Elastic imaging of subsurface Structure with Equivalent Offset Migration for multicomponent seismic data

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Seismic reflection survey is one of the most efficient techniques for exploring subsurface natural resources, such as oil or natural gas. Although conventional reflection imaging methods using poststack time migration work well for horizontal multi-layered structure, it is difficult to apply the conventional techniques to image complex subsurface structure. Prestack depth migration could be used to image such complex structure, but requires precise seismic velocity models with enough accuracy. Partial prestack migration is therefore used to estimate velocities as a trial-and-error method with the conventional post-stack processing methods. On the other hand, Equivalent Offset Migration (EOM) was proposed to exploit both advantages of the conventional post-stack processing and velocity analysis even for complex subsurface structure (Bancroft et al., 1998) as an alternative method to partial prestack migration, and draw attention in exploration geophysics for its computational efficiency and imaging accuracy.
In the conventional EOM, it is mainly to use the vertical component of received waveforms, not horizontal components. However, it is necessary to obtain S-wave velocity structure in order to establish the sub-surface model including petrophysical properties. We would like not to employ EOM to take the advantages of the processing efficiency but to extend it to use the horizontal components of waveforms for petrophysical analysis. We conduct numerical experiments to verify the possibility of extracting information about S-wave velocity structure using EOM with the horizontal components. Our numerical results show that EOM based on the horizontal components can increase the amount of information of S-wave velocity whereas some unique difficulties to the horizontal components should be addressed.

Keywords: Equivalent Offset Migration, Seismic Exploration

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Waveform Analysis of Borehole Acoustic Dipole Data in Transversely Isotropic Medium with a Tilted Axis of Symmetry

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It is important to understand anisotropic property around a borehole for effective production of oil and gas, efficient control of hydraulic fracturing, etc. In the conventional research, Vertical Seismic Profiling (VSP) has been used to estimate the anisotropic properties. However the 3-dimensional anisotropic properties around a borehole may not be well obtained using VSP because seismic waves covers only a low frequency band that degrades the spatial resolution. So this uncertainty causes some problems in practical fields for which some improvements have been waited for. In the present study, we propose a novel approach which uses the waveform of the cross dipole for more accurate measurement of anisotropic properties around a borehole.
We conduct numerical experiments of three-dimensional seismic wave propagation around a borehole using a Hamiltonian particle method (HPM). HPM has advantages in computational efficiency over the conventional lattice based methods. Our numerical model includes an anisotropic layer in a homogeneous medium. We generate seismic waves using the cross dipole placed inside the borehole, and record seismic waves which pass through the anisotropic layer at receivers also placed inside the borehole. We investigate the change of the recorded waveforms induced by the anisotropic layer. Distinctive feature can be observed when shear wave passes through the HTI (Transverse Isotropy with a Horizontal axis of symmetry) medium which is known as shear wave splitting. When shear wave reaches the HTI medium, it splits into two polarized shear waves: fast shear and slow shear. To detect the azimuthal anisotropy, Alford rotation has been applied in the previous studies. The wave excited from dipole source is recorded both the same and orthogonal components. After applying Alford rotation using all 4 waveforms, we could estimate the azimuth from the energy and degree of anisotropy from the phase difference.
We simulate seismic waves pass through an anisotropic layer. We change the anisotropic properties both in the order and the orientation of the symmetry axis. At first, we check the waveforms at receivers. If the anisotropic layer is HTI medium, fast shear and slow shear can be detected explicitly by applying Alford rotation. On the other hand, the symmetric axis of the anisotropic layer becomes tilted from HTI medium, the phase difference between fast shear and slow shear becomes smaller. This result indicates that if anisotropic layer tilts, we cannot estimate correct anisotropic parameters just by using the Alford rotation. On the other hand, we can observe an evident difference between fast and slow shear waveforms. Since this difference stems from the tilted angle of the anisotropic layer, inversion technique utilizing full-waveform (full-waveform inversion) could estimate anisotropic properties around a borehole with high accuracy and resolution.

Keywords: Anisotropy, Borehole

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Fundamental study of seismic emission tomography in terms of fluid pressure fluctuations

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Since it is essential to know where fluid moves in the subsurface, seismic emission tomography (SET) is now becoming a fundamental tool in the development of natural resources. The method has been applied in plural oilfields and provides images of fluid paths in the subsurface. However, the relationship between observed seismic data and fluid behavior in the subsurface has not been well understood yet, and there remains some skepticism to the performance of SET. In the present study, we conducted a numerical experiment for the understanding of the mechanism of seismic emission at the locations of subsurface fluid paths in order to extract more information about fluid behavior from observed seismic data. After that, we conduct quantitative assessment at seismic emission tomography utilizing micro-seismic signals induced by subsurface fluid flows inside fractures. We simulate fluid flow in a fracture using the Lattice Boltzmann method (LBM). We adopt two numerical models, i) intermittent flow in a parallel plate, and ii) a pore throat model with an oil droplet. We calculate stress changes at the fracture wall induced by unsteady flow for i) and multi-phase flow for ii). The unsteady flow is generated by cyclic pressure change at the inflow boundary. In this case, inner portion of the fracture is filled only water or oil. In the multi-phase flow, we consider transport of oil droplet in a fracture with a throat filled by water. After those experiment, we simulate seismic wave propagation and calculate received waveform at surface geophones. In the parallel plate model, larger shear stress change can be observed in the case of oil than water. This stems from more rapid change in fluid velocity close to the fracture wall due to the high viscosity of oil. In the case of the multi-phase flow in the pore throat model, about 8 Pa and 28 Pa of shear and normal stress changes are observed at the fracture wall when an oil droplet passes through the pore throat, whose width is 1 mm. Our results show that seismic wave generated in pore throat model where a oil droplet passing through a pore throat would have 10-27 m in the displacement amplitude at about 2 km distance. Although the amplitude of seismic waves generated by a single pore throat cannot be detected in field observations, the superposition of seismic waves would amplify the signal from the reservoir. We also confirmed that the integration of seismic waves over time using auto and cross correlations with those acquired at a place with some distance could magnify the detection capability. If there is 16000 pore throat in the sub-surface, taking correlation receive seismic wave over 20 days using passive seismic emission tomography. We think that the induced seismicity by fluid flow is strongly dependent on fluid flux, viscosity, volume fraction of multiple fluid phases in flow, geometry of fracture network, and many others. Further work is planned to investigate the relation of seismic wave amplitude with these parameters.

Keywords: seismic emission tomography, fracture modeling, Lattice Boltzmann method

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The role of physical and chemical processes of silica scale growth in geothermal wells

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One of the most significant problems faced in geothermal power plant is that of the deposition of amorphous silica, known as silica scaling. Currently there are a number of methods for controlling the deposition but the fundamental mechanisms that govern the precipitation of silica are not well understood. Although the method of calculating the deposition rate of silica based on reaction kinetics is widely available, it has been reported that the magnitude of deposition rate is extremely lower than that measured in the laboratories or in the fields (Malate and O'Sullivan, 1992; Weir and White, 1996). Since the inhomogeneous flow influences the deposition of the silica scale, which is an alternative process of scaling, the actual mechanism to transport colloidal silica to the wall surface in the flow should be considered in the deposition process, too. We established a scheme of the multi-scale simulation of silica scale precipitation considering the hydrodynamic effect to colloidal silica in the flow for understanding the mechanism.
The meso-scale approach is to investigate the motion of individual colloidal silica particles near the pipe wall with particle-wall interaction using Lagrangian method, while in macro-scale, we use a lattice Boltzmann method to model flow and solute-transport and use the scheme of building up silica scale. The meso-scale model is deployed to derive the deposition rate of colloidal silica, which is used for silica scale growth in macro-scale simulation. We then compare the amount of silica scale precipitation estimated from our simulation estimated with that of the observed both from laboratory experiments and from field observations.
Our results indicate that our simulation gives more realistic silica scaling qualitatively and quantitatively than the existing methods using only reaction kinetics. We conclude that the shear flow rate, which is closely related to the transport process of colloidal silica, is the one of the dominant factor, and that the hydrodynamic process needs to be taken into account to control the silica scaling.

Keywords: Silica scaling, Geothermal, Simulation

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Permeability variation due to sand particles in an infiltration flow using Smoothed Particles Hydrodynamics method.

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Sand control is recognized as a key issue to prevent troubles caused by sand with the production of oil or gas. Sand grains are produced by the increment of the effective stress in the sub-surface due to the production of fluid resources and are carried by the fluid. these grains could not only hinder the flow to decrease the permeability in reservoir but damage the production line. It is therefore important to take a measure for controlling sanding problem. Research has begun to use numerical simulations as a new methodology since the mechanism has not been well understood yet due to the complexity of solid-fluid interation behavior. In the present study, we focus on the problem in the prevention of fluid path in porous media and conduct numerical ezperiments to deal with the soil-fluid interaction. Among possible parameter such as average grain size, average pore throat diameter, fluid viscosity, pressure gradient, and many others, we focus our attention to the effect of grain shape in the mechanism to hinder the fluid flow in porous medium, i.e. to decrease the permeability. Existing studies have mainly considered grains of spherical shape becouse of the simplicity to deal with both solid-fluid and solid-solid interactions in their numerical models. It is, however, well known that the shape of grains could not be. We employed a Smoothed Particle Hydrodynamics(SPH) method, i.e., one of particle methods. To deal with non-spherical particles with arbitrary shapes at the same time in a simple way in our simulation. As an initial step, we modeled a pore throat with a 2D pipe, put immovable solid obstacles in a flow to respresent matrix grains, and movable sloid particle of both spherical and rectangular shapes as sand grains. After the simulation of the transportation of movable solid particles, we could observe the rectangular and circular grains to show different interaction behaviors with immovable particles and the variations of the permeability in time. Our results indicate that the shape of shape of grains has strong in fluence to the permeability in porous media. We think the shape of floating grains should be taken into account for evaluating the sanding problems.

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Mechanism of complex fracure creation in hydraulic fracturing

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Hydraulic fracturing has been used to improve the permeability of rock for development of unconventional resources. A complex fracture network created by hydraulic fracturing significantly improves the permeability of rock and increases the production of natural fluid resources. The heterogeneity of rock strength has in fact a great influence on the fracture shape created in uniaxial tension test, fracture toughness test, or hydraulic fracturing. Such heterogeneity is, however, rarely taken into account in the evaluation for complex fracture network creation in development of unconventional resources. The mechanism of fracture creation is not fully revealed yet, either. In the present study, we reveal the mechanism of complex fracture creation in the presence of heterogeneity in rock strength in the fracking. We perform a series of numerical simulation using models not only with strength heterogeneities but also as a function of brittleness that is kept constant in each model. As a results, it is turned out that the mechanism of complex fracture creation due to the heterogeneity in rock strength is completely different from that in brittleness. In hydraulic fracturing with heterogeneous models, a number of micro cracks are generated around the tip of main fracture that does not propagate straight due to these precedent micro cracks. In addition, pores with specific shape and the spatial inhomogeneity in the rock strength at the tip cause the divergence of main fracture and, then, a complex network of hydraulic fractures could be formed. In hydraulic fracturing of rocks with high brittleness, shear failures occur around the main fracture filled with fracturing fluid, and a lot of branches are created. Since the deformation of induced fracture is restricted in media of high Young modulus, fluid pressure acts on fracture surface becomes high. This induces strong shear stress field around main hydraulic fracture. In conclusion, the mechanisms of complex hydraulic fracture due to strength heterogeneity and that due to brittleness are completely different, and the heterogeneity in rock strength should be taken into consideration for the accurate evaluation of complex fracture creation.

Keywords: hydraulic fracturing , discrete element method, strength heterogeneity, brittleness

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Applicability of Phased Array Antenna for Ground Penetrating Radar for Subsurface Imaging

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Ground Penetrating Radar (GPR) has become important for detecting natural and artificial burial materials in the subsurface. However, there is a problem in the current practice of GPR surveys. In the field experiment, it is difficult to obtain subsurface images beneath surface structures such as buildings or trees. We would like to propose the utilization of a phased array antenna as a radar source. In our study, we take a GPR system as an example to emphasize the importance of the phased array system. We use a 3-D FDTD method to examine how efficiently our radar system works. Firstly, we describe the theory of numerical method and our strategy of controlling the direction of electromagnetic waves. Next, we compare a dipole antenna and the phased array antenna to evaluate the efficiency of the phased array system in the shallow subsurface. Finally, we move the phased array antenna along the survey line assuming actual GPR surveys. We applied a 3-D Kirchhoff migration method to estimate the position of anomalies in the subsurface. In addition, we use all the antenna units as transmitters and receivers in order to obtain higher resolution. Our result shows that the phased array antenna has an advantage in enhancing the signal-to-noise ratio and enhancing the amplitude of scattered waves from the reflectors located lateral to the survey line. This indicates the possibility to probe the subsurface even below obstacle that prevents the surveys on the surface. We conclude that our phased array system has a potential to be used as an angular scanner imaging tool that has not yet been attempted in the conventional GPR system. This GPR system may reduce the number of survey lines and lower the cost of GPR surveys.

Keywords: Ground Penetrating Radar, Phased Array Antenna, Geophysics

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Numerical Study for Anisotropic Influences on Elastic Wavefields Near Surface

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Anisotropic velocity analysis is important for understanding characterization of hydraulic induced fractures and near surface structure with sedimentary materials. There are many studies on seismic wave propagation in transversely isotropic and orthorhombic media (e.g., Thomsen, 1986; Alkhalifah, 2000). In most of those studies, the magnitude of anisotropy is assumed to be weak. In addition, there are few studies on seismic wavefields in quite strongly anisotropic media. Therefore, it may not be appropriate to apply their theories directly to strongly anisotropic subsurface media. It is necessary to understand the effects of the anisotropy on the behavior of seismic wave propagation in strongly anisotropic media in the seismic exploration. In this study, we investigate the influence of strong anisotropy on received seismic waveforms using three-dimensional numerical models, and verified capability of detecting subsurface anisotropy. Our numerical models contain an isotropic and an anisotropic (transversely isotropic) layer in an isotropic background subsurface. Since the difference between the two models is only the anisotropy in the vertical propagation velocity, we could observe the influence of anisotropy in the residual wavefield that is the difference in the observed wavefields of two models. The residual waveforms could be exploited to estimate both the order of anisotropy and the thickness of anisotropic layer in subsurface.

Keywords: Anisotropy, Elastic wavefiels, Numerical simulation

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Investigation of influence of dipping structures on microtremor exploration from case study research

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S-wave velocity structures have been estimated from dispersion curves of phase velocity, H/V spectral ratios, etc., using microtremor exploration technique. However the estimations are originally based on the assumption that underground structures have stratified horizontally. So, if structures have irregular, e.g., layers incline or discontinue, the structures estimated under the assumption of horizontal stratification have errors to some extent due to perturbation of wave filed at the irregular. On the other hand, it has been known that seismic waves are likely to be amplified at the irregular structures since the various seismic waves interfere with each other. So, accurate estimation of the irregular structures is needed for disaster prevention. Seismic reflection and boring surveys are powerful tools to estimate the irregular structures since boundaries of the structure are directly imaged or excavated. However sometimes they have difficulties in cost and space for their application, especially surveys of a wide range of areas are limited. Here, we focus on H/V spectral ratios, which are relatively easy to measure a wide range of areas with a small budget, to estimate a dipping structure.
In this study, we applied microtremor explorations to an anonymous site, where a shallow dipping layer has been found by preceding boring surveys. The fall of the dip is several 10m while the horizontal length is several 100m. We conducted spatially dense microtremor observations to observe H/V (Horizontal/Vertical) spectral ratios along the dipping structure. We attempted to image the dipping structure by the H/V spectral ratios. It is known that velocity structures are difficult to be determined only by H/V spectral ratios since they have a trade-off between S-wave velocity and layer thickness. So, reference structures were determined by the SPAC (SPatial Auto Correlation) method apart from the dipping structure. Using the information of the references, the dipping structure was successfully illuminated by the H/V spectral ratios. The estimated structure agrees with that of the preceding boring surveys. However the H/V spectral ratios become complex especially around the edges of the dipping structure (e.g., multiple peaks, obscure peaks, reclamation of valleys) due to the reflection, refraction, scattering waves, etc. The H/V spectral ratios are largely different from that of horizontally stratified medium. In this condition, the analysis of them is difficult since it is based on the assumption of horizontal stratification. Here, a question arises; how far (in terms of space) the dipping structure gives the effect on the wave field. To examine it, we synthesized the wave field using a numerical simulation using the estimated structure model. We divided the synthesized wave at the edges of the dipping structure into surface wave and the others (reflections, refractions and etc.), then, we calculated the original locations of the latter waves based on the method of back propagation. As a result, it was revealed that part of the dipping structure within one-wavelength from the edges gives major effect on the wave filed. It could disturb the H/V spectral ratio.
When we apply the microtremor explorations based on the assumption of horizontal stratification to dipping structures, it is important to note that the wave filed within one wavelength from the edges of the dipping structure is likely to be fluctuated. The estimated result may have errors to some extent.

Keywords: microtremor exploration, irregular structure, H/V spectral ratio

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Frequency-domain mesh-free finite difference operator for visco-acoustic wave equation

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We developed a new approach for visco-acoustic wave equation in frequency-domain using a mesh-free method. Recently, full-waveform inversion (FWI) has been used for investigating sub-surface properties with high resolution. One of the problems of FWI is the high computational costs, like computational memory and CPU time. This stems from forward modeling for calculating theoretical waveforms. So, it is important to improve the computational efficiency of forward modleing. There are two categories in forward modeling, i.e. time-domain and frequency-domain. The frequency-domain method has some advantages over the time-domain method. However, the frequency-domain modeling runs up the computational costs if the size of the coefficient matrix becomes large. So, it is important to decrease the degree of freedoms without sacrificing the accuracy. In the present study, we apply a mesh-free finite difference method to the frequency-domain modeling for saving the computational costs. Our numerical results show that the mesh-free finite difference method can improve numerical efficiency in keeping with high-accuracy. This indicates that the method can be an altanative to the conventional grid-based methods.

Keywords: mesh-free finite difference method, frequency domain

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Time-lapse imaging simulations using a few ACROSS seismic sources and sparse receiver spacing for oil/gas reservoirs

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1. Introduction

Recently unconventional oil and gas productions such as heavy oil, shale oil and gas, and oil below sub-basalt have increased. EOR technology is applied to the unconventional oil/gas field production and the time-lapse monitoring is essential for this technology. Although demands of the time-lapse approach for the EOR are increased, the recent circumstance of oil price requires the reduction of geophysical exploration costs. In ordinary seismic surveys, receiver and source spacing of 25 m are commonly used to obtain smaller bin sizes. Including the recent requirements in view in costs, we tried to prove the effectiveness of our time-lapse method considering cost reduction. In contrast to the conventional seismic exploration, we carried out two time-lapse imaging simulations for the deeper and shallower cases assuming a few seismic source and coarse geophone spacing.

2. Two time lapse simulations

The reservoir depths were assumed to be 2 km and 200 m. We calculated wave fields excited by vertical force by using the 3D finite difference method. By using the synthesized waveform data at selected receivers before and after the changes in physical properties of the presumed reservoirs, we calculated residual waveforms. We conducted 2D or 3D Kirchhoff migration using the residual waveforms to image the temporal-change.

2.1. Reservoir at 2 km

Assumed reservoir was 500 m in both horizontal dimensions, 20 m in thickness at 2 km depth. We examined linear receiver arrays with 5 m and 100 m spacing in simulation of 2D imaging. In 3D imaging, we used only one ACROSS seismic source and a geophone array with 200 m grid.

2.2. Shallow reservoir at 200 m

The next case was a very shallow heavy oil reservoir. We assumed a small reservoir of 20 m in both horizontal dimensions, 10 m in thickness at 200 m depth. We tested two array patterns with 106 and 25 geophones and one or two ACROSS sources.

3. Result

2 km depth case

The results show effective image retrieval even when using only one seismic source and a 200 m-spaced geophone grid array. In cases of linear array, we were unable to identify any significant differences between 5 m and 100 m spacing cases, which dramatically reduces the total installation costs of the monitoring system.

200 m depth case

Even when the source was 800 m apart from the target reservoir, the tiny target with 20 m-long x 20 m-wide x 10 m-thick was effectively imaged. In the case of by 106 and 25 receivers, we did not recognize significant changes. We also recognized that the simulation using two sources gave better image retrieval than using single source, and retrieved images could be controlled by receivers just above the target.

4. Discussion and conclusions

Although we conducted several simulations assuming V_P, V_S, density structure and their changes in the models, the actual production fields varied significantly from the model results. If we use actual structural datasets, the simulation might be more plausible and precise. The reservoir

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depth, noise conditions, locations of injection and production wells and properties of near surface layers, should be considered.
In this study, we confirmed the effectiveness by examining the results of simulations conducted with two heavy oil models at shallow and deep depths. We effectively imaged the model reservoirs for 200 m and 2 km depths. Using one ACROSS seismic source and geophones with 100-200 m spacing can produce a reliable reservoir image even for a reservoir of several tens of meters in size. The results obtained by simulations in two cases suggest high potential of our method in time-lapse application to heavy oil, permanent reservoir monitoring, and CCS.

Keywords: time-lapse, ACROSS technology, reverse time migration, backpropagation, oil reservoir, EOR

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Optical Fiber VSP using DAS (Distributed Acoustic Sensing) Technology

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Distributed optical fiber sensing technologies have been evolved over more than 30 years started with DTS (Distributed Temperature Sensing). DTS is now commonly used for well monitoring purpose in Oil & Gas business.
The follower, DAS (Distributed Acoustic Sensing) technology has been introduced more than 5 years for the demands of pipeline monitoring and intrusion detection. The latest optical fiber sensing technology now allows DAS to record Borehole Seismic signal including VSP (Vertical Seismic Profiling). The system is called ‘hDVS’ (heterodyne Distributed Vibration Sensing) in order to distinguish from pipeline monitoring system.
Unlike conventional VSP recording tools, which usually use electro-magnetic sensor or Geophone, hDVS/DAS uses optical fiber as vibration sensor. Multi-level borehole seismic tool including VSI (Versatile Seismic Imager) has been commonly used for VSP recording more than 15 years in order to save acquisition time. However, due to the sensing is limited as point basis where Geophone is located, the borehole seismic tool needs to be moved from the bottom section of the well up to surface in order to record VSP data for entire well. Massive number of seismic source shooting may be required, in proportion to number of tool settings. In the case using many numbers of sensor shuttles 20 or more, rig up or rig down time for the multi-level borehole seismic tool increases dramatically when number of the sensors deployed into the well increases. Hence, there is limitation to reduce acquisition time using conventional method.
On the other hand, due to the nature of electronics system, the maximum temperature, which can be deployed conventional borehole seismic tool, is limited up to 200 degC or even lower. In case of optical fiber, the core part of the fiber is made of high-silica glass, so that high temperature version of optical fiber is widely available over 200 degC. Hence, it can be deployed under high temperature environment on a permanent basis, where conventional Geophones cannot be used.
Since optical fiber can be deployed entire well depth as sensor, either permanently (e.g. Control Line) or temporary (Hybrid Logging Cable), the acquisition time required for hDVS VSP would be as small as few minutes, which is essentially the time required for Seismic Source firing, compare several hours to days for conventional VSP including the time required for multiple tool settings. This is absolutely new way of acquiring borehole seismic using fiber optic technology.
During the presentation, overview of hDVS/DAS system will be explained followed by examples of VSP data recorded during Field trials last few years.

Keywords: DAS, hDVS, Optical Fiber, VSP, Seismic

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