飛騨地方に発達する中新世岩脈群の古地磁気と回転運動

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Paleomagnetism and tectonic rotation of Miocene dikes in the Hida region, central Japan

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http://hoshi.a.la9.jp/index.htm

Central Honshu of Japan is an ideal field for the study of crustal deformation related to arc-arc collision. In this study we obtained rock magnetic and paleomagnetic results from early Miocene igneous rocks in central Honshu in order to examine rotational deformation caused by the collision of the Izu-Bonin-Mariana (IBM) arc with central Honshu. In Takane of the Hida region, gabbro intrusions and older sedimentary rocks are intruded by numerous andesitic dikes that comprise a parallel dike swarm. More than 240 oriented cores were taken at 38 sites in two localities for magnetic study. The andesites and gabbros generally have magnetite, and some andesites also contain pyrrhotite. The magnetite records easterly deflected remanent magnetization directions of dual polarities that pass the reversals test. Positive baked contact tests at two sites demonstrate that the easterly deflected direction is a thermoremanent magnetization acquired at the time of intrusion. The overall in situ (i.e., in geographic coordinates) mean direction for andesitic dikes is judged to be highly reliable, although there are two possible scenarios for explaining the easterly deflection: (1) clockwise rotation and (2) tilting to the northwest. We prefer the former scenario and conclude that ˜45 deg clockwise rotation occurred in Takane with respect to the North China Block of the Asian continent. This rotation must represent the clockwise rotation of entire Southwest Japan during the opening period of the Japan Sea. Very little difference is observed between the amount of the easterly deflection in Takane and those in the Tokai and Hokuriku regions, indicating no significant relative rotation. Thus, the crust beneath Takane has not suffered rotation caused by collision of the IBM arc with Honshu.

富士火山，古地磁気学的手法を用いたAD450～800の噴火推移の検討

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Examination of eruptive sequence of Fuji volcano from 450 to 800 A.D. using paleomagnetic method

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For the prediction of medium- and long-term volcanic eruption, detailed elucidation for the eruption age, frequency, and eruptive sequence of eruption events are very important. Therefore, we investigated paleomagnetic study in order to exam eruption events of Fuji volcano. The paleomagnetic method has several advantages, one of which is dating determination based upon similarity to the paleomagnetic secular variation model(JRFM2K.1), and which help comprehension for the simultaneity of eruption events from paleomagnetic directions. Here we report paleomagnetic results of the lava flows that erupted during 450 to 800 A.D.

Samples for paleomagnetic measurements were collected from 32 units of lavas and pyroclastic deposits. The samples were oriented by a sun compass to eliminate local magnetic anomalies. At each site, we collected 6 to 12 samples using core-drill. Samples were measured with AFD.

Samples of the Takamarubi lava flow, divided into some flow units, were collected from 5 sites. The mean directions of the Takamarubi lava flow roughly show two distinctive ranges. Both of the mean directions fit with the mean directions of the Aosawa lava flow, the Nakanochaya lava flow and the Hinokimarubi 1 lava flow, within a 95 range. There are possibility that the 4 units, showing similar petrological features, were simultaneous eruptions and erupted between 580 to 700 A.D.. These above suggest that several lava flows erupted from NE-SW eruptive fissures, intermittently. Based on eruptive sequence and historical records, Koyama (2007) identified that the Takamarubi lava flow erupted in the Enryaku era (800 to 802 A.D.). However, the eruptive product in the Enryaku era is rather newly classified Takamarubi-rindo lava flow (Takada et al.,2016) than the Takamarubi lava flow using paleomagnetic method. The stratigraphy between the lavas is conformable to the paleomagnetic dating. Our findings suggest that paleomagnetic method better dating and eruptive sequence of Fuji volcano.

中長期的な噴火予測をする上で噴火イベントの年代，頻度，そして噴火推移を詳細に解明することは重要である．古地磁気学的手法の利点は，火山噴出物の古地磁気方位を地磁気永年変化と対比する年代推定に加え，噴火イベントの同時性を相対的に捉えられることである．本報では，AD450～800に噴火したと推定される溶岩流の古地磁気方位の測定結果について議論する．

富士火山地質図第2版(高田ほか,2016）の層序区分に基づき，溶岩流，火砕丘32層を定方位サンプリングした．溶岩や火山体が及ぼす局所的な磁気異常の影響を排除するため，試料の方位付けにはサンコンパスを用いた．正確な古地磁気方位を得るために，同層準の溶岩でも数km離れた1～5サイト，1サイトあたり6～12試料を採取し，交流消磁装置・スピナー磁力計を用いて磁化方位を測定した．

北麓に分布する鷹丸尾溶岩流は，フローユニットを確認し，5サイトから採集した．それらの磁化方位はD=-20°，I=56°周辺の平均方位を示す3サイトとD=-8°，I=58°周辺の平均方位を示す2サイトに大別され，AD600頃とAD700頃に噴火した2回のフローユニットからなると推定される．下位の檜丸尾1溶岩流は，同じフローユニットとされる5サイトから採集した．それらの磁化方位はD=-20°，I=56°周辺の平均方位を示す2サイトとD=-14°，I=58°周辺の平均方位を示す3サイトに大別され，AD600頃とAD630頃に噴火した2回のフローユニットからなると推定される．檜丸尾1溶岩流より下位の中ノ茶屋溶岩流は，D=-17.5°，I=53.3°の平均方位を示し，AD580頃に噴火したと推定される．また，南麓に分布する青沢溶岩流の磁化方位は，D=-20°，I=52.9°の平均方位とD=-13.4°，I=57°の平均方位を示すサイトに分かれ，それぞれ北麓に分布する中ノ茶屋溶岩流と檜丸尾1溶岩流の平均方位とα95の範囲内で重複する．これら4層準は，岩石学的特徴も近似していることから，一連の噴火イベントと推定される．これらの噴火推移として，AD580～700頃の間，北東－南西方向に卓越する割れ目火口から断続的に複数の溶岩流が噴出した可能性が示唆される．一方，鷹丸尾溶岩流は史料からの年代推定(AD800～802)と年代観が異なる(小山,2007)．新たに区分された鷹丸尾林道溶岩(高田ほか,2016)の磁化方位は，古地磁気永年変化モデル(JRFM2K.1)から計算されるAD800のD=-15.5°，I=48.6°周辺の平均方位を示す．鷹丸尾林道溶岩は鷹丸尾溶岩の上位であり，層序と古地磁気方位からの年代推定が整合的である．古地磁気学的手法によって，噴火年代や噴火推移をより詳細化できる可能性が示唆される．

阿蘇カルデラ完新世火山岩の古地磁気強度測定

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Paleointensity study on Holocene volcanic rocks in Aso caldera

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We have conducted a paleomagnetic and paleointensity study on Holocene lava flows and pyroclastic rocks around the post-caldera cones in Aso caldera, central Kyusyu, Japan. Paleomagnetic directions obtained in this study are useful to recognize temporal correlation or distinction between the studied sites. Also, the paleomagnetic directions obtained from 22 sites around three cones and a scoria cone are distributed on a simple curve on the equal area projection, which record paleomagnetic secular variation (PSV) during the period between 4 and 3 ka. For the 22 sites recording the PSV curve, the LTD-DHT Shaw paleointensity method (Tsunakawa-Shaw method) was applied to the samples. Ninety-nine samples of the 22 sites were measured and 96 samples of 21 sites passed the selection criteria. Four or more paleointensities were obtained for 10 sites and their standard deviations were smaller than 10% of the means. The 10 mean values indicate that the paleointensity increased from 55 to 70 micro-T, which constrain the paleointensity variation between 4 and 3 ka in Japan. These new paleointensity data from Japan are higher than the paleointensity data reported from Europe. A possible explanation on the difference is that the non-axial-dipole affects the geomagnetic field during the period between 4 and 3 ka.

白亜紀入遠野花崗岩から分離した鉱物単結晶の岩石磁気及び古地磁気強度測定

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Rock-magnetic properties and paleointensity of single silicate crystals separated from the middle Cretaceous Iritono granite

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Understanding the long-term evolution of the geomagnetic field is a key for constraining the thermal evolution of the deep Earth, mantle convection, and the preservation of a surface environment conducive to life. To investigate geomagnetic field behavior through geological time, granites could be good rocks to study because of their nearly continuous record and long cooling times that can average out relatively short-term fluctuations of the geomagnetic field. However, paleomagnetic measurements on whole-rock granitic samples are often disturbed by alterations like weathering and lightning, and the presence of magnetically-viscous multi-domain magnetite.

One of the approaches to avoid weathering disturbances (but not lightning) is to separate single silicate crystals from granitic rocks and conduct paleomagnetic and rock magnetic measurements on them. Recently, several research groups have investigated paleointensities from single crystals of primary minerals such as plagioclase, pyroxene, zircon and quartz for their potential to avoid difficulties that frequently plague whole-rock measurements (e.g. Tarduno et al., 2007, 2010, 2012, 2015; Muxworthy and Evans, 2012). To provide solid ground for single silicate crystal paleomagnetism, paleointensity and rock-magnetic properties of single crystals should be systematically studied and compared to those of the host granitic rock.

We studied zircons, quartzes and plagioclases separated from a Cretaceous granite sample whose whole-rock paleointensity and rock-magnetic properties were studied previously, and found to be particularly stable and reproducible (Iritono granite, 100 Ma, Wakabayashi et al., 2006; Tsunakawa et al., 2009). The reported whole-rock paleointensity was 58.4+-7.3 micro T (2 sigma, before cooling rate correction). We first measured the natural remanent magnetization intensity (M_{NRM}) of several hundred samples for each mineral. Rock-magnetic property measurements such as low-temperature magnetometry, stepwise thermal demagnetization and hysteresis loop measurements were performed on the samples which had significant NRM; but we only found these in the plagioclase fraction. We focused our paleointensity studies on plagioclase, which was the only suitable mineral. Measurements were carried out using the superconducting quantum interference device (SQUID) magnetometer, magnetic property measurement system (MPMS) and Alternating Gradient Magnetometer (AGM) at Center for Advanced Marine Core Research, Kochi University.

Less than 1% of the zircon and quartz grains had M_{NRM} >4 pAm^2. Among them that did, pyrrhotite was the main magnetic carrier for the zircons, and both magnetite and pyrrhotite was present in the quartz, although the occurrence of magnetite-bearing samples was very low. In conclusion, they do not seem to be candidates for paleointensity measurements in case of the studied rock.

Twenty-three percent of the plagioclases showed MNRM high enough to study (>50 pAm^2). Rock-magnetic measurements suggested that the main magnetic carrier is single domain to pseudo-single domain state magnetite inclusions. We performed paleointensity measurements by the Tsunakawa-Shaw method (Yamamoto et al., 2003) to 17 plagioclase crystals. Nine samples passed the selection criteria of the paleointensity method. The obtained mean paleointensity was consistent with the reported whole-rock paleointensity though the standard deviation was relatively large (57.7+-23.3 micro T, 2 sigma). To our knowledge, this is the first report of single crystal paleoinensity study by the Tsunakawa-Shaw method. We conclude that paleointensity measurements were applicable to plagioclase, but to produce results comparable to conventional methods large numbers of crystals that cooled together would need to be studied.

Precise determination of Fe species in plagioclase crystals

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Silicate minerals such as plagioclase and pyroxene sometimes contain fine-grained magnetite crystals; such silicates are called magnetic silicates. Magnetic silicates are often appeared in plutonic rocks and are also appeared in lava flows. Natural remanent magnetizations (NRM) carried by magnetic silicates should play an important role in paleomagnetic records of whole rock and single crystal. Therefore, to elucidate crystallization mechanism of magnetite in silicate minerals and to understand origin of the NRM is of prime importance in paleomagnetism, while the mechanism has been poorly understood. In this study, to precisely determine the chemical species of Fe in the plagioclase crystals and to better understand the crystallization mechanism of magnetite, magnetic measurements combined with microscopic observation and synchrotron radiation study were conducted for single grain plagioclase crystals.

We prepared plagioclase crystals from a gabbroic anorthosite of the Duluth complex, a layered gabbro of the Oman ophiolite, and a medium-grained gabbro of the Murotomisaki gabbroic complex. The plagioclase crystals were collected under a stereoscopic microscope and used for the measurements after a hydrochloric acid leaching. The main series of measurements for the single grain plagioclase crystals were as follows: (1) To estimate a content of magnetic mineral in the plagioclase crystals, magnetic hysteresis loop was measured using an Alternating Gradient Magnetometer. (2) To investigate the average valence state of Fe, L_{III}-edge X-ray absorption near edge structure (XANES) measurement was performed at BL27SU of SPring-8. (3) To investigate chemical compositions of the plagioclase crystals, microscopic observation was conducted using electron microprobes. In addition to these single crystal measurements, low-temperature remanence measurements (field cooling remanence, zero field cooling remanence, and room temperature saturation isothermal remanence) were conducted for plagioclase grains using a Magnetic Property Measurement System.

The saturation magnetization value of plagioclase samples were 6-68 mAm^2/kg, 2-27 mAm^2/kg, and less than 1 mAm^2/kg for the gabbroic anorthosite, layered gabbro, and medium-grained gabbro, respectively. The low-temperature remanence curves of gabbroic anorthosite and layered gabbro plagioclase samples showed pronounced remanence reductions at around 100-140 K, indicating that the plagioclase crystals contained nearly pure magnetite. Assuming the saturation magnetization value of pure magnetite, we estimated the magnetite content. As a result, the magnetite content in plagioclase crystals were 60-740 ppm, 20-300 ppm, and less than 10 ppm for the gabbroic anorthosite, layered gabbro, and medium-grained gabbro, respectively. The XANES analysis showed that the average valence states of Fe in the bulk plagioclase crystals were 2.32-2.79, 2.69-2.92, and 2.72-2.94 for the gabbroic anorthosite, layered gabbro, and medium-grained gabbro, respectively. The microscopic observation showed that the Fe contents as FeO for the plagioclase crystals were nearly constant with an average of 2800 ppm and 1800 ppm for the gabbroic anorthosite and layered gabbro, respectively. Among these parameters there was inverse relationship between the magnetite content and average valence states of Fe, suggesting that the valence state of Fe could be a key factor in the crystallization mechanism of magnetite.

姶良Tnテフラを構成する火山ガラス粒子の岩石磁気特性の系統的検討

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Systematic examination on rock magnetic properties of the single volcanic-glass grains extracted from the Aira-Tn (AT) tephra

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There are many widespread tephra around Japan. In usual paleomagnetic and rock magnetic studies, analyses are typically made on an assemblage of tephra grains to investigate macroscopic remanent magnetizations. We had investigated rock magnetic properties of the single volcanic-glass grains extracted from an unwelded part of the Ito pyroclastic flow deposits in Kyusyu (2016 JpGU; 2016 SGEPSS). In the present study we conducted rock magneticmeasurements on the single volcanic-glass grains extracted from the fall-out Aira-Tn (AT) tephra deposits taken from an outcrop in western Kochi. Now our plan is to extract the single volcanic-glass grains from an AT tephra in a marine core and to conduct rock magnetic measurements on them. On the basis of the rock-magnetic measurements, we will discuss the possibility of paleomagnetic experiment using the single volcanic-glass grain in AT tephra.

日本周辺には数多くの広域テフラが分布する。従来の古地磁気・岩石磁気学的研究においては、テフラを構成する粒子群が集合体として獲得しているマクロな残留磁化を主な分析対象としてきているが、私たちは個々の粒子が獲得した残留磁化が分析対象になり得るか、姶良 Tn テフラ（AT）を対象に検討を進めている。このテフラは、約 2.6〜2.9 万年前に鹿児島湾北部に存在したと推定される姶良カルデラより噴出し、鹿児島県〜宮崎県中南部〜熊本県南部と極めて広く分布する巨大な入戸火砕流堆積物（A-Ito）の co-ignimbrite ash である（町田・新井, 2003）。特に、日本全域及び朝鮮半島にわたって広大な範囲に分布する最終氷期の重要な指標層として多方面から研究されてきた（町田・新井, 2003）。

武田ほか（2016JpGU、2016SGEPSS）では、宮崎県の A-Ito の非溶結部の露頭で採取した試料を篩分けして 20〜30 メッシュサイズ（595〜841 μ m）の砂粒を抽出し、さらに火山ガラス粒子を選別して、各種の古地磁気・岩石磁気学的分析を行った。塊状火山ガラス粒子は 324 個のうち 18 %が超伝導磁力計のブランクの 2 倍を上回る強い自然残留磁化（NRM）を保持していた。一方、軽石型火山ガラス粒子は 88 個のうち 85 %がブランクの 2 倍を上回る NRM を保持しており、さらに安定な消磁特性を示すものが多く、それらの磁化は保磁力の高い単磁区サイズのマグネタイトによって担われていることが示された。これらの粒子は噴出時に熱的なプロセスによって熱残留磁化（TRM）を獲得している可能性が示され、予察的ながらも 20〜30 μ T という古地磁気強度の推定値を得た。

さらに降下テフラの岩石磁気特性について検討を行うため、高知県西部の AT の露頭から試料を採取した。これらを篩分けして 20〜30（595〜841 μ m）及び 30〜40 メッシュサイズ（420〜595 μ m）の砂粒を抽出して火山ガラス粒子を選別して、各種の古地磁気・岩石磁気学的分析を開始した。一部の結果については武田ほか（2017JpCU）で報告しているが、本研究ではさらに分析を進めた結果を報告する。20〜30 メッシュサイズの粒子については、バブルウォール型火山ガラスは 345 個のうち 13 %が、軽石型火山ガラス粒子は 159 個のうち 19 %がブランク平均の 2 倍以上強い NRM を保持していることが分かった。それぞれいくつかの粒子に対して段階交流消磁を行ったが、全て、不安定な消磁の挙動を示した。30〜40 メッシュサイズの粒子については、バブルウォール型火山ガラスは 420 個のうち 1 %が、軽石型火山ガラス粒子は 240 個のうち 8 %がブランク平均の 2 倍以上強い NRM を保持していることが分かった。それぞれいくつかの粒子に対して段階交流消磁を行ったが、全て、不安定な消磁の挙動を示した。これらの挙動は、宮崎県の A-Ito から抽出した 20〜30 メッシュサイズの軽石型火山ガラス粒子の岩石磁気特性とは異なる。

今後、日本周辺から採取された海洋コア試料に含まれる AT も対象として、同様の検討をすすめ、それらの結果を合わせて報告する予定である。

黒曜石の磁化率周波数依存性による粒径分布

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Magnetic granulometry of Takanoobane obsidian using frequency dependence of susceptibility

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Obsidian is a volcanic glass containing abundant microlites of Fe-Ti oxides, which potentially serve as an ideal recorder of ancient geomagnetic field. Previous studies, especially focused on retrieving paleointensities from obsidians, demonstrated the high (above 500 deg.C) and narrow unblocking temperatures and the univectorial natural remanent magnetizations of obsidians. In this study, drilled cores of obsidians comprising upper and lower layers intervened by Takanoobane rhyolite lava flow from Aso volcano were analyzed to deduce grain size distributions spanning superparamagnetic (SP) and single-domain (SD) boundary.

Thermomagnetic curves on Takanoobane obsidians exhibited high Curie temperatures above 500 deg.C, indicating low-Ti titanomagnetite as a main magnetization carrier. Hysteresis loop shape varies from potbelly to nearly straight line, and sometimes resulted in wasp-waisted loops due to mixture of the two components. Hysteresis parameters are widely distributed on a Day plot; Some samples were along the single-domain and multidomain (MD) mixture line, but others are deviated to a large extent from the SD-MD line to a higher Hcr/Hc and lower Mr/Ms region, which is caused by high SP fraction. These hysteresis data suggest that the obsidians contain low-Ti titanomagnetites covering SP and SD ranges, but the grain size distribution significantly changes according to the vertical position. While upper obsidian layer and bottom part of lower layer have higher content of SP grains, obsidians just below the rhyolite lava are dominated by pseudo-single-domain (PSD) grains.

Frequency dependence of susceptibility, which is believed to indicate SP contribution, was measured at room temperature for a broad frequency band ranging from $1x10^{-1}$ to $5x10^{5}$ Hz using a combination of MPMS and ZH susceptometers. Only a small number of samples indicated unequivocal frequency dependences in the in-phase and out-of-phase components. Some samples with high SP fractions did not show any significant frequency dependences of susceptibility at room temperature as well as PSD samples. On the other hand, low-temperature frequency dependence clearly revealed different behaviors between SP and PSD samples. Smaller SP grains exhibited frequency dependence vastly below room temperature, and did not give any indication of room-temperature frequency dependence as mimicking PSD grains.

Significant grain size variation within a vertical column of obsidian suggest that grain size is greatly influenced by cooling rate and control the suitability for paleointensity determination. Obsidians certainly contain fine-grained titanomagnetites, but all of obsidian samples are not suitable for paleointensity measurements. Knowledge on grain size distribution for SP-SD-PSD range should be indispensable for paleointensity studies using obsidians.

黒曜石は鉄-チタン酸化物の晶子を豊富に含む火山ガラスであり，過去の地球磁場の理想的な記録媒体であることが期待できる．以前の研究，特に黒曜石からの古地磁気強度を得ることに焦点をあてた研究では，高温 (500 度以上) の狭いアンブロッキング温度および単一成分の自然残留磁化をもつことが示された．本研究では阿蘇火山の高野尾羽根流紋岩溶岩流の上・下層を構成する黒曜石の掘削コアを解析し，超常磁性 (SP) -単磁区 (SD) 境界にまたがる粒径分布を推定した．

高野尾羽根の黒曜石の熱磁気曲線は 500 度以上の高いキュリー温度を示し，磁化の担い手として低チタンのチタン磁鉄鉱を示唆する．ヒステリシスループの形状は，potbelly からほぼ直線に亘り，ときには 2 つの成分の混合に起因した wasp-waisted ループを生じた．ヒステリシスパラメータは Day プロット上に広く分布し，いくつかの試料は単磁区-多磁区 (MD) 混合線上にあったが，他の試料は SD-MD 線から高い Hcr/Hc および低い Mr/Ms 領域に大きく偏向し，これは高い SP の含有率を示す．これらのヒステリシスデータは，黒曜石が SP および SD 領域をカバーする低チタンのチタン磁鉄鉱を含むが，粒径分布は試料の垂直位置によって大きく変化することを示唆している．上層と下層の底部の黒曜石は SP 粒子の含有率が高いが，流紋岩溶岩の直下の黒曜石は疑似単磁区粒子 (PSD) 粒子によって支配されている．

SP の寄与を示すと考えられる磁化率の周波数依存性を，MPMS と ZH 磁化率計の組み合わせを用いて，$1x10^{-1}$ から $5x10^{5}$ Hz までの広い周波数帯域で室温で測定した．わずかな数の試料のみが，in-phase および out-of-phase 成分において明確な周波数依存性を示した．高い SP 含有率をもついくつかの試料は，PSD を含む試料と同様に，室温において磁化率の有意な周波数依存性を示さなかった．一方，低温での周波数依存性は，SP と PSD 試料の間で異なる挙動を明らかに示した．より小さい SP 粒子は，室温よりも大幅に低い温度で周波数依存性を示し，PSD 粒子のように室温での周波数依存性を示さなかった．

黒曜石での垂直方向の粒径変化が顕著であることは，粒径が冷却速度の影響を強く受け，古地磁気強度測定への適性を制御することを示唆している． 黒曜石は確かに細粒のチタン磁鉄鉱を含んでいるが，黒曜石の試料がすべて古地磁気測定に適しているわけではない．黒曜石を用いた古地磁気強度研究では，SP-SD-PSD の粒径分布の情報が不可欠である．

Rock magnetism applied to characterization of arc-backarc volcanism in the Okinawa Trough

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The Okinawa Trough is a back-arc basin located behind the Ryukyu arc-trench system. Its southern part is characterized by active rifting and complex arc-back-arc volcanism along the depression and is believed to represent a transition from a rifting stage to initial spreading [e.g., *Sibuet et al*., 1987]. The southern Okinawa Trough has a unique key to understand the first stage of oceanic lithosphere evolution, however the spatial distribution of the volcanism as well as their magma type remains unclear. It is needed to conduct extensive geophysical mapping such as magnetic anomaly in which signal is sensitive to volcanic edifices because volcanic crust contains rich ferromagnetic minerals (mainly titanomagentite). In order to establish a useful benchmark for understanding magnetic anomalies associated with arc-back-arc volcanism, we performed comprehensive rock magnetic analysis and petrological studies of seafloor rock samples collected in the southern Okinawa Trough. The measurements were conducted for basalt from the Yaeyama Ridge (YR) and Irabu knolls (IKs), dacite from the Hatoma knoll (HK), and rhyolite and pumice from the Tarama Knoll (TK).

The natural remanent magnetization (NRM) intensity shows 0.3-175.2 A/m in the YR, 0.8-214.4 A/m in the IKs, $<$0.1-3.8 A/m in the HK, and 3.1 A/m for dacite and 0.1-0.2 A/m for pumice in the TK. The magnetic susceptibility of all samples is too low to induce magnetic field under geomagnetic field intensity comparing with NRM intensity. The NRM intensity of volcanic rocks may vary in relation to several factors such as the geomagnetic field strength at the timing of remanence acquisition, amount and type of magnetic minerals, grain chemistry such as Ti content of titanomagnetite, magnetic domain state controlled by grain size distribution, and the degree of low-temperature oxidation. Therefore, we carefully examined magnetic properties, petrography, and geochemical signatures for understanding rock-to-rock NRM variation.

Thermomagnetic curves of volcanic rocks with low NRM ($<$1 A/m) from the YR, IKs, and HK show irreversible and complex Curie temperatures, suggesting these samples have been affected by hydrothermally alteration and/or oxidation which considerably decreases the NRM [e.g., *Gee and Kent*, 1994]. Low NRM of pumice from the TK is likely explained by low amount of titanomagnetite. The NRM difference between rhyolite and basalt is certainly explained by difference of magma iron content, which is diluted by the silica content in magma evolution. A rhyolite sample from the TK contains titanomagnetite as the magnetic carrier with a Curie temperature of 490-deg and shows magnetic domain state of pseudo single domain (PSD). One basaltic rock from the IKs shows similar Curie temperature and PSD signature. In addition, both samples show reversible thermomagnetic curves, suggesting that they have not been affected by low-temperature oxidation. The titanomagnetite amount of this TK's rhyolite (0.9 wt.%) is about one-third that of IKs's basalt (3.1 wt.%). This result is consistent with the bulk rock geochemistry. The NRM intensity is also about one-third (3.1 A/m to 9.4 A/m). These results indicate that lower NRM intensity of rhyolite was caused mainly by a smaller titanomagnetite content owing to low iron content diluted by silica content.

須恵器復元窯の試料を用いた新たな考古地磁気強度実験

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New archeointensity results on the samples from the reconstructed ancient kiln

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Yamamoto et al. (2015) reported that baked clay samples from the floor of a reconstructed ancient kiln provided a reliable Tsunakawa-Shaw (LTD-DHT Shaw) archeointensity (AI) estimate of 47.3 +/- 2.2 microT which is fairly consistent with the in situ geomagnetic field of 46.4 microT at the time of the reconstruction. The reconstruction was conducted to reproduce an excavated kiln of the seventh century in Japan and Sue-type potteries of contemporary style were also fired (Nakajima et al., 1974). Two of the potteries with reddish color were recently subjected to the Tsunakawa-Shaw archeointensity determinations, resulting in reliable AI estimates of 45.4 +/- 2.3 (N=6) and 48.2 +/- 2.7 microT (N=15) when specimens were heated in air in laboratory (Yamamoto et al., 2017 JpGU-AGU Joint Meeting).

We have had another opportunity to take samples from a new reconstructed ancient kiln in Japan which was fired in autumn 2016. The samples were two Sue-type potteries with grayish color (bowl-type and plate-type) and some blocks collected from inner wall of the kiln body. They were cut into mini specimens and then subjected to the Tsunakawa-Shaw experiment. Heating in laboratory was done either in air or vacuum.

For the bowl-type pottery, AIs of 46.9 +/- 2.8 (N=6, air) and 45.3 +/- 2.3 microT (N=6, vacuum) are obtained. They are indistinguishable each other and consistent with the IGRF field of 47.4 microT at the reconstructed location in 2016. For the plate-type pottery, AIs result in 41.8 +/- 1.3 (N=4, air) and 43.9 +/- 3.9 microT (N=4, vacuum). They are also indistinguishable each other but the former AI is slightly lower than the IGRF field.

For the inner wall, AIs of 45.0 (N=1, air) and 46.8 microT (N=1, vacuum) are obtained from a right-side wall, and those of 45.5 +/- 2.5 (N=2, air) and 47.7 +/- 3.0 microT (N=2, vacuum) are observed from a left-side wall. They are all indistinguishable and consistent with the IGRF field.

岩石磁気を用いた焼土断面における磁性鉱物の状態についての考察

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Rock magnetism on the magnetic minerals in the cross section of the old kiln floors

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The floor materials of ancient kilns have been a kind of the main target for the archeomagnetic direction study in Japan. The archeodirection results have indicated detailed paleodirection and its variation for the past years. However, magnetic minerals in the material were not well known and they thought that the main magnetic carrier is magnetite due to the indication in the demagnetizing process. In this study, we perform rock magnetic measurements (high temperature analyses, low temperature analyses, magnetic hysteresis analyses, ...) to obtain the information of the ferromagnetic minerals in the samples.

We sampled from the floor of Sayama Higashiyama old kiln (8C). The samples have 5-10cm thick and we observed the cross section of the floor. Near-surface floor of the kiln can separates into 3 - 5 layers in color and status. Background geology is quartz porphyry and the semi-underground kiln was constructed with digging several tens of centimeters into the soil. The rock magnetic measurements were performed for each layer.

In the IRM acquisition analyses, it is indicated that (1) main magnetic mineral is magnetite, (2) the size distribution of the magnetite, which is shown in the peak position of the derivative of the acquisition, shows rich variation in regard to the layers, and (3) in some layers, especially in the top and deeper layers, there are little signals in high remanent coercivity region around 1 T. The variation of the size of magnetic minerals is also shown in the low temperature magnetic analyses.

日本において考古地磁気学の主なターゲットは須恵器など歴史時代の土器を焼いた窯跡であった。床面試料を採取し古地磁気方位を測定することで詳細な地磁気永年変化を議論するに足るだけの精度をもった古地磁気方位情報を得ることができた。また、最近は床面試料を用いて古地磁気強度測定を行う試みも始まっている。ところが、対象となる床面に含まれる磁性鉱物の情報はあまり多くなく、須恵器窯であれば還元焼成であるからもっぱら磁鉄鉱、などと言う解釈が普通にされてきた。実際、段階交流消磁などを施した古地磁気結果を見る限りでその推察は間違っていないようである。

しかし、強度測定については磁鉄鉱以外の強磁性鉱物が入っていることはあまり望ましい状態ではなく、磁鉄鉱についても多磁区構造粒子が大勢をしめるのは都合が悪い。

そこで、本研究では古地磁気測定に対して予察的な情報をもたらすこと、および、考古学研究に対して焼成時窯内状態に関する情報をもたらすことを目的として、岩石磁気を中心とした測定を行った結果を報告する。

対象とした遺跡は岡山県備前市の佐山東山窯跡 (8 世紀) である。本窯跡は 2013 年度から発掘調査が断続的行われており、最近になって焚口と考えられる場所まで特定されつつある。今回は焚口付近、その少し上、および焼成部中央の床面より採取された断面試料について、各種岩石磁気測定を行った。現地の岩盤の地質は中生代の石英斑岩とされ、土壌化したものが堆積する中に数十 cm 掘り込んで半地下式登窯を作成している。床断面は色調等によって少なくとも３～５層に分別でき、それぞれの層について測定を行った。

行った実験は、熱磁気天秤を用いた熱磁気分析（おもに真空中)、振動磁力計を用いた磁気履歴分析、および MPMS を用いた低温磁気と常温下での等温残留磁化獲得実験である。

いずれの試料も主たる磁性鉱物は磁鉄鉱であるが、とくに焚口部のごく表層と数 cm 下の赤色化した層では赤鉄鉱と思しき高保持力磁性鉱物も確認された。これは焼成時の窯中とその下の土壌中における酸化状態を反映していると考えられる。また、箇所によって磁鉄鉱の粒子サイズにも大きな違いが見られた。

層の違いは窯床表層部に貼られていた粘土、および温度と熱の伝わり方を反映していると考えられる。表面付近ほど等温残留磁化が強いことがわかっており、これは表層付近では高温化で磁鉄鉱が晶出している可能性を示唆している。

遠洋性赤色泥中の生物源磁鉄鉱の形状と含有量の変動

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Abundance and morphology of magnetofossils in pelagic red clay around Minamitorishima, western North Pacific

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Recent investigations have discovered unexpected abundance of magnetofossils in oxic pelagic red clay. They have potential to be unique biogeochemical tracers in otherwise non-fossilferous sediments. Here we report the characteristics of magnetofossils in red clay in the western North Pacific. Magnetic measurements revealed that magnetofossils dominate the magnetic mineral assemblage of the sediments. Endmember analysis of isothermal remanent magnetization acquisition curves, supplemented by the analysis of S ratios, indicates that the magnetic assemblage can be unmixed into three endmembers: two for magnetofossils and one for terrigenous magnetic minerals. Direct counting of magnetofossil morphologies under a transmission electron microscope shows that each of the two magnetofossil endmembers represents equant magnetofossils and bullet-shaped magnetofossils, respectively. Stratigraphic variation of the endmember contributions revealed that the equant magnetofossils are dominant for the most part, but an interval around 7 m below seafloor shows unusual abundance of the bullet-shaped magnetofossils. This may reflect enhanced organic carbon flux to the sediments. The organic carbon content is low throughout the sediments, and it does not show any change corresponding to the increase of bullet-shaped magnetofossils, indicating severe remineralization of the organic carbon. On the basis of lithostratigraphic correlation to nearby drilling sites, we tentatively estimate the age of the bullet-shaped magnetofossil increase as sometime between the late Campanian and 25 Ma. These results demonstrate that environmental information can be obtained by magnetofossils from pelagic red clay.

現在の遠洋域の大部分を覆っている赤色泥は炭酸塩質・珪質の微化石をほとんど含まないが、生物源磁鉄鉱を多量に含んでいることが近年わかってきている。その古環境的意味を明らかにするために、南鳥島周辺の堆積物ピストンコアを対象に生物源磁鉄鉱の形状と含有量の変動を調べた。磁気測定と透過電子顕微鏡観察により、生物源磁鉄鉱が堆積物の主要な磁性鉱物であることが確認された。S 比と、等温残留磁化獲得曲線の端成分分析から、磁性鉱物集団は 2 種類の生物源磁鉄鉱と陸源磁鉄鉱の、3 成分の混合で説明された。透過電子顕微鏡観察と比較することで、2 種類の生物源磁鉄鉱端成分はそれぞれ、等方的な磁鉄鉱と弾丸状の磁鉄鉱であった。これら 2 種類の生物源磁鉄鉱の深度変化を見ると、ほとんどの深度で等方的な磁鉄鉱が支配的であるが、海底下 7 m 付近に弾丸状の磁鉄鉱が異常に増加する層が見つかった。この変化は有機炭素フラックスの増大を反映している可能性がある。一方、堆積物自体の有機炭素含有量は総じて低く、ほとんどが分解されてしまっているようである。周辺の掘削コアとの比較から、この弾丸状の磁鉄鉱の増大は約 25 Ma より古く、白亜紀カンパニアンより新しいだろうと考えられる。これらの結果は、生物源磁鉄鉱を用いることで赤色泥から古環境情報を読み取れることを示す。

走査型SQUID顕微鏡を用いた鍾乳石の古地磁気測定の試み

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Preliminary study on speleothem paleomagnetism using scanning SQUID microscope

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Reconstruction of past geomagnetic field is a key approach to unveil the mystery of geomagnetism and both volcanic and sediments archives have been employed. However, obtaining accurate chronology is a major obstacle using these samples. Recently, speleothems, which can be dated by U-series as well as radiocarbon techniques are utilized to study palaeogeomagnetism (e.g. Lascu et al., 2016). However, its weak magnetic signals preserved in samples hinder this archive to be widely used in the field. A scanning SQUID Microscope (SSM) can image very weak magnetic fields with high spatial resolution could solve this obstacles though no studies applied for speleothems have been reported to date. In this study, we have conducted paleomagnetic measurements on speleothems collected in Tongatapu Island, the Kingdom of Tonga with a SSM.

The stalagmites were obtained at Anahulu cave in Tongatapu island (around 21^o 13' S, 175^o 06' W). The ^{14}C age of the surface part of the stalagmite is ~10 ka and were cut perpendicular to the growing direction of stalagmite and shaped to thickness ~0.200 mm before used for measurement. The resolution is a 0.100 mm x 0.100 mm grid and the distance between the SQUID chip and the sample at ~0.200 - 0.300 mm.

We obtained natural remanent magnetization (NRM) of the average ~2 nT by using the SSM. Now we are operating progressive demagnetization (5 mT). In this talk, we will present initial results on speleothems.

鍾乳石を用いた古地磁気復元研究は、過去の地磁気記録を連続的・安定的に保存している可能性が高いことから、近年注目されてきている。例えば、Laschamp などの地磁気エクスカーションを記録している鍾乳石の薄切り試料の古地磁気測定結果と U-Th による精密年代推定を組み合わせることで、地磁気エクスカーションの年代値に制約を与えることに成功した研究などがある（Lascu et al., 2016）。一方、それらの研究は空間分解能と感度に乏しいという欠点が存在した。高空間分解能・高感度での磁気測定には、走査型 SQUID 顕微鏡（Scanning SQUID Microscope: SSM）を用いることが可能だが、これまで鍾乳石に適用した例はない。そこで本研究では、トンガ王国トンガタプ島で採取した鍾乳石について産業技術総合研究所の SSM（Kawai et al.,2016; Oda et al., 2016）を用いた磁気マッピング（古地磁気測定）を試みたので報告する。

試料はトンガタプ島内の Anahulu cave（21^o 13' S, 175^o 06' W 付近）で採取された石筍を用いた。石筍の年代は、石筍表層部に対し ^{14}C 年代測定を行うことで、およそ 1 万年前という年代を得た。採取した試料は、石筍の成長方向に対して垂直に切断し、厚さ~0.200 mm に整形し測定に用いた。0.100 mm x 0.100 mm グリッドの解像度、SQUID チップと試料の距離を~0.200 - 0.300 mm として測定を行った。

これまでに 2 試料に対して SSM による測定を行い、平均して石筍薄片試料の~0.300 mm 上で~2 nT の磁場強度が確認された。現在、段階交流消磁（5 mT）を進めており、本発表では、これらの測定結果について報告を行う予定である。

琵琶湖堆積物から得られた地磁気永年変化の高分解能記録

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High resolution record of paleomagnetic secular variation obtained from Lake Biwa sediments

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We have conducted measurements on one of the three piston cores taken from Lake Biwa off Takashima (BWK12-2; length 1633 cm). Sediment comprises of clay intercalated with at least 13 ash layers. Thirteen horizons were dated with 14C using plant pieces giving a maximum age estimate of more than 40 ka. Paleomagnetic cube specimens, u-channel samples and LL-channel samples were taken from the core. Paleomagnetic cube specimens were measured with a SQUID Rock Magnetometer at AF demagnetization steps of 0-80 mT. Results of inclination from the cube samples show an agreement with the paleosecular variation reported by Ali et al. (1999). For example, Inclination show a minimum of ˜40 ° at 2600 year BP and a maximum of ˜58 ° at 3400 year BP, both of which can be correlated with a minimum 'h' at 2400 year BP and a maximum 'i' at 2900 year BP presented by Ali et al. (1999), respectively. On this feature, pass-through measuremens on u-channel and LL-channel samples were conducted both at Geological Survey of Japan and Kochi Core Center. Paleomagnetic results after deconvolution for u-channel and LL-channel at two different laboratories with different sensor response functions will be compared together with the results of cube samples. Sensor response optimiazation will also be conducted. Further, the results measured with a scanning SQUID microscope on block samples taken from LL-channel samples will be used for inversion.

琵琶湖高島沖で採取した堆積物ピストンコア柱状試料について古地磁気測定を行い地磁気永年変化曲線の精密復元を行っているが、本報告は昨年の続報になる。ピストンコアは 2012 年に 3 本採取された内の 1 本（BWK12-2; 長さ 1633 cm）である。堆積物は主として細粒の粘土からなり、少なくとも肉眼で確認できる火山灰層を 10 層程度含む。堆積物の 13 層準から得られた植物片について 14C 年代を得ており、堆積物は過去 4 万年程度以上に相当することがわかっている。堆積物はピストンコアで採取された後に、1m 間隔で切断され、押し出した後に半割し、片方を古地磁気測定のために使用した。半割された堆積物は、窒素封入の上で密閉して 4 ° C で冷蔵保管している。また、堆積物表面から連続的に古地磁気キューブ試料（7cc）を採取し、隣接する形で u-channel（断面積 1.8 cm x 1.8 cm, 長さ 100 cm の採取も行った。さらに、一部を除いて LL-channel（断面積 1 cm x 1 cm, 長さ 100 cm の L アングルを 4 本組み合わせたもの）による試料採取も行った。

得られた古地磁気キューブ試料について 0-80 mT までの段階交流消磁と自然残留磁化の測定を産業技術総合研究所の超伝導岩石磁力計を用いて行った。測定結果の伏角を Ali et al. (1999) による永年変化曲線と暫定的に比較したところ、良く一致することが確認された。例えば、伏角は 2600year BP に 40 ° の極小値, 3400year BP に 58 ° の極大値をとるが、それぞれ Ali et al. (1999) の極小値 ' h '（2400year BP）および極大値 ' i '（2900year BP）に対応づけることができる。特にこの約三千年前の大きく変化する地磁気永年変化について、産業技術総合研究所と高知コアセンターの超伝導岩石磁力計を用いて u-channel 試料と LL-channel 試料の自然残留磁化のパススルー測定を行ったが、このデコンボルーション結果について比較検討行う。2 種類の磁力計のセンサーレスポンスの計算ソフトウェアの開発も行いつつあるので、これをあわせて紹介をする。また、LL-channel については SQUID 顕微鏡による測定結果のインバージョンを試みる。約 3000 年前の中東の考古遺物の測定からスパイク状の強い古地磁気強度が報告されており (e.g. Ben-Yosef, 2009; Shaar et al., 2011)、また氷床の 10Be と 14C の記録との関連性も指摘されているが (Fournier et al., 2015)、これらとの関連性も比較検討を行う予定である。

A Revisit to Component Analysis on Remanent Magnetization Curves

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The remanent magnetization curve is favorably measured to estimate the coercivity distribution of geological samples, which usually contain more than one magnetic component. As the magnetic components are often indicative of the associated geological or environmental processes, it is therefore desirable to quantify the contribution of individual components to the total remanent magnetization. This task can be achieved using the so-called unmixing method which fits a mixture model of certain end-member model distribution to the measured remanent magnetization curve. The lognormal, skew generalized Gaussian and skewed Gaussian distributions have been used as the end-member model distribution in previous studies, which are performed on the gradient curve of remanent magnetization curves. However, gradient curves are sensitive to measurement noise as the differentiation of the measured curve exaggerates the noise, which prevents the unmixing method from finding the correct components. Though either smoothing or filtering can be applied to reduce the noise before differentiation, their effect on biasing component analysis is vaguely addressed. In this study, we present a new model function that can be directly applied to the remanent magnetization curves and therefore avoid the differentiation. The new model function can not only approximate the lognormal distribution but also present more flexible skewness and kurtosis than lognormal distribution, which is a merit for modeling the coercivity distribution of complex magnetic component as it could avoid spurious component that is documented for the lognormal distribution. The new unmixing protocol is fully automated so that the users can be freed from the tedious work of providing initial guesses for the parameters for the mixture model and thus the subjectivity of component analysis is improved. We applied the unmixing method both to model and measured data, and compared the results with that obtained using other unmixing methods to better understand their interchangeability, applicability and limitation.

不均一磁化や異方的形状をもつ試料を測定するためのOffset Dipole Model

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An offset dipole model for quantification and correction of the effect of inhomogeneous magnetization or irregular shape

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The key assumption to the measurement of discrete, standard-sized samples in paleomagnetism is that they behave like magnetic dipole so that the magnetization vector can be determined by successive measurements of components in three orthogonal axes. However, such dipole assumption is not necessarily valid in cases that a sample has strongly heterogeneous magnetization, irregular shape, or both, and non-dipole components such as quadrupole and octupole are no longer ignorable. Previously, these non-dipole effects are believed to be present, but in not so systematic manner that affects the measurement significantly. This study established a theoretical flamework for the quantification of such non-dipole effects, and found that the non-dipole terms affect the measurement of the fundamental component with a conventional spinner magnetometer. This was proven by the fact that theoretical calculations of the model based on multipole expansion are consistent with the experimental data obtained by a specific magnetometer with high spatial resolution. Based on these results, a new analytical method is proposed to better document how dipolar a sample is, to quantify the non-dipolar effect in terms of an offset dipole, and to detect the dipole component of a non-dipole sample.

円柱や立方体といった標準的形状から著しく外れた試料を計る必要に迫られることがしばしばある。あるいは等方的形状であっても、磁化が不均一な試料もあろう。原因はともあれ、要はいかにして磁化の非双極子成分を除去するかということである。原理的には、センサーから試料を十分遠ざけることによって双極子成分だけを取り出せる。しかし、磁化が弱いときには、ある程度近づけて測定せざるを得ず、そうなると非双極子成分の影響が無視できなくなる。本研究では、スピナー磁力計の使用を前提に、このような非双極子成分が測定に与える影響を定量的に評価する方法を提案する。テストデータとして、空間分解能の高いMIセンサーを備えた多機能スピナー磁力計（Kodama, 2017）によって測定した結果を用いた。これらの実データと比較検討するために、多重極展開による offset dipole モデルを構築した。種々の波形や FFT スペクトルを検討した結果、この offset dipole モデルによって、測定波形から試料の磁気モーメントの offset や方位を復元できることがわかった。例えば、offset の程度を r=d/l（d:回転軸―offset dipole 間距離、l:回転軸―センサー間距離）とすると、各周波数成分の強度は、基本周波数が $1 + ar^2$、第２高調波が br、第３高調波が cr^2 となる（a, b, c は磁気モーメントの offset や方位に依存する定数）。このことから、基本周波数のみ計る既存のスピナー磁力計では、offset に起因する ar^2 の大きさのバイアスが加わることがわかる。著しく不定形ないし磁気的に不均一の試料をセンサーと近接距離で計る場合、このバイアス (’offset bias’) は 10%を越えることもある。本研究では、この offset bias を適切に補正する方法も提示する。

地球コア内の磁気不安定とダイナモ作用

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Magnetic instability and dynamo action in the Earth's core

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There are many unknowns on the Earth's dynamo action because numerical simulations with Earth-like parameters are difficult. Theoretical modeling is also difficult because the geodynamo is essentially nonlinear. Here I propose a simple model that may explain how the geomagnetic field intensity is determined. The model consists of two processes; the alpha effect and the magnetic instability. The former creates an axisymmetric magnetic field (e.g., a magnetic dipole) through interaction of non-axisymmetric (higher order) magnetic fields and fluid flows. The latter creates non-axisymmetric magnetic field through natural instability of an axisymmetric (toroidal) magnetic field. The idea is that the magnetic energy spectrum is determined so as to balance the magnetic energy transports between the axisymmetric and non-axisymmetric parts. I report recent results on magnetic instability and discuss the critical toroidal-field intensity, the critical wavenumber, and linear growth rate that may be plausible in the Earth's core condition. I also discuss whether this simple model can explain Earth and planetary magnetic field intensity.

伊能忠敬の山島方位記から十九世紀初頭の日本の地磁気偏角を解析する。第六回報告

辻本 元博 [1]
[1] なし

Analyzing the geomagnetic declination in early 19 century in Japan from Santouhouikireport 6.

Motohiro Tsujimoto[1]
[1] none

The Santouhouiki is a national treasure of Japan consist of 67 volumes data of approximately 200,000 magnetic compass survey azimuth data by 0degree 5min unit in 1800 to 1816,cover from eastern Hokkaido to Yakushima recorded by map surveyer Tadataka Inoh.We execute interdiscplinary and simultaneous analysis ofreal zimuth,magnetic declination,the position of the survey target points, precise position of survey refeence point where the value of declination to any target points are similar. We analyzed declination 207 points in Japan.NOAA's Histoical Declination viewer according to Andrew Jackson's Gufm1 are lack of the declination data in Japan from 17th centurry to 19 centuryequal to the term of national isolation of Japan. We must introduce the declination data analyzed from Santouhouiki to NOAA.

国宝山島方位記は地図測量家伊能忠敬により 1800 年から 1816 年に記録された北海道東部から屋久島迄の 67 巻の磁針測量方位角帳で測量対象地点及び測量実施地点の地名と 0 度 05 分単位の推計約 20 万件の磁針測量方位角が記録されている。我々は真方位角、地磁気偏角、測量対象地点詳細位置、そしていずれの測量対象地点への磁針測量方位角にも含まれる地磁気偏角が一定或いは近似になる精確な測量実施地点位置の学際同時解析を進めている。 新たに中部日本の内陸部の長野県を含め日本の 207 地点で地磁気偏角を解析した。アンドリユージヤクソンらのデータに基づくアメリカ海洋大気庁のヒストリカルデクリネーシヨンビユーワーは日本が鎖国した 17 世紀中期から１９世紀中期迄の日本のデータが不足しており、山島方位記からの解析値をアメリカ海洋大気庁のヒストリカルデクリネーシヨンビユーワーに導入する必要がある。

復元窯における古地磁気方位

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Paleodirection study of reconstruceted kiln

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Our recent archeomagnetic studies revealed the archeodirections from oriented baked earths from kilns, ovens and other artificially baked materials, and the direction of each age is almost consistent with the direction from the secular variation curve provided.

In this study, we show the results the paleomagnetic direction measurements from the floor of the kiln which was recent operated in order to confirm the paleodirection and the field direction observed.

The material for the paleomagnetism was sampled from the reproduced Sue ware kiln, which was operated in anoxic environments and up to the temperature of 1100-1200 C. The remanent magnetization shows higher intensity, lower concentration and higher broken-field of the second remanence than the results from actual archeomagnetic studies. The characteristic direction shows the almost exact declination and slightly shallower inclination than the observed field. The shallower inclination is likely due to macroscopic anisotropy caused by the high magnetic intensity.

考古地磁気学では、土器を焼いていた窯跡や住居趾、竈跡などの焼土から定方位試料を採取し、古地磁気方位測定をすることで、過去の地磁気方位を詳細に測定する。我々はこれまで、全国十数か所の焼土について定方位測定を行い、その結果は地磁気永年変化モデルなどと比較して概ね整合的であった。

今回は、土器焼成の復元実験のために作成・使用されている復元窯 (実験窯) において古地磁気用試料採取を行い、古地磁気方位・強度測定を行って、その地磁気記録の精度等を確認した。本発表では方位測定についての報告を行う (強度測定については本セッションで山本らよって発表される)。

試料は、窯跡研究会が兵庫県三木市に作成している須恵器窯を復元した実験窯 (2 号窯) において昨年 11 月に行われた土器焼成実験の後で採取した。本物の須恵器窯と同様に還元焼成を行うように設計され、温度もオリジナルと同様まで上がっている。測定した古地磁気方位は、我々が扱っている古代・中世の土器窯と比べて、残留磁化が強く、方位のばらつきが若干大きく、かつ、2 次的な成分が消える交流消磁レベルが少し高いものであった。特徴的な古地磁気方位は、偏角については現在の地磁気方位とほぼ同じであるが、伏角については若干浅くなる傾向が見られた。浅い伏角は強い磁化強度のために起こっている自己的な巨視的形状異方性の影響の可能性がある。

還元化学消磁による堆積物の熱消磁時CRMの抑制について（予察）

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On the suppression of CRM in demagnetization furnaces by the reductive chemical demagnetization (a preliminary study)

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Sedimentary rocks often have secondary components of chemical remanent magnetizations (CRM) during post depotional processes, lithification, diagenesis, and/or later chemical events, in addition to the detrital remanent magnetization (DRM). These secondary components are carried by iron-oxides, hydroxides, and/or sulfides. Some sedimentary rocks contain high-coercivity magnetic minerals (e.g. hematite), which cannot to be demagnetized by alternating field demagnetization (AFD). Such samples are usually submitted to thermal demagnetization (TD). But thermal alterations at higher temperature steps often introduce spurious CRM, which mask the primary component. Those spurious CRM would be due to magnetite grains transformed in the furnace from ferric minerals precipitated from the water flowing the channel between sedimentary grains. The siltstones and calcareous nodules taken from the Upper Cretaceous Himenoura Group, in Kumamoto Japan, is one of the examples. In order to avoid such spurious CRM, we tried Reductive Chemical Demagnetization(RCD) to remove the ferric minerals which might bear the magnetic minerals in the furnace. The method of RCD is already reported in the 138th and 140th Society of Geomagnetism and Earth, Planetary and Space Sciences, as an application to the reef-limestones. We tried the method to the siltstones taken from the Upper Cretaceous Ezo Group and performed several rock magnetic measurements.

A pair of samples are prepared by splitting the standard paleomagnetic core. One of the samples is submitted to RCD, and the other remain intact. The RCD is performed dipping the sample in the etchant (recipe: Ascorbic acid 5%, buffered by sodium bicarbonate, adjust it to around pH=5.6, ORP=-50mv) for 72 hours. We submitted both the samples to the strong-field thermomagnetic analyses. As the result, the sample without RCD shows slight Js drop at 150 degrees Celsius and 350degrees Celsius, followed by abrupt Js rise at 400 degrees Celsius. Increase of Js makes a peak at 450 degrees Celsius and it slowly decrease up to the Curie temperature of hematite at 680 degrees Celsius. On the other hand, the abrupt Js ascent at around 400 degrees Celsius was not seen in the RCD sample, while the Js drops at 150, 350, 580 and 680 degrees Celsius are the same as the other. This result suggests that the ferric minerals which make CRM at around 450 degrees Celsius are removed by RCD. The RCD procedure may work with other sediments which are suffered from the in-furnace CRM.

堆積岩には堆積時の初期構成粒子に加え，堆積後の海底や湖底，または陸上露出後に鉄の酸化物や水酸化物，硫化物として晶出する様々な二次的磁性鉱物が含まれている．特にヘマタイトなど保磁力の高い磁性鉱物が含まれる場合，交流消磁では完全に消磁できない．そういった試料の場合，熱消磁を行うことが一般的である．しかし，一部の堆積物には熱消磁の際，消磁温度の上昇に伴い試料中の磁性鉱物が熱変質し化学残留磁化 (CRM) を獲得してしまうため消磁できないものがある．例えば，上部白亜系姫浦層群から採取した泥質岩試料やノジュール試料は熱消磁を行うと 400 ℃付近で残留磁化が突然上昇するという挙動を示し，それ以降の初生磁化を取り出すことが困難となる．

我々は第 138 回および第 140 回地球電磁気・地球惑星圏学会において，礁性石灰岩に対して還元化学消磁を用いて二次磁化を担う磁性鉱物を選択的に取り除き，初生磁化を見出す手法を報告した．これは，二次磁化を担う磁性鉱物が，堆積物の粒子間水から晶出することによると予測し，粒子間水の流路に対して還元性エッチング液を流すというものである．今回はこの原理を応用し，蝦夷層群から採取した泥岩試料に対して還元化学消磁を施し，熱変質に関わる物質を選択的に取り除くことが可能であるかを実験した．この試料は通常の交流消磁では全体の 80 %程度までしか消磁ができず，熱消磁では 400 ℃付近で磁化が増加し，古地磁気測定が困難な試料であることを確認している．

１インチの古地磁気測定用コア試料を二分割にし，一方に還元化学消磁を行った．還元化学消磁は，5%アスコルビン酸溶液に炭酸水素ナトリウムを用いて調整したエッチャント（pH=5.6, ORP=-50mv）に試料を 72 時間浸した．これらの試料について真空雰囲気における飽和磁化の温度変化（Js-T 曲線）を熱磁気天秤を用いて測定した．還元化学消磁前の試料の飽和磁化は 150 ℃，350 ℃で減少しつつ，400 ℃付近で大幅に増加する挙動を示した．磁化は 450 ℃でピークに達しその後緩やかに減少しながら 680 ℃で 0 となる．これに対して，還元化学消磁後の試料では 450 ℃での磁化の増加が見られず，150 ℃，350 ℃，580 ℃での磁化の減少が確認でき，680 ℃で磁化が 0 になった．これらの結果は，この堆積物は 400 ℃付近で熱変質によって磁性鉱物を生成する性質をもっているが，還元化学消磁によって熱変質に関わる物質を選択的に除去したことを示している．熱消磁を行う前処理として還元化学消磁を適用することで，熱消磁が困難とされてきた堆積物に対しての対応策になる可能性がある．

Inverse magnetic fabric of anisotropy of magnetic susceptibility in tsunami deposits

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Preferred orientation of minerals (e.g., mineral fabric) preserve information about depositional processes that can be used to reconstruct flow orientation of sediments and magma. Anisotropy of magnetic susceptibility (AMS) is a proxy for determining the preferred orientation of magnetic minerals. Given that magnetic minerals, such as magnetite, mimic the alignment of rock-forming minerals, this technique is the easiest and quickest technique used to measure paleo-flow directions. Since the 2004 Indian Ocean Tsunami, this technique has been used on recent- and paleo-tsunami deposits to try to extract tsunami's information. However, it is unclear if the alignment of magnetic minerals measured by AMS are an accurate proxy for the tsunami's flow direction. Although some studies clarified that AMS can mimic magma flow directions by distribution anisotropy, it has not been interpreted the mechanism for unconsolidated sediments yet. It needs a verification to compare the results between AMS and the other magnetic anisotropy technique. Kon et al. (2017) used anisotropy of anhysteretic remanence magnetization (AARM) that can trace the alignments of remanence-carrying single-domain magnetic mineral. The AARM results indicate that lower susceptibility samples of tsunami deposits showed 'inverse magnetic fabric' where magnetic axes are interchanged. In this case, AMS cannot be used to determine paleo-flow direction. Based on this result, AMS methods alone may not be enough to measure paleo-flow directions from tsunami deposits. In this presentation, we explain such discrepancy by fabric tensor and also stereology. This understanding will help to estimate paleo-flow directions of unconsolidated sediments and also igneous rocks.

Effects of core electrical conductivity on the modeling of core surface flow in a magnetostrophic state

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Convective motions in the liquid outer core generate and maintain the Earth's magnetic field. It is possible to estimate fluid motions near the core surface from spatial distribution of the geomagnetic field and its temporal change known as secular variations. Many core surface flow models have been estimated so far on the basis of the frozen-flux hypothesis, where the magnetic diffusion term in the induction equation is neglected. It should be pointed out, however, that contribution of magnetic diffusion to temporal changes of geomagnetic field cannot be neglected in a viscous boundary layer at the core-mantle boundary (CMB). Hence, a unique approach to the modeling of core surface flow has been devised by Matsushima (GJI, 2015). In the method, magnetic diffusion within the viscous boundary layer is assumed to be influential in secular variations of geomagnetic field, whereas it is neglected below the boundary layer. Matsushima (2015) adopted the tangentially geostrophic constraint for the core flow below the viscous boundary layer.

Matsushima (SGEPSS, 2016) took into account the dynamic effect of magnetic field, and investigated core surface flow based on the tangentially magnetostrophic constraint. It turned out that the core surface flow estimated under influence of the magnetic field is definitely different from that on the geostrophic constraint. The electrical conductivity of core fluid is of significance in estimating a core surface flow. In fact, the Lorentz force depends on the electrical conductivity. Also, contribution of magnetic diffusion to temporal change of geomagnetic field depends on magnitude of magnetic diffusivity, or the electrical conductivity of core fluid. Furthermore, the radial component of the geomagnetic field just within the core is calculated from the radial component and its partial derivatives with respect to the radius, using a Taylor expansion at the core surface; the second derivative is obtained from the magnetic diffusion at the core surface. Hence, in this presentation, the effect of electrical conductivity of core fluid on core surface flow modeling is investigated.

内核半径の異なる回転球殻における地球ダイナモ維持に必要なレイリー数に関する研究

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A study of the required Rayleigh number to sustain dynamo with various inner core radius

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It is widely accepted that the geomagnetic field is sustained by thermal and compositional driven convections of a liquid iron alloy in the outer core. The generation process of the geomagnetic field has been studied by a number of MHD dynamo simulations. Recent studies of the Earth's core evolution suggest that the ratio of the inner solid core radius r_i to the outer liquid core radius r_o changed from $r_i/r_o = 0$ to 0.35 during the last one billion years. There are some studies of dynamo in the early Earth with smaller inner core than the present. Heimpel et al. (2005) revealed the Rayleigh number Ra of the onset of dynamo process as a function of r_i/r_o from simulation, while paleomagnetic observation shows that the geomagnetic field has been sustained for 3.5 billion years. While Heimpel and Evans (2013) studied dynamo processes taking into account the thermal history of the Earth's interior, there were few cases corresponding to the early Earth. Driscoll (2016) performed a series of dynamo based on a thermal evolution model. Despite a number of dynamo simulations, dynamo process occurring in the interior of the early Earth has not been fully understood because the magnetic Prandtl numbers in these simulations are much larger than that for the actual outer core.

In the present study, we performed thermally driven dynamo simulations with different aspect ratio $r_i/r_o = 0.15$, 0.25 and 0.35 to evaluate the critical Ra for the thermal convection and required Ra to maintain the dynamo. For this purpose, we performed simulations with various Ra and fixed the other control parameters. That is, the Ekman, Prandtl, and magnetic Prandtl numbers were fixed to be $E = 10^{-3}$, Pr = 1.0, and Pm = 3.0, respectively. For the initial condition and boundary conditions, we followed the dynamo benchmark case 1 by Christensen et al. (2001). In this model, the inner core is electrically insulating and co-rotating with the core-mantle boundary. The results show that the critical Ra increases with the smaller aspect ratio r_i/r_o. Critical Ra = 60, 100 and 200 are required for $r_i/r_o = 0.15$, 0.25 and 0.35 cases. The required Ra to sustain dynamo has similar behavior to the critical Ra: Ra $>$200, 200 and 400 are required for $r_i/r_o = 0.15$, 0.25 and 0.35 respectively. These tendencies are consistent with the results of Heimpel et al. (2005) for dynamo process in a large magnetic Prandlt number.

In this study, we performed dynamo simulations in the early Earth with different aspect ratio. It is confirmed that larger amplitude of buoyancy is required in the smaller inner core to maintain dynamo.

地球磁場は主成分が鉄で構成されている磁気流体が外核中で熱対流・組成対流することで維持されていると考えられている。地球磁場生成過程は数多くの MHD ダイナモシミュレーションによって研究されてきた。地球コアの進化に関する最近の研究によって、固体の内核半径 r_i に対する流体の外核半径 r_o の比 r_i/r_o は、過去約 10 億年にわたって 0 から 0.35 へと成長してきたと考えられている。一方、地球磁場は 35 億年以上にわたり生成・維持されてきたことが古地磁気計測により示されている。近年、現在より内核サイズが小さい初期地球を想定したダイナモ研究が進められている。Heimpel et al. (2005) はシミュレーション結果に基づいて、ダイナモが維持されるレイリー数を r_i/r_o の関数として示した。Heimpel and Evans (2013) は地球内部の熱史を考慮に入れたダイナモ計算を実行した。Driscoll (2016) は熱進化モデルを基にした一連のダイナモ計算を行った。これらの過去の研究では、磁気プラントル数は地球外核中の現実の値より大きい値が用いられており、検討の余地が残されている。従来からダイナモ研究は精力的に進められているが、初期地球内部で駆動されていたダイナモを十分に理解するためには、さらなる考察が必要とされている。

本研究では、半径比を $r_i/r_o = 0.15$, 0.25, 0.35 とした条件下での熱対流駆動ダイナモシミュレーションをそれぞれ行い、対流が発生する臨界レイリー数およびダイナモを維持するために必要なレイリー数を評価した。すなわち、一連の計算ではレイリー数のみを変化させて、他のパラメーターについてはエクマン数 $E = 10^{-3}$、プラントル数 Pr = 1.0、磁気プラントル数 Pm = 3.0 と共通の値を用いてシミュレーションを実行した。初期条件・境界条件は Christensen et al. (2001) で提案されたダイナモベンチマーク case1 に従った。このモデルでは、内核が電気的に絶縁されていて外核と共回転するダイナモモデルである。シミュレーションの結果から、半径比 r_i/r_o を小さくした場合、臨界レイリー数が大きくなることが示された。すなわち、$r_i/r_o = 0.15$, 0.25, 0.35 に対し、臨界レイリー数はそれぞれ Ra = 60, 100, 200 となった。また、ダイナモ維持に必要なレイリー数も同様の傾向にあることが示され、$r_i/r_o = 0.15$, 0.25, 0.35 のそれぞれの場合について Ra $>$200, 200, 400 となった。以上の傾向は、本研究より大きな磁気プラントル数の値を用いてダイナモ計算を実施した Heimpel et al. (2005) の結果と一致している。

本研究の結果から、内核サイズが小さい場合、ダイナモを維持するためにはより大きな浮力が必要になることが示された。

Kinematic dynamo action driven by top-down compositional convection

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The terrestrial bodies that maintain their intrinsic magnetic fields have dynamos in the fluid cores, in which convection is driven in various ways. As for compositional convection in the Earth's core, it is light element ejection into the outer core caused by inner core growth that fuels compositional buoyancy. In a body, iron ejection due to solidification of iron could occur at the core-mantle boundary under a certain condition, and the solidified iron falls downward like snow drop, that is so-called "iron snow", which would also power compositional convection. It strongly depends on temperature-pressure conditions and bulk sulfur content in the core which sort of compositional buoyancy contributes to convection. In this study, we focus on the iron snow process, which would happen at temperature and pressure lower than those in the Earth's core, and the associated dynamo mechanisms.

First, to understand a basic flow structure and properties of iron snow convection, onset of compositional convection in rotating spherical shells is studied as a linear stability problem. We consider the Boussinesq fluid contained in rotating spherical shells, of which radius ratio in the shell is 0.2. The linearized governing equations, that is, the momentum equation and the transport equation of composition, are solved as an eigenvalue problem at the Ekman number of 10^{-3}. As a result, we find the critical Rayleigh number of 36854, and the critical azimuthal wavenumber of four.

Then, using the eigen-mode velocity field, we solve a kinematic dynamo problem by time-stepping the magnetic induction equation. Stability of the initial dipole magnetic field is investigated. As the control parameter is the magnetic Reynolds number in the kinematic dynamo problem, we search for the critical value, at which growth rate of the initial dipole field is zero. Then, we examine spatial structure of the fastest-growing mode, its amplification process, and sustenance mechanisms of the dipole, i.e. the Bullard process.

数値ダイナモモデルにおけるジャーク様磁場変動検出の試み： 第二報

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Preliminary study of detecting jerk-like magnetic secular variation in a numerical dynamo model (II)

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The geomagnetic field, which is generated by the geodynamo, varies in a wide range of time scale. Focusing on short time scale variation, it is well known that a sudden and abrupt change in the first time derivative of the magnetic field (a V-shape-like change) occurs in typically one-year time scale. This abrupt change is called the geomagnetic jerk. Although we don't fully understand the mechanism of the geomagnetic jerk, it is said that the geomagnetic jerk is an internal origin in a broad sense. In this study, we examine magnetic field variation using a result of numerical dynamo simulation in order to see whether or not any jerk-like variation could be observed in the numerical model. The adopted values of the Ekman number in the model is $3x10^{-5}$. We investigate the magnetic field at the core-mantle boundary and the surface truncated at spherical harmonic degree 12 according to geomagnetic observations. In the previous report at the JpGU Meeting 2017, we showed a difficulty to calculate the first and, especially, second time derivatives with finite differencing due to rounding error. In order to resolve the problem, we have examined time-series of all the modes of Gauss coefficients, that is, 168 modes. It is found that the low-degree modes such as dipole and quadrupole, which slowly vary with respect to time, are most seriously contaminated by the effect of rounding. On the other hand, many of higher-degree modes, which shows more rapid temporal change, are less contaminated. Based on the analysis, we tried some other methods. Among them, smoothing time-series of Gauss coefficients turns out to be a useful method. We calculate time derivatives of Gauss coefficients as in the following way: (1) the first time derivative is calculated by finite differencing, (2) smoothing curve of the first time derivative is calculated, (3) the second time derivative is evaluated from the smoothed curve. Using the time derivatives obtained by the procedure, we investigate global secular variation and secular acceleration to search for any jerk-like rapid magnetic field change. We will report details of the analysis methods and results of the investigation.

地球磁場は地球ダイナモ作用によって生成・維持されている．その地球磁場の変動のうち，1年以上の周期の変動を地磁気永年変化といい，地球磁場の1階時間微分として表現される．地磁気永年変化が数年間程度の時間スケールにおいて，時折，急激な変動 (V字型の変動) を示すことがあり，この現象は地磁気ジャークとして知られている．地磁気ジャークの発生メカニズムについてはいまだに解明されていない点が多く存在するが，地球ダイナモに成因があると考えられている．本研究において，我々は数値ダイナモモデルで地磁気ジャークに類する磁場変動が再現されているか否かの検証を行った．ダイナモモデルに用いたエクマン数は $3x10^{-5}$ である．解析にはコア－マントル境界と地表での磁場三成分を用いた．その際，球面調和関数展開で12次までの係数を採用した．JpGU Meeting 2017では，中心差分を用いて1階時間微分と2階時間微分の計算を行ったが，丸め誤差の影響で，特に2階時間微分では，適切に計算をすることは困難であることがわかった．我々はこの問題を改善するために，ガウス係数の全てのモードの時系列について調査を行った．調査の結果，高次のモードより双極子や四重極子のような低次のモードの方が，緩やかな時間変化をすることがわかった．しかし，逆に，低次のモードの方が丸め誤差によるノイズが見られた．この解析に基づいて，我々はいくつかの方法を試みたところ，ガウス係数の時系列を平滑化することが有用な方法であることがわかった．我々以下の手順に沿って，ガウス係数の時間微分を行った．(1)差分法で磁場の1階時間微分を計算する．(2)磁場の1階時間微分を平滑化する．(3)平滑化した磁場の1階時間微分を用いて2階時間微分を計算する．我々は平滑化を行ったガウス係数を用いて，地磁気ジャークに類する磁場変動を調査した．本発表ではこの調査の詳細な解析方法と解析結果について報告する．