagation of fractures. Compared with active seismic methods, extensive microseismic data are available for microseismic imaging.

Cons:
Triggering activities are necessary for applications of the induced-microseismic imaging method.

2.8 Natural microearthquake imaging

Description:
A microearthquake or microseismic event is an earthquake with very low intensity. Natural earthquakes are driven by tectonic stress changes, as opposed to the induced earthquakes in the previous section. Natural microearthquake may be triggered by geological fault activities, or magma flow underground. Intense microearthquake swarm has been observed at Mammoth Mountain, Long Valley Caldera, California [15]. Long Valley Caldera has experiencing seismic and volcanic unrest since 1978. Chronic, low-level activation of magma system is associated with rapid earthquake activity [15]. The principle of natural microearthquake imaging is the same as that of induced microseismic imaging. Characteristics of fault and fracture zones can be obtained by mapping microearthquake data.

Objectives:
Natural microearthquake imaging can be used to characterize faults and fractures around the microearthquakes. The data collected at Mammoth Mountain, Long Valley Caldera, California, enable tomographic inversions for compressional seismic wavespeed and imaging faults and fractures throughout the upper 5 km in depth [15].

Pros:
Natural microearthquake imaging is more cost-effective compared with induced microseismic imaging, because no triggering activities are needed to generate natural microearthquake data. As a result, the data collection is not constrained around wellbores.

Cons:
Because natural microearthquakes are driven by tectonic stress, they may not happen in areas of interest.

3 In-situ state of stress measurement

Mechanical properties are characteristics that indicate the behavior of a material under an applied force or pressure. They usually include bulk and shear moduli, brittleness, hardness, stiffness, etc. Some of those properties can be evaluated using seismic methods, such as bulk and shear moduli. Some properties are difficult to be evaluated using seismic methods, like brittleness. Some properties may be more accurately estimated by direct measurements.

Description:
Coulomb's friction hypothesis is used to determine the combination of shear and normal stress that will cause a fracture of a material. The Mohr-Coulomb failure criterion represents the linear envelope that is obtained from a plot of the shear strength of a material versus the applied normal stress [16]. Coulomb

failure analysis of the propensity for frictional failure on the pre-existing natural fractures provides constrains on the state of stress in the reservoir. The in-situ stress monitoring helps determine whether the injectivity will induce failures on existing fractures [17]. Studies in various tectonic settings have shown that fractures that are optimally oriented and critically stressed for frictional failure often dominate fluid flow in low-porosity rocks [17].

Objectives:
This method can determine the orientation and failure of existing fractures. The depth of this analysis of stress can be thousands of feet because data for analysis of in-situ state of stress are obtained from well log.

Pros:
The measurements of stress are accurate because of the use of in-situ data.

Cons:
Because the data acquisition depends on well logs, this method can only investigate areas around well logs. Although the measurements of the stress are reliable, the criteria of the fracture failure can only provide a range of the possible failure orientation, which limits the accuracy of this method.

4 Electrical resistivity methods

Electrical resistivity methods are based on measurements of the response of the Earth to the flow of electrical currents. Electrical currents pass through the ground. Two potential electrodes are deployed to measure the resultant potential difference between them. Those measurements are used to estimate the electrical impedance of subsurface materials. The apparent resistivity can then be obtained because the apparent resistivity is a function of the measured impedance and the geometry of the electrode array [18].

4.1 Electrical resistivity tomography

Description:
Electrical resistivity tomography is a method using resistivity measurements to obtain a two-dimensional or three-dimensional resistivity model. The underlying idea is the same as seismic tomography. The only difference is electrical resistivity tomography is based on resistivity measurements instead of seismic measurements. The factors determining the resistivity include the temperatures of the material and the fluid stream within the fracture zones. Therefore, it is possible to use conductive fluid to enhance the contrast in resistivity between the rocks and fracture zones. The mineralization in the fractures will also affect the resistivity. All these influencing factors can be the results of the tomography.

Typically, electrical currents are injected into the subsurface through conducting electrodes deployed within the wells. The resulting electrical potentials are measured. Because of the large contrast in resistivity between water and rocks, the resistivity measurements could be efficiently used to indicate fracture locations [19] (Fig. 7).

Objectives:
The goal is to characterize fractures, such as the location and the size of fracture zones. The method also has potential to obtain the fluid content within a fracture zone. The resolvable size of the fracture zones is several meters.

Pros:

Because it is likely that fluid exists within the fracture zones, the fluid create large contrast in resistivity between the fractures and surrounding rocks. The contrast generates strong signals that facilitate the inversion. This is a unique feature that values this method.

Cons:
Because the electrodes have to be placed inside the wells, the measurements can be acquired are sparse. Fewer measurements lead to a lower resolution. This is a main drawback compared to seismic tomography.

4.2 Ground penetrating radar

Description:
Ground penetrating radar is a nondestructive geophysical method. This method produces a continuous cross-sectional profile or record of subsurface features without drilling. Usually ground penetrating radar transmits pulses of ultrahigh frequency radio waves down into the ground through a transducer or antenna. The released energy is reflected back where there is contrast of electrical conductivities and dielectric constants between different materials. The reflected energy will be picked up by the antenna. The ground penetrating radar antenna is pulled along the ground by hand or behind a vehicle. Ground penetrating radar profiles are usually used for evaluating the location and depth of buried objects. However, low frequency ground penetrating radar can also be used to detect the discontinuity of natural subsurface, such as faults and fractures [18].

Objectives:
This method can detect the locations of fractures. When it is used to locate fractures, a low frequency of ground penetrating radar should be used. The frequencies range is from 25 to 200 MHz. The penetrating depth is 30 to 100 feet.

Pros:
The equipment needed by this method is portable. The antenna can be held by hand. This method does not require drilling. Therefore, ground penetrating radar may serve as a way for preliminary inspection of the shallow regions.

Cons:
The resolution of this method for locating fractures is low. The probing depth is shallow compared with other methods.

5 Nanosensors

Description:
It is important for fracture characterization to acquire data about the reservoir pressure and temperature, near the wellbores and far out in the formation, to determine fracture parameters. One recently developed technique is to pass nanoparticles through pore networks, and detect those nanoparticles in the effluent. Scanning Electron Microscopy imaging demonstrates unambiguously that the nanoparticles can be transported through the pore spaces [19].

“The nanoparticles injected into Berea sandstone samples have provided a proof of concept in the use of nanoparticles as tracers. The nanoparticles were transported through the pore space of the rock and were detected in the effluent. The nanoparticles were also recovered through the 10 meter long sand-packed slim tube. Following the successful injection of spherically shaped nanoparticles, an investigation was initiated to assess the practicability of transporting wire-like nanoparticles (silver nanowires) through the pores of Berea sandstone. These nanowires serve as precursor for the injection of functional nanosensors such as pressure- and temperature-sensitive nanotracers." [20] (Fig. 8)

Objectives:
This method use nanomaterials as tracers in sensing reservoir properties in-situ. The recovered particles size distribution can be related to the size of fractures. The interwell connection and production history of the nanotracer can be used to determine the orientation of fractures. The nanomaterials can also carry information about the pressure, temperature and fluid type within a reservoir.

Pros:
This method extends the spatial range of in-situ measurements. Other pressure and temperature measurements are obtained only at a wellbore or a couple of feet around a wellbore. The nanoparticles can be injected at one well and recovered from another well. Therefore, the spatial range of the measurement is between the wellbores.

Cons:
This is a novel technique. Although breakthroughs in nanotechnology render great potential to this method, several issues are needed to be studied. The injection procedure and sampling strategies are still under development. The choice of the nanomaterials is still a topic of research.

6 Interwell correlation

Description:
This method is based on the assumption of steady-state, incompressible single-phase flow. This method uses the graph theory that has been widely applied in the Computer Science industry. The principle of this method is to compute the fastest path, most transmissible path and the largest flow path between the wells. Nodal analysis of the fracture network leads to a formulation which allowed explicit calculation of the flow rate along each fracture segment. Based on this information, the flow rate contribution can be computed for each path connecting any two wells. This results in a method for analyzing the connection of the fracture network [19].

Interwell correlation can determine the characteristics of a fracture network that connects the wellbores. This method can also obtain the temperature distribution through the fracture network (Fig. 9).

Pros:
Interwell correlation is a fast and simple method. This method does not have any numerical dispersion effects that would be introduced if the flow pattern is obtained by solving the fluid dynamic equation.

Cons:
This is a method used in enhance geothermal systems. Water flow between the wellbores is required by this method. In other applications, when water flow between the wellbores is not present, alternative media that connects the wellbores needs to be found.

7 Tiltmeter mapping

Description:
Tiltmeters, also referred to as clinometers, are used to monitor the change in inclination (rotation) of points on or in the ground or a structure [21]. Tiltmeters may be purely mechanical or incorporate vibrating-wire or electrolytic sensors for electronic measurement [22]. A sensitive instrument can detect

changes of as little as one arc second [22]. Tiltmeters are extensively used for various monitoring. One application is to monitoring orientation and volume of hydraulic fracturing [21, 22].

Tiltmeter fracture mapping measures the underground material deformation that is induced by the hydraulic fracturing. The deformation can propagate throughout the media, which can be picked up by tiltmeters. The measurements can be made on the surface or in the wellbore, which are named the surface tiltmeter mapping and the downhole tiltmeter mapping, respectively. The principle for the two different mappings is the same (Fig. 10).

Objectives:
This method can infer the geometry and the orientation of hydraulic fractures. The surface tiltmeter mapping can detect fractures with a depth range down to 10000 feet [23].

Pros:
Tiltmeter mapping is sensitive to the change of the position of the ground. Therefore, this method can provide good results of stimulation-induced fractures and the propagation of the fractures. It is possible to monitor fractures in real time using this method.

Cons:
Tiltmeter mapping is mainly used for monitoring hydraulic fractures. This method cannot be applied when there is no stimulation process undergoing.

8 Conclusions

Non-invasive methods such as seismic and electric methods can be used to image subsurface structures including fault and fracture zones in the early stage of site characterization. During the site development, utilizing triggered geophysical activities, methods like microseismic mapping and tiltmeter mapping can be used to further determine the characteristics of the sites. After boreholes are drilled, more detailed information can be obtained using in-situ measurements and the methods applicable in the boreholes such as vertical seismic profiling, nanosensor and interwell correlation. With all these geophysical techniques, we can gain crucial characteristics of a site for used fuel disposition.

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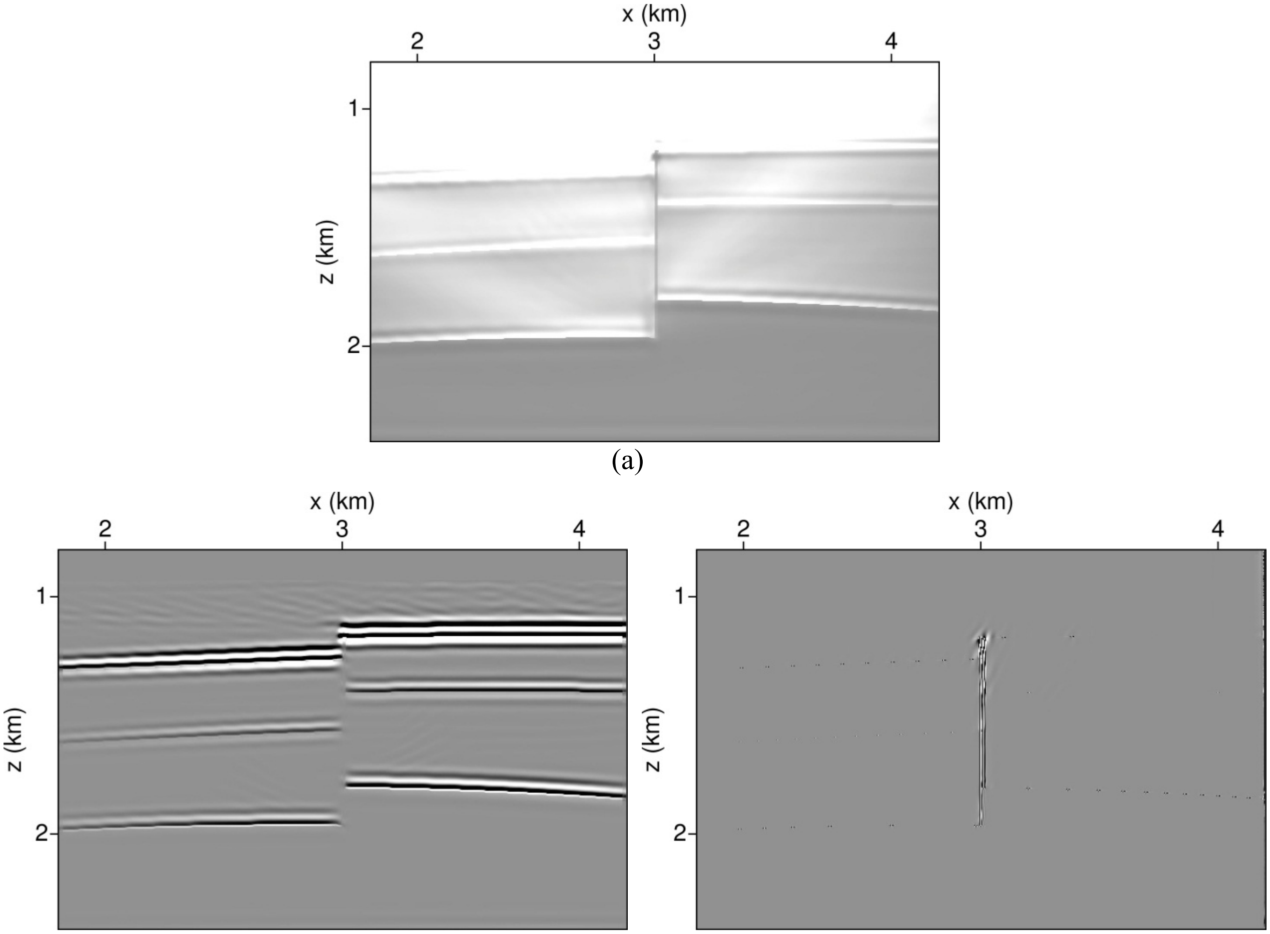
Table 1. Parameters of faults that can be estimated using the listed methods.

		Parameters of faults/fractures to be estimated					
		Location	Width	Dip	Stiffness	Conductivity	Fracture propagation
Seismic methods	Elastic-wave reverse-time migration	Y	Y	Y			
	Full-waveform inversion	Y	Y	Y			
	Seismic illumination analysis	Y	Y	Y			
	Vertical seismic profiling	Y	Y	Y			
	Effective stiffness tensor				Y		
	Microseismic imaging	Y		Y			Y
	Diffraction imaging	Y		Y			
In-situ state of stress					Y		
Electrical resistivity method	Electrical resistivity tomography	Y		Y		Y	
	Ground penetrating radar	Y				Y	
Nanosensors		Y					
Interwell correlation		Y					
Tiltmeter mapping		Y	Y	Y			Y

Table 2. General properties of the listed methods.

		Location of data acquisition	Image resolution	Need active seismic sources?	Resolvable depth
Seismic methods	Elastic-wave reverse-time migration	Surface or borehole	High	Y	Several kilometers
	Full-waveform inversion	Surface or borehole	High	Y	Several kilometers
	Seismic illumination analysis	Surface or borehole	High	Y	Several kilometers
	Vertical seismic profiling	Borehole	High	Y	The depth of the wells
	Effective stiffness tensor	Borehole		Y	The depth of the wells
	Microseismic imaging	Surface or borehole	High		The depth of the wells
	Diffraction imaging	Surface or borehole	High	Y	Several kilometers
In-situ state of stress		Borehole			The depth of the wells
Electrical resistivity method	Electrical resistivity tomography	Surface or borehole	Low		
	Ground penetrating radar	Surface	High		100 feet
Nanosensors		Borehole			The depth of the wells
Interwell correlation		Borehole			The depth of the wells
Tiltmeter mapping		Surface			The depth of the wells



(a)

(b)

(c)

Figure 1. Images of a 90°-dip fault using compressional waves with (a) the conventional-imaging condition, (b) up-going and down-going wavefield separation imaging condition, and (c) left-going and right-going wavefield separation imaging condition [1].

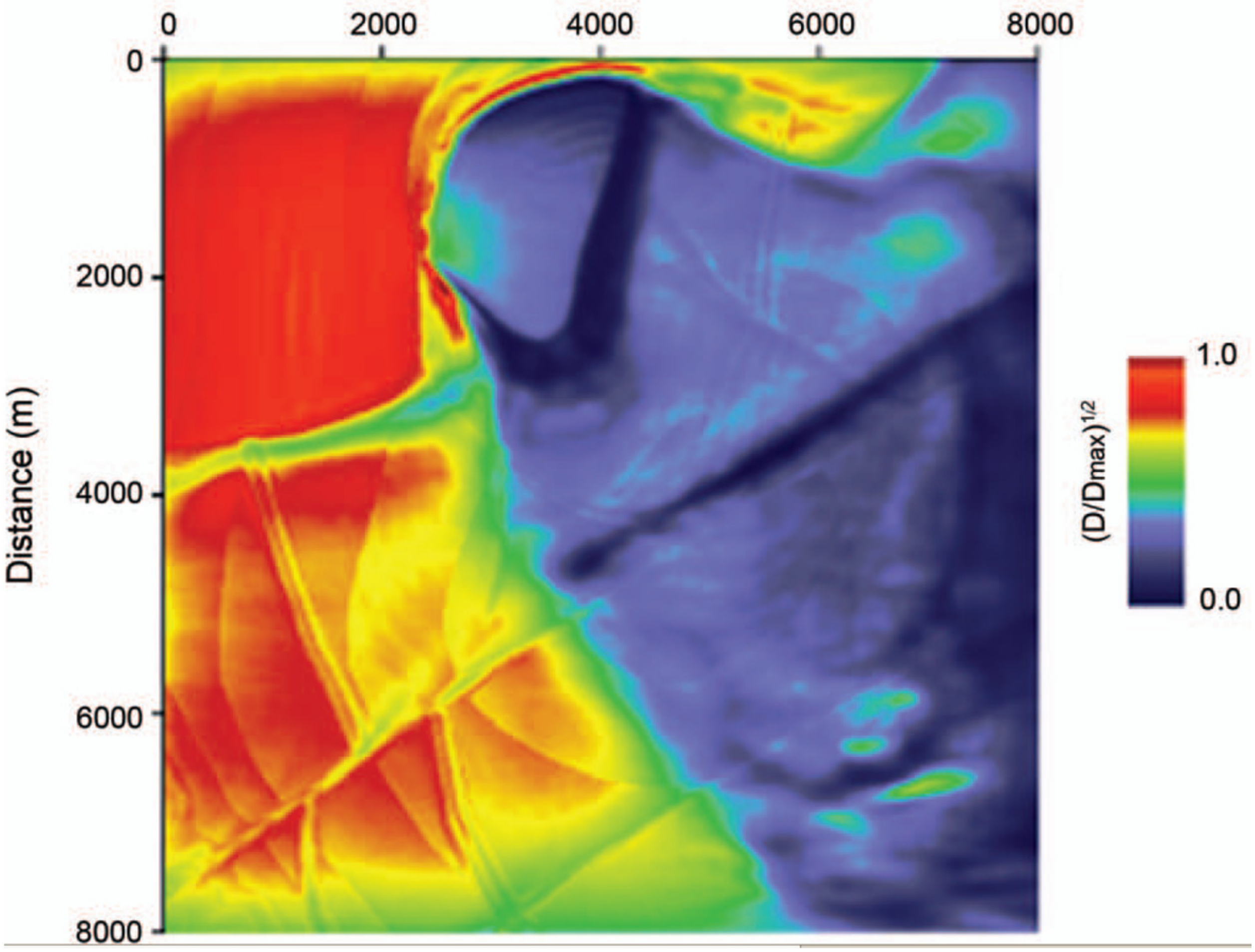


Figure 2. The total acquisition dip response associated with the contributions from all possible dipping events. The depth-image quality is superior at the left portion of the model, which corresponds to the strong illumination [4].

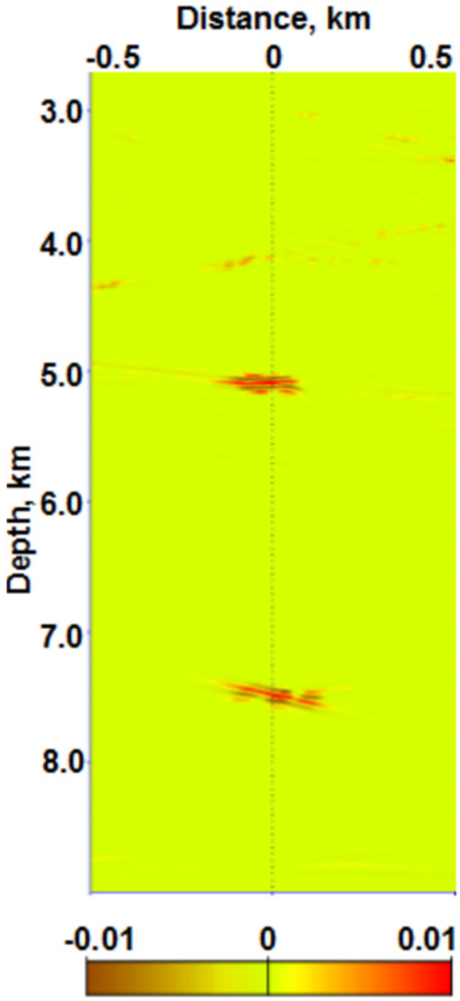


Figure 3. Image obtained using diffraction imaging with a part of Sigsbee synthetic data set [6].

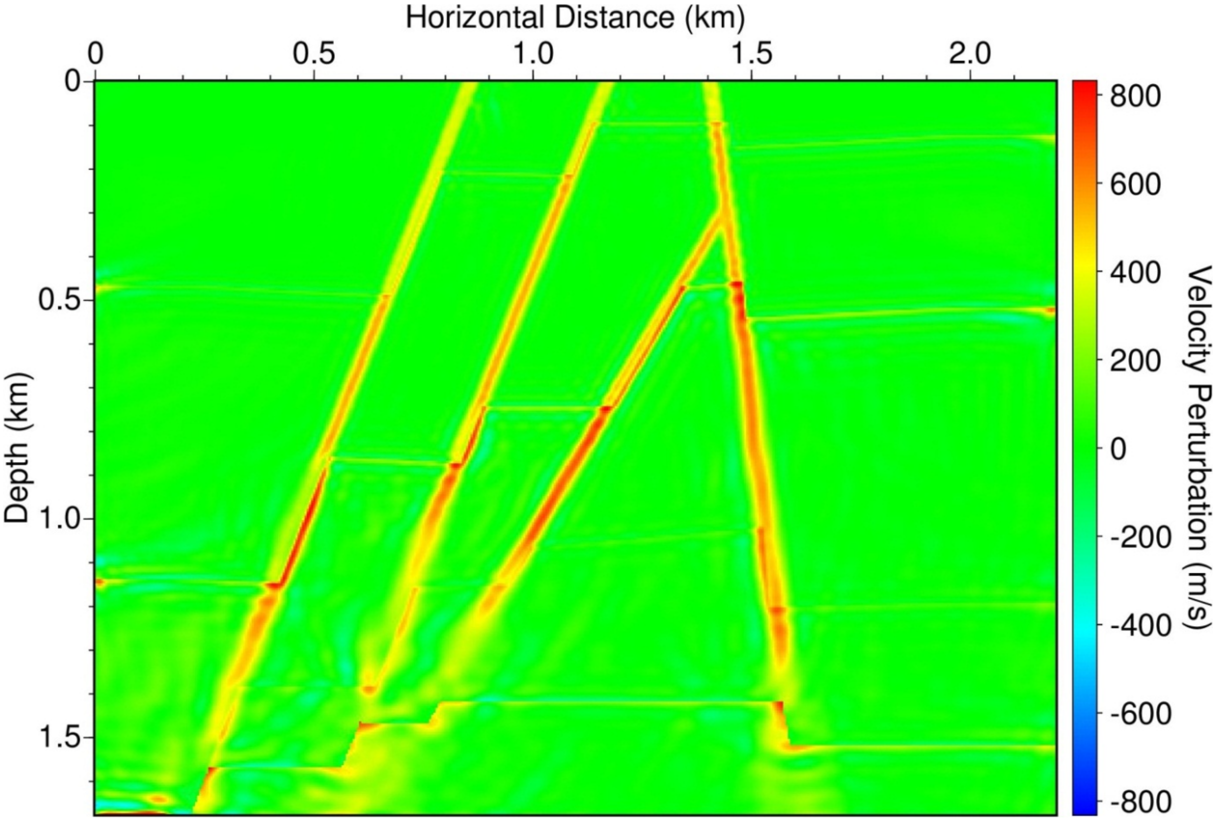


Figure 4. Reconstruction of steep faults obtained using full-waveform inversion with a wave-energy-based precondition approach (Modified from [9]).

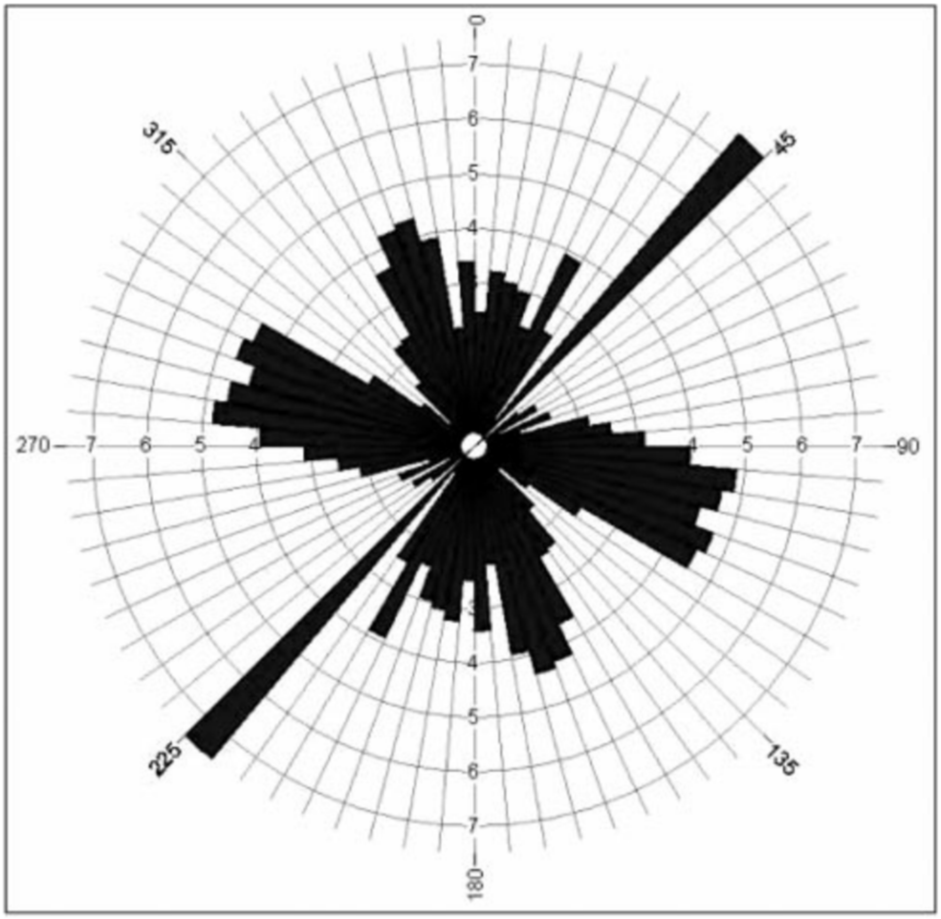


Figure 5. Rose diagram of open-fracture azimuths obtained using a borehole imager at the Weyburn field (Canada). (Fig.1 in [13])

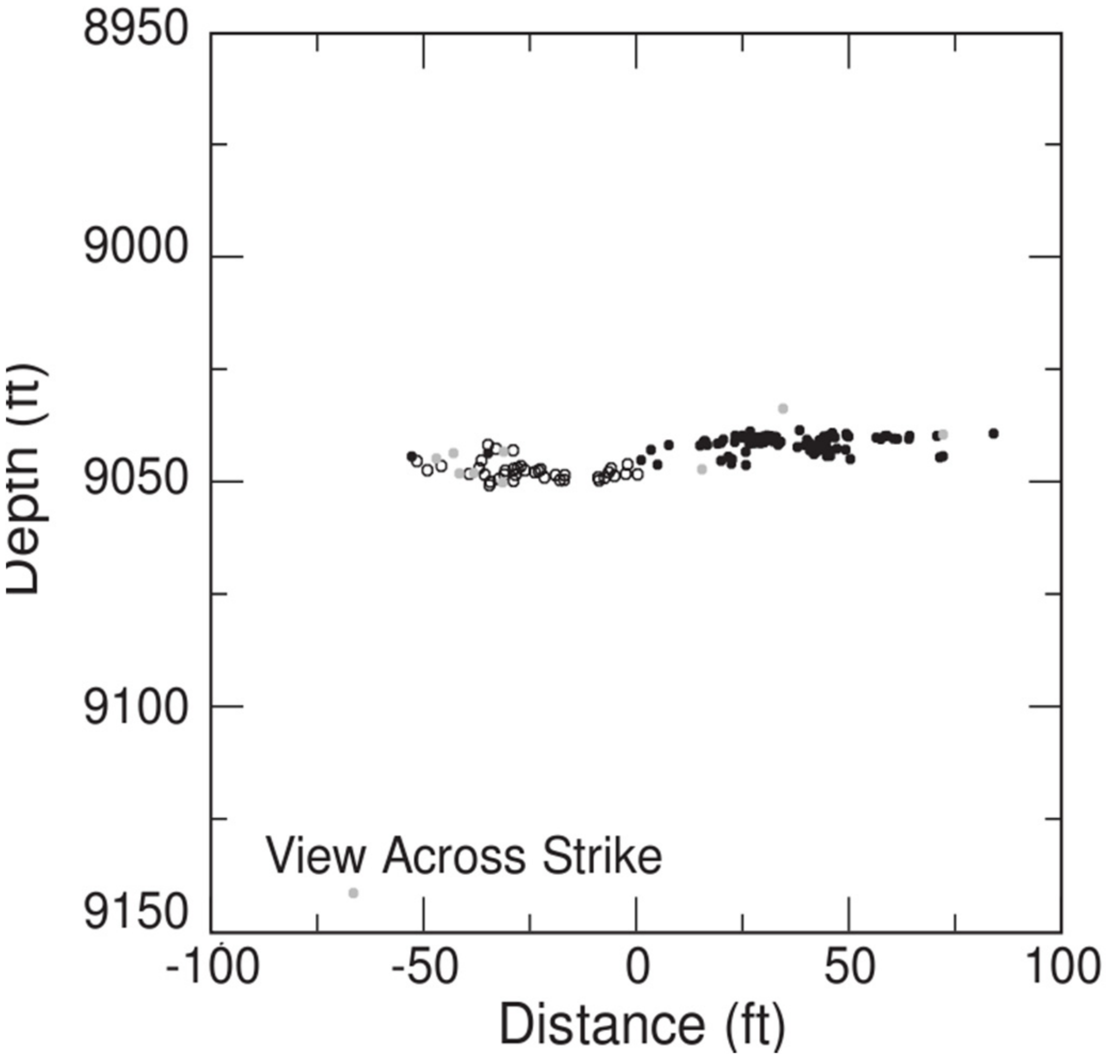


Figure 6. Hypocenters of microseismic events. Solid and open symbol events were distinguished by a change in the S-waveforms character and are spatially distinct [14].

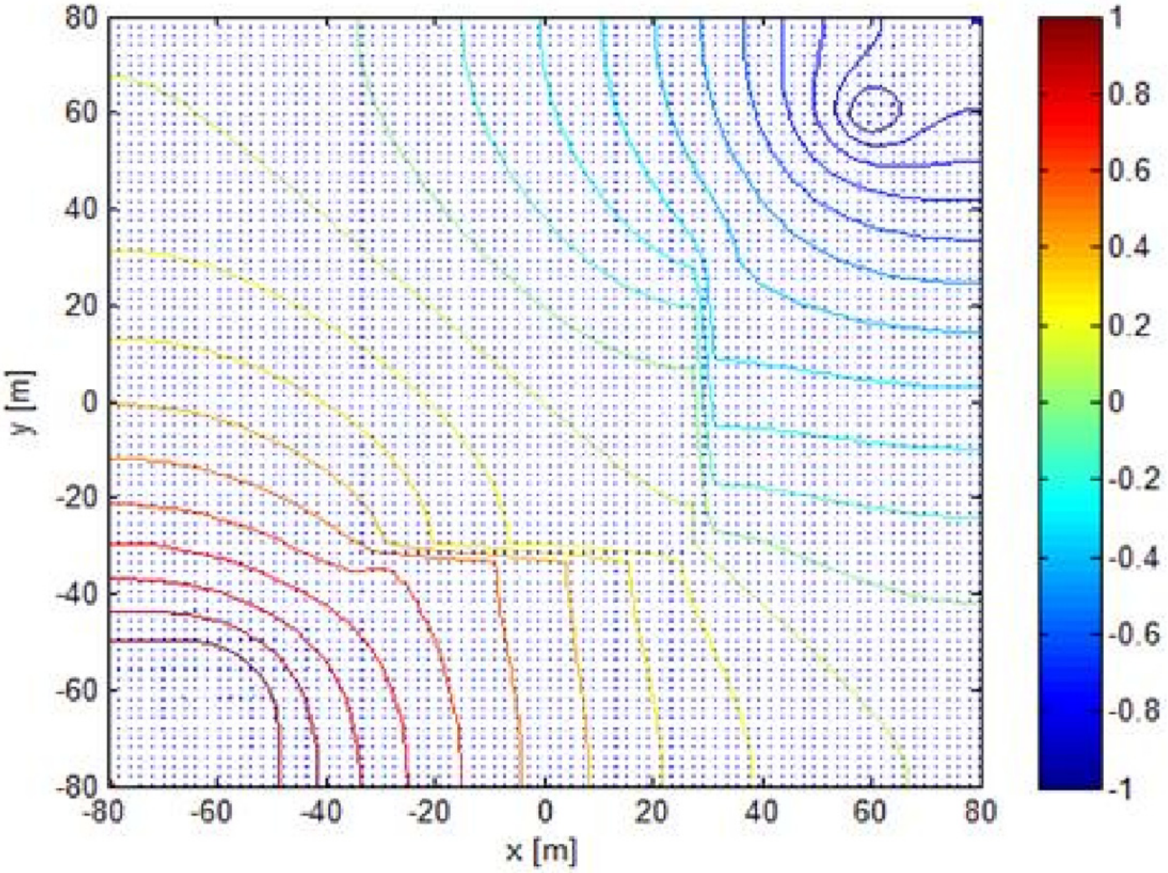


Figure 7. Example of the electric field distribution caused by a pair of fractures and obtained using electrical resistivity tomography [19].

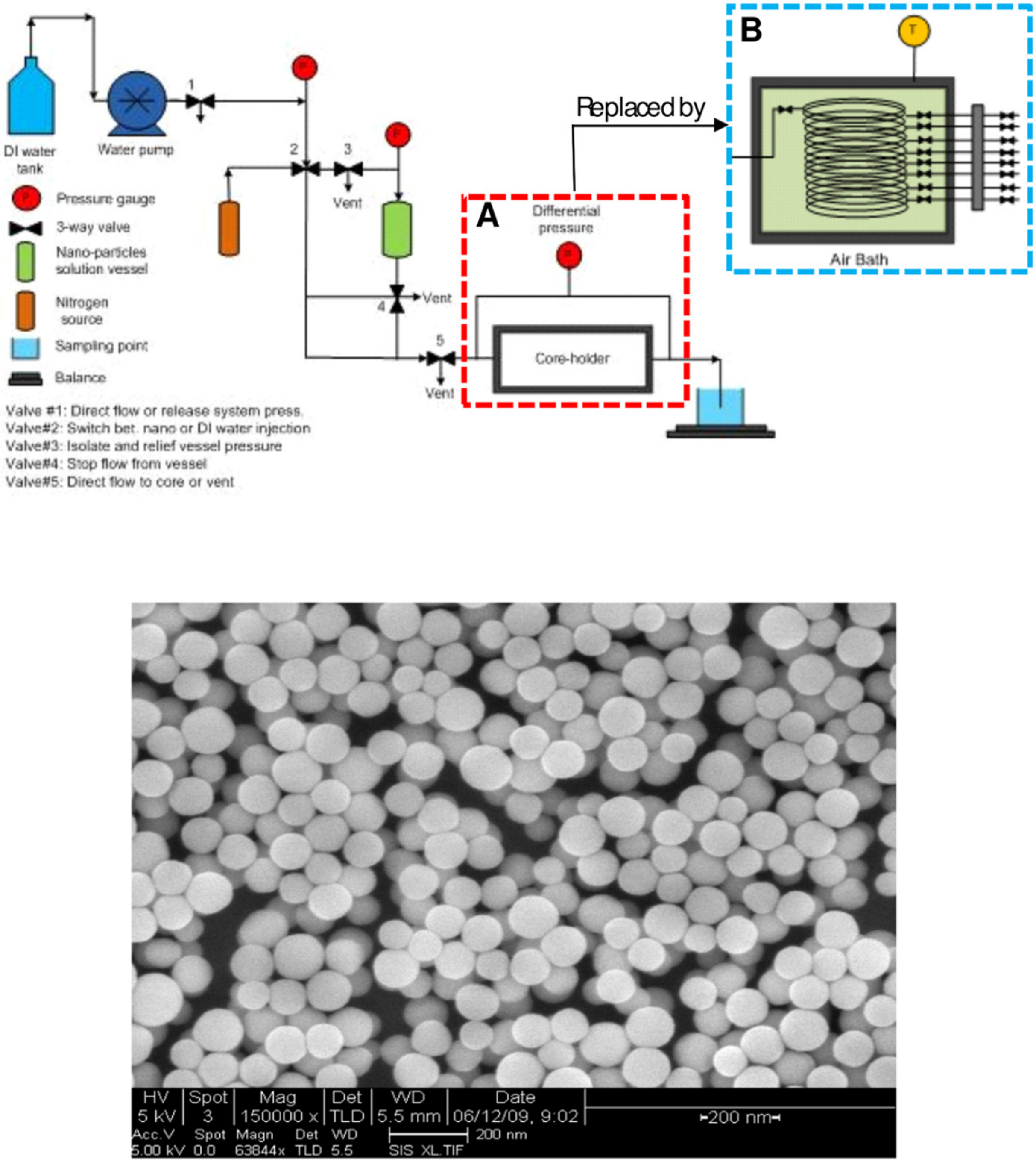


Figure 8. Experimental apparatus for nanofluid injection into (A) core samples and (B) sand-packed slim tube (upper panel Fig.1 in [20]), and SiO2 nanoparticle image obtained by Scanning Electron Microscopy (lower panel Fig.2 in [20]).

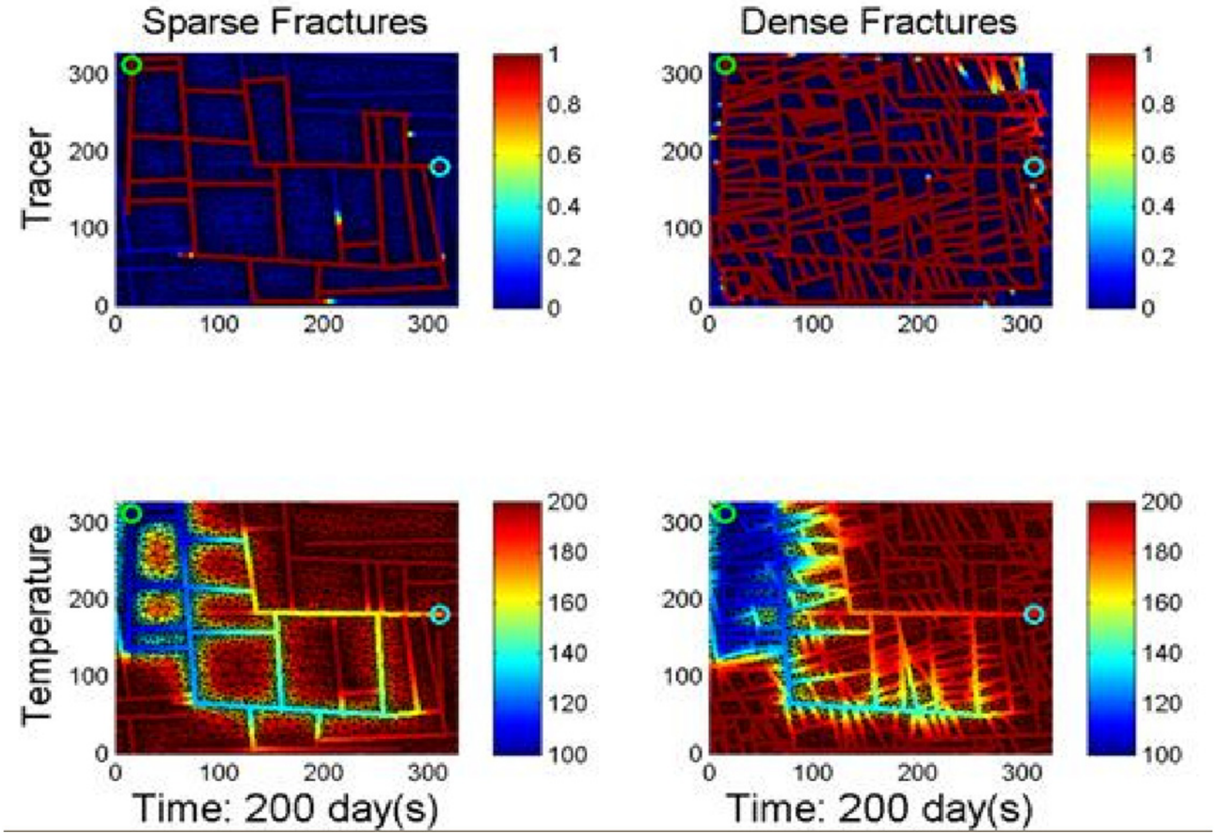


Figure 9. Modeled tracer and thermal signatures of sparse and dense fracture distributions [19].

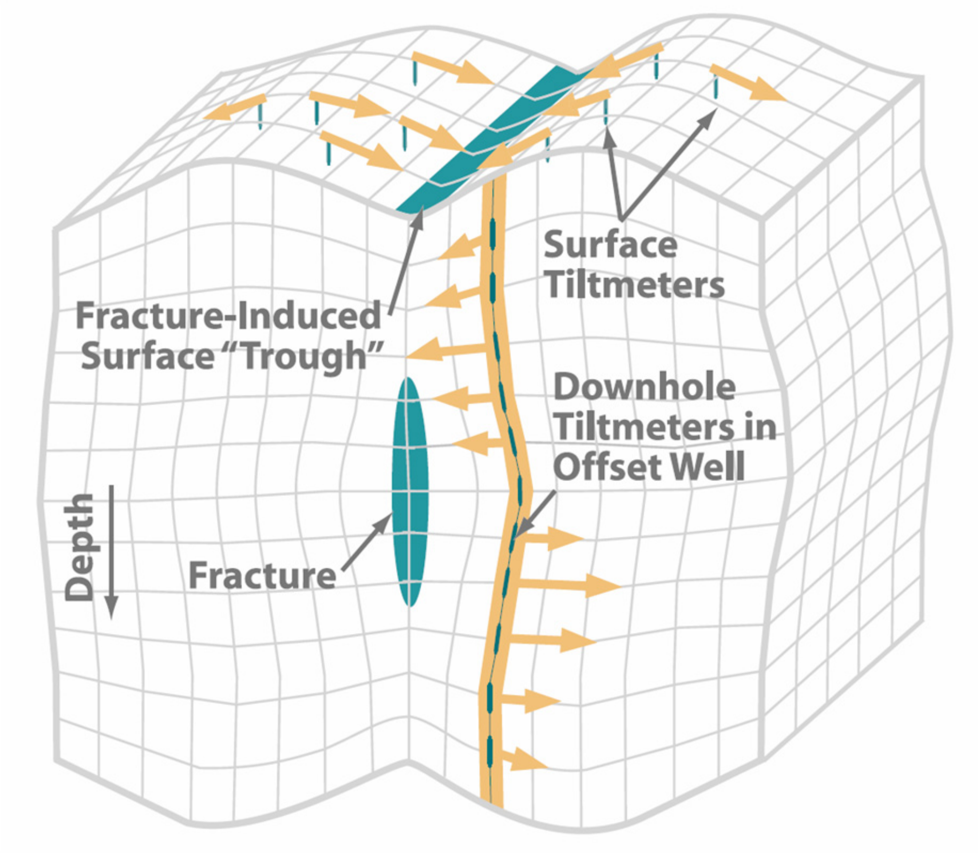


Figure 10. Displacement field induced by a vertically oriented hydraulic fracture. Tilt mapping involves inversion of the measured tilt field at many points on the surface and from downhole wireline arrays [24].