福岡県上本町遺跡の考古地磁気学 ―古墳時代以前の古地磁気方位に関する一考察―

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Archaeomagnetism in Kamihonmachi relic, Fukuoka -A study of the paleodirection before Kofun era-

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A total of 682 data is housed in “Japan Archaeomagnetism Database“ which compiled the most of products in Japanese archaeological research until the present. The number of data is so substantial in the world. However, it also has a problem that the number of the data every age is not constant, and 86% of the data is in the period between 5th to 14th century, because the most of the dataset is from the data obtained from Suemura relics complex in Osaka and ancient kilns of middle age in the Tokai area.

We carried out archaeomagnetic sampling in Kamihonmachi relic in Tagawa city, Fukuoka to understand the trend of paleodirection in ancient period when the data is insufficient. A lot of archaeological structure, between Yayoi era to Asuka era, have been excavated in the relics until the present. In this study, we sampled some baked-earth blocks from the burnt part of 3 remains named S-240, S-307, and S-374.

After cutting out the baked-earth sample into a 1.5 cm cubic specimen from, we carried out the rock magnetic experiments and the stepwise thermal demagnetization to evaluate the sample quality and the burning condition. In the result, it was estimated from the rock magnetism that S-374 was burnt under the highest temperature, S-307 was burnt under the middle temperature, and S-240 was burnt under the lowest temperature, respectively. And then, it was confirmed from stepwise ThD that the characteristic remanent magnetization of some samples are stable, although the intensities are relatively weak.

Then, we carried out stepwise AF demagnetization to restore the paleodirection of each remain. In the result, we obtained each direction as follows; D = -1.1^o, I = 33.6^o, a95 = 1.8^o from S-307 (n = 20), and D = -11.7^o, I = 45.5^o, a95 = 1.5^o from S-374 (n = 10). However, we did not restore the significant direction from S-240. The archaeological age of S-307‘s is undefined and that of S-374‘s is estimated to be early 6th century, respectively. Here we focus on the direction of S-307 which has a significant characteristic that the inclination is very shallow. The period that that has an inclination value shallower than 40^o is limited to be between 1550 A.D. and 1750 A.D. The S-307‘s typology suggests that this remain is not a modern structure. Therefore, if it assume that S-307 is a remain in the Yayoi era as same with some neighboring relics, it restores a paleodirectional trend that the inclination became deep approximately 10^o between Yayoi era and early 6th century.

In addition, we will start the further discussion about excavated artifacts, and carry out the new archaeological sampling in the relic soon.

これまでの日本における考古地磁気学研究の成果を集成した「日本考古地磁気データベース」には、現在までに合計で 682 個のデータが登録されている。このデータ数は、世界的に見ても非常に充実したものではあるものの、全データの約 86%が 5～14 世紀の年代区間に属するものであり、各年代を網羅するデータ数にむらがあるといった問題も同時に抱えている。これは、データセットの大半が大阪府の陶邑遺跡群と東海地方の中世窯から得られたデータによって構成されているからである。

そこで我々は、データが不足している年代区間のうち、特に古い時代の古地磁気方位変化についての理解を深めることを目的として、福岡県田川市の上本町遺跡において考古地磁気サンプリングを行った。この上本町遺跡では弥生時代～飛鳥時代にかけての集落遺構がこれまでに多数出土している。本研究ではこのうち遺構 S-240・S-307・S-374 と名付けられた 3ヶ所の遺構の被熱部より焼土試料を採取した。

採取された焼土を 1.5 cm 角のキューブ状試片に加工後、試料の素性や被熱状況について考察するために岩石磁気実験と段階熱消磁を行った。まず岩石磁気実験の結果からは、S-374 の被熱温度が最も高く、次いで S-307、S-240 はこの中では最も低温で焼成されたことが推測された。続いて段階熱消磁の結果からは、強度は比較的弱いものの、安定した固有磁化成分の存在が確認された。

次に遺構ごとの古地磁気方位を復元するために段階交流消磁を行った。その結果、S-240 からは有意な方位は復元できなかったものの、S-307 (n=20) からは偏角=－ 1.1^o、伏角=33.6^o、a95=1.8^o、S-374 (n=10) からは偏角=－ 11.7^o、伏角=45.5^o、a95=1.5^o という方位が得られた。考古学的な 2 遺構の推定年代は、現時点で S-307 が年代未確定、S-374 が 6 世紀前半とされている。ここで S-307 の方位に注目してみると、この方位は伏角が異常に浅いという顕著な特徴を持っていることがわかる。上本町遺跡の座標で描画した日本の標準曲線 (畠山ほか) 上で伏角値が 40^o よりも浅くなる時代は 1550～1750 年の約 200 年間に限られる。しかしながらこの遺構の型式は、この年代のような最近のものではない。ここで、仮に S-307 が周囲のいくつかの遺構と同様の弥生時代頃のものだとするならば、この値から S-374 の値に向かって 500 年ほどかけて伏角が 10^o ほど深くなったという地磁気の挙動が復元される。

本遺跡に関しては、これから出土遺物の詳細な検討が本格的に始まるとともに、弥生前期末ころと比定される遺構における考古地磁気サンプリングも予定されているため、今後は随時これらの新知見を反映させながら、さらに議論を進めていきたい。

琵琶湖堆積物による地磁気永年変化復元の試み：cmスケールからmmスケールに向けて

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Reconstruction of paleosecular variation from Lake Biwa sediments: Improvements in resolution from cm to mm scale

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We have conducted measurements on a piston core sample 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. Preliminary results of inclination from the cube samples show an agreement with the paleosecular variation reported by Ali et al. (1999). Results of u-channel and LL-channel with deconvolution will be shown together with a possible trial using SQUID microscope.

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復元を行いつつある。本報告では、その予察的結果について紹介する。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。全体的に本研究の伏角の特徴的極大値・極小値はAli et al. (1999)と比較して数千年年代値が古く出ているようである。さらに、u-channel試料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段階交流消磁による自然残留磁化のパススルー測定を進めている。これらの結果についてデコンボルーションを行い、古地磁気キューブによる測定結果との比較、センサー感度曲線の異なる2種類の磁力計の比較などを行う予定である。また、LL-channel試料についても段階交流消磁による自然残留磁化のパススルー測定を進めている。LL-channelについてはSQUID顕微鏡による予備実験結果も紹介の予定である。

深海底堆積物の古地磁気研究からのエクスカーション

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Some excursions from paleomagnetism in deep-sea sediment

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Our paleomagnetic studies using deep-sea sediments, and studies in a number of fields that have been done in connection with them are reported. The first is a area of studies using deep-sea sediment cores taken from the western equatorial Pacific Ocean. Ages of top sediments were estimated by ESR dating. Paleointensity variation was studied and wavelet analysis was performed. It was shown that the saturation isothermal remanent magnetization (SIRM) variations of the cores were caused by calcium carbonate disolution change. The second is a area of studies of environmental change using the sediment taken from ponds and lakes. The environmental magnetic studies were performed for the sediments taken from Lake Nakaumi and Lake Shinnji. The third is the area of the monitoring of heavy metal pollution of the tree in the environmental magnetic method. It was shown that simple inspection of heavy metal contamination of roadside tree may be able to be performed by using SIRM or magnetic initial susceptibility.

ここでは、筆者達が行ってきた、深海底堆積物を用いた古地磁気研究と、それと関連して行ってきた幾つかの分野での研究について紹介させて頂く。

筆者達は、1970年代から100万年スケールの古地磁気変動を明らかにする目的で深海底堆積物を試料として研究を行ってきた。その中で、西部赤道太平洋の水深4000m余りの海底から採取された2本のコア、KH73-4-7とKH73-4-8からは、多くの研究で有意義な結果が得られた。酸素と炭素の同位体比測定は行われたが、酸素について深さに伴う溶解の影響が大きくステージ区分による年代推定は困難であった。磁気層序と微化石による年代推定は可能であったが、コア最上部の年代についての情報は得られなかった。そこで、当時、鍾乳洞など試みられていたESR年代測定法を深海底堆積物に適用し、コア最上部の年代を求めた。また、2つのコアで炭素同位体比と飽和等温残留磁化（SIRM）が正の相関を示すことについて、SIRM変動が炭酸カルシウム溶解度変動によってもたらされたことを示し、氷期間氷期変動と一体をなす海洋大循環の様式の変動に伴って起こる炭酸カルシウム溶解度変動と炭素同位体比変動が、SIRM変動と炭素同位体比変動の相関をもたらしたことを示した。さらに、酸素同位体比によって年代が推定されている同じ地域から採取されたコアのデータを加えた、合わせて3本のコアについて、酸素同位体比変動のデータについて行われていたウェーブレット解析を試み、変動する周期説を提案した。

筆者達は、1990年代後半からは、人為的影響の加わった数百年スケールの中海・宍道湖堆積物について環境磁気的研究を行い、携帯型の採泥器を自作し化学分野の研究者と共にため池堆積物による地域環境変動の研究を行っている。東広島市には100年程度前から堆積物が残っているため池が多く分布している。ここでは、中海の飯梨川旧河口沖で採取されたコアについて、時代と共に三角州が拡大し河口が試料採取地点に近づいていることを示唆する卒論生の環境磁気的研究を紹介する。

筆者は、大学の自然環境科学実験で、環境磁気的方法による松葉を用いた微小粒子状物質汚染調査を試みたが、データ数を増やし分布を詳細に調べることは困難であった。総合科学研究科の、21世紀の特定課題について文理融合で研究を調整できる人材を育成するプログラムに、木質バイオマス普及で採用されたこともあり、街路樹や津波瓦礫などの重金属汚染を磁気的方法でモニタリングする事を考えた。その結果、自動車由来の汚染の場合には、重金属は、鉄あるいは磁性鉱物の量と相関が見られモニタリング可能である事が示された。津波瓦礫では、地域により鉄あるいは磁性鉱物と相関が見られる重金属が異なりその地域の土壌汚染或いは大気汚染の状況を反映していると考えられる。街路樹でも、近くに印刷所がある場所では銅が高濃度で観測されており、安全性は保証できないが、バイオマス利用不適切な物を迅速に特定する用途には有用な事が示された。

以下に主な研究内容を記す。

１．古地磁気強度変動とそのウェーブレット解析
２．深海底堆積物などのESR年代測定
３．氷期間氷期変動に伴う炭酸カルシウム溶解変動
４．南極宗谷海岸沿岸の湖沼堆積物の磁気的性質
５．河川堆積物の磁気的方法による土砂移動の研究
６．中海宍道湖堆積物の環境磁気的研究
７．環境磁気的方法による松葉を用いた微小粒子状物質汚染調査の試み
８．街路樹剪定枝などの磁気的な安全性検査手法の開発

海底堆積物中の生物源マグネタイトの低温酸化

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Low-temperature oxidation of biogenic magnetite in deep-sea sediments

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Magnetites in marine sediments of oxic environments such as surface sediments above the Fe-redox boundary and red clay cores that do not have the Fe-redox boundary usually have suffered low-temperature oxidation. This is evidenced, for example, by a blurred Verwey transition in low-temperature measurements, and explained as that a shell of a magnetite particle is oxidized to maghemite, whereas a core of the particle remains intact. Under a transmission electron microscope (TEM), it is often observed that biogenic magnetites (magnetofossils) in oxic environments are covered with very fine particles of a few nanometers in size. We applied a reductive etchant to a red clay sample, in which biogenic magnetite dominates the magnetic mineral assemblage. The reductive etchant was prepared to be -60 mV in the oxidation/reduction potential (ORP) and 5.7 in pH using ascorbic acid (5%) buffered with $NaHCO_3$. The fine particles covering magnetofossils were mostly dissolved by applying the etchant for 72 hours. We do not think that maghemite was altered by the etchant, because the results of low-temperature measurements (low-temperature cycling of SIRM acquired at 300K and thermal demagnetization of 10K SIRM) before and after applying the etchant were identical with each other and did not show the Verwey transition even after applying etchant, and because SIRM of the sample did not change for 72 hours. The color of the sediments is still reddish after applying the etchant, which also suggests that maghemite still remains. We estimate that the fine particles dissolved by the etchant may be hematite; Fe ions diffused from a magnetite lattice by low-temperature oxidation may have been combined with dissolved oxygen in interstitial water, which resulted in the production of hematite. The effect of the hematite dissolution by the etchant would not appear in the low-temperature measurements because the hematite particles are superparamagnetic in size, their total volume is smaller than that of magnetite-maghemite, and the saturation magnetization of hematite is much smaller than that of magnetite-maghemite. The low-temperature oxidation occurs in a geologically short period of time; magnetofossils with hematite cover are observed commonly under a TEM even in sediments at the sediment-water interface (the top of a pilot core).

Near-seafloor magnetics reveal hydrothermal alteration and strongly magnetized lava flow at the Irabu knolls, Okinawa Trough

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Magnetic mapping is of increasing interest in studies of seafloor hydrothermal systems because such data can promote the understanding of the location and spatial extent of hydrothermal alteration zones. Previous studies reported both reduced and enhanced magnetization at hydrothermal fields of different tectonic settings, suggesting that the destruction and production of magnetic minerals are controlled by geological and tectonic background. In order to characterize magnetic response of arc-backarc hydrothermal systems, we investigated the Irabu hydrothermal field (IHF) at the southern Okinawa Trough. The Irabu knolls are located on the axial area of backarc rift and consist of basalt to andesite. Near-seafloor vector magnetic measurements were performed using the AUV URASHIMA during the R/V Yokosuka cruise YK14-16. The seafloor rock samples from the same region were used for rock magnetic measurements and petrological observations. The integrated analysis of the magnetic anomaly and rock magnetic properties led to the following conclusions:

(i) The IHFs are associated with reduced magnetization reflecting the hydrothermal alteration of magnetic minerals present in the extrusive lavas and the deposits of non-magnetic hydrothermal material.

(ii) The basaltic lavas show high natural remanent magnetization (NRM) intensity ranging from 7 A/m to 214 A/m. These extremely strong NRM were caused by less oxidation, abundant single-domain-titanomagnetite grains formed under proper crystal growth rates, and low Ti content for titanomagnetites. These strongly magnetized host rocks produce large variations of magnetic anomalies in the Irabu knoll, resulting in a clear magnetic contrast between the IHFs and their surroundings areas.

(iii) The low magnetization zones (LMZs) related to the IHFs are located at the rim of the caldera floor in an elongated direction parallel to the local strike of the caldera, and extend into the caldera wall. These observations suggest that the hydrothermal fluids ascended through the caldera fault and caused accumulation of hydrothermal deposits and the occurrence of hydrothermally altered zones in both the caldera floor rim and wall.

(iv) The LMZ extends across several hundred meters along the caldera rim. Compared with similar hydrothermal fields of the Hakurei and Brothers situated in other arc-backarc volcanoes with summit calderas, it is clarified that hydrothermal systems controlled by caldera faults have horizontal spatial scale equal to or larger than those of detachment-controlled large hydrothermal fields at slow-spreading ridges such as the TAG. It is implied that the permeability structure and style of hydrothermal circulation may play important roles in the formation of the larger demagnetized hydrothermal fluid pathways at caldera-controlled systems.

Changes in source of lithogenic particles in the Ryukyu forearc region revealed from rock-magnetic properties

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Knowledge of source of sediment particles is key to understand the evolution of sedimentary environment and ocean circulation. Rock-magnetic parameters can be used as a sensitive proxy of source of sediment particles, especially lithogenic particles. In this study we conducted systematic rock-magnetic measurements of sediment sample in the Ryukyu forearc region, to reveal the changes in sedimentary environment and ocean circulation in the region.

Sediment core GH08-2004 was collected at the Ryukyu forearc region using a gravity corer during the GH08 cruise of R/V Hakurei Maru No.2. The sedimentation rate of the core was 3.2-15.6 cm/kyr and the age of the core bottom was estimated as approximately 26 ka (Amano and Itaki, 2016). Dried samples were used in a suite of rock-magnetic measurements. Using MicroMag 2900 alternating gradient magnetometer (AGM, Princeton Measurements Corporation), we conducted measurements of magnetic hysteresis parameters (coercivity B_c, saturation magnetization M_s, saturation remanent magnetization M_{rs}, and coercivity of remanence B_{cr}), isothermal remanence (IRM) acquisition curves, and first-order reversal curves (FORCs). We also measured low-temperature remanence curves using an MPMS-XL magnetic property measurement system (MPMS, Quantum Design): a thermal demagnetization curve during zero-field warming (ZFW) from 10 K to 300K for IRM imparted at 10 K in a field of 2.5 T after zero-field cooling from 300 K (ZFC remanence); a thermal demagnetization curve during ZFW from 10 K to 300K for remanence given by field cooling from 300 K to 10 K in a field of 2.5 T (FC remanence); and a low-temperature demagnetization curve for saturation IRM imparted at 300 K in a field of 2.5 T.

The ratio $J_{ZFC}(10)/J_{FC}(10)$ is lower than 1.4 from 26 ka to 14 ka while it increases to 1.6-2.0 after 13 ka, where $J_{ZFC}(10)$ and $J_{FC}(10)$ are intensities of ZFC remanence and FC remanence at 10 K, respectively. The samples during 26 to 14 ka show the Verwey transition of Ti-poor titanomagnetite in the low-temperature measurements, whereas the transition is unclear for the sample during 13 to 0 ka. The ratio M_{rs}/M_s slightly varies in 0.13-0.19 during 26 to 14 ka, and it gradually increases from 0.14 to 0.24 after 13 ka. These results suggest that source of lithogenic particles during 26 to 14 ka and 13 to 0 ka were different for each other, and it gradually changed from 13 to 0 ka. Taking into account the results of IRM acquisition curves and FORCs, we will discuss the changes in sedimentary environment and ocean circulation in the Ryukyu forearc region.

Preservation states monitoring of the 2011 Tohoku tsunami sediments, as determined by geochemical and rock magnetic analyses

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Near-shore marine sediments deposited along island arcs preserve evidence of past disaster events such as tsunamis. A tsunami occurred on 11 March 2011 off the Pacific coast of Tohoku, Japan, and the event is likely preserved in marine sediments. This study aims to constrain the distribution of tsunami deposits and its preservation states at Sendai Bay, located in the Tohoku area, by geochemical and rock magnetic analyses. Sediment samples from Sendai Bay were collected at four stations, located east of the epicenter of the 2011 Tohoku earthquake, between 2011 and 2015. The intensities of IRM unblocked at 500-700^{o}C in soft component is greater in the 2011 samples from offshore stations S-4 and S-5, suggesting the presence of material with a higher Curie point. However the increase of soft component intensity is not found in the 2013-2015 samples. Magnetic grain size parameters, Mr/Ms and Hcr/Hc, show a similar pattern in 2011-2012 samples, while the trend is not recognized in 2013-2015 samples. Cr content increased in the sediment samples just after the 2011 Tohoku tsunami, but it decrease in the 2013-2015 samples. It is suggested that sediments from the inner bay and/or coastal area were transported and redeposited by the 2011 Tohoku tsunami, and removed after 2013.

自然試料における短時間の磁気緩和の測定と岩石磁気への応用

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Measurement of slow magnetic relaxation in natural samples and its application to rock magnetism

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Dynamic magnetizations in natural rocks and sediments were measured as either exponential decay of magnetization in time domain or Debye-type magnetic relaxation of ac susceptibility in frequency domain. Both phenomena are physically identical, but their measurements require different instrumentation. This study provides results from various kinds of natural samples with different domain structures including SP, PSD, SD, and MD. Measurements were performed in frequency domain, and low-field magnetic susceptibility was measured over a number of frequencies ranging from 1 Hz to 1 kHz. Magnetic relaxations were found only from the PSD and MD samples. Each of them demonstrates Arrhenius-like straight line, but their gradient is greater for PSD than for MD. This suggests that these relaxations could be due to the oscillations of domain walls in local pinning sites, but the corresponding local energy barriers may be greater for PSD than for MD. Comparisons and interpretations of the data from samples of different domain state and grain size were made, and their application as a potential diagnostic tool for rock magnetism will be discussed.

PSD〜MD の火山岩や SP の卓越する古土壌は、短時間（$<10^{-4}$ s）の磁気緩和を示す (Kodama 2013; Kodama et al. 2014)。それらは時間領域と周波数領域で測定できるが、個々の磁性や目的に応じて使い分ける必要がある。パルス磁場を利用した時間領域測定 (Kodama 2015) は短時間で行える利点があるが、感度に限界があり弱磁化試料への適用は困難である。これに対し、SQUID 磁化率計（MPMS）を用いる周波数領域測定はほとんどの試料に適用できる。ただし、低周波数帯域（1 Hz - 10^3 Hz）に限定されるので低温測定が必要になる。本発表では、MPMS による周波数領域測定の結果と解釈、さらにそれらの岩石磁気学への応用を議論する。

SP から SD の磁区構造を代表する、火山岩（SD、PSD）・花崗岩（MD）・レス（SP）を測定した結果、1 Hz - 10^3 Hz で磁気緩和を示したのは PSD 火山岩と MD 花崗岩のみであった。それらはすべて Arrhenius 型の回帰直線を示すが、その勾配から推測される活性化エネルギー（＝異方性エネルギー）は、MD 試料が PSD 試料の数分の一である。これに応じて、Debye decomposition 法 (Ustra et al. 2016) で得られた緩和時間分布の中心値は MD 試料が最も短い。これは、緩やかに pinning された磁壁が交流磁場に同期して振動するためであろう。ただし、弱磁場（1 Oe）のため、Barkhausen jump のような磁化のとびは見られない。一方、SP や SD 試料が磁気緩和を示さない理由は、それらの緩和時間分布の上限や下限が PSD 試料より短い（SP）、あるいは長い（SD）ためであると考えられる。こうした推測は、パルス磁場を利用した緩和時間の直接測定結果 (Kodama 2015) と調和的である。これら各種測定法や数値解析を適宜用いることによって、これまで曖昧だった MD/SP/PSD/SD 各領域の境界に関する定量的な議論が可能となろう。

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消磁によるレスの磁気構造の変化

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Mapping of loess magnetic fabric changes by demagnetization experiments

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The behavior of the magnetic fabric of loess and paleosol pilot samples, originated from Hungarian succession, were studied by anisotropy of magnetic susceptibility (AMS) measurements during stepwise alternating field demagnetization (AFD) and isothermal remanent magnetization (IRM) experiments. The same samples were measured 10 times in every demagnetization step. The magnetic experiments were completed by scanning electron microscope (SEM) investigation.

The changing of the magnetic susceptibility (k), the replacement of the maximum (kmax) and intermediate susceptibilities (kint) and 45-120 deg. change in the orientation of the kmax were observed. The change of some AMS parameter, such as the shape of the magnetic susceptibility ellipsoid (T) was also notified. Besides the change of the T, no characteristic change of the degree of AMS (P) were observed.

In materials with low magnetic susceptibility, such as loess, the appearance of paramagnetic phyllosilicates (e.g. muscovite, chlorite) can be responsible for the possible replacement of the kmax and kint, which is possibly controlled by the crystallographic anisotropy of the phyllosilicates.

The flipping and the instability of the fabric orientation and also the change of the k possibly indicate the transformation of the domain structure of various magnetic components. This change is possibly indicated by the change of T also.

The behavior of the loess magnetic fabric, suggested above, draws attention to the difficulties of the magnetic fabric analysis. More care must be taken during the determination of the paleowind direction by the orientation of the kmax in the future studies of loess, when 45-120 deg. differences of the paleowind direction, triggered by crystallographic anisotropy and the change of the domain structure, could indicate absolutely different paleoenvironmental condition.

Effects of stably stratified region below the core-mantle boundary on the long-term core-mantle evolution

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Here we show an impact of stably stratified region below the core-mantle boundary (CMB) caused by the core-mantle thermo-chemical coupling in long-term core-mantle evolution model in numerical mantle convection simulations. To implement the core-mantle thermo-chemical coupling into the model, we assume chemical and baro-diffusion effects caused by an equilibrium chemical reaction of metal-silicate as a boundary condition of thermo-chemical structure of Earth's core based on Frost et al. [2010]. In addition, we also include the growth of sub-adiabatic shell if the CMB heat flow is below the isentropic heat flow. Using this model, important findings are shown as follows: 1. The initial CMB temperature would be 4800 to 4900 K rather than 6000 K derived from thermal evolution model without a stably stratified region. 2. Thickness of thermo-chemically stratified region would be strongly dependent of chemical diffusivity and 140 km with 10^{-8} mˆ2/s of chemical diffusivity, which would be consistent with propagation of MAC wave caused by geomagnetic secular variation for the thickness [Buffett, 2014] and theoretical computation of chemical diffusivity [Ichikawa and Tsuchiya, 2015], 3. The CMB temperature would be rapidly cooled down in first 100 Myrs and not changed after such a rapid cooling, which would be around 4000 to 4200 K. On the CMB heat flow, it would not be greatly changed with time neither, which is around 12 TW being consistent with recent theoretical formulation of core evolution [Labrosse, 2015]. Those evolution diagnostics would be consistent with a recent hypothesis on core evolution from melting temperature measurement in the deep mantle [Andrault et al., 2016]. This suggests that a stably stratified region caused by thermal and chemical effects would be the strongest heat buffer in various mechanisms on heat buffer for heat transfer across the CMB (partially molten region and compositional anomalies above the CMB). 4. The most important physical property for understanding core evolution is the thermal conductivity of Earth's core. For the best-fit scenario of core evolution with a stably stratified region, the thermal conductivity of core would be higher than 150 W/m/K, which is consistent with recent inferences from the electrical resistivity of core material on high P-T physics [e.g. Ohta et al., 2016].

Dynamic effects of the geomagnetic field on the modeling of core surface flow

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Fluid motions in the Earth's core give rise to secular variations of the geomagnetic field. Such core flows can be estimated from spatial and temporal distributions of the geomagnetic field. When one relies on the frozen-flux approximation to estimate a core surface flow, the magnetic diffusion term in the induction equation is neglected. However, in reality, there exists a viscous boundary layer at the core-mantle boundary (CMB), where the magnetic diffusion can play an important role in secular variations of geomagnetic field. Hence, Matsushima (2015) has devised a new approach to the modeling of core surface flow; the magnetic diffusion is explicitly incorporated within the viscous boundary layer, whereas it is neglected below the boundary layer at the CMB. It should be noted that the tangentially geostrophic constraint is also used for the flow below the boundary layer. That is, the dynamic effects of geomagnetic field on the modeling of core surface flow have not been taken into account so far. Here, the tangentially geostrophic constraint is relaxed, and the tangentially magnetostrophic constraint is used, as carried out by Asari and Lesur (2011).

Web を利用した古地磁気・岩石磁気データプロットツール

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Online plot services for paleomagnetism and rock magnetism

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In paleomagnetic and rock magnetic studies, we use a lot of types of graphics by which obtained data from the measurements are analyzed and plotted.

Many researchers in paleomagnetism often use not only general-purpose plotting programs such as Microsoft Excel but also single-purpose programs.

The maximum benefit of the latter is that we can make a beautiful figure for our own data. However, those programs require limited environment for their operation such as type of platform and hardware, type of operation system and its version, and so on. It is difficult to share the result and graphics among the collaborators who use different environments on their PCs.

Therefore, the best solution is likely a program operated on the most popular environment, web browsers.

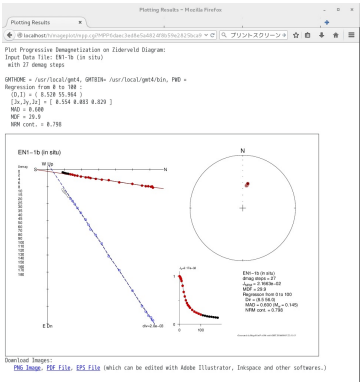
Now we develop a web service which was originally a program with a command-line user interface (non-GUI), and we prepared web pages for input of the data and options and a wrapper script which transfers the entered values to the program. The results, analyzed values and plotted graphs from the program are shown in the HTML page and downloadable.

In this talk, we introduce our program and service and discuss the philosophy and efficiency of these services.

地球科学ではそれぞれの研究分野や対象でさまざまな表現方法がある。その中にはエクセルのような汎用グラフソフトでは表現しづらいものや、途中に解析を伴うルーチンになっているものがあるため、専用の解析・プロットソフトを使用する場合も多い。古地磁気学・岩石磁気学でも様々な種類のデータプロットがあり、いわゆるザイダーベルトダイアグラム (消磁曲線) のように、汎用グラフソフトでは表示や軸の調整を個々のデータごとにしなくてはならないため作業が煩雑になりがちなものが多い。各研究者は (1) エクセルなどのソフトを手作業で使用する, (2) 自分で専用のプログラム (エクセルマクロを含む) を作成して使う, (3) 誰かが作ったプログラムを使う, のいずれかの対応をしているようである。(3) の場合、利用しているプラットフォームや所持するライブラリ・環境によって利用できるプログラムが異なり、共同研究者間で共有が難しいことがある。

今回、「どのプラットフォームでも簡単に使える」ことを主眼とした結果、ユーザーインターフェイス (入出力) を Web ブラウザに押し付けるのが最適であると考えた。つまり、プログラムに Web 入出力用のラッパー (HTML/PHP + CGI) を追加する事によって、手元の環境で動いている解析・プロットプログラムを Web サービス化することで、複数の研究者間でもプロットできる、取ったばかりのデータを気軽にプロットできる、環境を作成した。この考え方は決して新しいものではなく、多くの業界のサービスで実際に利用されているものであるが、今回は身近な分野にも利用できる (自前の既存スクリプト・プログラムにごく簡単なラッパー部分を足すだけで効果的な Web アプリが作成できる) ことを示すために行った。

本講演では、実際の Web サービスの紹介とともに、各プログラム部分の設計と効果等について議論したい。



砕屑岩脈の注入方向を磁気測定から探る：中新世小佐岩脈の例

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Injection direction of a clastic dike inferred from magnetic measurements: an example from the Osa dike

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

The Osa dike is a 50-70 cm thick sandstone dike intruding early Miocene sediments (Morozaki Group) on the Chita Peninsula, central Japan. An earlier investigation suggested that the dike formed by upward sand injection. A later study, however, found microfossils from the dike, whose age could be younger than the country rock, implying downward injection. Our study presented here was performed to solve the problem by means of magnetic measurements. Thermomagnetic results indicate magnetite is the main magnetic mineral. Hysteresis data fall into the pseudo-single-domain range. Analyses of alternating field and thermal stepwise demagnetization results revealed a north-northeasterly paleodeclination of normal polarity characteristic remanent magnetization. The age of this paleodirection of the Osa dike is possibly younger than that of the easterly paleodirection of the Morozaki Group that represents early to middle Miocene clockwise rotation of southwestern Japan. More importantly, anisotropy of magnetic susceptibility (AMS) measurements suggest imbrication of magnetic foliations that is consistent with downward flow within the dike. Therefore, downward injection is supported by both the paleomagnetic direction and the AMS result. We suggest that magnetic measurements can be a useful tool for determining the injection direction of clastic dikes.

陸上玄武岩の磁化率の磁場強度依存性

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Field-dependence of magnetic susceptibility for subaerial basalts

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Magnetic mineralogy of subaerial basalts are usually variable from sample to sample even in a single outcrop depending on oxidation state and microstructure of Fe-Ti oxides contained in the basalts. Retrieving paleointensity from subaerial basalts has been attempted for past several decades, and magnetic mineralogy is of prime importance for interpreting paleointensity experiments. Curie point (Tc) of bulk basalt specimen can tell us the composition of contained Fe-Ti oxides, but often we encounter multiple Tc from a single specimen.

Field-dependence of magnetic susceptibility has been known to be related to Ti-content of Fe-Ti oxides. Almost no field dependence is observed for Ti-free magnetite, whereas high-Ti titanomagnetite (e.g., ulvospinel content x = 0.6) exhibits several tens of percents field dependence for one order of field magnitude. Previous studies on drill cores of basalts showed a strong correlation of Tc and field-dependence of susceptibility. In this study we measured the field-dependence of magnetic susceptibility using a ZH susceptibility meter that can vary the field amplitude stepwise at 10, 20, 40, 80, 160 and 320 A/m (c.f., 80 A/m is almost equivalent to 0.1 mT).

For about four hundreds of subaerial basalt specimens from Izu-Oshima and Miyakejima islands, we observed linear dependence of susceptibility against field amplitude. This means the Rayleigh law still holds for the field amplitude range, and we can calculate initial susceptibility Xi and Rayleigh coefficient b. Here we will give the field-dependence susceptibility by the ratio of b/Xi instead of the previously employed empirical ratios like XHd(%). After selecting specimens with single Tc we plotted b/Xi and the single Tc, and found the value of b/Xi is about 1e-3 m/A for specimen with Tc less than 450 degC and rapidly decrease down to 1e-5 m/A with increasing Tc. We can assume that b/Xi represents the averaged Ti content of titanomagnetites in a bulk specimen containing titanomagnetites with different composition.

Interior part of lava flows showed low (below 0.2) Mr/Ms and b/Xi values larger than 1e-4 m/A. This results is interpreted that Fe-Ti oxide phenocrysts remain homogeneous and lava interior is generally not suitable for paleointensity studies. Some of the clinker samples have lower b/Xi and higher Mr/Ms, indicating that low-Ti and fine-grained titanomagnetite is contained in clinkers. Scoria samples have relatively Ti-poor titanomagnetites and showed scattered Mr/Ms.

For analyzing magnetic mineralogy, temperature dependence of strong-field magnetization or susceptibility is traditionally measured in order to obtain Tc. However, Tc is sometimes difficult to be determined and often multiple Tc are obtained from a single specimen. Measurement of susceptibilities at several steps of different field amplitudes can be performed at room temperature within a relatively short time (~10 minutes per specimen). Field-dependence of susceptibility is useful for detecting dominant Fe-Ti oxides contained in basalt samples and should be routinely applied for selecting samples of paleointensity studies.

陸上玄武岩の磁性鉱物は，含まれている Fe-Ti 酸化物の酸化状態と微細構造に応じて，単一の露頭でも試料によって異なることがしばしば起こります．陸上玄武岩から古地磁気強度を得る試みは過去数十年間行われてきましたが，磁性鉱物は古地磁気強度実験を解釈するための最も重要です．玄武岩試料のキュリー点（Tc）により含まれる Fe-Ti 酸化物の組成を知ることができますが，しばしば単一の試料から複数の Tc が得られます．

磁化率の磁場強度依存性は，Fe-Ti 酸化物のチタン含有量に依ることが知られています．マグネタイトでは磁場強度依存性がほとんどゼロであるのに対して，チタン磁鉄鉱（例えば，ulvospinel 比 x = 0.6）では磁場強度を 1 桁変えると数十%磁化率が変化します．以前の研究により，玄武岩のボーリングコアについて強い Tc と磁化率の磁場強度依存性の間の相関が得られています．今回は ZH 磁化率計を用いて，10，20，40，80，160 及び 320 A/m の磁場の振幅で磁化率の磁場強度依存性を測定しました (80 A/m はほぼ 0.1 mT に相当)．

伊豆大島と三宅島から得た約 400 個の陸上玄武岩試料について，磁化率が磁場強度に線形に依存することを確認しました．レイリーの法則はこの磁場の振幅の範囲では成立し，初磁化率 Xi およびレイリー係数 b を計算することができます．XHD（%）などの以前に経験的に使われた値に代えて，b / Xi 比によって磁場強度依存性を与えます．単一の Tc をもつ試料を選択して Tc と b / Xi 比をプロットし，450 ℃未満の Tc をもつ試料では b / Xi 比は 1E-3 m/A であり，Tc の増加に応じて急速に b / Xi 比が 1E-5 m/A まで減少することを確認しました． b / Xi 比はバルク試料中のチタン磁鉄鉱の平均的な Ti 含有量を表していると考えることができます．

溶岩流内部の試料は，低い Mr / Ms 比 (<0.2)， b / Xi 比は 1E-4 m/A よりも大きい値を示します． このことは溶岩流内部では Fe-Ti 酸化物斑晶が均質のままであり，一般的に古地磁気強度の研究に適していないことを示しています．クリンカー試料の一部は，低い Ti 含有量をもつ細粒のチタン磁鉄鉱が含まれていることを示す低い b / Xi 比および高い Mr / Ms 比をもっています．スコリア試料は比較的チタンに乏しいチタン磁鉄鉱をもっており，散乱した Mr / Ms 比を示しました．

磁性鉱物を分析するためには，強磁場磁化または磁化率の温度依存性を測定し，Tc を得るのが通常です．しかし，Tc を決めることはしばしば困難であり，多くの場合複数の Tc が単一の試料から得られます．磁場振幅のいくつかのステップにおける磁化率の測定は，室温で比較的短い時間（1 試料当たり約 10 分）で行うことができます．磁化率の磁場強度

依存性は玄武岩試料中に含まれる支配的な Fe-Ti 酸化物を検出するのに有用であり，古地磁気強度測定のための試料を選択するために適用できます.

水蒸気噴火の噴出物の磁気岩石学的特徴

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Magnetic petrological characterization of eruptive products from phreatic eruptions

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The 2014 eruption at Ontake volcano reminded us that a phreatic eruption can cause a devastating consequence even though its volume is quite small and there was no newly produced juvenile materials during the eruption. In order to clarify eruption processes and transport and emplacement mechanisms of the 2014 eruptive products from Ontake, we have carried out magnetic petrological analysis. Our results indicated that magnetic minerals in the 2014 eruptive materials are characterized by abundant pyrite and small amount of titanomagnetites, suggesting the materials were derived from a shallow hydrothermal reservoir. Thermomagnetic curves showed rapid increase of the induced magnetization above 380 degrees C, derived from decomposition of pyrite to magnetite. Using this magnetic petrological character, spatio-temporal re-distribution of the 2014 eruptive materials has been revealed.

Phreatic eruption of stratovolcano can occur when heated groundwater stored in a shallow hydrothermal reservoir within the volcanic edifice becomes pressurized and flashes to steam. Pyrite is a common mineral produced during hydrothermal alteration of Fe-bearing minerals. Therefore, pyrite can be used as a marker of a phreatic eruption. In order to examine the general presence of pyrite in materials derived from phreatic eruption, volcanic products from Yakedake volcano were investigated by using magnetic petrological methods and the results were compared with those from Ontake volcano. As a result, Yakedake samples did not show obvious evidence of pyrite. Dominant magnetic minerals were estimated to be titanomagnetites. It is suggested that physical and chemical condition or duration time of hydrothermal system differ between the two volcanoes.

Inverse geodynamo modeling to construct geomagnetic field models and dynamo scaling-laws

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Inverse geodynamo modeling has been employed for the modeling of the geomagnetic secular variation and the results were used to obtain candidate models for recent International Geomagnetic Reference Field (IGRF). There were no contributions on the determination of IGRF from Japan so far but we are planning to contribute on it in the future by presenting geomagnetic field models based on data assimilation.

It is well-known that the numerical dynamo modeling has been performed using parameter values far from those of Earth and planetary dynamos due to limitations of numerical computations. Validity of applying the numerical results on the studies of Earth and planets has been shown in several ways. For example, Christensen (2010) demonstrated that the scaling-law on the magnetic field strength obtained by numerical dynamo models by assuming the balance between the power supplied by the buoyancy flux and that dissipated by the Joule heat could predict the magnetic field strength of the planets rather well. Also, Christensen et al. (2010) showed a parameter regime in which the characteristics of spatial distribution of the geomagnetic field could be reproduced by numerical dynamos. Although the success of the scaling-laws, it is not clear whether the parameters assumed to deduce the scaling-laws, such as the length-scale of the magnetic field in the dynamo, are appropriate to discuss the planetary dynamos using numerical dynamos, i.e., whether they are common to both dynamos. In this presentation, we are going to examine the assumptions for the dynamo scaling-laws to clarify whether they are appropriate to discuss the geodynamo. Also, time-scales of the magnetic field variation in the numerical dynamo and geomagnetic field are discussed to clarify the conditions for the use of the information obtained by numerical dynamo models on geomagnetic field modeling.

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Magnetic field morphology affected by a stably stratified layer below the core mantle boundary

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A stably stratified layer below the core-mantle boundary (CMB) has been detected by seismic and geomagnetic field observations. Chemically or thermally stable stratification is suggested as its origin (Helffrich and Kaneshima, 2010; Buffett and Seagle, 2010; Pozzo et al. 2012; Ohta et al. 2016).

In the core, the geomagnetic field is maintained by thermally and chemically driven flows via dynamo action. Assuming the eddy diffusion in the core, the co-density has been used in dynamo modeling. However, the origin of stable stratification cannot be distinguished with the co-density approach. Hence, thermal and compositional convection must be treated separately. In this study effects of a stable layer of either origin below the CMB are examined, adopting thermochemical double diffusive convection. One of the remarkable results is the effect of a stably stratified layer on the morphology of the dynamo-generated magnetic field, that is discussed in this presentation.

走査型SQUID顕微鏡を用いた鉄マンガンクラストの測定: 微細磁気層序による成長モデルの検討

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Measurement of ferromanganese crust using a scanning SQUID microscope: Growth model by sub-millimeter scale magnetostratigraphy

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Ferromanganese crusts are chemical sedimentary rock composed mainly of iron-manganese oxide. Because the ferromanganese crusts grow very slowly on the sea floor at rate 3-10 mm/Ma, long-term deep-sea environmental changes can be obtained from the ferromanganese crusts. It is important to provide reliable age model and growth rate reconstructed from the ferromanganese crusts, while there are few studies on sub-millimeter scale age dating. To obtain sub-millimeter scale age, we conduct magnetic study on a ferromanganese crust sample using scanning SQUID (superconducting quantum interference device) microscopy (SSM). The ferromanganese crust using this study was sampled from Hanzawa Seamount (25.7098^{o}N 146.7484^{o}E 4362 m). Methods of magnetic measurements were adapted from Oda et al. (2011), which pioneered the investigation that estimate sub-millimeter growth rate using SSM. The vertical component of the magnetic field above a thin section sample of the ferromanganese crust was measured using SSM. As the result, sub-millimeter scale magnetic stripes originating from approximately magnetized regions oriented parallel to lamina were obtained. In addition, we attempted to remove noises retaining resolution of raw measurement data. After analyses, magnetic stripes could be recognized on the magnetic image. By correlating the boundaries of magnetic stripes with known geomagnetic reversals, we estimated that average growth rate of the ferromanganese crust sample from this seamount is 2.76 +/- 0.05 mm/Ma, which is consistent with that deduced from the ^{10}Be/^{9}Be dating method (2.56 +/- 0.04 mm/Ma).

鉄マンガンクラストは鉄・マンガン酸化物を主成分とし、海底の露岩を平板上に被覆する化学堆積物岩である。コバルト、ニッケル、白金、希土類元素などの有用金属元素を含有し、将来の資源として期待されている。また、成長速度が遅く陸起源物質の影響が少ないため、鉄マンガンクラストには長期にわたる海洋環境の記録が残されており、その正確な形成年代を決定することで過去の地球環境変動復元の可能性が指摘されている。

近年、古地磁気層序を用いた年代決定手法が注目されており、Oda et al. (2011) では、高解像度磁気マッピングを可能とする走査型 SQUID 顕微鏡（Scanning SQUID Microscope: SSM）を用いて、北西太平洋に位置する正徳海山より採取された鉄マンガンクラスト薄片試料の磁場垂直成分分布の測定を行い、測定から得られた磁気層序と地磁気極性年代表との対比から成長速度の推定を行った。この研究により SSM による鉄マンガンクラストの成長速度推定の手法が示された。

本研究では産業技術総合研究所と金沢工業大学によって共同開発された SSM（Kawai et al., 2016; Oda et al., submitted）を用いて鉄マンガンクラスト薄片試料の磁気測定結果から成長速度を推定し、成長過程を解明することを目指す。すでに北西太平洋に位置する拓洋第 5 海山から採取された試料に対し SSM による磁気測定、成長速度推定を行っており（野口ほか, JpGU2016 年大会）、今回は無人探査機 Hyper-Dolphin 4500 によって、同じく北西太平洋に位置する半沢海山（北緯 25.7098^{o} 東経 146.7484^{o}; 水深 4362 m）の露頭から直接採取された鉄マンガンクラスト試料の SSM による残留磁化の測定結果および、推定した成長速度ついて報告する。

通常の SQUID 磁力計による同地点試料のクラスト表層 16 mm の薄切り試料（各約 1.0 mm）の古地磁気分析結果から、計 5 回の古地磁気極性反転が確認され、約 2.54 +/- 0.19mm/Ma という成長速度が推定され、同地点試料表層 26 mm から算出された ^{10}Be/^{9}Be 年代値 4 点（2.56 +/- 0.04 mm/Ma）とも整合的であった（Noguchi et al., in press ）。また、10-20 mT の交流消磁によって 2 次磁化成分を分離でき、初生磁化成分を認定できている。そこで、SSM による薄片試料（27 x 21 mm）の測定は段階交流消磁の前および 5, 10, 15, 20 mT での消磁後にそれぞれ行い、各結果について磁気画像を作成した。その結果、15 mT および 20 mT 消磁後の磁気画像において、試料と同サイズの成長縞と平行な磁気パターンを確認した。

得られた磁気光学画像に試料画像を重ね合わせ、マンガンクラストの成長軸に垂直方向の磁気データを平均し取り出したところ、約 20 回の極性反転が確認できた。各境界に対し、大きな成長停止がなかったと仮定し、地磁気極性年代表 (GTS2012) との対比を行い、各境界の年代を算出した。各年代値から推定した成長速度は 2.76 +/- 0.05 mm/Ma となった。SSM を用いた薄片試料の磁気測定により、薄切り試料の磁気測定及びベリリウム同位体測定に比べ 4-5 倍の年代コントロールポイントを得ることができ、高分解能の成長モデルを構築することができた。

粘性残留磁化を用いた野島断層破砕帯の年代測定法:予察

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Preliminary result of Paleomagnetic Viscous Dating of Fault Gouge in the Nojima Fault, Japan

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Dating of an active fault is important task for tracing the history of large earthquakes and creating risk-management policies for future disasters from geological evidence. Generally, we employ a fault-offset method that a sedimentary layer is cut by an active fault, but this method can not apply if there is no overlying sedimentary layer over an active fault and the fault has only the outcrop of fault gouge. Direct age determination methods from fault gouge materials have been proposed such as potassium-argon method to an illite in fault gouge, fission track dating of epidotes in fault gouge, and electron spin resonance (ESR) dating to quartz grains in fault gouge. These methods are very powerful but hard to determine spatial distribution of ancient fault plane. Although scanning ESR microscopy reveal this, ferrimagnetic mineral productions by thermal decomposition ($>350^{o}$C) of paramagnetic minerals during frictional slips prohibit the application of ESR dating due to an overprint of un-pair electron ESR spectrum by ferrimagnetic resonance spectrum. Here, we propose an alternative paleomagnetic age determination to take advantage of the production of ferrimagnetic minerals during frictional slip. A newly-developed scanning SQUID magnetic microscopy by AIST and paleomagnetic viscous dating are employed to the Nojima fault gouge to determine slip planes and to reveal the age of their slip planes. Our preliminary results suggest that SQUID magnetic microscopy revealed the presence of highly magnetized slip zones less than 1millimeter. Alternating-field demagnetization (AFD) result shows that each slip zone has two different components both of characteristic remanence and viscous component. The direction of its secondary magnetization tends to record Earth’s current magnetic field. These results imply that we can use temperature-dependent viscous remanent magnetization to estimate the age of fault gouge. In this presentation, we will show the results of thermal demagnetization and derive the age of the fault gouge, using magnetic relaxation theory.

トンガ産迷子巨礫とその粘性残留磁気：予察

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Preliminary result of Paleomagnetic Viscous Dating of erratic boulders in Kingdom of Tonga

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In the Kingdom of Tonga, the island of Tongatapu, there are eight huge erratic coral boulders that are on the western coastline near the village of Fahefa. These boulders could only have come from the shoreline, as there are no nearby cliffs or hills. Tongatapu Island is 35-km∗20-km and consists of 3000-m-thick marine sediment deposits overlain by coral reef limestone. These boulders contain well-preserved corals, and living corals grow with a distinctly upright orientation. Field survey indicated that two of the boulders are clearly overturned; two are upright but tilted; and the others are upright and normal emplacement. The largest boulder is upright but clearly not attached at its base as it sits on hard rock and has anomalously thin soils compared to soils nearby on Tongatapu. Moreover, these boulders are 10-20-m above sea level and above any possible source, and all are 100-400-m from the present shoreline. Coral 230Th ages indicate that the coral formed during the last interglacial sea-level highstand, ca. 120-130ka. Therefore, it is believed that these boulders had been emplaced by a prehistoric tsunami. However, field evidence and radiometric age are controversial because soils beneath the boulders should be thicker due to its longevity of the emplacement. Thus, we need to determine the emplacement age and its emplacement mode of the boulders. Here we report preliminary results of the application of paleomagnetic viscous dating to the boulders. The coral boulders possess a measurable intensity of magnetic remanence by a spinner magnetometer. Our thermal demagnetization result of the largest boulder showed that paleomagnetic orientation of characteristic remanence indicates 150 degrees westerly horizontal rotation. In this presentation, we will show results of paleomagnetic viscous dating of these boulders.

陸域に分布する琉球層群の磁気層序－B-M境界の検討－

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Magnetic stratigraphy of the Ryukyu Group distributed in the land

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Middle Pleistocene is a significant climate transition period, which is called as MPT: Middle Pleistocene Climate Transition . MPT represents a change in glacial-interglacial periodicity, from 41kyr to 100kyr and in amplitude. At the same time, Ryukyu Islands experienced great change in sedimentation environment, in the relation to the expansion of the Okinawa trough and beginning of inflow to the back arc of the Kuroshio Current. Around the time of the MPT, there deposited reef limestones which recorded eustatic change of sea level around the Ryukyu Islands. Those limestones are widely distributed in Ryukyu Islands, because of active tectonic uplifts. As the on-land limestone strata of this period is rare, they are very important for studying MTP thus global climate changes.

In the investigation of MPT, the age correlation is very important. Reef limestones are primarily correlated by biostratigraphic ages. Calcareous nano fossils are used in the Ryukyu Group. Yamada and Matsuda (2001, 2002) shows the age of the Ryukyu Group distributed in Miyakojima as 0.95-0.41Ma. However, there is no datum level of calcareous nano fossils in this period, and they cannot accomplish the international correlation. Besides the biostratigraphy, another datum level of this age is Brunhes-Matuyama reversal boundary (0.78Ma). We tried to establish the magnetostratigraphy for the Ryukyu-Group of Miyakojima Island.

There are two significant difficulties in the study of magnetostratigraphy of reef limestones, so that there are the very few studies. The first problem is the weakness of their magnetizations. It had been considered that magnetic minerals were not present. But in recent years, the role of biogenic magnetite in the detrital remanent magnetization (DRM) acquisition is appreciated. It revealed that it is possible to examine the magnetostratigraphy. Accordingly, a couple of studies of magnetostratigraphy using core samples have been conducted (McNeel, 1988 Sakai and Jige, 2006). The second problem is the difficulty in establishing stratigraphy on reef limestones cropping on land. However, Nakamori(1986) showed a significant method in the stratigraphy of coral reef composite referring the relative sea-level changes. Following it, Yamada and Mastuda (2001, 2002) has established a sequence-stratigraphy of the Ryukyu limestones. Those works enable us the magnetstratigraphy of onland limestone sequnces.

Onland magnetstratigraphic studies rather than the core samples has two merits: 1) Declinations are measurable not only inclinations, as oriented samples can be taken. Very weak magnetization tends to bear large measurement errors. The angular difference for distinguishing the polarity is larger for oriented samples and the credibility of the polarity can be expressed by the latitude of VGP. 2) The reproducibility of the results can be granted as the accessibility to alternable sample is easy. In this study, oriented samples are collected from 20 sites referring Yamada and Matsuda (2001, 2002). We examine the polarity using the latitude of VGP. Some of the samples does not bear credible results by the conventional paleomagnetic procedures (alternating field and/or thermal demagnetization), so that we also applied a reductive chemical cemagnetization (RCD). The details of RCD information is already repoted in the Japan Geoscience Union Meeting 2016. As the results, we obtained credible results from the 18 sites, and they reveals a geomagnetic reversal boundary near the bottom of MY-Unit 4 of Yamada and Matsuda (2002). Comparing the biostratigraphy and present magnetostratigraphy, we determined the reversal boundary to be Brunhes-Matuyama boundary. It will help the international correlation of onland reef limestones, not only in Ryukyu-Group.

中期更新世気候変換期（Middle Pleistocene Climate Transition : MPT) は，海水準変動の周期が 4.1 万年から 10 万年へ長周期，大振幅へ変化した時期である．この時期の琉球列島周辺は，沖縄トラフの拡大と黒潮流の背弧側への本格的な流入により砂泥質な堆積物から，礁性堆積物へと変遷した．礁性堆積物を構成するサンゴを主体とした生物相は海水準変動を詳細に記録しており，MPT の環境変動解析に重要な役割を果たす．MPT の研究では国際的な年代対比が必要である．礁性石灰岩の年代決定は生層序年代によるのものが主流で，特に琉球層群においては石灰質ナノ化石による年代決定が行われている．琉球層群主部礁相が分布する宮古島の礁性石灰岩は 95 － 41 万年前の堆積物であることが山田・松田 (2001,2002) で報告されているが，この間には基準面がなく，国際対比はなされていない．この年代の基準面は生層序以外に着目すると，ブルン－松山地磁気逆転境界がある．そこで，宮古島の琉球層群について磁気層序の研究を行った．

礁性石灰岩の磁気層序，特に陸上露頭についての研究は２つの問題点により，研究されていない．１つ目の問題点は礁性石灰岩の陸上露頭での層位確立の困難さである．しかし，中森 (1986) により相対的海水準変動を用いたサンゴ礁複合体による層序確立法が示された．これを用いて山田・松田 (2001, 2002) が南琉球弧で琉球層群の詳細な層序を確立したことにより，陸上露頭での磁気層序が検討可能となった．２つ目の問題は，残留磁化が弱く，磁性鉱物が存在しないと考えられてきたことである．これについては近年，堆積残留磁化の獲得における走磁性バクテリア起源のマグネタイトの役割が理解されたことにより (Blakemore , 1980 Kirschvink,1980 Kirschvink and Chang , 1984) ，磁気層序の検討が可能であることが示された．これにより，コアを用いた磁気層序の研究がわずかながら行われている（McNeel,1988 Sakai and Jige,2006)．コアによる磁気層序の研究は伏角のみで極性を判断しているが，礁性石灰岩のように磁化が弱い試料は特徴的残留磁化の認識を誤り易い．本研究では，宮古島に分布する琉球層群について山田・松田 (2001, 2002) を元に 20

サイトから定方位で試料採集を行い，特徴的残留磁化の検出を試みた．得られた仮想的地磁気極 (VGP) を用いて磁気層序を検討した．礁性石灰岩は残留磁化が弱いため，通常の交流消磁・熱消磁では特徴的残留磁化方位の判別が困難な試料が多数あった．特に，MY-Unit2-4 にかけては，VGP の緯度が負を示すが，-10 度程度であり，正磁極ではないものの逆磁極ともいえず，明確な極性の判別ができなかった．そこで，二次的に化学残留磁化を獲得したであろう粒間にエッチャントを流し消磁する還元化学消磁（RCD）も用いた．RCD の詳細については日本地球惑星科学連合大会 2016 大会で報告した．

RCD を行った上で段階交流消磁を適用することで，二次磁化の除去を効果的に行うことができた．その結果，測定した 20 サイト中，18 サイトから優良な結果を得ることができた．MY-Unit2 から MY-Unit4 下部にかけては VGP の緯度が-60 度以下を示し，逆帯磁であることがわかった．これより上位の層準は正帯磁を示し，MY-Unit4 下部に地磁気逆転境界が存在することが明らかとなった．また，MY-Unit1 については，熱消磁の結果では VGP の緯度が 60 度以上となり正帯磁を示すが，RCD を行った上で交流消磁を行った試料は-20 度前後となり，逆帯磁の可能性を示唆する結果となった．MY-Unit2 から MY-Unit5 の結果を生層序年代（41-95 万年前）と対比すると，MY-Unit4 下部に見られる地磁気逆転境界はブルン－松山境界 (78 万年前）だと考えられる．陸域に分布する礁性石灰岩は，RCD を用いることで磁気層序の研究が可能であり，琉球層群に国際対比可能な年代面を決定することができた．

伊豆大島テフラの自然残留磁化の基礎研究

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Preliminary results of a paleomagnetic study on Izu-Oshima tephras

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It has been known that remanent magnetizations of widespread tephras of large eruptions are consistent with paleomagnetic directions obtained from the correlated welded tuffs of pyroclastic flow deposits (Reynolds, 1979; Nakajima and Fujii, 1995, 1998; Hayashida et al., 1996; Fujii et al., 2001). These data indicated that widespread tephras acquired a remanent magnetzation parallel to the paleomagnetic field soon after deposition. Since the widespread tephras recorded paleomagnetic directions, volcanic ash layers of small to middle scale eruptions, which deposited within a few km from volcanoes, may also record paleomagnetic direction. Yukutake et al. (1964a, b) reported the directions of natural remanent magnetization of tephras of Izu-Oshima volcano were consistent with the paleomagnetic directions obtained from lava flows although progressive demagnetizations were not applied to the samples. In this study, we collected tephra layers of Izu-Oshima volcanoes (Y1 and Y2 tephras) and the correlated lava flows in order to compare characteristic remanent magnetization of tephras with the paleomagnetic directions obtained from the lava flows. In this presentation, we will report preliminary results of progressive alternating field demagnetization on the samples.

過去の研究により、広域テフラの残留磁化方位（堆積残留磁化の方位）は、同時に噴出した火砕流の溶結部から得た残留磁化方位（熱残留磁化の方位＝古地磁気方位）と一致することが報告されている（Reynolds, 1979; 中島・藤井，1995, 1998; Hayashida et al., 1996; Fujii et al., 2001）。すなわち、広域テフラは堆積直後の古地磁気方位を記録する性質をもつ。一方、火山近傍（数 km 以内）に堆積したテフラについては、古地磁気方位測定の研究がほとんどない。唯一、Yukutake et al. (1964a, b) が伊豆大島火山のテフラの残留磁化方位を測定し、溶岩の残留磁化方位との比較を行うなどして、テフラは古地磁気方位を記録している可能性を指摘している。もし、火山近傍テフラから精度のよい古地磁気方位を復元できるならば、古地磁気永年変化の研究や火山層序学における対比の研究に火山近傍テフラを活用できると期待される。しかし、当時は段階交流消磁や段階熱消磁を適用していないので、“ 残留磁化方位 ” は 2 次磁化の影響を受けている可能性もある。そこで、本研究課題では、伊豆大島テフラ層の段階交流消磁実験を行い、その残留磁化方位が古地磁気方位であるか否かを検討する。この検討は、既に溶岩流との対比されているテフラ層 Y1、Y2（e.g. 小山・早川，1996）を用いる。これらのテフラから得られた残留磁化方位と溶岩流から得られた残留磁化方位（＝古地磁気方位）を比較する。

Y1 テフラ（1777-78 年）と Y2 テフラ（1684 年）については、各 2 サイトにおいて 10 cc プラスチックキューブを使って定方位試料を採取した。テフラ露頭に最初に治具を固定した上で、プラスチックキューブを静かに差し込む手法を開発して適用した。これにより、軟弱なテフラ試料の定方位の精度を高めている。Y1 テフラ・Y2 テフラに対比される Y1 溶岩・Y2 溶岩についても各 1 サイトずつ定方位試料を採取した。また、試料を採取したサイトにおいては、地磁気偏角の補正に用いるために太陽方位に基く地磁気偏角測定を行った。

これまでに Y1 テフラ・Y2 テフラの各 1 サイトの段階交流消磁が完了した。段階交流消磁は、最大 110mT までを 2.5 - 10 mT 間隔で行っている。その結果によれば、10mT 程度以下の磁化成分は 2 次磁化成分が見えるものの、10mT 以上の磁化成分は原点方向に直線的に減衰し、特徴的残留磁化方位といえる。各サイト 8 試料の特徴的残留磁化方位はまとまっており、平均方位を計算した。Y1 テフラは偏角 2.6 度、伏角 37.6 度（95%信頼限界 1.6 度）であり、Y2 テフラは偏角 6.9 度、伏角 32.5 度（95%信頼限界 2.9 度）が得られた。これらの平均方位は、95%信頼限界のレベルでみて、現在の地球磁場方位と異なり、また Y1 テフラと Y2 テフラの間でも異なる。少なくとも Y1 テフラ・Y2 テフラの残留磁化は 2 次的な残留磁化とは考えにくい。

入戸火砕流堆積物から抽出した粒子の古地磁気強度絶対値の推定へ向けて

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Towards the estimate of absolute paleointensity from single grains extracted from the Ito pyroclastic flow deposits

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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 measure macroscopic remanent magnetizations. In this study we have extracted single grains from an unwelded part of the Ito pyroclastic flow deposits, Kyusyu, Japan, and performed paleomagnetic and rock magnetic measurements on the extracted single grains. Takeda et al. (2016 JpGU meeting) reported that individual grains probably acquired thermoremanent magnetization (TRM) as natural remanent magnetization (NRM). It is expected that an estimate of absolute paleointensity is possible from each of these single grains. In this study we perform a series of rock magnetic and paleomagnetic measurements to test this possibility. We will report these results.

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、本研究では個々の粒子が獲得した残留磁化を分析対象として研究を進めている。武田ほか（2016年連合大会）では、入戸火砕流堆積物の非溶結部から20〜30メッシュサイズ（595〜841 μ m）の粒子を抽出し、各種の古地磁気・岩石磁気学的分析を行い、抽出した粒子が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を示した。したがって、個々のテフラ粒子を対象とした古地磁気強度絶対値実験の可能性が期待される。

本研究では、抽出した粒子を対象として、古地磁気強度絶対値の推定を行うための基礎的な検討を行った。具体的には、抽出した粒子に対して、自然残留磁化（NRM）に見立てた熱残留磁化（TRM0）を実験室内で30 μ Tの磁場中で610 ℃まで加熱することで与え、綱川-ショー法（Yamamoto et al, 2003）によって、この実験室磁場を確からしく復元できるかの検討を行った。

まず、軽石型火山ガラス粒子2個と岩片粒子1個を対象とした予察実験を行った。その結果、NRMに見立てたTRM0及び1、2回目加熱後のTRM1、TRM2は、段階交流消磁に対して安定的に消磁される挙動を示した。さらに、TRM0-TRM1、TRM1-TRM2グラフでは、相関係数r = 0.812〜1.00で直線性が認められ、その傾きは、一部の例外を除き0.808〜1.21であった。つまり、室内加熱によってTRMが十分獲得されたことが示唆されるが、加熱によってやや変質が起こっている可能性が考えられる。このような変質の補正を行うために各加熱の前後で非履歴性残留磁化（ARM0、ARM1、ARM2)を着磁したが、いずれも段階交流消磁に対して不安定な挙動を示し、ARM0-ARM1、ARM1-ARM2グラフは一部を除き相関係数r = 0.231〜0.715と直線性が認められなかった。このままでは、補正への利用は困難であると考えられる。

今後も実験を進め、試料数を増やすとともに、ARMを利用した補正のさらなる検討および、ARMの代替として等温残留磁化の利用などの検討も行い、それらの結果を合わせて報告する予定である。

白亜紀入遠野花崗岩から分離したジルコン単結晶の岩石磁気学測定

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Rock-magnetic properties of single zircon crystals separated from the middle Cretaceous Iritono granite

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The existence of Earth's magnetic Field over geological time is a key factor for understanding the thermal evolution of the deep Earth, and for the evolution and preservation of a surface environment conductive to life. however, paleointensity data from volcanic rocks older than 500 Ma is too sparse to detect long-term trends in the evolution of the geomagnetic field (e.g. Tauxe and Yamazaki, 2007). As granites have a more continuous recoud over geological time, and perhaps a higher preservation potential, several groups have investigated primary minerals such as feldspar and zircon as possible archives of geomagnetic paleointensity information. Zircons in particular are resistant to most chemical alternation and weathering, and provide firm age constrains on both their crystallization time and thermal metamorphic history. Thus when weathered of otherwise separated from granite they could potentially provide consistent paleointensity data over most of geological time. however, paleomagnetic and rock-magnetic information from single zircon crystals have not yet been compared to existing data from their host-rocks, thus it is not clear whether results from individual zircons of unknown provenance can be treated in the same way as data generated by traditional whole-rock measurements.

In this study, we tried to establish a method to measure the rock-magnetic properties and possible paleointensities of single zircon crystals separated from granitic rocks. We conducted magnetic measurements of zircons from the middle Cretaceous Iritono Granite whose whole-rock analyses are reported (Wakabayashi et al., 2006; Tsunakawa et al., 2009). First, we separated the zircons form the granite sample using non-magnetic methods and tools. Next, the natural remanent magnetization(NRM) of zircons mounted on double-stick tape was measured using a 2G SQUID rock magnetometer at Kochi University. 13 out of 1156 grains (1.1%) showed NRM intensities larger than the detection limit of the magnetometer (~20 pAm^2), although we were not able to exclude variable components of the sample handling system contributing to the remanence. Following this we took the ten most magnetic zircons to a RAPID-system 2G magnetometer in a class-1000 clean laboratory at the California Institute of Technology, where we were able to mount individual zircons on ~50 um-thick, acid-washed quartz-glass fibers by small spots of cyanoacrylic cement, thereby lowering the background noise of the sample handling system to the 1 pAm^2 level after an IRM saturation pulse. Stepwise acquisition of isothermal remanent magnetization(IRM) up to 1 T and stepwise alternating field demagnetization (AFD) of IRM were applied to the zircons. In the AFD experiments, 4 grains was successfully demagnetized, while the remaining 6 grains showed unstable behavior during experiments. NRM/IRM ratios of the successfully demagnetized grains were 0.038, 0.089, 0.21, and 0.68, respectively. The IRM of zircon grains with NRM/IRM ratios of 0.089 and 0.21 systematically decreased near to the origin by AFD treatment of 100 mT. AFD curve of a zircon grain with NRM/IRM ratio of 0.038 suggested presence of high coercivity ($>$100 mT) component. About 40% of the IRM of other grain remained at even 400 mT. Considering the magnetic components of their host-rock, the candidates of remanence carriers of zircons could be magnetite and pyrrhotite. Therefore, the present results were interpreted as zircon grains with the NRM/IRM ratio of 0.089 and 0.21 contain magnetite, and grains with that of 0.038 and 0.68 contain pyrrhotite (or + magnetite).

We are going to apply the same measurements to further more zircon grains, and perform low-temperature measurements and chemical analysis to reveal the magnetic inclusions which carry the remanent magnetization and their variation among single zircon crystals. We will discuss the comparison of rock-magnetic properties of the whole-rock and single zircon crystals.