陸上玄武岩の磁気ヒステリシスループのアンミキシング

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Unmixing magnetic hysteresis loops of subaerial basalts

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Magnetic hysteresis measurements are extensively performed to characterize magnetic mineral assemblages in rocks and sediments. Especially subaerial basalts contain abundant magnetic materials and have provided reliable hysteresis data even dated back to the age of low-sensitivity vibrating sample magnetometer. However, hysteresis data have remained underutilized; Just a few hysteresis parameters, such as coercivity or saturation magnetization, are obtained from the hysteresis data when drawing inferences on underlying magnetic assemblages.

Decomposition of isothermal remanent magnetization (IRM) acquisition curves is widely used to quantify mixed magnetic assemblages. In addition to fitting with parametric distribution functions, a linear unmixing is currently employed to separate IRM acquisition curves into several meaningful magnetic components. The linear unmixing has a crucial advantage in not requiring any assumption on basis functions.

The hysteresis data of recent or historical subaerial basalts, collected from Izu-Oshima and Miyakejima islands, were analyzed with the linear unmixing. These samples cover entire lava sections including upper clinker, interior, and lower clinker, and some samples were taken from scoria. The primary magnetic mineral is titanomagnetite with a wide range of Curie points spanning 150-580 degC. In some samples dual or triple Curie points were identified for a single specimen. The hysteresis loops exhibit a variety of shapes from potbelly to wasp-waisted, which seems to be related to the Curie points, that is, the ulvospinel content of titanomagnetite.

Hysteresis loops were preprocessed before applying the linear unmixing as fulfilling inversion symmetry of the upper and lower branches of loops [Jackson and Solheid, 2010]. The center of the loops were adjusted to the origin and the drift during loop measurement was corrected so as to compensate for the failure of loops to close. The maximum field of 1 T was not enough to saturate high-Ti titanomagnetite, therefore the approach-to-saturation analysis was employed to determine paramagnetic susceptibility instead of conventional linear fitting for a 0.7-1.0 T interval.

Remanent and induced hysteresis curves were calculated from the hysteresis loops and constituted a data matrix for the linear unmixing. This time I used the SISAL algorithm that was originally developed for unmixing hyperspectral data [Heslop and Roberts, 2012]. The data matrix was decomposed into a mixing matrix containing several end-members and a matrix holding the respective fractions. The end-member loops have characteristic shapes corresponding to high-Ti titanomagnetite, nearly pure magnetite and their grain sizes, and the fractions quantify a mixing ratio of magnetic components comprising hysteresis loops.

磁気ヒステリシスの測定は，岩石や堆積物中の磁性鉱物を特徴付けるために広く行われている．特に陸上玄武岩は磁性鉱物を豊富に含み，低感度の試料振動型磁力計の時代から信頼性の高い磁気ヒステリシスデータを提供してきた．しかし，ヒステリシスデータは依然としてあまり活用されていない．通常，保磁力や飽和磁化などのわずかなヒステリシスパラメータを求めるために用いられるだけである．

等温残留磁化獲得曲線の分解は混合された磁性鉱物の集合体を定量化するために広く使われている．パラメトリックな分布関数でフィッティングすることに加えて，現在では線形アンミキシングも使われている．線形アンミキシングは基底関数の仮定を必要としないところに大きな利点がある．

伊豆大島や三宅島から集めた最近または歴史溶岩の磁気ヒステリシスデータを，線形アンミキシングを用いて分析した．これらのサンプルは，上部クリンカ，内部及び下部クリンカを含む溶岩全体をカバーし，いくつかのサンプルはスコリアから採取した．主な磁性鉱物はキュリー点が 150〜580 ℃ の広い範囲に及ぶチタン磁鉄鉱である．いくつかのサンプルでは，二つまたは三つのキュリー点が単一の試料で同定された．ヒステリシスループは potbelly から wasp-waisted まで様々な形状を示し，キュリー点つまりチタン磁鉄鉱の ulvospinel 含有率と関連すると思われる．

線形アンミキシングを適用する前に，ループの上側と下側のブランチの反転対称性を満たすように前処理した [Jackson and Solheid, 2010]．ループの中心は原点に調整され，閉じていないループを補償するようにループ測定時のドリフトを修正した． 1 T の最大磁場は高チタン-チタン磁鉄鉱を飽和させるのに十分ではないため，常磁性磁化率を求めるため従来の 0.7〜1.0 T での線形フィッティングに代えて approach-to-saturation 分析を用いた．

残留および誘導ヒステリシス曲線をヒステリシスループから計算し，線形アンミキシングのためのデータ行列を構成した．今回は元々ハイパースペクトルデータのアンミキシングのために開発された SISAL アルゴリズムを使用した [Heslop and Roberts, 2012]．データ行列は，複数のエンドメンバーから成る行列とそれぞれの割合を示す行列に分解される．エンドメンバーループは，高チタン-チタン磁鉄鉱，ほぼ純粋な磁鉄鉱とその粒径による特有の形状をもち，その割合はヒステリシスループを呈している磁気成分の混合比を定量的に表している．

パルス磁気緩和と高周波磁気ヒステリシス

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Pulsed-field relaxation and high-frequency-field hysteresis

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Dynamic magnetizations in time domain and frequency domain were measured on different kinds of natural samples (igneous rocks and sediments). In the time domain, the rapid decay of magnetization after switching off a pulse was measured with variable pulse lengths (10^{-5}s to 10^{-2}s) and amplitudes (0.5 mT to 0.7 T). Hysteresis curves were measured in one cycle of positive and negative pulses with the different rate of field variation. In the frequency domain, low-field magnetic susceptibility was measured over the frequency rage (1 kHz to 500 kHz) corresponding to the pulse lengths in the time domain measurements. The hysteresis curves were broadly comparable to the corresponding portions of the hysteresis loops measured by a quasi-static method using a VSM. The dynamic coercivity, defined as the intersect with the abscissa in the negative field regime, increased as the pulse length reduced or the pulse peak increased. In strong fields (>0.5 T), irrespective of the kinds of samples, small amount of magnetization remained at the end of a pulse and decayed exponentially with the time constant being a few ms. In weak pulsed-fields, no such rapid relaxation was observed with the volcanic rocks except the sediments and soils rich in superparamagnetic (SP) particles. These results suggest that the relaxations in the strong fields could be due to the dynamics of the domain walls in the MD particles of the volcanic rocks, while those in weak fields may be ascribed to the SP particles present in these sediments. Results in the frequency domain were presented in the form of the frequency spectrum of the real and imaginary components of complex susceptibility. Comparisons and interpretations of the data in these different domains were made in terms of the relaxation times. Discussions on the numerical transformation of these data as well as their rock magnetic implications will be provided.

パルス磁場を利用することによって、ごく短時間の磁気緩和を測定することができる（Kodama, 2015）。本研究では、単一パルスだけでなく、連続した正負２パルスを印加できるパルス磁化測定器を用いて、高周波の磁気ヒステリシスに相当する磁化曲線と”保磁力”を得た。パルス磁場は、継続時間 10^{-5}s～10^{-2}s、強度 0.5 mT～0.7 T の範囲で可変である。これらのパラメータを変えることによって、いくつかの火山岩や堆積物（Tiva Canyon tuff、中国黄土）を対象に、緩和曲線や保磁力の変化を調べた。その結果、１）強パルス（>0.5 T）では、すべての試料で磁気緩和が観測され、それらの緩和時間は 10^{-4}s～10^{-3}s である。２）短時間（～10^{-5}s）の弱パルス（～0.5 mT）では火山岩試料に磁気緩和は見られないが、堆積物では時定数～10^{-3}s の緩和が見られる。３）パルス磁場変化率（dH/dt）が大きくなるにつれて、すべての試料で保磁力が増加し、それに応じてヒステリシス曲線（minor loop）が広がる。これらの時間領域での測定結果と周波数領域の結果（高周波磁化率スペクトル）を、相互にフーリエ変換・逆フーリエ変換して比較検討した。その結果とその他の岩石磁気特性とを総合すると、上記１）～３）は、MD 粒子中の磁壁形成や不可逆磁壁移動などに伴う”hysteresis relaxation”（Betancourt, 2011）、SP 粒子の緩和時間の磁場強度や周波数に対する依存性（Alexander et al., 2007）などによって説明することができる。

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SQUID顕微鏡による測定データの評価と補正：ノイズ・ドリフト・位置決め

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Evaluation and correction of data obtained by scanning SQUID microscope: Noise, Drift and Positioning

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We have developed a scanning superconducting quantum interference device (SQUID) microscope (SSM) for imaging magnetic field distribution of geological rock samples. The distance between the SQUID and the sample can be calibrated with magnetic field generated with a precision dc-current applied to a thin and long wire. Here we show evaluation and correction of data obtained by SSM including noise and drift of the system and positioning of geological samples. First, noise of the system and the environment was evaluated based on the measurements with and without XY stage. Second, drift of the system and the environment was evaluated and corrected based on the measurements with crossings in X and Y directions. Third, the magnetic field image of a geological sample was assigned precisely to the optical image based on two artificial magnetic dipole placed on a sample holder outside of the geological sample as magnetic markers. We adopted FeCo as a material for the dipole with a 500-nm-thick layer deposited on a silicon substrate with DC-sputtering. The whole evaluation, correction and assignment could be easily conducted with a MATLAB software under development.

中国レスにおける二次生成磁性ナノ粒子の探査

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Investigation of pedogenic nanoparticles causing magnetic enhancement in Chinese loess sediments

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Paleoclimatic signals have been recorded in various ways in Chinese loess sediments. Enhanced magnetic susceptibility (MS) of paleosol, about ten times higher than loess at most, is reflected by pedogenesis, the degree of which depends on intensity of summer monsoon. MS of loess-paleosol sediments is used even as a tool to estimate summer monsoon intensity, especially paleo-precipitation. However, these interpretations and application of magnetic enhancement are theoretically vulnerable because the pedogenic magnetic particles causing magnetic enhancement have never been detected.

In this study, we search for a detritus grain size band that is concentrated with pedogenic magnetic particles, using loess-paleosol sediment samples from a sequence from loess L8 to paleosol S8 in Lingtai, central Chinese Loess Plateau. MS ranges from 31~123 E-8m^3/kg for sequence L8-S8. We selected 2 specimens showing lowest (L8: 29 E-8m^3/kg) and highest (S8: 113 E-8m^3/kg) MS, which reflect extremely low and high degree of pedogenesis in each sequence respectively. The following experiments were conducted. First, we divided bulk samples into 3 subsamples with different grain size bands (D1: over 10 micrometers, D2: 10~1 micrometers, D3: below 1 micrometer). Trial and error was repeated to find a method of separation with small sample loss (below 1 % in sample mass). Second, we estimated their magnetic contribution to bulk magnetism by measuring MS. Third, we conducted IRM component analysis, magnetic hysteresis and thermomagnetic measurements to obtain more information for each subsample.

Assuming that the effect of pedogenesis is negligible for loess sample with the minimum MS (29 E-8m^3/kg), namely original MS of aeolian detritus is kept, the paleosol sample with the maximum MS (113 E-8m^3/kg) would have been subjected to an intensive magnetic enhancement by a 290 % increase in MS. Contributions to the enhancement differ with grain size bands; 8 % for D1, 45 % for D2, and 32 % for D3. Frequency dependence (FD) of MS that reflects the amount of super-paramagnetic (SP) particles for bulk samples is 5.2 for loess and 19.0 for paleosol, showing a large increase by 265 % due to pedogenesis. The pedogenic increase in FD of MS was calculated for each grain size band as 5 % for D1, 70 % for D2, and 30 % for D3. Thus, it is clear that pedogenically neoformed magnetic grains are concentrated in D2 and D3 bands, significantly contributed by SP particles. However, we note that the absolute values of MS in unit of E-8m^3/kg are 49.4 for D2 and 28.6 for D3, and FD in unit of E-8m^3/kg are 10.8 for D2 and 4.4 for D3. These results of MS measurements suggest the pedogenic magnetic particles are mainly concentrated in D2. In addition, the results of magnetic experiments mentioned above suggest that the pedogenic magnetic particles are ferrimagnetic particles with low coercivity such as magnetite or maghemite. Considering grain size of SP magnetite/maghemite particles being less than approximately 50 nanometers, the pedogenic SP particles must exist in detrital silicate minerals as inclusions. Results of other loess-paleosol sequences and TEM observations will also be shown in the presentation.

鉄還元境界を含む海底表層堆積物中における生物源マグネタイトの分布

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Distribution of magnetofossils in deep-sea surface sediments with Fe-redox boundary

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Magnetotactic bacteria are considered to be microaerophilic and most commonly live near or below the Fe-redox boundary (the oxic-anoxic transition zone). However, common occurrence of magnetofossils in Pacific red clay (Yamazaki and Shimono, 2013), which contains abundant dissolved oxygen and does not have a Fe-redox boundary, suggest that some species of magnetotactic bacteria live in an environment without a strong chemical gradient. In order to contribute to better understanding of the ecology of magnetotactic bacteria in deep-sea sediments, we have studied magnetofossils within surface sediments of the Japan Sea, where the Fe-redox boundary is known to occur several to tens of centimeters below the seafloor, with rock-magnetic techniques and TEM observations. Undisturbed surface sediments were taken with a multiple corer during the R/V Shinsei-maru KS-14-13 cruise in 2014. From dissolved oxygen and Fe (II) contents of interstitial water and color reflectance of the sediments, the Fe-redox boundary was clearly detected at 7 to 25 cm below the seafloor at three sites. The sediments consist of silty clay, and water depths of the three sites range between 1770 to 2710 m. In the component analyses of IRM acquisition curves, a magnetic component that has a mean coercivity of ˜65 mT and a small dispersion parameter (DP) occurs, which corresponds to the biogenic hard (BH) component of Egli (2004). At all three sites, the proportion of this component increases just below the Fe-redox boundary, which is associated with an increase in the ratio of ARM to SIRM. These results suggest increased abundance of magnetofossils with elongated morphologies like hexagonal prism and tear drop. On the other hand, FORC diagrams show sharp central ridges indicative of magnetofossils throughout the sediment columns regardless of the distance from the Fe-redox boundary, even at the sediment-water interface. The occurrence of magnetofossils was confirmed by TEM observations; magnetofossils are abundant in all samples, and all three major morphologies, octahedron, hexagonal prism, and tear drop, were observed. These results suggest that although some species of magnetotactic bacteria living in marine sediments prefer a chemical condition near the Fe-redox boundary, others may be aerotolerant and live in oxic environments. Where the Fe-redox boundary occurs at a large depth, say tens centimeters or more, a zone of remanent magnetization acquisition in sediments rich in magnetofossils is expected to be very wide, which results in much delayed remanence acquisition with loss of high-frequency signals.

多様な深海底蛇紋岩から明らかになった蛇紋岩化反応における磁鉄鉱の挙動

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Role of Magnetite in Serpentinization: Insights from Rock Magnetic Properties of Abyssal Peridotites

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Magnetic properties in serpentinized peridotites are of increasing interest in seafloor mapping and petrologic studies because such data can promote the understanding of serpentinization reactions and hydrogen creation in ultramafic rocks. In order to reveal the magnetic properties and magnetite growth in serpentinized peridotites, we have analyzed 30 serpentinized peridotite samples from a non-transform offset massif called the Yokoniwa Rise in the Central Indian Ridge. The results from multiple rock magnetic analyses and petrological observations illustrate the details of the creation and growth of magnetite in serpentinized peridotites that have undergone 17-100% serpentinzation. The magnetic carrier of these samples is pure magnetite, which did not suffer from maghemitization (low-temperature oxidation). The magnetic susceptibility ranged from 0.002-0.087 SI and increased nonlinearly with the progression of the serpentinization reaction. The natural remanent magnetization intensities of 0.2-8.4 A/m are comparable to those of basalts, which suggests that the remanence as well as induced magnetization of highly serpentinized peridotite can contribute to magnetization of the oceanic lithosphere. The amount of magnetite estimated from saturation magnetization increased nonlinearly from 0.1 wt% to 5.5 wt% with the progression of the serpentinization. Highly serpentinized peridotites have a well-developed serpentine mesh texture. Pseudo-single-domain (PSD) and multi-domain (MD) grains were formed during igneous processes in the mantle domain and/or during the initial stages of serpentinization. Super-paramagnetic (SP) particles were formed during the initial stages of serpentinization. Single-domain (SD) magnetite was formed during the later stage of serpentinization, and it is assembled inside of mesh structures composed of needle-like grains with strong magnetostatic interactions.

波形インバージョン法によるD”層内部の３次元S波地震波速度構造推定

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Full waveform inversion for 3D S-velocity structure in the D” region

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We formulate the inverse problem of waveform inversion for localized 3-D seismic structure, computing partial derivatives of waveforms with respect to the elastic moduli at arbitrary points in space for anisotropic and anelastic media. In this study we minimize computational requirements by using the Born approximation with respect to a laterally homogeneous model, but this is not an inherent limitation of our approach. We solve the inverse problem using the conjugate gradient (CG) method, using Akaike’s Information Criterion (AIC) to truncate the CG expansion. We apply our method to invert for 3-D shear wave structure in the lowermost mantle beneath Central America using a total of 2154 waveforms at periods from 12.5 to 200 s recorded at stations near the Pacific coast of North America for 29 deep and intermediate-depth events beneath South America. The resulting model shows lateral heterogeneity in the E-W direction, which may be associated with a subducted cold slab surrounded by hotter materials with slower velocities. Various tests show that our model is robust.

Viscous core-mantle coupling and core surface flow in a viscous boundary layer

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Secular variations of the Earth's magnetic field are caused by fluid motions in the electrically conducting core. Such core flows can be derived from the spatial distribution of the geomagnetic field and its temporal variation. Core flow models thus derived contain useful information on a realistic geodynamo mechanism, a physical state at the core surface, coupling of the core with the mantle which may have relation to the LOD (length of day), or the Earth's rotation rate, and so forth.

Most of core surface flow models have been obtained on the basis of the frozen-flux hypothesis, which is likely to be valid for a time scale much shorter than the geomagnetic diffusion time scale. The magnetic diffusion term is then neglected in the induction equation. It should be noted that a boundary layer at the core-mantle boundary (CMB) is presumed to be infinitely thin. In reality, however, its thickness would be finite, and the effect should be taken into account to estimate core flows near the CMB.

A new method to derive the core surface flow has been developed by Matsushima (2015); that is, the magnetic diffusion is incorporated inside a viscous boundary layer at the CMB, while it is neglected below the boundary layer as in the frozen-flux approximation. Temporal variations of core surface flows thus estimated have information on phenomena related with possible core-mantle coupling such as a geomagnetic jerk, the LOD, spin-up/spin-down of core flows, and so on. In particular, core surface flows inside the boundary layer show an interesting feature in relation with Earth's rotation.

磁場の影響のある対流に見られるパターンの遷移

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Transitions of convection patterns in thermal convection under a magnetic field

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Large-scale flow structure in the outer core and its variation may have relation to the geomagnetic field generation and polarity reversals. To study fundamental spatial structures of convective flow and their time variations, we performed both laboratory and numerical simulations of Rayleigh-Benard convection of an electrically conductive low-Prandtl-number fluid under a uniform horizontal magnetic field. The flow pattern is constrained, as the axes of convection rolls tend to align in the direction of the horizontal magnetic field. Transitions of flow structure such as repetition of reversals of flow direction occur when the intensity of the magnetic field is in a limited range for a given Rayleigh number. By analyzing both the laboratory experiments and numerical simulations, we clarified the process of transitions as well as their mechanism. The process can be regarded as an interaction between aligned convection rolls and global-scale mean flow. The occurrence of global circulation bends the aligned rolls in a style of the skewed-varicose instability and induces roll number reduction. In the other point of view, the transitions can be regarded as a competition between two flow modes having different roll numbers. To extract the fundamental flow structures and to quantify the mean roll number existing in time varying flow patterns, we utilize the proper orthogonal decomposition (POD) analysis. We succeeded in identifying competitive modes with time variations of their amplitudes. Convective flow regimes seen in the present setting are clearly classified by a few fundamental flow modes and variations of their relative intensities in time.

核－マントル境界の電気・熱伝導率を高温高圧実験によって明らかにする

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Experimental constraints on the electrical and thermal conductivity of the Earth's core-mantle boundary

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Heat in the Earth's interior is transported by convection in the mantle and core, and by conduction at thermal boundary layers. The electrical and thermal conductivity at the core-mantle boundary region determines the magnitude of heat flux from the core, and in intimately related to the formation of mantle plumes, the long-term thermal evolution of both mantle and core, and the driving force for generations of the geomagnetic field [1]. However, it is very challenging to directly determine the electrical and thermal transport properties of core and mantle materials at the core-mantle boundary conditions, 136 GPa and ˜4000 K. Therefore, the thermal conductivity in this region has been predicted to be 10 $Wm^{-1}K^{-1}$ for the lowermost mantle and 30 $Wm^{-1}K^{-1}$ for the outermost core based on large pressure and temperature extrapolations of laboratory data [2]. These values have been widely used for simulation of the mantle and core dynamics, and estimation of core heat flux. Recent technical progress both in the high-pressure experiment and the theoretical calculation enables us to reveal high pressure and high temperature behavior of thermal conductivities of lower mantle minerals and core materials. Our recent experimental studies regarding the electrical and thermal conductivity of core and mantle materials indicate below.

1. Our results showed that the thermal conductivity of a mixture of $MgSiO_3$ bridgmanite and MgO periclase which are main constituents of Earth's lower mantle was about 11 $Wm^{-1}K^{-1}$ at the core-mantle boundary conditions, which is consistent with conventional estimate [3,4].
2. We found the electrical conductivity of pure iron which is main component of the Earth's core was two to three times higher than conventional estimates at the core-mantle boundary conditions, which means the thermal conductivity of core also had much higher value [5].

These results are in good agreement with recent theoretical calculations. Our results if the thermal conductivities of the lowermost mantle and the outermost core support the recent notion go high core-mantle boundary heat flow, implying rapid secular cooling, an inner core younger than 1 Giga years, and ubiquitous melting during early Earth [5].

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地球深部に蓄えられた熱は対流あるいは伝導によってコア、マントル、地殻を移動する。地球のコア－マントル境界の電気・熱伝導率はコアからマントルへと移動する熱の流量の決定に必須の物理量であり、マントルプルームの形成や、コアとマントルの熱進化、地球磁場の生成・維持に大きな影響を与えている [1]。しかし、実際のコア－マントル境界に相当する圧力温度条件である 136 GPa, ˜4000 K でのコア・マントル物質の電気・熱伝導率の直接決定は容易ではない。そのため、過去 20 年近く、比較的低圧における実験結果の外挿からコア－マントル境界の熱伝導率はマントル側でおよそ 10 W/m/K、コア側でおよそ 30 W/m/K と推定されていた [2]。そして、これらの値を用いてマントルやコアの対流シミュレーションやコアからの熱流量の見積もりが行われていた。しかし、近年の高温高圧実験技術の向上と理論計算の発展によって、実際のコア－マントル境界条件における物質の電気・熱物性の決定が可能となってきた。本研究で行った高温高圧その場でのコア・マントル物質の電気・熱伝導率測定は以下のことを示している。

１． 下部マントルの主要構成鉱物である $MgSiO_3$ ブリッジマナイトと MgO ペリクレースの混合物のコア－マントル条件での熱伝導率はおよそ 11 W/m/K と過去の推定値と調和的である [3,4]。
２． コアの主成分である純鉄のコア－マントル条件での電気伝導度は従来の予想値の２～３倍高く、このことはコアの熱伝導率もこれまでの予想の２～３倍高いことを意味する [5]。

これらの実験結果は最近の理論計算の結果とも調和的であり、コア－マントル境界は特にコア側において、これまでの予想よりも高い熱輸送能力を持つことがわかった。コア－マントル境界の高い熱輸送能力は、過去の地球深部がマントル底部で大規模な融解を起こすほどに高温であったことを示唆している [5]。また、コアの冷却速度は内核の成長速度と密接に関連しているため、コアの熱伝導率の上方修正は内核の年齢の見積もりを大きく変えるかもしれない。

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Rock-magnetic properties of single zircon crystals sampled from the Yangtze River

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Geomagnetic field paleointensity data provide critical information about the thermal evolution of the Earth, and the state of the geomagnetic field has been shown to be closely related to the surface environment. While it is pivotal to understand the variations in geomagnetic field intensity throughout the history of the Earth, data are still too scarce to resolve billion-year-scale geomagnetic field variation. This is primary because of the lack of geological samples for older eras, which often result in unsuccessful paleointensity experiments.

This study focuses on a paleointensity experiment using single zircon crystal. Zircon crystals play an important role in paleomagnetic studies because they have several mineralogical advantages: (1) they commonly occur in crustal rocks, (2) precise age determinations with U-Th-Pb and (U-Th)/He analyses are possible, and (3) they have highly resilient responses to alterations and metamorphism.

Recently Sato et al. (submitted) reported the rock-magnetic properties of the single zircon crystals sampled from the Nakagawa River, which crosses the Tanzawa tonalitic pluton in central Japan. They demonstrated that the various rock-magnetic properties such as natural remanent magnetization (NRM), isothermal remanent magnetization (IRM), hysteresis parameters, and transition temperature could be measured using the standard magnetometers (SQUID magnetometer, MPMS, and AGM). Combining these rock-magnetic parameters, they proposed the sample selection criteria for paleointensity experiments using single zircon crystals.

In this study, we conducted rock-magnetic measurements for 1050 single zircon crystals sampled from the Yangtze River. Zircon crystals from the Yangtze River showed four peaks in the age distribution with the highest peak at 0.3-0.5 billion years ago, second one at 0.8 to 1.0 billion years ago, third one at 1.8-2.0 billion years ago and a minor peak at 2.5 to 2.7 billion years ago (Rino et al., 2008), and we can effectively collect the zircon crystals with crystallization ages for the last 1.0 billion years ago.

The NRM intensity (M_{NRM}) of the single zircon crystals varied from 10^{-13} to 10^{-10} Am^2, and 102 crystals (9.7%) had M_{NRM} larger than 4 x 10^{-12} Am^2. For 86 zircon crystals with M_{NRM} larger than 5 x 10^{-12} Am^2, low-temperature demagnetization (LTD) treatment was conducted and the memory (NRM intensity after LTD treatment, $M_{NRM-LTD}$) was measured. The $M_{NRM-LTD}$/M_{NRM} values were larger than 0.45, suggesting that the zircon crystals may have stable remanent magnetization.

Now we plan to measure IRM intensity and hysteresis loop. Combining the rock-magnetic parameters for the zircon crystals, we will discuss the feasibility of the paleointensity experiment using single zircon crystals from the Yangtze River.

上総層群のMatuyama-Brunhes地磁気逆転：千年スケールの特徴

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Millenial scale features of the Matuyama-Brunhes transition from the Kazusa Group, central Japan

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

A 54-m oriented core of the Kokumoto Formation in the Kazusa Group drilled along the Yoro River at Tabuchi, Chiba Prefecture reveals detailed features of the Matuyama-Brunhes (MB) transition. The core mostly consists of silts. One meter long u-channel samples were prepared from 3 to 52 m depth. Discrete samples were also collected at 2 cm to 50 cm intervals. Magnetizations were measured every 1 cm using a 2G cryogenic magnetometer for u-channel samples, subjected to alternating field demagnetizations (AFD), while both AFD and thermal demagnetization was used for discrete samples. Preliminary oxygen isotope data on planktonic foraminifera (*Globorotalia inflata*) suggest that the main MB polarity boundary, just underlain by the Byakubi-E tephra layer, lies between the sea-level highstand of marine isotope stage (MIS) 19.3 and the MIS 19.2 lowstand. Characteristic remanent magnetizations of u-channel samples calculated by principal component analysis reveal a multiple rapid reversal interval (MRI), a very important feature characteristic of the final stage of the MB transition, which lies between depths correlated with highstand 19.3 and lowstand 19.2. The MRI spans about 1.7 m in depth, during which the virtual geomagnetic pole crossed the geographic equator at least 11 times. An astronomical age model suggests that the MRI was ca 2 kyr in duration, predating 776 ka and postdating 779 ka. The relative paleointensity proxies from the core show quite similar variations with the global paleointensity stack Sint-800, especially the post-reversal intensity recovery from both records exhibits a high degree agreement. The MRI just coincides with the lowest intensity interval of Sint-800, and can be correlated with similar intervals observed in the Osaka Group, Chinese loess-paleosols, and deep-sea sediments. The MRI may be a useful tool for correlation in high-resolution magneto-climatostratigraphy.

富士火山溶岩による絶対古地磁気強度測定：古地磁気強度と大気の放射性炭素の関係性

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Paleointensity study on lava flows of Fuji Volcano and implications for atmospheric 14C

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We applied the LTD-DHT Shaw paleointensity method (Tsunakawa-Shaw method) to lava flows of the ages for the last 30 kyr. The studied lava flows of Fuji Volcano and the other volcanoes were dated by 14C ages, which were reported for the charred material, wood, or organic sediment. Our preliminary results suggest that the absolute paleointensities and atmospheric 14C production rates at the 14C ages show a good correlation. On the basis of this correlation, paleointensity variation for the last 30 kyr can be reconstructed from the 14C production rate.

過去数万年間の古地磁気強度変動は、地球磁場の永年変化や地球表層への宇宙線入射量の変動を把握する上で必要な基礎データである。過去数万年間については、考古学試料や火山岩による古地磁気強度データが多数存在するものの、ばらつきが大きく、あきらかに古地磁気強度測定の精度（~10%）をこえている。このことから、現存のデータベースには、精度の低いデータや誤ったデータが多数含まれていると推察される。本研究では、炭素14年代が報告されている富士火山の溶岩にLTD-DHT Shaw法（綱川-ショー法）を適用することで、過去1万年間における信頼度の高い絶対古地磁気強度データの復元を試みる。さらに、他の火山の1〜3万年前の溶岩からも古地磁気強度を復元した上で、過去3万年間における絶対古地磁気強度と大気の放射性炭素生成量（炭素14）の関係性を検討する。予察的な結果によれば、得られた絶対古地磁気強度データと放射性炭素濃度には、明確な相関が確認できる。この相関に基くことで、放射性炭素濃度変動から過去3万年間の古地磁気強度変動を推定することができる。また、本研究で得られた絶対古地磁気強度と放射性炭素濃度の相関関係と既存のモデル計算の結果を比較することで、過去3万年間における平均的な太陽活動度が現在よりも低いことも示唆される。

北中国クラトンから得た原生代中期の古地磁気極

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A Mesoproterozoic paleomagnetic pole from 1.32 Ga sills in the North China Craton

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The Paleo-Mesoproterozoic super continent Columbia including the north China Craton is believed to have been exist between ~1800 Ma and ~1500 Ma (e.g. Zhao et al., 2004).The purpose of this study is to make paleomagnetic constraints to reveal the behavior of North China Craton (NCC) during the break-up of Columbia.

We report a Mesoproterozoic paleomagnetic pole position from the diabase sills from northern NCC. We have conducted paleomagnetic and rock magnetic measurements on ten sills in the Mesoproterozoic Xiamaling Formation near Chendge, northeast of China. An U-Pb age of 1320 +/- 6 Ma have been reported from the sills (Li et al., 2009). Paleointensity results with basic paleomagnetic and rock magnetic experiment results had been reported in 2014 SGEPSS meeting.

The characteristic high temperature components are obtained from five sites, one of which indicates reversed polarity. The mean direction is D=-8.3^o and I=-3.1^o (alpha95 =33.7^o) after tilt correction. This direction has passed fold test and baked contact test, indicating the primary origin of the high temperature component. The corresponding paleomagnetic pole is positioned at 349.8^{o}E and 47.6^{o}N (A95=24.4^o).This 1.32Ga pole lies between 1.35Ga pole (Chen et al., 1350) and 1.27Ga pole (Zhang et al., 1270Ma). The APWP indicates that the NCC has been located within low latitudes during this period.

古始生代花崗岩に含まれる離溶磁鉄鉱の岩石磁気と古地磁気

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Rock magnetism and paleomagnetism of tiny exsolved magnetite in plagioclase from a Paleoarchean granitoid in the Pilbara craton

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[1] JAMSTEC; [2] TiTech; [3] The University of Tokyo; [4] National Museum of Nature and Science

Granitoids are widespread in Precambrian terranes as well as the Phanerozoic orogenic belts, but they have garnered little attention in paleomagnetic studies, because granitoids often contain abundant coarse-grained, magnetically unstable oxides. We have reported the first example of tiny, needle-shaped, exsolved oxides in plagioclase in a Paleoarchean granitoid in the Mount Edgar Complex, Western Australia. The magnetic properties of single plagioclase crystals with the exsolved oxide inclusions have been studied to determine their paleomagnetic recording fidelity. Demagnetization experiments and hysteresis parameters indicate that the oxide inclusions are near stoichiometric magnetite and magnetically very stable. First-order reversal curve (FORC) diagrams reveal negligible magnetostatic interactions. Minimal interactions are also reflected by very efficient acquisition of anhysteretic remanent magnetization. Single plagioclase crystals exhibit strong magnetic remanence anisotropies, which require corrections to their paleodirectional and paleointensity data. Nonetheless, quantitative consideration of anisotropy tensors of the single plagioclase crystals indicates that the bias can be mitigated by properly averaging data from a few tens of single crystals. From the nonlinear thermoremanence acquisition of the plagioclase crystals, we estimate that the plagioclase crystals can reconstruct paleointensity up to 50 micro-T. Local metamorphic condition suggests that those magnetites may carry remanence of 3.2 to 3.3 Ga. We will also discuss the preliminary paleomagnetic data from the Mount Edgar Complex.

花崗岩は顕生代に限らず先カンブリア系のテレーンにも広く分布している。しかし、花崗岩は多くの場合粗粒な磁鉄鉱を含むため、古地磁気の対象としてはあまり用いられてこなかった。我々はピルバラ地塊の古始生代の花崗岩（Mount Edgar 複合岩体）中の斜長石が、単磁区サイズの離溶磁鉄鉱を含むことを発見した。斜長石単結晶の岩石磁気分析から、これらの磁鉄鉱は古始生代の地磁気記録を保持し得ることがわかった。磁気異方性と熱残留磁化の飽和について検討した結果、数十個の斜長石を平均することで、古地磁気方位は正確に復元でき、古地磁気強度も約 50 micro-T までは正確に復元できることがわかった。発表ではさらに、予察的な古地磁気分析結果について報告する。

陶邑窯跡群試料を用いた近畿地方における地磁気永年変化の再検討 (III)

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Reexamination of geomagnetic secular variation in Kinki District using samples from Suemura kilns (III)

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In 1960s-70s, enormous number of kilns were excavated in Sakai city and its vicinity, Osaka prefecture for a large residential development. Enhanced archeological studies, especially for massive amount of pottery kilns (Sue ware of 5th to 10th century) were carried out by Osaka Prefectural Government. Archeomagnetic researches were also conducted by prof. Kawai and his colleagues of the Osaka University. As the result, the geomagnetic secular variation curve from the 5th century to the 10th century was drawn (e.g. Hirooka 1971; Shibuya 1980). However, there are problems from the present paleomagentic view point. The natural remanent magnetizations (NRM) were measured by astatic magnetometer and demagnetization was not made. Fortunately, those samples are stocked in Osaka Ohtani University, and we moved them to Okayama Science University and Kumamoto University, for conducting systematic remeasurement study of their NRM after alternating magnetic field demagnetization (AFD). We already reported paleomagnetic directions in 2012 and 2015 JpGU meeting. This time, we report the secular variation curve drawn from the results.

1960-70 年代に、大阪府堺市周辺で大規模な宅地造成工事が行われ、それに伴い膨大な古窯跡（陶邑古窯跡群）が発掘された。それら古窯跡の考古地磁気研究は当時の大阪大学・川井研究室が行った。その結果、5 世紀から 10 世紀の地磁気永年変化曲線 (SVC) が提案されている (例えば Hirooka, 1971; Shibuya, 1980)。しかし、その測定は無定位磁力計によるもので、また、消磁も行われていないと言う問題点があった。幸いそれらの試料は現存しており、大阪大谷大学で保管されていた。岡山理科大学と 熊本大学ではそれらの試料をもらい受け、2011 年から系統的な再測定を始め、2012 と 2015 年の JpGU 測定結果について発表した。今回は、測定結果から推定されるこの時代の地磁気永年変化曲線について議論する。

まず、各サイトの孤立値を MacFadden (1982) を用いて 95%信頼限界で取り除き、平均を取った。そのうち $\alpha_{95}<4^o$ のサイトのみを取り出し、SVC 推定に用いることとした。過去の研究は考古編年に基づいて方位を平均して、SVC を求めている。今回は、考古編年の基となっている器形のレンジに重なりがあること、遺物の年代と窯の最終焼成年代に異同があることを考慮し、方位変動のみから SVC を求め、年代スケールの導入に考古年代を用いることを試みた。これは、高い測定精度 (特に高い試料方位精度) と膨大なサイト数が可能としたものである。

SVC は曲線とサイト平均方位の距離の自乗、SV の速度変動の自乗などの線形結合をペナルティー関数として、それを最小化するように決定した。その結果、詳細な考古年代に依存することなく（SVC が折り重なっているので、大まかな年代は用いた）SVC を決定することが可能となった。

得られた曲線の概要は既存のものと大きく異なるものではなかったが、移動平均を用いなかったことから、振幅は大きくなっており、実際の SV を反映していると考えている。また、SVC から年代割り振りから、窯跡数の年代変動を見るできて、工人集団の消長の見積もりに使えそうである。この結果は、今後の地磁気変動に寄与するばかりでなく、器形編年と独立な年代軸を提供する可能性を示しており、考古学的な応用も広がることを期待している。

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。第四回報告

辻本 元博 [1]
[1] なし

Analyzing the early 19th century’s geomagnetic declination in Japan from Tadataka Inoh’s Santou Houi Ki the 4th report.

Motohiro Tsujimoto[1]
[1] none

The Santouhouiki is a national tresure of Japan,consist of 67 volumesledger 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 excute interdisciplinary and simultaneous analysis of real azimuth,magnetic declination,precise position of the survey reference point and target points where the value of declination to any targets are similar or proximate. We analyzed declination at 189 points in Japan.

The declination analyzed from Santouhouiki in wide area from Tsushima to north western coast of Kyushu are developed to 1 degree west more than the declination expressed in Historical magnetic declination viewer by Gufm1published from NOAA. There are no data of declination in Japan from mid 17 century
to mid 19 century,equal to the term of national isolation of Japan.It is necessary to introduce the declination data analized from Santouhouiki to Andrew JAckson Gufm1.

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の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 189 地点
で地磁気の偏角を解析した。１９世紀初頭の日本の地磁気偏角の分布が判明しつつある。山島方位記からの解析値は対馬から九州北西部にかけての広域な範囲でジヤクソンらのｇｕｆｍ１に基づくアメリカ海洋大気庁の偏角の歴史図よりも約１度西偏の進行が早い。ジヤクソンらのｇｕｆｍ１は鎖国した１７世紀中期から１９世紀中期迄の日本のデータが欠落しており、山島方位記からの解析値をｇｕｆｍ１に導入して計算しなおす必要がある。

福井県越前焼古窯の古地磁気学

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Archeomagnetism of Echizen-yaki old kilns

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http://mag.center.ous.ac.jp/

Archeomagnetism is a branch of paleomagnetism, whose subjects are manually baked relics and archeological ruins. Results from archeomagentism are often much accurate and much stable than those from other paleomagnetic samples such as volcanic rocks and sediments. Especially in Japan, potteries and old kilns of Sue ware have been a good target of archeomagentic studies. The reasons are that Sue wares were fired in high-temperature (~1200C) anoxic environment in the kilns and stable magnetite is the main carrier of the magnetic moments, and that the production of the Sue wares and population of the kilns were concentrated and have been well preserved. However, Sue ware had been developed till the middle of Heian era and there were very little kilns remaining after the 11th century. Here we report the results of paleomagnetism and rock magnetism for Echizen-yaki old kilns in Fukui prefecture, central Japan. Echizen-yaki is one of so-called "Six Old Potteries" which were originated in the middle-age of Japan and have been baked till the present age. Echizen-yaki has the roots in Sure ware and began in the late Heian era. Therefore Echisen-yaki is likely a good target of the paleomagnetic study following the Sue wares.

古地磁気学の対象を人間が残した被熱遺構や被熱土器片に求める考古地磁気学は、古地磁気学の中でも残留磁化の安定性、確実性および年代値の精度等にとくに優れ、数千年間未満の比較的最近の地磁気永年変化 (方位・強度) を求めるための研究に使用されてきた。とくに日本においては、5〜10 世紀に発達した須恵器とそれを焼くために使用した窯跡を利用した考古地磁気学が発展してきた。考古地磁気学の対象として須恵器とその窯跡が特に優れている理由は、釉薬を使用せず焼成温度が高温になること、還元焼成のため土器・窯面ともにマグネタイトが主要磁性鉱物で安定であること、地域内に置いて窯跡が集中的に作成され、かつ、使用後に破壊されずに保持されるケースが多いこと、などがあげられる。しかし、須恵器は平安時代中期以降衰退してしまうため、それ以降の地磁気永年変化研究のためには他の陶磁器窯跡を使用する必要がある。実際これまでの考古地磁気学では 11 世紀以降の対象遺跡は東海地方の常滑・瀬戸といった遺跡に依存することが多い。本研究で対象とする越前焼は、起源が中世にまで遡り現在まで続く日本六古窯の 1 つとされ、福井県越前町 (旧織田町、旧宮崎村) を中心として作陶されてきた陶器である。越前焼のルーツは須恵器で、須恵器が衰退する平安時代後期には製作が始まっていたと考えられている。そのため、越前焼の土器および窯跡は、ポスト須恵器の考古地磁気学として大変重要な位置にあると考えられる。しかし、これまで越前焼窯跡を対象とした考古地磁気研究は数えるほどしか行われておらず、その考古学年代値との突き合わせも不十分である。このたび我々は、越前町の 2 地域より合計 3 つの窯跡についてよく焼成された窯床面の古地磁気用試料を採取することができた。本発表ではこれまでに得られた古地磁気・岩石磁気測定の結果を紹介し、越前焼窯跡の考古地磁気研究材料としての可能性を議論する。

山梨県北杜市上原遺跡の考古地磁気学的研究

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Archeomagnetic study of Kamihara ruins in Hokuto city, Yamanashi Prefecture, Japan

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Recently, we have carried out archeomagntetic study using baked soil which was found at ruins around Matsumoto city, Nagano Prefecture (Saito, 2014; Henmi and Saito, 2015). According to our previous studies, declination values were slightly lower than those from secular variation (Hirooka, 1971; Hatakeyama et al., in prep.). The studied area is located around the northwestern end of the region where the local magnetic anomaly is distributed (GSI, 2010). The anomaly has possibly continued in the past several thousand years, resulted in the lower declination values obtained from the ruins at Matsumoto city. In order to examine the influence of the local magnetic anomaly, we started the archeomagntetic study at Kamihara ruins in Hokuto city, Yamanashi prefecture, where is located at the center of the region of the local magnetic anomaly. Ten rock magnetic samples using plastic cubes and 23 archeomagnetic samples coated by gypsum were obtained from baked and unbaked soil.

As a result, samples from the baked soil had stable TRMs whose directions were probably parallel to earth magnetic field at the time when TRM was acquired. The unbaked soil samples had multi-component and NRMs separated at higher demagnetization levels were relatively unstable. Rock magnetic results revealed IRM of both samples almost saturated at 40mT. SIRM of baked soil samples demagnetized smoothly at lower demagnetization level. On the other hand, unbaked soil samples hardly demagnetize until 10mT, resulted in kinked demagnetization curves. Because NRM and susceptibility of both samples showed similar values, it seems that amount of magnetic minerals in baked samples did not differ those in unbaked samples. According to our results, magnetic minerals in both samples were probably (titano-) magnetite. Grain sizes in baked samples seemed to become larger due to heating when TRM was acquired, resulted in different rock magnetic behavior from unbaked samples.

我々は最近、長野県松本市付近で発掘された遺跡で見つかった焼土を用いて考古地磁気学的研究を進めている (齋藤, 2014)。これまで松本市で発掘された２つの遺跡（高畑遺跡、和田太子堂遺跡）の研究を行い、遺跡の年代として妥当な考古地磁気方位を有していることを報告した (邊見・齋藤, 2015, JPGU)。しかし松本市周辺で得られた考古地磁気方位は、永年変化曲線 (広岡,1971; Hatakeyama et al., in prep.) から東にずれる傾向がある。国土地理院の偏角図 (2010.0 年値) によれば静岡―甲府―諏訪付近にかけて偏角値が 1～2 度程度低い領域が広がっており、この非双極子成分の影響によって過去においても甲信地方では偏角が低かった可能性がある。

今回、北杜市埋蔵文化センターの協力を得て、山梨県北杜市上原遺跡から竈跡と考えられる焼土を採取することができた。プラスチックキューブを用いて 4 つの住居跡の被熱箇所から 7 個、非被熱箇所から 3 個のパイロットサンプルを採取した。さらに方位測定用試料として、石膏で固めた焼土試料を 7 つの住居跡から 23 個採取した。石膏試料については整形作業を行い、現在分析を進めている。プラスチックキューブによる試料については、被熱の程度や磁化の安定性、磁性鉱物の岩石磁気学的特徴を検討するために、帯磁率測定、NRM の交流消磁実験、ARM および IRM 着磁・消磁実験を行った。交流消磁実験の結果、被熱試料は低消磁段階から高消磁段階まで、原点に向かってほぼ一直線の直線性の良い磁化を獲得していることがわかった。キューブ試料は方位づけの精度が高くないため精細な議論はできないが、得られた磁化方位は住居毎に異なり、住居の使用年代を反映した考古地磁気方位が記録されている可能性が高い。非被熱試料については、NRM 強度や帯磁率の値は被熱試料とそれほど変わらないが、NRM の交流消磁結果は被熱試料ほど直線性が良くなく、特に高消磁段階で原点に向かわない不安定な磁化成分が分離される傾向がある。

IRM の着磁実験では、どちらの試料も 40mT 程度で飽和した。ロウリーフラーテスト (Lowrie and Fuller, 1971) の結果は IRM 曲線が ARM 曲線の上側に位置する MD タイプを示したが、被熱試料の IRM 消磁曲線は低消磁段階から減衰する滑らかな曲線となったのに対し、非被熱試料は 10mT までほとんど消磁されず、15mT 以降に大きく消磁される特徴を示した。また IRM 消磁実験の MDF は、被熱試料の 10～12.5mT に対し、非被熱試料は 20～25mT と大きい値を示した。NRM 強度や帯磁率がそれほど変化していないため、被熱によって新たに磁性鉱物が大量に生産されたとは考えられず、また IRM 獲得曲線が 40mT で飽和していることからヘマタイトなどの高保磁力成分の寄与もほとんどないと考えられる。おそらく磁化を担っている磁性鉱物は MD サイズの (チタノ) マグネタイトと考えられ、被熱試料は加熱されたことによって磁性鉱物粒子サイズが大きくなった可能性がある。

上原遺跡で採取された被熱試料は当時の地球磁場と平行方向の熱残留磁化を保存していることが期待される。また非被熱試料とは岩石磁気分析の結果から区別できることがわかった。以上を踏まえ、さらに分析をすすめ甲信地方の考古地磁気について議論をする予定である。

八丈島津波石の古地磁気学的研究

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Paleomagnetic research for Tsunami boulder in Hachijo Island

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In Hachijo Island, there is isolated andesite boulders at an altitude of 20-m above sea level situated on the western side of the land. One of these is about 3000-4000kg in weight without any sign of organic carbon, such as fossils. Such huge boulders are paid some attentions as a key to understanding of past tsunami events. If it is the coral boulder, we can estimate the date of past tsunami by using radiocarbon dating. However, there is no way to estimate the date of the volcanic boulders without any organic fossils. One of an alternative way to date volcanic boulders is the cosmogenic nuclide exposure dating because it simply accumulate on boulder surface. But, the cosmogenic dating can not apply to the boulders if the boulder had experienced multiple rotations. Recent study tried to reveal the date of multiple emplacements of coral boulders in Ishigaki Island, Japan, by using paleomagnetic approach. Therefore, we applied this approach to this volcanic-origin boulder and tried to examine when tsunami event had occurred, and how it had moved. Boulders acquire the secondary magnetic component, called viscous remanent magnetization (VRM) after tsunami. The secondary viscous remanence is acquired to the original magnetic vector after the boulder has been removed from the original state. And by using Neel's thermal activation theory, the magnetization at low temperature for a long time can be demagnetized at high temperature in a short time. So we can count backward to the age when VRM was acquired (i.e. the past tsunami event). And we can understand how they emplaced, by displacement of direction of magnetization. In the presentation, we will present the current results.

拡張型磁気緩和による年代決定法の石垣島サンゴ津波石への応用

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An extended magnetic relaxation dating to tsunamigenic coral boulders in Ishigaki Island, Japan

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Identification of an isolated boulder displaced and eventually transported by tsunamis plays a crucial role in the assessment of the occurrence of paleotsunami events. One of the most important evidence to the understanding of past tsunami events is to accurately date them from boulders. In Ishigaki Island, Japan, coral boulders that had been transported by tsunamis were distributed on the beach and land areas. In previous researches, large numbers of radiocarbon dating for coral boulders revealed the multiple tsunami events during past 2500 years. Although the first deposited age of a coral boulder could be established by using radiocarbon dating, there is a lack of information for subsequent transported ages. A viscous remanent magnetization (VRM) dating method can be used to date any geological event that results in significant movements of a rock. If a magnetic-mineral bearing rock is moved or re-oriented, the magnetism of the smaller magnetic grains re-aligns to the direction of the ambient magnetic field with time. This phenomenon is well known as Neel's (1949, 1955) single-domain (SD) relaxation theory. Pullaiah et al. (1975) derived a time-temperature (t-T relation) relation by assuming Neel's (1949, 1955) theory of magnetite. In principle, an experimental combination of short relaxation time and high temperature for removing VRM can determine the unknown relaxation time (tsunami age) at room temperature. Sato et al. (2014) applied VRM dating for comparing the radiocarbon age of these boulders. However, the age determined from t-T relation showed older age than radiocarbon dating for the same boulders. Recent work has shown that departures from Neel's theory can generally be attributed to VRM carried by coarse magnetic grains because their magnetization responds much more slowly. A natural rock contains many magnetic grains, with a wide variety of sizes and shapes, described by grain distribution. In an aggregate of the distribution, the relaxation form has been explained by a stretched exponential function. Thus, we reanalyzed published VRM decay data by stretched exponential law, and the results provided a reasonable fit to the experimental data. Furthermore, the extended t-T relation based on the stretched exponential has shown to be effective for experimental results of coral boulders.

北西太平洋IODP Site U1408から予察的に見積もるクロンC18nにおける相対古地磁気強度変動

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Preliminary estimate of relative paleointensity variation during the Chron C18n from IODP Site U1408 in the Northwest Atlantic

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We have been working on paleomagnetic and rock magnetic measurements on the sedimentary sections recovered from Integrated Ocean Drilling Program (IODP) Site U1408 in the Northwest Atlantic, off Newfoundland. The measurements were done on u-channel samples using a pass-through superconducting rock magnetometer in a manner that remanent magnetizations (natural, anhysteretic and isothermal remanent magnetizations: NRM, ARM and IRM) were subjected to stepwise alternating field (AF) demagnetizations up to 80 mT and are measured with 1 cm spacing at each step.

Yamamoto et al. (2014 SGEPSS fall meeting) reported that the interval at ~33-157 mcd (meter composite depth) covered the Chrons C18n.1n to C20n and that the interval at ~37-90 mcd showed relatively constant ARM and IRM intensities as well as ratios of ARM to IRM (ARM/IRM). It is expected that this interval can potentially provide relative paleointensity (RPI) estimate during the middle Eocene. We will report the preliminary result of RPI estimate during the Chron C18n, based on normalized NRM intensities by ARM and IRM. The result will be compared with the RPI covering the same period reported from the equatorial Pacific (Yamamoto et al., 2014).

北西大西洋ニューファンドランド沖のIODP Site　U1403から採取された海洋コアからの古地磁気強度相対値変動の解明に向けて

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Towards the estimate of relative paleointensity variation from the marine cores from IODP Site U1403 in the Northwest Atlantic

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Marine sediment is an important recorder of the past environmental changes. It can provide important information to investigate the environmental change continuously back in time, once a high-resolution age model is constructed by multiple techniques. Integrated Ocean Drilling Program (IODP) Expedition 342 recovered marine sediment cores from the Northwest Atlantic, off Newfoundland, to investigate the environmental change from the Paleocene to the Eocene. Our objective is to estimate relative paleointensity (RPI) variation for that period. In order to achieve this, we have been working on paleo- and rock magnetic measurements from the cores recovered from IODP Site U1403, for the interval cored by an advanced piston corer (25-160 mcd: meter composite depth).

Fukami et al., (2015 JpGU meeting) concluded that the interval covered the period between 35.706 Ma (chron boundary C15r/C16n.1n) and 49.344 Ma (C22n/C22r). They also measured rock magnetic parameters of ratio of anhysteretic remanent magnetization (ARM) to isothermal remanent magnetization (IRM) (ARM/IRM) and S-ratios (-0.1 and -0.3 T) on the 88 discrete samples taken from Hole A, indicating that the interval at 50-90 mcd showed relatively constant values of the parameters and thus is suited for an estimate of RPI variation. As this interval covers the period between 40.145 Ma (C18n.2n/C18r) and 45.724 Ma (C20r/C21n), it can potentially provide the RPI variation covering the period older than that reported by Yamamoto et al., (2014) (about 23-41 Ma) which has been known as the oldest RPI record.

To estimate RPI variation from the interval, we measure natural remanent magnetization (NRM), ARM and IRM from u-channel samples at 1 cm resolution using stepwise alternating field demagnetization. Then we normalize NRM by both ARM and IRM and examine whether or not they have correlations with rock magnetic parameters. Until now, we have finished the measurement of ARM (AF: 100 uT, DC: 80 mT). Normalized intensity of the NRM by ARM (NRM/ARM) always shows the minima at the chron boundaries and fluctuates largely during chrons. These characters are the same as those commonly reported for RPIs of the last 3 Myr and older. We will continue to do measurements of IRM and rock magnetic parameters and report these results.

海底堆積物は過去の環境変動を時間的にほぼ連続して記録している試料であり, 地質時代に遡る環境変動を解明する上で重要な情報源となる. 統合国際深海掘削計画 (IODP) 第 342 次研究航海では, 暁新世から始新世の気候変動解明を目的に, 北西大西洋ニューファンドランド沖から海底堆積物が掘削された (Expedition 324 Scientisits, 2012). 我々は、当該期間における古地磁気強度相対値変動の解明を目的とし, IODP Site U1403 より掘削された海洋コア (25-160 mcd: meter composite depth) を対象とした, 古地磁気・岩石磁気学的研究に取り組んでいる.

Site U1403 における 25-160 mcd の区間は 35.706 Ma (クロン境界 C15r/C16n.1n)-49.344 Ma (C22n/C22r) の期間をカバーすると推定されている (深見ほか, 2015). また, Hole A より採取した 88 個の discrete sample を対象に非履歴性残留磁化 (ARM) に対する等温残留磁化 (IRM) の比 (ARM/IRM), S 比 (-0.1T, -0.3T) などの岩石磁気パラメーターの測定を行った結果, とくに 50-90 mcd の区間が岩石磁気的に比較的均質な層準であることが判明し, 古地磁気強度相対値変動を推定するのに適していると結論している (深見ほか, 2015). この区間は 40.145 Ma (C18n.2n/C18r)-45.724 Ma (C20r/C21n) の期間をカバーしているため, 海底堆積物による古地磁気強度相対値変動の中でも最も古い時代をカバーしている Yamamoto et al., (2014) による報告 (約 23-41 Ma) よりもさらに過去に遡る変動を明らかにできる可能性がある.

古地磁気強度相対値変動の推定にあたっては, まず U-channel 試料の自然残留磁化 (NRM), ARM, IRM 強度をそれぞれ段階交流消磁により測定し, NRM 強度に対して ARM および IRM 強度によって規格化を行う. これらの規格化強度が岩石磁気パラメーターと相関をもたないかどうか検討を行い, 岩石磁気的要因によらない変動を明らかにすることを目指す. 現在までに ARM(AF: 100 μ T, DC: 80 mT) の段階交流消磁測定を終えている. 50-90 mcd の区間における ARM による NRM の規格化強度 (NRM/IRM) はクロン境界でゼロに近い極小, クロン内では周期的な極大および極小を伴う変動を示す. これらの特徴は過去 300 万年およびそれ以前の期間について報告されている古地磁気強度相対値変動の一般的な特徴と一致している. さらに, 今後は IRM 強度や岩石磁気パラメーターの測定をすすめ, これらの結果を交えた考察を行う.

海底堆積物を用いた2〜3.2 Maの相対古地磁気強度変動に関する研究：堆積残留磁化獲得深度の検討

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A study on relative paleointensity from 2 to 3.2 Ma using marine sediments: implication for depth-lag of pDRM acquisition

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It is important to determine variations of the past geomagnetic field strength for better understanding the geodynamo. This study aims to estimate relative paleointensity of the geomagnetic field (RPI) beyond 2.0 Ma. Marine sediments can preserve temporally continuous paleomagnetic records. Piston core samples obtained from the West Caroline Basin in the western equatorial Pacific (R/V MIRAIMR14-02 cruise, core PC01) were used. The saturation isothermal remanent magnetization (sIRM) was imparted to normalize the natural remanent magnetization (NRM) intensity to obtain RPI. The RPI record covers from ˜0.65 to ˜3.2 Ma. The age model was established for sediments older than 1.8 Ma using both the magnetostratigraphy and oxygen-isotope stratigraphy. In comparison with the IODP U1314 core data (Ohno et al., 2012), paleointensity variations between two cores generally coincide in the period from 2.1 to 2.75 Ma. If we assume the depth-lag of remanent magnetization acquisition of 15 cm, a large difference of the sedimentation rate between this study (˜0.5 cm/kyr) and IODP Site U1314 (˜10 cm/kyr) should cause an apparent time shift of ˜30 kyrs between the two RPI records. However, no such shift was observed. This result implies that the depth-lag of the studied core is very small. We plan independent estimation of depth-lag using ^{10}Be-based paleointensity around the Gauss-Matuyama boundary.

過去の地磁気強度変動を求めることは、地磁気ダイナモ論への制約などから重要である。本研究では、時間連続な地磁気レコーダーとして海底堆積物を用いる。これまで報告されたデータの少ない、200万年より古い年代の強度変動を高い信頼性で見積もることを研究目的とする。試料として西部赤道太平洋西カロリン海盆で採取されたピストンコア試料 (「みらい」MR14-02 航海、サイト PC01) を用いた。自然残留磁化強度を飽和残留磁化強度で規格化することにより 0.65-3.2 Ma の年代で相対古地磁気強度を得た。年代は古地磁気層序と酸素同位体比層序双方から得た。酸素同位体比は 1.8 Ma 以前で LR04 標準曲線と整合的に対比させることが出来た。北大西洋で採取された IODP Site U1314 コアによる相対古地磁気強度データ (Ohno et al., 2012) と対比させたところ、2.1-2.75 Ma の範囲でよく一致した。ここで、堆積物の磁化獲得深度を場所や年代に依らず 15 cm であると仮定するとき、U1314 コアで 10 cm/kyr、本研究で 0.5 cm/kyr という堆積速度の違いから、相対古地磁気強度には見かけ上 ˜30 kyr 程度の系統的な年代相違が生じると考えられる。しかし相対古地磁気強度のパターンには一様な傾向の年代相違が見られなかった。この結果から、本研究コアにおける堆積残留磁化獲得深度が非常に浅いことが示唆される。今後 ^{10}Be を用いたガウス・松山境界付近の古地磁気強度復元によっても、堆積残留磁化獲得深度を独立に見積もることを予定している。

超マフィック型海底熱水系における高磁化帯の起源

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Origin of Magnetic Highs at Ultramafic Hosted Hydrothermal Systems

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Near-seafloor vector magnetic measurements were performed on an inactive ultramafic-hosted hydrothermal vent field, called Yokoniwa, using a deep-sea manned submersible *Shinkai6500* and an autonomous underwater vehicle *r2D4*. The Yokoniwa Hydrothermal Field has developed at a non-transform offset massif of the Central Indian Ridge. The distribution of crustal magnetization from the magnetic anomaly revealed that the Yokoniwa Hydrothermal Field is associated with enhanced magnetization, as seen at the ultramafic-hosted Rainbow and Ashadze 1 hydrothermal sites of the Mid-Atlantic Ridge. The results of rock magnetic analysis on seafloor rock samples (including basalt, dolerite, gabbro, serpentinized peridotite, and hydrothermal sulfide) showed that only highly serpentinized peridotite carries high magnetic susceptibility and that the natural remanent magnetization intensity can explain the high magnetization of Yokoniwa. These observations reflect abundant and strongly magnetized magnetite grains within the highly serpentinized peridotite. Comparisons with the Rainbow and Ashadze 1 suggest that in ultramafic-hosted hydrothermal systems, strongly magnetized magnetite and pyrrhotite form during the progression of serpentinization due to hydrothermal circulation. After the completion of serpentinization and production of hydrogen, pyrrhotites convert into pyrite or nonmagnetic iron sulfides, which considerably reduces their levels of magnetization. Our results revealed origins of the magnetic high and the development of subsurface chemical processes in ultramafic-hosted hydrothermal systems. Furthermore, the results highlight the use of near-seafloor magnetic field measurements as a powerful tool for detecting and characterizing seafloor hydrothermal systems.

熊野前弧海盆における地震性タービダイトの微細構造解析

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Microstructure analysis of marine seismogenic turbidites in Kumano forearc basin

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An elongated depression was located in an ENE-WSW direction between the southern margin of the forearc basin and the outer ridge off Kumano. A terminal basin that captures all sediments supplied from outside is developed within this depression, making it an adequate site to study paleoseismology using seismogenic turbidites.

Previous study results reveal the Cs-137 and Pb-210 that the upper 17-cm mud layer was deposited immediately after the 2004 off Kii Peninsula earthquakes (Ashi et al., 2015, JpGU Meeting abstract). We herein investigate the characteristics of marine seismogenic turbidites based on various measurements including their compositions, X-ray CT images, and anisotropy of magnetic susceptibility (AMS). We observed a very thin fine-grained sand layer of 6 mm thick at 17 cm below seafloor and a volcanic ash layer of 15 cm thick at 5.1 m. The X-ray CT image shows seven silty clay laminations thinning upwards at 6 -15 cm below seafloor with homogeneous clay based silt above it, and several foraminifera-enriched layer below 1.7 m. The AMS parameters decrease upwards in the interval showing parallel/cross laminations and the lowest value is measured in the overlying silt layer. Moreover, the paleocurrent directions showed the NW-SE flow direction. These results indicate that the upper 17 cm layer beginning from the very fine-grained sand can be interpreted to be formed by a low density reflected gravity flow between the SE and NW dipping slopes of the basin. Structural observations by X-ray CT scanner reveal characteristic structures yielding various orientation oblique to bedding plane at the mud layer 17 cm below seafloor, suggesting that the structure is likely formed by coseismic deformation accompanied by the earthquake in 2004 or earlier ones. Magnetic fabrics derived from AMS measurements and the structure observed by X-ray CT scanner also agree to this picture.

熊野沖の前弧海盆の南縁と外縁隆起帯の間には，東北東－西南西方向に伸びた深い凹地が分布し，外から流入した堆積物が流れ出ることのないターミナル海盆が発達する．この地点は陸上河川からの直接の堆積物供給もないため，地震性タービダイトを用いた古地震研究に適している．この堆積盆より採取された柱状試料のセシウム 137 と過剰鉛-210 濃度の分析の結果は，上部 17 cm の泥質層は 2004 年紀伊半島南東沖地震の際に堆積したことを示す（芦ほか，2014，地質学会秋季大会）．本発表は，同試料の組成，粒度，X 線 CT 画像，帯磁率異方性から地震性堆積物の特徴の解明を目的とした．

試料の肉眼観察では，海底下 17 cm に厚さ 6mm の極細粒砂層が認められ，それ以浅は塊状の泥からなる．また, 海底下 5.1 m には厚さ 15 cm の火山灰層が認められた. 一方，X 線 CT 画像には海底下 6～15 cm に上方へ薄層化するシルト質の葉理が 7 枚確認でき，海底下 1.7 m 以深では有孔虫が密集している層が多数確認できた．平行および斜交葉理の発達する部分では, 帯磁率は上方への減少がみられ，上位のシルトで最も低い値を示す．また, 帯磁率異方性から北西-南東方向の古流向が示唆された. これらの結果から, 極細粒砂から始まる上記の層は地震動によって生じた低密度の混濁流が堆積盆底の北側の南東傾斜の斜面と南側の北西傾斜の斜面の間を往復して形成されたと考えられる．17 cm 以深は主にシルト質堆積物からなるが, X 線 CT 画像には，層理面に対して斜交する様々な方向を向いた構造が認められ，2004 年かそれ以前の地震による震動変形と解釈できる．帯磁率異方性による磁気ファブリックと X 線 CT 画像に見られる構造も良い対応を示す.

磁気インピーダンスセンサーを用いた高感度スピナー磁力計（続報）

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Sensitive spinner magnetometer using magneto-impedance sensor- II

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A sensitive spinner magnetometer was developed using a pico-Tesla resolution Magneto-Impedance sensor (MI sensor), a special kind of MI sensor with a resolution of 1 pT. To detect weak magnetic signals from natural samples, a MI gradiometer comprising of a pair of the MI sensors was employed. This MI gradiometer was equipped to a commercial spinner magnetometer (SMD-88, Natsuhara Giken, Osaka). It was demonstrated that this new-type spinner magnetometer is capable of measuring weak magnetic samples with the sensitivity approximately two orders of magnitude greater than the previous one.

磁気インピーダンスセンサー（Magneto-Impedance sensor: MI センサー）は、小型・高感度・低消費電力の磁気センサーとして、広く実用化されている。そのうち特に高感度の MI センサーを岩石磁化測定に利用する試み（Kodama, 2014年 SGEPSS 秋学会）をもとに、既存のスピナー磁力計を必要最小限の改修で高感度化することに成功した。使用した磁力計は夏原技研製のスピナー磁力（SMD-88）で、そのフラックスゲートセンサーに加えて、差動結合した一対の MI センサーを配置した。MI センサー専用の増幅回路とローパスフィルターを付加するのみで、SMD-88 の既存ハードフェアとソフトウェアを利用して測定ができる。必要があれば、フラックスゲートセンサーに切り替えて測定することもできる。MI センサーを使用すれば、フラックスゲートよりも約二桁高い感度と広いダイナミックレンジ（1 to 10^{-6} mAm^2）の測定が可能となる。

Precise determination of Fe species in plagioclase crystals: a case study for gabbroic anorthosite of the Duluth complex

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Silicate minerals such as plagioclase and pyroxene sometimes contain fine-grained magnetite crystals; such silicates are called magnetic silicates. Magnetic silicates are ubiquitous in mafic and intermediate plutonic rocks (Dunlop and Ozdemir 1997; Gee and Kent 2007). As the middle and lower crust have greater mafic composition than the upper crust (Rudnick and Gao 2004), magnetic silicates should play an important role in controlling the magnetic properties of deep crustal rocks. For understanding the sources of magnetic anomalies, which are often originated from thick magnetized layers within the crust (Shive et al. 1992 and reference therein), it is crucial to investigate the exsolution mechanism of magnetite in silicate minerals.

In this study, to precisely determine the chemical species of Fe in the plagioclase crystals, magnetic measurements combined with microscopic observation and synchrotron radiation study were conducted for single grain plagioclase crystals. We prepared plagioclase crystals from gabbroic anorthosite of the Duluth complex at Forest Center, Minnesota, USA (FC1, Paces and Miller 1993). The plagioclase crystals were collected under a stereoscopic microscope and used for the measurements after a hydrochloric acid (HCl) leaching for two days.

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 (Micro-Mag 2900, Princeton Measurements Corporation) and magnetic hysteresis parameters (saturation magnetization Ms, saturation remanence Mrs, coercivity Bc, and coercivity of remanence Bcr) were calculated. (2) To investigate chemical compositions of the plagioclase crystals, microscopic observation was conducted using a field emission electron microprobe (JXA-8530F, JEOL) at Tokyo Institute of Technology and an electron microprobe (JXA-8900R, JEOL) at Geological Survey of Japan. (3) To investigate the average valence state of Fe, K-edge X-ray absorption near edge structure (XANES) measurement was performed at BL-12C of Photon Factory. 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 (MPMS-XL5, Quantum Design).

The magnetic hysteresis parameters resulted in the single-domain (SD) and pseudo-single-domain (PSD) range on the Day plot (Day et al., 1977), and the Ms values ranged from 3 to 63 mAm^2/kg. The low-temperature remanence curves showed pronounced remanence reductions at around 100-120 K, indicating the existence of low-Ti titanomagnetite. The presence of magnetite was also suggested by the linear combination fitting of XANES spectra, and thus, we confirmed that the plagioclase crystals contained nearly pure magnetite. We estimated the magnetite content assuming the Ms value of pure magnetite (92 Am^2/kg, Hunt et al. 1995). As a result, the magnetite content ranged from 40 to 680 ppm with an average of 270 ppm in weight.

The microscopic observation showed that the FeO contents for the plagioclase crystals were nearly constant with an average of 2800 ppm in weight. Thus, about 76-99% of Fe was contained in the plagioclase crystal and the remaining Fe was exsolved as magnetite crystals. The XANES analysis showed that the average valence states of Fe in the bulk plagioclase crystals were 2.53 +- 0.10. So far, there was no clear relationship between the magnetite content and the valence state.

A new method for Chemical Demagnetization of Carbonate rocks

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Chemical demagnetization (CD) has been used primarily for the red sandstones. However, it has not been applied to carbonate rocks in spite of the utility in stratigraphic and chronological studies. It is because strong acid such as hydrochloric acid is commonly used for the CD of red rocks, and unfortunately it dissolves carbonate rock itself. We examined a reductive rather than acidic etchant to remove magnetic minerals and to leave the carbonate framework intact, and an efficient etchant flow procedure for removing the iron ions from the specimens.The Fe^{2+} ions are soluble under a certain rage of the pH-pE diagram (Henshaw and Merrill,1980), in contrast to the Fe^{3+}ions which is not soluble almost in any conditions. For the ease of handling and disposal, we decided to use ascorbic acid as the reducing agent. In addition, using sodium hydrogen carbonate as a buffer, pH=6.5 and ORP=-10˜15mv solution is prepared. The range is that Fe^{2+} ions are soluble and carbonates are not soluble.

The samples are Quaternary reef limestones of the Ryukyu Group. The reef limestones tend to have been exposed on shore several times, from the time of deposition up to now, and may acquire chemical remanent magnetizations (CRM) by the precipitation of magnetic minerals from the water passing between carbonate grains. As the etchant for CD reaches directly to those magnetic minerals, it should be very efficient to remove the secondary magnetization related to those CRM.

Another new point proposed here is a etchant flow system. Conventional CD was immersing the sample to an etchant during a predetermined time. Here, the etchant continuously flows between the grains of the specimen. It is because to help the reduced iron ions flow to the outside of the sample. Advection is almost always faster than diffusion.

Using drip-feeder, the adjusted reducing agent is supplied to flow for 72 hours at the rate of approximately 0.05ml / sec.

The alternating field demagnetization (AFD) after the CD is effective to recover the primary magnetization. The alpha95 and virtual geomagnetic pole latitude (VGP Lat.) are improved from 57.3 and -13.4 to 26.0 to -84.9, respectively, comparing with those samples without with AFD. but without CD. The clear polarity and better concentration indicate that the CD is very effective, and the recovered direction is primary.

The Ryukyu group including this carbonate rocks, have been found to be deposited 0.95 ˜0.41Ma from calcareous nano fossils (Yamada, 2002). It consists of coral fossils and rhodlith fossils, thus natural remanent magnetization is weak as about 0.075 ˜0.352mA/m. It can not be demagnetized completely even 100mT of AFD, and progressive thermal demagnetization experiments does not yield a good concentration like alpha95 is 50. The sites meet to a criteria of polarity (VGP Lat = more than 60 or less than -60) is less than 10% in overall. In application of CD plus AFD, it is possible to obtain a result of the significant improvement in alpha95 and VGPLat. in all sites, and it is possible to establish magnetstratigraphy of whole section. As the age markers for reef limestones are very scares, the magnetostratigraphy can be a powerful tool for date the limestones.

化学消磁はこれまで主に赤色砂岩に対して用いられてきた．しかし，層序の対比や生層序年代が多く報告されている炭酸塩堆積物には用いられていない．これは赤色岩などの化学消磁でエッチャントとして用いられてきた塩酸などの強酸が炭酸塩岩全体を溶解するためである．今回我々は，炭酸塩岩を溶解しない磁性鉱物のエッチャントと，効率的な化学消磁の手順について検討を行った．

炭酸塩岩の化学消磁では，酸を主体としたエッチャントが使えないので，還元剤を用いることとした．磁性鉱物中の鉄イオンが Fe^{2+} となり溶液中に溶け出すことを予想したのである。Henshaw and Merrill(1980) の pH-pE ダイヤグラムをもとに条件を検討し，使用および廃棄が容易なアスコルビン酸を用い，炭酸塩岩 (炭酸カルシウム $CaCo_3$) が反応を起こさないよう，炭酸水素ナトリウムをバッファーとして溶液を pH6.5 (ORP= -10〜15mv) に調整した．

試料は，琉球層群の第四紀礁性石灰岩を用いた．礁性石灰岩は堆積時から現在までにおいて複数回の陸上露出を行い，粒間を通り抜ける水分に含まれる鉄イオンが酸化し析出することで化学残留磁化を獲得している．粒間に析出した磁性鉱物のみを消磁する手段として化学消磁は最適であろう．従来，化学消磁はエッチャントにサンプルを一定時間浸す方法であった．今回，新たな手法として化学残留磁化を得たであろう粒間へ還元剤を流し続けることで，析出した化学残留磁化をもつ磁性鉱物を水溶性の Fe^{2+} イオンへ還元すると共に，サンプルの外へ流すことを考えた．これは，還元剤を流し続けることで，粒間に磁性鉱物を再付着させないためである．

調整した還元剤を，サンプルに点滴チューブを用いて一定間隔 (およそ 0.05ml/sec) で 72 時間流し続けた．その結果，通常の段階交流消磁のみを施した試料と，化学消磁＋段階交流消磁を行った試料の比較で，残留磁化方位の平均の 95%信頼限界 (α_{95}) が 57.3 から 26.0，仮想地磁気極 (VGP) の緯度が-13.4 から-84.9 と，集中がよくなるとともに、双極子磁場方位に近い方位に改善した。これから、化学消磁は有効で初生磁化を取り出すことができたと考えている。

この炭酸塩岩を含む琉球層群は，山田 (2002) で石灰質ナノ化石から 0.95-0.41Ma の堆積物であることがわかっている．サンゴ化石や石灰藻球化石・生細砕物を主体としており，自然残留磁化強度が 0.075〜2.352mA/m と弱い．通常の段階交流消磁では 100mT でも完全に消磁できず，段階熱消磁では，α_{95} が 50 前後となる．極性を判定するパラメーターの VGP の緯度は，60 以上もしくは-60 未満になるサイトは全体の 10 %に満たなかった．他のサイトの試料にも化学消磁を適用することで，段階交流消磁が有効となり，α_{95}，VGP の緯度ともに大幅に改善した結果を得ることができ，古地磁気層序の議論が可能となった．今回の結果は，年代決定の手段の少ない礁性石灰岩に年代軸を設定する新たな手法を提供するものと考えている。

Mapping of the Martian magnetic anomalies on the surface with the SVM method

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Strong magnetic anomalies of the crustal origin have been detected by the satellite observation, although Mars has no global magnetic field of the core dynamo origin at present (Acuna et al., 1998). Using Mars Galobal Surveyer (MGS) observations, the Martian magnetic anomalies mapped so far are normalized at high altitudes: vector mapping at 400 km altitude by magnetometer observations (e.g. Acuna et al., 2001; Connerney et al., 2005), and total intensity mapping at 185 km altitude by electron reflectometer observations (e.g. Lillis et al., 2008). The observed magnetic anomalies often show some systematic patterns such as magnetic stripes and demagnetization due to impact. Connerney et al. (2005) reported several lineated magnetic anomalies of about 25 degree wavelength in the Meridiani region. This pattern may imply possible existence of plate tectonics of the early Mars like the present Earth. Therefore the Martian magnetic anomalies could provide crustal constraint on thermal evolution of the Mars.

The magnetic field observation at 400 km altitude results in convolution of the neighboring crustal magnetic fields within ˜800 km in diameter (˜13 degrees on Mars). Thus, it may be difficult to detect fine structures of the crustal magnetic fields at high altitudes due to rapid attenuation of short wavelength components with respect to altitude. If the magnetic anomaly mapping has higher spatial resolution, more useful information would be obtained in comparison with surface features, that is, topography, geology and so on. In the present study, we have applied the Surface Vector Mapping (SVM) method to Martian magnetic anomalies, which is originally developed for the lunar magnetic anomaly mapping on the surface (Tsunakawa et al., 2014; 2015).

The regional SVM method has been applied to the Terra Sirenum region on the southern hemisphere. Mapping result of radial components on the surface shows elongated magnetic anomalies of about 3 degree width which is much shorter than that in the previous map (Connerney et al., 2005). Based on the SVM result, we calculated the magnetic fields at 200 km altitude to show good consistency with the magnetic fields at similar altitudes observed by MGS during aerobraking phase (1997-1999; e.g. Purucker et al., 2000). We also applied the regional SVM method to the Meridiani Planum near the equator, where plate tectonics was suggested (Connerney et al., 2005). Although a few elongated magnetic anomalies can be seen on the SVM map, the overall patterns of magnetic anomalies are complicated due to relatively short wave length components. We will discuss possible implications as well as effects of the data preprocessing and dependence of analyzed region in relation to the reliability of the Martian SVM analysis.

東南極大陸、ラングホブデ・日の出岬地域のリュツォホルム岩体の古地磁気情報

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Paleomagnetic information from Langhovde and Cape Hinode areas in the the Lutzow-Holm Complex, East Antarctica

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Although East Antarctica had been considered to behave as a single craton in the period from the break-up of Rodinia to the formation of Gondwana continent, tectonic blocks with different movements have been suggested in East Antarctica recently. The Lutzow-Holm Complex (LHC), extending in the coastal region between longitudes 39 and 45E in East Antarctica, is a metamorphic belt of amphibolite to granulite facies. The LHC provides geochronological data of about 500 Ma, indicating that the LHC had suffered the Pan-African orogenic event related to the amalgamation of Gondwana members. Previous paleomagnetic data from East Antarctica has supported the amalgamation event. In order to re-examine tectonic movements in East Antarctica during the amalgamation process, paleomagnetic analyses has been performed on the LHC, and palemagnetic results from Langhovde and Cape-Hinode blocks will be presented.

In Cape Hinode area, metamorphic rocks of granulite facies exist, whereas amphibolite facies metamorphic rocks are exposing in the surrounding areas. SHRIMP zircon ages of about 1.0 Ga were reported from the metamorphic rocks, and there are no evidence for ˜500 Ma event in zircons in the rocks. Cape Hinode area has been thus regarded as an extraneous block (called Cape-Hinode block (CHB) in this study) in the LHC. Metamorphic rocks and intrusive rocks (granites, mafic dikes) were collected at 13 sites in Cape Hinode area. In Langhovde area, granitic rocks and metamorphic ones of granulite facies were collected at 42 sites.

Progressive thermal demagnetization analyses provided characteristic remanent magnetic components (ChRMs) carried by magnetite, which were isolated in high temperature above 500C, and site-mean directions of the ChRMs were obtained at 16 sites in Langhovde area and 5 sites in Cape Hinode area. The mean directions were well grouped in each area, and provided paleomagnetic poles close to mean paleomagnetic poles of 500 and 510 Ma in the synthetic APWP for East Gondowana. According to K-Ar and Ar-Ar mineral (hornblende and biotite) ages of 530-480 Ma form metamorphic rocks and pegmatites in Cape Hinode area, it is suggested that the CHB had been belonged to the LHC as well as Langhovde area at about 500 Ma, and that the LHC had constituted East Antarctica and East Gondowana at that time. It is implied that the CHB might have suffered a metamorphic event of granulite facies in a different region before 500 Ma.