Temporal variations in magnetic signals generated by the piezomagnetic effect for dislocation sources in a uniform medium

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Fault ruptures in the Earth’s crust generate both elastic and electromagnetic (EM) waves. If the corresponding EM signals can be observed, then earthquakes could be detected before the first seismic waves arrive. In this study, I consider the piezomagnetic effect as a mechanism that converts elastic waves to EM energy, and I derive analytical formulas for the conversion process. The situation considered in this study is a whole-space model, in which elastic and EM properties are uniform and isotropic. In this situation, the governing equations of the elastic and EM fields, combined with the piezomagnetic constitutive law, can be solved analytically in the time domain by ignoring the displacement current term. Using the derived formulas, numerical examples are investigated, and the corresponding characteristics of the expected magnetic signals are resolved. I show that temporal variations in the magnetic field depend strongly on the electrical conductivity of the medium, meaning that precise detection of signals generated by the piezomagnetic effect is generally difficult. Expected amplitudes of piezomagnetic signals are estimated to be no larger than 0.3 nT for earthquakes with a moment magnitude of ≥7.0 at a source distance of 25 km; however, this conclusion may not extend to the detection of real earthquakes, because piezomagnetic stress sensitivity is currently poorly constrained.

Keywords: piezomagnetic effect, dislocation source, temporal variations, magnetic field, electrical conductivity

Three-dimensional node-based FEM method using unstructured grid for electromagnetic volcano monitoring systems

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In recent years, magmatic and/or phreatic eruptions occurred in many volcanos in Japan. In Aso volcano in the centre of Kyushu island, Japan, for example, a magnetic eruption occurred on November 25th, 2014, for the first time since the last magmatic event approximately 22 years ago. To monitor the activity of Aso volcano, our group in Kyoto University have been operating an electromagnetic (EM) 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, bz. By means of this system, we succeeded in detecting temporal changes in ACTIVE response functions, amplitude ratios of bz to the transmitted electric current (nT/A), before and after the magmatic eruption on Nov. 25th, 2014.
In order to quickly analyze data obtained by the ACTIVE-type EM volcano monitoring systems, we developed a new three-dimensional forward code, by adopting the node-based finite element method (FEM). We use unstructured tetrahedral grid to represent arbitrary conductivity structure and complicated topography of volcanos. We directly solve the induction equation only in terms of the magnetic field, since only the magnetic fields are obtained in ACTIVE observations. The reasons why we adopted the conventional node-based FEM are that (1) the node-based FEM is superior to the popular edge-based FEM methods (e.g., Schwarzbach and Haber, 2013) from the perspective of the computational memory, (2) the continuity of the magnetic field is naturally guaranteed provided they are defined at nodes, (3) linear problems in node-based FEM are easily solved by iterative methods, e.g. Conjugate Gradient (CG) method, and thereby (4) we can easily implement parallel computations using MPI. It was illustrated that our forward code is able to calculate the accurate vertical component of the magnetic field, in comparison to the analytical solution of Ward and Hohmann (1988), when a horizontal electric dipole is located just on 1-D layered structure. Now we are trying to improve the convergence ratio in COCG (Conjugate Orthogonal CG; van der Vorst and Melissen, 1990) solver using the divergence free condition of the magnetic field.
In the presentation, we first introduce the ACTIVE system operated in Aso volcano and share some observed data before and after the magmatic event. Second, we show the methodology of our new three-dimensional node-based FEM code and show its accuracy through some numerical experiments.

Keywords: volcano, monitoring, finite element, three-dimensional

Examination of Estimation of Geomagnetic Changes Using Deep Learning Technology

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Electromagnetic changes associated with earthquakes have been investigated previously. In our research, we have employed the magnetometers for seismomagnetic observations. We have reported successful observation of “co-faulting" Earth’s magnetic field changes. The Magnetic fields began to change almost simultaneously with the onset of the earthquake rupture and grew before the first P wave arrival. Such magnetic signals are most probably generated by the changing stress field due to earthquake rupturing, i.e. the piezomagnetic effect. On the other hand, this observation result suggested that the geomagnetic variation signal accompanying fault movement, whose sources are the piezomagnetic effects, is very small.
To discuss a feasibility of a new system for a super-early warning of destructive earthquakes using measurement of EQ-piezomagnetic effects, we have important problems to be solved. Then we examine an estimation method of geomagnetic changes using deep learning technology. This technology is also applied to speech processing, image processing, or analysis method of financial fields. In this study, we investigate the estimation of geomagnetic field changes using magnetic signals observed from multiple points. We show the estimation results using deep learning technology and the future works for detecting the local geomagnetic changes.

Keywords: estimation of geomagnetic field, deep learning

Development of Data Server for Proton Magnetometer with the Crustal Deformation Database System

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Recognized the importance of demagnetization monitoring to phreatic/hydrothermal eruptions, we have developed a data server system for proton magnetometer time-series data processings. PM201-SCS (Neo-Science, Co. Ltd.), one of the most popular proton magnetometer in Japan, is equipped with semi-real time data transfer system. The time-series data are transferred with an e-mail once a day through 3G network in the PM201-SCS. After receiving the e-mails from PM201-SCS at each site, the developed server right away performs the following data processing automatically: (1) diagnose status of each site’s magnetometer, (2) convert the e-mail data into user-friendly formats including WIN-format (cf. http://eoc.eri.u-tokyo.ac.jp/WIN/index.html), (3) reduce noise, and (4) store the data in the Crustal Deformation Database system (CDD). CDD was developed by Yamaguchi et al., (2010), and user can use functions such as drawing and download the time-series from Web browser. Our server enables users to access the daily time-series through the CDD. In this presentation, we will introduce the details of the server using an example of time-series data observed around Zao volcano.

Keywords: Proton Magnetometer, Crustal Deformation Database System

Time-domain inversion of the electrical conductivity profile in the Earth using ground-based magnetic observatory data.

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We estimated radial electrical conductivity distribution in the Earth using both vector geomagnetic observatory data and a forward solver in time-domain. The major difference between the time-domain and frequency-domain approach rests in the way of processing the finite-length time series of transient inducing and induced fields. In the frequency-domain, response functions are usually estimated at discrete frequencies, by splitting the time-series into multiple segments and applying Fourier transformation to each segment. As the periods increase, quality of response functions is reduced in the case of the frequency-domain approach. In addition, the frequency-domain approach should not be applied to the transient data since Fourier transformation premises periodicity for the time-series in concern. On the other hand, the time-domain approach exploits all the data in the time-series by fitting the entire waveform of the magnetic field including rapid variations such as sudden storm commencements. The quality of long period signals that are able to penetrate the deeper region of the Earth is not reduced in the time-domain. We can, therefore, estimate the deep distribution of conductivity using shorter time-series than in the frequency-domain. Specifically, we applied the time-domain approach to the vector geomagnetic observatory data with one minute sampling interval all around the globe. In order to extract the induced field, we subtracted the vector average for 5 quietest days of the month from the raw time-series. Contrary to the newly available data sets from recent low-Earth-orbiting satellite missions, the traditional ground-based data has biased distribution over the globe. We eliminated observatories in some congested places. We then separated the residual time-series into internal and external origin. The separated internal magnetic field can be reproduced using forward response of the radially symmetric conducting sphere to the separated external magnetic field. A heterogeneously conducting shell was placed at the top of the radially symmetric sphere so as to account for large scale surface contrast such as ocean-continent distribution. We solved an inversion problem with an objective function consisting of linear combination of data misfit and a regularization term that constrains the smoothness of the conductivities. Moreover, we estimated the internal Gauss coefficients' sensitivities for each shell of the radially symmetric conducting spheres by F-test and revealed that the lower mantle conductivity has a large influence on the magnetic field on the surface of the Earth after about more one day from the instance when the external magnetic field was applied. As a result, we estimated a conductivity profile of the Earth. This is the first profile that was estimated by a combination of inversion in time-domain and the vector geomagnetic observatory data over the globe. We will further discuss the necessary length of time-series in order to estimate the lower mantle conductivity accurately.

Keywords: conductivity, magnetic storm

One-dimensional resistivity structure of Iwo-yama, Kirishima Volcanoes

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Iwo-yama is the youngest volcano in the Kirishima volcanic group, Kyushu Island, Japan. The volcano was formed at the eruption in 16~17th century (Tajima et al., 2014). Around Iwo-yama and Karakuni-dake, tectonic earthquakes have increased at a depth of 1 to 5 km since December 2013, and volcanic tremors have occasionally occurred since July 2015 (Japan Meteorological Agency, volcanic activity commentary document). Furthermore, the fumarolic gases at a temperature of 80℃ appeared on 14 December 2015 for the first time in 12 years, at the southwest of the crater of the Iwo-yama. The leveling survey detected the ground uplift during June to December 2015, and its pressure source was estimated at a depth of 700 m, the eastern part of the crater (Matsushima et al.,2015). The top of the hypocenters of tectonic earthquakes seems to be located at a depth of 1 km around the Iwo-yama, where the electric conductive clay layer was estimated by the previous resistivity structure investigation (Aizawa et al., 2013, EPS). From these evidences, we speculate that the supply rate of high temperature fluids beneath Iwo-yama has increased, and causes the increase of pore pressure beneath the clay layer, resulting in the increase of earthquakes. In order to examine this hypothesis, we conducted the broadband (200~0.0005Hz) magnetotelluric measurements around the Iwo-yama. From 21 December 2015 to 12 January 2016, we recorded two components of electric fields at 5 observation sites around the crater, and five components of electric and magnetic fields at an observation site located 500 m northeast of the Iwo-Yama. In this presentation, we will show the average one-dimensional resistivity structure of Iwo-yama, and will discuss the association with the earthquakes.

Self potential (SP) survey at the Rokugo alluvial fan in Akita Prefecture, Japan

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Self-Potential (SP) observation is one of the geophysical exploration. It has been used in the volcanic and geothermal area in order to investigate the hydrothermal water convection. Although a large number studies have been made on the relationship between SP and groundwater flow, a little is known as relationship between “topographic effect” and groundwater flow or groundwater level.
In this study, SP survey was carried out at the shallow groundwater field. And, we estimate of possibility to observe what “topographic effect” of SP at shallow groundwater field. It was investigated in a place where there is a lot of groundwater level data and gradient data.
We have selected Rokugo alluvial fan in Akita prefecture, is because of the groundwater level data has been recorded. Rokugo alluvial fan has an area of approximately 4km from east to west, and approximately 5km from north to south. Its area is 14km^2. SP Observations at Rokugo area were carried out in September-November, 2015.
From the observation result, it was possible to find a SP decreases section as the altitude increases. In the case of Rokugo alluvial fan, the topographic effect is -1.0 ~ -3.7mV/m.

Keywords: Self Potential, groundwater, topographic effect

Sources of self-potential variations associated with Nojima water injection tests

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The repeated water injection experiments have been done at Nojima fault since 1997 to study the properties and healing processes of the fault. The Nojima fault is the surface fault rupture of the Hyogoken-Nanbu Earthquake (Mw6.9) of 1995. We measured self-potential variations associated with water injection experiments using 1800m borehole. The following three characters of self-potential variations were observed in common with the repeated water injection experiments during 1997 to 2003 : 1) self-potential variations appeared to correspond to the operation of water injections, 2) these variations were observed at all the observation sites around the water injection borehole, 3) the negative voltage appeared around the water injection borehole. Observed self-potential variations are explained with an electrokinetic effect due to the subsurface fluid flow of the injected water. The charge in voltage in the aquifer is conducted to the whole part of the injection well through the highly conductive iron casing pipe. The iron borehole pipe acts as a line source of electric current. However, after 2004 water injection experiments the positive voltage appeared on the far side from the borehole. The local positive voltage is not explained by the above model. In this paper, we report a new model, which consists of the line source model and a dipole source, to explain the observations and its problems.

Keywords: Nojima Fault, self-potential, streaming potential

An attempt of a four-terminal measurement to the cylindrical-shape rock sample for the high-density resistivity imaging

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Recently, electromagnetic surveys were carried out around several fields for imaging heterogeneities around seismogenic zones or volcanic activities (e.g., Yoshimura et al., 2009; Nurhasan et al., 2006; Aizawa et al., 2004). Obtained resistivity images are interpreted by using several mixing laws (e.g., Archie, 1942), relationship between the porosity of rock and its connectivity. However, applicability and scalability of such interpretations have not been clarified. Laboratory experiments are essential for getting detailed information about that.
In this study, we employ a rock samples such as used in compression tests. Several studies have reported about observations of a cluster of microcracks in rock samples (e.g., Kawakata *et al.*, 1999). Accordingly, high-resolution resistivity imaging enables us to compare with distribution of microcracks in the rock sample in order to assess the applicability and scalability of mixing laws. We have carried out feasibility studies by simulated experiments (using conductive plastic and conductive epoxy) as the first step of a laboratory experiment in the previous studies. As a result, we obtained an electric potential distribution on the surface of the sample, and succeeded to detect structure in the sample by measurements using a lot of electrodes. On the other hand, in rock experiments, electric potential distribution was not observed because a leakage current was caused by high contact resistance.
In the present work, the experimental approach was improved by a floating measurement so as to prevent a leakage current in rock experiments. Furthermore, we attempted a simple four-terminal measurement for the rock samples. As a consequence, a constant potential was observed at the surface of cylindrical-shape granite if we use 10mm×10mm square size electrodes.

Keywords: rock experiments, electrical resistivity, electrical measurements

Large-scale electrical resistivity structure around the Western Part of Shikoku

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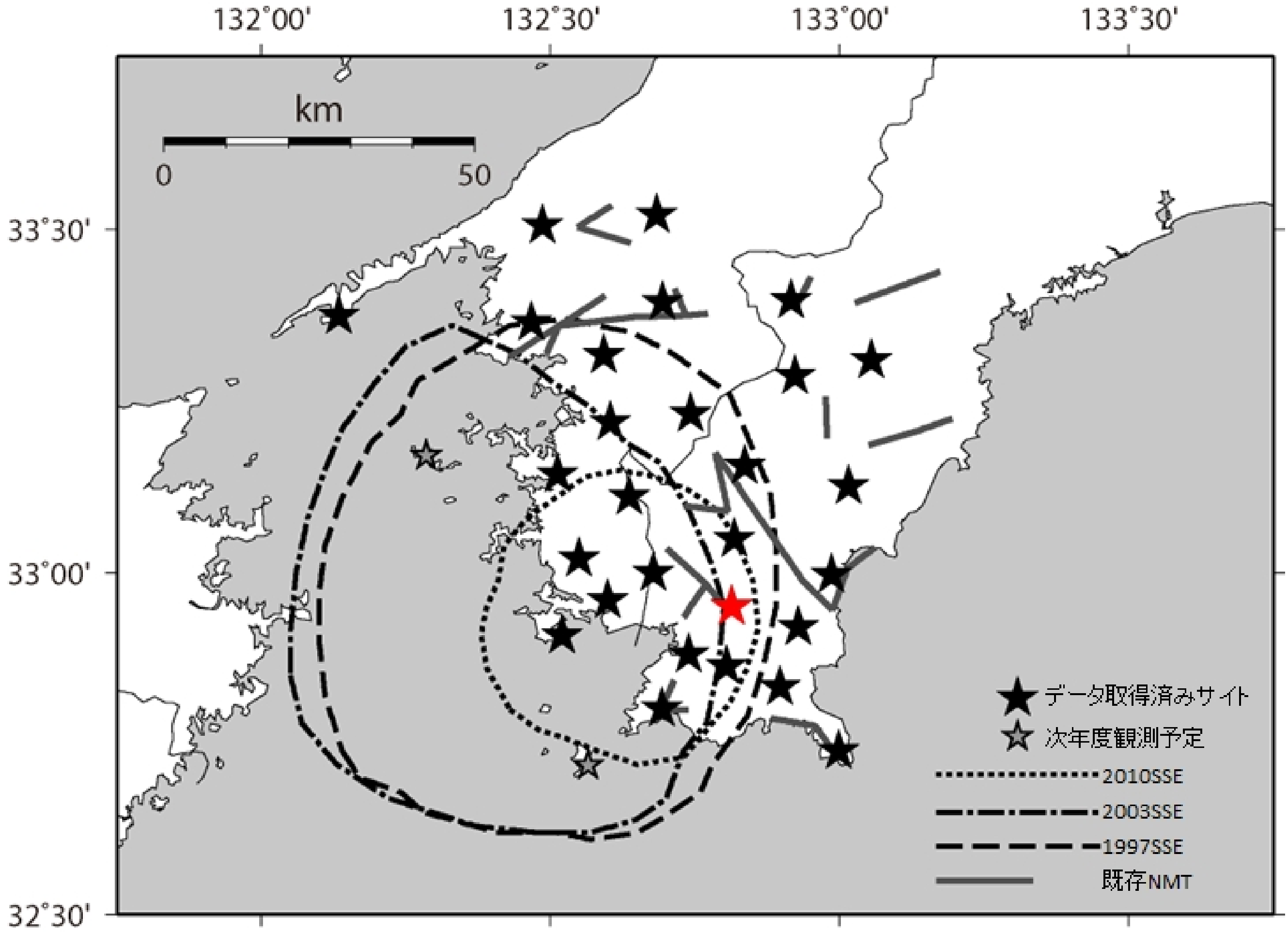
Recent geodetic observations detect recurrent slow slip events (SSE), which occurred beneath the Bungo Channel and southwest Shikoku Island, with interval of approximately 6 years (e.g. GSI, 2010). In order to reveal a three-dimensional resistivity structure around SSE region, we are carrying out wideband magnetotelluric (MT) surveys. We also plan to establish a permanent long-term MT monitoring network that aims to detect temporal changes of resistivity structure during SSE cycle. In January 2015, we installed a long-term MT instrument as a pilot observation at Sukumo Observatory of DPRI, Kyoto University located above the eastern edge of the Bungo SSEs.

In this presentation, we will report the present state of wideband MT surveys and estimation of a large-scale electrical resistivity structure. As of February, 2016, MT surveys were performed at 28 sites by using Phoenix wideband MT instruments. In the most of sites, high quality MT responses were obtained using the BIRRP code (Chave and Thomson, 2004) for the period range 0.01 to 10,000sec. The spatial distributions of the phase tensor ellipses and the induction vectors suggest that resistivity contrasts are located around SSEs. We will show the outlines of our research project, characteristics of obtained MT responses, and report preliminary results of three-dimensional inversions.

Keywords: electrical resistivity structure, Bungo Channel, slow slip events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Shallow Resistivity Structure around the MTL Fault Zone (Izumi segment) deduced from the dense AMT observations

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The Japan Median Tectonic Line (MTL) Fault Zone along geological boundary of th MTL shows right-lateral strike-slip activities and extends for about 360km. Izumi segment of the MTL Fault zone consists of the Gojodani and Shobudani faults, etc. Wideband Magnetotelluric (MT) soundings were carried out across these faults (Disaster Prevention Research Institute, Kyoto University, 2015) previously. The obtained resistivity model was characterized by a contrast around the MTL. However, the shallow resistivity structure was not so clear.

In order to delineate fine subsurface structure around these faults, we carried out audio-frequency magnetotellurics (AMT) measurements at 38 sites along a 5km profile perpendicular to the Gojodani and Shobudani faults in November, 2014. Relatively good quality MT responses were estimated at 37 sites. Resulting conventional two-dimensional inversion analyses, we obtained a high resolution two-dimensional resistivity model. To pick out robust properties of resistivity model, we developed a new procedure and applied to our data.

Obtained robust model is characterized by a conductive and two resistive zones. The conductive zone is interpreted to be the Shobudani sedimentary layer and a clear contrast is recognized inside the Shobudani layer just beneath the surface trace of the Gojodani fault.

Keywords: Magnetotelluric, The Japan Median Tectonic Line Fault Zone, The dense observations

Magnetotelluric survey of the Miki fault, the Yamasaki fault system, southwest Japan

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Introduction
Clear electrical conductivity variation is expected to be identifiable in the vicinity of an active fault (e.g., Ritter *et al.*, 2005), and the electrical conductivity distribution can provide a new image of the subsurface structure of an active fault. The audio-frequency magnetotelluric (AMT) method is a powerful tool for investigating the electrical conductivity structure of active faults in the upper few km of the Earth’s crust. In particular, this method is more sensitive to the structure of a strike-slip fault, where vertical to high-angle fault planes and fracture zones are expected, than seismic reflection or refraction surveys.
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).
AMT surveys have made at 81 stations along 7 survey lines across the faults of the NW group, while the survey has made at only 17 stations along 1 survey line across the fault of the SE group. It is important to make clear the subsurface structure of the SE group to know the whole nature of the YFZ and difference between the NE and SE groups of the main part of the YFZ. In the SW group, we focused on the Miki fault and its general strike of N60°W (Hyogo Prefecture,1999).
Observation
An AMT survey was undertaken in November June 2015 at twelve stations along the transect across the Miki fault, this transect is laied near the trench excavation survey site by Yoshioka *et al.*, (2008). The remote station of the magnetic field was made ~25km north from the northeastern end of the transect to analyze the data using the remote reference method (Gamble *et al.*, 1978). Two horizontal components of electrical field and three components of magnetic field were measured.
Analysis
After MT response functions were obtained, we adopted the phase tensor analysis (Caldwell *et al.*, 2004) to estimate dimensionality of the resistivity structure beneath the study area and to determine the direction of the regional strike, if the structure is two-dimensional. Then the two-dimensional resistivity model was constructed using the code of Ogawa and Uchida (1996).
Result
The optimum model obtained (named MKI model) is characterized by the three conductive zones. The boundary between shallow two conductive zones is locate at the surface trace of the Miki fault (AIST, 2008). The bottom of another deep conductive zone found in the northeastern side of the Miki fault corresponds to the lower boundary of the between Osaka Group.

Keywords: Miki fault, Yamasaki fault system, active fault, resistivity structure, Magnetotelluric method

A research report on the fundamental investigations of an electrical resistivity structure beneath Chugoku and Shikoku regions, southwestern Japan(2015)

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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 2015 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.
However, recent observation result conflicts with the model advocated by the group including the author that has studied electrical resistivity in Sanin region (ex, Shiozaki et al.,2015). That is, there is a possibility that the deep low resistivity area beneath the Sanin region does not exist in series. 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.
Therefore, in this study, mainly using the wide area electromagnetic data of eastern and central Tottori Prefecture, we tried to extract the key feature of the dimension and the strike direction of resistivity structure beneath Shikano-Yoshioka fault and its surrounding area. The results of this analysis will be shown here.
(2) On the other hand, in the Shikoku region, investigations were carried out mainly in the outer zone, and the result suggested that a remarkable conductive area should exist in the upper crust and that the conductive area in the central and western part should have a clear relation with the non-seismic area. These studies suggest that high conductivity(low resistivity) is possibly caused by the existence of deep crustal fluids, which probably play an important role in the inland earthquake occurrence mechanism of these regions. Therefore, in order to grasp a whole tectonic setting, from the fore to the back arc side in the southwestern Arc, quantitative discussions based on the wideband MT survey covering whole these regions should be required (Shiozaki et al.,2014).
In order to elucidate the regional characteristics of the large scale resistivity structure, fundamental wideband MT observations have been conducted at 10 sites in the observations gap area in the east and central region of Shikoku from late Oct to late Nov 2015. Based on a one-dimensional structure analysis using invariant impedance, a preliminary research result shows that it is consistent with the relationship between resistivity and seismicity from the former studies in the Shikoku regions.
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. This study was supported by the

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Keywords: electrical resistivity, fundamental investigation, Chugoku and Shikoku region

