The utility of marine controlled-source EM in subduction zone applications: Imaging the Nicaragua megathrust plate interface

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Electrical resistivity soundings are ideally suited to map fluids and quantify porosity, and provide important independent constraints that are complimentary to seismic observations. As a result of recent technological advancements in instrumentation and numerical modeling, the controlled-source electromagnetic (CSEM) method is emerging as a reliable tool for imaging offshore tectonic margins. In 2010, we collected CSEM data along a 280 km profile spanning the incoming plate, trench, and forearc slope offshore of Nicaragua, the first large-scale survey at a subduction zone. The results highlight the utility of CSEM for imaging seafloor gas hydrates, fluid pathways along faults, and subducted sediments marking the plate interface. We used the porosity estimates from the resistivity observations to quantify the fluid budget in the incoming oceanic crust and the outer forearc. The data were highly sensitive to the channel of subducted sediments, allowing us to track the evolution of the fluid budget along the megathrust plate interface in the region that ruptured during the Mw 7.7 1992 tsunami earthquake.

Sensitivity analysis of high conductivity anomalies in the upper mantle beneath the Society hotspot

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We obtained a three-dimensional (3-D) electrical conductivity image of the upper mantle around the Society hotspot in French Polynesia, and we have found four high electrical conductivity anomalies in the upper mantle. One of them has already been introduced in Tada et al. (2016), which is a distinct high electrical conductivity anomaly and may be continued from the transition zone up to at a depth of approximately 50 km below the sea level. Although the other conductive structures have not been mentioned in Tada et al. (2016), they are also distinct features. Besides, collaborating with results from seismic tomography (Isse et al., 2016; Obayashi et al., 2016), it is crucial to check sensitivity and validity of each anomaly. So, in this presentation, we will present detail procedures for obtaining the 3-D electrical conductivity structure and discuss what we really constrain in the 3-D structure.

Keywords: 3D inversion, marine magnetotelluric method, electrical conductivity structure, mantle plume, Society hotspot

Noise reduction of horizontal components of magnetic field by means of Independent Component Analysis and its application to the Magnetotelluric survey in Boso peninsula

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We carried out a MT survey in the Boso peninsula (Chiba, Central Japan) to investigate the resistivity structure of the area where the slow slip events have occurred at least five times within 20 years. Large artificial noise contaminated in the MT data and the resistivity and phase showed near field effect at the frequency band below 1Hz. To avoid the local noise, we attempted to apply the independent component analysis (ICA).
ICA is one of the multivariate analysis methods and in which complicated data sets can be separated into all underlying sources without knowing these sources or the way that they are mixed. It assumes that the mixing is liner, and yields the relation x(t)=*A*s(t), where input signals x(t), mixing matrix *A* and source signal s (t). The matrix $W\,(=A^{-1})$ is computed in the ICA. In this study, we used the frequency domain ICA program for complex signals to deal with the phase part. This is an extension of FastICA algorithm which was introduced by Aapo and Hyvärinen (2001) and is based on a fixed-point iteration scheme for complex valued signals.
We applied the ICA method to improve horizontal magnetic components in MT data. Two components of ICA using both the data observed in Boso area and the noise free magnetic data observed in Esashi, Sawauchi or Kakioka Magnetic Observatory was applied for each magnetic component. The magnitude of magnetic intensity varies over large ranges in wide frequency band. To work ICA effectively, we needed to divide into narrow frequency bands and applied the ICA at each band. After applying ICA, in order to extract noise free component which showed high correlation with data in noise free site, we kept the noise free component and set to 0 in other noise component. Then we applied inverse matrix of *W* to obtain original x, i.e. $x(t)=W^{1}u'(t)$, where u'(t): components vector after ICA, x(t): the original data vector. Finally, we used the BIRRP processing to calculate the apparent resistivity using improved horizontal magnetic components.
After the ICA processing, the apparent resistivity showed gentle change and the phases take non-zero values. This result meant that some parts of the noise components such as near field noise were removed. These results revealed that ICA has a potential to handle noisy data. But, the ICA processing not every frequency band worked effectively and the horizontal magnetic components were well improved by the conventional remote reference method. Finally, the most suitable apparent resistivity and phases were chosen for each frequency band from the results of both methods.
We estimated the resistivity structure using the improved data and discussed the structures in relation to geological structure and the presence of fluid.

Keywords: MT methods, Magnetotelluric, independent component analysis

MT survey at Boso Peninsula, Japan and its preliminary results -Effectiveness of Multi-channel Singular Spectral Analysis (MSSA)-

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A magnetotelluric (MT) survey is one of the methods to understand the underground electric properties. In Boso area, Japan, there are three main topics to perform the MT survey; (1) to estimate underground resistivity structures related to the plate boundaries, seamount, asperities, and slow slip events; (2) to obtain a regional realistic resistivity structure for the numerical simulation in generation and propagation mechanisms of electromagnetic precursors, and (3) to develop a new MT technique to reduce the cultivated noises such as DC-driven train system and factories. For challenges to solve them, we decided to carry out the MT survey in Boso area, Japan during 2014 - 2016. Due to sensing down to 100 km depth, we used induction and fluxgate magnetometers. We set 41 and 12 sites for induction and fluxgate type magnetometers, respectively.
To remove noises from MT data, we attempted remote reference method that is conventional MT method in frequency domain. Hereupon, MT impedance at southern Boso area is improved to a certain degree. In other hand, the one at northern Boso are is not very improved. Therefore, we attempted MSSA (Multi-channel Singular Spectrum Analysis) for MT data in time domain to improve MT impedance. We performed SVD (Singular Value Decomposition) of original time series in MSSA, and reconstructed time series by using the principal components that indicate relatively high correlation in horizontal geomagnetic field between observation site and remote reference site. Then, unexpected MT impedance seen after remote reference method is tend to be restrained. It supposedly indicates that preprocessing MT data in time domain is effective and promise.
We calculated underground resistivity structure from southwest to northeast by using long period sites' data, there is low resistivity region (0.1 –10 ohm-m) around 1 - 2 km depth. This region possibly indicates fluid in sediment layers overlying large amount of surface at Boso area. There is low resistivity region (0.1 –10 ohm-m) under about 3 –10 km depth at southwest site, which possibly indicates ultramafic rock or accretionary prism pushed up by subducting seamount.

Reevaluation of resistivity sturcture beneath the Ohara fault of the Yamasaki fault zone, southwest Japan

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The Yamasaki fault zone (YFZ) consists of the Nagisen fault, the main part of the YFZ, and the Kusadani fault. The main part of the YFZ is further divided into a northwestern (NW) group (the Ohara, Hijima, Yasutomi, and Kuresakatouge faults) and a southeastern (SE) group (the Biwako and Miki faults) based on their latest faulting events and mean slip rates; AD 868 and 1.0 m/kyr for the NW group vs. AD400 - 600 and 0.8 m/kyr for the SE group (Okada, 1987; Earthquake Research Committee, 2013).
Magnetotelluric methods are powerful methods of surveying the subsurface structure of active faults as characteristic electrical conductivity variations are expected around an active fault. Among available methods, the audio-frequency magnetotelluric (AMT) method is useful because of its high spatial resolution for the depth range concerned. Many AMT surveys have been made along lines across the main part of the YFZ, aiming to reveal conductivity structure beneath each faults and relationship between them. Ueda et al. (2010) made an AMT survey along the line (~10 km) across the Ohara fault and proposed the two-dimensional resistivity model. However the model did not delineate resistivity structure well because of wide station spacing and severe artificial noise, so we made an additional AMT survey along the same line and established the new 2D resistivity model (OHR model)
The Ohara model is characterized by one resistive region (R1) and four conductive regions (C1 - C4). Region C1 locates just beneath the surface trace of the Ohara fault, region C2 exists to the northeastern side of the surface trace in depths 0.5 –1.0km, and region C3 is located to southwest of the surface trace and whose top depth is ~1.0 km.
Other two-dimensional resistivity models of the Ohara and Hijima faults have been proposed along two lines; the OHJ model along the line across both the Ohara and Hijima faults (Ueda, 2010) and the HJM model along the line across the Hijima faults (Yamaguchi et al., 2010). Three common features on resistivity structure were recognized; (1) Near surface conductive region commonly recognized just below the surface trace or between two surface traces, (2) Conductive regions are located to the northeastern side of the Ohara fault in depths 0.5 –1.0km, but not to the northeastern side of the Hijima fault, and (3) Conductive regions whose top depth is ~1km are recognized to southwestern side of both the Ohara and Hijima faults.
In this presentation, we outline observation, data analysis, and modelling process, then explain characteristic conductive regions of the newly obtained OHR model. Finally, we show along strike variation of resistivity structure beneath the Ohara and Hijima faults.

Keywords: active fault, resistivity structure, Yamasaki fault zone, Ohra fault, Magnetotelluric method

Reliability estimation of MT-data inversion using principal component analysis

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Magnetotelluric (MT) method, one of electromagnetic survey methods, is used for resource exploration and active fault survey. At the estimation of subsurface resistivity structure, inversion algorithms based on the least-square scheme are adopted to the observed apparent resistivity and phase. The optimal resistivity model obtained by the inversion is recognized as the approximate solution of true structure, because of the noise at measurement and the constraints at inversion. Therefore, the reliability of resistivity model is mandatory. In previous researches, the reliability could be confirmed with changing a part of the optimal model, how apparent resistivity and phase calculated from the modified model differ from the observed ones. However, this reliability test is qualitative and subjective. In this research, we develop a new way to test the reliability of the resistivity model objectively and quantitatively.
Evaluating an enormous number of model parameters takes much amount of computation time. On the other hand, reliability test of major resistivity anomalies makes the time shorter. In this research, we use principle component analysis (PCA), which can extract the primary structure from data, and try extraction of the major anomalies in an optimal model obtained by inversion. Concretely, a two-dimensional resistivity model is split into series of one-dimensional models for PCA. The principle components show the common features of resistivity distribution in horizontal or vertical direction. To modify the optimal model, we modify the principal components and the scores. Finally, we created thirty different resistivity models from the optimal model. Based these new models, a root mean square error between the observed and calculated apparent resistivity and phase are used to discuss the reliability of optimal model, as usually done in the previous studies.
In order to examine the validity of this technique, we used MT synthetic data (TE mode) on a model having high and low resistivity anomalies. We found that the assumed two resistivity anomalies in the inverted model appeared in the first principle component in PCA. We changed the principle component scores, and succeeded in shifting the anomalies vertically and horizontally. Moreover, we tried to visualize the reliability range of position/values of anomalies. The obtained reliability map corresponds to sensitivity trend of MT inversion in TE mode.
We also applied this technique to more complicated resistivity model. As a result, anomalies in the models were also detected properly, and the quantitative reliability of each anomaly was evaluated automatically. In future prospects, we will improve this technique for more quantitative estimation of reliability of models, and adopt it to MT inversion with real data.

Keywords: magnetotellurics, PCA, 2-D inversion

Multi-spacing MT observation regarding anomalous phase responses

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The magnetotelluric (MT) impedance tensor exhibiting anomalous phases greater than 90 degrees are sometimes observed. Since simple 1D or 2D models do not generate such responses, the appearance of them puts a difficulty on the analysis of MT data. The origin of anomalous phases due to characteristic geo-electric structures has been extensively investigated: some attribute to 3D conductive objects and others to 2D anisotropic structures. On the other hand, noises, imperfection of device or tiny objects near an observation site might induce anomalous phase behavior. Inspecting these possibilities and discriminating them for each data will contribute to improve the interpretation of MT responses.

Anomalous phases were observed at several sites in the observation in western Shikoku (Yoshimura et al, 2016). To exploit more detailed properties, we performed a denser, multi-spacing MT observation around one of the sites showing anomalous responses in that observation. Along with standard MT method measuring three components of magnetic field and two components of horizontal electric fields (3H2E), we measured redundant four components of electric fields (3H4E) at two sites. This is intended to examine the possibility of device or tiny objects.

The estimated response functions show the reproducibility of anomalous responses irrespective of the arrangement of electrodes, which confirms that the cause is different from device or tiny objects. Responses at different sites impose some restrictions on the spatial distribution where anomalous phases appear at this region, and we discuss the origin of anomalous responses.

Keywords: MT method, anomalous phase

DC potential imaging of a granite surface

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To reveal resistivity structure of small-scale (˜10 cm) rock samples is an important topic for the purpose of deciphering results of geophysical explorations, but considered to be difficult so far. It is difficult to inject electric current into a resistive rock sample and to measure the potential distribution on it. It is also difficult to prevent leakages, which makes it almost impossible to measure the electrical potential on a highly resistive rock samples. In addition, there are a few materials that can be attached on the surface of a rock sample in arbitrary shape as electrodes with conduction performance. For these reasons, simultaneous measurements of electrical potentials at multiple points on a rock sample have not been achieved.

We have developed an experimental set-up to achieve the potential measurement of rock samples as follows. Potential of the rock sample with very high resistance was measured by using an electrometer with extremely high input impedance. Leakage current was prevented by "floating measurement", in which circuits of measurements are separated from the ground. The high-density electrode arrangement on the rock sample surface is achieved by using electrodes made from conductive epoxy, which is not conventionally used as electrode.

Using these methods, we measured potential distribution on the granite surface into which direct current was injected. Obtained results agree roughly with numerical simulations, meaning the new experimental set-up reasonably works.

Keywords: electrical resistivity of rocks, laboratory tests, electrometer with extremely high input impedance, floating measurement, conductive epoxy

Electrical impedance measurement of geothermal reservoir rock under fluid-flow test

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The estimation of underground water saturation is essential in geothermal fields, particularly for an enhanced geothermal system (EGS). Recently, electromagnetic exploration using magnetotellurics (MT) has been applied to the geothermal fields for estimating water saturation. However, the relationship between the electrical impedance obtained through this method and the water saturation in the reservoir rock has not been well known. Our goal is to elucidate this basic relationship via fluid-flow experiments, and as our first step, we developed a technique to measure and analyze the electrical impedance of geothermal reservoir rocks under fluid-flow test. In this test, at first, reservoir rock samples were filled with nitrogen gas (P_p = 10 MPa) under 20 MPa of confining pressure; the gas emulates the superheated steam that is observed in the geothermal fields. Then, brine (1wt% KCl, 1.75 S/m), which emulates the artificial recharge to the reservoir, was injected into the samples. After the flow rate of the drainage fluid stabilized, the brine injection pressure was increased (11, 12, 14, 16 and 18 MPa) and decreased (18, 16, 14, 12 and 11 MPa) to vary the water saturation in the samples. During the test, water saturation, permeability, electrical impedance (at a frequency of 10^{-2}-10^{5} Hz) and elastic wave velocity were measured. As a result of fluid-flow test on andesite (Makizono lava formation, Japan), the electrical impedance dramatically decreased from 10^5 to 10^3 Ω because of the brine injection. This remarkable change could be due to the replacement of pre-filled nitrogen gas with the brine. After the brine injection, the electrical impedance decreased with increasing injection pressure (small changes in water saturation) by up to 40%. After increasing the injection pressure, the pressure was decreased to study the hysteresis of each parameter. The electrical impedance increased with decreasing injection pressure in the pressure-decreasing phase, and this electrical impedance was smaller than that observed in the pressure-increasing phase (up to 27% at 11 MPa of injection pressure). However, the P-wave velocity was almost constant (less than 1%) at that time. These results indicate that the electrical impedance varied with small changes in water saturation in the pressure-decreasing phase, whereas P-wave velocity did not show any variations. In other words, this suggests that electrical impedance could be sensitive to minor changes in water saturation compared with P-wave velocity. Therefore, electrical impedance could have potential to monitor changes in water saturation in geothermal reservoirs.

Keywords: electrical impedance, elastic wave velocity, water saturation, fluid-flow test, EGS (Enhanced Geothermal System)

Continuous measurement of electrical conductivity for monitoring contact state of simulated fault during frictional sliding

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In laboratory experiments, monitoring the mechanical parameters of simulated fault with other observables during fault slipping will provide us with valuable information to understand the frictional property of rocks and thus the mechanics of earthquake. From this viewpoint, we focused on the electrical property of fault, which has a potential to monitor the contact state on the sliding surfaces. We used a pair of cylinders of metagabbro from India as the specimens and installed them into the rotary-shear frictional testing apparatus at NIED. This testing apparatus allows us to take electrical signals of sensors on the rotary specimen via the slip ring even during the rotation. The diameter of the specimen was 25 mm and the length was 30 mm. To measure the extremely high resistance of dry rock specimens, we adopted two electrometers (Keithley 6514) whose maximum input impedance was 200 TΩ. One electrometer was used to input DC current across the simulated fault and another one was used to measure electrical potential across the fault. First, we conducted a preliminary test under stationary condition to grasp the electrical property of the simulated fault. Since transient response of the electrical potential was observed by the sudden input of electrical current, we recognized that the contacting fault should be modeled as a parallel circuit of resistors as well as capacitors. From the transient response curve, we estimated the resistance and capacitance of the fault under the normal stress ranged from 0.1 MPa to 8 MPa. The experimental results showed that the resistance decreased and the capacitance increased as the normal stress increased This can be interpreted as increase in real contact area of asperities and decrease in height of the asperities at high normal stress under the assumption that the real contact area and the rest of the area (i.e., the noncontact area) work as the resistor and the capacitor, respectively. This suggests we can estimate the real contact area from the measurements of resistance and capacitance as far as the conductivity (inverse of resistivity) of the asperity is constant. Next, we monitored the conductivity of fault under a subseismic slip rate (5.3×10^{-3} m/s) and a constant normal stress of 3 MPa. Friction coefficient, defined as the ratio of shear stress to normal stress, showed typical slip weakening; it increased to 0.8 when slip started, then decreased to 0.2 followed by the fluctuation between 0.2 and 0.6. The electrical conductivity data demonstrated quite similar variation to the frictional strength; when the friction coefficient increased, the conductivity increased, and vice versa. From the measured conductivity data, we further estimated the change in the real contact area and its strength with slip. The estimated change suggests that the initial asperities were fully destroyed at a very early stage and the subsequent gouge comminution phase was dominant in the slip-weakening process. We also conducted similar experiments at seismic slip rate (1 m/s) under the normal stress of 3 MPa. In this mechanical condition, the fault rock melted by the frictional heating and lost its strength so much. Hirose and Shimamoto (2005) reported that the weakening process in this condition is composed of two weakening stages and one strengthening stage between them. They interpreted that these are related to the formation of melt patches and the subsequent growth to molten layer during frictional melting. Our conductivity monitoring quantitatively but clearly confirmed these processes by the rapid increases in conductivity in the two weakening stages. These results confirm that the conductivity is a superior tool to probe the contact state of the fault slipping at various slip rates.

Keywords: Electrical conductivity, Friction experiment, Fault, Asperity