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論 文 内 容 要 旨

The purpose of this study is to investigate in detail the magma formation processes of three large Pleistocene calderas in NE Honshu (Naruko and Onikobe calderas) and Kunashir Island (Mendeleev caldera). Here I pay attention to a detailed study of the mineralogy of pyroclastic flows and mineral and melt inclusions from phenocrysts of eruptive rocks. Based on the data obtained, I reconstruct the history of magmatic chamber development that led to the final large caldera eruptions. In addition to basic petrological studies, we address two relevant petrological topics as applied to the objects under study: (1) time scales of magma formation and mobilization based on diffusion profiles in quartz and orthopyroxene and (2) calculation of the water excess that forms during the formation of these magmas under shallow crustal conditions.

The structure of this thesis consists of six chapters. The first chapter and last chapters are introduction and conclusion, respectively. The second chapter devoted to the detailed petrological investigation of Mendeleev caldera eruption occurred 40 thousand years ago in Kunashir Island. A comprehensive examination of pumice mineralogy revealed that the early 'gabbro-noritic' assemblage, comprising plagioclase, augite, hypersthene, and Fe-Ti oxides, crystallized due to Mg-hornblende dehydration breakdown. Considering the rhyolitic compositions of the primary melt inclusions in these minerals, it is likely that their occurrence is linked to dehydration partial melting accompanying magma generation. The absence of mineral zoning and melt-inclusion compositions indicating precursor mafic or

intermediate parental melts suggests that partial melting was the primary mechanism for felsic magma generation during the 40 ka Mendeleev caldera eruption. This magma comprised rhyolitic melt mixed with mafic products from the amphibole breakdown reaction, resulting in a dacitic magma composition. In the final stages of magmatic evolution, minor amounts of plagioclase and quartz crystallized directly from the residual rhyolitic melt, as confirmed by the evolutionary trends of the melt inclusion compositions. The data indicate that the magma was generated at depths ranging from 107 to 314 MPa (~4.2 to 12.3 km), likely through the partial melting of amphibole-bearing crustal rocks. Crystallization of the early minerals occurred at these depths, while the later quartz-plagioclase assemblage crystallized as a consequence of magma ascent to depths of 3-4.5 km. This suggests that the magmatic system of Mendeleev volcano extended from the magma source to the caldera eruption reservoir, potentially occupying most of the upper crust of Kunashir Island. I suggest that partial melting of amphibole-bearing crustal rocks can be triggered by repeated intrusions of hot mafic magma into the middle crust. This process aligns with the findings of (Martynov & Martynov, 2017), who inferred regional stretching of Kunashir Island during the Pleistocene, leading to substantial thermal inflow into the island-arc crust from multiple intrusions of mantle-derived mafic magmas.

The third chapter is detailed petrological description of Naruko caldera eruption (Yanagisawa deposit) and two Onikobe caldera eruptions (Shimoyamazato and Ikezuki deposits). In this section, by studying in detail the mineralogy and inclusions in the Onikobe and Naruko caldera-forming deposits, the nature of the origin of their magmas were elucidated. In both cases, the magmas were dislocated in upper crustal low-depth conditions before eruption. The “mafic” clots in the Ikezuki magma indicate a significant influence of more primitive magmas. But it remains unclear whether this was partial melting of more primitive crustal rocks or whether the mafic assemblages are xenoliths from the parental melt, the crystallization of which led to the formation of Ikezuki dacites. Detailed observation of the distribution of mineral zoning patterns allows us to suggest that the most probable mechanism of Shimoyamazato magmas is the rejuvenation of Ikezuki magmas due to the strong influence of hotter magmas. The mobilized portions of magma were re-equilibrated with the rhyolite melt. The process was not accompanied by significant mixing and hybridization of newly formed magmas. Before the eruption, both magmas stored at 777–858°C, 87–197 MPa. There is not significant difference in P-T conditions. Ikezuki

magma relatively depleted in H_2O content than Shimoyamazato. The magmas of the Yanagisawa eruption (Naruko caldera) were generated at P-T conditions of 790–838°C, 126–157 MPa. Yanagisawa magmas formed by rejuvenation of crustal mush zone due to the injection of hotter primitive magmas. This process was not accompanied by magma mixing, but only heat and volatiles were injected into the mush to form the Yanagisawa magmas. Mineral zoning in Yanagisawa phenocrysts reflects the multiple injections of hotter magma below rhyolites that lead to thermal convection and remobilization of the resident magma. These conditions led to the formation of an association of phenocrysts with broad reverse zoning and did not provoke an eruption long enough to generate 10 km^3 of chemically homogeneous magma (given that the entire range between the two eruptions is 27 thousand years). Thus, those observations suggest that rejuvenation processes of already existing magmas stored in the upper crust are critical in the preparation of large explosive eruptions in NE Honshu.

Chapter 4 is devoted to a study of the timescales of formation and mobilization of magmas from both eruptions of the Naruko caldera. The fourth chapter is inspired by the chapter three as minerals of Naruko caldera deposits have abundant diffusion zoning which indicate different mixing and mobilization processes. Thus, based on diffusion profiles in orthopyroxene and quartz, we provide important information about geological processes and their duration before final catastrophic eruption. In Yanagisawa magma, we observe strong evidence of the remobilization of the upper-crustal magma supported by widespread reverse zoning. Multiple reverse zoning predominantly on the orthopyroxene rims indicated the repetitive process of heating the Yanagisawa magmas shortly before the eruption. This process also occurred within centuries years, but this process was most prevalent only decades prior to eruption. Narrow dark rims suggest triggering of eruption through mafic recharge, which occurred within years to decades. Zoning patterns within quartz from both eruptions are similar to those in orthopyroxene. Thus, quartz could have been present throughout the evolution of the Naruko magmas together with orthopyroxene. Quartz from Shimoyamazato pumice presents a lighter (high-Ti) core than rim or absence of zoning. While Yanagisawa quartz usually have a reverse zoning pattern with significantly resorbed cores and often contains bright rims. Based on the interpretation of mineral chemistry and zoning patterns, it can be inferred that several important processes govern the formation and behavior of melt bodies in the crust. These processes include melt segregation, magma body assembly from the source

mush, and the residence of magma in the upper crust. The timeline for these processes spans from a few decades up to thousands of years. Notably, priming events, such as heating caused by basaltic injection, appear to occur in the years leading up to the main eruption (e.g. rims in orthopyroxene from Yanagisawa or Quartz zoning). These findings emphasize the complexity of the processes involved in the formation and movement of melt bodies within the crust. They suggest that the assembly and residence of magma can take considerable time, ranging from decades to millennia. Occurrence of priming events preceding eruptions highlights the potential significance of short-term processes in influencing volcanic activity.

In the fifth chapter, I estimated an excess of water during formation of felsic magmas through the crystallization of more primitive magmas and partial melting of amphibole-bearing crustal rocks. These two scenarios are a theoretical estimate of the magmas of the Naruko and Mendeleev caldera eruptions considered in the example previously described in detail. On the basis of hypothesis that Naruko magma originated through simple batch crystallization of the basaltic andesite (the most primitive sample from the Naruko volcano), Rhyolite-Melts modeling results suggest that the Naruko rhyolites can be obtained by 70% crystallization of parental melts with initial concentrations of H_2O=4.2 wt. %, CO_2=0.001 wt. % and at a pressure of 1.5 kilobars. Based on the Rhyolite-Melts results and mass balance calculation, we estimated the mass of water that could be dissolved in the parental magma in the final Naruko rhyolite and the part that was not dissolved in the final rhyolite and probably was separated as a free fluid. We estimate that the parental melt contained 3.86 Gt bulk water content when the final rhyolite dissolved only 1.36 Gt. Thus, approximately 2.5 Gt of water (65 wt.%) has not been dissolved in the rhyolitic endmember but became excessive due to pressure limitation of water dissolution in the melt. For Mendeleev volcano, a realistic scenario where water-unsaturated melts are separated from the source at 3 kbar and accumulated in a shallow chamber at pressures and temperatures corresponding to quartz crystallization. In this case, water saturation occurs not during generation of melts at the source, but during their uprising and degassing. In the pre-eruptive melt was dissolved 3.8-5.7 Gt (Mean is 4.82 Gt) of water. During the uprising of melt from the source to the pre-eruptive magma body, degassing occurred and provide water excess of 1.03-5.34 Gt (18-53 wt.% of initial mass). In both considered cases, the amount of released water is comparable to the amount which is dissolved in the final pre-eruptive melt (in terms of orders).

（別紙）

論文審査結果の要旨及びその担当者

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論　文　題　目	Formation and evolution of silicic magma plumbing system and fluid genesis in subduction zone of NE Japan - Kuril region （東北日本－千島地域の沈み込み帯における珪長質マグマ上昇の形成・発達過程と流体の発生に関する研究）
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論文審査結果の要旨

東北日本から北海道，さらに千島列島にかけての地域は，太平洋プレートが沈み込み，地震多発帯ならびに多くの火山が分布する非常に活発な地域であり水を大量に含む海洋地殻が沈み込み，地球内部への流体の供給が行われている．この海洋地殻（スラブ）が，マントル内で溶融・脱水し，マントルウェッジ，さらに地殻へマグマとそれに含まれる流体が供給されていると考えられている．しかしながら，沈み込み帯での火山による下部地殻－上部地殻への流体の供給量については，物的証拠が乏しく不明な点が多く残されていた．本研究は，東北日本と千島列島の火山についての火山岩岩石学的研究を基礎に，沈み込み帯における地殻への珪長質マグマと流体供給システムについて明らかにしたもので，全編６章よりなる．

第１章は，緒論であり，カルデラを形成する火山形成の時間発展，およびマグマシステムと流体供給の現在の研究状況をまとめ，本研究の目的を述べている．
第２章は，千島列島，国後島に分布するメンデレーエフ火山について，この火山をもたらしたマグマの進化過程を解明し，この火山は，地下４から 12 km の比較的浅い環境で，角閃石を含む地殻物質の部分溶融により，珪長質マグマが形成されたことを明らかにしている．あわせて二次イオン質量分析装置を用いてメルト包有物の化学分析を行い，マグマに含有されていた揮発成分（二酸化炭素と水）の濃度を定量的に明らかにしている．千島列島には多くの火山があるが，角閃石を含む地殻物質の部分溶融により珪長質マグマの形成を明らかにした初めての研究であり，またマグマ中の流体の量を推定した有用な成果を得ている．
第３章は，東北日本　本州弧の火山前線に位置するカルデラ噴火火山である鳴子火山と鬼首火山の火山噴出物の研究から，両火山の活動史とマグマ形成の温度・圧力条件およびその進化過程を解明している．斑晶の累帯構造の解析から，各噴出層のマグマ形成のプロセスおよびその温度，圧力条件を推定している．さらに，メルト包有物の分析から，この両火山のマグマは，ほぼ水に飽和した状態で賦存していたことを明らかにしており，重要な成果である．
第４章は，鳴子火山と鬼首火山の火山噴出物中の，特に直方輝石と石英中の元素の濃度の連続変化を測定し，その結果をもとに固結時のマグマ環境の時間変化の見積もりを行い，結晶分化作用時の温度変化に時間的制約条件を与えており，マグマの進化を考察するうえで有用な成果を得ている．
第５章は，各火山を形成したマグマの性質とその環境変化の基礎情報をもとに，マグマ中の流体の量的変化を明らかにしており，メンデレーエフ火山を形成したマグマは，約５Gt の水を含有しており，それがマグマの結晶化のプロセスで，次第に地殻中に放出され，最終的な珪長質マグマに残留する水と地殻中に放出される水の量はほぼ等しい量となっていることを明らかにしている．これによって，本州弧，千島弧において火山によって地殻にもたらされる流体の量を推定でき，超臨界地熱貯留層の起源流体の量的推定ができるなど，きわめて重要な成果である．
第６章は結論である．

以上要するに，本論文は，東北日本　本州弧から千島弧にいたるカルデラ噴火火山のメンデレーエフ，鳴子，鬼首の火山岩，火山砕屑岩，その中のメルト包有物の解析から，マグマの発生深度とその進化，マグマの結晶化の過程での水の含有と地殻中への放出量を解明して，沈み込み帯において火山によって地殻中にもたらされる流体量を解明し，地殻中の流体環境に一定の制約を与え，地震，火山爆発，また工学的には超臨界地熱の開発に応用展開することができ，地球科学ならびに環境科学の発展に資するところが少なくない．

よって，本論文は博士(学術)の学位論文として合格と認める．