火山灰追跡モデルPUFFの開発と空中濃度推定
Development of Volcanic Ash Plume Tracking Model PUFF and Estimation of the Airborne Ash Density

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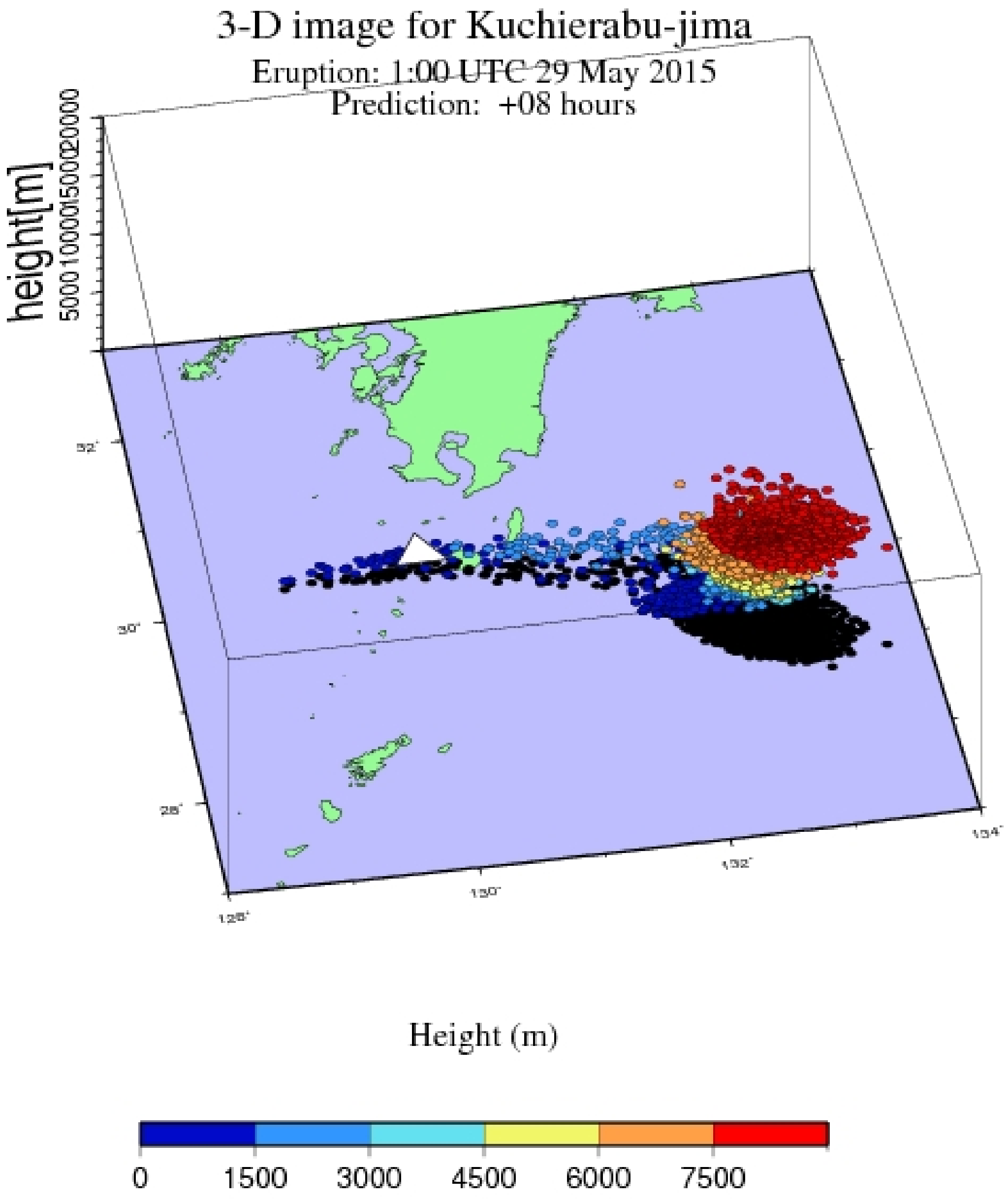
航空機が空中の火山灰に突入すると、エンジン停止を始めとする航空機の危機的な被害が発生する。したがって、空中を浮遊する高濃度の火山灰は、航空安全上とても危険な存在であり、リアルタイムで空中の濃度分布を推定する必要がある。国際民間航空機関 (ICAO)の情報では、空中に 2 mg/m3 以上の濃度の火山灰が存在するとき、その領域は航空機にとって危険とされている。この危険領域をリアルタイムで推定するシステムの構築が望まれている。

本研究では、1990年にアラスカ大学で開発された火山灰追跡モデルPUFFに、世界的に見て観測体制が最も充実している桜島火山を対象に開発されたリアルタイム噴出率推定モデルを結合した火山灰輸送拡散モデルについて説明する。さらに、このモデルを2015年5月に噴火した口永良部島火山に応用し、屋久島での降灰地上観測から空中を浮遊する火山灰の濃度の推定を行った結果を紹介する。空中の火山灰は「ひまわり8号」の衛星画像と同様の輸送拡散を示し、8時間後に火口から200km離れた地点に移動しても100 mg/m3 の濃度の領域が存在することが推定された。この情報は航空安全にとって重要と考えられる。

キーワード：火山灰予測、火山灰噴出率、航空安全、口永良部島、PUFFモデル、ひまわり8号
Keywords: Volcanic ash plume prediction, Emission rate of volcanic ash, Aviation safety, Kuchinoerabu-jima, PUFF model, Himawari-8


3-D image for Kuchierabu-jima
Eruption: 1:00 UTC 29 May 2015
Prediction: +08 hours
height[m]
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32°
30°
28°
128°
130°
132°
134°
Height (m)
0
1500
3000
4500
6000
7500

Fluid dynamics of very large plumes generated by explosive super-eruptions

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Explosive super-eruptions releasing several hundreds to thousands of km^3 of magma with extremely intense flow rates occurred in the geological past of the Earth. They impacted significantly the climate and global ecosystems. Because of lack of direct observation, plume dynamics of these eruptions are poorly understood. Simple integral models based on the Buoyant Plume Theory (Morton et al., 1956; Woods and Wohletz, 1991) have been commonly used to describe them. The validity of the assumptions behind these models (e.g., self-similarity, constant air entrainment coefficient) should be validated, because the dynamics of super-eruptions can be totally different from a simple buoyant plume. We used a three-dimensional (3D) computational fluid dynamic model (Suzuki et al., 2005) to investigate the main features of these gigantic plumes characterized by Mass Flow Rate (MFR) ranging from 10^9 to 10^{11} kg/s. The lower end of the range corresponds to the most intense Plinian columns such as the 1991 Pinatubo eruption, while the upper end to the most extreme co-ignimbrite plumes such as the Toba eruption occurred 74 ka.

We performed 3D simulations of super-eruptions and compared these results with those of the previous models. At the steady-state for low and intermediate MFR, radii of the umbrella cloud spread as function of time with the same asymptotic behavior predicted by simple box models (Woods and Kienle, 1994) and this dependence can be used to estimate MFR. Simulation results also indicate that the co-ignimbrite plume radius,, growths with MFR with the same scaling for MFR *vs* run-out distance predicted by previous simple models of pyroclastic flows by Bursik and Woods (1996). On the other hand, the maximum heights simulated by the 3D model showed the complex dependency on the MFR, which are significantly different from those of the simple integral model (Woods and Wohletz, 1991). This difference indicates that it is necessary to consider new scaling laws of the effective air entrainment coefficients for using the simple integral models as an extrapolation in order to reproduce the gigantic plumes. Results have large implications on the assessment of the intensity and the impact of these explosive super-eruptions on the Earth climate and past ecosystems.

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キーワード：超巨大噴火、火山噴煙、流体力学
Keywords: super-eruption, volcanic plume, fluid dynamics

Numerical simulations of a two-layer shallow-water model for pyroclastic density current

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During an explosive volcanic eruption, a hot mixture of volcanic particles and gas is continuously ejected from the volcanic vent and develops an eruption column. When the density of the mixture remains higher than that of the ambient air, the eruption column collapses to produce pyroclastic density currents (PDCs). PDCs are characterized by strong density stratification, whereby a dilute current (particle suspension flow) overrides the dense basal current (fluidized granular flow). The dynamics of PDCs is affected by physical processes within each of the dilute and dense parts, such as thermal expansion of ambient air entrained into the dilute part and basal resistance in the dense part. It also depends on the particle transport between the dilute and dense parts. We aim to understand these effects on PDC dynamics and the resulting run-out distance, by using numerical simulations.

We have developed an unsteady two-layer model to describe density currents with strong density stratification. In this model, each of dilute and dense parts is assumed to be uniform in any vertical section and is formulated by shallow-water equations. In the dilute part, the effects of particle settling, entrainment of ambient air, thermal expansion, interfacial drag between the dilute and dense parts, and resistance of ambient at the flow front are taken into account. In the dense part, the effects of basal resistance, sedimentation, and the particle supply from the dilute part are included. The equations are numerically solved by the finite volume method using the HLL scheme. A stationary dilute mixture with its higher density than that of the ambient air is initially (i.e., $t = 0$) set in the rectangular reservoir with a solid backwall, and an additional mixture with the same composition as the initial mixture is supplied to the reservoir at a constant rate at $t > 0$. A density current is produced on a horizontal ground surface by an instantaneous release of the mixture at $t = 0$ and the subsequent steady supply of the mixture in the reservoir.

We calculated time evolution of a PDC (e.g., thicknesses and velocities of dilute and dense parts, and thickness of deposit). The result is divided into two stages. In the first stage (Figure 1a), the dilute part propagates, and the dense part develops. Because the dense part propagates slowly owing to basal resistance, the maximum run-out distance in this stage is determined by the front position of the dilute part (L_1). In the second stage (Figure 1b), the density of the frontal region of the dilute part falls to that of the ambient air owing to particle settling and thermal expansion of entrained air. The mass of this frontal region ascends from the current into a co-PDC plume (i.e., co-ignimbrite ash cloud), whereas the dilute part around the source forms a steady dilute density current. The run-out distance of the steady current (L_S) is much shorter than L_1. Subsequently, the dense part extends beyond L_1, and the run-out distance of the PDC is determined by the front position of the dense part (L_D).

Previously, the run-out distance of PDC was estimated on the basis of a steady one-layer dilute PDC model (Bursik & Woods, 1996). This run-out distance corresponds to L_S, and does not represent L_1 or L_D. Therefore, the run-out distance proposed by the previous study may be underestimated.

キーワード：火砕流、浅水波方程式、2層流モデル、到達距離、粒子サスペンション流、粒子流
Keywords: pyroclastic density current, shallow-water equation, two-layer model, run-out distance, particle suspension flow, granular flow

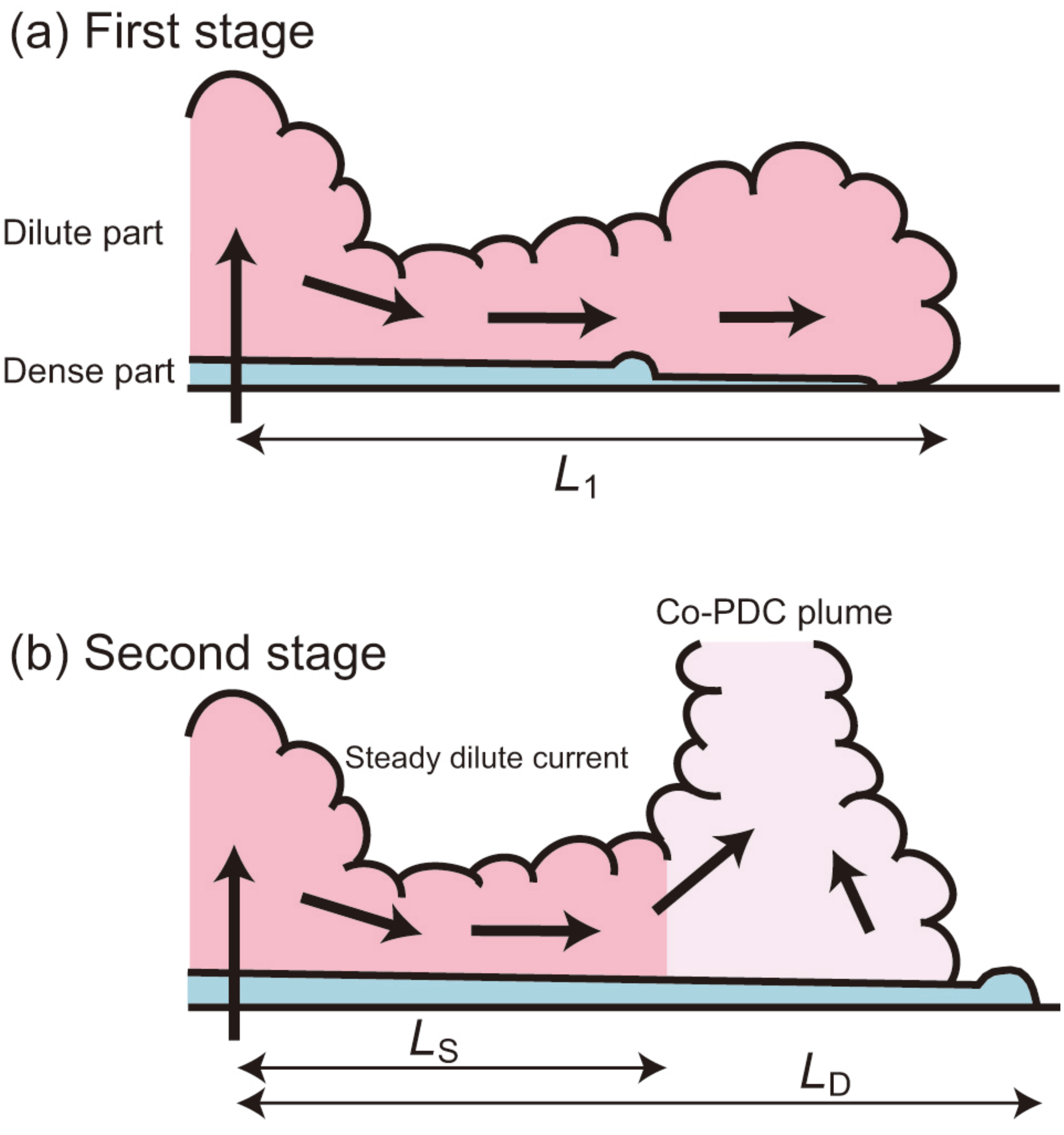

Figure 1 Schematic illustrations showing time evolution of a PDC.

A refractive index model of volcanic ash derived from satellite infrared sounder measurements for applications of HIMAWARI-8 retrieval algorithm

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Japan Meteorological Agency (JMA) has been developing a retrieval system to provide volcanic ash products from HIMAWARI-8 infrared measurements through a volcanic ash detection/evaluation algorithm. For the estimation of ash cloud parameters, i.e. cloud top height, optical depth, particle size, and associated mass loading, accurate radiative transfer calculations in the modeled atmosphere are important. Because optical properties of the ash clouds strongly depend on the ash refractive index, a dataset of spectral refractive index in the infrared region for various types of volcanic ash materials is desirable. The current models of refractive index for volcanic ash, which were published more than thirty years ago, are insufficient in spectral resolution as well as in the number of alternatives for the use of multi-channel satellite remote sensing.
As reported in the literatures, refractive index of volcanic rocks and/or ash materials at infrared wavelengths had been estimated in laboratory from the spectral reflectance for the applied infrared light. The situation of satellite infrared sounder measurements for volcanic ash clouds in the atmosphere over land/ocean is essentially similar to the laboratory measurements. It suggests that the ash refractive index can be estimated from the infrared spectroscopy by satellites in condition of no ice/water clouds contamination and if the other unknown parameters, i.e. the ash cloud parameters, the atmospheric profile, and surface temperature/emissivity, are determined in advance or derived simultaneously. The estimated refractive index of the ash material by satellite infrared sounder has a potential to improve volcanic ash retrieval by HIMAWARI-8 for the same ash clouds and also for the ash clouds erupted from the same type of volcanos. In this work, a refractive index model, which derived from the measurements of infrared sounders, AIRS and IASI, for some volcanic events is proposed.

キーワード：火山灰、複素屈折率、ひまわり８号
Keywords: volcanic ash, refractive index, Himawari-8

粒径分布の層序変化からみた新燃岳2011年準プリニー式噴火
Temporal variation of the 2011 Shinmoe-dake subplinian eruption inferred from the stratigraphic GSD variation

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降下火砕堆積物を構成する火砕物の粒径分布は空間的に変化し，噴出物の輸送過程と噴火の時間発展を反映していると考えられる．降下火砕堆積物の粒径分布から噴火現象を復元するために，これまでに我々は噴出物輸送と堆積過程に関する理論的研究を行い，噴火現象と堆積構造の間に成り立つ定量的な関係を導出してきた．本件では降下火砕堆積物の粒径分布の層序変化から噴出初期の粒径分布の時間発展を推定する2次元モデルを新燃岳2011年噴火に応用する．

新燃岳は2011年1月26日から27日にかけて3日の準プリニー式噴火を経験した．一連の噴火現象は，地球物理学的観測によって，噴火最中の噴煙柱高度（新堀・他, 2013）や地殻変動量（Ueda et al., 2013）の時間変化が報告されている．一方，1回目の準プリニー式噴火で形成された降下火砕堆積物中を構成する火砕物の粒径分布は，堆積層下部で上方粗粒化し，その後堆積層上部で上方細粒化している（入山・寅丸, 2015）．2次元モデルを用いて堆積物粒径分布の層序変化を噴出初期の粒径分布の時間変化に変換し，地球物理的に観測された噴火の時間変化と粒径分布の時間変化を直接比較する．

応用の結果推定された噴出初期の粒径分布の時間変化は，粗粒粒子が噴火初期に増加し，噴火後期に減少する変化を示した．粒径分布の時間変化の特徴を定量的に評価するため，推定された粒径分布を時間ごとに冪分布近似を行い，冪数の時間変化を調べた．その結果，噴出初期粒径分布は，噴火初期で冪数が減少（粗粒化）し，噴火後期で冪数が増加（細粒化）することが示された．

定常条件下での噴煙モデル計算により，噴出物の粒径分布，噴出率および最大噴煙高度の関係が得られている（Girault et al., 2014）．本研究によって得られた粒径分布の時間変化および，観測によって得られた噴煙高度の時間変化をモデル計算の結果と比較したところ，噴火中の噴出率の時間変化が示唆された．粒径分布および噴煙高度から期待される噴出率は，噴火初期に噴出率が増加し，噴火後期に噴出率が低下するという時間変化を示し，測地学的な観測によって得られる地殻変動量の時間変化と整合的である．

キーワード：粒子サイズ分布、火砕物、時間発展、噴出率
Keywords: grain-size distribution, pyroclasts, temporal variation, mass eruption rate

Pyrrhotite oxidation as a tool for reconstructing thermal structure of eruption columns

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Entrainment of ambient air is a key process in eruption cloud dynamics as it thermally expands and produces buoyancy. Because magma fragments (pyroclasts) are cooled and oxidized by air entrainment, petrological analysis may evaluate independently the entrainment process. To quantify the degree of interaction between fragmented magma and entrained air, we focused on oxidation of pyrrhotite (Po, $Fe_{1-x}S$) in the pyroclasts. In this study, we simulated cooling of pyroclasts to examine the coupling between degree of oxidation and eruption dynamics. Cooling of pyroclasts was simulated using a newly-developed routine for a three-dimensional (3-D) eruption column model, while oxidation kinetics of Po are already relatively well understood. By testing the parameter sensitivity of the degree of oxidation and comparing simulated and natural oxidation degrees for a Plinian eruption, we examined the usefulness of Po oxidation as a marker for magma-air interaction and an indicator of eruption-column thermal structure in the 3-D model.
Three simulations with different mass discharge rates and magma temperatures were performed based on the 3-D eruption column model. In the simulations, two types of thermal structures corresponding to jet flow and fountain flow (Suzuki and Koyaguchi 2012) were observed with magma discharge rates of 10^6–10^7 kg/s and ~10^9 kg/s, respectively. Both of the flow types included an “unmixed core” (or high mass fraction zone) in the column. The fountain-type maintained high temperature longer than the jet-type because the fountain-type unmixed core was not eroded until extensive air entrainment occurred at the top of the fountain.
The oxidation degree of pyroclasts was then calculated on the basis of predicted temperature change of particles in the eruption column. Po in volcanic rocks is often oxidized to form magnetite (Mt, Fe_3O_4) and then hematite (Hm, Fe_2O_3) (Matsumoto and Nakamura 2012). The growth rate of Hm from Mt can be applied to measure the oxidation degree of pyroclasts as it has been determined experimentally (Païdassi 1958). Calculations of Hm width were made for approximately 300 to 1000 oxidation markers in the eruption column for each simulation condition, and expressed as frequency distributions of oxidation degree. Our calculations showed that Hm-width distribution varied according to the mass discharge rate (i.e., flow type) and initial magma temperature. The distribution of oxidation degree was broad in the case of fountain-type, whereas it was narrow in the case of jet-type. In addition, an eruption column which has a high initial magma temperature and jet-like structure was characterized by a long-tailed distribution, which results from a presence of high oxidation degree markers. These results indicate that Po oxidation can be potentially used for characterizing the thermal structure of eruption columns.
We also compared calculated Hm widths with petrographic data from the Sakurajima 1914 Plinian eruption. The Hm widths based on the simulation were approximately one-third the thickness of those observed in natural pumices. Three potential explanations for this discrepancy are: (1) thermal conduction of the pumice clasts, which is neglected in the present 3-D model, affects the Po reaction degree; (2) Po reaction rate was underestimated; and/or (3) Po oxidation started in the volcanic conduit before magma fragmentation, possibly accompanying open-system outgassing of the magma.

キーワード：噴煙柱、酸化、磁硫鉄鉱
Keywords: eruption column, oxidation, pyrrhotite