Application of Cluster Analysis to GNSS Data in the Angular Velocity Space: Identification of Crustal Blocks and Evaluation of Plate Interaction

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The motion of a rigid plate on a sphere is expressed as rotation around an axis that passes through the center of the earth. Recently, statistical approaches were proposed to identify boundaries of crustal blocks from observed GNSS data. Simpson et al. (2012) showed that through a cluster analysis of GNSS data, block boundaries can be distinguished objectively. Savage and Simpson (2013) extended the study by adding an iterative algorithm to take account of the effect of spherical geometry. These studies successfully showed a way to identify block structures in the West Coast of the U.S.

However, it is still difficult to apply the method to global GNSS data in order to identify plate blocks considering the effect of spherical geometry. So, we developed a more intuitive method to tackle this problem.

The relationship among the geographical location of the GNSS station, observed velocity at the GNSS station, and candidates of the Euler pole can be expressed as a vector equation: the cross product of an angular velocity vector and a position vector of a GNSS station is an observed velocity vector.

From this relationship, candidates of the Euler pole can be expressed as a straight line in the angular velocity space. We can expect that each line that correspond to each GNSS data in the same rigid crustal block crosses at a point in the angular velocity space.

To spot a crossing point, we made a matrix whose components correspond to the distance between lines. In order to find a structure in the matrix, we analyzed this matrix using a clustering algorithm called a Bayesian Community Detection model. The method provides a block matrix structure within it for a given threshold. By this analysis, we can spot the candidates of Euler poles as a crossing point based on the distances of lines in the angular velocity space. Each identified crossing point would represent a cluster, namely a crustal block.

However, an actual crustal block has internal deformation in it. So, we considered how such deformation affect the deviation of the lines from their original crossing point. We first analyzed the same data set of Simpson et al. (2012) in the San Francisco Bay Area, West Coast of U.S. for comparison.

The obtained result had four major crossing points, which was almost the same as Simpson et al. (2012). However, if we gave a smaller threshold, we obtained 16 minor clusters which reflect internal deformation of crustal blocks. The minor crossing points almost aligns on a straight line that connects the major crossing points.

These minor crossing points can be attributed to the effect of coupling on the faults that bound major blocks in this area. If there is some coupling on such faults, crustal movement must systematically deviate from the rigid block rotation due to internal elastic deformation caused by fault coupling. In other words, we can extract information about fault coupling from this clustering analysis.

A self-organizing map exploratory analysis of the flow duration curve in the United States

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The flow duration curve (FDC) describes the full range of streamflow magnitude observed at a site, and is strongly influenced by upstream conditions of the basin. Upstream conditions are quantified using basin characteristics, such as mean elevation and annual precipitation. A large variety of data now exists to characterize basins in the United States (US). However, a greater understanding of how this data relates to the FDC is critical, considering basin characteristics are typically the basis for predicting the FDC of ungauged basins. The present study performs an exploratory analysis of the FDC and characteristics of 918 basins in the US using a neural network technique called the self-organizing map (SOM). The SOM is applied for its ability to cluster and visualize fine-scale variation in large datasets. Both of these exploratory frameworks (i.e. clustering and visualization) are used to compare individual flows of the FDC to basin characteristics. Clusters based on common basin characteristics poorly agree with those of the FDC (36% agreement), which is less than prior work in smaller study areas, such as Italy. This is an important point because clusters based on basin characteristics are used to deploy models for predicting the FDC. Basin characteristics primarily cluster basins into geographic regions, whereas the FDC generates clusters of basins distributed throughout the US. Geographic proximity therefore may not be an indicator of similarity in the FDC between basins. Variation of the FDC is also unrelated to some common basin characteristics, such as topographic variables, as indicated through SOM data visualizations. This may partially explain the disagreement between the two sets of clusters. The disagreement may also be because basin characteristics are only associated with certain parts of the FDC, but not the overall FDC. For instance, aridity, an index of precipitation lost to evapotranspiration, suppresses high flows possibly due to lower antecedent moisture conditions that moderate storm flows. High flows are also related to spring snowmelt represented using the percent of precipitation delivered as snow. Another association to a part of the FDC is that average to low flows vary with groundwater contributions (i.e. baseflow). Basin characteristics describing surface runoff are more related to high flows, whereas subsurface drainage has more influence on average to low flows. The processes that generate different flows should be accounted for in the clusters used to predict the FDC, and future research should evaluate if the tradition of using a single set of basin characteristics to cluster basins for predicting the FDC should be revised to select different basin characteristics depending on the flow targeted for prediction.

Keywords: basin hydrology, flow duration curve, self-organizing map, cluster analysis, data visualization, United States

Uncertainty quantification for groundwater management in the Danish buried valley systems by means of regression tree-based surrogate models

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Uncertainty quantification is a key component for decision making in groundwater management. Such applications involve the building of large complex spatial models, the application of computationally intensive forward modeling codes and the integration of heterogeneous sources of uncertainty.
An integral step for uncertainty quantification is to condition models to a variety of data. In the Danish groundwater management this consists of head, streamflow, recharge, well and geophysical (SkyTEM) data. Uncertainty quantification requires model calibration. This is a challenging problem when dealing with complex systems (such as the Danish buried valley system) and a wealth of data. Another difficulty is computational cost, since a proper model calibration should account for all data, all model variables and geological heterogeneity requires running many forward flow models.
In this research, a workflow is proposed to find posterior multivariate distribution of model parameters and predictions. First, dimensionality reduction with mixed principle component analysis (PCA) is performed to incorporate different types of available data. A regression model is built for uncertain model parameters and misfit between simulated and observed data. As a regression model, we use a boosted regression tree because it offers high quality predictive model in nonlinear problems. Another advantage of tree-based approach is that we can obtain predictor importance, which can be directly used in sensitivity analysis.
Models that match the data are found by Approximate Bayesian Computations (ABC), where the likelihood is simply an indicator function of data mismatch. ABC requires exhaustive Monte Carlo sampling and running forward models. By using the regression model as surrogate forward model, we can obtain models conditioned to the data without intensive full forward runs. Regression models can also be constructed for predictions, such as the effect of establishing new wells for extraction.
We illustrate our method using a real field problem of decision making in the Danish groundwater system. Decisions include where to relocate drinking wells while minimizing the change of water produced and effects on farms and industrial areas. Well head and stream data are observed from monitoring wells. The proposed workflow is used to understand the effect of each parameter and to obtain the posterior distribution of 20 forecasts with newly acquired data.

Keywords: uncertainty quantification, regression analysis, model calibration, groundwater management

隕石および小惑星の可視近赤外反射スペクトルの多変量解析
Multivariate analysis of visible to near-infrared reflectance spectra of meteorites and asteroids

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Asteroids and meteorites have been considered as remnants of the early evolution of the solar system and understanding their formation history provide constraints on the physical and chemical conditions of the solar nebula and its subsequent evolution [1]. In order to better understand the compositions of asteroids, mineralogical relationship between asteroids and meteorites have been studied based on reflectance spectra obtained by ground- and space-based telescope [2]. Their relationship, however, remains poorly constrained except for a S-type asteroid Itokawa and LL chondrites [3]. Although spectral similarities have been suggested between V-type asteroids and HED meteorites and between carbonaceous chondrites and C- and/or D-type asteroids, detailed relationship is not well constrained. The major obstacle to compare asteroids and meteorites is that the classification scheme between asteroids and meteorites are fundamentally different. Asteroids are classified mainly based on the shape of their reflectance spectra and orbital parameters [4], while meteorites are classified by detailed petrology and mineralogy [5]. Based on principal component analysis, Britt et al. (1992) [6] compare reflectance spectra of asteroids with those of meteorites. They find that most of principal components of meteorite spectra are offset from those of the bulk of the asteroid population. However they used only eight color spectra and the spectra are limited within visible wavelength from 0.35 to 1.0 μm. Since characteristic absorptions are observed in the near-infrared range, including pyroxene (2 μm) and hydrated silicates (3 μm), using reflectance spectra with a wider wavelength range could result in a better spectral matching between asteroids and meteorites. In this study we developed a database of reflectance spectra for asteroids and meteorites with wavelengths ranging from 0.4 to 4 μm and perform multivariate analysis.
We obtained reflectance spectra for meteorites and asteroids from RELAB [7] and the database of Planetary Spectroscopy at MIT [8], respectively. Asteroid spectra for 3 μm band are obtained from previous studies [e.g., 9]. All the spectra were sampled with cubic spline fits at a wavelength interval of 0.05 μm. Meteorite spectra are chosen based on the following criteria: (1) particulate sample, (2) phase angle is 30°, (3) sample is from valid/known meteorite, (4) not heated/laser-irradiated, inclusion or impact melt sample, (5) not moon sample or lunar meteorite. The developed database includes 534 meteorite spectra and 369 asteroid spectra. We performed principal component analysis on the database and measure how well each meteorite group and asteroid group is separated on the principal component space. Our preliminary analyses show that (1) using spectra from 0.4 to 2.5 μm, accuracy of separation among ordinary chondrites, carbonaceous chondrites, HED meteorites is significantly improved compared with the case using spectra from 0.4 to 1.0 μm, and (2) the accuracy of separation is not significantly improved when using meteorite spectra from 0.4 to 4 μm compared with the case using spectra from 0.4 to 2.5 μm.

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キーワード：小惑星、隕石、反射スペクトル
Keywords: asteroids, meteorites, reflectance spectra

Relationship between reflectance spectra of meteorites and asteroids visualized by the correlation distance and t-SNE

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Classification of asteroids based on orbits, sizes, and reflectance spectra have been performed for decades to understand the nature of small bodies. As for asteroids, asteroid taxonomic systems based on color, albedo, and spectral shape have been developed and modified/expanded to grasp their variations. While each spectral class is believed to represent a specific composition of asteroids, their correlation is still not fully understood because of the nature of reflectance spectrum of rock-forming minerals; The relationship between reflectance spectra of an asteroid and a meteorite is essentially difficult to unravel without detailed analyses of the shapes of spectra. Even so, several previous attempts exist to statistically solve this issue. For example, Britt et al (1992) successfully produced a map of statistically defined spectral similarities and found that principal component analysis is successful at characterizing the primary spectral variance in the asteroid and meteorite populations. In other words, statistical classifications of spectral types without detailed interpretation of spectral shapes can be useful to overview the variation and relationships within a spectral data set, even though there are known difficulties of comminution, melting, mixing, and space weathering. In this work, we expand the above idea by applying to a wider and denser datasets of reflectance spectra for both meteorites and asteroids. We use published databases of RELAB's laboratory measurements of meteorites and Planetary Spectroscopy at MIT's asteroid spectra, which are resampled by cubic spline fits in the wavelengths ranging from 0.45 to 2.45 μm with the wavelength resolution of 0.05. We statistically analyze the distance of spectra by means of such as Partial Autocorrelation, Dynamic Time Warping, Pearson Correlation, and Euclidean distance. Results are visualized by using 6 kinds of schemes including t-SNE (t-Stochastic Neighbor Embedding). We find that correlations of both meteorites and asteroids are generally shown by this simple scheme. Preliminary results indicate that (1) V-type asteroids generally match HED meteorites, (2) S-type asteroids locate near ordinary chondrites but they do not entirely match each other, which may reflect the effect of space weathering (3) C-type asteroids match carbonaceous chondrites and they are separated into a few sub clusters.

キーワード：小惑星、隕石、反射スペクトル
Keywords: asteroid, meteorite, reflectance spectra

Systematic attribution of observed circulation trends to external forcing and internal variability

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The atmospheric circulation can be efficiently described by just a few regime states or teleconnection patterns. For the systematic identification of these regime states a novel space-time clustering method has been developed (FEM-BV-VARX). This method identifies persistent regime states which are important for predictions. In my presentation I will discuss the use of this method for the attribution of circulation trends and extreme events.

Keywords: Regime States, Circulation Trends, Extreme Events, Clustering Method

Data-driven science for solving problems in geosciences

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Recent technological development of measurement and observation enables us to obtain a large amount of high-dimensional data. Effective use of high-dimensional data requires a robust framework to make the tight connection of information science to the original purpose of data analysis derived from various scientific disciplines [1]. Since 2013, we have launched a big scientific project entitled as "Initiative for high-dimensional data-driven science through deepening sparse modelling (FY2013-FY2017)" funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan. The aim of this project is to establish a novel framework of data analysis for natural sciences, namely, data-driven science. Its target fields are very wide including geosciences, astronomy, biology, and medical and brain sciences. In this presentation, we introduce the concept of data-driven science and some applications to geosciences [e.g. 2-5].

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キーワード：データ駆動科学、スパースモデリング、機械学習
Keywords: data-driven science, sparse-modeling, machine learning

Source Term Estimation for atmospheric release In Nuclear Accidents Using ensemble Kalman filter: a validation with wind tunnel experiment

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In a nuclear accident, the source term which contains the release rate of atmospheric radionuclide leakage is a key issue of the nuclear emergency response. One effective way to obtain the source term is the inverse modelling method that is based on radionuclide transportation process and environment radiation monitoring data. However, the inverse modelling method may be sensitive to specific site conditions. Therefore, a case-by-case validation is important.

In this study, a source term estimation method based on the Ensemble Kalman filter (EnKF) data assimilation technique was proposed for source term estimation and a wind tunnel experiment that simulated a highly heterogeneous Chinese nuclear power plant site was performed to validate this method.

The EnKF method takes the concentrations measured at different positions as input parameters and iteratively refined the source term estimate by reducing the discrepancy between the experimental measurements and the concentration prediction that is obtained by certain atmospheric transport model based on the estimated source term. In order to improve the accuracy of the transport model, CALMET was used to generate the wind field that is necessary to drive RIMPUFF.

A 1:2000 wind tunnel was performed to comprehensively evaluate the performance of the proposed method, which simulated both ground and stack release scenarios with a dominant wind direction at a typical Chinese nuclear power plant. The incoming flow in the wind tunnel is adjusted according to the annual mean wind speed and vertical profile that has been measured in recent years near the NPP site. The experiment simulated a ground release scenario by using CO as the tracer gas, which the release position is in the center of the nuclear power plant site. Concentrations are measured at 264 positions in the downwind direction of the release, which equals to 6500m away from the source in a real world scale. The estimated release rate was compared with the true release rate that was used in the wind tunnel experiment, in order to assess the convergence and accuracy of the proposed method. Meanwhile, the concentration measured in the wind tunnel was both qualitatively and quantitatively compared with the simulation values that are calculated by CALMET-RIMPUFF using the estimated release rate.

The validation results demonstrate that the proposed method has a fast convergence rate. The estimated release rate matches the real one used in the experiment well for both release cases, which the bias is less than 50% for the worst case estimate. As for the concentrations predicted with the estimated release rate, they are not only qualitatively consistent with the spatial distribution of the measured concentrations, but also show satisfactory results with respect to statistical evaluation metrics for both release cases. The Pearson correlation coefficient is higher than 74~87%, the FAC2 is 42~54% and the FAC5 is 77~80% for all the experiment cases. The source term estimation of the stack release case slightly outperforms that of the ground release case, due to the better atmospheric transport modelling. The experiment also reveals that CALMET-RIMPUFF tends to underestimate the concentrations, which are the primary source of the bias in the estimates. Therefore, the atmospheric model is critical for the performance of the source term estimation, which shall be our future work focus.

Keywords: Source term estimation, Data assimilation, Atmospheric dispersion, Radioactive release
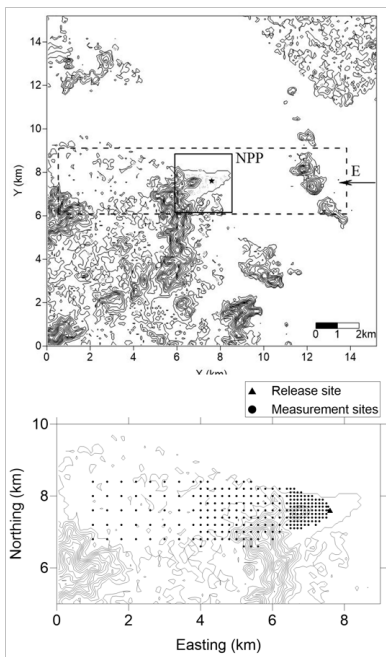

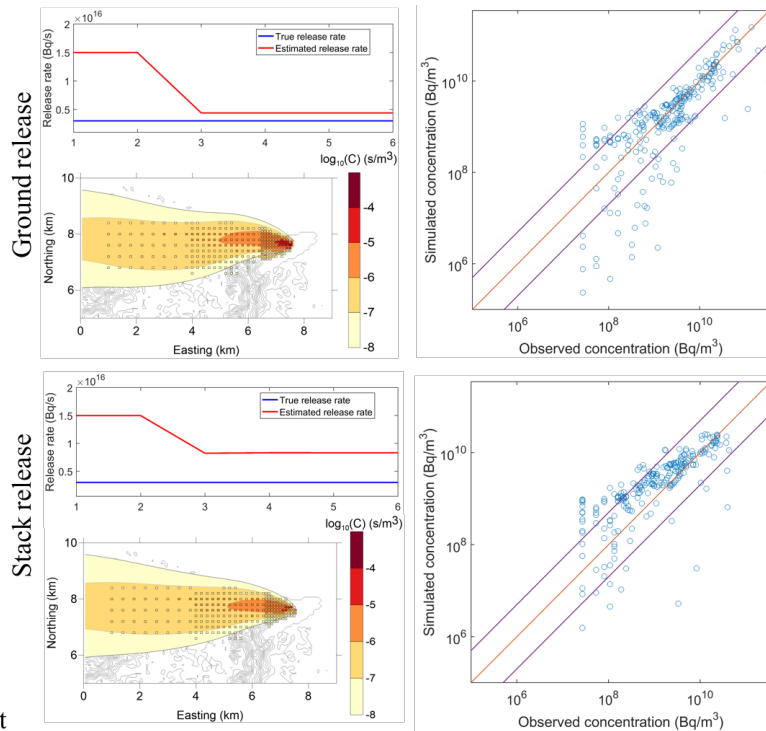Fig. 1 Topography and measurement network of the wind tunnel experiment

Fig. 2 source term estimation results. Convergence curve, simulated plume using the source term estimate and the corresponding scatter plot

岩石ー水相互作用を支配する不均質反応の時空間ダイナミクスの統計的推定

Bayesian inversion analysis of nonlinear spatiotemporal dynamics of heterogeneous reactions in rock-water interactions

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It is essential to extract nonlinear dynamics from time-series data as an inverse problem in natural sciences. We propose a Bayesian statistical framework for extracting nonlinear spatiotemporal dynamics of surface heterogeneous reactions from sparse and noisy observable data. Surface heterogeneous reactions are chemical reactions with conjugation of multiple phases, and they have the intrinsic nonlinearity of their dynamics caused by the effect of surface-area between different phases. We employ sequential Monte Carlo algorithm and other statistical algorithm to partial observation problem, in order to simultaneously estimate the time course of hidden variables and the kinetic parameters underlying dynamics. Using our proposed method, we show that the rate constants of dissolution and precipitation reactions, which are typical examples of surface heterogeneous reactions, and the diffusion constants, as well as the spatiotemporal changes of solid reactants and products, were successfully estimated only from the observable temporal changes in the concentration of the dissolved intermediate product.

[1] Omori et al., Bayesian inversion analysis of nonlinear dynamics in surface heterogeneous reactions, Phys. Rev. E, 94, 033305 (2016)

キーワード：データ駆動科学、機械学習
Keywords: Data-driven science, Machine learning

Detection of principal dynamical modes of changing climate

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The success in empirical climate modeling strongly depends on selection of model variables used for reduced representation of system's dynamics. In fact, we can say that the states of the climate system are determined by a combination of external perturbations (forcings) and unknown internal variables. Thus, the detection of principal internal modes of changing climate is crucial point in modeling problem. In the presentation the method for extraction such modes from data is presented. The method is based on the Nonlinear Dynamical Mode (NDM) expansion [1,2], but takes into account forcing time series applied to the system: each NDM is represented by hidden time series governing the observed variability, which, together with external forcing signals, are mapped onto the data space.

In this work the method is used for reconstructing and studying the principal modes of global climate variability on inter-annual and decadal time scales, adjusted for the external forcings such as anthropogenic emissions, variations of the solar activity and volcanic activity. The structure of the obtained modes as well as their response to external factors, e.g. forecast their change in 21 century under different CO_2 emission scenarios, are discussed.

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Keywords: nonlinear dynamical modes, data expansion, empirical modeling

Data-adaptive Harmonic Decomposition and Stuart-Landau closure modes

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Novel signal processing technique will be presented that estimates power and phase spectra of mutivariate dataset via data-adaptive modes obtained in time-embedded phase space. The key feature of the Data adaptive Harmonic decomposition (DAH) method relies on the construction of covariance matrices that exploit cross correlations differently than in Principal Component Analysis and Multichannel Singular Spectrum Analysis. Eigenmodes associated with DAH covariance matrices form an orthogonal set of oscillating data-adaptive harmonic modes (DAHMs) that come in pairs and in exact phase quadrature for a given Fourier frequency, aka *sine* and *cosine.*

The recent Multilayer Stochastic Model (MSM) framework introduced in [Kondrashov, Chekroun and Ghil, 2015] emphasizes the ubiquitous role of nonlinear, stochastic as well as memory effects for the derivation of data-driven closure models with good skill in simulating and predicting main dynamical features of the targeted spatiotemporal field as an output of a high-end geophysical model, or as a set of observations. However, if the input data are not numerous enough and exhibit mixture of different spatiotemporal scales, the analysis may reveal multiple predictors and complex model structure. The DAH decomposition provides an attractive data-adaptive alternative via multilayer stochastic Stuart-Landau models (MSLM), which reduce the data driven modeling effort to elemental MSMs stacked per frequency with fixed and much smaller number of coefficients to estimate. In particular, the pairs of data-adaptive harmonic coefficients (DAHCs), obtained by projecting the input dataset onto DAHMs, can be effectively modeled within a universal parametric family of simple nonlinear stochastic models - coupled Stuart-Landau oscillators stacked per frequency, and driven at all frequencies by the same noise realization. DAH-MSLM results for climate modeling and prediction will be presented.

Keywords: stochastic inverse modeling, climate prediction, data-adaptive decomposition

Conditional stochastic model chains in reduced space: Towards efficient simulation of non-stationary typhoon precipitation patterns

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Stochastic simulation of realistic and statistically robust patterns of Tropical Cyclone (TC) induced precipitation is a challenging task. It is even more challenging in a catastrophe modeling context, where tens of thousands of typhoon seasons need to be simulated in order to provide a complete view of flood risk. Ultimately, one could run a coupled global climate model and regional Numerical Weather Prediction (NWP) model, but this approach is not feasible in the catastrophe modeling context and, most importantly, may not provide TC track patterns consistent with observations. Rather, we propose to leverage NWP output for the observed TC precipitation patterns (in terms of downscaled reanalysis 1979-2015) collected on a Lagrangian frame along the historical TC tracks and reduced to the leading spatial principal components of the data. The reduced data from all TCs is then grouped according to timing, storm evolution stage (developing, mature, dissipating, ETC transitioning) and central pressure and used to build a dictionary of stationary (within a group) and non-stationary (for transitions between groups) covariance models. Provided that the stochastic storm tracks with all the parameters describing the TC evolution are already simulated, a sequence of conditional samples from the covariance models chosen according to the TC characteristics at a given moment in time are concatenated, producing a continuous non-stationary precipitation pattern in a Lagrangian framework. The simulated precipitation for each event is finally distributed along the stochastic TC track and blended with a non-TC background precipitation. The proposed framework provides means of efficient simulation (10000 seasons simulated in a couple of days) and robust typhoon precipitation patterns consistent with observed regional climate and visually undistinguishable from high resolution NWP output. The framework is used to simulate a catalog of 10000 typhoon seasons implemented in a flood risk model for Japan.

Keywords: Reduced models, Stochastic simulation, Typhoon precipitation

Data-driven Nonlinear Dynamical Models for Forecast of Climate Variability

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We apply new methodology of empirical modeling and forecast of nonlinear dynamical system variability [1] to study of climate systems' variability. The methodology is based on two approaches: (i) nonlinear decomposition of spatially distributed data [2], that provides low-dimensional embedding for further modeling, and (ii) construction of empirical model in the form of low dimensional random dynamical ("stochastic") system [3].
The methodology abilities are demonstrated by modeling and forecast of ENSO system variability. Three monthly data sets are used: global sea surface temperature anomalies, troposphere zonal wind speed, and thermocline depth; all data sets are limited by 30 S, 30 N and have horizontal resolution $1^0 \times 1^0$.
We compare results of optimal data decomposition as well as prognostic skill of the constructed models for different combinations of involved data sets. We also present comparative analysis of ENSO indices forecasts fulfilled by our models and by IRI/CPC ENSO Predictions Plume.

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Keywords: Nonlinear Dynamical Model, Forecast of Climate Variability, Nonlinear Data Decomposition

Data-driven model for investigation of the mid-Pleistocene transition

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In this work we apply a data-driven model for the analysis of complex spatially distributed geophysical data. We are focused on the investigation of critical transitions on paleo timescales. Namely we investigated mid-Pleistocene transition which led to change of dominate cycles of glacial variability in Pleistocene.

We demonstrate the good performance of applying our data-driven model to analysis of paleoclimate variability. In particular, we discuss the possibility of detecting, identifying and prediction of the mid-Pleistocene transition by means of nonlinear empirical modeling using the paleoclimate record time series.

The study is supported by Government of Russian Federation (agreement #14.Z50.31.0033 with the Institute of Applied Physics of RAS).

Keywords: Data-driven Modeling, Critical Transitions, Time Series Analysis, Mid Pleistocene Transition

元素拡散を考慮した斑晶鉱物の累帯構造の解析: ベイズ統計に基づくアプローチ

Analysis of zonal structure of phenocryst minerals considering element diffusion: Approach based on Bayesian statistics

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　火山岩中の斑晶に見られる累帯構造からは，メルトとの平衡が保証されれば分配係数を用いて自由度が大きく均質化のタイムスケールの短いメルト組成や結晶化条件の時間変化に関する時系列データが得られ、地殻内部での分化プロセスに関係する物理プロセスの情報や，初生マグマに関する制約が可能になると期待される．しかし、結晶中の元素の拡散のために分配係数を用いた解析では不十分な場合が多い．一方で、元素拡散の影響を受けた組成累帯構造から，拡散の影響を見積もることができれば，時間情報を得ることができる．しかし、多段階の結晶化過程を反映し累帯構造が複雑になると，解析時に考慮すべきパラメータ数が増加し，パラメータ間の依存関係も複雑になる．本研究では，多段階の結晶化過程を経験した斑晶鉱物の累帯構造から元素拡散の影響を定量的に評価し，その影響を取り除いた累帯構造を推定した上でメルト組成情報を復元し，マグマが経験した物理プロセスを解明する手法を開発する．

　今回我々は，結晶成長とそれに引き続く元素拡散による組成累帯構造形成に関するフォワードモデルを構築し，モデルを特徴づけるパラメータをParallel tempering Markov Chain Monte Carlo (PT-MCMC) 法で推定した．ここでは人工的に生成したデータにノイズを加算したものをテストデータとし，正しいパラメータが再現されるかどうかを試した．本モデルでは，累帯構造が何度かの結晶成長によって形成され，それぞれの結晶成長の後に元素拡散が進行するステージがあるものと仮定した．結晶成長ステージの区分については，orthopyroxeneであればCr_2O_3のような拡散速度の小さいプロファイルに基づき制約した．

　メルト組成がolivine，orthopyroxene，spinelの結晶分別によって変化する結晶化モデルを採用した．モデルでは、計算の起点となるメルト組成は天然の溶岩のうち最も初生的なものの全岩組成とし，繰り返し微小量の固相が分別されるか，溶融して液相に加えられるとした．固相はそれぞれ球対称で，計算ステップごとにメルトと局所平衡である組成をもつ球殻が成長するものとした．分配係数は固相ごとに常に一定であるとして計算を行った．olivineとorthopyroxeneは微量元素および主要成分のMgO，FeO，SiO_2のみに影響を与えるものとした．Spinelは微量元素組成のみに影響を与えるものとした．

　Ozawa (2004)の方法に基づき，無次元化した拡散方程式を計算した．拡散係数は温度依存性のみを考慮した．計算スキームとして，空間方向は二次精度中心差分，時間方向は後退差分を採用した．上記のフォワードモデルと累帯構造の分析値を用い，擬似的な温度を表現するパラメータで拡張した8列のマルコフ鎖を生成し，parallel tempering Markov Chain Monte Carlo method (Hukushima & Nemoto，1996)によりパラメータ推定を行った．規定回数のサンプリングの後，得られたサンプルのヒストグラム形状を確認しながら，パラメータの最適値を平均値またはモード値から決定した．

　各ゾーニングセクションにおいて以下の5種類のパラメータをサンプリングした．
　結晶成長ステージにおける初期Mg#，最終Mg#，orthopyroxeneモード比，spinelモード比，および元素拡散ステージにおける最大圧縮時間の対数．

キーワード：火山岩、結晶成長、元素拡散
Keywords: Volcanic rocks, Crystal growth, Element diffusion

キーワード：火山岩、結晶成長、元素拡散
Keywords: Volcanic rocks, Crystal growth, Element diffusion

Managing soil organic carbon sequestration in China's croplands

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Increasing the soil organic carbon (SOC) pool in croplands can not only promote crop production but also mitigate climate change; however, the amounts of organic C that are input to balance the soil C loss and for targeted soil C sequestration in China's croplands are unclear. By using a biogeophysical model (Agro-C), we performed simulations with a high spatial resolution (10 km×10 km) across China's croplands to quantify the rate of C input under given scenarios. The model simulations showed that an average C input of 2.1 Mg C ha^{-1} yr^{-1} is required to stop soil C loss and that SOC density could approach the global mean of 55 Mg C ha^{-1} by 2050 when 5.1 Mg C ha^{-1} per year is incorporated into the soils of China's croplands. The quantified C inputs showed a large spatial disparity, depending on the existing SOC level, mean annual temperature and precipitation. The existing SOC level in Heilongjiang Province, where the cropland area accounts for 9.2% of the national total, is much higher but the current C input is much lower than it is in other regions in China. Increasing the organic C input should be given priority in this province; otherwise, the risk of SOC loss may increase.

Spatial modeling by joint use of physical law and geostatistics for grade analysis in geofluid-caused ore deposit

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Fluids play an important role in various aspects related to ore deposits and are crucial to the formation and development of ore deposits. This study aims to develop a method combines spatial statistics and physical law for metal contents in an ore deposit. Semivariogram clarified spatial correlation structure of the metal data and then kriging and sequential Gaussian simulation were used to generate spatial distribution of ore grade in three-dimensions. Transports of ore fluid and deposition process of metals were assumed as a physical process governed by the advection and diffusion. Analytical and numerical solution of an advection-diffusion equation was applied to ore grade data by calculating key parameters, advective velocity and diffusion coefficient. In order to simulate accurately, parameters were then revised as variables in different zone according to geological structure and geostatistical model. Matsumine and Fukazawa mines, typical large kuroko deposits in the Hokuroku district, Akita Pref., northern Japan, are selected to verify the combined method. Metal elements such as Cu, Zn, and Pb (chief metals of kuroko) of drilling cores were used for the spatial and physical modeling analyses. This method termed SPG (Spatial modeling by joint use of Physical law & Geostatistics) presents general main paths of ore fluid with respect to source, flow direction, and flow rate. The same technique and SPG are applied to a hydrothermal deposit in Sulawesi Islands, Indonesia. As the result, high metal content zones are well clarified and characterized, and a fluid flow pattern that formed the zones is expressed as colloidal texture which could indicate temperature and pressure changes in shallow subvolcanic activities.

Keywords: ore deposit, metal content, fluid flow, geostatistics, advection-diffusion

Solar terrestrial modelling: Application of systems methodologies

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The response of the magnetosphere to changes in the solar wind is the result of the a complex series of processes, each acting over disparate scales in both space and time. The basic premise of physics based modelling is to understand each of these processes separately before coupling them into a single model. This diversity in process mechanisms and their temporal/spatial scales is one of the main reasons that such models have not been developed. Systems science provides a complementary route for modeling. This data driven approach involves the study of the evolution of a system as a whole based on a set of driving parameters. In this presentation we show how the application of systems modelling can be used to investigate such complex problems in space physics as magnetospheric response to the solar wind to the evolution of turbulence. In contrast to other data driven methodologies, systems techniques can also advance understanding of the micro-processes within the system. In addition, use of the systems approach, and especially frequency domain analysis, may be employed to validate analytical and numerical models.

Keywords: systems modelling, magnetospheric processes, solar wind response

データ駆動科学への日本列島地球化学データベースの適用：出版データ利用にあたっての問題点と解決法
Geochemical database of Japanese islands for data-driven science: problem and solution of published domestic data

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Geochemical database of Japanese islands for data-driven science: problem and solution of published domestic data

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Recent progresses in the earth science have introjected a data-driven approach, which deals with a huge amount of high-dimensional data. Gathering several kinds of data, e.g. major element composition, trace element composition and isotopic ratio, with GPS-position data can provide a better understanding of the geological phenomena. For such kind of big data science, several databases covering geochemical, geochronological, and petrological data are constructed and available on the internet, such as PetDB, SedDB and GeoRoc. These databases are constructed by collecting a number of published data. However, the existing international databases are based on the collection of studies in the international publication of societies and projects. The data in the publication of non-international journals and domestic institutes are rare in the international datasets. As a result, compositional data of rocks from Japan arc are not fully covered by these databases. Therefore, we construct a geochemical database for those published in the Japanese language and provided in domestic journals.

We collected literature including geochemical data of Japanese islands published from 1980's to present. During the data compilation, we took special care of position data. Position data are crucial for understanding geographical distribution of geochemical components, and also important to estimate geo-neutrino flux from the crust. Increasing availability of handy GPS logger provides easy access to the standardized position data. However, many of the published geochemical data still lack GPS-position data, and of course, old publications provided position information only by map images. We use Google Earth for reading position data from map images. The geological map of papers including sampling points is projected on Google Earth. Latitude, longitude and altitude of the sampling points on the map are obtained based on the coordinate system on the Google Earth.

The articles published in 1980's and 1990's are usually provided as scanned PDF of a printed paper, and thus, tables are provided as images. Furthermore, some journals still provide tables as images. Despite the developed OCR (optical character recognition) technique, the transformation of image tables to numerical data requires checking by eyes of a human. In addition, pdf files provided by some publishers (e.g. J-stage) are protected and data in the file are not directly available for computer-based treatments. To overcome these problems, we have edited this new geochemical database.

Our database covers several rock types including volcanic rocks, plutonic rocks, sedimentary rocks,

metamorphic rocks, and so on, and from Hokkaido to Kyushu Island (Figure 1). The main purpose of our database is "basement characteristics" of the Japanese islands: therefore, we pay great attention to collecting data mainly plutonic, metamorphic and sedimentary rocks. One of the important points of out database is covering rock types other than the volcanic rocks, because many parts of the existing geochemical database is focused on volcanic rocks, and metamorphic and sedimentary rock data are rare. The compiled database is going to be published under the appropriate science commons license, although the idea of *science commons* has not been widely accepted among the geoscientists (Watanabe & Noguchi, 2010). We will provide information about our database on the website (http://dsap.jamstec.go.jp).

This database will be used to multiple purposes, such as multivariable statistical analyses (Iwamori et al. , 2017), estimateon of the average crustal compositeon (e.g. Togashi et al., 2000), geographyc statistical analyses and the estimateon of the crustal geo-neutrino flux (Enomoto et al., 2007).

キーワード：位置情報、公表地球化学データ、日本列島の基盤岩、地球化学データベース
Keywords: position data, published geochemical data, Basement of Japanese islands, geochemical
database
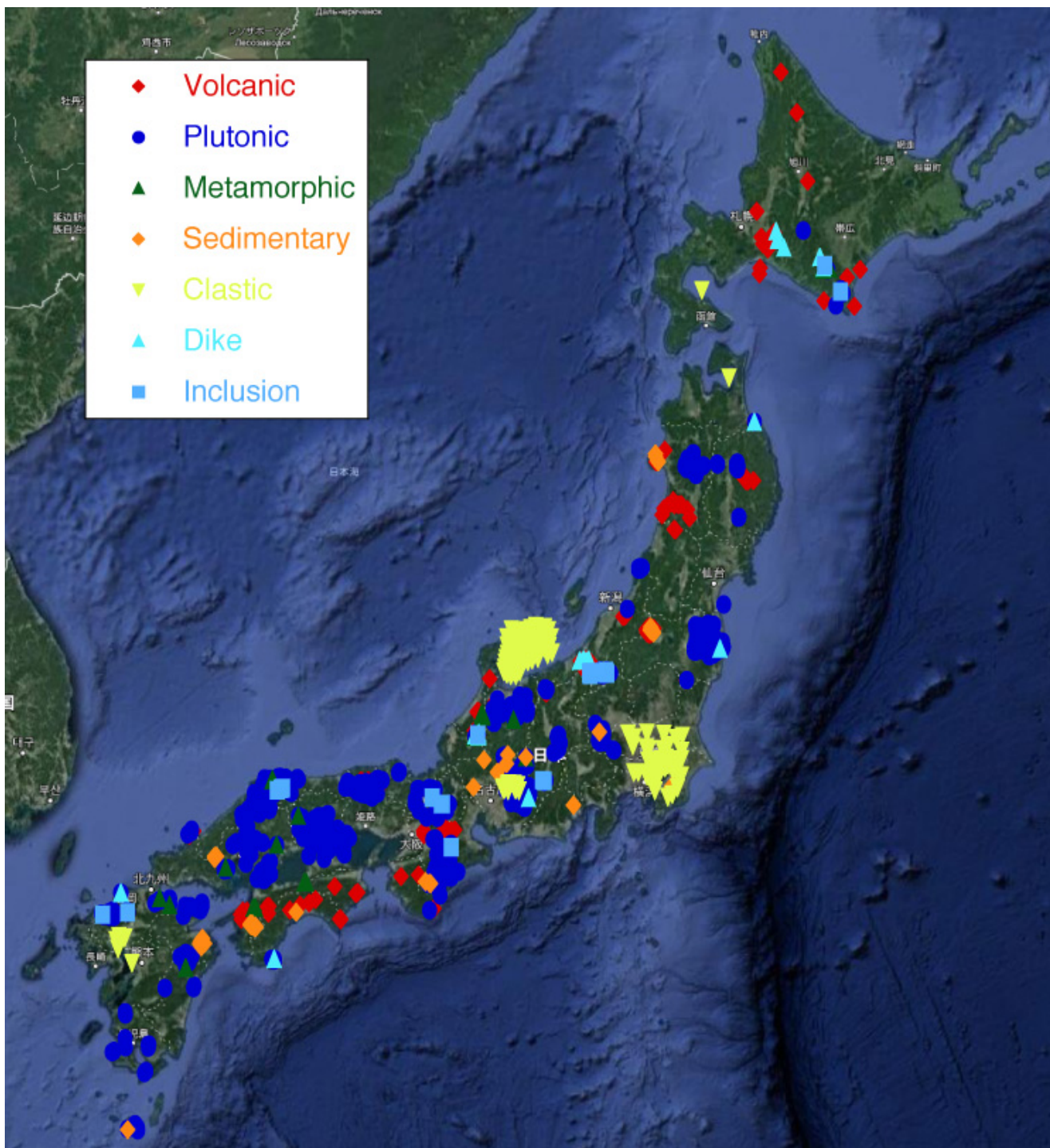
Geochemical characteristics of paleo-tsunami deposits using multiple classification analysis

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Cataloguing and assessing tsunami records are important for long-term tsunami prediction and for tsunami-hazard mapping. However, like on a number of other tsunami-susceptible coastlines, historical records of tsunamis are too short to develop a predictive chronology of events. Understanding the geochemical characteristics of tsunami sediments is significant for revealing the mechanisms of tsunami inundation. Principal component analysis (PCA) can be used to extract geochemical features of tsunami sediments. It is one of the most pervasive multivariate analysis techniques which can be used for extracting the hidden structure and pattern from high-dimensional data in various fields of natural and social sciences. We conducted field surveys in February and March 2016 in Wakabayashi, Sendai City. The sedimentary sequence contained a disturbed sandy soil at the top, overlying a mixed layer with the To-a and Jogan tsunami deposit, as well as characteristic sand layers at about 50 cm, 103-113 cm and about 140 cm depth. The core was analyzed using an ITRAX X-ray fluorescence core scanner, which provides high resolution semi-quantitative elemental data, as well as photographic and radiographic images. Major elements (Si, K and Ca etc) showed high counts at 100~110 cm depth, while the distribution of minor and trace elements (Zn, Cr and Zr etc) was more variable. The Mo ratio (Mo coh/Mo inc) which is an indicator of organic content was, as expected, lower in sandy layers than in the peat. The PCA was performed using normalized counts of 17 major elements and minor/trace elements. The PAC was showed geochemical characteristics of tsunami deposits in a comprehensive fashion. The above 3 factors, such as PC1, PC2 and PC3 can explain the processes that contribute to the chemical variations. These results and the other geological evidences can be useful for understanding the mechanism of the tsunami indentation.

キーワード：津波堆積物、多変量解析、地球化学的特徴

Keywords: tsunami deposits, multiple classification analysis, geochemical characteristics

Sparse feature selection for clustering and sample-wise distance, with application to geochemical data

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　個々の火山体や岩体からの複数サンプル、一つの岩石サンプル内での多点局所分析など、多くの地球化学データは、それぞれが高次元の組成データを持つ多数のサンプルからなる集合である。しかし、これまでの多くの地球化学研究は、せいぜい数元素間の関係性や、もしくは特定の数個の試料にのみ注目するといった、低次元空間で行われてきた。データの解析に関しても、端成分の化学組成など事前の情報を与えた手法が主体であった。岩石からプロセス情報を抽出するためには、多変量多サンプルからなる高次元データをそのまま取り扱うことが重要である。また、これまでの研究はデータの分布が持つ情報を有効に活用し切れていない。しかし、多数のデータがなすデータ分布の広がりや形状には、岩石生成過程での地球化学プロセスが反映されているはずである。多次元空間内でのデータの分布そのものを定量的に取り扱ったデータ駆動の研究を行うことで、これまでの研究よりもより多くの情報が岩石から抽出できることが期待される。このようなデータを取り扱うために、本研究では、粒子の各次元の観測値がなす「分布」を考え、分布間の距離を測ることでサンプルの特性を反映した比較を実現した。

　分布の仮定をしない、ノンパラメトリックな方法で分布間距離を推定し、各特徴量に対応した「距離」を定義する。「要素距離」の重み付き和で全体の距離を定義し、この重みを用いてクラスタリングを行う。さらに重みにスパース制約を課して特徴選択することで、集合間の距離と、距離を特徴付ける量（本研究の場合は元素種や同位体比）を求めることが出来る。距離を特徴付ける量を求めることが出来ること、また、すべてのサンプルに、解析に使用するすべての元素の分析値がある必要がないということが本手法の利点である。

　岩石化学組成データベースpetdb (http://www.petdb.org)を利用して3988サンプル、最大49元素 (5同位体、10主要元素を含む)のMORBデータをコンパイルし、解析に使用した。空間分布を元に全地球のMORBを数クラスターに分析し、化学組成を比較した。空間変化を特徴付ける元素や、クラスター同士の距離を本手法を用いて求めた。その結果、MORBの組成は、東西半球に別れてクラスタリングされること、MORB組成の空間変化を特徴付ける量としては、Sr同位体が重要であることが分かった。この東西半球のクラスタリングは、Iwamori et al. (2015)等で示された構造と整合的である。Sr同位体比は、ソースマントル中のスラブリサイクル物質の量に敏感であることから（Hoffman, 1997; Albarede, 2009など）、空間分布を決定づけるのはSr同位体比であるという本研究の結果は、東西半球で沈み込み起源の物質の分布が異なっていることを示唆する。

キーワード：中央海嶺玄武岩、機械学習、地球化学データ

Keywords: MORB, Machine learning, Geochemical data

粒子形状に基づいた火砕物のクラスター分析手法の検討
Cluster analyses for volcanic pyroclasts using grain shapes

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Our motivations for this study are: 1) classify volcanic ash using statistical techniques, and 2) identify eruption styles from parameterized grain shape of pyroclasts. One of the extractable factors which we can infer eruption styles and mechanisms is grain morphology of ejected pyroclasts. They would tell us characteristics of magma vaporization and fragmentation (e.g., Heiken and Wohletz, 1985). Numbers of researchers have been tried to parameterize grain shapes and discussed its formation and fragmentation story. Thanks to the development of grain analyze instruments and techniques, we can parameterize visuals (shape and intensity) for thousands of grains easily in short time. Previous studies have applied an automated particle analyzer (APA) for grain shape of volcanic ash. Leibrandt and Le Pennec, 2015 tested several measurement conditions, then presented an efficient protocol. Using this protocol, Liu et al., 2015 compared the characteristics of grain shape parameters among components (dense, vesicular, and shards) and eruption styles. Thus, we are closing to know eruption style and characteristics by grain shape analysis using the APA. To simplify this system, first we should test this method in simpler cases, i.e., monogenetic volcanoes.

This study verified several patterns of clustering for volcanic pyroclasts. We used 47 samples which were collected in several places of Japan and Iceland. These pyroclasts were formed in three types of monogenetic eruptions; magmatic, phreatomagmatic, and rootless. Each sample consist of more than 100 grains. We measured grain shapes and intensities using an APA: Morphologi G3STM (Malvern InstrumentTM) in AIST. Using parameterized grain data, we performed cluster analyses on R software (R Core Team, 2016) with the hierarchical procedure (Ward's method) and Euclidean distance. In test analysis using analog grains, it is found that scaling of each parameters before clustering are unnecessary. We performed clustering in 2 steps; make grain types and clustering among samples using percentages of each grain type. In this presentation, we will show processes and results of our clustering, and consider better way to apply the cluster analysis to natural volcanic products.

キーワード：クラスター分析、火砕物、粒子形状
Keywords: cluster analysis, pyroclast, grain shape

高速且つ高精度な定量組成マッピング手法の開発とチェコ共和国Nové Dvory産超高圧エクロジャイトへの応用

Fast and precise quantitative compositional mapping and its application to the Nové Dvory ultra-high pressure eclogite.

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Rocks often show chemical inhomogeneity in various scales owing to layers, veins, and so on. To evaluate such inhomogeneity, quantitative compositional mapping would be a powerful tool, since ordinary EPMA quantitative analysis takes large time (> 1 min/spot). Lanari et al. (2014) established a fast analytical technique by combining qualitative mapping (> 100 msec/px) and quantitative analyses (ca. 20 spots/phase). To make quantitative map data, they performed mode analysis for the map data by k-means cluster analysis, calibrated the relationship between map intensity and real concentration for each element of each phase, and applied the calibration to the modal composition. Their technique saves great time, but the analysis still takes long time for the large samples due to recommended analytical conditions of spatial resolution (< 10 μm pixel size) and dwell time (> 100 msec/px) for the mapping, e.g. 55 hours for the area of 100mm^2. This study aims to shrink analysis time further.

The mapping time is proportional to the spatial resolution in $O(N^2)$ and the dwell time in $O(N)$. Thus, decreasing the spatial resolutions saves more time than decreasing the dwell time. Yet, it increases the amount of pixels containing multi-phases, especially when a mapping area contains fine-grained minerals. This problem can be solved by modifying methods of (a) clustering, (b) estimating calibration curves, and (c) applying calibration curves after Lanari et al. (2014).

(a) The soft-clustering is preferred to the hard-clustering (k-means) because it explains proportion of phases in pixels. Since compositional distribution of the map data can be approximated by mixtures of Poisson distributions, this study employed the mixture-Poisson-distribution-model clustering.

(b) Calibration curves for trace components of phases, i.e. elements not included in the stoichiometry, tend to contain large errors. For such components, calibration curves are determined by using all phases.

(c) Composition of a pixel containing various phases is obtained from a weighted mean of concentrations estimated by the calibration curves of each phase, which is weighted by the modal composition of the pixel.

The newly developed technique is applied to the Nové Dvory eclogite, containing pyroxene-rich layer (Layer-P) and garnet-rich layer (Layer-G) in mm-scales. Garnet (Grt) between these layers has Mg-richer core (ca. Fe23Mg56Ca21) than Grt in Layer-G (c.a. Fe30Mg32Ca38), and both Grt show similar rim compositions (ca. Fe28Mg44Ca28). The core compositions probably reflect the inhomogeneity of the protolith (Yasumoto & Hirajima, 2015), though the cause of the inhomogeneity is unclear. Compositions of these layers are estimated by our technique. Qualitative mapping is done in the area of 10 mm * 33 mm with 20 μm pixel size and 120 msec dwell time, taking ca. 55 hours. Total wt% of Layer-P is improved by the technique of ours (97 wt%) than Lanari et al. (2014) (91 wt%), while that of Layer-G are comparable (97 wt% and 98 wt%, respectively), probably because fine-grained texture of Layer-P compared to Layer-G.

The estimated compositions show Mg-Cr-rich (XMg = Mg/(Mg+Fe) = 0.79; Cr2O3 = 0.14 wt%) for Layer-P and vice versa for Layer-G (XMg = 0.64; Cr2O3 = 0.07 wt%). One possible explanation is that Layer-P and

G are metamorphosed from pyroxene-rich and plagioclase-rich layers of gabbro, respectively. However, a large difference in XMg of Layer-P and G is unlikely for the gabbro-origin. Cr content of both layer and Mg/Fe ratio of Layer-P are also unlikely high (e.g. general gabbro: Cr2O3 < 0.01 wt%; XMg ≈0.65). Field occurrence shows dominance of Layer-G with minor Layer-P, indicating that Layer-P was crystallized from pyroxenite melt intruded to gabbroic host (Layer-G), and Layer-G partially reacted with the melt. This idea is supported by presence of pyroxenite melt intrusions (XMg = 0.80-0.91; Cr2O3 = 0.2-1.7 wt%) in peridotite which hosts the study eclogite (Svojtka et al., 2016).

キーワード：定量組成マッピング、岩石メルト反応組織、超高圧、エクロジャイト
Keywords: Quantitative Compositional Mapping, Rock-Melt Reaction Textures, UHP, Eclogite

AN EVALUATION OF THE APPLICATION OF X-RAY MICROSCOPY IN UNDERSTANDING GOLD LOSSES IN TAILINGS

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1. Carl Zeiss Microscopy、 2. Petrolab Limited C Edwards Offices
1. Carl Zeiss Microscopy, 2. Petrolab Limited C Edwards Offices

The extractive metallurgy of gold is largely controlled by mineralogical factors such as the presence of refractory gold, particle size, gangue mineral associations, presence of preg-robbers, oxygen and cyanide consumers, and locking characteristics in base metal sulphides.

Light microscopy and automated mineralogy techniques are regularly used to characterise the effect of these variables on gold recovery. However, despite their widespread application there are a range of limitations when grades are low. Typically, the analysis of low-grade samples requires the preparation and analysis of numerous polished blocks. This is often costly and time consuming, with complexities regarding analysing statistically representative particle quantities and problems overcoming stereological bias. This is compounded by the "nugget" effect and high tenor nature of gold mineralisation.

X-ray Microscopy techniques have the potential to overcome many of these problems, in particular the statistical representivity of analysis, removing stereological bias and effectively locating phases that are present in ultra-trace proportions. In this paper we outline the potential benefits of employing X-ray Microscopy (XRM) in characterising gold losses from a typical Cu-Au porphyry project, which were illusive in 2D based analysis. The talk will also outline additional application areas of XRM within the extractive value chain.

機械学習により検出された累進変成作用下での全岩化学組成の発展的変化
Progressive evolution of the whole rock composition during metamorphism revealed by machine learning technique

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Geochemical evolutions with respect to the major components of the metamorphic rocks during the subduction-related metamorphism are documented on the basis of multivariate statistical analyses applied for mapped metamorphic rocks collected from the Sanbagawa metamorphic belt in central Shikoku, whose metamorphic conditions range from the pumpellyite-actinolite to epidote-amphibolite facies. Recent progress of computational and information science provides a number of algorithms revealing a hidden structure of large datasets. This contribution applied k-means cluster analysis (KCA) and non-negative matrix factorization (NMF) to a series of metapelites, which is the main lithotype of the Sanbagawa metamorphic belt. The analyzed dataset contains 235 sample with 14 elements accumulated from the literature. As a result, we obtain five clusters in KCA and four endmembers for NMF which successfully explains compositional variations of the studied dataset.

The result of KCA clearly shows that the chemical compositions of the metapelites are different between the western part (Besshi area) and eastern part (Asemigawa area) of the studied dataset. In the western part of the studied dataset, clusters show a good correspondence with the metamorphic grade. In the higher metamorphic grade part, a monotonous decrease in SiO_2 and Na_2O and an increase in other components are detected. On the other hand, the compositional change with the metamorphic degree is less obvious in the eastern part. Endmember decomposition using NMF revealed that the evolutional change of the whole rock composition correlated with the metamorphic grade is approximated to a stoichiometric increase of garnet-like component in the whole rock composition. This phenomenon could be related to the precipitation of garnet and effusion of other components during progressive dehydration. Thermodynamic modeling considering the evolutional change of the whole rock composition predicted followings: (1) the lower-grade whole rock composition prefers the crystallization of garnet at the conditions of the garnet zone while biotite becomes stable together with garnet in higher-grade whole rock compositions at the same PT conditions, (2) the higher-grade whole rock composition can retain more H_2O than the lower-grade one. These results indicated the mechanism suppressing the dehydration at the high-pressure metamorphic conditions. Perhaps such kind of mechanism should be considered in the forward modelling in treating the fluid cycle in subduction zones, though quantitative model has not been established yet.

キーワード：機械学習、三波川変成帯、沈み込み帯、シュードセクション、物質循環
Keywords: machine learning technique, Sanbagawa metamorphic belt, subduction zone, pseudosection analysis, material cycle

独立成分分析による抽出基底を用いたダストストームの領域検出
Automatic detection of Martian dust storm's area using basis images extracted by Independent Components Analysis

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This study was performed for automatic detection of Martian dust storm's area from satellite images of Mars, using basis images extracted by Independent Components Analysis (ICA). Normalized images are divided into several patch images with the predetermined size. A classifier is trained by coefficients which are multiplied by the basis to reconstruct the patch images based on the basis images. When we detect dust storm's areas from test images, we evaluate whether a target patch is included in a dust storm or not, shifting the target patch horizontally and vertically by one pixel. Then, a pixel may be included in many patch images. The pixel is regarded as included in a dust storm if more than half of patches including the pixel are recognized as the dust storm by the classifier. Precision, recall and F-score are used for evaluation of the method, and F-score is 0.87. The method developed in this study can accurately detect dust storm regions from Mars images.

キーワード：火星、ダストストーム、独立成分分析
Keywords: Mars, dust storm, Independent Components Analysis

AUV搭載高精度マルチセンサデータの解析にもとづく熱水噴出孔位置の推定
High precision hydrothermal plume survey based on multi-sensor data processing

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To date, multi-beam echo sounder (MBES) equipped on Research vessels and AUVs has been widely accepted as a powerful tool for detecting interception of any rising, buoyant hydrothermal plumes, without water sampling (Nakamura et al., 2015). Although utilization of water column sonar data enabled us to achieve certain results, to find new vents, this approach is not sufficient to distinguish gas seeps and hydrothermal vents, and moreover, it is inadequate to determine hydrothermal plumes with a low gas content. To improve efficiency and accuracy of exploring hydrothermal plumes and to understand their properties, we use multi-sensor data such as temperature, turbidity, redox potential, and methane concentration. These sensors were equipped on AUV Urashima, which was programmed to fly at an altitude of ~200 m above the seabed, at an average speed across the seafloor of ~1.3 m/s. An area of 2000 m x 5000 m on the seafloor can routinely be surveyed, at 400 m line spacing, during a single AUV Urashima dive. In this presentation, we will overview oceanographic, chemical and acoustic sonar data obtained during AUV Urashima Dives 217, 250, 251, and 252 in the Okinawa Trough, and will introduce data-driven analytical techniques to determine chemical properties of the water masses, and make a comparative review of 3 discrete hydrothermal fields. Each hydrothermal field has different features: i) Yokosuka Field, the highest temperature vent-site on record in the Okinawa Trough (364.1˚C at 2183 m depth), shows strong water column acoustic reflections and consistently detectable sharp peaks in turbidity, redox potential, and methane concentration. ii) Futagoyama Field is characterized by its gas seeps, strong water column acoustic reflections, and little change in turbidity and redox potential. iii) hydrothermal field off-Kume Island, which includes at least 9 active hydrothermal vents, is characterized by its acoustically invisible plumes, low H_2S content, as well as sharp peaks in turbidity, redox potential, and methane concentration. These case studies will provide an insight into the feature of each hydrothermal activity, and ensure much more efficient use of deep-submergence assets such as human occupied vehicles and remotely operated vehicles during follow-on studies.

キーワード：熱水、AUV、沖縄トラフ、機械学習
Keywords: hydrothermal, AUV, Okinawa Trough, machine learning

中期三畳紀の海洋無酸素事変に関する化学層序学的解析
Chemostratigraphic analysis on the Middle Triassic (Anisian) Oceanic Anoxic Events

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Superanoxia across the Permian Triassic boundary, which has a long duration from the late Middle Permian to the early Middle Triassic (about 20 million years), is globally recognized and debated well in the context of the end Permian mass extinction. However, few studies focus on the integrated decoding of the recovery processes in the Anisian from Superanoxia because of limited application of geochemical proxies. To reconstruct the interactions between the environmental factors from multi elemental data, principal component (PC) analysis was performed on the Middle Triassic chemostratigraphy of the pelagic deep sea sequence in the Mino belt, central Japan. Major and trace element concentrations in the samples were determined by X–ray fluorescence spectrometry (XRF). Before PC analysis, the data matrix (438 samples and 20 elements) was normalized for constant sum. As a result, six PCs were statistically accepted and capture 77% of the total variability. The sedimentological interpretations for the components were as follows. PC1 represents the chemical weathering intensity of terrigenous materials. From the time series data of the PC1 scores, a frequency analysis detects dominant sedimentary cycles similar to the Milankovitch cycles. PC2 is the direction along the enrichment of redox sensitive elements. These records indicate astronomical driving force behind the oceanic redox evolution during the Middle Triassic. PC3 might be related to the deposition of the siliceous claystones called the Toishi type lithofacies. PC4 explains the depletion and accumulation of ferromanganese oxides precipitated from seawater across the anoxic event intervals. PC5 might be interpreted as mixing with heterogeneous materials because the scores shows no systematic variations with the lithostratigraphy and a sample with an anomalously high score has a remarkable chemical composition. PC6 might reveal the abundance of biogenic materials. Further non parametric approaches and conodont biostratigraphic correlations would lead to superior paleoenvironmental reconstruction by predicting more precise sedimentological components.

大気中ラドン濃度変動の対数周期振動べき乗則の変化点
Change point in log-periodic power law time series of atmospheric radon concentration

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　ラドンは，天然に存在する無色無臭のウラン系列に属する半減期が約3.8日の放射性の希ガス元素である．ラドン（^{222}Rn）はラジウム（^{226}Ra）がアルファ崩壊することによって生成される．大気中ラドン濃度は，地震発生に関連して異常変動すると報告されてきた．例えば，1995年の兵庫県南部地震発生前に，神戸薬科大学で観測された大気中ラドン濃度は異常変動をし，高い濃度を示したと報告されている(Yasuoka and Shinogi, 1997)．このことは地殻中の応力変化が地表からのラドン散逸を促し，大気中ラドン濃度異常を引き起こしたと考えられている(Yasuoka et al., 2009)．また1995年兵庫県南部地震の約半年ほど前から，大気中ラドン濃度が対数周期振動を含むべき乗則に従って増加していたことが報告されている(Yasuoka et al., 2006)．対数周期振動を含むべき乗則は，臨界現象モデルの一つで，臨界点に向かってゆらぎ（対数周期の振動）をともなって発散する特徴がある．地震発生に関連した対数周期振動のべき乗則は，大気中ラドン濃度のほかに，積算ベニオフ歪(Newman et al., 1995)，地下水中の塩化物イオン濃度(Johansen et al., 1996)，相対沈降量(Igarashi, 2000)にも確認されている．

　観測データにべき乗則のモデルをあてはめる場合，非線形最小二乗法を行う．そこでは，どの期間のデータにモデルを適用して推定すればよいのかということが問題となる．これまでの研究では，データ期間を適当に区切って誤差を評価することで探索的に行われてきた(例えば，Igarashi, 2000)．そこで，本研究では時系列データの構造がどの時点で変化するかを表現するリカレンスプロットという手法を用いて，大気中ラドン濃度の積算値の傾向がどの時点で変化しているかの評価を行い，その結果に基づいてべき乗則のモデルをあてはめた．解析データとして，福島県立医科大学で2003年1月-2011年2月の間に観測された大気中ラドン濃度の積算値を使用した．

　大気中ラドン濃度の積算値に見られるべき乗則は，2011年東北地方太平洋沖地震時に向かって発散している様子が確認された．またリカレンスプロットの結果からは，2008年茨城県沖地震(*Mw* 6.8)を境に，データの構造が変化していることが確認された．2011年の東北地方太平洋沖地震に関しては，積算ベニオフ歪にもべき乗則の増加が報告されており(Xue et al., 2012)，巨大地震発生前のべき乗則に従うエネルギー散逸が大気中ラドン濃度の積算値に現れたと考えられる．

キーワード：大気中ラドン濃度、地震先行現象、対数周期振動、リカレンスプロット
Keywords: atmospheric radon concentration, earthquake precursor events, log-periodic power law, recurrence plot

Modelling nitrous oxide emissions in a wheat-maize system of North China Plain

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Concentrations of atmospheric nitrous oxide (N2O), a potent greenhouse gas, has been continuously increasing and cropland soils are one of the largest sources of N2O. Variations in environmental and anthropogenic alterations have great impacts on both the frequency and magnitude of N2O emissions. Based on the measurements from a wheat-maize system of North China Plain, we parameterized the APSIM model which was initially developed in Australia, for simulating nitrous oxide emissions under different agricultural management practices. After calibrating one of the key parameters, i.e., fraction of N2O lost in nitrification (k2), the results showed that the model can well capture the daily nitrous oxide fluxes under different nitrogen fertilization treatments, but underestimated some large peak fluxes. By pooling all data together, the calibrated APSIM model also showed a good performance in representing the cumulative N2O emissions with various treatments at both annual and finer (monthly and daily) time scales.

Seismic wavefield imaging in the Tokyo metropolitan area, Japan, based on the replica exchange Monte Carlo method

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Earthquakes sometimes cause serious disasters not only directly by ground motion itself but also secondarily by infrastructure damage, particularly in densely populated urban areas. To reduce these secondary disasters, it is important to rapidly evaluate seismic hazards by analyzing the seismic responses of individual structures due to the input ground motions. Such input motions are estimated utilizing an array of seismometers that are distributed more sparsely than the structures.

We propose a methodology that integrates physics-based and data-driven approaches in order to obtain the seismic wavefield to be input into seismic response analysis. This study adopts the replica exchange Monte Carlo (REMC) method, which is one of the Markov chain Monte Carlo (MCMC) methods, for the estimation of the seismic wavefield together with one-dimensional local subsurface structure and source information. Kano et al. (2017) conducted numerical tests, showing that the REMC method was able to search the parameters related to the source and the local subsurface structure in broader parameter space than the Metropolis method, which is an ordinary MCMC method. The REMC method well reproduced the seismic wavefield consistent with the true one. In contrast, the ordinary kriging, which is a classical data-driven interpolation method for spatial data, was hardly able to reproduce the true wavefield even at low frequencies. This indicates that it is essential to take both physics-based and data-driven approaches into consideration for seismic wavefield imaging.

Then the REMC method is applied to the actual waveforms observed by a dense seismic array MeSO-net (Metropolitan Seismic Observation network), in which 296 accelerometers are continuously in operation with several kilometer intervals in the Tokyo metropolitan area, Japan. The estimated wavefield within a frequency band of 0.10–0.20 Hz is absolutely consistent with the observed waveforms. Further investigation suggests that the seismic wavefield is successfully reconstructed at frequencies up to 0.30 Hz in terms of the variance reduction (VR), but the VR gets rapidly worse in higher frequencies. On the other hand, the velocity response spectra of the reconstructed wavefield show good agreement with the observations even in higher frequencies up to 1.0 Hz in terms of the combined goodness-of-fit (CGOF), which measures the misfit in the velocity response spectra. In summary, the proposed seismic wavefield imaging based on the REMC method is effective < 1.0Hz, which is enough to evaluate large-scale seismic hazards in almost all infrastructures.

キーワード：首都圏地震観測網、地震動イメージング、マルコフ連鎖モンテカルロ法
Keywords: MeSO-net, Seismic Wavefield Imaging, MCMC

# Stochastic modeling of temperature extremes over continental US and Canada

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An extremely statistically accurate, essentially bias-free empirical emulator of atmospheric surface temperature is applied for meteorological risk assessment over the domain of continental US and Canada. The resulting prediction scheme achieves an order-of-magnitude or larger gain of numerical efficiency compared with the schemes based on high-resolution dynamical atmospheric models, leading to unprecedented accuracy of the estimated risk distributions. The empirical model construction methodology is based on our earlier work, but is further modified to account for the influence of large-scale, global climate change on regional US weather and climate. The resulting estimates of the time-dependent, spatially extended probability of temperature extremes over the simulation period can be used as a risk management tool by insurance companies and regulatory governmental agencies.

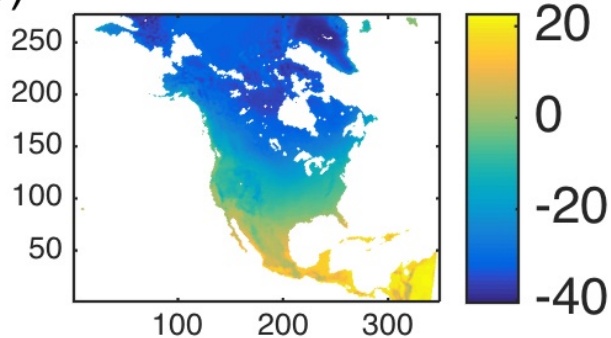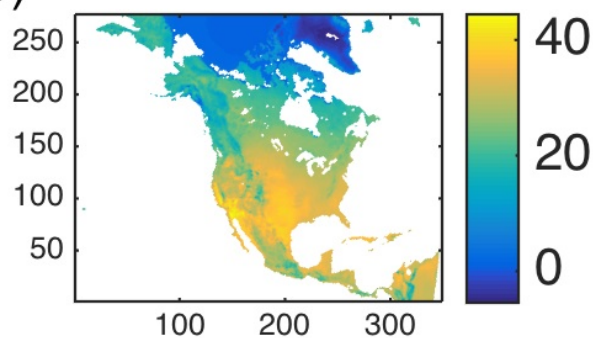Keywords: Stochastic modeling, Temperature extremes, Risk assessment
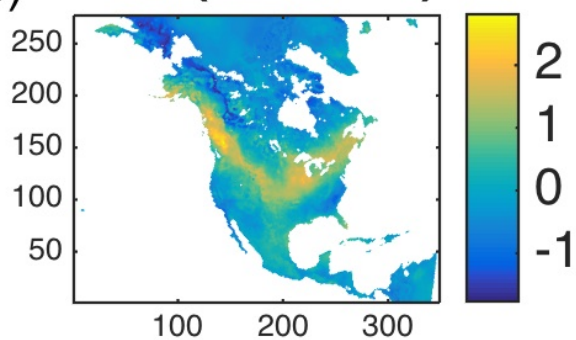
(a) T2 2.5%, DJF Obs
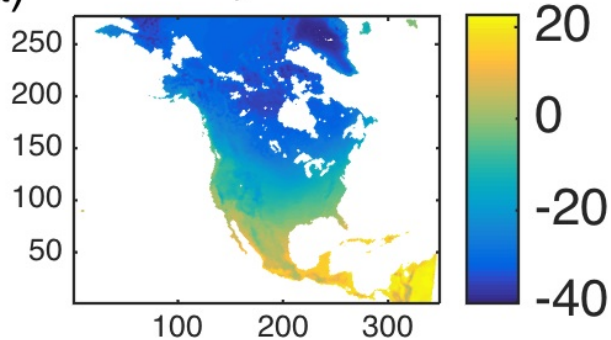
(b) T2 2.5%, DJF Sim

(c) Diff. (Sim-Obs)

(d) T2 97.5%, JJA Obs
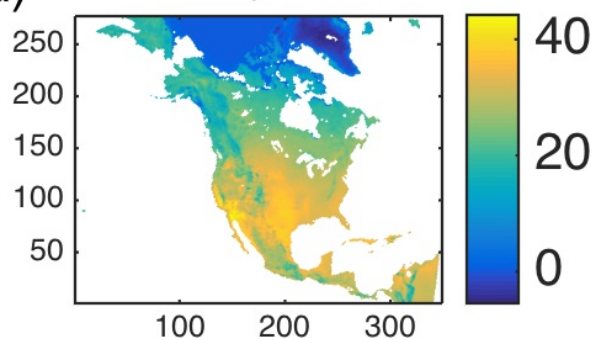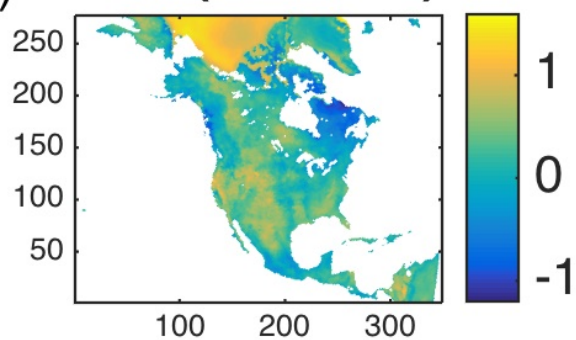
(e) T2 97.5%, JJA Sim

(f) Diff. (Sim-Obs)

Data driven analysis for a prediction method of arsenic adsorption to soils

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Arsenic is a trace element that is toxic to plants, animals and humans. Arsenic moved to the surface of the earth via ground water can cause skin diseases. Thus it is important to predict the amount of arsenic in soil. However, it is too difficult to describe the absorbed amount of arsenic in soils because in the surface in soil it occurs as and that forms two types of complexes (inner-sphere complex and outer sphere complex), which we can't distinguish. We used regression analysis as a new predictive method for arsenic adsorption. Arsenic adsorption tests were conducted using nine type soils and applying Freundlich isotherm. At the same time, we measured the 13 characteristic values of soils (pH, EC and the content of Na, Mg, Al, Si, P, S, K, Ca, Ti, Mn and Fe). Finally, simple and multiple regression analysis were used as a method of data driven analysis. The simple regression was applied to relate all parameters to Freundlich constant and exponent. In multiple regression, we calculated all combination from measured 13 parameters. They were also applied to relate Freundlich constant and exponent are associated. The best model expression was selected from calculated 91 formulas by using the coefficient of determination and Student's t-test., which proves the effectiveness of regression coefficients. The best model formula, which showed 95% reproducibility, consisted of the EC value, and Ti and Al content. This indicates that arsenic adsorption by soils is mainly arsenic competing with salts, and the occurrence of titanium iron and an Al-bearing mineral. We showed the availability of data driven analysis for predicting arsenic adsorption.

キーワード：土壌、吸着、重回帰分析、ヒ素
Keywords: soils, adsorption, multiple regression analysis, arsenic

Multivariate analysis on major element compositions of Apollo 16 impact melt

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Impact melt rocks and clasts form Apollo 16 landing site record heavy bombardment history called the Late Stage Heavy Bombardment (LHB) supported by impact reset ages of the impact melt rocks clustering around 4.1–3.8 Ga [e.g. 1-3]. However, the age clustering might include a sampling bias; for example, some rocks could record the same impact event. Therefore, attempting to identify and characterize individual impact events is important to understand LHB. Bulk compositions is one of important factors to identify the impact event. Bulk chemical composition of impact melt thought to maintain almost average composition of pre-impact target material. Classification of Apollo 16 impact melt has established using trace element compositions using Sc and Sm [4]. Based on the method, impact melts are classified into major 4 groups, Group1 to 4. However, most of the impact melt especially small mass samples does not have such information. Therefore, we are developing new classification scheme using only major element compositions.

We have compiled 330 published data of major, minor, and trace element compositions of Apollo 16 impact melt rocks and clasts [e.g. 4-9]. We selected samples which have 9 major and minor element data (Si, Ti, Al, Fe, Mg, Ca, Na, K, and Cr) and have been already classified by conventional method using trace element information (95 total data). We conducted principal component analysis (PCA).

Our PCA results indicate a difference between mafic and felsic impact melt rocks, although sub-types of Group 2 melt are widely distributed. PC1 distinguishes between mafic and felsic impact melt; more specifically, felsic melt is distinct from mafic melt relatively rich in Fe and/or Mg and poor in Al, Na, and K (wt.%). These elemental compositions have good correlation with PC1 (correlation coefficients are -0.98 and 0.99 respectively for Fe+Mg and Al+Na+K). In addition, our work shows PC2 results correlating with the Mg/Fe weight ratio (correlation coefficient is -0.81; Fig. 2). When we plotted Al+Na+K (wt. %) and Fe/Mg (weight ratio) of Apollo16 impact melt rocks, the plot has similar trends when compared to the PCA-based trends, although the y axis (PC2 and Fe/Mg) is slightly different. Hence, this plot is also useful in the identification of impact melt types using only 5 major elements (Al, Na, K, Fe, and Mg).

Our PCA results indicates that Apollo 16 impact melt rocks can be statistically classified by using only 9 major elements, as well as trace element abundances. Moreover, our results indicate that impact melts can also be classified by using 5 elements by plotting Al+Na+K and Mg/Fe.

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キーワード：全岩組成、月面試料、インパクトメルト
Keywords: Bulk composition, Lunar samples, Impact melt

Trans-dimensional imaging of random velocity inhomogeneity at southern Ryukyu arc

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Precise imaging of randomly inhomogeneous structure is essential to describe wave scattering processes of high frequency seismic waves. Recent studies have constructed a fundamental basis of 2D or 3D imaging of power spectral density of random velocity inhomogeneity (e.g., Takahashi et al. 2013). Yet, it is difficult to know how small-scale spatial variations of random inhomogeneities can be extracted from observed seismic wave data. Here we used the reversible Jump Markov chain Monte Carlo (rjMCMC) (Green 1995) to achieve an adequate spatial-resolution imaging of random inhomogeneity. The rjMCMC is a framework of trans-dimensional parameter-sampling under a target distribution. Under the Bayesian framework, we can use this method to solve inverse problems of which number of unknown parameters is variable. In this study, a study area is partitioned into discrete Voronoi cells. A parameter sampling under a posterior probability is conducted with changing number and spatial layout of Voronoi cells, and unknown parameters in cells. Ensemble average of MCMC samples around the maximal posterior would be an optimal result with an adequate spatial resolution. Regularization term for this inversion is defined as a difference between the maximal and minimal values of power spectral density at a large wavenumber. This regularization is a relatively weak constraint, but gives stable reconstructions of original structures in synthetic tests.

We applied this method for S-waves data (4-8Hz, 8-16Hz and 16-32Hz) recorded at southern Ryukyu arc, Japan. Seismic stations consist of 30 ocean bottom seismographs and 6 onshore stations that were temporary deployed for 3 months. Inversion result shows two significant anomalies. One is a strong inhomogeneity in the mantle wedge beneath islands at 30-40km depth. This anomaly, however, shows no clear correlation with other geophysical observations. Another one is imaged beneath a submarine volcano off the southern Ryukyu arc. This inhomogeneity has a gentle spectral gradient at large wavenumber. Similar inhomogeneity was commonly observed in other volcanic rock areas, and then this anomaly may be related magma inclusions. Stable extraction of these anomalies is mainly because of the rjMCMC and weak regularization term. We may say that the rjMCMC is an important basis for precise imaging of underground structures.

Si-metasomatism during sea floor serpentinization and estimation of its kinetic parameters

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Water-rock interaction is dominant process at the Earth surface and its kinetics is important for understanding geological, climatic, and biological process of the planet. Kinetic parameters of chemical reaction were usually determined by laboratory experiments; however, due to its sparseness and noise, estimating exact parameter is often difficult. To estimate the parameters exactly, machine-learning algorism were proposed (Omori et al., 2016): however, such machine-learning algorism for water-rock interaction has not been tested with real experimental data.

In this study, we applied machine-learning algorism to extract the kinetic parameter of water-rock interaction. Serpentinization is representative hydration process at slow-spreading ridge and play crucial roles on rheological, magnetic, seismic and thermal properties of sea floor. Hydrothermal experiments (230-degree C, 2.80MPa) were carried out in olivine (Ol)–quartz (Qtz)–H_2O system, as analogues of crust-mantle boundary. By using unique tube-in-tube type hydrothermal experiments vessel, spatial and temporal data were obtained.

After the experiments, the mineralogy of the reaction products in the Ol-hosted region changed with increasing distance from the Ol–Qtz boundary, from talc to serpentine + magnetite. On the other hand, in Qtz-hosted region, talc was also formed. Talc zone was formed 1.0 mm from the boundary in Ol-hosted region, whereas it also formed 0.5 mm from the boundary in Qtz-hosted region.

The observed mineral distribution was modeled by reaction-diffusion equation. To model our experiments, we set eight reaction rate constants; diffusion constant for $SiO_{2(aq)}$ and rate constants for olivine→talc, olivine→serpentine, olivine→brucite, serpentine→talc, talc→serpentine, serpentine→brucite, and brucite→serpentine. Firstly, Markov Chain Monte Carlo (MCMC) method were used to calculate the rate constants. This method was tested with artificial data and estimates the true value of kinetic constants with <0.5 % error. However, application of MCMC method to experimental data failed in estimating kinetic parameters, probably because the system studied here is expected to have several local minima. Here, to overcome this problems, we use an optimization algorithm of the exchange Monte Carlo method (Hukushima and Nemoto, 1996) and rate law during serpentinization will be discussed.

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Impact of COSMIC GPSRO assimilation on Indian summer monsoon simulation using variable resolution LMDZ5-DART data assimilation system

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Impact of assimilation of COSMIC GPS radio occultation (RO) data in simulating mean monsoon circulation and rainfall of Indian summer monsoon (ISM) 2015 will be examined in this study using the newly developed LMDZ5-DART ensemble based data assimilation system. The LMDZ5 model is an atmospheric component of the IPSL global model, which has the capability to generate denser grids over an area of interest using coordinate stretching. This unique feature of the model enables its use for finer regional scale simulations without increasing the number of grid points. The Indian summer monsoon is the strongest component of the global monsoon system and monsoon circulations are important to the Indian and surrounding region because they provide a significant fraction of seasonal rainfall. Much of the Indian Ocean is characterized by a lack of in situ measurements; thus, numerical models rely on remote sensing data and prior forecasts to generate an analysis over this region. The COSMIC GPSRO measurements provide globally distributed atmospheric refractivity soundings including over the Indian Ocean. The GPSRO measurements have relatively high vertical resolution compare to satellite radiances in the lower troposphere and are not contaminated by clouds or precipitation. Hence, This study will explore the improvement in ISM simulation using assimilating GPSRO data on top of the observations, which is being used in NCEP/NCAR reanalysis. Two experiments will be performed; the first one is the control experiment where only observations from NCEP/NCAR reanalysis will be assimilated, and the second one is similar to the first experiment, but also GPSRO data are assimilated in LMDZ5-DART system. The results from above experiments will be presented at the conference.

キーワード：Data Assimilation、COSMIC GPSRO、Indian summer Monsoon
Keywords: Data Assimilation, COSMIC GPSRO, Indian summer Monsoon

Projective analysis of staple food crop productivity in adaptation to future climate change in China

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Climate change continually affects our capabilities to feed the increasing population. Rising temperatures have the potential to shorten the crop growth duration and therefore reduce crop yields. In past decades, China has successfully improved crop cultivars to stabilize, and even lengthen, the crop growth duration to make use of increasing heat resources. However, because of the complex cropping systems in the different regions of China, the possibility and the effectiveness of regulating crop growth duration to reduce the negative impacts of future climate change remain questionable. Here, we performed a projective analysis of the staple food crop productivity in double–rice, wheat–rice, wheat–maize and single rice and maize cropping systems in China using modeling approaches. The results indicated that from the present to the 2040s, the warming climate would shorten the growth duration of the current rice, wheat and maize cultivars by 2–24 days, 11–13 days and 9–29 days, respectively. The most significant shortening of the crop growth duration would be in northeast China, where single rice and maize cropping dominate the croplands. The shortened crop growth duration would consequently reduce crop productivity. The most significant decreases would be 27%–31%, 6%–20%, 7%–22% for the late crop in the double rice rotation, wheat in the winter wheat rice rotation and single maize, respectively. However, our projection analysis also showed that the negative effects of the warming climate could be compensated for by stabilizing the growth duration of the crops via improvement in crop cultivars. In this case, the productivity of rice, wheat and maize in the 2040s would increase by 4%–16%, 31%–38%, 11%–12%, respectively. Our modeling results implied that the possibility of securing future food production exists by adopting proper adaptation options in China.

Keywords: model projection, climate change, crop productivity, adaptation

交換モンテカルロ法を用いた角閃石固溶体の非理想パラメータの最適化
Optimization of non-ideal parameters of amphibole solid solution using exchange Monte Carlo Method

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Minerals in rocks possess huge information on dynamics of the Earth's interiors within their chemical compositions and textures. Recent progress of analytical instruments and computation abilities enable us to open new approaches to extract information from rocks by machine-learning techniques. In this study, we show the results of petrological optimizing problem by using exchange Monte Carlo method (Hukushima and Nemoto, 1996; Okamoto et al., 2015).

Estimates of P-T paths of metamorphic rocks are of special importance for understanding dynamic behaviors of subduction zones and crusts. Based on Gibbs' phase rule, when the number of compositional variables of a mineral is larger than the degree of thermodynamic freedom of the system, we can obtain pressure and temperature solely from chemical composition of the mineral; this approach is called as Gibbs' method (Spear 1993). Amphibole is one of the most suitable minerals for this analyses, because (1) amphibole is common in various metamorphic rocks, and (2) it has the complex compositions which compositional variables can compensate the degree of freedom, and (3) it commonly show a growth zoning, which is useful for drawing continuous P-T path during its growth. Okamoto and Toriumi (2001; 2004) applied this method to mineral assemblage of amphibole –plagioclase –epidote –chlorite - water in eight component system, in which thermodynamic freedom, f, is four. By using amphibole compositions, which is written as solid solution of six or seven components, they succeeded in decompression P-T paths from zoning of amphiboles in the Sanbagawa belt.

One of large problems on this thermodynamic analysis using amphibole is the lack of accurate activity model of amphibole due to its complex compositions. Even when we assume simple regular solution model (symmetrical), 21 non-ideal parameters (Margules parameters) are required for mixing of seven endmembers. In binary solution, the Margules parameter is the critical temperature of the solvus, but it is difficult to obtain solvus temperature accurately from complex solid solution like amphibole. Alternatively, Okamoto and Toriumi (2004) proposed the other approach for determining the Margules parameters by using the framework of Gibbs' method as follows. Since the system described above (thermodynamic freedom = 4, independent amphibole component = 5; one amphibole composition is excess), we can estimate one compositional variable of amphibole itself as well as P, T and the composition of other minerals. Accordingly, we can compare the calculated and observed compositions. Using various amphibole compositions from natural metamorphic rocks, we can optimize the Margules parameters from numerous natural data. However, this optimization problem on such many parameters (21 W's) would have several local minimums or broad minimum, and the results would be sensitive to the analytical errors of amphibole compositions. To overcome this hardly-relaxing problem, in this study, we construct the optimization scheme by using the exchange Monte Carlo Method (Hukushima and Nemoto, 1996). We succeeded the performance of the algorithm by using the synthetic data. We will discuss the applications to natural system and seek appropriate ways to obtain the realistic P-T paths from zoned minerals.

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キーワード：角閃石固溶体、活動度モデル、交換モンテカルロ法

Keywords: amphibole solid solution, activity model, exchange Monte Carlo method

Statistical approach in the microboudin method for palaeostress analysis: reliability of the relationship between far-field differential stress and proportion of microboudinage structure of columnar grains

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The microboudinage structure of columnar mineral grains can be used as a passive marker in the palaeostress analysis of the metamorphic tectonites. In this presentation, we demonstrate the stress estimation by the numerical model that uses grain-shape data to calculate the relationship between the proportion of microboudinaged columnar grains (p) and the far-field differential stress (σ_0). This model combines weakest link theory and the shear-lag model. Weakest link theory is used to derive the fracture strength of grains, whereas the shear-lag model is used to determine the relationship between the differential stress within a grain (σ) and σ_0. An intact grain becomes a microboudinaged grain when σ is higher than its fracture strength at a specific point within the grain. The relationship between p and σ_0 can be used to estimate the magnitude of differential stress. Here, we make calculations of p for all intact grains under increasing σ_0 regardinig 50–1000 tourmaline grains shape data. These data are randomly collected from the original 1432 tourmaline grains shape data. Using the calculation result, we enable to evaluate the number of measurement grain to carry out a reasonable palaeostress analysis. This procedure will contribute to resolve the particularly time consuming when conducting stress analysis for a large number of samples within a metamorphic belt.

キーワード：古応力解析、数値シミュレーション、マイクロブーディン応力計、電気石、マイクロブーディン構造

Keywords: palaeostress analysis, numerical simulation, microboudin palaeopiezometer, tourmaline, microboudinage structure