PyPARmC: A new software for the analysis of remanent magnetization curves

Xiangyu Zhao[1]; Masakazu Fujii[2]; Yusuke Suganuma[2]
[1] Paleomag, NIPR; [2] NIPR

Discriminating magnetic minerals of different origins in natural samples is useful to reveal their associated geological and environmental processes, which can be achieved by the analysis of remanent magnetization curves. The analysis relies on the choice of the model distribution to unmix magnetic components. Three model distributions were proposed in past studies, namely, the lognormal, skew normal and skew generalized Gaussian distribution (SGG) distributions, which are related to the normal distribution. Recently, a new model distribution, the Burr type XII distribution, is proposed as a model distribution. We demonstrate that the component analysis is sensitive to model distribution as well as measurement noise. As a consequence, the decomposition is subject to bias that is hard to tell due to the lack of ground-truth data. It is therefore recommended to compare results derived from various model distributions to identify spurious components. So far, however, each software for unmixing remanent magnetization curves supports one model distribution only, which discourages users to compare different model distributions. A new software, PyPARmC (Python Package for Analysis of Remanent Magnetization Curves), that provides all available model distributions is developed. PyPARmC also provides an automated protocol for assigning parameters necessary to initiate the component analysis, which can greatly reduce the efforts of users and therefore improve the efficiency and objectivity of component analysis. Samples ranging from igneous rocks, marine sediments, red beds, biogenic magnetite and synthetic minerals are analyzed using the software to compare the suitability of model distributions.

Submersible Magnetics for Understanding Off-axis Volcanism and Hydrothermal Systems of the Central Indian Ridge

Masakazu Fujii[1]; Kyoko Okino[2]
[1] NIPR; [2] AORI, Univ. Tokyo

Hydrothermal circulation within oceanic lithosphere is a fundamental process in mid-ocean ridges, and it essentially affects the solid-Earth cooling, ocean temperature, and material cycles. The Kairei and Yokoniwa hydrothermal fields are located at an off-axis volcanic knoll of the Central Indian Ridge, and known as their unique geological background where both mafic and ultramafic rocks are involved. Despite intensive investigations, their geological and geophysical background is still debated. Here, we show new results of near-seafloor magnetic data obtained by the submersible Shinkai 6500. We investigated crustal magnetization of the hydrothermally altered zone and surrounding off-axis lava flows, and evaluated their intensities compared to previously reported values at axial areas of seafloor spreading environments. The Kairei hydrothermal field is characterized by low coherence between observed and modeled anomalies and low values of magnetization. This result suggests that magnetic minerals within basaltic lava flows were likely altered by hydrothermal fluid circulation. The variation pattern in the observed magnetic anomalies above the lava flows is in phase with that of modeled magnetic anomalies for a simple assumption with a magnetization direction parallel to the geomagnetic field. This result suggests that this lava flows preserve normal magnetic polarity corresponding to the Brunhes chron. The estimated magnetization intensity reaches 20 A/m in this area, which is clearly greater than that of previously reported off-axis areas. This study provides new insight into the distribution of highly magnetized lava flows and indicates the distribution of recent off-axis volcanic activity, which is potentially linked to sub-seafloor hydrothermal circulation.

Comprehensive study of the relationship between exsolved magnetite and host plagioclase: implication for crustal magnetizations

Masahiko Sato[1]; Masashi Ushioda[2]; Ryoichi Nakada[3]
[1] Dept. EPS, UTokyo; [2] IEVG, GSJ, AIST; [3] JAMSTEC

Natural plagioclase crystals sometimes contain fine-grained magnetite inclusions, which are considered to be originated from exsolution at subsolidus condition. The exsolution process can crystalize and hold nearly pure fine-grained magnetite in deep crustal rocks, and natural remanent magnetizations (NRM) carried by the magnetite bearing plagioclase should play an important role in the source of magnetic anomaly. Therefore, to elucidate crystallization mechanism of magnetite in plagioclase crystal and to understand origin of its NRM is of prime importance in paleomagnetism and rock-magnetism, while the mechanism has been poorly understood yet. 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.

Plagioclase crystals were prepared from natural mafic-plutonic rocks. A gabbroic anorthosite from the northwestern part of the Duluth complex, a layered gabbro from the Sumail massif of the Oman ophiolite, two layered gabbro from the Haylayn Block of the Oman ophiolite, and a medium-grained gabbro from the Murotomisaki gabbroic Intrusion were crushed into mineral grains. 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 synchrotron radiation facilities. (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. On the basis of measurement results, we will discuss a relationship between the content of magnetite and the Fe state in plagioclase crystal and will evaluate the contribution to crustal magnetizations.

Magnetotaxis in oxic pelagic red clay? Assesment from magnetic anisotropy

Yoichi Usui[1]
[1] JAMSTEC

Abundant biogenic magnetite produced by magnetotactic bacteria has been reported from oxic clayey pelagic sediment (red clay). On the other hand, red clay often fails to give reasonable paleomagnetic records. Because biogenic magnetite is an ideal, stable ferromagnet enabling efficient magnetotaxis, it is a mystery why red clay is a poor paleomagnetic recorder. One hypothesis is that the bacteria may not use the magnetite for magnetotaxis in the fully oxic sediment, and the alignment of biogenic magnetite is not strongly controlled by the geomagnetic field. To test this hypothesis, I analyzed magnetic anisotropies of red clay collected around Minamitorishima. Anisotropy of magnetic susceptibility (AMS) shows simple sedimentary fabric for most of the samples without preference in azimuth. However, at a depth corresponding to the highest biogenic magnetite content, AMS shows inverse fabric with a clustering of minimum direction to a certain azimuth. Furthermore, anisotropy of anhysteretic remanence (AARM) yields horizontal foliation, and the maximum AARM shows clustering to a direction similar to the minimum direction of the inverse AMS. Preliminary comparison with the core orientation recorded by orientation tools indicates that the AARM-max direction broadly agrees with the North-South direction. This demonstrates that the biogenic magnetite preferentially aligns along the geomagnetic field, suggesting that the bacteria performs magnetotaxis even in the fully oxic sediment. The poor paleomagnetic results should be explained by other factors such as slow and intermittent sedimentation, or oxic diagenesis. The result also demonstrates that paleomagnetic direction except polarity may be recovered by magnetic anisotropy from biogenic magnetite even when remanence is completely overwritten.

礁性石灰岩古地磁気測定における二次CRM除去の重要性

穴井 千里 [1]; 望月 伸竜 [2]; 渋谷 秀敏 [3]
[1] 熊大・先端科学・地球環境; [2] 熊本大学; [3] 熊大・先端科学・地球環境

The function of chemical treatment for the magnetostratigraphy - a case study on reef limestones -

Chisato Anai[1]; Nobutatsu Mochizuki[2]; Hidetoshi Shibuya[3]
[1] Dep't Earth & Env., Kumamoto Univ; [2] Kumamoto University; [3] Dep't Earth & Env., Kumamoto Univ.

We have reported the magnetostratigraphy of reef limestones using a new chemical demagnetization method at the society of Geomagnetism and Earth, Planetary and Space Sciences meeting (138th, 140th and 142th). In these presentations, we devised reductive chemical demagnetization (RCD) and discussed the results for establishing the magnetostratigraphy of reef limestones. The selective removal of secondary chemical remanent magnetization (CRM) is indispensable in paleomagnetic studies of reef limestone. The CRM appears to be carried by ferric minerals precipitated in voids or between grains in a rock, and the chemical reaching must be effective removing secondary CRM. However, conventional chemical demagnetization with a strong acid is not applicable for carbonate rocks. Therefore, we devised reductive chemical demagnetization (RCD) using ascorbic acid solution as a reductant, and confirmed its effect from rock magnetic experiment and paleomagnetic measurement. In this report, we describe the details of the magnetostratigraphy of the Ryukyu group in Miyakojima island and compare the magnetostratigraphy of the same group in Irabujima island, and discuss the significance of RCD.

The RCD is most effective on the MY-Unit1, which is a stratigraphic unit at the bottom of the Ryukyu group in Miyakojima island. Results of thermal demagnetization (TD) in Site: Q-4 of MY-Unit1 showed clear normal polarity at D=0.9° and I=39.4° (MAD=3.5°). However, the result applying RCD + alternating field demagnetization (AFD) on the same site showed reversed polarity at D=163.7° and I=-38.2° (MAD=14.9°). Site: Q-28 of MY-Unit1 shows similar results. On the other hand, in some sites from upper MY-Unit2 and 3, the result of RCD + AFD shows clear reversed polarity, while the TD gives ambiguous intermediate polarity. This suggests that MY-Unit1 acquires a severer secondary CRM which is hard to separate with TD than other units.

Sakai and Jige (2006) reported that the Ryukyu group in Irabujima covers from Jaramillo subchron to Brunhes chron. They noticed, however, that the magnetostratigraphic assignment is not compatible with the oxygen isotopic stage and the calcareous nano fossil datum. Their upper boundary of Jaramillo subchron (1001 ka) is higher than these reference strata (987 ka). This stratigraphic horizon is correlated to MY-Unit1 of the Miyakojima Ryukyu group, whose NRM is in normal polarity by a stronger secondary CRM. Their results could also be affected by the CRM which might be removed by RCD. In the paleomagnetic measurements of reef limestones, it is extremely important to remove secondary CRM, and RCD will help finding the more accurate the geomagnetic reversal boundary.

沖縄県宮古島に分布する琉球層群の磁気層序の確立およびその手法である還元化学消磁法の考案について第138，140，142回地球電磁気・地球惑星圏学会において詳細を報告してきた．これらの報告では，礁性石灰岩の磁気層序を確立するために還元化学消磁法（RCD）を考案し，その結果について議論を行った．礁性石灰岩の古地磁気研究で重要なことは二次化学残留磁化（CRM）の選択的消去であり，その二次CRMを獲得する磁性鉱物の晶出または沈殿箇所は試料内部の空隙や粒子間であると推察される．これらを効果的に取り除く方法は化学消磁が適当であるが，一般的な強酸を用いた化学消磁では炭酸塩岩に利用できない．

そこで，還元剤としてアスコルビン酸溶液を用いて消磁する還元化学消磁（RCD）を考案し，岩石磁気実験や古地磁気測定からその効果を確認している．本報告では，確立した宮古島琉球層群の磁気層序の詳細および，隣接する伊良部島琉球層群の磁気層序との対比を行い，RCDによる事前処理の重要性について議論する．

宮古島に分布する琉球層群の最下部層（MY-Unit1）は特に顕著なRCDの効果が確認できたユニットである．MY-Unit1のSite:Q-4について熱消磁（TD）を行った結果は，D=0.9°, I=39.4°（MAD=3.5°）で明瞭な正磁極を示す．しかし，同サイトについてRCD＋交流消磁(AFD)を行った結果はD=163.7°, I=-38.2°（MAD=14.9°）で逆磁極を示す．MY-Unit1のSite:Q-28も同様の結果である．しかし，RCD+AFDの結果が明確な逆磁極を示すMY-Unit2およびMY-Unit3の各サイトはTDの結果は不明瞭で中間帯磁を示す．このことは，MY-Unit1が他の層準と比較してより強力なTDでは分離が難しい二次CRMを獲得していることを示唆する．

伊良部島に分布する琉球層群はハラミヨサブクロン上部からブルンクロンまでの磁気層序がSakai and Jige (2006)によって報告されている．彼らは，酸素同位体ステージおよび石灰質ナノ化石層序との対比により年代を見出しているが，ハラミヨサブクロン上面境界（1001ka）はこれらの基準面（987ka）よりも上位で確認されており調和的でない．この層準は宮古島琉球層群のMY-Unit1と対比され，二次CRMの獲得により正磁極を示している可能性があり，RCDを用いて再検討する必要があるだろう．礁性石灰岩の古地磁気測定を行う際には，RCDによる事前処理により二次CRMを除去することが極めて重要な実験手順であり，より正確な地磁気極性境界を見いだすことが可能となるだろう．

酸化されたマグネタイトに担われた黒部川花崗岩の自然残留磁化

福間 浩司 [1]; 伊藤 久敏 [2]; 山田 隆二 [3]; 久保 貴志 [4]; 竹原 真美 [5]
[1] 同志社大・理工; [2] 電中研; [3] 防災科研; [4] 黒部市吉田科学館; [5] 九大・理・地惑

Retrieving primary magnetizations carried by oxidized magnetite from the Quaternary Kurobegawa Granite

Koji Fukuma[1]; Hisatoshi Ito[2]; Ryuji Yamada[3]; Takashi Kubo[4]; Mami Takehara[5]
[1] Dept. Env. Sys. Sci., Doshisha Univ.; [2] Central Research Institute of Electric Power Industry; [3] NIED; [4] Kurobe Yoshida Science Museum; [5] Earth and Planetary Sciences, Kyushu Univ.

Since granitic magma bodies cool down slowly and the prolonged crystallization process leads to formation of coarse-grained or exsolved iron oxides and sulfides, natural remanent magnetization (NRM) of granite often comprises of several components extending over broad ranges of unblocking temperature and coercivity. The Quaternary Kurobegawa Granite, which is the youngest granite with U-Pb ages ~0.8 Ma and forms the Hida Mountain Range (the Northern Japanese Alps) elevated to 3000 m above sea level, provides a unique opportunity to study primary magnetizations of young granites. Also the paleomagnetic analyses of the Kurobegawa Granite and surrounding rocks contribute to elucidate the emplacement and deformation processes related to the mountain building. We collected oriented blocks at eight sites of the Kurobegawa Granite and five sites of the surrounding granite and volcanics. Because low unblocking temperature (<150 degC) and low AF coercivity (<10 mT) components occupy significant portion of NRM of the granite specimens, we applied first low temperature demagnetization with liquid nitrogen and then performed thermal demagnetization at every 25 degC step from room temperature up to 600 degC with the automated magnetometer-demagnetizer systems Tspin. Low temperature demagnetization erased 10-75% of initial magnetization. Low temperature cycling of 2.5 T isothermal remanent magnetization (IRM) down to 5 K exhibited dual transitions at 120 K of magnetite and at about 100 K of maghemite for most specimens, and 34 K transitions of pyrrhotite for some granite specimens. Ubiquitous middle-range unblocking temperature (250-400 degC) of NRM and IRM and kinks at about 300 degC of thermomagnetic curves show that maghemite carries significant portion of stable magnetization along with magnetite. Oxidation of magnetite occurs during emplacement of the Kurobegawa Granite and is responsible for the primary magnetization. Magnetization directions at most of sites are well clustered for the Kurobegawa Granite and are of normal polarity without exception. The primary magnetizations postdated the age ~0.8 Ma of U-Pb geochronology with a closure temperature 900 degC and were acquired during the Brunhes chron (<0.77 Ma). While no tilting nor deformation was found out from the site-mean directions of the Kurobegawa Granite, its surrounding rocks showed discordant directions.

花崗岩質のマグマはゆっくりと冷却され，長い期間に亘る結晶化の過程で粗粒または離溶した酸化鉄および硫化鉄が形成されるため，花崗岩の磁化はしばしば広いアンブロッキング温度や保磁力に亘る複数の成分から成る．U-Pb 年代が 0.8 Ma と花崗岩としては地球上で最も若い年代を示し，海抜 3000 m に達する飛騨山脈 (北アルプス) を構成する黒部川花崗岩は，若い花崗岩における初生磁化の獲得を研究するよい機会を与える．また，黒部川花崗岩とその周辺の岩石の古地磁気学的解析は，山脈形成に関連した花崗岩の定置と変形の過程を解明するのに貢献できる．黒部川花崗岩の８地点，周辺の花崗岩や火山岩の５地点で定方位ブロックを採取した．低いアンブロッキング温度（<150 ℃）および低い保磁力（<10 mT）をもつ磁化成分が花崗岩試料の自然残留磁化（NRM）のかなりの部分を占めるため，初めに液体窒素による低温消磁を適用し，その後熱消磁炉付き自動磁力計 Tspin を用いて室温から 600 ℃ までの 25 ℃ ステップで熱消磁を行った．低温消磁により 10-75% の NRM が消磁された．300 K から 5 K までの等温残留磁化の低温サイクリングは，ほとんど全ての試料でマグネタイトによる 120 K とマグヘマイトによる約 100 K の二重の転移を示し，いくつかの花崗岩試料では 34 K のピロータイトの転移も検出された．NRM および IRM の熱消磁で見られた普遍的な 250-400 ℃ のアンブロッキング温度および約 300 ℃ の熱磁気曲線における屈曲は，マグヘマイトがマグネタイトとともに安定した磁化を担っていることを示す．黒部川花崗岩が定置されるときにマグネタイトの酸化が生じ，様々な酸化度のマグネタイトが初生磁化を担っている．黒部川花崗岩の各地点では磁化方向がよく集中し，例外なく正の極性を示す．初生磁化は閉鎖温度 900 ℃ をもつ U-Pb 年代の 0.8 Ma に遅れ，Brunhes 期 (<0.77 Ma) に獲得された．黒部川花崗岩の各地点の平均方向から傾斜や変形は見られないが，周辺の岩石は黒部川花崗岩と一致しない方向を示す．

New paleomagnetic data from early Miocene sediments in central Japan and tectonic implications

Takuro Matsuo[1]; # Hiroyuki Hoshi[2]
[1] Kariya High School; [2] Dept Earth Sci., Aichi Univ. Education

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

We present new paleomagnetic data obtained from early Miocene (ca. 18-17 Ma) sediments in three areas (Iwamura, Tengudana and Niinotoge) in central Japan. Oriented cores consisting mainly of mudstones and intercalated fine felsic tuffs were collected at more than 50 sites. Stepwise thermal demagnetization of both natural and isothermal remanent magnetizations suggests magnetite as a main magnetic carrier, with possible presence of greigite in rock samples from some sites. Site-mean directions of characteristic remanent magnetization components are all reverse polarity, suggesting deposition within the same reverse polarity chron, probably Chron C5Dr. Declinations of the site-mean directions are mostly southwesterly and deflected clockwise from the expected direction, indicating clockwise rotation after deposition. These declinations are similar to those from early Miocene and older rocks of the main part of the SW Japan arc, while they are significantly different from the undeflected paleomagnetic direction from Tomikusa, located 10-20 km northeast of Niinotoge. Thus, the Iwamura, Tengudana and Niinotoge areas are located on the main part of the SW Japan arc. It is suggested that the main part of the SW Japan arc has its eastern 'rotational' boundary with a differentially rotated piece of crust between Niinotoge and Tomikusa.

Geomagnetic paleointensity experiments on diverse contemporaneous materials from a monogenetic volcano

Ahn Hyeon-Seon[1]; 山本 裕二 [2]
[1] Gyeongsang National Univ; [2] 高知大

Geomagnetic paleointensity experiments on diverse contemporaneous materials from a monogenetic volcano

Hyeon-Seon Ahn[1]; Yuhji Yamamoto[2]
[1] Gyeongsang National University; [2] Kochi University

Reconstructing full vectors of the Earth's magnetic field over time and space is vital for deepening our understanding of the Earth's deep interior and its evolution. However, in particular, obtaining reliable paleointensity (PI) estimates is often difficult due to frequent occurrence of unwanted experimental results, which are generally caused by non-ideal materials for PI experiments as magnetic remanence carriers, surely common in nature. So, investigating relations between unwanted PI results and inherent non-ideal magnetic signatures of material and thus attempting to connect them can be a good way to immensely improve the reliability of PI determination and the acquisition rates. To this end, volcanic and archeological materials of the recent past and historical period and experimentally simulated ones, having known initial magnetic fields that we want to seek, have been frequently utilized. In this work, we have utilized diverse contemporaneous products from an old monogenetic volcanism, i.e. the 3.7 ka Songaksan eruption in Jeju Island, to investigate behaviors of PI results with two different methods. It is expected to have a good opportunity to explore effects of magnetic signatures on PI results and finally make the best faithful PI determination.

The 3.7 ka Songaksan eruption is known to be a sequence of basaltic phreatomagmatic and magmatic eruptions, providing a variety of products including basaltic juvenile and non-juvenile pyroclasts within tuff ring deposits, ponded trachybasaltic lava and scoria deposits with spatters/agglutinates. Of which, currently two kinds of volcanic materials, i.e. juvenile pyroclasts and lava, have been applied to PI experiments with the Tsunakawa-Shaw method and the IZZI-Thellier method in conjunction with rock-magnetic characterizations based on thermomagnetic curve, hysteresis parameter and first-order reversal curve analyses. These samples could be characterized by different magnetic mineral phases, domain states and magnetostatic interactions as follows. [1] Type I: juvenile pyroclast, dominance of magnetic mineral phase having a low curie temperature (Tc) of about 150-280 ^{o}C with occasional co-existence of a Tc~540-600 ^{o}C phase, single-domain (SD)-like particles with suppressed magnetostatic interactions or mixtures of SD and superparamagnetic-domain particles, thermal stability in temperatures between room temperature (Tr) and ~300 ^{o}C; [2] Type IIa: trachybasalt lava, a single Tc~580 ^{o}C phase, magnetostatically interacting SD-like particles, thermal stability between Tr and 610 ^{o}C; [3] Type IIb: trachybasalt lava, a single Tc~580 ^{o}C phase, magnetostatically interacting pseudo-SD particles, thermal stability between Tr and 610 ^{o}C. IZZI-Thellier PI experiments for type I specimens show near-ideal results for the temperature ranges up to the temperature at which the pyroclasts were emplaced (less than ~300 ^{o}C), giving PI estimates of ~50-65 micro T. For type IIa specimens, IZZI-Thellier PI results all show sagging non-ideal Arai plots allowing variable slopes corresponding to ~10-85 micro T, but the corresponding Tsunakawa-Shaw experiments all show ideal results giving PI estimates of ~20 micro T. For type IIb specimens, both IZZI-Thellier and Tsunakawa-Shaw results show apparently a consistent PI estimate of ~60 micro T, although the IZZI-Thellier results show somewhat zigzagged Arai plots. Most of the acceptable PI estimates from different specimens with different magnetic remanence carriers are concentrated at around 60 micro T (~20% higher than the present-day), which may indicate an actual surface magnetic field value at that time. This can suggest that juvenile pyroclastic rocks can be good materials to have promise for PI determinations. On the other hand, the highly biased PI estimates of ~20 micro T for apparently ideal Tsunakawa-Shaw results of type IIa lava specimens should be investigated further to seek the cause.

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Preliminary report on depositional environment and relative paleomagnetic intensity of IODP Site U1490

Yuho Kumagai[1]; Norihiro Nakamura[2]; Robert G. Hatifield[3]; Toshitsugu Yamazaki[4]; Yuhji Yamamoto[5]
[1] Earth Science, Tohoku Univ.; [2] IEHE, Tohoku Univ; [3] Oregon State Univ.; [4] AORI, Univ. Tokyo; [5] Kochi University

We report preliminary paleomagnetic results from between ~180-258 meters composite depth (mcd) of International Ocean Discovery Program (IODP) Site U1490 recovered during Expedition 363. The aims of Expedition 363 were to reveal the role of the Western Pacific Warm Pool (WPWP) in regional and global climate variability. The recovered cores span a broad spatial and temporal range from the middle Miocene to late Pleistocene. Pelagic sediments recovered from IODP Site U1490 (western equatorial Pacific, 2341 m water depth) are composed of calcareous and siliceous nannofossils with varying proportions of clay and ash. Seismic reflection data of Site U1490 revealed current-controlled mud waves that are prominent deeper than ~180 meters below sea floor but gradually decrease in amplitude up-section. Since deep water is enriched in dissolved oxygen due to downwelling in polar regions, the mud waves were probably formed in an oxic environment by deep water currents, inhibiting the dissolution of magnetic minerals in the sediments.

Shipboard analysis revealed that the paleomagnetic data is uninterpretable in terms of geomagnetic field behavior between ~25-180 mcd at Site U1490 because magnetic minerals have been dissolved by diagenetic alteration. However, in the upper ~25 mcd and below ~180 mcd sediments have a stable magnetization that span from the present to the early Pleistocene (0-1.9 Ma) and from the middle to late Miocene period (~9-19 Ma), respectively. The latter represents recovery of an exceptionally long, continuous, core sample that provides an opportunity to study long-range past variations of the paleomagnetic field.

We will report the measurement of natural remanent magnetization (NRM), anhysteretic remanent magnetization (ARM), and isothermal remanent magnetization (IRM) on U-channel samples from splice sections of Site U1490 and develop a preliminary estimate of relative paleomagnetic intensity (NRM_{20mT}/ARM_{20mT}). NRM was demagnetized with stepwise alternating-field (AF) demagnetization in peak fields of 20-80mT and reveals two additional geomagnetic reversals than the 34 identified on-board ship using a single peak AF demagnetization of 20 mT. The range of NRM_{20mT}/ARM_{20mT} is 0.002-0.36 with lowest values accompanying the reversal horizons. Future works include the periodic analysis of relative paleomagnetic intensity and its normalizer to check whether orbital modulation affects the paleomagnetic record of this site as has been previously reported in other Pleistocene age cores from the WPWP.

エルサッサ数の地球物理的意味

桜庭 中 [1]
[1] 東京大・理・地球惑星

The geophysical meaning of Elsasser number

Ataru Sakuraba[1]
[1] Dept. of Earth and Planetary Science, Univ. of Tokyo

We present results of linear instability of axisymmetric toroidal magnetic field imposed inside a rotating fluid sphere, and discuss the geophysical meaning of the Elsasser number that plays a central role in the magnetic instability. We use the magnetostrophic approximation in which viscous and inertial terms are neglected in the equation of motion of incompressible rotating fluid. We assume an axisymmetric toroidal field that is maintained by some external mechanical and electromotive forces. When the Elsasser number, that is proportional to the product of electrical conductivity and square of maximal toroidal field intensity and inversely proportional to the product of density and rotation rate, becomes about 10, the field becomes unstable irrespective of the toroidal field structure and a prograde slow wave propagates. The azimuthal wavenumber is inversely proportional to the size of the cross section of the toroidal magnetic field. This is the resistive instability in which a finite resistivity is important. The linear growth rate becomes maximal when the Elsasser number is of the order of 10 to 100, and the maximal value is proportional to the wavenumber.

If the magnetic instability occurs when the Elsasser number is about 10, it is suggested that a toroidal field created by planetary dynamo action should be destroyed by magnetic instability. And it is also implied that there is an upper bound in the Elsasser number of the planetary magnetic field. If the dynamo action that creates an axisymmetric toroidal field and the magnetic instability that destroys it are balanced in the saturation state, the ratio of the Elsasser number to the critical Elsasser number does not exceed 10, and the magnetic field intensity does not increase infinitely even if the magnetic Reynolds number is huge.

本発表では、まず回転流体球に印加された軸対称トロイダル磁場の線形不安定について、計算結果を紹介し、さらにそこで中心的な役割を果たす無次元数であるエルサッサ数の地球物理的意味について議論する。非圧縮電磁流体の運動方程式において、粘性項と慣性項とを無視する磁気地衡流近似をもちいる。適当な外力および起電力を仮定し、定常軸対称トロイダル磁場を維持する。電気伝導度と磁場強度の最大値の自乗との積に比例し、密度と自転速度の積に反比例する、エルサッサ数が 10 程度になると、そのトロイダル磁場分布にかかわらず、不安定が起こり、遅い波が東向きに伝搬する。東西方向の波長は、与えたトロイダル磁場の磁力管の断面の大きさにおおむね比例する。有限の電気伝導度が重要なレジスティブ不安定であり、エルサッサ数が数十から 100 程度で線形成長率が極大になる。成長率の大きさは、波長の自乗に反比例する。

エルサッサ数が 10 程度になるとかならず磁気不安定が起こるとすると、惑星ダイナモがつくるトロイダル磁場は、ある強度以上になると不安定によって壊される、ということが示唆される。したがって、惑星磁場のエルサッサ数には上限があるのではないか、ということが示唆される（Zhang and Fearn, GRL 1993）。もし、軸対称トロイダル磁場をつくるダイナモ作用と、その磁場を壊して非軸対称の遅い波を励起する磁気不安定とがつりあうことによって磁場強度が決まっているとすると、エルサッサ数の臨界エルサッサ数に対する比はせいぜい 10 程度が最大であって、磁気レイノルズ数をどんなに大きくしても、無限に大きくはならない。

数値シミュレーションに基づく内核半径の変化が臨界レイリー数付近での回転球殻対流に与える影響についての研究

西田 有輝 [1]; 加藤 雄人 [2]; 松井 宏晃 [3]; 松島 政貴 [4]; 熊本 篤志 [5]
[1] 東北大・理・地球物理; [2] 東北大・理・地球物理; [3] UC Davis EPS; [4] 東工大・地惑; [5] 東北大・理・地球物理

Influences of inner core radius on thermal convection in a rotating spherical shell near the critical Rayleigh number

Yuki Nishida[1]; Yuto Katoh[2]; Hiroaki Matsui[3]; Masaki Matsushima[4]; Atsushi Kumamoto[5]
[1] Dept. Geophys., Grad. Sch. Sci., Tohoku Univ; [2] Dept. Geophys., Grad. Sch. Sci., Tohoku Univ.; [3] UC Davis EPS; [4] Dept Earth & Planetary Sciences, Tokyo Tech; [5] Dept. Geophys, Tohoku Univ.

Instinct geomagnetic field is thought to be sustained by a dynamo action of fluid iron alloy convection in the outer core. Recent studies suggest that the solid inner core was nucleated about 1 billion years ago and after that it has grown to the present size from thermochemical calculations [e.g., O'Rourke and Stevenson, 2016]. There is a probability that change of the convective-rigion geometry influenced on the outer core convection, but geodynamo has sustained over 3.5 billion years from paleomagnetic analyses [e.g., Biggin et al., 2015]. It is important to reveal properties of dynamo in a rotating spherical shell corresponding to the past Earth in the perspective of understanding magnetohydrodynamics and elucidating the environment of the past Earth. Because there are a few studies, in which Heimpel et al. (2005) discussed dynamo onset in the various inner core radii, geodynamo different from the current inner core size has not been fully understood. In the present study, using a numerical dynamo code Calypso [Matsui et al., 2014], we carried out non-magnetic thermal and dynamo simulations in three different aspect ratios: r_i/r_o = 0.15, 0.25, and 0.35 (the present value), where r_i and r_o are the inner core and outer core radii, respectively. In order to quantify a convection structure, we calculated a length scale of flow in azimuthal direction [cf. King and Buffett, 2013]. As a result, it is revealed that in both cases of r_i/r_o = 0.25 and 0.35, the dominant length scale in MHD cases is the same as that in non-magnetic cases in the range of Rayleigh number where dynamo is not sustained, 1.0 Ra_{crit} <Ra <1.9 Ra_{crit} in r_i/r_o = 0.25 and 1.0 Ra_{crit} <Ra <1.3 Ra_{crit} in r_i/r_o = 0.35. Ra is the Rayleigh number and Ra_{crit} is the critical Rayleigh number. It is also found that the scale of structure in non-magnetic cases gets larger than that in the Ra range of non-sustained dynamo cases, but that in MHD cases is comparable to non-sustained dynamo cases in the range of Rayleigh number where dynamo start to be sustained, in both cases of aspect ratios, 2.2 Ra_{crit} <Ra <2.8 Ra_{crit} in r_i/r_o = 0.25 and 1.5 Ra_{crit} <Ra <2.0 Ra_{crit} in r_i/r_o = 0.35. It is specifically shown that the dominant mode in thermal convection is changed from m = 2 to m = 1 in r_i/r_o=0.25 and from m = 4 to m = 3 in r_i/r_o=0.35 with Ra increasing. On the other hand, it is also shown that the dominant mode in dynamo cases convection remains for m = 2 in r_i/r_o = 0.25 and m = 4 in r_i/r_o = 0.35. These results show that the mode of maximum growth rate depends on Ra and initial magnetic field. In order to understand the structure of convection, it is needed to investigate what modes are easy to grow. It is known that the critical Rayleigh number in a rotating spherical shell is a function of the spherical harmonic degree, the aspect ratio, and the Ekman number [e.g., Bisshop, 1958; Chandrasekhar, 1961; Roberts, 1968; Busse, 1970]. We also compare the results of our simulations in thermal convection with these studies.

地球の固有磁場は外核における鉄流体の対流によるダイナモ作用によって維持されていると考えられている。外核の大きさは地質学的年代で見ると変化してきた。すなわち、約 10 億年前以前には内核が存在しなかったのが約 10 億年前に内核が形成され、その後現在まで成長してきたと熱進化モデル計算から議論されている [e.g., O'Rourke and Stevenson, 2016]。ジオメトリーの変化はその年代ごとに外核対流が変化してきた可能性を示すが、地球ダイナモは過去約 35 億年間維持されてきたことが古地磁気解析から明らかになっている [e.g., Biggin et al., 2015]。内核が現在より小さい、過去の地球に対応する回転球殻中のダイナモの性質を明らかにすることは過去環境の解明の上でも磁気流体力学的にも重要である。しかしながら、ダイナモ発生条件について考察した Heimpel et al.(2005) などはあるものの十分研究が進んでいない。そこで我々は、数値ダイナモコード Calypso[Matsui et al., 2014] を使用して 3 通りの異なる外核 (r_o) 内核 (r_i) 半径比、つまり r_i/r_o=0.15,0.25,0.35(現在) において磁場なし熱対流計算とダイナモ計算を実施した。実現される対流構造を把握するために、King and Buffett (2013) を参考に経度方向の流れの典型的なスケールを計算した結果、r_i/r_o=0.25 では 1.0 Ra_{crit} <Ra <1.9 Ra_{crit} において、また r_i/r_o=0.35 では 1.0 Ra_{crit} <Ra <1.3 Ra_{crit} において、つまり r_i/r_o=0.25,0.35 のいずれの場合にもダイナモが維持されない程の小さいレイリー数 (Ra) では磁場なし熱対流も MHD 計算もスケールは変わらないことが示された。ここで、Ra_{crit} は臨界レイリー数を表す。さらに、Ra を徐々に増加させダイナモが生じ始める条件付近、すなわち r_i/r_o=0.25 では 2.2 Ra_{crit} <Ra <2.8 Ra_{crit} において、r_i/r_o=0.35 では 1.5 Ra_{crit} <Ra <2.0 Ra_{crit} においてスケールを計算した結果からは、いずれの外核内核半径比でも熱対流の構造が Ra の小さい条件での計算結果に比べて大きくなる一方で、MHD 計算での構造は大きな変化は認められないことが示された。すなわち、r_i/r_o = 0.25 の場合には熱対流の支配的なモードが Ra の変化に伴い m=2 から m=1 へ、r_i/r_o=0.35 の場合には m=4 から m=3 へと変化する一方で、MHD 計算では、いずれの Ra においても支配的なモードが r_i/r_o=0.25 の場合には m=2、r_i/r_o=0.35 の場合には m=4 となることが示された。以上の結果は熱対流において成長率が最大となるモードが Ra の増加に伴い変化したことを示しており、どういう状況でどのモードが成長しやすいかを調べることが、実現される対流の様子を理解する上で重要である。そこで本研究では、線形項のみを考慮した熱対流シミュレーションを実施して比較することにより、最大成長モードの Ra 依存

性について考察する。過去の研究では、回転球殻熱対流において臨界レイリー数は球面調和関数の次数と内核外核半径比、エクマン数の関数になることが示されており [e.g., Bisshop, 1958; Chandrasekhar, 1961; Roberts, 1968; Busse, 1970]、これを参考に磁場なし熱対流の場合に得られている我々のシミュレーション結果を比較検討する。さらに、磁場なし熱対流とダイナモのシミュレーション結果を比較することにより、対流に与える磁場の影響についても考察する。

A core surface flow and acceleration model toward building IGRF-13SV

Masaki Matsushima[1]; Hisayoshi Shimizu[2]; Futoshi Takahashi[3]; Takuto Minami[4]; Shin'ya Nakano[5]; Hiroaki Toh[6]
[1] Dept Earth & Planetary Sciences, Tokyo Tech; [2] ERI, University of Tokyo; [3] Kyushu Univ.; [4] ERI, Univ. Tokyo; [5] The Institute of Statistical Mathematics; [6] DACGSM, Kyoto Univ.

The International Geomagnetic Reference Field (IGRF) is a standard mathematical description in terms of spherical harmonic coefficients, known as the Gauss coefficients, for the Earth's main magnetic field and its secular variation. It is used not only for scientific studies but also for practical application, such as navigation and physical surveys. We are going to submit a candidate model to the next IGRF revision, the 13th generation of IGRF (IGRF-13), in 2020. We plan to model a geomagnetic secular variation (SV) rather than the geomagnetic field itself using our strong points, such as geodynamo numerical simulations, data assimilation, and core surface flow modeling.

To predict a geomagnetic secular variation, a geomagnetic secular acceleration, the second derivative of the geomagnetic field with respect to time, must appropriately be described. The geomagnetic secular acceleration is given by the time derivative of the magnetic induction equation, in which not only core fluid velocity but also core fluid acceleration should be investigated.

According to Fournier et al. (2015), core fluid acceleration could be neglected to forecast the geomagnetic secular variation through data assimilation to build a candidate model of IGRF-12. It should be pointed out, however, that this procedure might not be applicable to a period during which a geomagnetic jerk, defined as a sudden change in the geomagnetic acceleration, occurs. That is, acceleration of core fluid is likely to have a large effect on the geomagnetic secular acceleration.

Hence, in this presentation, we attempt to model the velocity and acceleration of core fluid near the core surface toward building IGRF-13SV. Modifying the method of Matsushima (2015), we estimate fluid acceleration as well as fluid velocity inside and below the viscous boundary layer at the core-mantle boundary from geomagnetic field models. This leads to estimation of the first and second derivatives of the radial component of geomagnetic field inside and below the viscous boundary layer. Then we investigate influence of fluid acceleration on the geomagnetic secular acceleration related with short-term geomagnetic secular variation. The velocity and acceleration of core fluid can be used as an initial state in geomagnetic data assimilation and geodynamo numerical simulations.

SVM法による月・火星・水星・地球の磁気異常マッピング

綱川 秀夫 [1]
[1] 東工大・理・地惑

Magnetic anomaly mapping of Moon, Mars, Mercury and Earth with SVM method

Hideo Tsunakawa[1]
[1] Dept. Earth Planet. Sci., Tokyo TECH

Magnetic field observations by spacecraft showed many magnetic anomalies on Moon, Mars and Mercury (e.g. Coleman et al. 1972; Connerney et al., 2005; Johnson et al., 2015) as well as Earth (e.g. Maus et al., 2007). These magnetic anomalies are considered as crustal origin, yielding valuable information about the crustal structure and the ancient global magnetic field. We have developed Surface Vector Mapping (SVM) method to provide magnetic anomaly maps from datasets observed at various altitudes (Tsunakawa et al., 2014, 2015). Global and/or regional maps of magnetic anomalies with SVM method will be reported for Moon, Mars, Mercury and Earth.

人工衛星による月・火星・水星の磁場観測から、磁気異常の存在が報告されている（e.g. Coleman et al. 1972; Connerney et al., 2005; Johnson et al., 2015）。いずれも地殻物質起源の磁気異常であり、地殻構造や過去のグローバル磁場について多くの情報をもたらすと考えられている。本研究では、人工衛星など上空から観測した月・火星・水星・地球の磁気異常データに SVM 法を適用した結果を紹介する。

従来の月磁気異常グローバルマッピングは高度 30 km のものであり（e.g. Richmond and Hood, 2008; Purucker, 2008)、月表面でマッピングされた地形図・地質図・元素鉱物図と比較すると空間分解能が不足していた。分解能の向上を図るため、月磁場観測データの解析法として Surface Vector Mapping (SVM) 法が考案された（Tsunakawa et al., 2014）。SVM 法の特徴は、(1) 様々な高度における磁場観測データから月表面の動径成分磁場を求める逆境界値問題として取り扱うこと、(2) 得られた磁場動径成分の分布から月表面 3 成分の磁場を求めること、(3) ベイズ統計を適用してノイズ成分の効果的な除去を可能にしたことにある。

SVM 法を月周回衛星 Kaguya、Lunar Prospector の全球観測データ（10-45 km 高度）に適用し、月表面の磁場 3 成分グローバルマッピングを行った（Tsunakawa et al., 2015）。得られた結果に基づき、磁気異常分布と地形との相関（e.g. Halekas et al., 2002）、月極移動の可能性（e.g. Takahashi et al., 2014）などを詳細に検討した。また、SVM 磁気異常分布から、月周辺空間における磁気異常起源磁場を容易に計算することができ、月周辺プラズマ環境の解析に使われている。

Mars Global Surveyor の火星磁場観測データ（高度約 400 km）にも、SVM 法を適用した。解析の結果、火星の磁気異常は従来のモデルよりも短波長の構造を持つこと、地形標高と全磁力に相関が見られることが示唆される。また、MESSENGER による水星磁場観測データ（北半球の中高緯度地域、高度 10-60 km）に SVM 法を適用し、スポット状磁気異常の存在を確認した。

地球の海洋磁気異常については、船舶・航空機・人工衛星により膨大な観測が蓄積されており、グローバル磁気異常図も公開されている（e.g. Maus et al., 2007）。本研究では、詳細に観測されている東北日本の太平洋沖に着目し（Nakatsuka and Okuma, 2007）、太平洋プレートの沈み込みに伴う海洋磁気異常（Oshima and Kasuga, 1988）をスラブ上面にマッピングすることを試みた。解析法としては、全磁力磁気異常からスラブ上面の磁気ポテンシャルを求める方法（SVMp 法）を考案した。三陸沖の強い磁気異常を避けて解析する必要があり、解析対象地域のスラブ深度は約 25km までである。予察的解析で得られた海洋磁気異常パターンには、スラブ深度や地域による差異が見られ、スラブあるいはその上側にある陸側地殻の磁化構造に関する情報が期待される。

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

辻本 元博 [1]
[1] なし

Analyzing the geomagnetic declination in 19 century Japan from Santou Houi Ki recorded by Inoh. 7th report

Motohiro Tsujimoto[1]
[1] none

The Santou Houi Ki is a national treasure of Japan, consist of 67 volumes ledger of approximately 200,000 magnetic compass survey azimuth data by 0 degree 5 minute unit in 1800 to 1816,cover from eastern Hokkaido to Yakushima recorded by map surveyor Tadataka Inoh. We executed the inter disciplinary and simultaneous analysis of real azimuth, magnetic declination, precise position of target points and the survey reference point where the value of magnetic declination to any target points are similar or approximation. We analyzed the magnetic declination at 227 points in Japan. In the World, there are lack of declination data in Japan from middle 17 century to middle 19 century equal to the term of national isolation of Japan. It is necessary to introduce the declination data analyzed from Santou Houi Ki to Historical Declination Viewer according to Gufm1 by Andrew Jackson et al. Add the comparison table of both geomagnetic declination data in 1800 to 1816 in each region from Honshuu to Kyuushuu.

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。測量対象地点緯度経度、測量実施基点緯度経度、真方位、地磁気偏角を同時解析する。測量実施基点から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位置を逆算して日本の 227 地点で地磁気偏角を解析した。　欧米では日本が鎖国した 17 世紀中期から１９世紀中期迄の日本の地磁気偏角のデータが不足している。その為山島方位記からの解析値をアンドリユー・ジャクソンらの Gufm1 に基づく NOAA アメリカ海洋大気庁の Historical Declination Viewer に導入する必要がある。1800 年から 1816 年迄の本州から九州の各地での両方の地磁気偏角データの比較表を付す。

Dating of tsunami boulders from Ishigaki and Tongatapu Islands

Tetsuro Sato[1]; Norihiro Nakamura[2]; Kazuhisa Goto[3]; Yuho Kumagai[4]; Hiroyuki Nagahama[5]; Koji Minoura[4]
[1] AIST; [2] IEHE, Tohoku Univ; [3] IRIDeS, Tohoku Univ.; [4] Earth Science, Tohoku Univ.; [5] Earth Sciences, Tohoku Univ.

Fields of reworked boulders are amongst the most impressive sedimentary evidence of past catastrophic tsunami and extreme storm events. Dating the deposition time of these boulders enables prediction of frequency-magnitude patterns of high-energy wave events. Although large radioisotopic age datasets from marine organisms reveal the reworking history at some sites, it is debated how one or several events are identified from individual boulders. As an attempt to overcome challenges for dating the dislocation of single boulders, we used a viscous remanent magnetization (VRM) dating method. Reworked boulders are expected to acquire a VRM approximately parallel to the geomagnetic field. The magnitude of such a VRM depends on several factors, including the time since reworking and ambient temperature for which there are well-known theoretical relationships. VRM unblocking temperatures can, therefore, be a powerful tool for determining the reworking age of boulders and can be used to assess geological hazards. In this study, VRM unblocking temperatures of samples from Ishigaki and Tongatapu Islands are compared with two candidate time–temperature relationships for VRM acquisition. The Pullaiah nomogram is applicable to assemblages of single-domain magnetite particles. Based on the Pullaiah nomogram, some samples appear to have anomalously high VRM unblocking. To estimate reworking ages of anomalous boulders, we use an alternative time–temperature relationship defined by a stretched exponential law. This approach is applicable to assemblages of single-domain, vortex state, and multi-domain magnetite particles. Moreover, we measured first-order-reversal curve (FORC) diagrams to confirm domain state. We suggest that future VRM dating can be undertaken using a combination of two time-temperature relationships and FORC diagrams.

R004-16 **会場: B** **時間: 11月24日 16:15-16:30**

房総半島のブルン松山地球磁場逆転境界の熱消磁による極性判定；FORC解析による磁性鉱物同定と加熱による磁性鉱物変化の検出

小田 啓邦 [1]; 中里 裕臣 [2]; 佐藤 哲郎 [3]; 七山 太 [3]
[1] 産総研・地質情報; [2] 農研機構; [3] 産総研

Primary remanent magnetization during Matuyama-Brunhes reversal from Boso Peninsula: Change of magnetic minerals detected by FORC

Hirokuni Oda[1]; Hiroomi Nakazato[2]; Tetsuro Sato[3]; Futoshi Nanayama[3]
[1] IGG, GSJ, AIST; [2] NARO; [3] AIST

We report magnetostratigraphy from an outcrop in Boso Peninsula, which is considered to record Matuyama-Brunhes polarity transition. The outcrop is ˜4m height, facing west and situated along a roadside in Terasaki, Chiba Prefecture, Japan. The sediment mainly consists of massive silt of Kokumoto Formation, Kazusa Group. The outcrop shows several tephra layers including TNTT (Byk-E) residing close to Matuyama-Brunhes polarity transition (e.g. Suganuma et al., 2015; Okada et al., 2017).

In order to identify the polarity of primary remanent magnetization recorded, we have taken 55 paleomagnetic drill cores at intervals of 1-10 cm. Progressive alternating field demagnetization (PAFD) was conducted on all sub-samples taken from the drill cores. The higher coercivity (>20 mT) magnetization component has mostly positive inclination (normal polarity) and shows a swing to negative inclination (reversed polarity) at 76-91 cm below TNTT. Progressive thermal demagnetization shows sharp drop in remanent magnetization by heating up to 175 degC. By heating above 175 degC, magnetization decreases gradually up to 300˜350 degC and becomes unstable above 300˜350 degC. According to the experimental protocol proposed by Okada et al. (2017), ThD followed by AFD was conducted in order to extract primary remanent magnetization hidden by the secondary magnetization both in vacuum and in air. The extraction of primary remanent magnetization was only partially successful, however, the polarity boundary could be located within +-50cm from the tephra layer Byk-E.

FORC analyses on bulk samples and principle component analyses (PCA; Lascu et al., 2015; Harrison et al., 2018) show at least three components. The three components are considered to be dominated by multidomain magnetite, single domain/vortex state (PSD) magnetite, or greigite with coercivities higher than magnetite (up to 200˜300 mT). Volcanic ash layer shows highest proportion of multi-domain magnetite. In order to understand the difficulty of thermal demagnetization, we heated a bulk sediment sample up to 400 degC in air and monitored using FORC diagrams with PCA. The results show a decrease of greigite component during heating accompanied by a sudden decrease at 350 degC. By heating from 350 degC to 400 degC, significant amount of low coercivity (0˜30mT) magnetic mineral was formed.

Absolute and relative paleointensity variations at the Matuyama-Brunhes transition from the Haleakala lava sequence on Maui

Nobutatsu Mochizuki[1]; Robert S. Coe[2]; Brian R. Jicha[3]; Brad S. Singer[3]
[1] Kumamoto University; [2] University of California, Santa Cruz; [3] University of Wisconsin-Madison

Sequences of lava flows are one of the best materials to recover accurate and precise paleomagnetic field behavior across the Matuyama-Brunhes (M-B) transition, because successive lava flows can provide temporal variations of intensity as well as direction combined with 40Ar/39Ar dating. This study has made paleointensity measurements on samples from the Haleakala lava sequence on Maui, which records the M-B transition (Coe et al., 2004). The Tsunakawa-Shaw method (previously we call the LTD-DHT Shaw method) was applied to 35 specimens of 20 lavas. Ten specimens passed the selection criteria. 11.8 +/-0.1 microT (N=2) and 4.8 microT (N=1) were obtained for two lavas recording the transitional directions. 25.1 +/-0.6 microT (N=4) and 28.3 +/- 1.1 microT (N=2) were determined for two lavas recording normal polarity, just after the transitional field. It appears that the selection criteria are too strict for the samples recording the M-B transition since the samples probably acquired a weak TRM in a weak field. Thus, we also applied a slightly relaxed criteria to the results; six results passed the relaxed criteria. For the flows recording the transitional behavior, mean of paleointensity estimates is 6.0 +/- 3.9 microT (N=9). We also check paleointensity estimates without such criteria. These estimates, which are the same as Rolph and Shaw (1985) paleointensity estimates, are consistent with the estimates with the strict criteria and those with slightly relaxed ones. It should be also noted that NRM/ARM values have a good correlation with the absolute paleointensity estimates by three variants of Shaw method noted above. Thus, the NRM/ARM values can be used as another indicator of paleointensity variation. On the basis of these absolute and relative paleointensity estimates from Haleakala on Maui, combined with those from Tahiti (Mochizuki et al., 2011), we will discuss the characters of paleointensity variation across the M-B transition. We have re-dated the Haleakala lava sequence such that relative to astronomically-calibrated 28.201 Ma age of the Fish Canyon sanidine standard; the 40Ar/39Ar age of this lava sequence that records the last stage of the M-B transition is 772 ± 2 ka (2 sigma).

R004-18 **会場: B** **時間: 11 月 24 日 16:45-17:00**

中国レスの高精度気候層序に基づく Matuyama-Brunhes 地磁気逆転の解析

兵頭 政幸 [1]; 番匠 健太 [2]; 安田 裕紀 [1]; 楊 天水 [3]
[1] 神戸大・内海域; [2] 神戸大・理・惑星; [3] 中国地質大・地球科学

Analysis of Matuyama-Brunhes reversal based on high-resolution climatostratigraphy of Chinese loess

Masayuki Hyodo[1]; Kenta Banjo[2]; Yuki Yasuda[1]; Tianshui Yang[3]
[1] Research Center for Inland Seas, Kobe Univ.; [2] Planetology, Kobe Univ.; [3] Earth Sciences, China Univ. Geosciences

http://www.planet.sci.kobe-u.ac.jp/geol/hyodo.html

Multiple millennial-to-centennial scale paleoceanic and climatic events were recently found in the Marine Isotope Stage (MIS) 19 interglacial, in which the Matuyama-Brunhes (MB) geomagnetic reversal occurred. The events enable to construct a detailed chronostratigraphy for MIS 19. We applied the method to the summer monsoon (SM) record from a 7-m thick loess-paleosol sequence of Lingtai in the Chinese Loess Plateau. As a result, we obtained bi- to sub-centennial resolution records of the MB transition as well as of the East Asian monsoon. Progressive thermal demagnetizations at 15 steps for all samples show stable decay curves of magnetic vectors, yielding reliable paleomagnetic field directions with MAD of 3.0 in average by principal component analysis. Transitional magnetic fields, defined as those having directions with a virtual geomagnetic pole (VGP) latitude deviated by > 45 degrees from the pole, lie within a 60-cm thick section between the SM peak of S8 and the SM minimum of L6, correlated with sea-level highstand MIS 19.3 and lowstand MIS 19.2, respectively. This directional transition zone consists of a main polarity boundary, two precursor episodes, and a rebound episode. The new chronostratigraphy date the main MB boundary at about 778 ka, and the directional transition zone to range from about 779 to 777 ka. The durations of episodes are estimated to be about 100 years. The VGPs of Lingtai have a cluster in the southwest Pacific together with those from Java, Hawaii, and Canary.

地磁気逆転と山陰海岸ユネスコ世界ジオパーク

井口 博夫 [1]
[1] 兵庫県立大・地域資源

Geomagnetic reversal and the San'in Kaigan UNESCO Global Geopark

Hiroo Inokuchi[1]
[1] Regional Resource Management, Univ. of Hyogo

A geopark is a kind of natural park containing geological heritage that has great scientific importance and value or that is simply beautiful to look at. Geological and geomorphological conditions not only reflect the earth's history but also have direct relevance to people's lives and cultures. Geoparks help us learn about and enjoy the earth's activities as a set of heritages. The San'in Kaigan UNESCO Global Geopark (UGG) obtained admission to the GGN in 2010. The San'in Kaigan UGG was readmitted to the GGN in 2014. The GGN became an official program of UNESCO in 2016.

A geological heritage that has great scientific importance in the San'in Kaigan UGG is the Genbudo Cave in Toyooka City, Hyogo Prefecture. Genbudo Cave is the place where it was discovered that geomagnetic reversal occurred in the Quaternary. Dr. Motonori Matuyama of Kyoto University discovered that basalt at Genbudo Cave exposed by a volcanic eruption about 1.6 million years ago had a polarity opposite to the present geomagnetic field in 1926. This discovery indicated that there was a period in which the earth's magnetic field was opposite to what it is today. Called ”””"Matuyama reversed chron"”””, the discovery of reversal geomagnetic field has greatly contributed to the development of the theory of plate tectonics. An international agreement was made to recognize the Matuyama reversed chron as indicating the beginning of the Quaternary era, making it an index to be used for determining the boundary between two different geological eras in 2009.

Graduate School of Regional Resource Management was established in 2014. It is composed of geologists managing the geopark ecologists reintroducing the oriental white storks into the wild and sociologists studying community development. Geo-stories in the geopark are provided by geological, ecological and social studies. Collaborations of these different study fields will improve the understanding on the geopark.

Genbudo Cave is composed of basaltic lava with beautiful columnar joints and a representative geoheritage in San'in Kaigan UNESCO Global Geopark. Genbudo Basalt is located on both banks of large river called Maruyama-gawa and is hard to erode in comparison to the rocks in around area. Therefore, valley become sharply narrow at the Genbudo area and wide basin (Toyooka Basin) spreads in the upstream side of the Genbudo. Most of Toyooka Basin become extensive wetlands and rice fields and provide prey fields for oriental white storks. Japanese native oriental white storks became disappear in the wild field in 1971, but they have been bred by Hyogo Park of the Oriental White Stork and released into the wild for the first time in 2005.

Willow (withy) growing naturally in wetland is used for wicker trunk in the past. This technology has been applied in current manufacture of bags which are major local industry in this area.

Next Geo-story is relationship between geology and food. Catching of snow crab and breeding of Japanese beef cattle are representative primary industry in the San'in Kaigan UGG. Furthermore, there are many sake breweries in the Geopark. They are closely related to geology of the Geopark.

Main theme is ”””"Geological features, the natural environment, people's lives and the formation of the Sea of Japan"”””.

「ジオパーク」は単なる自然公園ではなく，地形・地質が美しいだけでなく科学的に価値のある地質遺産を含む地域のことである．その地域の地質や地形の形成の過程や歴史が明らかにされているというだけでなく，地形や地質と人々の暮らしや文化の関係が明らかにされ，楽しく学べる地域である．山陰海岸ユネスコ世界ジオパークは，2010 年に世界ジオパークに認定され，2014 年に再認定されたユネスコ世界ジオパークである．世界ジオパークは 2016 年からユネスコの正式プログラムとなった．

山陰海岸ジオパークで世界的に価値がある地質遺産は兵庫県豊岡市の「玄武洞」であり，第四紀における地球磁場の逆転の発見につながった場所である．1926 年，京都帝国大学の松山基範博士は，約 160 万年前の火山活動で形成された玄武洞の玄武岩が，現在の地球の磁場と反対の方向に磁化していることを発見し，この発見をきっかけに，磁場が現在の向きとは反対の時代があったことを示した.「松山逆磁極期」と呼ばれ，松山先生の発見が地球科学におけるプレートテクトニクス説の構築に大きく寄与したことは言うまでもない．また，2009 年 6 月には，地質年代である「第四紀」の始まる時期について，松山逆磁極期を一つの目安として国際的に合意が得られており，地質年代の境を決める指標の一つとしても使われている．

兵庫県立大学大学院地域資源マネジメント研究科は，2014 年にジオパークをはじめとする地質資源とコウノトリの野生復帰などの生物資源と社会や文化資源を総合的に理解して科学的に地域資源を活用することを目的として設立された．ジオパークにおいては，地形・地質資源と生物資源・社会文化資源の関係を“ ジオ・ストーリー ”として，ジオパーク内の地域資源を理解するために重要であると考えている．

玄武洞は柱状節理の美しい場所であり，ジオパーク内の観光地であるが，浸食されにくい玄武洞溶岩や流紋岩体が円山川の河口付近の川幅を狭め，浸食されやすい花こう岩体や第三紀の堆積岩・火山岩類が分布する上流側で広い谷を形成し盆地地形（豊岡盆地）を呈す．豊岡盆地が湿地であったことと一度は日本の空からいなくなったコウノトリが最後まで野外に見られたことや豊岡の主要な産業である鞄産業と関係していること，さらに，豊岡での地震災害や洪水と

の関係をジオ・ストーリーとして紹介する．

また，山陰海岸ジオパーク内で主要な食材であるズワイガニ，但馬牛そして日本酒と地質の関係について紹介する．山陰海岸ジオパークのメインテーマは「日本海の形成に伴う多様な地形・地質と人々の暮らし」である．

『日本の地球電磁気学の歴史 －IGY の前までを中心にして－』の著書計画について

永野 宏 [1]; 佐納 康治 [2]
[1] 朝日大学; [2] 朝日大・経営

On a project of reviewing ””History of geomagnetic researches in Japan - focusing on the history before IGY””

Hiroshi Nagano[1]; Yasuharu Sano[2]
[1] Asahi Univ.; [2] Asahi Univ.

The present prosperity of geomagnetism and planetary science is often told as the fruit of modern scientific activities during and after IGY (International Geophysical Year), such as Antarctic expeditions, rocket observations, or launch of satellites. This, however, does not mean that geomagnetism blossomed out suddenly after IGY. It could develop after IGY, owing to, and also based on, the large achievements for which the scientists of former years have exerted themselves for a number of centuries. Actually, observations of terrestrial magnetism, atmospheric electricity, and earth current have already started in early Meiji Era. In Showa Era, our country participated in The Second International Polar Year, and observations of ionosphere and atmospherics also begun around this time. Hence, it may be quite significant to reveal all the history after Meiji Era concerning to geomagnetism in Japan. The authors have been reviewing the whole history of geomagnetism in Japan for many years, with our manuscript finally arriving at the stage of describing the post-war history before IGY.

The outstanding feature of geomagnetic studies in Japan can be seen in its close relationship with international research activities. In early Meiji Era, young scientists of high abilities came to Japan as ””foreign advisors hired by Japanese government”” with recommendation by Professor W. Thomson (later Lord Kelvin) at the University of Glasgow in United Kingdom. They taught many fields of science and technology including experimental physics at University of Tokyo and at the Imperial College of Engineering, bringing the Scottish liberal atmosphere into education. Excellent students were sent to Europe by the Japanese government after graduation, to study more in their specialty. They became eminent scientists after coming back to Japan, for example, R. Shida, who observed earth current in Japan during the First Polar Year observation period. Aikitu Tanakadate, known as the pioneer of geomagnetism in Japan and also known as the inventor of electro-magnetic declinometer, also went to the United Kingdom from 1888 to study under W. Thomson and A. Schuster. Tanakadate became one of the members of Committee on Terrestrial Magnetism and Atmospheric Electricity which was established in 1896 in the International Meteorological Organization (present World Meteorological Organization). It was the first international scientific committee for geomagnetic researches. Geomagnetic study in Japan is thus inseparably related to the global research network, so the authors paid enough attention to referring to the world-wide trend of geomagnetic researches as well as to that of Japan.

Our book will consist of nine chapters; chapters one to seven are provisionally completed. Historical periodizations adopted in our investigation are as follows:

Chapter 1. Prehistory of geomagnetism until the end of Edo Era (until 1850)
Chapter 2. Dawning of geomagnetism in Japan (from 1850 to 1891)
Chapter 3. Creation of geomagnetism in Japan (from 1891 to 1912)
Chapter 4. Extension of geomagnetism in Japan (from 1912 to 1926)
Chapter 5. Japanese participation in the Second International Polar Year (from 1926 to 1940)
Chapter 6. Geomagnetic researches in Japan during the World War II (from 1940 to 1945)
Chapter 7. Foundation of Society of Terrestrial Magnetism and Electricity of Japan (from 1945 to 1957)

Chapter 7 is published on the web, and is linked to the homepage of SGEPSS, as is presented in the bulletin of SGEPSS No.233 (July, 2018). The authors are deeply grateful to Prof. T. Araki (professor emeritus of Kyoto University) and to the steering committee of SGEPSS.

Remaining two chapters (Chapter 8. Large development of geomagnetism in Japan at the time of IGY; Chapter 9. Prosperity of geomagnetism in Japan after IGY) will also be coming in near future.

現在の地球電磁気学・地球惑星圏学の大発展は、IGY でのロケット観測やそれ以後の人工衛星での観測、また、南極での観測など、IGY を契機とした成功が大きく関係している。だからといって、我々の学問が IGY から始まったわけではなく、その成功の基礎には、明治以来の地磁気や地電流・空中電気の観測、国際極年観測などのエポックとなる事柄や、昭和に入ってから開始された電離層観測や空電の観測など、多方面での地球電磁気学の発展が関係していた。それゆえ、現在の大発展の基礎となる、明治以来の我が国の地球電磁気学の歴史を明らかにすることは極めて重要であると云える。我々は長年、「日本の地球電磁気学の歴史（IGY の前までを中心にして）」に取り組んできたが、漸く執筆が学会創成期の戦後の部分（IGY 以前）に辿り着いた。

さて、我が国の地球電磁気学の発展の特徴としては、早くから国際的な研究ネットワークに組み込まれていたことが挙げられる。英国グラスゴー大学教授 W. トムソン（後のケルビン卿）が、若い優秀な学者を明治政府が要請したお雇い外国人教師に推薦し、彼らは東京大学や工部大学校で自由な実験物理学重視のスコットランド教育を実践した。そして優秀な卒業生が、グラスゴー大学などへ留学し、帰国後大いに活躍することとなった。例えば初期の頃には、電気工学者

ではあるが、第一回国際極年で地電流観測を行った志田林三郎が挙げられる。また、我が国の地球電磁気学の開祖である田中舘愛橘も 1888（明治 21）年に英国に留学し、トムソンやシュスターからの指導を受け、帰国後には、学んできたことを生かして磁力計開発を行った。地球電磁気学の国際的な最初の委員会は、国際気象委員会の下に 1896（明治 29）年に設置された「国際地球磁気及び空中電気分科会」であるが、田中舘愛橘は 1910（明治 43）年にこの分科会の委員となっている。このように、我が国の地球電磁気学の発展史は、世界の地球電磁気学の動向と密接に結びついており、我々は、関連する国際的な地球電磁気学の動向にも注意を払った。

各章の時代区分は下記のようであり、漸く第 7 章までを、未完ではあるが、一応執筆することができた（括弧内に内容の一部を記す）。

第 1 章　幕末までの地球電磁気学前史（～1850 年頃）
（『本草和名』中の磁石の記述、谷秦山、荒井郁之助らによる偏角観測など）
第 2 章　日本の地球電磁気学の黎明期（1850 年頃～1891（明治 24）年頃まで）
（第一回国際極年観測、田中舘愛橘によるエレクトロマグネティック方位計など）
第 3 章　日本の地球電磁気学の形成期（1891（明治 24）年頃～1912（明治 45）年頃まで）
（震災予防調査会での地磁気観測、田中舘愛橘による全国地磁気測量の結果報告など）
第 4 章　日本の地球電磁気学の成長期（1912（大正元）年頃～1926（大正 15）年頃まで）
（柿岡地磁気観測所の開設、国際的な SC 調査委員会での田中舘愛橘の活躍など）
第 5 章　第二回国際極年を契機とした発展（1926（昭和元）年頃～1940（大正 15）年頃まで）
（第二回国際極年観測、畠山久尚と長谷川万吉の地磁気研究、電離層観測など）
第 6 章　戦時体制下での地球電磁気学（1940（昭和 15）年頃～1945（昭和 20）年頃まで）
（永田武の岩石磁気の研究、電波物理研究所の設立と戦時研究など）
第 7 章　日本地球電気磁気学会の創設（1945（昭和 20）年頃～1957（昭和 32）年頃まで）
（電波物理研究所の存続と廃止、日本地球電気磁気学会の創設など）

第 7 章は、学会会報（第 233 号、2018 年 7 月）にあるように、荒木徹先生（京都大学名誉教授）のご支援と、運営委員会のご厚意とにより、学会 HP へリンク掲載されている。

また、この後は、「第 8 章　IGY での大躍進（1957 年頃～1967 年頃まで）」と、「第 9 章　その後の日本の地球電磁気学の大発展（1967 年頃～現在）」とを予定している。

古地磁気・岩石磁気用データプロットツール

畠山 唯達 [1]
[1] 岡山理大・情報処理セ

Online/offline plotting tools for paleomagnetic and rock magnetic data

Tadahiro Hatakeyama[1]
[1] IPC, Okayama University of Science

http://mage-p.org/mageplot/

In paleomagnetism and rock magnetism, we use some types of the plotting method which is not hardly used in other area of Earth sciences. To plot those data, specific tools which are bundled with the instruments and distributed among the researchers. Almost all tools depend on the computational environments; e.g. working only on a specific operating system or demanding to install a specific library. Here we introduce a web-service including plotting tools for the data obtained in paleomagnetism and rock magnetism. In the web service, the user interface (UI) is a web browser. All web browsers widely distributed are based on the common protocol and display almost same look and feel. In our plotting service, the user can copy the data from their own spreadsheet program (e.g. Microsoft Excel) and paste to the text box in the input page, and get the plotting results in the image formats of PDF, EPS and PNG. Now we provide four plotting tools on our site; the Zijderveld diagram of stepwise demagnetization in paleomagnetism, the plot of paleomagnetic directions and their means on an equal-area projection, the plot of thermo-magnetic analysis by the Curie balance (Natsuhara Giken, NMB-89), and the hysteresis loop by the vibrating sample magnetometer (PMC MicroMag 2900/3900). Here, we will also introduce the source code of the plotting programs working on the local machine.

古地磁気学・岩石磁気学では他の地球科学分野ではほとんど使用しない特殊なプロットや機械からの出力を表示することが多い。そのようなデータをキレイにプロットするために、機械に付属したものや、研究者間で配布されている専用のプロットツールがいくつも開発され流布している。しかしそれらの多くは特定のプラットフォーム（OS）や特別なライブラリを必要とするため、共同研究者間でもプロットの共有をすることが困難である場合が多い。そこで我々は、プロットするためのツールを開発するのに加え、ウェブサービス用のフロントエンドを開発し、ネットワークにつながっていてウェブブラウザを使用すれば誰でもどこからでもデータをプロットできるようなシステムを構築した。このサービスを使えば、ユーザは解析とプロットを行うバックエンドで使うツール（Linux, Perl, GMT, gnuplot など）をインストールすることなく、データを解析し描画することができる。プロットしたグラフなどは、PDF, EPS, PNG の各形式でダウンロードして自分で加工することもできる。

今回は、一昨年の大会で発表した消磁曲線（ザイダーベルトダイアグラム）表示、および、古地磁気方位表示（等積投影上）サービスの改良に加え、新たに追加した熱磁気天秤（夏原技研製 NMB-89）の出力や振動磁力計（PMC 社製 MicroMag 2900/3900）の出力に対応したプロットツールの紹介も行う。また、オフラインでも使用できるソースコードの公開も行ったので、それについても紹介したい。

Regularity of recent geomagnetic jerks estimated using wavelet analysis

Hisayoshi Shimizu[1]
[1] ERI, University of Tokyo

Regularity of a time series after a singularity represents the exponent of the function with time that fits the time variation after the singularity. This concept can be applied to represent the characteristics of a geomagnetic jerk that is a sudden variation of secular acceleration of the geomagnetic field components. Wavelet analysis has been applied to identify occurrence time of geomagnetic jerks and their regularities.

The regularity depends on the time variation of the geomagnetic field components at the surface of the dynamo region, i.e., core-mantle boundary (CMB), and also on the electrical conductivity of the mantle, especially its lower part. It has been attempted to use wavelet analysis of geomagnetic jerks to estimate the electrical conductivity of the lower mantle (Alexandrescu, M. et al., 1999), and also to discuss the electrical heterogeneity in the D" region (Shimizu and Utada, 2017, JpGU meetiing). Regularity of a jerk-like magnetic field variation due to geodynamo models has not been examined yet although Manabe and Takahashi (2018, JpGU meeting) were keen to identify magnetic field jerks in a geodynamo model by other method.

The regularity of geomagnetic jerk will become a quantity that should be reproduced by geodynamo modeling, especially that employ geodynamo assimilation to examine dynamical processes in the core and to forecast the future geomagnetic field. In this presentation, we are going to show regularity of recent geomagnetic jerks that occurred around 2003 and 2007 (e.g. Chulliat et al., 2010) and compared these with those occurred around 1969 and 1978. The regularity of recent jerks seems to be higher than the older ones, and this would represent that the dynamical process in the core that produced the recent and older geomagnetic jerks can be different from each other.

Kinematic dynamo associated with a drifting columnar convection

Hinami Taniguchi[1]; Futoshi Takahashi[2]
[1] Kyushu Univ.; [2] Kyushu Univ.

The terrestrial bodies that maintain their intrinsic magnetic fields have dynamos in the fluid cores, in which convection is driven in various ways. In case of the Earth, it is believed that compositional convection, which is fed by light element ejection from the ICB upon inner core growth, is dominant and powers the geodynamo: it is so-called 'bottom-up' type convection. 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 kinematic dynamo associated with a top-down type drifting flow, and solve the kinematic dynamo problem numerically.

Let us consider an electrically conducting fluid contained in a rotating spherical shell, in which the velocity field is prescribed as a drifting columnar flow. The velocity field is obtained by solving a linear stability analysis for top-down type convection as an eigenvalue problem. The imaginary part of the eigenvalue associated with the critical mode gives us the drift rate of columnar convection. The Ekman number and magnetic Prandtl number are $2.0*10^{-4}$ and 0.10 respectively. The control parameter is the magnetic Reynolds number in the kinematic dynamo problem. The induction equation is solved by time-marching with a minute initial dipole field given as a seed. We search for the critical value giving the neutral growth rate of the dipole field to understand a basic feature of the kinematic dynamo driven by top-down type drifting columnar convection. As a result, it is found that the magnetic fields at the onset repeats a periodic change consisting of asymmetric growth and decay phases. In the growing phase, the magnetic energy is dominated by the small-scale components, whereas in the decaying phase the magnetic fields show a large-scale feature dominated by the dipole component. Although numerical convergence is a concern, which should be checked higher resolution calculations, such an asymmetric behavior with respect to time may be associated with geomagnetic excursions and reversals, during which the dipole field is substantially reduced and then, the geodynamo might act in nearly a kinematic manner.

Morphology of dynamos by double diffusive convection with a stably stratified layer beneath the core-mantle boundary

Futoshi Takahashi[1]
[1] Kyushu Univ.

Seismic and geomagnetic observations reveal the presence of a stably stratified layer below the core-mantle boundary. Effects of the stably stratified layer on convective motions in the fluid outer core, and the resultant dynamo processes are investigated to gain insights into the origin of the layer. In this study, we use a dynamo model adopting double diffusive convection with an either thermally or compositionally stably stratified layer. Regardless the origin of the stable layer, of which thickness is 0.1 fold of the core radius, the resultant magnetic fields show weak non-dipolar fields, whereas strong-field dipolar dynamos are obtained in the runs without the stably stratified layer. In order to be compatible with the observed geomagnetic field strength and secular variation, it is suggested that the stably stratified layer should be thinner or more weakly stably stratified. When the compositional driving is dominant as in the present Earth's core, the attenuating effects through the compositionally stably stratified layer is stronger than that through the thermal one. From a viewpoint of the magnetic field, it is suggested that a relatively thin stably stratified layer of thermal origin is preferable.

古地磁気学的手法を用いた富士火山、鷹丸尾火砕流堆積物の噴火推移の解明

馬場 章 [1]; 渋谷 秀敏 [2]; 内山 高 [1]
[1] 富士山研; [2] 熊大・先端科学・地球環境

Elucidation of eruptive sequence of Takamarubi pyroclastic flow deposit at Fuji volcano using paleomagnetic method

Akira Baba[1]; Hidetoshi Shibuya[2]; Takashi Uchiyama[1]
[1] MFRI,Yamanashi Perf.; [2] Dep't Earth & Env., Kumamoto Univ.

http://www.mfri.pref.yamanashi.jp/

For the understanding of volcanic history and prediction of medium- and long-term eruption, detailed elucidation of type, scale, frequency, and sequence of eruption events is very important. Paleomagnetism can contribute especially to determine frequency, based on similarity to the paleomagnetic secular variation model (JRFM2K.1), and time sequence of a series of events, based on the similarity of paleomagnetic directions. Here we report paleomagnetic results of Takamarubi pyroclastic flow deposit which is newly discovered in the field survey at the northeastern foot of Fuji volcano.

Takamarubi pyroclastic flow deposit is located below the Takamarubi lava flow distributed in the JGSDF Camp Kita-Fuji, and can be confirmed from the Yohei-nagare river bed (about 1,430 m high) to the northeastern frank (about 1,120 m high). It has a length of about 3.6km, with the maximum width of 700m and the layer thickness of 2 to 15m. The eruption scale estimated to be about 1,240m^3 in the trial calculation by the average cross-section method. It is about five times as large as the eruption scale of Takizawa B pyroclastic flow deposit (242 m^3: Mt. Fuji volcano hazard map review committee (2002)) used for Mt. Fuji volcano hazard map. From the ^{14}C dating of charcoals under the pyroclastic flow deposit, it is dated as 1,500 $\pm$ 30 yr BP and 1,490 $\pm$ 30 yr BP, which is translated to be around 590 A.D. However, Japanese trees tend to be calibrated older for decades than real age when calibrated with IntCal based on American and European trees (Nakamura et al., 2013), thus we tried to date using a paleomagnetic method.

Samples for paleomagnetic measurements were collected from 3 sites of Takamarubi pyroclastic deposit. They were oriented by a sun compass to eliminate local magnetic anomalies. At each site, we collected 16 to 20 samples using an engine powered core picker. Samples were measured using a spinner magnetometer with alternating field demagnetization (AFD) and thermal demagnetization (ThD). The mean directions of the Takamarubi pyroclastic flow deposit roughly show two distinctive ranges. These are estimated to be two flow units erupted around 600 A.D. and 630 A.D. As a result of ThD, the magnetic minerals are titanomagnetite from the Curie temperature (520 to 580 degrees C.) and flowed at a temperature higher than 580 degrees C. The accessories materials of the pyroclastic flow deposit have high and low temperature components bounded at 420 degrees C. It is clear that the low temperature component coincides with the directions of the essential materials of the pyroclastic flow deposit, so that it was heated in the flowing and stationary process.

Based on paleomagnetic method, Baba et al (2017: SGEPSS) identified that several lava flows erupted between 580 to 700 A.D. from NE-SW eruptive fissures, intermittently. The mean directions of the Takamarubi pyroclastic flow deposit fit with the mean directions of those lava flows, within a95 range. There are possibilities that the 5 units, showing similar petrological features, were simultaneous eruptions. Our findings suggest that paleomagnetic method can clarify the eruption time gap, gradual changes and eruptive sequence of Fuji volcano.

噴火イベントの把握や予測を行うためには，噴火事象の規模や様式，それらの時間変化などを時空間的に理解することが必要である．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，古地磁気方位の変位量から噴火イベントの同時性，時間間隙を捉えられることである．本論では，富士火山北東麓の野外調査において新たに発見された鷹丸尾火砕流堆積物の古地磁気方位の測定結果及びそれから推定される噴火推移に関して議論する．

鷹丸尾火砕流堆積物 (新称) は，富士火山北麓，北富士演習場内に分布する鷹丸尾溶岩流の下位にあり，標高 1,430m の与兵衛流河床から標高 1,120m 地点まで分布域が確認できる．また，露出が確認できるだけでも長さ約 3.6km，最大幅 700m，層厚 2〜15m あり，平均断面法での試算では約 1,240m^3 と見積もられ，富士火山防災マップで試算に用いられた滝沢 B 火砕流堆積物 (242m^3:富士山ハザードマップ検討委員会 (2002)) のおよそ 5 倍の噴火規模と推計される．火砕流下部の炭化木片の ^{14}C 年代測定からは，1,500$\pm$30yr BP，1,490$\pm$30yr BP の年代値が得られ，A.D.590 頃と推定される．一方，日本産樹木は，欧米産樹木に基づく IntCal で較正されると真の年代よりも数十年は古く較正されてしまう (Nakamura et al.,2013)．そのため，古地磁気学的手法を用いた年代推定を行った．

鷹丸尾火砕流堆積物からは，定方位サンプルを 3 サイトから採取した．火山噴出物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，試片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，1 サイト当たり 16〜20 試料を採集し，スピナー磁力計を用いて古地磁気方位を測定した．段階交流消磁実験による鷹丸尾火砕流堆積物の磁化方位は，D=-17.3 ${}^\circ$，I=55.8 ${}^\circ$ を示す 1 サイトと D=-13 ${}^\circ$,I=57 ${}^\circ$ 付近を示す 2 サイトに分かれ，A.D.600 頃と

A.D.630 頃に噴火した 2 回のフローユニットと推定される．また，鷹丸尾火砕流堆積物の定置温度を明らかにするため，段階熱消磁実験を行った．段階熱消磁実験の結果，主要な磁性鉱物はキュリー温度 (520〜580 度) からチタノマグネタイトであり，580 度以上の高温で流下したことが推定される．また，火砕流に取り込まれた類質岩片は，420 度を境に高温成分と低温成分に分かれ，低温成分が火砕流堆積物の本質物の磁化方位と一致することから，流下・定置過程において被熱されたことが明らかである．

馬場ほか (2017:SGEPSS) は，富士北麓に分布する鷹丸尾溶岩流，檜丸尾 1 溶岩流，中ノ茶屋溶岩流と南麓に分布する青沢溶岩流の各サイト平均方位から，A.D.580〜700 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流下した噴火イベントであった可能性を示した．鷹丸尾火砕流堆積物は，この一連の溶岩流を噴出した噴火イベントの平均方位と一致し，全岩化学組成や岩石学的特徴も類似していることから，同じ噴火イベントで発生したと推定される．溶岩流と火砕流堆積物のサイト平均方位の変位量からは，数十年間隔で火砕流発生から溶岩流の流出に移行する噴火活動が起こったと推定される．古地磁気学的手法によって，噴火様式が漸移的に変化し、時間間隙から噴火イベントをより鮮明にすることができる．

地磁気永年変化による日本海溝の層厚地震性タービダイトの層序対比

金松 敏也 [1]; 池原 研 [2]
[1] 海洋研究開発機構地震センター; [2] 産総研・地質情報研究部門

Stratigraphic Correlation of Seismo-Turbidites in Japan Trench using Paleomagnetic Secular Variation

Toshiya Kanamatsu[1]; Ken Ikehara[2]
[1] CEAT, JAMSTEC; [2] The Institute of Geology and Geoinformation, AIST

A thick turbidite unit associated with the 2011 Tohoku-oki earthquake, and two older thick turbidite units, which are most likely to have been induced by great earthquakes similar to the 2011, were discovered in the Japan Trench floor. Dating those deposits is crucial to understand the recurrence of Tohoku-oki earthquake. Because the basins are located in the hadal zone, obtaining detailed stratigraphic ages is generally difficult. However, paleomagnetic secular variation has been proved to be useful approach to date slope sequences in the Japan Trench composed of frequent thinner turbidite sequences below CCD. We tested if the similar approach can work for thick turbidite sequences in the trench. Paleomagnetic and rock-magnetic analyses were carried out on the samples. We measured magnetizations of demagnetized NRM, and ARM. Magnetic properties indicate unique patterns, which are useful for stratigraphic correlations. We compared the paleomagnetic secular variation patterns to a reference based on magnetic properties correlation. Especially declination changes can be well corelated to that of the reference. We confirmed precise correlations of turbidite units in Japan Trench are possible, and the secular variation is available up to 4,000 years ago at least in the Trench basin.

2011 年の東北地方太平洋沖地震によって形成された、層厚のタービダイトが、日本海溝で発見された。またより古い、２層の層厚タービダイトも発見され、これらは 2011 年のような超巨大地震があったことを示唆していると考えられる。このイベント堆積物の年代を知ることは、Mw9 クラスの地震周期がどのようであるか理解するために極めて重要であるが、水深が炭酸塩補償深度（CCD）の堆積物の年代決定は一般的には難しい。しかし CCD 以深でも陸側斜面の堆積物に記録されている地磁気永年変化を使うことにより、層序対比と年代決定が可能であることが分かった。さらに先ほどの層厚タービダイトが産出する水深 7500m 以上の超深海帯に位置する海溝底の堆積物の年代決定も、同様な方法で可能かを検証した。岩石磁気パラメーターの変動と、識別された火山灰を対比の手段として使うことにより、古地磁気データはコア間でよく対比でき、また琵琶湖から求められているリファレンスとの記録も良く対比できた。超巨大地震の発生を示唆する層厚タービダイトの年代決定が、少なくとも 4,000 年前まで可能であることがわかった。

日本における4.5-3千年前の古地磁気強度変動の復元

治田 有里紗 [1]; 望月 伸竜 [2]; 渋谷 秀敏 [3]
[1] 熊大・自然・地球; [2] 熊本大学; [3] 熊大・先端科学・地球環境

Paleointensity variation in Japan for the period between 4.5 and 3 ka

Arisa Haruta[1]; Nobutatsu Mochizuki[2]; Hidetoshi Shibuya[3]
[1] Dep't Earth & Env., Kumamoto Univ.; [2] Kumamoto University; [3] Dep't Earth & Env., Kumamoto Univ.

According to the paleointensity detabese, one may think paleointensity has been measured all over the world and it has been restored for the last several thousand years. However, paleointensity should be obtained at multiple areas in the world in order to compare effect of the non-axial-dipole field. In Japan, the reported paleointensity data are unevenly distributed for the last several thousand years and they are scarce between 4 and 3 ka. In this study, we measured paleomagnetic directions and intensities from lava flows and pyroclastic rocks around the post-caldera cones in Aso caldera, central Kyusyu, Japan so as to obtain paleointensity variation in this period. We applied Tsunakawa-Shaw method to samples. 145 samples of the 29 sites were measured and 124 samples passed the selection criteria. For 26 sites, three or more paleointensities were obtained and their standard deviations were smaller than 15% of the means. We adopted the paleointensities from the 26 sites for discussion in this study.Incidentally, paleomagnetic directions determined about 30 sites show a paleomagnetic secular variation curve. The carbon-14 ages of 3.3 ka and 4.1 ka were reported for Komezuka lava and Akamizu lava, respectively. On the basis of the paleomagnetic secular variation curve and the two ages, we estimated the erupted ages of the other lavas and pyroclastic rocks. We found paleointensity in Japan increases from 50 microT to 70 microT during the period between 4.5 and 3 ka . The VADM increase in Japan appears to occur at 1 kyr before the increase in Europe.

古地磁気強度測定は世界中で行われ、古地磁気強度データベースによると、過去数千年間における古地磁気強度は復元されているように思われる。しかし、地球磁場は非双極子磁場成分の影響を受けるため、その影響を把握するには異なる地域の古地磁気強度を比較する必要がある。また、古地磁気強度データのばらつきは大きく、誤った測定値が少なからず含まれている可能性もある。ここで日本でのデータを見てみると、年代によるデータ数の偏りがあり、特に4〜3千年前の古地磁気強度データは乏しく、信頼度の高いデータがほとんどない。本研究では、この年代を含む古地磁気強度の復元を目的として、阿蘇中央火口丘群の溶岩・スコリアを採取し、古地磁気方位および古地磁気強度測定を行った。

古地磁気強度測定はTsunakawa-Shaw法を用いて行った。145サンプルを測定し、そのうち124サンプルが合格基準を満たした。サイトレベルで見ると、29サイトのうち26サイトにおいて、3個以上の古地磁気強度が得られ、かつ、平均に対する標準偏差の割合が15%以下となった。本研究では、この26サイトの古地磁気強度を採用して、以降の議論に用いる。

古地磁気方位測定によって得られた約30サイトの古地磁気方位は、永年変化曲線を描くように分布する。これらの溶岩のうち、米塚溶岩 (3300年前) と赤水溶岩 (4100年前) にはそれぞれ炭素年代測定による年代が報告されている。この二つの溶岩の年代と永年変化曲線から、他の溶岩・スコリアの噴出年代を推定した。

以上により、約4.5千年前から3千年前の古地磁気方位・古地磁気強度変動を復元できた。日本における古地磁気強度は、この期間におよそ50 μTから70 μTに上昇したことがわかる。この上昇傾向は、ヨーロッパで測定された古地磁気強度の上昇傾向と似てはいるものの、そのタイミングは日本の方が1000年程度早い。

UDECON ソフトウエアによる古地磁気連続試料の自然残留磁化のデコンボルーションの実例

山本 裕二 [1]; 山崎 俊嗣 [2]; 金松 敏也 [3]
[1] 高知大; [2] 東大大気海洋研; [3] 海洋研究開発機構地震センター

Example deconvolution of natural remanent magnetization of a continuous paleomagnetic sample using the software UDECON

Yuhji Yamamoto[1]; Toshitsugu Yamazaki[2]; Toshiya Kanamatsu[3]
[1] Kochi University; [2] AORI, Univ. Tokyo; [3] CEAT, JAMSTEC

Paleomagnetic records of marine sediment cores have often been obtained by pass-through measurements, which are known to smooth and alter magnetic signals. Amongst many efforts, a standalone open-use graphical software UDECON (Xuan and Oda, 2015) has been developed to deconvolve pass-through measurement data. As a case study to assess the applicability of the software to deconvolve natural remanent magnetization (NRM) of a continuous paleomagnetic sample, we chose 40 discrete samples from a piston core recovered in the northeast Pacific. We measured NRMs after alternating field demagnetization at 20 mT for both discrete samples and a simulated continuous sample, made by connecting the discrete samples.

The discrete samples show centimeter-scale variations in NRM. Such variations are smoothed out and mostly disappear in the results of the simulated continuous sample. However, after using the software to deconvolve the data, the variations are almost completely restored. Good agreement between the discrete sample data and the deconvolved data indicates that the deconvolution by the software is very successful. We observe detailed features of a directional reversal in the data from the discrete samples and in the deconvolved data but not in the data from the simulated continuous sample. This emphasizes that the deconvolution analysis by the software is a powerful tool to extract detailed features from continuous paleomagnetic records obtained by pass-through measurements.

南太平洋トンガ王国の鍾乳石に対する走査型 SQUID 顕微鏡を用いた古地磁気測定の適用

福與 直人 [1]; 小田 啓邦 [2]; 横山 祐典 [3]
[1] 東大・大海研、東大・理・地惑; [2] 産総研・地質情報; [3] 東大・大海研

Scanning SQUID microscopy applying for a speleothems obtained from Tonga, the southern Pacific

Naoto Fukuyo[1]; Hirokuni Oda[2]; Yusuke Yokoyama[3]
[1] AORI, Univ. Tokyo; EPS, Univ. Tokyo; [2] IGG, GSJ, AIST; [3] AORI, Univ. Tokyo

Speleothems are thought as an ideal record of paleomagnetism since they retain continuous geomagnetic records in stable condition as well as their applicability for radiometric datings such as U-series and radiocarbon techniques. A previous study reconstructed the natures of paleomagnetism during the Laschamp excursion successfully (e.g. Lascu et al., 2016), though their weak magnetic signals 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, and hence could potentially solve this obstacles. However no studies have been reported using paleomagnetic study using speleothems to date. In this study, we have conducted paleomagnetic measurements with a SSM on speleothems collected in Tongatapu Island, the Kingdom of Tonga.

The stalagmites were obtained at Anahulu cave in Tongatapu island (around 21 degrees 13 minutes S, 175 degrees 06 minutes W) in 2016. The ^{14}C age of the surface part of the stalagmite is around 10 ka and were cut perpendicular to the growing direction of stalagmite and shaped to thickness of ca.0.2 mm before they have been used for measurements.

We obtained natural remanent magnetization (NRM) of the average ca.1.5 nT with the SSM. Also, we compared magnetic fields between the surface layer and the inner layer. The signals were statistically different, hence we successfully were able to obtain very small magnetic field change due to differences in laminated structures of a speleothem at submillimeter scale with SSM. Further, we operated first-order reversal curve (FORC) measurements using the alternating gradient force magnetometer (AGM). The results show that this speleothem can contain mixture of magnetites with different domain states. We also present the map of rock magnetic parameters calculated by inversion of Isothermal Remanent Magnetization (IRM) measured with SQUID microscope. In this talk, we will present initial results.

鍾乳石は、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、鍾乳石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、Laschamp 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) を用いることが考えられるが、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) を行なった。

試料はトンガタプ島内の Anahulu cave（21 度 13 分 S, 175 度 06 分 W 付近）で採取された石筍を用いた。石筍の年代は、石筍表面付近の部位に対し 14C 年代測定を行い、約 1 万年前という形成年代を得た。採取した試料は、石筍の成長方向 に対して垂直に切断し、厚さおよそ 200 マイクロメートルに整形し 100 マイクロメートル四方グリッドの解像度で測定した。

SSM による測定の結果、平均して石筍薄片試料の 300 マイクロメートル上で約 1.5 nT の磁場強度が確認された。また、最表層の暗灰色層と内部の明灰色層の磁場強度の間には統計上有意な差が認められた。これは堆積構造の違いによる 微小な残留磁化強度の変化をサブミリスケールで捉えている可能性がある。さらに、産業技術総合研究所の交番磁場勾配磁力計 (Alternating gradient force magnetometer: AGM) を用いて First-order reversal curve (FORC) 測定を行った。先行研究 (例えば Muxworthy et al., 2006; Roberts et al., 2017) と比較すると、本研究で用いた鍾乳石に含まれる磁性体は複数の磁区構造からなるマグネタイト粒子の混合物である可能性がある。

さらに、SQUID 顕微鏡を用いた等温残留磁化 (IRM) の測定結果を解析し、磁性鉱物の含有率をマッピングした。本発表では、これらの解析結果についても報告を行う予定である。

沖縄トラフ海底熱水鉱床試料の岩石磁気測定

加藤 千恵 [1]; 大野 正夫 [1]; 畠山 唯達 [2]; 石橋 純一郎 [3]; 戸塚 修平 [3]; 島田 和彦 [3]
[1] 九大・比文・地球変動講座; [2] 岡山理大・情報処理セ; [3] 九大・理・地球惑星

Rock-magnetic studies on seafloor hydrothermal deposits in the Okinawa Trough

Chie Kato[1]; Masao Ohno[1]; Tadahiro Hatakeyama[2]; Jun-ichiro Ishibashi[3]; Shuhei Totsuka[3]; Kazuhiko Shimada[3]
[1] Division of Earth Sciences, SCS, Kyushu Univ.; [2] IPC, Okayama University of Science; [3] EPS, Kyushu Univ.

Investigation of the mineral assemblage of seafloor hydrothermal deposits are crucial for understanding its formation environment and process. Rock-magnetic measurements of the deposits are quick and effective to detect accessory magnetic minerals which are sensitive to the environment. We report our preliminary results of rock-magnetic measurements conducted on seafloor rock samples of a sulfide chimney in the Noho Site, Iheya Small Ridge and drilled core samples from Sites C9025 and C9026 in the Izena Hole, Okinawa Trough. We selected four samples from 74.7 to 82.9 m in depth of core C9025 and five samples from 65.2 to 84.1 m in depths of core C9026, where pyrrhotite was identified by the on-board X-ray diffraction analysis. Low-temperature magnetic measurements such as field cooled (FC) remanence and zero-field cooled (ZFC) remanence and low temperature cycle of room-temperature isothermal remanent magnetization (IRM) were conducted using a Magnetic Property Measurement System (MPMS). IRM acquisition experiments was performed up to 1 T by an Alternating Gradient Magnetometer, and up to 5 T on selected samples using the MPMS.

Chimney sample from Iheya Small Ridge showed decrease of FC and ZFC remanences near 100 K during zero-field warming. Considering the X-ray diffraction patterns, it could be attributed to a Cu-Fe-S phase with sphalerite-type structure reported by Wintenberger et al. (1994). However, the chemical composition analyzed by FE-EPMA was close to that of $CuFe_2S_3$ isocubanite rather than the reported composition $CuFe_3S_4$. Pyrrhotite was also recognized by low-temperature magnetometry, XRD and chemical analysis.

In the core samples from Izena Hole, FC remanence was 2-3 times larger than the ZFC remanence, and an extremely hard component which does not saturate even at 5 T was shown in the IRM acquisition curve. These features indicate the contribution of goethite (Liu et al. 2006), which might have been formed by alternation in laboratory. Signals of Cu-Fe-S phase and pyrrhotite were also distinguished in some of the core samples. In addition, a sharp decrease of room-temperature IRM at 50 to 70 K was observed during the low-temperature cycle. These features could not be explained by any of the magnetic minerals noted above, and therefore suggest the presence of other magnetic component(s).

地磁気３成分異常から推定される四国海盆の海底拡大史

羽入 朋子 [1]; 沖野 郷子 [1]
[1] 東大・大海研

Seafloor spreading history in the Shikoku Basin inferred from vector magnetic anomalies

Tomoko Hanyu[1]; Kyoko Okino[1]
[1] AORI, Univ. Tokyo

http://ofgs.aori.u-tokyo.ac.jp

Magnetic anomalies associated with paleo-arcs and backarc basins provide the information on the paleo-latitude and/or rotation of the Philippine Sea Plate, as well as magmatism in the transitional phase from arc volcanism to backarc volcanism. Shikoku Basin, located in northeastern part of the Philippine Sea Plate, was considered to be formed as a back-arc basin during Late Oligocene to Middle Miocene. Analysis of the magnetic anomalies in the Shikoku Basin has been conducted since 1970s. Recent study (Okino, 2015) identified the clear NNW-SSE oriented magnetic lineations north of 25-degree-north. In the south, the almost N-S oriented magnetic lineations in the Parece Vela Basin were also identified, suggesting that two basins were linked ca. 22 Ma. However, there is a missing piece of backarc evolution between 25-degree-north and 21-degree-north, where the amplitude of magnetic anomalies is too low to identify the magnetic isochrons. The area is a key to understand when and how the paleo Izu-Bonin-Mariana arc was completely separated and two basins started to evolve as one system.

To tackle this question, vector magnetic survey based on the shipboard three component magnetometers (STCM: Isezaki, 1986) was carried out in the southwestern part of the Shikoku Basin during KH-18-02 cruise of R/V Hakuho-maru. The total magnetic data were also obtained by using the ship-towed Proton magnetometer. Vector magnetic anomalies and magnetic boundary strikes are calculated from vector magnetic data. We will present the identification of magnetic anomalies and structure of magnetic basement, and will discuss the detailed seafloor spreading history during the joint phase of two basins.

磁性細菌 Magnetospirillum magnetotacticum MS-1 が獲得する残留磁化とその性質のさらなる検討

政岡 浩平 [1]; 諸野 祐樹 [2]; 山本 裕二 [1]
[1] 高知大; [2] JAMSTEC・高知コア

Further examination of properties of remanent magnetization carried by magnetotactic bacteria M. magnetotacticum MS-1

Kohei Masaoka[1]; Yuki Morono[2]; Yuhji Yamamoto[1]
[1] Kochi University; [2] JAMSTEC-Kochi

Variation of the past geomagnetic field is recorded in marine sediments as a fossil magnetization, called natural remanent magnetization (NRM). It has begun to be pointed out that NRM of the sediment is carried not only by detrital and aeolian magnetic grains but also by biogenic magnetic grains originated from magnetotactic bacteria. To investigate characters of NRM carried by biogenic magnetic grains, Masaoka et al. (2018JpGU) cultured the microaerobic bacteria *Magnetospirillum magnetotacticum* MS-1 in laboratory and made samples using them for remanent magnetization measurements by simulating a very early process of sediment formation. They reported properties and characters of the remanent magnetization carried by the samples including simulated NRMs. We have further continued the investigation and will report results.

海底堆積物には自然残留磁化（NRM）として過去の地磁気変動がほぼ連続的に記録されている．その NRM の記録媒体である磁性鉱物は磁性細菌にも起源をもつことが知られているが，磁性細菌起源のマグネタイトが NRM を獲得する過程や，獲得される NRM の性質については未解明の部分が多い．

政岡ほか（2018JpGU）では，磁性細菌*Magnetospirillum magnetotacticum* MS-1（以下 MS-1）の分譲を受けて大量培養を行い，密度勾配を利用して分離した MS-1 の細胞群が堆積物形成過程のごく初期において NRM を獲得するプロセスの模擬実験を行い，試料を作製した．この研究では，試料ごとに細胞数を一定とし（1 試料 2.835 $\times 10^9$ cell/7 cc），異なる強度の外部磁場（0-100 μT）を作用させて NRM を獲得させている．NRM の方位は印加磁場の方向と一致し，NRM 強度と試料作製時の外部磁場強度との間には 0-30 μT と 30-100 μT の範囲で独立した 2 つの直線関係がみられたことを報告している．さらに，一定の磁場下で非履歴性残留磁化（ARM）と等温残留磁化（IRM）を獲得させたところ，ARM 強度と IRM 強度は試料作製時の磁場強度の増加に伴って徐々に増加するが，その差は NRM に比べて非常に小さいという結果も報告している．

今回は，政岡ほか（2018JpGU）で報告している結果の再確認と，外部磁場方向の違いによる獲得 NRM 強度への影響を検討することを目的とした．２つの異なる外部磁場方向（方向 1：偏角 0 度・伏角 0 度，方向 2：偏角 0 度・伏角 45 度）と 5 つの異なる外部磁場強度（0, 20, 30, 60, 90 μT）の組み合わせのもと，政岡ほか（2018JpGU）と同様の手順で MS-1 の細胞群が NRM を獲得するプロセスの模擬実験を行い，試料を作製した．この際の細胞数は，政岡ほか（2018JpGU）で作製した試料の細胞数と同一とした（1 試料 2.835 $\times 10^9$ cell/7 cc）．これらの NRM の性質を調べるとともに，それぞれ一定の磁場下（方向 1）で非履歴性残留磁化（ARM）と等温残留磁化（IRM）を着磁して，これらの性質についても調べた．

方向 1 の外部磁場下で作製した試料の NRM 方位は印加磁場の方向と一致していた．NRM 強度は 0.697-7.608 $\times 10^{-8}$ Am^2 であり，試料作製時の磁場強度との間に 0-30 μT と 30-90 μT の範囲で独立した 2 つの直線関係がみられた．ARM 強度は 0.952-1.365 $\times 10^{-8}$ Am^2，IRM 強度は 0.782-1.024 $\times 10^{-7}$ Am^2 であり，両者ともに試料作製時の磁場強度とともに増加する傾向があるが，獲得された磁化強度の差は NRM に比べて非常に小さい．これは，政岡ほか（2018JpGU）で得られた結果とよく一致している．

方向２の外部磁場下で作製した試料の NRM 方位も印加磁場の方向と一致していた．NRM 強度は 0.697-7.367 $\times 10^{-8}$ Am^2 であり，試料作製時の磁場強度との間には，0-30 μT と 30-90 μT の範囲で独立した２つの直線関係がみられ，方向 1 の外部磁場下で作製した試料と同様の結果を得た． ARM 強度は 0.952-1.181 $\times 10^{-8}$ Am^2，IRM 強度は 7.815-8.763 $\times 10^{-8}$ Am^2 であり，方向 1 の外部磁場下で作製した試料に比べてその差が小さくなった．

相対古地磁気強度の指標として用いられる NRM/ARM および NRM/IRM は，方向 1 の外部磁場下で作製した試料と，方向２の外部磁場下で作製した試料を比べると，試料作製磁場強度 30 μT 以上の範囲においてやや異なる傾向を示している．これは，試料作製時に，外部磁場方向および強度に依存して MS-1 の細胞群が効率的に配向するため，残留磁化の異方性の影響が無視できないことを示唆していると考えられる．

法科学のツールとしての岩石磁気-掘り起こされた場所の特定-

川村 紀子 [1]; 石川 尚人 [2]
[1] 海上保安庁・海保大; [2] 京大・人環

Rock magnetic analysis as a forensic tool to detect previously disturbed ground

Noriko Kawamura[1]; Naoto Ishikawa[2]
[1] JCGA; [2] Human and Environmental Studies, Kyoto Univ.

https://researchmap.jp/norikokawamura/

For a successful criminal conviction to occur, it is essential to locate forensically important evidence disposed of in soil. In this study, we attempted to use a rock magnetic method as a forensic search tool to detect evidence hidden in the ground. A 2.5 m long survey line was provided in the campus ground of Japan coast guard academy. A 0.1 m x0.2 m x0.7 m sized hole was created and was buried in the soil. Magnetic susceptibility (MS) was measured using a ZH instruments magnetometer at every 0.1 m along the line. Each sample position was measured six times. MS indicates relative higher values at the disturbed ground. A core sample of 7 cm length was collected by a soil sampler at around the disturbed ground. The grain size of the soil core is classified silty sand with granule, and it increases with burial depth. Dried soil samples were taken from the core at 1 cm intervals and were packed into 1 cm^3 plastic cubes. Rock magnetic measurements; MS, anhysteretic remanent magnetization (ARM), isothermal remanent magnetization (IRM), isothermal magnetization (Mrs), saturation magnetization (Ms), coercivity (Hc), and remanence coercivity (Hcr) were conducted for on the cubes. MS shows a peak at 2 cm in depth. ARM and SIRM indicate that the values gradually decrease with depth. It implies that the relatively high MS layer was at one time in the past exposed surface soil and as a result could be considered disturbed ground. In order to identify the magnetic minerals within the soil samples, thermomagnetic analysis (Js-T) was performed on four samples which are collected from the surface (0-0.2 m), middle (0.3-0.5 m) and deep soils (0.6-0.7 m) at the disturbed ground. All samples indicate that the declines of the decline in the MS curves at 580^{o}C and 680^{o}C. A slight inflection in the susceptibility curves at around 300^{o}C-400^{o}C is was also recognized. It suggests that this is due to the presence of maghemite and hematite. Almost all data plots in the pseudo-single domain (PSD) region for (titano-) magnetite on the Day plot (Mrs/Ms and Hcr/Hc). Magnetic grain size also increases with burial depth, and is consist with grain size distribution. The values of disturbed ground are located in the central part of all samples which are implied the all layer contribution. MS peaks have been recognized three month later when the disturbed ground was covered by weeds and the hole is undetectable. This result proves that MS can detect the location of disturbed ground even three months post-disturbance.

Fabric tensor and its application to magnetic fabric of sediments and dikes

Norihiro Nakamura[1]; Shusaku Kon[2]; Hiroyuki Nagahama[3]
[1] IEHE, Tohoku Univ; [2] Nippon Koei Co., Ltd.; [3] Earth Sciences, Tohoku Univ.

Anisotropy of magnetic susceptibility (AMS) is a proxy for determining the preferred orientation of magnetic minerals. Given that fabric of magnetic minerals, such as magnetite, is coaxial to the alignment of rock-forming minerals, this technique is the easiest and quickest technique used to reconstruct paleo-flow directions of sediments and magmatic dikes. This consideration results from the mathematical framework on AMS by Owens (1975): bulk anisotropy of magnetic susceptibility depends on an angular density distribution of uniaxial grains of anisotropic susceptibility. However, the grain-size dependence and characterization of angular distribution have not been described in the framework, yielding the non-coaxiality to prevent the estimation of paleo-flow direction. For example, Kon et al (2017) found inverse magnetic fabric of AMS in tsunami deposits. This is a natural example for the non-coaxiality that AMS minimum axis is coaxial to the alignment of fine grained magnetites. In this presentation, we introduce the concept of fabric tensor and explain such discrepancy by fabric tensor and also stereology. This understanding will help to estimate paleo-flow directions of sediments and also magmatic dikes.

複数タイプの FORC ダイアグラムを用いた磁区構造の識別と犬山赤色チャートへの適用

HU PENGXIANG[1]; 小田 啓邦 [2]
[1] 産総研
ANU; [2] 産総研・地質情報

Magnetic domain state diagnosis using multiple FORC-type diagrams and their application to the Inuyama red chert

PENGXIANG HU[1]; Hirokuni Oda[2]
[1] AIST;
ANU; [2] IGG, GSJ, AIST

First-order reversal curve (FORC) diagrams provide a practical approach to assess switching and interaction field distributions, which provide valuable information about magnetic domain states. FORC diagrams are a complex representation of remanent, induced, and transient magnetizations that can be assessed individually using additional FORC-type measurements. Recently developed remanent, transient, and induced FORC diagrams provide substantial information in addition to conventional FORC diagrams that aids comprehensive domain state diagnosis for mixed magnetite particle assemblages. Transient FORC diagrams provide a measure of nucleation and annihilation fields of magnetic vortices and domain walls, remanent FORC diagrams enable detection of stable single domain (SD) behavior along with thermally activated particles near the superparamagnetic (SP) to stable SD threshold, while strong induced magnetizations are evident for stable SD particles in induced FORC diagrams. Triassic-Jurassic red cherts from the Inuyama section near Nagoya represent a complex mixture of magnetite and hematite. Using new FORC-type diagrams mentioned above, SD hematite, non-interacting SD biogenic magnetite, vortex state magnetite, and SP particles are identified in red chert samples. Our results demonstrate the application of FORC-type diagrams in interpreting the domain state of complex mixtures of ferrimagnetic and antiferromagnetic minerals in natural archives.