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 $x(t)=As(t)$, 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 Ωbecause 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

A trial of automatic structure analysis for magnetic survey in case of sharp boundaries of magnetization

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Utilizing the modern computing technology, highly complex structure can be automatically analyzed by inverse technique in geophysical exploration. Usually a number of blocks are assigned in the structure model numerically constructed and finally the parameters like as magnetization, density, and conductivity are determined for respective blocks. If the number of the blocks is larger than the number of observed data, that is so-called the under-determined problem. To solve the under-determined problem in inversion analysis, we have to include additional condition like as smoothness. The smoothness is one of promising condition in order to solve the under-determined problem and widely used. The resulted structure model with smoothness is a reasonable model in various cases. However, a structure model with non-smoothness is sometimes necessary in specific problem. We have an opportunity to conduct a magnetic survey at the site above the dacite intrusive rocks. This is one of stereotypes of structure with non-smoothness boundary. We want to have the technique to automatically analyze this kind of structure with sharp boundaries. Here we try to show one of effective algorithm to seek the numerical model with sharp boundaries. The algorithm is a kind of grid searches but effectively saving the amount of calculation. Firstly the structure model with two parameters alone, i.e. with two kinds of the values of the magnetization. Next the structure model with three parameters and more. So far, the algorithm is able to apply to the magnetization in magnetic survey or density in gravity survey. But this kind of algorithm is expected to apply to the problems with conductivity in the future.

Keywords: magnetic survey, grid search, Inversion

Development of aeromagnetic survey system using multicopter.

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Aso Volcanological Laboratory of Kyoto Univ. and Neoscience Inc. has developed an aeromagnetic survey system using multicopter. This system consists DJI S1000 multicopter and Bartington Mag566 fluxgate magnetic sensor and it can be measured magnetic 3-component data at very high sampling in the specified area fully automatically. Using this system, it is expected that we can acquire the magnetic field data on the active area of the volcano even while eruption is occurring.
To test our survey system, we conducted an aeromagnetic survey on Komezuka volcano, located in the northwestern part of the post-caldera central cones of Aso volcano, central Kyushu Island, Japan, on Aug., 2016. Komezuka is a basaltic monogenetic volcano comprising a scoria cone. On this volcano, Hasimoto et al. (2007) measured dense magnetic total field anomaly by ground-based observation. Applying magnetic upward continuation to this data, we can estimate the magnetic anomaly on the arbitrary point above the Komezuka volcano. Comparing this estimated anomaly and observed data acquired by our survey system, we verified the accuracy of our survey system and in our presentation, we will report this result.

Keywords: aeromagnetic survey, multicopter

Attempt at three-dimensional modelling of temporal change in resistivity structure beneath Aso volcano through the magmatic eruption in November, 2014

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In Aso volcano in the center of Kyushu island, Japan, a magnetic eruption occurred on November 25th, 2014, for the first time since the last magmatic event in 1993. Since the magmatic eruption in 2014, phreatic/phreatomagmatic eruptions have occurred several times in Aso volcano recently. To monitor the activity of Aso volcano, a group in Kyoto University have been operating an electromagnetic monitoring system, ACTIVE (Array of Controlled Transient Electromagnetics for Imaging Volcano Edifice; Utada et al, 2007), around the active first crater of Aso volcano. ACTIVE system in Aso volcano consists of one transmitter that transmits electric currents into the ground through two electrodes, and several induction-coil receivers that observe only the vertical component of the magnetic field. In ACTIVE observation results before and after the magmatic eruption on November 25th, 2014, we found obvious temporal changes in the response function, the amplitude ratio of the received magnetic field to the transmitted electric current (nT/A). At the western rim of the first crater, larger amplitudes of the response function were observed over frequencies ranging 10 to 100 Hz after the magmatic eruption. Some movement of underground water/magma may be responsible for the temporal changes.
In order to interpret the ACTIVE data obtained before and after the magmatic eruption including topographic effects appropriately, we developed a three-dimensional forward code, by adopting a vector finite element method (FEM). In our forward modelling, the induction equation in terms of the vector potential, A, is solved with the gauge potential of phi=0 (Hano, 1991). We adopted unstructured tetrahedral mesh to represent arbitrary resistivity structure and complicated topography of volcanos. We demonstrated accuracy of our forward code in comparison to an analytical solution of Ward and Hohmann (1988), in a situation where a horizontal electric dipole is located just on one-dimensional layered structure. Currently, we are trying to apply an existing background conductivity structure obtained by AMT surveys to the background structure in our modelling, to investigate the cause of the temporal changes in the ACTIVE responses. In our presentation, we plan to show our results of forward modelling to interpret the temporal changes observed by ACTIVE system before and after the magmatic eruption in November, 2014.

Keywords: Aso, volcano, electromagnetic, monitoring, resistivity

3-D electrical resistivity model beneath Aso caldera for clarifying magmatism in the lower crust

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Aso caldera, with a diameter of up to 25 km, is situated on the island of Kyushu in the Southwest Japan Arc. The caldera was formed during 270–90 ka by four huge eruptions that produced hundreds of cubic kilometers of pyroclastic deposits. A number of post-caldera cones/volcanoes exist at the central part of the caldera and Naka-dake, one of the cones, has cyclically erupted since the sixth century. In the past few years, Naka-dake experienced a magmatic eruption in November 2014, a phreatomagmatic eruption in September 2015, and an explosive eruption with spewing volcanic ash 11,000 m into the air in October 2016.

The crustal structure beneath Aso caldera has been studied previously by electromagnetic and seismic surveys. Seismic tomography of the crust has identified low-velocity anomalies beneath the caldera that may correspond to magma chambers [e.g., Sudo and Kong, 2001; Abe et al., 2010]. Sudo and Kong [2001] reported a spherical low-velocity anomaly centered at 6 km depth that flattens at 10 km depth to the west of Naka-dake. Abe et al. [2010] reported a large, low S wave velocity layer at a depth of about 17 km, corresponding to the Conrad discontinuity in and around Aso caldera. Hata et al. [2016] revealed a possible magma pathway in the form of a significant series of electrical conductive anomalies in the upper crust, extending north from Naka-dake at depths of >10 km. However, the space resolution of a magnetotelluric (MT) survey was insufficient to examine the lower crustal structre in the electrical resistivity/conductivity model for a deep-seated magma reservoir associated with the post-caldera magmatism beneath Aso caldera.

We had carried out a MT survey of about 40 sites mainly at the outer part of the caldera from Nov. to Dec. 2016 in addition to the previously obtained about 50 sites in the caldera from Nov. to Dec. 2015. By using the period range between 0.005 and 2,380 s of MT data for about 100 sites in total, we try to perform three-dimensional (3-D) inversion analyses in order to obtain a crustal-scale electrical resistivity structure (model). In the inversion process, we use a parallelized DASOCC inversion code [e.g., Siripunvaraporn and Egbert, 2009]. In this presentation, we will show the new crustal-scale resistivity model beneath Aso caldera.

Predicting 3-D resistivity structure from magnetotelluric data in the southern geothermal area of Hokkaido, Japan

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Geothermal gradient is high in Oshima Peninsula located in the southern part of Hokkaido. Especially in "Yakumo-Nigorikawa geothermal zone" located in the central part of the Peninsula, where recent volcanic activity is not seen, the geothermal gradient is the highest. Many geothermal features and hot springs are found in this zone, and many geothermal studies have been performed in various ways. We carried out new Magnetotelluric survey in Yakumo area at 20 stations, and reported 2-D resistivity structure used 2D inversion code (Ogawa and Uchida, 1996) last year. We tried to construct 3D resistivity structure using ModEM (Egbert and Kelbert, 2012) based on same site data. However, resistivity structures are different from 2D resistivity structure. To investigate validity of 3D resistivity structure, we checked reproducibility of a rectangular structure. The result showed that; when we distributed observation points equal short spacing regularly, we got good reproducibility, but inverted structure did not fit the original shape. We concluded, based on the test inversion, that we need to use short spacing equality distribution of data points to get good inversion result. The site distribution is not equal array and space distribution in Yakumo area survey, and we could not get correct 3D structure.

Keywords: Magnetotelluric method, 3-D inversion, ModEM

Wideband MT survey in Aridagawa non-volcanic earthquake swarm region, Wakayama Prefecture

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An active non-volcanic earthquake swarm has been observed at the north western Wakayama area. Kato et al. (2010) performed high-resolution tomographic imaging of seismic velocities and proposed that these swarms are triggered by circulating fluids and fluid pressure fluctuations driven by the thermal anomaly of the solidified diorite magma. In 2009, Uyeshima et al.(2010) performed MT survey in the Aridagawa area, southern margin of swarm activity, and detected conductive anomaly structure that presume the existence of connected interstitial water. But the details of the relationship between the swarm activity area and resistivity structure have not still understood well.

In 2015, we performed wideband MT survey at another profile across the Aridagawa area. Five component electromagnetic fields were measured at 5 sites by ADU-07 (Metronix Geophisics). We obtained continuous 1024Hz data, which were saved in the CF-memory once per an hour. After the survey, we made 32Hz and 1Hz data by downsampling. To avoid leakage current noise from the DC train (the Kisei main line), in analyzing the 1024 Hz data, we used only midnight data that was obtained from JST 2 to 5 a.m..

MT responses of a frequency band of 384-0.039Hz were estimated using remote reference method and the robust processing code BIRRP (Chave and Thomson, 2004). From the GB decomposition analysis (Chave and Smith, 1994, Toh and Uyeshima, 1997) and geological features, we considered that the optimum regional strike is in the EW direction. We tried to obtain a 2-D resistivity structure along N-S profile with the aid of the REBOCC 2-D inversion code (Siripunvaraporn and Egbert, 2000). In this presentation, we show the results of 2-D inversion and the relationship with the swarm activity.

Keywords: Wideband MT survey, Aridagawa region, Wakayama Pref., non-volcanic earthquake swarm region

A research report on the fundamental investigations of an electrical resistivity structure beneath Chugoku and Shikoku regions, southwestern Japan(2016)

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In order to contribute to a reduction in damage caused by earthquakes and volcanic eruptions, heterogeneities of crustal and upper mantle structure should be clarified based on fundamental investigations of electrical resistivity structure in Chugoku and Shikoku regions, southwestern Japan arc.
In this presentation, a research report on fundamental surveys for the following two topics, using data acquired in 2016 incorporated in the existing data, will be shown.
(1) Our research group has shown that there is a clear relationship between resistivity and seismicity in the Sanin and Shikoku regions. In the eastern part of San-in region, it was found that a conductive area exists in the deep crust part under the seismic region, which is a resistive area, along with the seismic activity area stretching nearly in the east and west direction. Harmonious research results has been shown from geodetic GNSS(GPS) data analysis by Nishimura (2015) who implies that relationship between strain concentration zone in Sanin region and the occurrence of the 1943 Tottori earthquake, the 1983 Tottori Chubu earthquake, and the 2000 western Tottori earthquake. Assuming that inland earthquakes occur because of local stress concentration caused by heterogeneity beneath a seismic activity band (Iio, 2009), the heterogeneity in this area should be clarified hereafter.
In this background, a Magnitude (M) 6.6 Earthquake in the Central Tottori Prefecture on October 21, 2016 occurred. Before this earthquake, there were earthquakes frequently occurred since October 2015 in the area about 10 km east of the area where the 2016 earthquake occurred, and the east side is the western extension of the Kano and Yoshioka faults, the 1943 Tottori earthquake fault. In order to elucidate the heterogeneous structure of the lower crust beneath the seisimic region, we set up several survey lines across the central focal region of the Chubu region to carry out wideband MT observation. According to the result of one-dimensional analysis of Bostic inversion based on determinant impedance by integrating existing MT data, it was shown that the low resistivity region exists continuously in the form of a band around the depth of 10 km in the region.
(2) In the Shikoku region, in order to elucidate the regional characteristics of the large scale resistivity structure, fundamental wideband MT observations have been conducted at 8 sites in the observations gap area around the central part of Shikoku region.
By integrating the existing MT data, we tried model analysis using the program code of Ogawa and Uchida (1996) assuming that the midwestern part of Shikoku region has a two-dimensional structure of N75E strike direction harmonious with the geological structure. The preliminary resistivity model shows interesting features; the north-dip resistivity structure matching with the hypocentral distribution found at the upper crustal depth in the northern part of the Median Tectonic Line, etc.
Acknowledgments: This study was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under its Observation and Research Program for Prediction of Earthquakes and Volcanic Eruptions, and also supported by 2016 Tottori Prefecture Environmental academic research promotion promotion project. We would like to express sincere gratitude for the Nittetsu Mining

Consultants Co. Ltd. kindly let us use their continuous geomagnetic records as remote references. We used joint research equipment of Kyoto University Disaster Prevention Research Institute for observation of this research. Reference magnetic field record is free data Last of all, we would like to express our thanks to T.Higa of Kyoto University and T.Yamamoto, M.Fukunari, Y.Yoshida and F.Okabe of Tottori University for their help during data acquisition.

Keywords: Earthquake in the Central Tottori Prefecture on October 21, 2016, Shikoku region, electrical resistivity, fundamental investigation

Nation-wide spatial distribution of the ultra-long period magnetic transfer functions in the China Mainland

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China mainland located in the south part of the Eurasian continent is an interesting area, where the Pacific plate is subducting from the east, and the Indian continent collides from the south. Recently, several seismic tomography researches revealed stagnant Pacific slab deep below the central to northern part of China. High crustal heat flow as well as the Neogene-Quaternary basaltic volcanic activities in the NE China area has been interpreted due to the subducting or stagnant Pacific slab and possible fluid supply from the slab. India-Eurasia collision also causes significant crustal uplift in the Tibet and clockwise rotation in the eastern part of the suture. Investigation of nation-wide very deep electrical conductivity structure beneath China mainland will enable us to have a better understanding of the dynamics of the continent and generation mechanism of the intra-continental earthquakes and volcanoes, since electrical conductivity is particularly sensitive to the presence of interconnected highly conductive phases, such as partial melts or aqueous fluids.

In this study, in order to elucidate the mantle electrical conductivity structure down to the transition zone beneath whole China mainland, we investigated the geomagnetic records obtained by the National Geomagnetic Center of China. We analyzed hourly geomagnetic data from 42 stations with absolute measurements for nearly 8 years (2008/01/01-2016/12/31). After we calculated the angle between azimuth of the geomagnetic pole and that of the geographic pole at respective stations with the aid of the IGRF models, we obtained the geomagnetic data rotated to the geomagnetic dipole field coordinates. The vertical component to the horizontal components transfer functions (GDS transfer functions) and inter station horizontal field transfer functions of periods up to 100days were estimated with the aid of the remote reference method with a robust estimation scheme. In the presentation, we will show the characteristics of the spatial distribution of both the GDS and the horizontal transfer functions. We will also show results from the OCCAM 1-D inversion with minimum and smooth structure constraints by using the GDS transfer functions.

Keywords: geomagnetic depth sounding, horizontal transfer function, china mainland, ultra long period, mantle electrical conductivity structure

Synthetic test for a 3-D global inversion of the electrical conductivity by using the Sq band

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The electrical conductivity is sensitive and enhanced due to the presence of fluids, high thermal anomaly, metals and so forth, and is one of the important physical parameter to elucidate the interior and dynamics of the Earth. The electromagnetic sounding is a suitable tool to reveal the electrical conductivity strucutre in the deep Earth, and has been widely used for over a hundred years. For shorter periods than 10000 sec, a plain wave approximation of the EM field may be valid and generally used in, say, magnetotelluric method. For longer periods than a few day, a simple P10 distribution approximates well the EM variations in global scale. An intermediate band, however, has complex distribtusions and careful consideration of a spatial distirbution of the EM variation must be necessary.
In this study, we test the 3D global inversion by using the syntetic data with higher modes of the spatial distirbution. In a forward modeling part, an integral equation method is used, as the boundary conditions are already satisfied in synthtic Green's functions and thus numerical grids are not necessary in the air. In an inversion part, a quasi-Newton method and an adjoint approach are adapted to reduce a number of forward calculations.
In this presentation we show the synthtic results and discuss the possibility to elucidate the electrical conductivity structure in the mantle, especially, mantle transition zone and around by using the Sq field data.

Keywords: Sq, electrical conductivity, inversion

Estimation of the seafloor electromagnetic responses in the mixed excitations band by using Sompi Spectral Analysis

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Electromagnetic (EM) responses such as magnetotelluric (MT) impedance and geomagnetic depth sounding (GDS) response in the period range between several minutes to one day are used to study the electrical conductivity in the upper mantle. Spatially uniform and quasi-random magnetic field variations due to geomagnetic disturbances are considered as the source field in regional EM induction studies using the EM responses. However, the magnetic field variations in the period range from 10^4 to 10^5 seconds contain those with different spatial structure such as the solar quiet (Sq) daily variations and those induced by the ocean tide. Because of this, the period band is referred to as mixed excitation band (ME band). Careful treatment of EM field data is necessary to estimate responses in the ME band that reflect actual conductivity structure. For example, Baba eta al. (2010) estimated the EM responses using a method based on Fourier transform after removing line spectra of EM field variations at periods of Sq field variation and constituents of ocean tides. However, it has been shown that the estimated observed responses in the ME band still contain signatures of non-uniform and westward- propagating source field (Shimizu et al., 2011). Estimating EM responses free from these effects in the ME band is a challenge for the ocean bottom EM induction studies. In this study, we aim to have better estimates of EM responses in the ME band by selecting signals of the vertically propagating plane-wave source carefully. For this purpose, we employ the Sompi method (e.g., Kumazawa et al.,1990) that can identify existing wave elements (or namisos) in time series with a high frequency resolution. The Sompi method is applied for two horizontal magnetic field components at once (Asakawa eta al.,1988) to find complex frequency of namisos and then the amplitude and phase of three magnetic field and two horizontal electric field components are determined by assuming that they have common frequency of variation. Obtained line spectra for the EM fields are used to select suitable namisos for EM response estimation by a least square method. The criteria to select namisos are (1) selecting namisos in period ranges that are sufficiently away from those of Sq harmonics and ocean tides, (2) selecting namisos that do not show the westward propagating nature similar to the Sq field, and (3) selecting namisos with a quasi-linear polarization in the vertical plane. In this study, we applied criterion (1) at first. Then, the criteria (2) and (3) were applied to the namisos selected by criterion (1) separately. It was confirmed that responses estimated using (2) or (3) at periods shorter than 10^4 seconds are almost identical to those estimated by Baba et al., (2010) within the estimation error at periods shorter than 10^4 seconds. However, the abrupt change of EM responses at periods around 10^4 seconds in the previous work became smaller after applying criterion (2). On the other hand, the value of EM responses estimated using criterion (3) also reduced significantly at the shorter period of the ME band. Results of these two cases show that signatures of the Sq field variation in the EM responses are reduced at the shorter period part of the ME band up to $2x10^4$ seconds. However, we could not obtain statistically significant responses at longer periods because sufficient number of namisos was not available after the namiso selections. Using Sq field variation itself as the source field at the longer period in the ME band is another way to utilize EM field information to constrain the electrical conductivity of the mantle.

Asakawa, E., et al. (1988). *J. Geomagn. Geoelec.,* 40: 447-463.
Baba, K., et al. (2010). *Phys. Earth planet. Inter.,* 183: 44-62.
Kumazawa, M., et al. (1990). *Geophys. J. Int.,* 101: 613-630.
Shimizu, H., et al. (2011). *Geophys. J. Int.,* 186: 193-206.

Keywords: Sq, Electromagnetic response

Localized variations in the geomagnetic field and their relation with tectonic activities

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Localized variations in the geomagnetic field is believed to be related with tectonic activities.
I extract the local variations by means of the principal component analysis.
No obvious relation have been found between the extracted local variations in the geomagnetic field and tectonic activities.

Keywords: geomagnetic field, secular variation, localized anomalies, tectonic activities, principal component analysis

