地中の電流源による 2 次元静電場の海洋と山脈を考慮した解析的解法

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Analytic 2-D electrostatic fields by underground electric current sources considering seas and mountains

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A certain sort of analysis of GPS-TEC suggests appearance of ionospheric disturbances prior to huge earthquakes. Especially, when considering the ionospheric perturbation prior to huge earthquakes in the subduction zone of oceanic plates, the mountains along island arcs are expected to efficiently propagate the electric field from the electric current source generated in the subduction zone to the ionosphere through the atmosphere. These expectations, however, lack considering the attenuation of the electric field along the seas which are more conducting by orders of magnitude than the solid earth. The present study shows the procedure to analytically evaluate the electric field which appears in both the ground and the air considering the existence of both the seas and mountains due to a certain electric current source in the ground, no matter what the generating mechanism is, based on assuming the simplest structure of the electrical conductivity.

The structure is assumed to be 2D of which the strike is along trench axis. The ground and the air which are assumed to be isotropic and homogeneous are regarded to be a conductor and a dielectric, respectively. The existence of the ionosphere is ignored in the present evaluation for simplicity. The seas which are parts of the boundary between the ground and the air are approximated as perfect conductors with infinitesimally small thicknesses. The shape of the mountains surrounded by the seas are expressed so that its boundary to the air on the section perpendicular to the strike coincides with two legs of an isosceles triangle of which the height of the base coincides to the sea level. The resultant boundary conditions for the electrostatic potential are: zero along the seas for both the ground and the air, and zero gradient in the ground perpendicular to the boundary between the air and the solid earth due to the disappearance of the electric current density perpendicular to the boundary.

When solving 2D electrostatic potential, expressing the section perpendicular to the strike with a complex plane, and expanding the electrostatic potential to a complex potential, its imaginary part can express the electric field lines. By obtaining the electrostatic potential caused by the electric current source and satisfying the boundary condition, the stream function expressing the electric field lines can be obtained with the electrostatic potential and the Cauchy-Riemann equation.

At the limit of the flat mountains with seas, the electrostatic potential can be obtained with the Airfoil equation (Tricomi, 1985) which is an inhomogeneous Fredholm integral equation of the first kind with the Cauchy kernel, satisfied by the tangential electric field at the boundary between the solid earth and the air. The mathematical expression of the complex potential in both the ground and the air can be obtained with the electrostatic potential on the boundary using Chebyshev polynomial expansion of the first and second kinds (Tricomi, 1985).

At the limit that the height of the mountains is non-zero and that the seas are neglected, the complex potential can be obtained with a conformal mapping of the potential from another complex plane on which the height is zero and the boundary is flat. The transformation formula is given as a Schwarz-Christoffel transformation which transforms both a part of the flat boundary to the legs of the isosceles triangle, and the rest of the flat boundary to flat boundaries, expressed with the Gauss hypergeometric function.

By the combination of the derivations of the complex potentials, the potential can be obtained considering both the seas and the mountains. The characteristics of the electrostatic potential and the electric field lines are shown in detail for two cases that the electric current source is located along inland faults and subduction zones.

巨大地震に先行する電離圏の異常の発生が GPS-TEC の解析から指摘されている。特に海溝型巨大地震に先行する電離圏の異常を考察する場合には、島弧に沿った山脈が、沈み込み帯で発生すると仮定する電流源による電場を大気中へと効率的に伝える経路となることが期待されている。しかしこのような想定においては、固体地球より良導的な海洋の存在が海底下で水平電場を減衰させる影響が無視されている。本研究は電流源の発生過程によらず、地中に何らかの電流源を想定した場合に、海洋と山脈を考慮して地表と大気中に現れうる静電場を、最も簡単な電気伝導度構造を仮定して解析的に見積もる手法を示す。

構造は海溝軸に平行な走向を持つ 2 次元構造を仮定する。大地と大気は等方均質なそれぞれ導電体と誘電体とみなす。電離圏の存在は無視する。大地と大気の境界のうち、海洋は微小厚さの完全導体と近似し、島弧を模した山脈の両側に分布するものとする。山脈の形状は、走向に直交する断面が海面高度に一致した底辺を持つ二等辺三角形で現されるものとする。このとき静電ポテンシャルの境界条件は、境界面のうち海面では大地側と大気側で共通に無限遠における値に等しくゼロ、固体地球と大気との境界では大地側では地表に直交する電流密度の消失から法線方向の勾配がゼロとなる。

2 次元の静電場を解く際に、構造の走向に直交した 2 次元断面を複素平面で表現し、静電ポテンシャルに代わって複素ポテンシャルを考察すれば、その虚部は電気力線を表現する。電流源によって生じる、境界条件を満たした静電ポテンシャルをまず解けば、電気力線を表現する流れ関数は静電ポテンシャルと Cauchy-Riemann の方程式とから導かれる。

まず山脈の標高をゼロとした極限では、平面大地と海洋とを考慮した境界条件に対して静電ポテンシャルは、地表面における接線電場が満たす、Cauchy 核をもつ非斉次第一種フレドホルム積分方程式、Airfoil 方程式 (Tricomi, 1985) から得られる。Tricomi(1985) が示す、第一種及び第二種 Chebyshev 多項式を用いた多項式展開で表現される境界面の静電ポテンシャルから地中及び大気中の複素ポテンシャルの数学的表現が得られる。

一方、山脈の標高が有限で海洋を無視した極限では、複素ポテンシャルの解は山脈の標高をゼロとした場合の解の等角写像によって得られる。写像を表現する変換式は、山脈の形状を模した境界面に平坦面を写像する Schwarz-Christoffel 変換から得られ、仮定からはガウスの超幾何関数を用いて表現される。

以上の解法の組み合わせにより、海洋と山脈の両方を考慮した場合の複素ポテンシャルを求めることが出来る。静電ポテンシャル及び電気力線の、電流源を沈み込み帯と内陸断層のそれぞれを模した位置に配置した場合の特徴について本発表で詳述する。

R003-02 **会場: B** **時間: 11月25日 9:15-9:30**

Heterogeneous electrical resistivity image around the long-term Slow Slip Events beneath the Bungo Channel region, southwest Japan

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Recent geodetic observations detect recurrent slow slip events (SSEs), which occurred beneath the Bungo Channel and southwest Shikoku Island, with interval of approximately 6 years (e.g. GSI, 2010). To reveal a large-scale three-dimensional resistivity structure around this SSEs region, we carried out wideband magnetotelluric (MT) surveys around the western part of Shikoku Island. As of June, 2016, MT surveys were performed at 31 sites by using Phoenix wideband MT instruments. In the most of sites, high quality MT responses were estimated by using the BIRRP code (Chave and Thomson, 2004) for the period range 300 Hz to 10,000 sec (Yoshimura et al., 2016). In addition, we used 8 more MT and telluric data obtained for different purposes; 6 sites from the opposite side of the Bungo Channel, namely the eastern part of Kyushu Island, measured by Metronix ADU and NT System Design ELOG systems (Aizawa et al., 2017) and 2 sites from the region of the central part of SSEs measured by Phoenix MTU system (Okazaki et al., 2017). These additional data were also reprocessed by the BIRRP code. In this study, we totally used 38 sites for three-dimensional inversions.

Using obtained MT responses, we constructed a three-dimensional resistivity model around the SSE region. We inverted the impedance tensor and the vertical magnetic transfer function by the "femtic" inversion code developed by Usui (2015). The "femtic" inversion code employs the edge-based finite element method for unstructured tetrahedral elements and estimates the subsurface resistivity structure and the distortion tensor for each observation site. The total number of nodes and elements in the discrete model are 211,378 and 1,321,175, respectively. The elements, excluding those located in the air and sea water regions of the mesh, were grouped into 41,282 unknowns of model parameters. The main features of the obtained three-dimensional model are 1) a moderate conductive zone in the central part of SSEs 2) whose trenchward extension shows more conductive and 3) conductive zone surrounding the SSEs regions. These results suggest that the lateral electrical heterogeneity could have controlled the slip distributions of SSEs along the upper boundary of the Philippine Sea slab.

Magnetotelluric transect of the Unzen graben and its correlation with seismic profile

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We conducted broad-band magnetotelluric (MT) survey along north-south trending survey line across the Unzen graben. MT survey line is located approximately 2 km west of the latest lava dome and consisted of 27 stations on 9 km profile. We estimated 3-D resistivity structure and investigate its correlation to the seismic reflection structure by Matsumoto et al. (2012), which was conducted in the same survey line. The best-fit resistivity structure shows the first resistive layer underlain by the second moderate conductive layer. The first resistive layer, which is interpreted as a water-unsaturated layer, is cut by four faults, i.e., the faults are relatively conductive. The second layer, which is interpreted as water-rich layer, also shows relatively conductive values near the faults. By assuming that the faults are imaged as relatively conductive zones, we infer the dip angles and its deep extensions of four faults. Beneath Chijiwa fault, which is the longest and the most active fault of the Unzen graben, the dominant conductor (C1) with the width of 2 km extend down to a depth of 4 km. C1 corresponds to the zone of strong reflection, and the pressure source B of Kohno et al. (2008) is located near the C1. In this study, we interpret C1 as the zone of fracture network generated by the Chijiwa fault to which the magmatic volatiles are supplied from the deeper pressure source B. In the center of the study area, vertical high resistive body (R1) exist and correspond to the zone of low seismic reflection. We interpret R1 as the zone of cooled dyke complex that may acted as a volcanic conduit.

山崎断層系那岐山断層帯に属する那岐山断層・那岐池断層の地下浅部比抵抗構造

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Resistivity structure beneath the Nagisen fault zone, Yamasaki fault system, southwest Japan

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The Yamasaki Fault system (YFS) of southwest Japan is a typical left-lateral strike-slip fault system that extends for over 80 km and consists of three fault zones (the Nagisen Fault zone, the main part of the YFS, and the Kusadani Fault). The Headquarters for Earthquake Research Promotion (2013) reported the Nagisen Fault zone consists of the Nagisen and North Tsuyama Faults. Recently, Okada et al. (2016) reported the Nagisen Fault zone is formed by three fault segments; the Koegatawa Fault, the Nagisen Fault, and the Nagiike Fault.

The Nagisen Fault zone is interesting in showing different feature in fault activity from other two fault zones (e.g. sense of horizontal displacement, slip rate, the latest event time). However, even fundamental factor such as fault dip has not been determined., so we made an audio-frequency magnetotelluric (AMT) survey to reveal subsurface structure of this fault zone.

An AMT survey was undertaken at 12 sites along a transect of 2 km laid across the Nagisen and the Nagiike Faults in October 2017. We estimated MT impedances according to the remote reference processing procedure (Gamble et al., 1978), then they were subjected to dimensionality analysis using the phase tensor method (Caldwell et al., 2004). The result shows that resistivity structure is two-dimensional, and its strike is east-west. The two-dimensional resistivity model (NGS model) along the transect was determined using the two-dimensional magnetotelluric inversion code (Ogawa and Uchida, 1996). The NGS model is characterized by northern conductive and southern resistive zones with north-dipping sharp boundary between them.

It is interesting that surface location of the north-dipping sharp boundary corresponds to the surface trace of the Nagiike Fault and its dip angle is also consistent with estimated dip-angle obtained by surface geological survey. So, we conclude that the sharp resistivity boundary indicates a subsurface fault plane of the Nagiike Fault. As resistivity contrast between northern and southern zones is difficult to explain by geological setting, we conclude that the resistivity contrast is mainly caused by fault activity of the Nagiike and Nagisen Faults.

はじめに

山崎断層帯は岡山県苫田郡鏡野町から兵庫県三木市に至る活断層帯で，那岐山断層帯，山崎断層帯主部，草谷断層の3つの起震断層で構成される．このうち西端に位置する那岐山断層帯は声ヶ乢断層，那岐山断層，那岐池断層および津山北方の断層からなる．那岐山断層帯は隣接する山崎断層帯主部と一般走向，傾斜，ズレのセンス，平均活動間隔，最新活動時期などが異なる (地震調査研究推進本部地震調査委員会，2013).

観測

那岐山断層・那岐池断層の地表トレースに直交するように約 2km の測線を設定し，この測線上に約 200m 間隔で 12 点の観測点を設けて Audio-frequency Magnetotelluric 法（AMT 法）による観測をおこなった．測定は，2017 年 10 月に MTU-5A(Phoenix Geophysics 社，カナダ) を用いて電場水平 2 成分（東西，南北成分）および磁場 3 成分（東西，南北，鉛直成分）を測定した．また測線の北端から北北東に約 10km 離れた地点に磁場参照点を設けた.

データ解析およびモデル解析

SSMT2000（Phoenix Geophysics 社，カナダ）を用いて Remote Reference 法（Gamble et al.,1979）に基づき，観測で得られた磁場と電場のデータから，各観測点の MT 応答関数を算出した．これらのうち信頼度が高いと考えられる周波数帯のみを以降の解析に用いた．まず，Phase tensor 法（Caldwell et al.，2004；Bibby et al.，2005）を用いて，測線周辺の比抵抗構造の次元は 2 次元であり，その走向は EW 方向であると判定した．次に，その走向に直交するようなモデル測線に沿う比抵抗モデルを求めた．モデル解析には ABIC 最小化による平滑化拘束付き 2 次元比抵抗インバージョンコード（Ogawa and Uchida，1996）を用いて，深さ 2km までの 2 次元比抵抗モデル（NGS モデル）を得た.

結果と解釈

NGS モデルは北側に低比抵抗な領域，南側に高比抵抗な領域が存在し，その間に北に約 60 度傾斜する境界が存在することで特徴づけられる．那岐山断層・那岐池断層で得られている地形学的知見および地質的知見と NGS モデルとを比較し次の結論を得た.

・那岐池断層の地表位置と地表での傾斜は，NGS モデルを特徴づける北側に傾斜する境界と整合的である．このことはこれまで十分に決まってはいなかった那岐池断層の傾きが，NGS モデルからより確かな傾きが推定されたことを示す.

・北と南の比抵抗のコントラストは地質の違いからは説明できない.

・北側の領域は那岐池断層の断層運動により，上盤側が破砕し流体が浸入したことで低比抵抗になった可能性がある．
本発表ではこの特徴的な那岐山断層帯で行った地磁気地電流法（MT 法）観測，得られた比抵抗構造について発表する．

北海道北部の蛇紋岩地域における三次元比抵抗モデリングおよび磁気異常解析

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3-D resistivity modeling and magnetic anomaly analysis around a serpentine area in the northern Hokkaido

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A large serpentinite body in northern Hokkaido, Japan (Pinneshiri serpentinite mass; Niida and Kato, 1978), for which aeromagnetic surveys showed a high magnetic anomaly of over 1,000 nT (GSJ, 2005), may be a key to understand fault ruptures and crustal development of island arcs as the following reasons. (1) Serpentine contributes to the transportation of aqueous fluid in a subduction zone. (2) Serpentinites largely affect frictional behaviors of a fault. Actually, the serpentinite body is located on a clear boundary between high and low seismicity areas in northern Hokkaido (Takahashi and Kasahara, 2005), and on the fault of inland slow earthquake (Mw 5.4, Ohzono et al., 2015). In order to discuss the distribution of the serpentinite body especially for its deep extension and the distribution of crustal fluid, we conducted a MT survey at three sites on the serpentine body. Using the MT data by this survey and existing MT dataset at 45 sites around the study area, we modeled a resistivity distribution based on 3-D inversion procedure (Tada et al., 2012). A preliminary inversion result shows a conductive zone beneath the serpentinite body, which implies fractured or clayed serpentinites. In addition, we performed a land magnetic survey across the centre of the serpentine area using a portable overhauser magnetometer. The magnetic anomaly is about 2,000 nT in maximum and seems to reflect local distribution of serpentinites (magnetite). Result of the analyses of magnetic anomaly with past aeromagnetic survey data (GSJ, 2005) will be discussed in the presentation.

ACTIVE データから推定される阿蘇山 2014-2016 年活動期の比抵抗構造時間変化

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Temporal variation in the resistivity structure of Aso volcano during the active period from 2014 to 2016

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In November 2014, magmatic eruptions started at Aso volcano approximately 20 years since the last magmatic events. The magmatic eruptions stopped in May 2015 due to subsidence of the bottom of the first Nakadake crater. However, subsequent eruptions followed the magmatic events, namely the phreatic eruption in September 2015 and the phreatomagmatic explosion in October 2016. After the explosion in October 2016, the activity of Aso volcano led to the current volcanic quiescence.

During the activity from November 2014 to October 2016, we conducted several campaign observations based on the ACTIVE system (Array of Controlled Transient- electromagnetics for Imaging Volcano Edifice; Utada et al. 2007). ACTIVE system installed at the first Nakadake crater of Aso volcano consisted of a transmitter located northwest of the crater with four or three receiver stations of vertical induction coils through the active period. The ACTIVE observations succeeded in detecting temporal variations in the resistivity structure over the magmatic eruption period. Response variations started in November 2014 has a peak in February 2015 and slightly returned to the values before the eruptions in August 2015.

We implemented three-dimensional (3-D) inversions based on the finite-element method with unstructured tetrahedral mesh, to interpret temporal variations in the ACTIVE response, accounting for topographic effects. The 3-D inversions revealed that temporal variations in the ACTIVE response were attributed to (1) a broad increase in resistivity at the peak elevation of 750 m to 850 m, present not only just beneath the crater bottom but also outside the crater, and (2) a decrease in resistivity at the elevation of 1050 m on the western side of the crater (Minami et al. 2018). The increase in resistivity can be ascribed to decrease of the amount of conductive groundwater in the upper part of the aquifer located at the elevation lower than 800 m. The decrease in resistivity might be due to a temporal hydrothermal fluid reservoir during the eruption period formed by high-pressure fluid escaping from the conduit zone. This study demonstrates that 3-D modelling of ACTIVE responses can be effective in understanding temporal variations of volcanic hydrothermal systems.

In the presentation, we propose a scenario for variation in the hydrothermal system during the active period from our inversion results. We also plan to add inversion results from ACTIVE data in August 2017 to the scenario, to extend our scenario to the present quiescent stage.

能動震源ACROSSの開発と地震波モニタリング

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Active seismic source monitoring through the development of ACROSS

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ACROSS, which stands for Accurately Controlled Routinely Operated Signal System, was conceptually designed by Kumazawa and Takei (1994), and a system for practical use was started to be developed in Nagoya University in 1995. The development efforts spread into some institutions and now about 10 vibrators are in operation in and outside of Japan. All of them have a common design of operation that have established in the first few years of development in the discussion among researchers and students headed by Kumazawa. Among them are a GPS synchronization and a repeating frequency modulation (FM) operation, which are principal subjects of ACROSS operation. A source synchronization technique to GPS clock was developed to make a remote synchronization to receivers because the GPS signal were already used as a reference clock for seismic observations. The repeating FM operation is designed so that a same FM operation repeats with a constant time interval. FM operation is a combination of up-sweep and down-sweep of rotational frequency of ACROSS source to cover a certain frequency range as a source signal. This operation produces multiple narrow spectral peaks with constant frequency interval, improving stacking efficiency for quite a long time period to have a good signal-to-noise ratio. Another but notable advantage of the repeating FM operation is separation ability among signals of ACROSS sources that cover common range in frequency. Spectral peaks of repeating FM operation can be shifted so that none of the peaks are shared by multiple ACROSS sources in operation. This enables simultaneous operation of multiple sources in a common frequency range.

An important result in the earlier period of the development of ACROSS is the detection of temporal variation of seismic velocity observed in Awaji test site, near the Nojima fault of 1995 Kobe earthquake (Ikuta et al. 2002, Ikuta and Yamaoka, 2004). They found coseismic delays of seismic velocity caused by strong ground motions. They also proved that the change is induced by the pressure increase of ground water based on the observation of anisotropic change in both seismic velocity and strain measurements. The observation of coseismic delays are now very commonly observed in seismic interferometry observation.

Tsuji et al. (2017) found a secular increase of seismic velocity as well as coseismic decrease, probably for the first time in such monitoring experiments. They analyzed the 10-year-long monitoring results of ACROSS source in the central part of Shizuoka prefecture, Japan, and found a secular increase for 13 Hi-net stations around the source. This can be interpreted as a gradual closure of cracks probably by a precipitation of minerals from the ground water.

Temporal change is also detected in a volcano area, with use of ACROSS being deployed in Sakurajima volcano, Japan. Maeda (2015) revealed the difference of amplitude of transfer function between the active and inactive periods of the volcanic eruptions. Yamaoka et al. (2017) detected a temporal change of transfer function at the time of magma intrusive event of Sakurajima in 2015, suggesting the stress change of volcanic body.

In spite of achievements above the limitation of single ACROSS source became obvious. A use of multiple ACROSS sources, for example, of the order of 10 source operation should be put into practical use. To achieve the purpose low-price ACROSS source should be developed.

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Controlled source electromagnetic approach with EM-ACROSS signal

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The electromagnetic accurately controlled, routinely operated signal system (EM-ACROSS) is a system which was ported from the seismic monitoring system and applied in controlled source electromagnetism (CSEM) sounding technique. We specially designed this system for a CSEM experiment at Kusatsu-Shirane volcano to investigate the subterranean space in this volcano region.

We firstly made an initial experiment for confirming the ability of this system by comparing with the magnetotelluric (MT) measurement. In this initial experiment in 2017, a signal was designed by superposition of 11 harmonics with binary frequencies, same amplitudes and random phases. A function generator, which was synchronized with a GPS clock, stored the above-mentioned signal and continuously sent it to an amplifier after a pulse trigger. The amplifier increased the voltage of the input signal 80 times then outputted the amplified signal to electrode dipole. The output signal from both the function generator and the amplifier were recorded by a digital signal logger. The transmitter system sent the signal by electromagnetic wave from southern foot of Motoshirane volcano to the receivers which located at Mount Kusatsu-Shirane. We chose the MTU-5/5A series MT units to be receivers. The receivers continuously measured the electromagnetic field from two electrode dipoles and three inductive coil censors with 15 Hz sampling rate. The initial experiment was run for four days. The transmitter system which was used in second stage experiment was modified to two amplifiers, and the transmitted signal was redesigned with pseudo binary frequencies from primary number to avoid the harmonic distortion.

The frequency spectrum of the data from both function generator and transmitter should be also checked for the accuracy of transmitted signal. The first step of the receiver data processing was time series data division. The whole time series data was divided into many ¥'frames¥' with same data length. The linear detrending method was chosen to remove the effects from strong, long term nature noise. The second step was converting the data from time domain to frequency domain by fast Fourier¥'s transform (FFT) by each frame. The third step was removing the outlier in frequency domain which either the real part or imaginary part was out of two standard deviation range then stacking the data. We calculated the impedance from the received data which was sent from different polarizations of dipoles, and the approximate apparent resistivity and impedance phase to compare with the value from MT.

The frequency spectrum of received data presented the enhancement in the signal-to-noise ratio (SNR) by data stacking. The anti-noise ability of this system was confirmed with a data from one site which measured some broadband continuous anthropogenic noise. The MT data was strongly affected by that noise which presented abnormal apparent resistivity and impedance phase. Nevertheless, the approximate apparent resistivity and impedance phase from EM-ACROSS was much closer to the value in other sites. The initial experiment in our first stage presented the requirement of a greater number of the frames to reduce the noise floor in longer period, that is the reason of the decision for running a long-term measurement in the second stage.

The initial experiment pointed out several details for improvement which were considered while we modified the design of transmitter system. It provided at least twice of the frames in one day by using two amplifiers with parallel injections. The forward modeling which used the parameter from transmitter data from the initial experiment in the first stage can be used to check the radiation pattern of this system, and be a reference for the allocation of new sites.

信号源の空間不均質性が地磁気変換関数に与える歪み

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Disturbance of geomagnetic transfer functions by spatial heterogeneity of source field

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It is well known that the heterogeneity of source field strongly affects the magnetotelluric (MT) responses and geomagnetic transfer functions (TF). These electromagnetic responses are used for visualization of subsurface structure, and recently time-lapse MT has been conducted for monitoring the subsurface environment, especially around geothermal area. Therefore, understanding of behavior of the heterogeneous source field to the MT responses and TFs becomes a key for accurate imagining of subsurface structures and their monitoring since the false temporal changes can be triggered if the geomagnetic variation is not homogeneous (e.g., Egbert et al., 2000; Romano et al., 2014). In the conventional methods, the TFs of horizontal magnetic field between two sites have been used to evaluate the spatial characteristics of geomagnetic variation since the horizontal magnetic field basically reflects the strength of source field. However, the TF-based evaluation of source field characteristics requires long time-series data for accurate estimation of TF at both sites. In this study, we focus on the raw spectrograms (i.e., time-frequency domain) of geomagnetic data, which have huge information and will be suitable for accurate and detailed discussion on the source field. We applied the Non-negative Matrix Factorization (NMF) (Lee and Seung 2000; Kameoka et al., 2009), which can extract the independent components from the spectrogram, and expanded the NMF to the Multi-Channel NMF (MC-NMF) in order to extract the common components from several geomagnetic spectrograms. We applied MC-NMF to the horizontal geomagnetic data obtained at several geomagnetic observatories, and extracted the independent components. We found north-south heterogeneities of some components in horizontal geomagnetic spectrograms. Then, we calculated the temporal stability of TFs during 2000-2010, and found that the low stabilities of TFs are obvious if the components in geomagnetic spectrograms have large spatial heterogeneities. We also found that the horizontal-vertical geomagnetic transfer functions (so called as tipper) indicate instabilities in case of larger spatial heterogeneities of geomagnetic spectrograms. As a result, we conclude a successful evaluation of the spatial characteristics of geomagnetic variation based on our method. In further studies, we expect that our method will reduce the unwanted effect due to the heterogeneous source field, and derive the TFs and MT responses with higher accuracy.

Comparison between observed and calculated Sq variations at the surface of the Earth - preliminary results

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We report on a preliminary result of analyzing the observed computed Sq variations at the surface of the Earth on Oct.8-10, 2007. The computed Sq variation was obtained from the GAIA model by Fujita et al. (2018). The observed one was collected by the INTERMAGNET program, WDC for geomagnetism, Kyoto, Geospatial Information Authority of Japan, the 210MM project, etc. We used the 1 hour values of the geomagnetic field for 3 days to extract the Sq variation for comparison with calculated one by GAIA.

The three vector components of the geomagnetic field were decomposed in order to remove unnecessary variations such as the main field and variations of the magnetospheric origin. The main field was estimated by using the CHAOS-5 model. Spherical harmonic coefficients of the residual show that a significant dipole field is included indicating the existence of the variation of the magnetospheric origin. Since the dipole component shows a long term variation, a trend component computed by a Kalman filter procedure was removed from the residual geomagnetic field.

The spherical harmonic analysis was applied to the extracted Sq variation at worldwide sites and obtained SPH coefficients for the external field were compared with those from the geomagnetic field computed from the GAIA. A location difference between the computed and observed Sq was investigated in order to a spatial shift which the GAIA model contains.

Plane-wave and flat Earth approximations in EM induction studies

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In electromagnetic sounding methods, such as the magnetotelluric method, studies are usually carried out by treating (1) the inducing field as spatially uniform and (2) the Earth as a semi-infinite conductor with a plane surface. These treatments are both approximations of the electromagnetic induction due to the incidence of a laterally non-uniform inducing field into the conducting spherical Earth. Although the basic theoretical concept was established many decades ago by A.T. Price, L. Cagniard, T. Rikitake, S.P. Srivastava, etc., the physical conditions for these two approximations are not fully and systematically understood, and some confusion appears in the literature. This presentation attempts to re-examine the basic formulation of the electromagnetic induction within the homogeneous conductor in both spherical and Cartesian coordinate systems and to clarify how the conditions for the two approximations were derived in a systematic manner. The result reveals that solutions in the two coordinate systems are consistent with each other at an appropriate limit and that the two approximations result in neither indefinite nor non-unique problems, as suggested in some previous studies, if approximation conditions are properly applied. In addition, a few corrections to related chapters and/or sections of classic papers and textbooks are obtained as a by-product of this research.

再解析 network-MT データによる阿蘇カルデラの 3 次元比抵抗分布モデル：ダイポール配置の検討

畑 真紀 [1]; 上嶋 誠 [2]; 田中 良和 [3]; 橋本 武志 [4]; 吉村 令慧 [5]; 大志万 直人 [5]
[1] 東大・地震研; [2] 東大・震研; [3] 京大; [4] 北大・理・地震火山セ; [5] 京大・防災研

3-D electrical resistivity models beneath Aso caldera by reanalysis network-MT data: The evaluation of dipole arrangements

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Aso caldera was formed by a series of huge eruptions, with a volcanic explosivity index of 7, during 270-90 ka and post-caldera cones were formed in the caldera. A post-caldera cone of Naka-dake is a quite active volcano, which experienced magmatic and phreatomagmatic eruptions, and an explosive eruption with spewing volcanic ash 11,000 m into the air during 2014-2016. Thus, it is important to understand the subsurface structure in the caldera. In and around Aso caldera, network-MT surveys for the electric field (the electric potential difference) were carried out in 1995 by using long metallic wires/dipoles of the commercial telephone company's networks [e.g., Tanaka et al., 1998; Hashimoto et al., 1999; Uyeshima et al., 2002; Hata et al., 2015]. We determined two components of network-MT response functions between the potential differences for every dipole and the two horizontal components of the magnetic field at the Kanoya Geomagnetic Observatory.

We performed three-dimensional (3-D) inversion analyses by using the above-mentioned network-MT data in a period range from 640 to 10,240 s, and obtained two electrical resistivity models to evaluate the difference of model resolutions due to the difference of dipole arrangements. One of the models was obtained by inverting a data-set whose dipoles were arranged independently in the caldera [Hata et al., 2018]. The other model was obtained by inverting another data-set whose dipoles shared the endpoints with the adjacent dipoles. In the caldera, the dipoles are arranged in a meshed pattern. Through the 3-D inversion analyses, we used a data space Occam's inversion code modified for the network-MT data of long dipoles [e.g., Siripunvaraporn et al., 2004]. In this presentation, we show the details of the 3-D resistivity models and comparison between the two models.

草津白根山の３次元磁化構造について

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Three dimensional magnetic structure of Kusatsu Shirane volcano

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Kusatsu Shirane Volcano is located in the northwest of Gunma prefecture, Japan. The activity of Kusatsu Shirane volcano is divided into three active phases. First phase was the activities of Matsuozawa volcano formed in about 600,000 years, spewing andesitic lava and volcanic clastic materials to form a compact stratovolcano. The second phase was about 550,000 to 300,000 years ago and spurted pyroclastic flows and thick andesitic lava flows into the east and south direction. The last activities began about 16,000 years ago, with the period of inactive during the period from 20,000 to 300,000 years in between. During this period, the main activities were occurred at the summit of the mountain, and forming a Shirane and Moto-Shirane volcanos as well as Yugama which is a most active area during the recent activities.

On this volcano, aeromagnetic and aero-electro-magnetic observations were conducted by the MLIT in 2013 in order to obtain the information about the electro-magnetic structure of this volcano. Using the magnetic anomaly data obtained by this observations, we tried to investigate the detailed subsurface magnetic structure of this volcano by the 3D magnetic inversion. In our presentation, we will show the results of the estimated 3D magnetic structure of Kusatsu Shirane volcano.

草津白根火山は群馬県の北西部、吾妻川を挟んで南の浅間火山と相対する位置にある火山である。この火山は基盤山地の肩付近を噴出源とするために、非対称で東方向に延びた形をしており，比較的なだらかな山頂部には、白根山や本白根山等の火砕丘群が南北に並び、水釜、湯釜、涸釜など多数の火口が分布している。草津白根火山の活動は、3 つの活動期に区分されている。第 1 期の活動は、約 60 万年に形成された松尾沢火山の活動で、安山岩質溶岩と火山砕屑物を噴出して小型の成層火山を形成した。第 2 期の活動は、約 55 万年前～30 万年前で、大規模な火砕流の噴出や厚い安山岩質溶岩を東・南方向に噴出した。その後 20～30 万年間の活動の休止期を挟んで、約 16,000 年前から第 3 期の活動が始まった。第 3 期の活動は主として山頂部での活動で、白根火砕丘や本白根火砕丘の単成火山を形成し、新期の溶岩流（殺生溶岩など）をやはり東・南方向に噴出し、また、水釜や湯釜などの火口も形成された。近年では硫化水素などによる人的災害などのほかに、山頂付近での水蒸気爆発などの活動が生じている。

草津白根火山では、山体構造の把握を通した草津白根山火山噴火緊急減災対策砂防計画の精査を目的として、平成 25 年に国土交通省により空中磁気・電磁観測が行われた。この観測は白根山、本白根山を含む約 6 km x 6 km の範囲内で、ヘリコプター（アエロスパシアル　AS350B3）を用いて行われた。我々はこのデータを使用させていただき、空中磁気観測のデータを用いて詳細な 3 次元磁化構造解析を行った。本発表ではこの解析結果について報告する。

オリジナルのデータは、ヘリコプターに搭載されたセシウム磁力計の全磁力データに対し、日変化補正、IGRF 補正及び機体磁気補正を施した全磁力磁気異常データである。これに対し上方接続 (Nakatsuka and Okuma, 2005) を適用し、一様なグリッド上のデータに変換した。さらに、観測範囲のスケールを超える長波長な磁気異常の影響を除くため、1 次傾向面解析を施し線形トレンドを除去した。このデータを入力として、インバージョンにより山体内部の磁化強度分布を求めた。

この解析の結果、地下 1km 程度までの磁化構造が得られ、その結果から以下のような特徴が明らかになった。析領域は、青葉溶岩、香草溶岩、本白根溶岩など複数の溶岩流で表面を覆われており、表層 (地表～地下 150m) の磁化は、山体内部の平均的な磁化より高い値を示す。しかしその中に低磁化を示す領域が点在している。湯釜周辺の地下には顕著な低磁化は見られないが、南東側に高磁化域が存在する。本白根の北側火口地下に高磁化を示す領域が存在し、地表から地下 500m 程度まで続いている。本白根火口群を取り巻くように低磁化域が分布しており、地下 1km 以深まで連続している。本発表ではこれらの解析結果の詳細について紹介する。

謝辞：今回使用した草津白根火山における空中磁気データは、国立研究開発法人土木研究所・(旧）砂防研究グループを通して提供を受けました。

三宅島３次元比抵抗構造解析（序報）

Gresse Marceau[1]; 上嶋 誠 [2]; 長谷 英彰 [3]; 相澤 広記 [4]; 山谷 祐介 [5]; 小山 崇夫 [6]; 畑 真紀 [7]
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Preliminary report of three-dimensional electrical resistivity structure in Miyakejima

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Miyakejima has a last eruption in 2000 and the next event is going to be expected soon. To detect the temporal precursory change of the resistivity structure, it's essential to infer the resistivity structure in a still state.

The ERI has conducted the MT surveys in 2003-2005, and 2012 in Miyakejima. By using these MT data, the three-dimensional structure is estimated.

The WSINV3DMT code (Siripunvaraporn and Egbert, 2009) is used to invert the full impedance and geomagnetic transfer function data by various mesh refinement and data filtering.

As the result, a highly conductive area is detected just beneath the crater, especially, southern part of a crater which is a current active region with fumaroles. It may be a cray cap rock commonly found in the volcano with hydrothermal system.

栗駒火山昭和湖周辺におけるAMT観測

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[1] 秋田大・国際資源; [2] 秋田大・国際資源

AMT measurements around Lake Showa, Kurikomayama volcano, northeast of Japan

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Resistivity is one of important physical parameters in order to research underneath structure of active volcanoes. The existence of volcanic fluid like as geothermal hot water and magma is closely related to the resistivity and conductivity (conductivity is the reciprocal of resistivity). MT (Magnetotelluric) method which is making use of natural electromagnetic variation is especially useful to estimate the subsurface resistivity and to investigate the volcanic structure. AMT is one of MT methods using the electromagnetic wave ranging the audio-frequencies and its exploration depths are from a couple of hundred meters to several kilometers. Since exploration depths of AMT are thought to most important active zone of volcanic fluid, AMT method and auxiliary using of wide-band MT method are recently expected to figure out the structure and to monitor the volcanic activity.

Now we focus the Kurikomayama volcano closely at the triple junction of borders of Akita, Iwate and Miyagi prefectures, northeast of Japan. Kurikomayama volcano is one of important active volcanos and its most recent striking activity was a phreatic eruption in 1944. The site of 1944 eruption is now remained as a crater lake called Lake Showa. Besides the Lake Showa, upstream of a gorge called Jigoku-dani and volcanic gas is even now emitted there.

We installed several AMT sites on the volcanic body of Kurikomayama volcano and one of sites is alongside Lake Showa and Jigoku-dani. We just collected the time series of geomagnetic and telluric date of AMT and report the characteristics of primary data and initial analyses using phase tensor, induction arrow, one- and two-dimensional structure analysis.

So far the several researches of 2- and 3-dimensional resistivity structure of the crust including Kurikomayama volcano have been reported (for example Mishina, 2009; Ichihara et al., 2014). Mishina (2009) firstly report the 2-dimensional resistivity structure targeting the deep volcanic fluid beneath the Kurikomaya volcano. The result of Mishina (2009) suggested the existence of volcanic fluid at the depth of several kilometers under the volcano. Our research target is shallower depth than the research of Mishina (2009) and the purpose is the volcanic structure and the fluid related to phreatic eruption.

R003-P05 **会場: Poster** **時間: 11 月 25 日**

Wideband Magnetotelluric Survey across the Dabbahu Rift in the Afar Depression, Ethiopia

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The Afar area (Ethiopia) is well known as one of continental rifts transitioning to oceanic spreading centers. In order to delineate subsurface electric properties and document an initial stage of the formation process of magnetic stripes, we carried out wideband magnetotelluric (MT) measurements and ground magnetic survey along a common profile in 2016 and 2017. This profile, approximately 55km long, cuts across the Dabbahu rift in the Afar Depression. In MT survey, we obtained electromagnetic and electric data at 14 sites using MTU-5A (Phoenix Geophysics) and ELOG1K-PHX (NT system design) systems. In magnetic survey on foot, we recorded total magnetic fields at 2.4 meters above the ground every 4 seconds by utilizing GSM-19 Overhauser magnetometer (GEM systems). In this presentation, we will introduce the outline of our project and show an inversion result of MT survey.

我々は、地上において海洋底拡大現象が進行しつつあるエチオピア・アファール凹地において、地磁気縞状異常の獲得形成過程を解明する研究プロジェクト（石川他, 2017）を進めている。調査域は、2005〜2009 年に発生した Dabbahu Rift でのダイク貫入イベントの南方延長にあたり、地下構造を把握することは、同種のイベントの発生可能性の評価にも資すると考えられる。プロジェクトの最終目標である無人飛行機による空中磁気探査に先立ち、Dabbahu リフトを横切る測線を設定し、2016 年度には地上踏査による磁気探査を、2017 年度には広帯域 Magnetotelluric (MT) 探査を実施した。MT 探査により推定される地下比抵抗構造は、リフトにおける温度構造を反映している可能性が高く、地磁気獲得の背景場を理解するために有用であると考える。

地上磁気探査では、GSM-19 オーバーハウザー磁力計 (GEM systems) を使用し、地上高 2.4m にセンサーを維持しつつ 4 秒サンプリングで、約 60km の測定を行った。同時にハンディGPS により、1 秒ごとのトラックログを記録し、位置情報とした。外部磁場（日変化や磁気擾乱）の影響を補正するために、測線の西部に位置する Samara 大学敷地内に参照点を設置した。参照点との単純差を求め、磁気異常を概観すると、大局的には先行研究 (Bridges et al., 2012) と調和的なパターンが得られた。一方、短波長の分布については、lava flow を越える個所において、数 1000nT に達するスパイク上のシグナルが確認された。しかしながら、その振幅は flow 毎に異なり、磁化強度の違いを反映している可能性が高い。

広帯域 MT 探査では、地上磁気探査測線に沿うように約 4km 間隔で計 14 点において、電磁場変動データを取得した。器材は、MTU5A (Phoenix Geophysics) ならびに ELOG1K-PHX (NT システムデザイン) を使用し、14 点中 5 点では電場変動のみの収録であった。予察的な解析として、MTU5A で計測した 10 点のデータを時系列処理し、⊠測定座標系による TM モードのみを用いる、⊠ lava flow や正断層群の走向 N45W に座標回転をし TM, TE の両モードを用いる、2 つ手順の二次元解析を行った。時系列解析では Chave & Thomson (2003) のコードを、2 次元構造解析には Ogawa & Uchida (1998) のコードを使用した。両者の構造は、大局的には差異は目立たないものの、測線中央部の下部良導域の形状に違いが確認できた。大局的な構造は、本研究測線の南方での先行研究 (Didana et al., 2014; 2015) や北方での先行研究 (Desissa et al., 2013; Whaler et al., 2012) に共通して、現在の拡大中心軸周辺の深部から浅部に盛り上がる低比抵抗体に特徴づけられる。さらに、東西には高比抵抗体が存在するが、非対称性が確認された。この非対称性は、拡大軸の両側の拡大速度の違いの原因もしくは結果である可能性がある。

本発表では MT 観測を中心に、これまで未処理であった点の処理を進め、現時点で取得しているデータを最大限に活用した構造推定の結果を報告する。加えて、2018 年度に予定している追加の MT 観測について、概要ならびにそのねらいを紹介する。

AMT 調査と広帯域 MT 調査を併用した地下比抵抗構造の解明－特性の異なる 3 つの活断層の比較－

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Resistivity structure around the Gomura fault zone using AMT and WMT surveys: Comparison among three characteristic fault segments

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The Gomura fault zone in the Tango Peninsula, Kyoto, consists of three fault segments, the Go-seihou, Gomura and Chuzenji faults parallel to each other. These faults show different features in fault activity (e.g., mean slip rates and latest events). The Go-seihou fault is a very short segment (~2.8km long) with no clear horizontal displacement. During the 1927 Kita-Tango earthquake, a clear surface rupture has appeared along the Gomura fault, while there was no displacement along the Chuzenji fault geomorphologically recognized as an active fault. As they run nearly parallel within about 3km distances of simple geological setting, the Gomura fault zone is suitable for studying the relationships between differences in subsurface structure and fault activity.

Magnetotelluric methods are powerful for surveying the subsurface structure of active faults based on electrical conductivity variations expected around an active fault especially on strike-slip faults, and many studies have been conducted (e.g. Unsworth et al., 1997; Ikeda et al., 2013). In this method, lower frequency magnetic fluctuation is used as a signal source to study the deeper portion including seismogenic regions, but the spatial resolution decreases as the signal frequency decreases. Thus, we must use high-frequency signals to image a shallow part with higher spatial resolution. In this study, we apply both audio-frequency magnetotelluric (AMT) and wide-band magnetotelluric (WMT) methods to reveal the resistivity structure from the surface to seismogenic depths for the three fault segments.

We made observations along the same survey line as preceding two AMT surveys by Yamaguchi et al. (2016) and Mimura et al. (2017, JpGU); seven sites were set for the WMT and two sites were added to the former studies.

We estimated MT responses according to the remote reference processing (Gamble et al., 1978). For the data analysis of the AMT survey, prior to a model analysis, we investigated the dimensionality of shallow resistivity structure by the phase-tensor analysis method (Caldwell et al., 2004) and then determined the 2D dimensionality with a strike of N30W. The MT responses of a lower-frequency band obtained by WMT are supposed to be influenced by surrounding highly conductive sea water, because the survey area is located about 5km inland from the coast line. By forward modeling, we estimated that its effect is restricted to the MT responses in the frequency band lower than about 10Hz. Thus, we apllied a 3D model analysis method for the data obtained by WMT.

In this poster presentation, we will show the shallow and deep resistivity structure across the three parallel faults, and discuss its geological and geophysical interpretation.

郷村断層帯は京都府の丹後半島に位置する活断層帯で，陸上部は郷西方断層，郷村断層，仲禅寺断層の 3 つの断層で構成されている．郷西方断層は断層の長さが 2.8km と非常に短く，横ずれ変位を示す地形は不明瞭である．郷村断層は 1927 年の北丹後地震の際に左横ずれを主とする顕著な地表地震断層を生じた．一方で，仲禅寺断層は北丹後地震の際には活動しなかったものの，明瞭な河谷の左横ずれ屈曲が見られる．このように郷村断層帯では断層の長さ，平均変位速度，最新活動時期など断層運動の特性が異なる断層が数 km 以内に近接し，並行して位置している．加えて郷村断層帯周辺は，ほとんどが花崗岩の岩盤からなり地質が一様で単純なため，断層の地下構造と断層の特性を比較するのに好適である．

活断層を対象とした物理探査の 1 つに Magnetotelluric 法（MT 法）がある．従来の活断層を対象とした MT 調査では震源域を含む地下深部に重点を置いていることが多く，得られた構造の浅部の解像度は，地質学的な調査によって得られるそれと比べ十分とは言えない．したがって，地形・地質学的知見との対比を念頭に置き，活断層の震源域から地表までの連続的な構造を理解するためには深部に重点をおいた調査のみだけではなく，浅部を対象としたより詳細な調査も行う必要がある．本研究では，活断層の地下浅部から深部までの連続的な構造（特に浅部では高解像度の構造）の把握を目指し，郷村断層帯において Audio-frequency Magnetotelluric 法（AMT 法）と広帯域 MT 調査を行った．

郷村断層帯周辺では 2013 年，2016 年に AMT 調査が行われており（山口ほか，2016；三村ほか，2017，JpGU），本研究ではこれらの調査が行われた測線と同じ測線上において観測を行った．広帯域 MT 調査ではおよそ等間隔になるように 7 点の観測点を，AMT 調査では過去の観測点を補間するように 2 点の観測点を配置した．

AMT 調査，広帯域 MT 調査のデータ解析ではともに Remote reference 法（Gamble et al., 1978）に基づいて MT 応

答関数を算出した．AMT 調査のデータ解析では，Phase Tensor 法（Caldwell et al., 2004 ; Bibby et al., 2005）を用いて比抵抗構造の次元の判定を行った．その結果，郷村断層帯周辺の浅部の比抵抗構造は 2 次元であり，その走向は N30W であると判断された．

観測地域は日本海から内陸に約 5km 入った場所に位置し，広帯域 MT 調査で得られた MT 応答関数は海の影響を受けている可能性が考えられた．その影響をフォワード計算によって評価した結果，約 10Hz より低周波数側では海の影響を受けていると判断された．さらに，断層周辺の浅部の比抵抗構造の走向が N30W であるのに対し，海陸境界の走向はおよそ N60E であるため，海の影響を受けていると判断した広帯域 MT 調査のモデル解析は 3 次元で解析を行うことが妥当である．したがって，本研究では AMT 調査の結果は 2 次元モデル解析を行い，広帯域 MT 調査の結果は 3 次元モデル解析を行った．

本発表ではこのようなモデル解析によって得られた郷村断層帯の浅部から深部までの比抵抗構造を紹介し，並行する 3 つの活断層との関係を議論する予定である．

四国西部におけるネットワーク MT 観測について

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On the Netowrk-MT observation in the western part of Shikoku

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In the Bungo channel region at the western margin of the Nankai megathrust rupture zones, the long-term slow slip events (SSE) repeatedly occurred about every 6 or 7 years and we expect the next event soon.

In order to examine influence of interstitial fluids on occurrence of the SSE, we have started the Network-MT survey in the western part of the Shikoku Island facing the Bungo channel since April, 2016. We use metallic telephone line network of the Nippon Telegraph and Telephone Corp. to measure the electrical potential difference with long baselines of from several kilometers to 10 and several kilometers. We selected 17 areas in the western part of the Shikoku Island and installed 3 or 4 electrodes in the respective areas. The electrical potential differences measured in this way are known to be less affected by small scale near-surface lateral resistivity heterogeneities (e.g. Uyeshima, 2007). We also measure the geomagnetic field by using fluxgate magnetometers at two stations in the target region. With the aid of the BIRRP code (Chave and Thomson, 2004), we could estimate the frequency-domain response functions of good quality.

In this presentation we will show the 3-D electrical resistivity structure in the target region and compare with regional seismicity. In the inversion, we used the 3-D DASOCC inversion code (Siripunvaraporn et al., 2004), which directly invert the Network-MT response between the voltage difference and the magnetic field.

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Lateral heterogeneity of nominally 'normal' oceanic upper mantle in the northwestern Pacific

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Old (>130 Ma) 'normal' oceanic upper mantle, which is expected to be cooled over time just by thermal conduction, has been investigated through marine magnetotellurics. One-dimensional electrical conductivity profiles were obtained for areas in the northwest (Area A) and the southeast (Area B) of the Shatsky Rise in the northwestern Pacific (Baba et al., 2017). Supposing that the bottom of resistive upper mantle layer is defined as the depth where the gradient of resistivity changes from minus values to almost zero, the thicknesses of resistive layer for Area A and Area B is about 100 km and about 150 km, respectively. The profiles are significantly different in the thickness, although the lithospheric mantle ages are almost the same; 130 Ma in Area A and 145 Ma in Area B. This means that it is difficult to explain this difference by the half-space model (Lister et al., 1990) or the plate-cooling model (Stein and Stein, 1992).

In this study, we investigate the lateral heterogeneity of the upper mantle beneath the two areas separately by using a three-dimensional inversion approach (Tada et al., 2012; Baba et al., 2013). For Area A, we found that a high electrical conductivity anomaly elongated from the northeast to the southwest in the area at the depths deeper than around 100 km, which is mostly parallel to the seafloor age of 130 Ma and Kuril Trench. On the contrary, there is little horizontal heterogeneity from the shallow lithosphere to the deeper asthenospheric mantle in Area B. In this presentation, we will interpret the three-dimensional features to discuss the cause of the difference between Area A and Area B.

南部マリアナ背弧拡大海嶺下の上部マントル比抵抗構造の解明

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Imaging upper mantle electrical resistivity structure beneath the southern Mariana back-arc spreading ridge

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Back-arc spreading ridges in the southern Mariana Trough are slow-spreading ridges but have features suggesting enhanced melting beneath the ridges and influences on seafloor spreading processes by fluid derived from the subducted Pacific slab underlying the ridges. To reveal melting and dehydration processes and dynamics in the upper mantle in the southern Mariana Trough, we conducted a marine magnetotelluric (MT) experiment along a 120 km-length transect across a ridge segment at 13^{o}N. We obtained electromagnetic field data at 9 stations along the transect, and analyzed them for estimating MT responses, striping bathymetric distortion from the responses, and imaging a 2-D electrical resistivity structure by 2-D inversion of TM-mode responses. A resultant 2-D inversion model showed 1) a conductive area at 10-20 km depth beneath the ridge center, the center of which slightly offsets to the trench side, 2) a moderately conductive area expanding asymmetrically under the conductor of 1), 3) a resistive area thickening from the ridge center up to about 40 km on the remnant arc side, and 4) a resistive area with a constant thickness of about 150 km on the trench side. These model features suggest 1) a melt body beneath the ridge center, possibly containing slab-derived water, 2) mantle wedge hydrated by the subducted slab, and melting area produced by asymmetric passive upwelling and buoyant active upwelling in the hydrous mantle wedge, 3) residual lithospheric mantle off the ridge center, and 4) mantle wedge and subducted Pacific lithospheric mantle that are both cold. The electrical resistivity structure obtained in the southern Mariana Trough, which clearly contrasts with the structure of the central Mariana Trough at 18^{o}N in that this lacks a conductor beneath the ridge center, provides insights on the mantle dynamics and its relation to the characteristic tectonics and many kinds of observational results in the southern Mariana Trough.

We carried out synthetic tests to check the validity of data analyses applied to the real data, because we have a 2-D transect data to a possible 3-D electrical resistivity structure at the southern Mariana Trough. The tests consist of 1) Bathymetric correction for MT responses produced from a 3-D electrical resistivity structure, and 2) 2-D inversion only using TM-mode response of 3-D MT response produced from a 3-D electrical resistivity structure. In addition, we conducted other tests to check reliability of the 2-D inversion model from the real data. We will present details of these tests.

南部マリアナトラフ背弧拡大海嶺は、低速拡大だが、海嶺軸下での豊富な部分溶融と、海嶺軸直下に沈み込んだ太平洋スラブから脱水した水が背弧拡大過程に影響を与えている可能性を示唆する特徴を持つ。南部マリアナトラフの上部マントル中の部分溶融や水の分布とマントルダイナミクスを明らかにするため、海底電磁気観測を 13^{o}N 付近の海嶺セグメントを横断するおよそ 120 km 長の測線に沿って行った。9 観測点で得られた電磁場時系列データを解析し、電磁気応答関数にみられる地形効果を補正したあと、TM モードの応答関数の 2 次元インバージョンにより 2 次元比抵抗構造を推定した。得られた 2 次元モデルは次のような特徴を示す。1) 海嶺軸下だがわずかに海溝側にずれた深さおよそ 10-20 km にある低比抵抗域、2)1) の低比抵抗域の下に非対称に広がる（古島弧側により広がる）低比抵抗域、3) 海嶺軸から古島弧側に向かい厚くなる（およそ 40 km 厚さまで）海底下の高比抵抗域、4) 海溝側の海底下にある厚さがおよそ 150 km 一定の高比抵抗域、である。これらの特徴は、1) 沈み込んだスラブ起源の水を含む可能性のある、海嶺軸下の部分溶融域、2) 沈み込んだスラブからの脱水により含水化したマントルウェッジと、その中での受動的マントル上昇流と浮力性の自発的マントル上昇流によってできる部分溶融域、3) 海嶺軸外に存在する溶け残りマントル、4) 低温のマントルウェッジと沈み込んだ太平洋スラブ、を示唆する。南部マリアナトラフの比抵抗構造は、中部マリアナトラフ 18^{o}N 付近の比抵抗構造と比べて海嶺軸下に明瞭に低比抵抗域の存在を示しており、南部マリアナトラフのマントルダイナミクスや、そのテクトニクス・種々の観測結果との関係について示唆を与える。

観測データに適用したデータ解析（3 次元比抵抗構造の可能性がある場所で取得した 2 次元測線の海底データの解析）が有効かどうかを検証するシンセティックテストを行った。検証したデータ解析は次のものである。1) 海底下の比抵抗構造が 3 次元の場合の海底電磁気データの地形補正、2) 3 次元比抵抗構造に対して TM モードデータのみを用いて行う 2 次元インバージョン解析。これらに加え、観測データから得られた 2 次元比抵抗構造の信頼性を検証するテストを行った。以上のテストの結果についても発表する。

GAIA Sq モデルを用いたマントル電気伝導度構造の推定

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Estimation of electrical conductivity in the Earth's mantle by using the GAIA Sq model

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We've tried to estimate the electrical conductivity of the mantle structure by using the Sq variation derived from the GAIA (Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy).

The GAIA assimilates the meteorological reanalysis data (JRA-55) to the whole atmosphere-ionosphere coupled model and thus it is the well-modelled Sq field. We use this Sq model as an inducing field.

First we executed spherical harmonic expansion of the magnetic field of the GAIA for 3 day time series up to 50, which correspond to three sequential solar quiet days. And then, three-dimensional forward modeling in the spherical coordinate was executed in the frequency domain. Now, we suppose the 1-D structure in the Earth under the ocean-land lateral contrast. As the results, the calculated geomagnetic data inversely converted to the time domain could be closer to the observed time series data, compared to the GAIA Sq field itself, that is, total of RMS data misfit at 71 stations decreases by 40%.

Next, we try to find the best fit 1-D model in the mantle. We suppose the basic 1-D model as a standard model in the northwest Pacific by Baba (2017). We also try other models which are more or less conductive, and as the results, the original model or slightly more conductive model is the best to explain the vertical magnetic field data of Sq. We also try to estimate the 3-D electrical conductivity model in the Earth's mantle by using the Sq model of GAIA, and discuss it.

周期帯 10^4～10^5 秒の MT レスポンス推定について

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On estimation of magnetotelluric response for the period range between 10^4 and 10^5 seconds

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For estimation of magnetotelluric (MT) response functions at the periods between 10^4 and 10^5 seconds from seafloor electromagnetic data, the effects of complex external source fields (e.g., geomagnetic solar quiet daily variations (Sq) and tides) are necessary to take into account. One of the ways to deal with this problem is to determine the amplitude and phase of time variation for known periods of Sq and tides and to subtract them from the observed data (detiding). However, the reduction of the effects is not enough to obtain reliable MT responses (Shimizu et al., 2011).

In this study, I first revisit the impact of detiding on MT response estimation. The reduction of the line spectra was improved if the annual variations of the amplitude of these variations, which is manifested as line spectra at both sides close to the periods, are considered. However, the resultant MT responses still show unrealistic feature. I then applied independent component analysis (ICA) to separate Sq-like field component from the observed magnetic data. Sq field is based on the current in the ionosphere, which is excited by heating of neutral atmosphere by Sun. Then, I may suppose that the simplest instantaneous mixing model can be applied by treating the data with local time of each station. Applications of the ICA to real seafloor array data seems that it was succeeded qualitatively to detect Sq like components by investigating the detailed time variation and power spectrum of each independent component and correlations of mixing coefficients to longitude and latitude. Quantitative evaluation of the independent components is necessary to study farther for establishing the method applicable to general data.

海底電磁気データより MT レスポンスを推定するに当たり、10^4～10^5 秒の周期帯においては、複雑な外部磁場ソース（地磁気静穏日日変化 (Sq) や海洋潮汐など）の影響を考慮する必要がある。従来は、時系列データから既知の周波数の変動分の振幅・位相を最小二乗的に推定して差し引く（detide）ことが行われているが、MT レスポンスは十分な精度では求まらず、Sq 場などの除去が不完全であることが影響していると考えられている（Shimizu et al., 2011）。

本研究では、まず detide の効果を改めて検証する。Sq 信号の振幅の季節変動を組み込むことで、ラインスペクトルの除去効果は上がるが、MT レスポンスには非現実的な変動が残る。次に、多変量解析手法の一つである独立成分分析を海底電磁気アレイデータへ適用し、Sq 様成分を観測データから分離することを試みる。Sq は、電離層が太陽によって温められる効果を反映した電流系によっているので、アレイデータを各観測点の経度にあわせたローカル時間で揃えることにより位相差を考えなくて良いとすると、最も単純な信号混合モデル（信号が時間遅れ無しに混合する）を適用できる。予備的な解析として、フィリピン海で 2005 年 11 月から約 1 年間同時観測した海底磁場データに適用した。分離した独立信号から Sq に関連した成分を特定するために、各信号の時間変動の特長のほか、パワースペクトルや、混合係数の緯度・経度との相関を参考にした。本発表では、その詳細を示し、Sq 場分離の実現可能性と、MT レスポンスの推定精度向上の可能性を議論する。

半無限媒質中の動的電磁誘導により生成される地震時電磁場変動 (2):数値例

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Induced electromagnetic field by seismic waves in stratified media in Earth’s magnetic field (2): Numerical examples

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Seismic waves accompany electromagnetic (EM) variations because Earth’s crust involves a variety of EM properties such as finite electrical conductivity and ion contents. If we can catch the EM variations just after the earthquake rupture, we will know the occurrence of earthquake before the arrival of seismic waves at observation point. However, quantitative aspects of EM variations arising from seismic waves have not sufficiently understood.

In the present study, I focus on the motional induction mechanism that possibly explain some parts of EM variations accompanying with seismic waves. A theoretical work on EM variations arising from the motional induction has been presented by Gao et al. (2014), but their work assumed uniform full-space medium. In contrast, the present work assumes stratified media which correctly incorporate the effect of the ground surface. I apply a calculating method developed both in seismology (e.g. Kennett, 2013) and in EM studies (Haartsen and Pride, 1997), and derive a set of expressions describing the spatial-temporal variations of the EM field after the onset of rupture.

In a previous meeting, I presented the procedure to derive a set of formula that provides theoretical variations of the EM variations arising from the motional induction. In the present meeting, I will present some of numerical examples, and discuss on their qualitative features.

地震動はさまざまなメカニズムを通じて電磁場変動を生成する。そのメカニズムには、界面導電現象、動的電磁誘導、ピエゾ電気・磁気などがある。各々について、生成される電磁場変動の計算方法が考察されている。主要なメカニズムだと考えられているのは界面導電現象である。たとえばパークフィールド地震時に観測された電磁場変動のかなりの部分が界面導電現象で説明できたとする報告がある [例えば Gao et al. 2016, GRL]。しかし、観測値と計算値の間には依然として小さくない不一致が含まれており、その他のメカニズムの寄与も無視できないと考えられる。

本研究では、動的電磁誘導 (motional induction) に起因する地震時電磁場変動について考察する。特に先行研究で扱われていない層構造媒質の場合について議論する。昨年 (2017 年) の講演では、半解析解の導出について紹介した。本講演では、具体的な数値例を示し、その定性的性質について議論する。

iTACFEM-3D: アダプティブ四面体メッシュを用いた CSEM 三次元インバージョンコードの開発

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iTACFEM-3D: Three-dimensional inversion with tetrahedral mesh adaption for CSEM problems associated with volcano sounding

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Controlled-source EM methods are important in monitoring volcanic activities for its steady source power. To promote the use of CSEM methods for volcano monitoring, I am now developing an open-source CSEM inversion code using tetrahedral mesh adaption based on the finite element method (FEM), currently dealing only with electric grounded-wire sources. I named the code iTACFEM-3D (inversion using Tetrahedral-mesh Adaption for Controlled-source EM problems based on FEM). Since the code is developed using Fortran90, it is easy to handle and modify for scientific communities. The inversion can refine the mesh suitably for updated models through iterations, where the finer mesh is achieved around conductive anomalies emerged. The inversion code adopts the Gauss-Newton scheme and a direct solver, PARDISO, from Intel MKL library. The inversion allows us to choose either of fixed or decreasing trade-off parameters for the regularization. The former is for L-curve inversions while the latter for the cooling strategies (e.g. Schwarzbach and Haber 2009). The inversion code has been already applied to the real CSEMS data obtained by the ACTIVE system (Utada et al. 2007) at Aso volcano, Japan, in 2014 to 2015, without its adaptive feature (Minami et al. 2018).

In this study, I apply the inversion code to seek effective observation network of the ACTIVE system for volcano monitoring. So far, our numerical experiments revealed that more than one source with a circular induction-coil receiver network around the crater can clearly image the top of upwelling magma 200 m beneath the active crater when Aso volcano is assumed. In the presentation, I share results of further investigation about feasibility of several ACTIVE networks for detecting a variety of temporal variations in the resistivity structure, using iTACFEM-3D.

野島断層注水実験時に観測された自然電位変動解明のためのアナログ実験（序報）

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Preliminary report of analog simulation of self-potential variations associated with water injection at the Nojima fault

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Water injection experiments at the Nojima fault which is an earthquake fault associated with the 1995 Hyogoken-Nanbu earthquake have been conducted since 1997 to monitor the recovery process of the fault. Negative self-potential variations synchronized with the water injection have been observed around a water injection borehole. These variations can be explained well with an electrokinetic model with the flow of water from the injection borehole to the ground. In this model, a metallic casing pipe of the water injection borehole acts a current electrode. However, positive self-potential variations at the casing pipe have been observed. These variations can't be explained well with the simple electrokinetic model. We report preliminary results of analog simulation experiments using a sand-box to make clear the mechanism of these self-potential variations.

本研究では，断層の回復過程を解明するために実施された野島断層注水実験時に注水に関連して観測された自然電位変動の中で，未解明な変動についての発生メカニズムを明らかにするためのアナログ実験の結果について報告する。

1995 年の兵庫県南部地震の地表地震断層である野島断層の回復過程を探るために 1997 年以降数年毎に注水実験が実施されてきた。注水時には，注水に同期した自然電位変動が注水孔周辺で観測されており，その自然電位変動の原因は注水孔から周辺部に注入水が流出することにより発生した流動電位と考えられる。注水の流入速度と発生電位の大きさの関係から，地下の透水係数の時間変化の推定が試みられている（例えば，Murakami et al.,2001;Murakami et al., 2007）。

野島断層における注水実験だけでなく，地熱地帯における生産井や還元井を使った揚水や注水実験に伴う自然電位変動は，地下で発生した流動電位を導体である井戸のケーシング・パイプ全体が電流電極として作用するというモデルで説明されている。通常ケイ酸塩鉱物が主体となる岩石中を水が流れると，流出側が電気的に負にそして流れてゆく方向が電気的に正になる流動電位が発生する。そのため，注水実験では流入水の流出に伴い注水孔の周辺が電気的に負に変化する。

野島注水実験でも，注水に同期して注水孔周辺が電気的に負に変化する変動が観測されている。しかし，注水孔のケーシング・パイプを電極と見立てて計測すると，ケーシング・パイプそのものは電気的に正に変動することがわかっている。また，ケーシング・パイプの極近傍はその影響を受けているようにも見える。この現象は，従来のケーシング・パイプを電流電極とするモデルでは説明できない。そのため，このような電位変動が起きる仕組みを明らかにするためにアナログ実験を開始したので，予備的な実験結果について報告する。

実験には，28cm x 16cm x 16cm のプラスチック・ケースに硅砂を入れ，注水孔のケーシング・パイプを模したものとしてステンレス・パイプ（外径 18mm）や塩ビ・パイプ（18mm）を使用した。プラスチック・ケースの側面ならびに底面に穴を開けて注水がケース外に流出するようにした。また，この実験における注水時間は 1 から 5 分程度と短時間であるため，長期安定性を必要としないのでステンレスの釘あるいは板を電極として使用した。電極を注水孔からの距離 4cm，7.5cm，11cm，15cm の位置に設置し，19cm の位置に電位計測の基準となる電極を設置した。電位計測には白山工業の LS-3350 を使用し，サンプリング間隔 0.5 秒で計測をおこなった。なお，注水操作は手動でおこなっているため，電位変動の極性変化にのみ注目した実験をおこなっている。

まず，比較のため注水孔ケーシング・パイプを模したパイプとして絶縁体である塩ビ・パイプを使用した場合には，注水によりすべての電極において電気的に正になる変動が観測された。これは，この実験ではケースが小さいく水の流入の仕方により表面に向かって流れる水が多いためと考えられる。次に，ステンレス・パイプを用いた場合には，ステンレス・パイプそのものは正に変動し，他の電極では注水直後は負に変動するが時間とともに水の上昇による影響（ステンレス・パイプと同様の変動）を受けるという結果が得られている。ステンレス・パイプの作用を明らかにするために深さ方向の電位計測などを今後進めてゆく予定である。