R003-01
Zoom meeting A　：11/3　AM1　(9:00-10:30)
09:00-09:15

AWAGS データの球帽関数調和解析でのパラメータ設定について

#市來　雅啓[1],藤田　清士[2],Wang　Liejun[3],Lewis　Andrew[3],Hitchman　Adrian[3]
[1]東北大院理,[2]阪大・工,[3]オーストラリア地球科学研究所

Parameter setting for spherical cap harmonic analysis of AWAGS data

#Masahiro Ichiki[1], Kiyoshi Fujita[2], Liejun Wang[3], Andrew Lewis[3], Adrian Hitchman[3]
[1]Grad. School of Sci, Tohoku Univ.,[2]Technology, Osaka Univ,[3]Geoscience Australia

To separate internal and external potential of the static geomagnetic Sq field in Australia, we evaluate the optimal parameter setting for spherical cap harmonic analysis (SCHA). We discuss an appropriate spherical cap width and degree of expansion in this study.

Torta and De Santis (1996) describe that over 60 degrees is acceptable for the cap width of SCHA for European data. This study does not treat Fourier harmonics in time domain, but snapshot of the Sq field model. We utilized the synthetic Sq field data based on Malin (1974) model. The three-component Sq field is synthesized at AWAGS stations (Chamalaun and Barton, 1993) in terms of UT=2 h and p=1 (period=24 hour) with 3 % Gaussian noise. Our previous SCHA program (Toh et al., 2004) uses a priori information assuming frozen-flux theory (Gubbins, 1983) and the singular value decomposition. In this study, we used the original program of Haines (1988), but evaluated the solution using Akaike Information Criterion (AIC). The SCHA program of Haines uses the stepwise regression method. Using the synthetic Sq data described above, we tested spherical cap width 20, 30, 40, and 60 degrees with various degree of expansion and F-level.

The sampling theorem tells the allowable maximum degree of expansion decreases as the spherical cap width goes narrower. But the use of the maximum degree of expansion and small F-level threshold, says almost zero, leads inappropriate solution which gives very small AIC and data misfit but different Sq spatial pattern. This indicates calculated values coincide with observed data at only station points, and fictitious smaller wavelength components survive. To avoid this, we should limit the maximum degree of expansion smaller than that deduced from the sampling theorem, and confirm that AIC has minimal value in terms of the number of parameters. When we use an appropriate maximum degree of expansion and F-level, AIC takes larger values with wider spherical cap width. However, the spatial pattern calculated from the result by 60 degrees of spherical cap width most recovered that of synthetic data. Consequently, we should use over 60 degrees of spherical cap width in SCHA for Sq data of p=1 with AWAGS station distribution, and our test results in the same conclusion of Torta and De Santis (1996).

オーストラリア広域の地球磁場内外起源ポテンシャル分離を目的として、球帽調和関数解析のパラメータ設定を再考した。考察したのはデータの再現度による最適な球帽幅と次数についてである。

既に Torta and De Santis (1996 GJI)はヨーロッパでの観測点分布と時間軸のフーリエ解析を前提として Sq データの再現度の観点から最適な球帽幅として 60° 以上が望ましいと述べている。今回は時間軸のフーリエ解析は考慮せず、あるスナップショットにおける空間的なデータの再現度で球帽幅を評価した。ここでは合成データとして、Malin (1974 Phil. Trans. Roy. Soc. Lon.)による UT=2h の Sq モデル（p=1(周期 24 時間モード)）で、3 成分の振幅それぞれに 3%の誤差を与えてデータを作成し、球帽幅 20～60° での球帽調和関数解析を行った。観測点分布は、オーストラリア全土の AWAGS データ（Chamalaun and Barton, 1993 JGG）と同じ分布である。AWAGS データそのものの球帽調和関数解析は Stening et al. (2008 EPS)の研究がある。

これまでの我々の球帽調和関数解析では Gubbins (1983 G. J. Roy. astr. Soc.)による先験情報で制約をかけ、特異値分解法でガウス係数を求めていたが(Toh et al., 2004 EOS)、今回は球帽調和関数解析を開発した Haines (1988 Comp. Geosci.)によるプログラムを改良した。Haines (1988)では、先験情報無しで線形回帰における変数増減法（stepwise 法）によってガウス係数を求めているが、stepwise 法では F 検定で変数増減を行い最小二乗誤差で評価を行っている。今回は AIC 最小化で解の評価を行った。

球帽幅が狭い程、空間サンプリング定理から次数の上限は減少する。観測点間隔のサンプリング定理の上限とほぼ同じ程度まで次数を増やし、且つ変数選択の F 値閾値を下げた場合、変数の数が増加するにつれ AIC もデータの misfit も著しく大きく減少するが、得られたガウス係数の解による空間パターンは Sq の空間形状と全く一致せず、観測点位置でのみデータを合わせて、短波長成分が卓越する結果となっている。従って、変数の数に対して AIC が極小値を持つような範囲で変数選択の F 値閾値を設定しなければならないことが分かった。その上で、球帽幅が大きい程、次数も AIC も大きくなりがちだが、実際には、得られた Gauss 係数で空間パターンを描かせたところ、観測点間のデータの無い処も含めると、球帽幅が最大の 60° が最も合成データの空間パターンを再現できた。このことから、データの合いに関わらず、オーストラリアの観測点分布で且つ p=1 の Sq 空間波長を扱う場合は、60° 以上の球帽幅で解析することが適当で、Torta and De Santis (1996)と同じ結論が得られた。

R003-02
Zoom meeting A ：11/3 AM1 (9:00-10:30)
09:15-09:30

Three-dimensional combined inversion scheme of the wideband-magnetotelluric method and the Network-MT method

#Yoshiya Usui
ERI

I developed a three-dimensional combined inversion scheme of the wideband-magnetotelluric method and the Network-MT method, using the edge-based finite element method. When using the wideband-magnetotelluric method, it is sometimes difficult to obtain accurate long-period data especially in noisy areas, resulting in lower sensitivity to deep subsurface structures. In addition, observed data of the wideband-magnetotelluric method can be affected by small near-surface heterogeneities of the electrical resistivity because the electric potential differences measured by dipoles with relatively small length (typically from several tens of meters to hundreds of meters). With the Network-MT method, in which metallic telephone cables several kilometers in length are used to measure electric potential differences, above two problems are alleviated owing to long observation duration and long electrode spacings. The Network-MT method, however, has a disadvantage that it has a lower resolution to the shallow fine structure because it is often difficult short-period data, typically of periods shorter than 10 s. The combined inversion of the wideband-magnetotelluric method and the Network-MT method has a potential to estimate subsurface electrical resistivity structure from the shallow part to the deep part because it comprises the advantages of the two methods and makes up for each other's disadvantages. In this presentation, I show the algorithm of the developed combined inversion scheme and the results of the verifications using the synthetic models.

R003-03
Zoom meeting A　：11/3　AM1　(9:00-10:30)
09:30-09:45

跡津川断層系周辺での面的広帯域 MT 観測

#吉村　令慧 1),小川　康雄 2),深井　雅斗 3),中川　潤 1),波岸　彩子 1),相澤　広記 4),山本　有人 5),山崎　友也 1),三浦　勉 1),中本　幹大 1),長岡　愛理 1),高村　直也 6),大志万　直人 1)
1)京大・防災研,2)東工大・火山流体,3)東工大・理・地惑,4)九大地震火山センター,5)九州大学大学院理学府,6)NT システムデザイン

Dense broadband magnetotelluric array around the Atotsugawa Fault System

#Ryokei Yoshimura1), Yasuo Ogawa2), Masato Fukai3), Jun Nakagawa1), Ayako Namigishi1), Koki Aizawa4), Yuto Yamamoto5), Tomoya Yamazaki1), Tsutomu Miura1), Mikihiro Nakamoto1), Airi Nagaoka1), Naoya Takamura6), Naoto Oshiman1)
1)DPRI, Kyoto Univ.,2)VFRC, Titech,3)Earth and Planetary science, Tokyo Tech.,4)SEVO, Kyushu Univ.,5)Earth and Planetary Sciences, School of Science, Kyushu University,6)NT System Design Inc.

The Atotsugawa fault system, the northern part of central Japan, is in a deformation belt with high strain rates, known as the Niigata-Kobe Tectonic Zone (NKTZ). This system is composed of three right-lateral strike-slip faults (the Atotsugawa, Mozumi-Sukenobe, Ushikubi faults). In 1858, the Hietsu Earthquake (M 7.0) occurred along the Atotsugawa fault. Although high seismicity has been observed along this fault by the recent modern seismograph network, the distribution of microearthquakes shows a spatially heterogeneous feature. To discuss the role of the Atotsugawa fault system in the NKTZ, Yoshimura et al. (2009) revealed a two-dimensional electrical resistivity model passes through the relatively low-seismicity segment and the deepest area of the seismicity cutoff along the Atotsugawa fault. Yoshimura et al. (2006) tried to clarify the heterogeneous electrical resistivity structure along the Atotsugawa fault by using two-dimensional profile data parallel to the fault. Although such two-dimensional modeling is of value to grasp an essential image around the fault, it is necessary to obtain a three-dimensional electrical resistivity structure for a detailed comparison with the spatial heterogeneity of the seismicity along the Atotsugawa fault. To investigate the relationship between the heterogeneous distribution of microearthquakes and electrical resistivity structure, we planned to conduct dense broadband magnetotelluric (MT) array and estimate three-dimensional resistivity structure around the Atotsugawa fault system.
In addition to the above existing MT data, we obtained magnetotelluric/telluric data at 46 new sites around the Atotugawa fault system in 2019 by using MTU5A (Phoenix Geophysics Ltd.) and ELOG-MT/ELOG-PHX (NT System Design Inc.) systems. The number of sites can use in this project amounted to 73, including 27 existing MT data. The average recording duration of new sites was 10 days. At the telluric-only sites, magnetic data from the nearest magnetotelluric sites were used for estimations. In most sites, high-quality MT responses were estimated using the BIRRP code (Chave and Tomson, 2004).
In this presentation, we will introduce the outline of our project and show the preliminary results of broadband MT observations.

R003-04
Zoom meeting A ：11/3 AM1 （9:00-10:30）
09:45-10:00

御嶽山山頂部付近における１次元比抵抗構造モデル

#西嶋　就平1),市原　寛1),堀川　信一郎1),前田　裕太1),田ノ上　和志1),松廣　健二郎1),國友　孝洋1)
1)名古屋大学大学院環境学研究科

1-D Resistivity Model around the Summit Area of Mt. Ontake Volcano

#Shuhei Nishijima1), Hiroshi Ichihara1), Shinichiro Horikawa1), Yuta Maeda1), Kazushi Tanoue1), Kenjiro Matsuhiro1), Takahiro Kunitomo1)
1)Graduate School of Environmental Studies, Nagoya Univerisity

Mt. Ontake volcano is located between Nagano Prefecture and Gifu Prefecture and is the second highest volcano in Japan. Mt. Ontake volcano erupted four time in recorded history. Because electrical resistivity is physical quantity sensitive to molten rocks and pore fluid in rocks, investigating of its distribution in volcanoes is essential to understand mechanisms of eruptions. Around the Mt. Ontake volcano, two previous studies investigated 3-D resistivity distribution. Abd Allah & Mogi (2016) modeled subsurface resistivity distribution beneath the top of Mt. Ontake volcano using the grounded electrical-source airborne transient electromagnetic (GREATEM). Ichihara et al. (2018) clarified resistivity distribution below the southeast flank of Mt. Ontake volcano based on the magnetotelluric (MT) sounding. However, resistivity structures below 1 km depth have not been investigated around the top of Mt. Ontake volcano. Thus, distribution of magma chamber and origin of hydrothermal activities are not well understood. In this study, we conducted MT measurements around the top of Mt. Ontake volcano to clarify the 3-D resistivity structure including deep area.

We measured AMT (Audio-frequency MT) data at nine sites on 10-12 September and 7-11 October, 2019. The observation sites were located mainly near the point of eruption in 2014, on the Otaki trail and on the Kurosawa trail in the south part and east part of MT. Ontake, respectively. We used ADU-07e system from Metronix Geophysis Co. around the top of Mt. Ontake volcano. The sampling frequencies are 32, 1024, 32k, and 524kHz. The data were recorded 1-2 days for the two lower sampling rate data and 1-3 hours for the two higher sampling rate data. Then, we estimated MT impedances at each observed site using BIRRP program (Chave & Thomson, 2004). We applied the remote reference technique. For the two lower sampling rate data, we used horizontal magnetic field data from site OKR at Ohkura village, Yamagata Prefecture observed by Geothermal Energy Research & Development Co. For the two higher sampling rate data, we used horizontal magnetic field data at the observation site which observed the same time with target observation site. The calculated MT impedances can be estimated with good accuracy down to about 3 Hz at seven sites, except for two sites located near the top of the mountain and observed on the same day. The estimation accuracy of the two stations set up around the summit was poor at all frequencies. This is thought to be the effect of external noise.

One-dimensional resistivity modeling was performed from the MT impedances at the seven AMT sites. We assumed that the subsurface consists of three horizontal resistivity layer and searched the best fit resistivity parameters to explain the estimated MT impedances. Although the fitting quality differs at each observation site, the estimated one-dimensional structure generally explains the MT impedances. At the three observation sites in the south area, a high resistivity layer (>1000 Ωm) was found in the surface layer and a resistivity layer of about 100 Ωm was found underneath. At the three observation sites to the east area, a high resistivity layer (512-2048 Ωm) was found in the surface layer and a low resistivity layer was found underneath. The resistivity model in the site near the crater of the 2014 eruption shows a trend of low resistivity (5-64 Ωm) for all the layers. In contrast to the results of Abd Allah & Mogi (2016), our results show a thicker high resistivity layer on the surface and a lower resistivity in the second layer at the southern site. The resistivity values and thicknesses in the eastern sites are relatively consistent with previous studies up to the second layer, but the third layer suggests the existence of a lower resistivity layer.

In the future, we will conduct long-term observations to clarify the deeper resistive structures and investigate the causes of the noise that affects the MT impedance, especially at the low frequency, and improve the MT impedance.

御嶽山は長野県と岐阜県の県境に位置する日本で2番目の標高を誇る火山であり，有史以降4度の水蒸気噴火を起こしている．比抵抗はマグマや岩石中の間隙流体に敏感な物理量であるため，火山域で比抵抗構造を解明することは重要である．これまで，御嶽山周辺において，Abd Allah & Mogi (2016)による山頂部の空中電磁探査やIchihara et al. (2018)による南東麓地域におけるMT（Magnetotelluric：地磁気地電流)法探査によって比抵抗構造が推定されている．しかし山頂域直下の深さ1km以深の構造は解明されておらず，噴火に関するマグマや熱水域などの分布に関する議論が進んでいない．そこで，本研究では御嶽山山頂域においてMT法探査を行い，地下深部までの3次元比抵抗構造の解明を目的とする．

御嶽山山頂域周辺で2019/9/10~12と10/7~11にかけてAMT（Audio-frequency MT）観測を9地点において行った．観測点は2014年噴火が発生した地点付近を中心に、南側の王滝口登山道および東側の黒沢口登山道上に配置した．観測にはMetronix Geophysis社のADU-07eを用いた．サンプリング周波数は32,1024,32kおよび524kHzであり，低周波側は1~2日，高周波側は1~3時間の期間で観測した．次に，各観測におけるMTインピーダンスをBIRRP

(Chave and Thomson, 2004)を用いて推定した．リモート・リファレンス点には低周波側には地熱技術開発株式会社が観測をしている山形県大蔵村 OKR の水平磁場データ，高周波側には同日に御嶽山で観測した水平磁場データを用いた．推定した MT インピーダンスは山頂周辺に設置し同日観測をした 2 地点を除いて 7 地点の観測点で，3Hz 程度まで推定精度を良く求められた．山頂周辺に設置した 2 地点の観測点は全周波数で推定精度が低かった．これは外部ノイズの影響であると考えている．

次に，推定精度の低い 2 地点を除いた 7 地点の MT インピーダンスより，水平 3 層構造を仮定し 1 次元比抵抗構造解析を行った．観測値と推定された構造から計算された見かけ比抵抗，位相のサウンディングカーブを比較した．それぞれの観測点でフィッティングの良さは異なるが，推定した 1 次元構造で概ね説明できた．南側の 3 地点の観測点では表層に 1000Ωm を超える高比抵抗層があり，その下に 100Ωm 程度の比抵抗層が推定された．東側の 3 地点の観測点では表層には高比抵抗層（512~2048Ωm）が存在し，深部に低比抵抗の存在が示唆された．2014 年に噴火した火口近くの観測点は，今回推定した構造の中で唯一，全体的に低比抵抗(5~64Ωm)な傾向を示した．Abd Allah & Mogi (2016)の結果とは，南側の観測点では表層の高比抵抗層がより厚く存在し，2 層目はより低比抵抗が存在することを示唆した．東側の観測点では 2 層目まで比較的整合性のある比抵抗値と厚さを示したが，3 層目はより低比抵抗層の存在を示唆した．

今後，深部までの比抵抗構造を明らかにするために長期観測を行い，MT インピーダンスに影響を与えるノイズの原因（特に低周波側）を精査し，MT インピーダンスの改善を行う予定である．

R003-05
Zoom meeting A　：11/3　AM1　(9:00-10:30)
10:00-10:15

広帯域 MT 法探査から推定される雌阿寒岳の 3 次元比抵抗構造とマグマ供給系

#井上　智裕 1),橋本　武志 1),田中　良 1),山谷　祐介 2)
1)北大・理・地震火山センター,2)産総研

3-D resistivity structure and magma plumbing system of Meakandake volcano inferred from broadband magnetotelluric survey

#Tomohiro Inoue1), Takeshi Hashimoto1), Ryo Tanaka1), Yusuke Yamaya2)
1)ISV, Hokkaido Univ.,2)FREA, AIST

We performed a broadband MT survey around of Mt. Meakandake in 2018 and 2019. Meakandake is one of the active volcanoes in the southwestern part of Akan caldera in eastern Hokkaido. Recently, a remarkable ground inflation occurred on the northeastern foot of Meakandake. We planned a magnetotelluric survey to investigate the electrical structure to cover both Meakandake and the deformation source. In this study, we describe our 3D resistivity model and discuss the magma plumbing system beneath Meakandake.

In recent years, a remarkable ground inflation was reported on the northeastern foot of Mekandake from 2016 to 2017. The main pressure source was modeled as an opening of a sill-like crack at a depth of about 3 km from Meakandake to Lake Akan hot spring area (about 7 km long and 2 km wide) (Hokkaido Univ, 2019). However, relationship between the ground deformation and the volcanic activity of Meakandake was unknown. Neither of the previous resistivity surveys (NEDO, 1992; Takahashi et al., 2018) did not cover the above-mentioned inflation area.

Therefore, in this study, we newly deployed 26 broadband-MT sites by using the MTU-5/5A system (Phoenix Geophysics Ltd) at 26 broadband-MT sites around Meakandake. Then, we performed a 3D resistivity inversion by ModEM (Egbert and Kelbert, 2012; Kelbert et al., 2014) based on the data combined with supplemental AMT/MT data that was previously obtained in 2010. We started from the initial model with a uniform resistivity at 100 Ωm that was meshed in 48(x), 48(y), 85(z) blocks (horizontal 250 to 128,000 m, vertical 25 to 256,000 m). The atmosphere and sea water were fixed at 10^8 Ωm and 0.3 Ωm, respectively.

The modeling by the 3D inversion has revealed the low resistivity C1 (about 1-10 Ωm) extends from 0.5 km BSL to deeper part of Meakandake, and the low resistivity C2 (about 1-10 Ωm) around Mt. Fuppushidake. On the other hand, no remarkable low resistivity anomalies appeared in the area where the pressure source was assumed at the northeastern foot of Meakandake. We performed some sensitivity checks, in which the deeper extension of the low resistivity bodies (C1 and C2) was varied. As the result, C1 was found to be meaningful down to about 30-70 km BSL and C2 was to about 15 km BSL. In addition, the westward dipping of C1 was necessary to reproduce the anomalous phase at some sites in the west of Makandake. Furthermore, a low resistivity slab of 1 to 10 Ωm that imitated a sill-like intrusion of magma or hydrothermal water was placed at the presumed inflation source area with a fixed upper depth of the slab at 1.5 km BSL and a varying thickness in order to examine its effect on the MT response. Then, we confirmed that effect of the low resistivity slab was insignificant when it had a bulk resistivity above 10 Ωm, or when it was thinner than 200 m. In other words, our MT data did not exclude the possibility that there was an intrusion event at the location of the pressure source in 2016-2017.

The low resistivity body C1 was considered to be a part of the volcanic vent, since it was distributed along the lower limit of the micro-seismic hypocenters at the shallow part of Meakandake. If this is the case, the uppermost part of C1 was probably connected to the active vents of Meakandake through subvertical conduits. Meanwhile, the sill-like inflation in 2016-2017 was suspected to be a lateral intrusion that branched from a certain depth of C1. Compared with the epicenter map, regional earthquakes seemed to occur in the relatively low resistivity zones.

As the next step, we plan to perform additional MT measurements to investigate the details of anomaly C1.

私たちは，北海道東部の阿寒カルデラ内に位置する活火山であり，近年その北東麓で顕著な地盤膨張が観測されている雌阿寒岳において，2018 年と 2019 年に広帯域 MT 法探査を行った．本研究では，2010 年に阿寒湖畔で行われた AMT/MT 探査のデータも用いた 3 次元比抵抗インバージョンの結果に基づき，雌阿寒岳のマグマ供給系について議論する．

2016 年から 2017 年にかけて雌阿寒岳北東麓で顕著な地盤膨張が検出された．この地盤変動の主要部は，雌阿寒岳から阿寒湖温泉にかけて深さ約 3 km に位置する長さ約 7 km×幅約 2 km のシル状クラックの開口で説明されている（北大, 2019）．雌阿寒岳のマグマ供給系について具体的な描像があれば，山麓の地盤変動との関係について考察が可能だと考えられる．しかし，先行研究の比抵抗構造探査（NEDO, 1992; Takahashi et al., 2018）では，膨張源領域と雌阿寒岳を同時に解析した深部の構造は明らかにされていない．

そこで，本研究では，2018 と 2019 年に MTU-5/5A （Phoenix Geophysics 社製）を用いて， 26 地点で新規に観測を展開した．これらに 2010 年のデータを加えた 39 地点の観測データを用いて，初期比抵抗値 100 Ωm, 48×48×85 メッシュ(水平 250～128000m, 鉛直方向 25～256000 m)の初期モデルによる 3 次元比抵抗インバージョン(ModEM, Egbert and Kelbert, 2012; Kelbert et al., 2014）を行った．大気と海はそれぞれ 10^8 Ωm と 0.3 Ωm で固定した．

3次元比抵抗インバージョンによるモデリングの結果，雌阿寒岳直下の0.5 km BSLから西に向かって深部に伸びる低比抵抗体C1（約1－10 Ωm）と，雌阿寒岳の北に位置するフップシ岳周辺に低比抵抗体C2（約1－10 Ωm）が見られた．一方，雌阿寒岳北東麓の圧力源が想定される領域には明瞭な低比抵抗異常は現れなかった．各低比抵抗体（C1，C2）の大きさを深さ方向に変化させたモデルの応答曲線を観測値と比較する方法で感度チェックを行なった結果，C1は約30～70 km BSL，C2は約15 km BSLまで感度があると判断した．C1に関しては水平方向にも感度チェックを行い，C1の西側への広がりを抑制すると，雌阿寒岳西麓の異常位相（Zyx成分）を説明できないことが明らかになった．また，明瞭な比抵抗異常としては現れなかったシル状圧力源の位置（1.5 km BSL）に，マグマもしくは熱水溜まりを想定した低比抵抗体を置き，その比抵抗値や厚さを様々に変化させたモデルからフォワード計算によって，応答曲線にどの程度影響が現れるかを検討した．その結果，圧力源の媒質が10 Ωm以上のバルク比抵抗値である場合や，200 mよりも薄いシル状マグマ（または熱水）であれば，応答曲線に有意な影響が現れないことが確認できた．

本研究で得られた低比抵抗体C1は，深部まで伸びていることや雌阿寒岳浅部の震源分布の下限に沿うように分布していることから，高温の火道の一部を反映していることが考えられる． C1の直上は雌阿寒岳の火口域となっており， 2016年のシル状圧力源は，C1のやや深部で側方に分岐した貫入イベントであった可能性がある．また，得られた3次元比抵抗モデルと阿寒地域の震源分布と比較すると，低比抵抗側に震源が集中するような傾向が見られた．今後，雌阿寒岳の山頂域に観測点を追加して，C1の形状をより精度よくしていく予定である．

R003-06
Zoom meeting A ：11/3 AM1 (9:00-10:30)
10:15-10:30

UNDERSTANDING UNZEN VOLCANO MAGMATIC SYSTEM USING BROADBAND MAGNETOTELLURIC OBSERVATION

#Agnis Triahadini, Koki Aizawa[2)], Keita Chiba[2)], Yuto Yamamoto, Kanta Miyano, Kazunari Uchida[2)], Tasuku Hashimoto
Grad.Sch.Sci.,Kyushu Univ,[2)]SEVO, Kyushu Univ.

Unzen Volcano is an active lava domes complex located in Shimabara Peninsula, Nagasaki, Japan. Since the great eruption in 1990-1995, this volcano has been receiving intensive observations. From previous studies, magma plumbing system models have been suggested. The models favor main magma chamber located about 15 km under Chijiwa bay in west offshore Shimabara Peninsula. Subordinate magma chambers located shallower and closer to the summit, Fugendake. Geodetic measurement by Kohno et al (2008) proposed four deformation sources (from beneath Unzen's summit to its west, namely A,B,C,D) from the latest eruption. The four sources are situated below the intensive hypocenters zone occured before eruption reported by Umakoshi et al (2001). The most intensive sources are D-source which explains inflation occured after the eruption stopped. Meanwhile the C-source experienced intensive deflation during eruption. Magnetotelluric (MT) method is highly sensitive to conductive zone caused by fluid rich zone or melt rich magma. Hence, we present our result from 23 broadband MT stations in southern half of Shimabara Peninsula which were installed on December 2019. Our purposes of the study are to determine magmatic system of Unzen based on resistivity structure, comparing to seismic velocity data (Saiga, personal comm), seismicity (Umakoshi et al 2001) and geodetic data (Kohno et al 2008) and to explain its structural control. Our preliminary resistivity structure outlines shallow low resistivity layer until about 2 km bsl, particularly in the southern part of Shimabara Peninsula. This low resistivity zone roughly coincides with position of several faults in southern Shimabara that was reported by Sugimoto et al (2005). We highlight broad high resistivity zone underlies Shimabara Peninsula at around 5 km bsl to greater depth. It may represent plutonic rock. On the southwestern Chijiwa Bay, low resistivity zone is imaged and this zone possibly extends to around D-source. Expanding observation sites are planned to be conducted this year to fully answer our study objectives.

R003-07
Zoom meeting A ：11/3 AM2 （10:45-12:30）
10:45-11:00

日向灘周辺における３次元の比抵抗モデリング

#中村 捷人 [1],市原 寛 [2],後藤 忠徳 [3],松野 哲男 [4],多田 訓子 [5],佐藤 真也 [6]
[1]名古屋大学大学院環境学研究科,[2]名古屋大学地震火山研究センター,[3]兵庫県立大学大学院生命理学研究科,[4]神戸大学海洋底探査センター,[5]海洋研究開発機構海域地震火山部門,[6]京都大学大学院工学研究科

3-D resistivity modeling around the Hyuganada area

#Hayato Nakamura[1], Hiroshi Ichihara[2], Tadanori Goto[3], Tetsuo Matsuno[4], Noriko Tada[5], Shinya Sato[6]
[1]Graduate School of Environmental Studies, Nagoya University,[2]Earthquake and Volcano Research Center Graduate, Nagoya University,[3]Graduate School of Life Science, University of Hyogo,[4]Kobe Ocean Bottom Exploration Center, Kobe University,[5]Research Institute for Marine Geodynamics, Japan Agency for Marine-Earth Science and Technology,[6]Kyoto University, Graduate School of Engineering

Hyuganada area is located on the frontal area of subduction zone where the Philippine Sea plate is subducted beneath the Eurasian plate. The subduction of the Kyushu-Palau Ridge (KPR) on the Philippine Sea plate is recognized beneath the south-west part of the Hyuganada area (e.g. Park et al., 2009). Two earthquakes around magnitude 7.5 occurred in 1662 and 1968 on their plate boundary interface. Slow earthquakes such as shallow tremor (Yamashita et al., 2015) and long-term slow slip event (SSE) (Takagi et al., 2019) have also been discovered there. Moreover, it is known that the coseismic rupture regions of the 1707 Hoei and the 1968 Hyuganada earthquakes did not reach the subducted KPR, while it can cause stress concentrations and trigger earthquakes (e.g. Yamamoto et al., 2013). These various events may be associated to pore fluid and lithological heterogeneity around the plate boundary.
Because electrical resistivity is sensitive to fluids and sediments, exploring a electrical resistivity structure is a great tool to detect them in the plate boundary. Magnetotelluric (MT) sounding is a passive exploration method to reveal electrical resistivity structure of underground using natural electromagnetic variations. This method is sensitive to deep structural heterogeneous compared with other electromagnetic explorations. In this study, we performed 3-D resistivity modeling around the Hyuganada area based on MT impedances to understand the relationship between various types of earthquakes and fluids.
Electromagnetic data were recorded at 12 stations around the Hyuganada by Ocean Bottom Electro-Magnetometers (OBEMs). We applied the BIRRP code (Chave and Thomson, 2004) to estimate MT impedances from time series data of the electromagnetic fields. The horizontal magnetic field data recorded at Kakioka Geomagnetic Observatory were also used as the data of the remote reference site (Gamble et al, 1979). In general, coast and oceanic topography has strong influence on MT impedances in marine MT surveys, known as “coast effect" and “topographic effect" (e.g. Key and Constable, 2011; Matsuno et al. 2007). The Hyuganada area has such a complex topography that we must consider their effects correctly not to lead wrong structures. Thus 3-D forward modeling was performed to confirm whether the responses reflected on subsurface resistivity structure or not, before an inversion analysis.
We performed 3-D resistivity modelings by using the code of Tada et al. (2012). The resistivity models were incorporated with bathymetry based on ETOPO-1 (Amante et al., 2009). The calculation area extended about 2,200 km deep and 4200 km * 4200 km widths to avoid edge effects. The number of model blocks used for these calculations was 63 * 63 * 61 (+7 air layers). The block size inside observation area was 100 m with depth and 5-8 km widths of horizontal directions. At all stations, apparent resistivities in short periods is smaller than those in long periods, and they imply the existence of conductive layer regarded as sediment just below the seafloor. Then, we made the resistivity model composed of a half-space with 0.3 ohm-m ocean and 1 ohm-m conductive layer directly under the seabed.
First, we calculated the models whose the conductive layer thickness was uniform. Because the conductive layer thickness and background resistivity were unknown, we varied the two unknown values in 0.2-16 km and 2-500 ohm-m. The optimum model, which was detected by using the least root mean square (RMS) misfit, at each site had indicated that conductive layer thickness on south side is thicker than on south part throughout the survey area.
Second, we made a model with non-uniform thickness of conductive layer on the basis of above results. This model had the 1 ohm-m conductive layer whose thicknesses were 0.5 km in north side, 2 km in middle side and 4 km in south side. The model impedances almost correspond with the observed one in east side stations. However, this result also indicates that the simple 3 layers model could not explain the observed impedances enough, especially at central and south-west stations. It implies that MT responses estimated from observed data reflect not only coast and topographic effect, but also subsurface resistivity structure.
Finally, 3-D inversion analysis was performed by using the model as the initial model. The optimum model involves that resistive region overlapping with the slip area of 1968 Hyuganada earthquakes (Yagi et al., 1998). It also implies that the region where KPR subducted is more conductive. These features could reflect heterogeneities of pore fluid and lithological distribution associating with the various types of fault rupturing in the Hyuganada area.

日向灘ではフィリピン海プレートがユーラシアプレートの下に沈み込んでおり，そのプレート境界面において M7.5 程度の地震が発生している．一方で浅部低周波微動（Yamashita et al., 2015）や長期的スロースリップイベント（SSE）

（Takagi et al. 2019）といったスロー地震の発生も確認されている．さらに日向灘南西部では，九州-パラオ海嶺がユーラシアプレートの下に沈み込んでいる（例えば，Park et al., 2009）．九州-パラオ海嶺が沈み込むことにより海山の前方に応力集中を生み出すため地震の引き金となり得る一方で，1707 年宝永地震や 1968 年日向灘地震では破壊の伝播を妨げていたことが分かっている（例えば，Yamamoto et al., 2013）．このように日向灘周辺では多様な現象が確認されており，これらはプレート境界面における構造の不均質性や間隙流体の存在が関係していると考えられている．

比抵抗は，流体や堆積物の存在に敏感な物理量である．そのため，比抵抗構造を推定することにより，プレート境界面周辺の流体や堆積物の存在について議論することが可能であると考えられる．地磁気地電流(MT)法は自然起源の電磁場変動を利用して地下の比抵抗構造を求める手法であり，プレート境界面が存在する数十 km 以深の比抵抗構造にも感度を持っている．そこで本研究では，地震と流体の関係や九州-パラオ海嶺沈み込み域における構造の不均質性を理解することを目的とし，海底で観測した電磁場データを用いて日向灘周辺における 3 次元の比抵抗モデリングを行った．

解析には日向灘周辺の海底 12 地点に設置した海底電位差磁力計(OBEM)によって得られた電磁場データを用いた．この時系列の電場と磁場のデータから BIRRP（Chave and Thomson, 2004）を用いて，各観測点での MT 応答関数を推定した．リモートリファレンス（Gamble et al, 1979）を適応する際に，柿岡地磁気観測所の地磁気データ（サンプリング周期 1 s）を使用した．

海底での MT 応答関数は，“coast effect"や“topographic effect"といった地形による影響を強く受けることが知られている（例えば，Matsuno et al., 2007; Key and Constable, 2011）．日向灘周辺の海底地形は特に複雑であるため，これらの効果を正しく反映しなければ，誤った比抵抗構造を導くと考えられる．そこで，まず海底地形を考慮した単純な比抵抗モデルによる順解析を行い，地形による MT 応答関数への影響を確認した．

3 次元の比抵抗モデリングでは，ETOPO-1（Amante et al., 2009）に基づいて海底地形を取り入れた比抵抗モデルを設定し，Tada et al. (2012)のコードを用いて解析を行った．計算領域は東西約 4200 km，南北約 4200 km，深さ約 2200 km とし，ブロックの数を 63×63×61（+7 空気層）に設定した．観測点が存在する範囲におけるブロックの大きさは，水平方向が 5-8 km，深さ 100 m である．データから推定した短周期の見掛け比抵抗は，1-3 Ωm と低比抵抗であり，堆積層の存在を示すと考えられる．これを踏まえて，海水層（0.3 Ωm）と海底直下の低比抵抗層（1 Ωm），そしてその下の均質な比抵抗層（以下背景層）の 3 層から構成される比抵抗モデルを作成した．

まず，低比抵抗層の厚さを観測域内で一様とし，その厚さと背景層の比抵抗値をそれぞれ 0.2-16 km と 2-500 Ωm の間で変化させて順解析を行い，RMS ミスフィットに基づいて各観測点における最適モデルを調べた．その結果，北側の観測点では低比抵抗層が薄く，南側では厚くなっている傾向が確認された．また東側の観測点における最適モデルの RMS ミスフィットは相対的に低い値を示した．

次に，RMS ミスフィットが低かった東側の観測点の最適モデルに基づいて背景層の比抵抗値を 100 Ωm とし，低比抵抗層の厚さが一様でないモデルを作成した．このモデルでは観測域を北部，中部，南部に三分割し，それぞれにおける低比抵抗層の厚さを 0.5 km，2 km，4 km に設定した．このモデルの MT 応答関数を計算したところ，東側の観測点においては推定した MT 応答関数とほぼ一致した．一方で，この単純な 3 層モデルでは，観測域中央部や南西部でデータをあまり説明できないことが確認された．よって，推定した MT 応答関数は海底地形の効果のみでなく，地下の比抵抗構造を反映していることが示された．

最後に，このモデルを初期モデルとして，3 次元逆解析を行った．その結果，観測域中央に高比抵抗体が存在し，その位置が 1968 年日向灘地震のすべり域（Yagi et al., 1998）と重なっていることが確認された．また，観測域の外側ではあるが，九州-パラオ海嶺が沈み込んでいる領域は相対的に低比抵抗であることが示唆された．これらの比抵抗異常は，地下構造の不均質性や間隙流体の存在を反映していると考えられ，日向灘におけるスロー地震や通常地震の発生に関係している可能性がある．

R003-08
Zoom meeting A ：11/3 AM2 （10:45-12:30）
11:00-11:15

Simulation of tsunami-generated electromagnetic fields for the 2009 Samoa and 2010 Chile earthquakes

#Zhiheng Lin(1), Hiroaki Toh(2), Takuto Minami(3)
(1)Kyoto Univ.,(2)DACGSM, Kyoto Univ.,(3)Kobe Univ.

The motion of seawater by oceanic waves, such as tsunamis, in the geomagnetic field can generate induced electromagnetic (EM) fields. The tsunami-generated EM field can be observed by the ocean bottom electro-magnetometer (OBEM) (e.g., Toh et al., 2011). Numerical simulation of the tsunami-generated EM field can help us to estimate the arrival time, amplitude (e.g., Minami et al., 2015) and propagation direction (e.g., Lin et al., 2019) of tsunamis. Previous studies on the tsunami-generated EM field simulation have not been done for great epicentral distances due mainly to weak signals contained in observed EM data. Fortunately, in the geophysical observations on the French Polynesian seafloor in the Pacific Ocean (TIARES Project: Suetsugu et al., 2012), they observed significant EM fields by tsunamis of the 2009 Samoa (Mw 8.1) and the 2010 Chile (Mw 8.8) earthquakes. We, therefore, will compare the observed data and the simulation of tsunami-generated EM fields by these two tsunamis.

The array of OBEMs by TIARES Project was settled at 4000m-5000m depth of seafloor from February 2009 to December 2010. During the observation period, the OBEMs recorded the 2009 Samoa and 2010 Chile tsunamis by three-component magnetometers with 1min sampling. The tsunamis passed over the TIARES area after 5 hours and 10 hours from each onset of the tsunamigenic earthquakes. As shown by the Kp index (<1+: Bartels, 1957), external fields were quiet on both Sep 29, 2009 and Feb 27, 2010. As a result, the tsunami-generated vertical magnetic component has high signal-to-noise ratios and show similar waveforms with seafloor pressure signals. A wavelet analysis of the observed tsunami-generated magnetic fields revealed that the main period range was 5 to 16min in Samoa event and 6 to 30min in Chile event, while both amplitudes were approximately 0.5nT.

Tsunami-generated EM fields were computed by the three-dimensional time-domain finite element tsunami simulation code (Minami et al., 2017). This code has been applied to calculation of the 2011 Tohoku tsunami-generated EM field. We used JAGURS (Baba et al. 2015), a kinetic tsunami simulation code based on the Boussinesq dispersion wave, to obtain tsunami horizontal velocity field for long distance propagation. We confirmed the suitability of JAGURS simulation by comparing the sea-level change observed by two DART (Bernard et al., 2010) stations (DART 32412 and DART 51406) in the eastern Pacific. Then, we calculated the tsunami-generated EM field at the array of OBEMs with realistic bathymetry and a high-resolution mesh. In the presentation, we will further discuss possible causes for the difference between the simulation and observation.

R003-09
Zoom meeting A　：11/3　AM2　（10:45-12:30）
11:15-11:30

電気トモグラフィーのために必要な岩石試料表面の電位分布面的測定手法の性能評価

#鈴木　健士[1],吉村　令慧[2],山崎　健一[2],大志万　直人[2]
[1]京都大学大学院 理学研究科 地球惑星科学専攻,[2]京都大学防災研究所

Performance evaluation of potential distribution measurement on rock surface as a prerequisite for electrical tomography

#Takeshi Suzuki[1], Ryokei Yoshimura[2], Ken'ichi Yamazaki[2], Naoto Oshiman[2]
[1]Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University,[2]Disaster Prevention Research Institute, Kyoto University

An important geophysical issue is determining the resistivity of rocks under various conditions. Previous studies have measured the resistivities of various rock samples in a variety of conditions. However, most previous studies focused only on the bulk resistivity of rock samples. To characterize the internal resistivity structure of rock needs electrical data from many small electrodes attached around its surface, which is difficult. Therefore, we developed a new method for stable, multi-point, electrical measurement on rock samples that is effective at high contact and sample resistance. By using the new method, we performed the electrical measurement of intact granite samples using a simple electrode array constituted the first step toward electrical tomography measurements. A 40-electrode array acquired the potential distribution on the granite's surface in response to injected current. Spatial distribution of the obtained potential fairly agreed with those estimated for a cylindrical sample with a uniform resistivity, indicating the preciseness of the obtained potential distribution.
The measurement with the electrode array was also applied to dry granite with vertical dike cuts of a few mm thickness. Changes in the potential distribution caused by the vertical dike cuts were detected. It indicates that inhomogeneous structures such as fractures can possibly be visualized by our measuring procedure.

様々な条件下で色々な岩石の比抵抗を測定することは、地球物理学における重要な課題のひとつである。これまでに多くの岩石種の比抵抗が様々な条件下で調べられてきた。しかし、それら研究の殆どはバルクとしての比抵抗に焦点を当てており、岩石内部の比抵抗構造の解像を意図した研究例は少ない。岩石内部の比抵抗構造を求めるには、試料表面に多くの小さな電極を取り付け、電流印加・電圧測定を安定的に行う必要があるが、それは非常に難しい。このような背景を受け、これまでに我々は、岩石試料に対する安定した多点での電気測定手法を構築してきた。手法が、高接触抵抗・高試料抵抗の試料に対しても適用可能であること、高い安定性を有することは、繰り返し測定により確認された。
本研究では、岩石試料の電気トモグラフィー実現に向けて、新たに構築した測定手法が電位分布を多測定点で正確に測定できるかを確認した。測定対象物は円筒形の花崗岩試料とし、合計40個の電極を試料側面に張り付け、岩石を貫く2点の電流電極間に電流を印加した。それにより生じた円筒側面の電位分布を38点の電位電極で測定した。得られた測定値の分布は、適当な値の一様な比抵抗をもつ円筒形試料に電流を印加した場合に期待される電位分布とよく一致した。
次に試料内部の不均質構造が検出可能か評価するため、厚さ数mmの垂直なダイク状の切込みを入れた花崗岩試料に対しても同等の測定を実施した。ダイク状の切込みは圧縮試験等で生じる線状配列するクラック生成領域を模したものである。いくつかの電極配置による測定結果として、ダイク状の切込みに起因する有意な電位分布の局所的変化を検出した。

R003-10
Zoom meeting A ：11/3 AM2 （10:45-12:30）
11:30-11:45

Detection of Fluid Passes by Audio-frequency Magnetotelluric Survey in the Wayang-Windu Geothermal Area, Indonesia

#Tada-nori Goto, Yuji Yamada(2), Mohamad Nur Heriawan(3), Irwan Iskandar(3), Katsuaki Koike(2)
Univ. Hyogo,(2)Kyoto Univ.,(3)Institute of Technology Bandung

In the Wayang Windu geothermal field, Indonesia, the hydrothermally alteration zones are detected based on the remote sensing, which are located near the of topographical lineaments. The alteration zones are also characterized as high radon anomalies in soil gas. These findings imply that fracture zones in this field play an important role for path way of deep high-temperature fluid to the land surface, and also have a potential of deep hydrothermal reservoirs. For verification of this hypothesis, geophysical surveys at the ground surface of the Wayang Windu field with the non-destructive way are useful. In this study, we conducted the audio-frequency magnetotellurics (AMT), which is one of the electromagnetic geophysical surveys in Wayang Windu. Since the resistivity greatly decreases at buried water-rich/clay-rich geological zones, the AMT survey is known to be a powerful tool for imaging the fracture zones and related hydrothermal alteration zones beneath the geochemical anomalies. The AMT data were obtained at 38 sites in northern and middle of the Wayang Windu field. The obtained apparent resistivity includes the static shift and distortion effects. We applied the spatial averaging of apparent resistivity densely obtained in this study, and estimated the degree of static shift at each site. As a preliminary result, we constructed quasi three-dimensional (3-D) resistivity structure in the Wayang-Windu area from the surface to the depth of about 1km. It is based on a one-dimensional (1-D) structure using a rotational invariant value of impedance (Zssq). Before the application to the field data, we checked that a stitched 1-D model, used as a quasi 3-D structure, is valid to understand regional subsurface features in a geothermal field based on numerical simulations, although the detailed resistivity anomalies could not be resolved. In the preliminary quasi-3D structure, we found that low resistivity features are obvious along fractures and lineaments. Some of them are located close to the manifestations. Our result possibly can indicate fracture zones with the deep and high-temperature gas/water upwelling.

R003-11
Zoom meeting A　：11/3　AM2　(10:45-12:30)
11:45-12:00

A hydrothermal model of Aso volcano based on multiphase flow simulation and resistivity structures from ACTIVE and AMT survey data

#Takuto Minami[1], Marceau Gresse[2], Mitsuru Utsugi[3], Wataru Kanda[4]
[1]Kobe Univ.,[2]ERI, Univ. Tokyo,[3]Aso Vol. Lab., Kyoto Univ.,[4]KSVO, Tokyo Inst. Tech.

Resistivity structures inferred by inversions of Magnetotellurics (MT) or other electromagnetic (EM) sounding data always face difficulty in interpretation. In volcanic regions, imaged low resistivity zones are considered to be hydrothermally altered rocks that sometimes act as impermeable cap rocks (e.g. Yoshimura et al. 2018, EPS), hydrothermal fluid-rich zones (e.g. Gresse et al. 2018, SR), sulfur-rich zones (e.g. Kanda et al. 2019, EPS), or zones for high fraction of partial melts (e.g. Hata et al. 2016, GRL). Hence, constraining the cause of low/high resistivity values requires additional information. Hydrothermal multiphase flow simulation appears as an effective choice to interpret shallow resistivity structures in volcanic regions. Multiphase flow model can deal with the phase change in hydrothermal fluid due to temperature-pressure conditions within volcanic edifice, where the temperature and the volumetric fraction of hydrothermal fluid in porosities are connected to resistivity values.

We tried to interpret the three-dimensional (3-D) resistivity structure inferred by AMT (Audio-frequency MT) surveys (Kanda et al. 2019, EPS) and the 3-D resistivity change model (Minami et al. 2018, EPS; 2019, SGEPSS), inferred by a controlled-source EM volcano monitoring system, ACTIVE (Utada et al. 2007), by multiphase flow simulation using the TOUGH2 code (Pruess et al., 1999). We constructed a simple hydrothermal model with input of magmatic source at depth of crater bottom (H2O source with high temperature-pressure) under axisymmetric configuration centering the first crater of Nakadake with azimuthally averaged topography. For the path of magmatic source, we set a cylindrical conduit of 65-m radius just below the crater bottom which has a relatively high permeability compared to the surrounding rocks. We set porosity to 0.2 and the heat capacity to 1000 J/kg/K homogeneously below the surface. After obtaining a hydrothermal model, we converted information of temperature, fluid phase, and rock properties to resistivity values via Archie's law, neglecting the surface conductivity. Our simple resistivity model based on the multiphase flow simulation succeeded in reproducing the macroscopic features of the 3-D resistivity structure of Kanda et al. (2019, EPS), hereafter referred to as “KA model". We found from the comparison that the high resistivity layer just below the surface of KA model corresponds to highly air-saturated zone, while the conductive cone below the crater bottom of the first crater of Nakadake in KA model can be attributed to temperature distribution due to upwelling hot hydrothermal fluid. Furthermore, our simple resistivity model generated high resistivity zone in the conduit ~100 m below the crater, possibly corresponding to resistive change 400 m below the crater bottom imaged by the ACTIVE inversion (Minami et al., 2018). This resistive change is due to pressure reduction and change to gaseous phase of the input hot hydrothermal fluid. The discrepancy in the elevation of the resistive change may be accounted for by the presence of impermeable zone beneath the crater bottom (Kanda et al. 2019, EPS), which is not included in our hydrothermal model currently.

As well as the hydrothermal modelling, we recently started to develop a joint inversion code incorporating ACTIVE and MT inversions. The part of ACTIVE inversion follows the methodology of Minami et al. (2018), while the MT part follows that of Usui et al. (2017). We are going to update the resistivity change model obtained by ACTIVE inversions (Minami et al. 2018, EPS; 2019, SGEPSS) by conducting joint inversions of ACTIVE and AMT to explain time evolution of ACTIVE responses and AMT survey data consistently. In the presentation, we plan to report our updated resistivity change model and their interpretation using a hydrothermal models based on the multiphase flow simulation.

R003-12
Zoom meeting A ：11/3 AM2 （10:45-12:30）
12:00-12:15

注水実験に伴う自然電位変動－断層近傍の物理特性の検出に向けて－

#村上　英記
高知大・自然科学系

Self-potential variations associated with water injection experiments

#Hideki Murakami
Natural Sciences Cluster, Kochi Univ.

We observed the self-potential around the water injection borehole installed on the Nojima fault during repeated water injection experiments from 1997 to 2018. The observed self-potential variations included large leakage currents and some small self-potential variations associated with water injection. Most of the self-potential variations associated with water injection can be explained as streaming potential due to the water flow from the borehole to rocks. However, there were self-potential variations that could not be explained by the streaming potential even though the variations of self-potential started with the start of water injection. In this paper we discuss the possibility that these variations are caused by redox reactions induced by water injection.

1995年兵庫県南部地震(Mw=6.9)の地表地震断層である野島断層の回復過程の検出を目的とした注水実験が1997年から2018年の間に実施された。注水実験では野島断層近傍に設けられた1800m孔に対して注水を実施し，注水期間中の周辺部の微小地震活動，800m孔底の歪み変化，800m孔の湧水量変化，そして地表における自然電位変化などの測定が実施された。注水に伴うこれらの変動から，1995年の地震により生じた地下の透水性の増加（破砕度の増加）が地震後の数年で減少し定常状態に達したことが明らかになった。ただし，ほとんどの注水実験では深度540m付近のケーシング・パイプの継ぎ手からの流出であることが1800m孔内に設置された温度計から推定されているので，断層破砕帯そのものの変化というよりは断層近傍の深さ540m周辺の変化として解釈すべきである。

地表において1800m注水孔周辺で実施した自然電位測定において，1例を除いて注水に同期した自然電位変動が観測されている。その自然電位変動の特徴は，注水の開始と停止操作に同期した電位変動であり，変動の極性は注水孔から離れた基準点から見て負に変動する，また変動の大きさは注水孔からの離れると小さくなる，というものである。これらの特性は，注水孔から周囲の岩石中に水が流出することにより発生する流動電位（ゼータ電位は負とする）を，導体である注水孔が地表面までつたえているというモデルで説明が可能である。まこのモデルを使い地下の透水性を評価してきた。しかし，2000年代中頃から注水孔から離れた地点で注水に同期した自然電位変動の極性が逆（変動極性が正）になる場合が表れた。また，1800m孔の地表面の注水口を電極と見立てて電位差を計測すると同じく正側に変動する結果が得られている。また，2018年度におけるこの正側への変動の収束には注水停止後1週間以上かかっている。これらの変動を，先の流動電位モデルで説明することは難しい。注水実験時の自然電位変動から，地下の水理特性の変化をより正確に検出するにはこれらの自然電位変動を説明する必要がある。

注水を実施しない状態での地表面における電位分布は，注水孔を中心にした負の電位異常を形成している。一般的に，この電位異常は，ケーシング・パイプが地表付近の酸化環境と深部の還元環境を貫いているために，深部の低酸化還元電位部分から地表付近の高酸化還元電位部分へ導体であるケーシング・パイプ中を電子が流れ，周囲の地層中を電流（深部で外向き，浅部で内向き）が流れるために発生すると考えられている。この状況は第一近似として，地表付近に負の電荷，深部に正の電荷を持つ双極子モデルで表現できる。流動電位で説明できない自然電位の変動の一部について，注水による酸化還元状況の変化に起因する電位変動で説明可能であるかを議論する。

野島断層注水実験における自然電位変動の観測は，大志万直人，吉村令慧，山口　覚，西上欣也及び京都大学防災研の技官・院生諸氏との共同研究として実施をおこなったことを記して感謝いたします。