Inversion of Gravity Anomalies Using Primal-Dual Interior Point Methods

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Structural inversion of gravity datasets based on the use of density anomalies to derive robust images of the subsurface (delineating lithology and their boundaries) constitutes a fundamental non-invasive tool for geological exploration. The use of gravity data to estimate and interpret the substructure based on its density properties have proven efficient; however, the inherent non-uniqueness associated with most non-seismic geophysical datasets make this the ideal scenario for the use of recently developed robust constrained optimization techniques. We present a constrained optimization approach for a least squares inversion problem to characterize 2-Dimensional Earth density structure models based on gravity anomalies. The formulation inverts Bouguer gravity anomalies using polygons along with Primal-Dual Interior-Point methods for the optimization of the results, which include equality and inequality physical and structural constraints. We validate our results using synthetic density crustal structure models with varying complexity and illustrate the behavior of the algorithm using different initial density structure models and increasing noise levels in the observations. Moreover, we apply the approach to the Southern Rio Grande Rift (SRGR) region using previously obtained receiver function results as constraints for the inverted density profiles. We produce constrained crustal models that characterize the SRGR showing a shallower Moho (30 km) in the region, which is thicker than previously suggested. Based on its validation and implementation, we conclude that the algorithm using Primal-Dual Interior-Point methods is robust and always honors the geophysical constraints. Advantages of using this approach for structural inversion of gravity data are the incorporation of a priori information related to the model parameters (coming from actual physical properties of the subsurface) and the reduction of the solution space contingent on these boundary conditions.

Keywords: Earth, Inversion, Gravity anomalies, Primal Dual Interior Point methods

Depth estimation of the magnetic basal sources associated with the Curie Isotherm, from aeromagnetic data in Baja California Sur (Mexico) using spectral and geostatistical analysis.

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Nowadays techniques and technologies used in geophysical exploration focused on finding additional natural resources besides those of fossil origin, has new improvements based on theories applied so far only in researching field, such as spectral, and geostatistical analysis in order to estimate the origin of basal magnetic sources known as the depth of Curie´s isotherm; very important issue on geothermal deposits.
Fourier analysis applied to potential fields allows the depth estimation of interfaces into the Earth's crust with high contrasts of magnetic susceptibility or density. This method, applied to the magnetic field, uses the relationship among the magnetic anomalies’ power spectrum, depth and size of such sources. (Spector and Grant, 1970; Bhattacharyya and Leu, 1975; Blakely, 1995 and Ruiz and Introcaso, 2004).
From spectral and geostatistical analysis proposed by Okubo and Bhattacharyya (1985; 1970) it is possible to estimate the depth of basal magnetic source associated with of Curie's isotherm depth whose temperature ranges between of 580 and 600 ˚C. (Blakely, 1988, 1995; Tanaka et Al., 1999 and Frost and Shive, 1986).
This study is based on the aeromagnetic data acquired by the Mexican Geological Survey and processed to estimate the depths of the magnetic sources in the Tres Vírgenes area, Baja California Sur, Mexico.
The area of interest was divided in seven windows with squares of 64 Kilometers; knowing that the maximum depth that can be estimated depends on the length of the 2π window. Main magnetic field was included in each window.
In order to estimate depths, the Spector and Grant (1970) methodology was applied; such process assumes that a set of vertical prisms are the sources of the anomalies on the aeromagnetic charts. These prisms define a distribution of magnetic sources, computing its radial power spectra, obtaining its square root, and its natural logarithm it is possible to associate its second slope of the resulting function with the magnetic structure´s top depth defined as Zt.
On the other hand, the geostatistical analysis was done following the methodology published by Bhattacharyya, Leu (1975, 1977) and Okubo (1985) where the radial power spectrum rise to the square root and divided by the absolute value of the wave number. After that the natural logarithm was obtained in order to find the centroid depth (Z0) of the magnetic structure. The basal depth of the magnetic structures defined as Zb was calculated by the ratio (2Z0 - Zt).

The average depth in the area of interest in Tres Virgenes; ranges between 5 to 6 kilometers. It is possible to correlate such results with heat flow values and estimate the current potential of the Tres Virgenes geothermal field and its surroundings.

Keywords: Curie´s isotherm, Tres Virgenes, radial power spectrum

Influence of near-surface strongly anisotropic medium on P-to-S wave conversion

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In the fields of earthquake disaster prevention and energy resource exploration, understanding the properties of seismic anisotropy is important for obtaining various information about subsurface, for example, its structure, regional stress field and selective orientation of crack opening direction. In some cases, like near surface and reservoir rocks, formations are estimated to be strongly anisotropic for elastic wave propagation. To extract anisotropic information from seismic exploration data, many researches have conducted elastic anisotropy studies. However, most of these studies are based on the assumption of weakly anisotropic media (Thomsen, 1986). Our previous studies showed that strong anisotropic media in the subsurface significantly influence the seismic waveforms especially on the PS converted waves. In the present study, we apply the reverse time migration (RTM) to the PS converted waves to determine the depth of anisotropic layer. To extract PS converted waves from observed data, we also develop a novel wave separation method. We demonstrate the effectiveness of our method using a numerical experiment. Our numerical result shows that our method can image layer boundary between isotropic and anisotropic layers which generates strong PS converted waves.

Keywords: Seismic anisotropy, PS converted waves

A study in tectonic structure in Taiwan in the susceptibility domain

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3-D velocity-susceptibility models were constructed by using the velocity retrieved from seismic tomography transferring into susceptibility through characteristics of minerals and/or rocks determined by Vp and the Vp/Vs ratio in Taiwan. Simulated magnetic anomalies computed from those models via forward methods were compared with the magnetic anomaly map retrieved from field prospection to determine a double constrained model. Profiles sliced from the determined model were utilized to examine well-known tectonic structure reported in the previous studies to confirm the feasibility of the velocity-susceptibility transformation. The determined model shows earthquakes often located in the low-susceptibility in the western side of Taiwan. In contrast, no clear relationship between earthquake locations and susceptibility can be found in volcanic areas. Aseismic areas in the southern part of the Central Mountain Range are dominated by intrusion of igneous with high susceptibility. The Philippine Sea plate subducting beneath the Eurasian plate at the latitude of about 24.5° in the eastern side of Taiwan also can be revealed by a downward high-susceptibility zone. In short, the 3-D velocity-susceptibility model provides a novel view of the dominant susceptibility and heat on tectonic structure and geological evolution.

Keywords: Magnetic anomaly, Velocity tomography, Magnetic susceptibility

Accurate seabed modelling using finite difference methods

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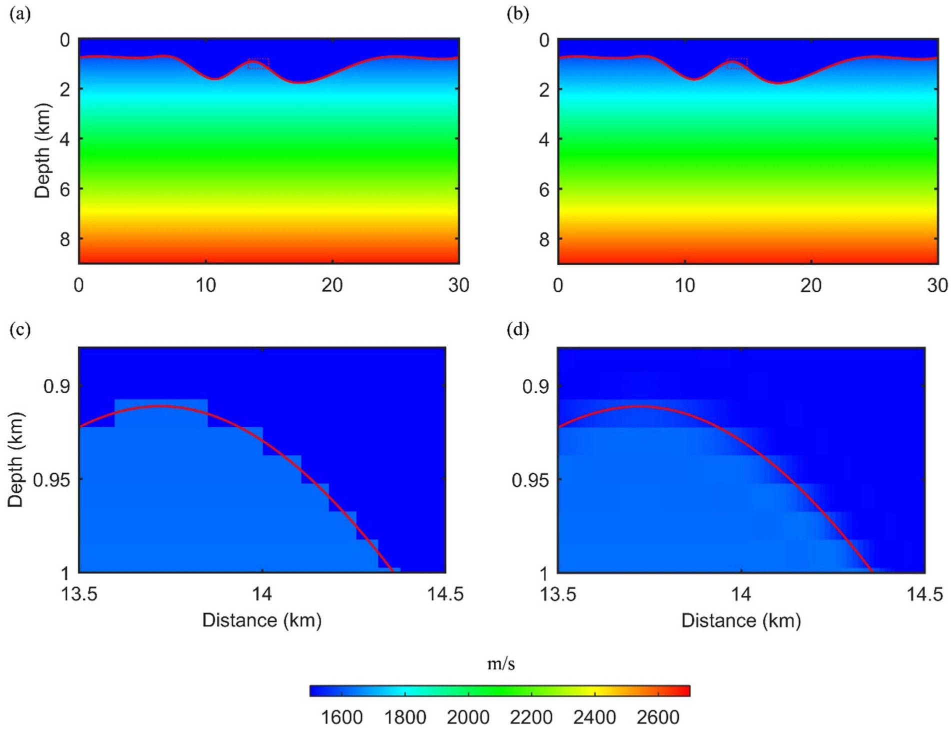
Finite difference is the most widely used method for seismic wavefield modelling. However, most finite-difference implementations discretise the Earth model over a fixed grid interval. This can lead to irregular model geometries being represented by ‘staircase’ discretisations, and potentially causes mispositioning of interfaces within the media. This misrepresentation is a major disadvantage to finite difference methods, especially if there exist strong and sharp contrasts in the physical properties along an interface. The discretisation of undulated seabed bathymetry is a common example of such misrepresentation of the physical properties in finite-difference grids, as the seabed is often a particularly sharp interface owing to the rapid and considerable change in material properties between fluid seawater and solid rock. There are two issues typically involved with seabed modelling using finite difference methods: firstly, the travel times of reflections from the sea bottom are inaccurate as a consequence of its spatial mispositioning; secondly, artificial diffractions are generated by the staircase representation of dipping seabed bathymetry. In this paper, we propose a new method that provides a solution to these two issues by positioning sharp interfaces at fractional grid locations. To achieve this, the velocity model is first sampled in a model grid that allows the centre of the seabed to be positioned at grid points, before being interpolated vertically onto a regular modelling grid using the windowed sinc function. This procedure allows for undulated seabed bathymetry to be represented with improved accuracy during modelling. Numerical tests demonstrate that this method generates reflections with accurate travel times and effectively suppresses artificial diffractions.

Keywords: finite difference, seabed bathymetry, integer grid, fractional grid, staircase, sinc interpolation



An acoustic velocity model containing an undulating seabed, sampled using the (a) Integral Grid Model and (b) Fractional Grid Model methods. (c) and (d) are enlarged views of the areas outlined by the red dotted squares in (a) and (b), respectively. The red curve in each panel indicates the true position of the seabed.

An accurate and efficient finite-difference operator for the frequency-domain wave propagation

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We newly developed a finite-difference (FD) operator for the frequency-domain acoustic wave propagation. This operator uses a stretched stencil to avoid the numerical anisotropy. In general, direct solvers for sparse matrices are used in exploration geophysical community because they have some advantages over iterative ones , i.e. frequency dependent attenuation and multi-source configuration can be simply implemented. In the frequency-domain modeling, the computational costs (calculation time and computational memory) depend on not only the number of neighbors but also the bandwidth of the impedance matrix. So usage of higher-order schemes is not always conducive to the improvement of the computational costs.
In the present study, we use a stretched stencil of FD operator not to increase the bandwidth in the impedance matrix. Coefficients of the stencil are determined by a minimization process. We investigate the accuracy of our scheme using dispersion analysis and numerical experiment. They show that the proposed scheme can improve not only accuracy but also efficiency compared to the conventional 9-point scheme proposed by Jo et al. (1996).

Keywords: finite-difference method, frequency-domain

Full Waveform Inversion with Nonlocal Similarity and Adaptive Sparsity-Promoting Regularization in the Gradient Domain

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Seismic inversion is a highly nonlinear and ill-posed problem. In a typical seismic survey, aperture size, source frequency bandwidth, and source and receiver distribution are limited. Therefore, the inversion results usually suffer from strong artifacts and reduced resolution.

In this study, we propose a novel full waveform inversion (FWI) method with a nonlocal similarity prior and adaptive sparsity-promoting regularization in the gradient domain. First, we invoke a self-similarity between patches extracted from a single velocity model. In other words, these patches have a certain level of redundancy. To exploit this property, we adopt a regularization term that finds and stacks together the k most similar patches into a 3D cube for each patch from the velocity model, and then require that the cube be sparse under a 3D orthogonal sparsifying transform. A second regularization term is a generalization of total variation with learning-based dictionaries, which provide a good estimation of the gradient field. Since the gradients emphasize high-frequency components of the velocity model, a better reconstruction of the gradients means a more accurate reconstruction of high spatial frequencies, hence higher resolution.

The proposed optimization problem can be solved by the Alternating Direction Multiplier Method (ADMM), in which the original problem can be transformed into several sub-problems and then be solved by looping through those sub-problems till convergence or for a certain number of iterations. The first sub-problem is similar to the traditional FWI with a quadratic regularization term, which is easily solved by the l-BFGS method with the gradient computed using the adjoint method. The other sub-problems can be solved by hard-thresholding and dictionary learning methods such as K-SVD. We test the proposed method on the BP 2004 velocity model. Compared with traditional FWI, our new technique can better reconstruct sharp edges like salt body boundaries, and is also able to effectively reduce artifacts and noise. Quantitatively, the result from the proposed method has higher structural similarity index (SSIM) and also lower mean square error.

Wave-equation based techniques to explore crustal structure along the axis of the East Pacific Rise 9ºN

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With the recent improvements and accessibility to enhanced computational power, we are now able to apply more sophisticated methods to deep-water, active seismic datasets and explore the Earth’s oceanic crust in greater detail. Here, we use a suit of wave-equation based techniques to look at the structure of the upper oceanic crust formed along the East Pacific Rise (EPR) between 9º16’ and 9º 56’ N. The 2-D multi-channel, collected in 2008 along the EPR, we first extrapolate to a constant level just above the seafloor to suppress seafloor diffractions and to facilitate further inversion processes. We then apply wave-equation tomography, using first refraction arrival, to extract information on long- to mid-wavelength structures within the first 500 m of the upper crust. The resulting velocity model shows presence of localized low velocity anomalies, 5-10 % lower than the background velocity. The most prominent one is observed within the hydrothermally and magmatically dynamic region located north of 9º46’ N, represented by well defined pipe-like zones of low velocity we interpret as presence of hydrothermal pathways. Their spatial distribution and association with previously mapped geological features help us to discriminate between the up- and down-going pathway. The two anomalies present beneath the two vent clusters are interpreted as the up-going fluid pathways. We suggest the remaining anomalies collocated with the morpho-tectonic deviations of the ridge axis as the ideal loci for seawater to penetrate the crust and potentially establish the down-going stream. The velocity model obtained from wave-equation tomography is further used as a starting model for waveform inversion. As the wave-equation tomography provides good match in travel-time and phase of the refraction event within the given data window, we can perform waveform inversion even though the low frequency and offset of the data is limited (useful signal > 4 Hz and offset range is smaller than 6 km) that could lead to cycle skipping. The resulting velocity introduced additional details in velocity models, which are spatially matched with individual fine-scale tectonic discontinuities and or vent orifices, and reflect processes related to local fracturing and cracking.

Keywords: wave-form inversion, mid-ocean ridge, hydrothermal circulation

Waveform-based Gradient method for estimating hypocenter mechanism before observing aftershocks

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There are a lot of examples in numerical estimation of physical mechanisms of earthquakes. Due to the limitation in the number of available seismographs in the world in the past, the estimation either using CMT solutions or Monte-Carlo type inversion schemes has been dominant in the literature. The former assumes a hypocenter of an earthquake to be a point source, although the fault plain to the earthquake should have some finite physical dimensions, and estimates the mechanism of the earthquakes (strike-slip, normal or reverse). The latter assumes the hypocenter as a group of fault planes to cover the finite-scale earthquake fault and gives the idea which part of the fault plane has worked as asperities, etc. The methods have been used to quickly estimate what kind of earthquake has taken place in a short period after the occurrence of each earthquake but they have limitations. Indeed, the former models earthquakes only using the initial quarter to half the wavelength and ignores any tailing waveforms and the latter assumes the location of a fault plane that caused the earthquake using the distribution of aftershocks. Those have been remaining shortcomings, since we need to watch the distribution of aftershocks carefully to identify the fault location. Since the number of seismometers have been increasing, we may be able to improve the situation to utilize some leading-edge technologies such as wave theories. After the development of a 2D slip fault model, we try to estimate the location of hypocenter only with earthquake waveforms observed by an increased number of seismometers.

Keywords: Earthquake, Inversion

Application of Reverse Time Migration to Electromagnetic Data in the Fictitious Wave Domain

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Recently, deep reservoirs under gas clouds become possible targets in the oil industry. Since one of the main obstacles to develop them is strong attenuation of wave energy inside the gas clouds, it is important to extract signals come from target reservoir. In recent years, analytical transformation of the diffusive Maxwell's equation to the wave domain one could be a powerful tool to obtain seismic-like data in CSEM. Proposed advantages like higher sensitivity to the changes and lower CPU time, could make the solutions of Maxwell's equations in the fictitious domain more powerful for discovering the earth structures compared to the diffusive domain ones. So, it would be possible to monitor the deeper structures using the data set in the fictitious wave domain even under strong attenuating media assumption. In this study, we apply the Reverse Time Migration (RTM) imaging algorithm in the fictitious domain to investigate a deep reservoir in a conductive (attenuating) media. RTM exhibits a great ability in handling of the steeply dipping structures and complicated velocity models. We demonstrate the effectiveness of our approach using numerical experiments. Synthetic data set of CSEM is prepared by the finite-difference method. We use three types of received components for RTM; i) Ex (electric field in x-direction), ii) Ey (electric field in y-direction), iii) Hz (magnetic field in z-direction). The vertical and horizontal electric field of marine CSEM method are important because they respond to the edges of structure. The horizontal magnetic field response presents an additional and useful measurement for the marine CSEM method (Li and Constable, 2007). Each component has a distinctive characteristic. So, the effect of each component on the migration image is investigated and compared with each other.

Keywords: Maxwell's Equations, Reverse Time Migration, Diffusive Domain, Fictitious Wave Domain

Monitoring seismic velocity changes caused by offshore earthquakes using DONET ambient noise records

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Subduction zones, where a tectonic plate subducting beneath the other plate, megathrust or interplate earthquakes could be generated repeatedly. Because of the nature of interplate earthquakes, the process of plate subduction governs the distribution, mechanics, and style of slip along the interplate fault. At the Nankai Trough subduction zone, located beneath the Pacific Ocean off the southeast coast of Japan, we have installed a seismic observation system, named DONET (Dense Oceanfloor Network system for Earthquake and Tsunamis), which includes seafloor broadband seismometers and borehole seismometers to monitor the seismic activity and the process of earthquake generation including the stress accumulation.

To elucidate earthquake generation and preparation process, it is necessary to investigate how the stress could be accumulated not only in deeper part but also in the shallow sediments, what the role of interstitial fluid could be in the stress accumulation processes, etc. There are some conventional methods to measure these physical properties, such as borehole strainmeter, borehole breakouts or borehole dynamic tests. However, these methods have some difficulties from the viewpoints of technical and/or cost. Therefore, we need to have some other methods to see the state and time variation of the stress in the subseafloor.

In this study, we applied seismic interferometry technique to ambient noise records observed by DONET seafloor seismometers to obtain time dependent seismic velocity as a proxy of stress state below seafloor. We calculated zero-offset horizontal and vertical pseudo shot records from every 1 hour ambient noise records in two years continuous data since July 2014, which were observed by three components of DONET seismometers. Obtained pseudo shot records are then stacked every 240 hours (10 days). Clear events are visible in both vertical and horizontal components of the pseudo shot records, which could be reflected P- and S-waves from the bottom of the shallow sediment layer, respectively. Then we applied the stretching interpolation method to the obtained pseudo shot records. Results confirmed that time variation of P- and S-wave velocity in the shallow sediment layers are stable with its velocity changes of less than 1 percent without large seismic events.

On 1 April 2016, a large offshore earthquake, the off Mie earthquake (Mw = 6.0), occurred. DONET KME18 seismometer is located in the vicinity of the source region with horizontal distance of less than 10 km, and clearly observed co- and post-seismic events including aftershocks and tremors. In pseudo shot records obtained from the KME18 seismometer, large S-wave velocity change of 5 percent maximum, was observed as co- and post-seismic velocity change with duration of approximately 20 days, although velocity change of P-wave was less than 1 percent in the same duration. Results confirmed that change of pore fluid migration and crack distributions, which could be caused by strong motion of the large earthquake, are observable as a proxy of stress distribution and changes below each seismometer by using ambient noise records.

We plan to perform further analysis and discussion including S-wave anisotropy analysis and more quantitative discussion of the relationship between seismic velocity, its anisotropy, pore-fluid pressure and stress for this approach to be used as simple stress monitoring tool to understand the mega-thrust earthquake preparation and generation cycle.

Keywords: Nankai Trough, Mega-thrust earthquake, DONET, Velocity monitoring, Seismic interferometry

Estimation of Shear wave anisotropy of Transeversely Isotropic medium by Full Waveform Inversion

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In reflection seismic survey, relatively low resolution information can be obtained over a wide range, whereas the borehole logging data contains a high precision data in a narrow range. It is important to estimate the physical properties by integrating these two kinds of information. Recently, anisotropic structure in the subsurface has drawn attention because of its impact on the seismic survey and interpretation. The velocity of seismic wave varies due to natural fractures, sediment structures and selective crystal structures of subsurface materials. Understanding anisotropic properties is important to estimate dynamic properties such as deformation and stress of rock inside the earth and to estimate the composition of minerals.
In this research, a numerical experiment is conducted on the sonic logging model which contains the anisotropic layer. A cross dipole, which consists of two orthogonal dipole sources, is used as a transmitter. For the anisotropic model, a transversely isotropic medium with a horizontal axis of symmetry with five independent elastic elements is set. According to previous studies, it is suggested that the received waveform obtained by the cross dipole measurement changes with the degree of anisotropy of the rock. Distinctive feature can be observed when shear wave passes through the anisotropic layer and splits into two polarized waves: fast shear and slow shear. We attempt to estimate the elastic parameters using the shear waves. Full waveform inversion (FWI) is applied to estimate the elastic parameters directly. FWI is one of the techniques to estimate the ground physical properties with high accuracy and resolution by updating the model parameters so as to minimize the residual between the observed and the calculated waveforms. As a result, it was suggested that highly accurate estimation of elastic parameters is achieved by applying FWI to the layer where anisotropy exists. Although the resolution depends on the receiver interval in conventional slowness time coherence method, it is suggested that FWI can estimate ground physical properties with high resolution.

Keywords: Anisotropy, Full Waveform Inversion, Borehole Geophysics

Quantitative simulation of silica scale deposition from physical kinematics perspectives

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Silica scaling restricts the heat extraction and deteriorates the power generation efficiency in geothermal systems. Although drug injection and pH adjustment are practiced in various fields as a countermeasure against this problem, they are still in a stage where trial and error are repeated. The main obstacle of this problem is that the mechanism of silica scaling has not been revealed yet.
In order to predict silica scale precipitation and establish an effective countermeasure means, it is indispensable to construct a numerical calculation model. However, scale deposition phenomenon consists of some processes in which a wide variety of physical and chemical elements are intertwined complicatedly, so that the way to find a method leading to elucidation of its mechanism is extremely steep. There have been a large number of studies on silica scale deposition rate, but order of magnitude difference is pointed out between experimental data and predicted value gained from simple chemical kinetics. Several other contradictions are reported when we analyze the scale deposition process from a chemical point of view, so detailed analysis incorporating new elements is required.
As a part of a novel initiative, Mizushima *et al.* (2016) proposed a scale precipitation prediction method that took physical factors into account, and reproduced the increase of local scale deposition depending on fluid flow velocity.
In our research, we propose a complementary method which enables more accurate prediction of silica scale deposition by introducing several physical actions which were not completely considered in the simulation method constructed by Mizushima *et al.* (2016). We regard the silica involved in scale deposition as spherical colloidal particles and evaluate the mechanical balance in the process where the silica particles flowing in the medium fluid adhere to the wall surface and the condition in which the particles once attached to the wall surface peel off again. We perform direct numerical simulations by making discretized motion equation for individual particles in fluid and the equation considering the rotational moment balance for the particles on the wall surface. With this direct numerical analysis, it is possible to track the particle behavior stably without any restriction due to the grid intervals.
We applied all possible physical kinematic effects to a fine particle including drag force by fluid, gravity, buoyancy force, Van der Waals attractive force, electrostatic repulsive force, and Brownian motion, which is dominant in the diffusive behavior of particles. We set a 2D parallel plate channel with and without the slip flow condition. In the process of particle adhesion to the wall, we calculate particle motion by setting particle arrangement. Particles are moved in the fluid by diffusive effect mainly based on Brownian motion till they reach the wall vicinity where adhesive force is dominant. In the process of particle detachment from the wall, we evaluate the moment balance with random elements and count the number of particles peeling off the wall. The final scale deposition rate per unit surface area was given by using 100,000 realizations.
Our simulation results of silica deposition rate show good agreement with the experimental data (Hosoi and Imai,1982). Furthermore, our analysis of the shear flow effect on the detachment of deposited particles makes it possible to explain the trend of field observation (Mercado *et al.*, 1989). It is a remarkable achievement in this research that we elucidate once again the necessity to incorporate the physical process into the prediction of scale deposition. Since our quantitative simulation has wide expandability, the proposed method can be a novel tool to evaluate the influence of particle deposition in not only geothermal systems but also oil and gas fields.

Keywords: geothermal energy, scale, silica scale

Fundamental study for estimating azimuthal shear wave anisotropy by applying VSM in marine airgun survey

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Recently, shear wave explorations have been conducted to obtain not only geological structure but also lithological properties of subsurface materials. Although the utilization of shear wave has been drawing the attention, it has been thought difficult to use shear waves in the marine environment due to the lack of shear modulus in water. Some shear sources have been developed for the use in water, they were assumed to use stingers to sub-seafloor or to have surface directly contacting seafloor material that would raise the time cost of survey or risk environmental impact in the utilization.
In the present study, we apply the virtual source method originally proposed by Bakulin et al. (2004) to overcome the existing problems of time cost and environmental impact to exploit the use of non-contact seismic sources in the marine environment. We improved the virtual source method (VSM) to virtually enable the emission of shear waves in water even for air-gun shot records so that the estimation of shear wave structure in the subsurface becomes possible. We confirmed the effectiveness of the proposed approach using a synthetic seismic data set produced by a 3-dimensional finite-difference simulation with the rotated staggered grid. We set a single ocean bottom seismogram (OBS) on the seafloor and an array of explosive acoustic sources in water beneath the surface. In the subsurface, an anisotropic and an isotropic layers are alternately stacked as a geological model. The azimuthal directions of 45- and 60-degrees of anisotropic layers of horizontal axes of symmetry to the survey line are assumed. It has been proved that the application of our VSM and the Alford rotation could lead us to the assumed azimuthal direction in the subsurface for about two third of the shot locations in the survey line.

Keywords: VSM, Seismic interferometry, S-wave survey, marine survey

AVO analysis using horizontal component of seismic data in equivalent offset migration method

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On exploring subsurface resources such as oil or natural gas reservoirs, seismic reflection survey has been widely implemented in order to image subsurface structures. In recent years, utilization of S-wave or converted wave is required for estimating lithology or petrophysical properties of reservoir rock. However, such an analysis of S-wave seismograms had been relatively difficult. On the other hand, equivalent offset migration (EOM) proposed by Bancroft et al. (1998) is one of the prestack time migrations and has been found to be effective method for imaging S-wave information on the common scatter point (CSP) gather with recorded horizontal component in our previous study. Furthermore, S-wave AVO effect has also been confirmed by the amplitude reversal of S-wave event on the CSP gathers.
Therefore, we propose the procedure of accurate estimation of densities and shear modulus with S-wave source. First, we conduct numerical experiment with a 2D layer model using horizontal point force to obtain horizontal component seismic data, in which we can get higher S/N data about S-wave. Second, we implement EOM with those data to get CSP gather, and calculate each cross-correlated value versus incident angle as observed waveform information. Third, in contrast, we generate calculated waveform information as a function of incident angle and physical properties with geometrical spreading, radiation pattern and S-wave reflection coefficient. Finally, we can estimate the optimal solutions by minimizing the misfit from the both information.

Keywords: AVO analysis, Equivalent offset migration, Common scatter point gather

Numerical analysis of passive seismic emission tomography method using oscillation caused by multiphase flow

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Recent years, passive seismic emission tomography, which utilizes seismic signals induced by fluid flow inside reservoirs, has drawn attention to visualize the subsurface. For example, Ted et al. (2016) use the oscillation caused by the oil flowing in the production well to estimate the position of the production well. They detect production well correctly even in the noisy situation near the highway. They conclude that in future they might be able to detect the location of cracks, through which fluid pass through, created by hydraulic fracturing. In addition, Erokhin et al. (2014) estimates the reservoir’ s location and extent using a long period of time records on surface receivers. However, these attempts are experimental, and it is not sufficient to theoretically elucidate the mechanism of oscillation caused by fluid flowing. In this study, we calculate two-phased flow i) oil-water flow model and ii) gas-oil flow model using Lattice Boltzmann Method (LBM) to observe oscillation caused by fluid flowing. LBM is a method to simulate Newtonian fluid with collision models such as Bhatnagar-Gross-Krook. We adopted LBM because it is good at parallel calculation and it can easily deal with multiphase flow. After calculating the seismic waves caused by the stress disturbance occurred in the pore throat using LBM, we calculate waveforms at receivers using the wave propagation solution using Green function under the assumption of isotropic homogeneous medium.

In oil-water flow model, we detect induced waveform with the maximum amplitude of about 30 Pa when an oil droplet passes through the pore throat. On the other hands, we detect 250 Pa of maximum amplitude when a gas bubble passes through the pore throat. Since we can observe the substantial changes of received waveforms due to the difference of fluid property, it suggests the possibility to estimate the change in the properties of the fluid in the reservoir from the observed micro seismic waves. Using those micro seismic waves, we estimate the location of the reservoir. Next, we record micro seismic waves while the reservoir size is gradually expanded. As we change the using record duration for estimate reservoir location, the estimated result is changed and it was consistent with the simulation model. This result shows the effectiveness of PSET using fluid flowing for monitoring reservoir which is producing oil.

Keywords: Passive seismic, LBM

The effect of flowing small particles on flow characteristics and closure of pore in porous media

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In the production of fluid resources from subsurface reservoir, sanding is the most problematic phenomena which could prevent effective production and sometimes chokes the flowline. The cause of the phenomena is thought as the detachment of sand particles in the matrix of formation to flow into pores of reservoir. These sand particles reduced the permeability of porous flow in the formation and could result in the decrease of production. To evaluate "sanding", it is needed to find the mechanism of this. But it is difficult because many factors affect this phenomenon, e.g. fluid viscosity, shape of sand particles. So, we investigate the mechanism of "sanding" using numerical simulations.
We investigate the effect of some factors; viscosity of flowing fluid, shape of sand particles, and the velocity of fluid. We found that permeability is dramatically decreased by closure of fluid pass when high viscous fluid flows in porous media. In terms of the shape of sand particles, square grains suppress the probability of closure of flow pass because square particles can change the length of particle orthogonal to flow direction by rotation. On the other hand, the velocity of fluid does not affect the decrease of permeability and the probability of closing so much. The decrease of permeability is almost the same among all velocity situations.

Keywords: permeability, sand particles, particle method

Fundamental research on the role of differential stress in hydraulic fracturing in strength-anisotropic medium

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Hydraulic fracturing is a technique to enhance the permeability around the borehole to create fracture networks in oil and natural gas reservoirs. Since the performance of hydraulic fracturing is not fully predictable beforehand, it is important to pre-estimate the extension and the connectivity of artificial fractures for a given condition such as in-situ stress and various mechanical properties of reservoir rock. It, therefore, has been drawing attention to achieve this with a method of numerical simulation in recent years.

Although microscopic failures and propagation of cracks are known influenced by the ratio of the maximum to the minimum radius of spherical elements, the viscosity of injected fluid, the existence of natural fractures, etc., the propagating direction of hydraulic fractures is in the direction of horizontal maximum stress in an isotropic medium. Since reservoir rock of shale oil or gas is anisotropic in the mechanical properties inferred from several laboratory tests, the propagating direction of hydraulic fractures is known strongly affected by the direction of anisotropy axis. Since there is few researches conducted on the numerical simulation of hydraulic fracturing in strongly anisotropic media with the existence of differential stress towards the borehole, it is necessary to examine the role of the differential stress. We give mechanically anisotropic properties such as uniaxial compressive strength, uniaxial tensile strength, permeability, etc., based on the calibration of microscopic parameters of DEM to represent macroscopic parameters of the reservoir rock. The empirical assumption of macroscopic uniaxial tensile strength distribution is introduced into microscopic strength of the model. Contact and bond forces are given to neighboring particle elements in the model, and both tangential stresses from interstitial fluid are applied to each particle.

The result showed that if the differential stress is large, hydraulic fractures tend to propagate in the direction of maximum principal stress whereas hydraulic fractures tend to propagate in the direction of bedding plane under low differential stress.

Moreover, this information suggests that in the shale reservoir, which has mechanical anisotropy, the differential stress has important role in estimating the propagation direction of hydraulic fractures.

Keywords: distinct element method, hydraulic fracturing, strength anisotropy, shale

Development of Phased Array Ground Penetrating Radar for near surface exploration

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A portable and non-destructive geophysical tool, Ground Penetrating Radar (GPR), enables us to quickly detect the objects in the shallow subsurface such as cavity, electric cables or water pipes. It is increasingly applied for preventing near surface hazards. Although the resolution of GPR under the antenna is generally very high, the resolution out of the survey lines is depending on the shape of the antenna. We have recently introduced a phased array antenna as a new radar source to overcome this problem (Kikuchi *et al.*, 2016). We showed that comparing with the conventional dipole antenna, the phased array antenna increased the signal-to-noise ratio in observed data resulting from heterogeneity of subsurface and it improved the migration results for the reflectors located lateral to the survey line. However, the coupling effect between array antennas on generated waveform was not taken into consideration. In this study, we calculate the mutual impedance to evaluate the mutual coupling of the array to determine the suitable antenna arrangement. Then, we conducted some GPR surveys in more practical conditions. We use a FDTD method to simulate the propagation of electromagnetic (EM) wave field. Kirchhoff migration method is used to make a 3-D image of subsurface. Our results show that the phased array antenna provides more reliable migration results compared to the dipole antenna we have designed. We conclude that our developed new GPR has an advantage in detecting objects between the survey lines or under the surface structures where we cannot draw a survey line. This will surely lead to the reduction of the cost of GPR surveys.

Keywords: Ground Penetrating Radar, mutual coupling

Walkaway surface wave survey: a new method for obtaining wide frequency band phase velocities utilizing walking noises along a linear seismic array

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We propose a new passive seismic survey method for obtaining phase velocity curves of Rayleigh waves in a wide frequency band utilizing walking noises along a short-spacing linear seismic array. The method is featured as a technical extension of “hybrid surface wave survey method” we proposed in 2014, and is originated from the passive surface wave survey method named “Linear Array Microtremor Survey” (LAMS), also proposed by the last author in 2011. In the LAMS, spatial autocorrelation (SPAC) analysis is employed for the calculation of a dispersion curve for an arbitrary pair of seismic records estimating random or isotropic microtremor source. Furthermore, the linear array or setting a number of geophones along a line enables us to obtain more accurate phase velocity curves by applying common midpoint spatial autocorrelation (CMP-SPAC) analysis proposed by the third author in 2015. The hybrid surface wave survey is characterized as the combination of active and passive surface wave survey simultaneously conducted along the same seismic line. A number of geophones, set along a line at 0.5 to 2 m intervals, are used to record active surface hitting waveforms and passive microtremor. Two dispersion curves, one is for a higher frequency part calculated from common midpoint cross-correlation (CMP-CC) analysis to active survey records, and the other is for the lower frequency part calculated from passive data applying CMP-SPAC analytical method, are combined to form a single dispersion curve for a specific CMP in a survey line. The method enables us to reconstruct a dense 2D S-wave velocity profile along a line up to 50 m in depth or more using conventional 4.5 Hz geophones. One of the advantages of hybrid surface wave survey is its robustness to the traffic noises or positive utilization of them vice versa. It means it is more suitable for the method to set the line along trunk, heavy traffic highways. We have conducted hybrid surface wave surveys along operational highways which had traffic flows of 300 to 1,500 vehicles per hour. During the field tests, we found a more effective noise source. That is, random walking but along the survey line. We could efficiently obtain wide frequency band dispersion curves emulative to both active and passive survey, only from passive seismic data including noises generated by waking along the survey line. The method is expected to expand the surface wave survey for delineating high-resolution 2D S-wave velocity structure in large urban areas.

Keywords: surface wave, passive seismic, linear array, walkaway noise

Repeatability of time-lapse measurements using ACROSS in Saudi Arabia

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Introduction

To do the time lapse for monitoring of injected CO_2 in CCS (carbon capture and storage) and EOR, we have used the ACROSS (Accurately Controlled and Routinely Operated Signal System) methodology to monitor the change of subsurface (Kasahara *et al.,* 2010; Kasahara and Hasada, 2016). To evaluate the true subsurface change, it is necessary to clarify the repeatability of the measurement system including instrumental parts of seismic source and receivers. Many factors contribute to repeatability of observation; seismic source signature, ground coupling of source and/or receivers, fixing accuracy of source and/or receiver locations, media along paths, and true subsurface changes (Kasahara and Hasada, 2016). In this presentation, we will examine the repeatability of our measurements by the field data in Saudi Arabia.

We used data obtained by 30 seismic stations in Al Wasse field in 2013–2014 and 2015. In addition, we carried out the refraction survey using the ACROSS seismic source. In the source-gather records the first arrivals decayed at the offset distance further than 700 m. This is thought to be caused by velocity inversion just below the top layer. The characteristics of weak first arrivals at the distance around 500–700 m might affect the repeatability

NRMS Repeatability

Kragh and Christie (2002) proposed NRMS for the repeatability between two traces. If two traces are uncorrelated, the NRMS error is 200%. If one of the traces has half amplitude of the other, the NRMS is 66.7%. In the case of the Gulf of Mexico, the best values were 18–30% (Kragh and Christie, 2002). Eiken *et al.* (2003) obtained approximately 40% NRMS by two surveys with 25 m lateral offset. For most of 4D survey, 10–30% is thought to be a typical good value (Johnston, 2013).

Results of repeatability estimation

We examined the NRMS repeatability using a geophone in the ACROSS source room. Though the analyzed duration is short, the NRMS during 12 days were less than 2%. We can clearly identify daily variations in this source room data possibly caused by housing deformation due to the large variation of outside temperature. The source was in the desert area in winter and the outside temperature was so low during nighttime.

Next, we calculated the travel time variation (dT) and the amplitude variation (dA) for the field stations using the cross-correlation of P-wave portion. The dT and the dA in some stations show small temporal variation during two periods with about two-years interval. We also calculated NRMS using the same P-wave portions. NRMS variation of the stations #33 and #53 were smaller than 5% in the first and the second periods, and it is similar results seen in dT and dA.

Considering the NRMS at ACROSS source room, the NRMS of source itself is small (< 2%) and the environmental changes affect the NRMSs of the field stations showing very large variations. Because the field geophones were located at the surface and the test field has more than 64 water-pumping stations, the apparent NRMSs observed at the grid stations show great temporal variation, which are considered time lapse itself. In addition, the weakening of first-arrivals mentioned above could affect the NRMS variation.

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Keywords: Time lapse, Subsurface, CCS, repeatability, ACROSS