Two positive-feedback mechanisms controlling the bifurcation of gas-escape processes during volcanic eruptions

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The dynamics of conduit flow is affected by density change of magma due to gas-escape and viscosity change due to crystallization. The processes of gas-escape and crystallization, therefore, lead to diverse features of volcanic eruptions such as a transition from a lava-dome forming eruption to an explosive eruption. The diverse features of eruption sequence are investigated using a model of magma plumbing system composed of a conduit and a magma chamber in elastic rocks, in which the effects of lateral and vertical gas-escape, as well as that of crystallization, are taken into consideration (Kozono and Koyaguchi, 2012). Here, using this model, we estimate the effects of gas-escape on the diverse features of eruption sequences.

Generally, the dynamics of conduit flow is controlled by the relationship between chamber pressure (P) and mass flow rate (Q) for steady conduit flow (the P-Q relationship). The diverse features of eruption sequence can be explained by the variation in the P-Q relationship. The variation in the P-Q relationship can be systematically described using the two reference relationships of extreme cases: the efficient gas escape (EGE) case and the no gas escape (NGE) case. The P-Q relationship for general cases is located between the EGE and NGE cases. In the P-Q relationship for general cases, there are two mechanisms that cause a transition from the EGE case to the NGE case and bring forward its change (the two positive-feedbacks).

The first positive feedback occurs during the waxing stage of an eruption. As the magma flow rate, Q, increases in the waxing stage, magma porosity increases with increasing Q because of less efficient gas escape, which leads to further increasing in Q because of reduction of gravitational load. This feedback mechanism causes complex dynamics; Q changes abruptly and/or cyclically even if magma supply at depth gradually increases. This abrupt increase in Q may account for the transition from a stable lava-dome eruption to an explosive eruption.

The second positive feedback occurs during the waning stage of an eruption. During the waning stage, as the chamber pressure, P, decreases, the pressure inside the conduit also becomes lower than the lithostatic pressure. The decrease in pressure inside the conduit reduces the efficiency of the lateral gas escape. This reduction of lateral gas escape increases magma porosity, which, in turn, leads to a decrease of the gravitational load and a further decrease in P. This feedback mechanism is particularly important in the sense that it controls the magnitude of decrease in chamber pressure during eruption (i.e., pressure drop), and hence, the scenario towards the end of an eruption.

Results of an extensive parametric study indicate that whether the second feedback mechanism plays a role or not is sensitive to a slight change in the permeability of the country rocks. For the condition where this feedback does not work, an eruption ends when the initial overpressure of magma chamber is relaxed. When this feedback plays a role, on the other hand, even after the initial overpressure of magma chamber is relaxed, an eruption continues until the chamber pressure becomes as low as the static pressure of gas-rich magma.

キーワード：マグマ供給・噴出系モデル、脱ガス作用、噴火推移、分岐現象
Keywords: magma plumbing system model, gas-escape process, eruption sequence, bifurcation

Mechanisms of transitions in eruption style at the end of the 1912 eruption of Novarupta, volcano, Alaska

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The 1912 Novarupta eruption consisted of five episodes ranging from strong Plinian (mass eruption rates of 1.1 –5 x 10^8 kg/s) to stable, steady dome effusion. Sixty hours of Plinian explosions erupted first predominantly rhyolite (Episode I) and then dacite with minor amounts of andesite (Episode II-III). Episode IV produced a dacitic block bed, interpreted as the product of complete destruction of a dacite plug/dome via Vulcanian explosions, before extrusion of a rhyolite dome in Episode V.
The transition in style and intensity from powerful explosions to dome growth is represented by three shifts in eruption style. We describe here the mechanisms of the first two shifts (lower Episode III to upper Episode III and upper Episode III to Episode IV).

The switch from sustained Plinian eruption to an unsteady subplinian phase during Episode III was brought about by progressive increase in the level of outgassing of the dacite melt remaining in the conduit. This is seen in a steady increase in the amount of dense dark grey juvenile ejecta as the outgassed melt slowed the rate of magma ascent and began to 'choke' the shallow conduit. The deposits are well bedded and markedly less dispersed than the Plinian falls of episodes I, II and early Episode III.

The second shift was from unsteady subplinian eruption (end to Episode III) to non-sustained transient Vulcanian explosions in Episode IV. Highly diverse juvenile blocks from Episode IV provide special insight to the state of the magma as an eruption passes from powerful sustained Plinian eruption to passive dome growth. They supply a picture of a dynamic and complex shallow conduit, now dominated by partially or completely outgassed dacitic melt that was resident at shallow levels, prior to fragmentation in repeated small Vulcanian explosions. Small total and individual explosion volume estimates, suggest that individual explosions during Episode IV disrupted the conduit to only shallow depths. Our data (1) suggest that different explosions tapped small yet diverse parts of the conduit's architecture and (2) require a more complex model than repeated progressive evacuation in a top-down fashion of a simple horizontally stratified magma-filled conduit. The shallow conduit architecture involved both the juxtaposition of domains of contrasting texture and vesiculation state and the intimate mingling of different textures on short vertical and horizontal length scales at the contacts between these domains.

Keywords: Plinian, Vulcanian, transitions in explosive eruptions

What can “nanolites” tell us about eruption styles?

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Crystallization of groundmass minerals record physicochemical conditions of magmatic processes upon eruption. Mujin and Nakamura (2014) reported that different assemblages of the nanolites in pyroclasts of the 2011 eruption of Shinmoedake, the Kirishima volcano, recorded the bifurcation conditions of the eruption styles. The pyroxene nanolite crystallized in both of the sub-Plinian products and the lava extrusion and Vulcanian products of the 2011 activity, whereas the plagioclase nanolite followed that of pyroxene only in the lava extrusion and Vulcanian products. They pointed out that the presence of plagioclase nanolites indicates the prolonged residence (or transit) time in the shallow conduit or crater (under large ΔT) at magmatic temperature prior to the lava extrusion and the Vulcanian explosions. The lack of plagioclase nanolite gives the upper limit of the duration in which the magma ascent through the shallow conduit in the sub-Plinian eruptions, whereas the appearance of plagioclase nanolite gives the lower limit of magma residence time for Vulcanian explosions.
Following their study, we report the presence of nanometer-scale crystals down to 1 nm in the pyroclasts from the Shinmoedake 2011 eruption and their mineralogical characteristics based on field emission-scanning electron microscopy and transmission electron microscopy.
The main finding regarding nanolite crystallization is a gap (hiatus) from ~100 to 30 nm in the size distribution of pyroxene in a dense juvenile fragment of a Vulcanian explosion. The finer-sized crystals of ~20–30 nm were defined as “ultrananolites.” In the dense fragment sample, bright spots of ~1–2 nm in diameter were recognized in high-angle annular dark-field scanning transmission electron microscopy images. These spots are presumed to be Fe–Ti oxide, although their mineral phase was not determined due to their small size. If so, the 1–2 nm crystals are ultrananolite with a ~9 nm gap from titanomagnetite nanolites. The pyroxene ultrananolite and Fe–Ti oxide nanolite and ultrananolite are assumed to have been formed by the additional increase in ΔT through cooling and oxidation, possibly by fragmentation followed by rewelding at the crater. Another important finding is that crystals smaller than a few tens of nanometers for pyroxene and a few hundred nanometers for plagioclase did not exist (or their number densities were too low for accurate determination). This indicates presence of practical minimum size of the crystals. These observations show that nucleation of the nanoscale crystals ceased, at least practically, in the late stage of groundmass crystallization owing to increased interfacial energy and decreased melt diffusivity in a dehydrated melt, whereas crystal growth was mostly continuous. The observation that pyroxene crystallization practically ceased before plagioclase nanolite appeared is consistent with the similarity in pyroxene characteristics such as the minimum crystal size of nanolite and the boundary size between microlite and nanolite between sub-Plinian and Vulcanian products, although plagioclase nanolites are found only in the Vulcanian products. The differences in the conditions between lava extrusions and Vulcanian explosions may be recorded in the later stage crystallization of plagioclase and Fe-Ti oxides.

塩素濃度マッピングを用いたマグマの発泡・気泡溶解の痕跡の解読
Chlorine mapping as a new tool to investigate the degassing processes of silicic magma

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＜はじめに＞

マグマの発泡と気泡の消滅（開放系脱ガス，再溶解）は，マグマ密度を著しく変化させ，噴火様式を支配する主要過程と考えられている．しかし，この過程が火道内のどのような深度・タイミング・回数・メカニズムで起こるのか，詳細はほとんど理解されていない．これを解明する方法の１つは，石基ガラスの塩素濃度マッピングを行うことである．塩素は拡散が遅いので，脱ガス時に形成された拡散プロファイルが均質化せずに残っており，脱ガス履歴を解読できる可能性がある．実際，一見均質な石基中に，複雑な塩素濃度分布が存在することが確認されている（吉村・中川2016鉱物科学会）．本研究ではこの考えをさらに進めるため，そもそも発泡や気泡溶解が起きたとき，どのような塩素濃度の空間分布が作られるべきかを実験で調べた．

＜実験方法＞

円柱形に成型した流紋岩質黒曜石（和田峠産，初期含水量0.6 wt%）をMgOセラミクスの開放系円筒容器に入れ， 10または30気圧，1000℃で3〜24h加熱した．このような実験を行うと，試料には，①均質に発泡した中央部と，②気泡が全く存在しないガラス層の周縁部の２つの部分が作られることが知られている．この形成メカニズムはYoshimura and Nakamura (2008)で示されており，加熱初期には中心・周縁を問わず全体的に発泡するが，試料表面では拡散脱水が進行するため，メルト含水量が飽和溶解度を下回り，気泡が再溶解し，周縁層が発達するのである．したがって，１つの実験試料の中に，１）気泡が成長しつつある部分，２）溶解しつつある部分，３）すでに気泡が溶解しガラス層となった部分の３つを同時に観察することができる．実験後，試料断面を研磨し，FE-EPMAを用いて塩素濃度マッピングを行った．

＜結果と考察＞

試料内部はほぼ均質に発泡した．一方，周縁部には気泡が含まれないガラス層が発達した．ガラス層近傍の気泡は，それより内側の気泡に較べ小さく，溶解中であることが読み取れる．FE-EPMAによるマッピングでは，さまざまな種類の塩素濃度不均質が観察された．まず，試料中央部では，気泡に近づくほど塩素濃度が低下する様子が観察された．これは，気泡成長に伴い塩素が吸引されていることを示すものと考えられる．一方，溶解しつつある気泡では，気泡に近づくほど塩素濃度が高まる分布が見出された．これは気泡溶解に伴い，ガス中の塩素が周囲メルトに再び吐き出されているものと考えられる．周縁部のガラス層内部には，塩素濃度の高い円形領域がスポット状に点在していた．これは，気泡自体は既に溶解・消滅したものの，塩素を放出した痕跡が残っているものと考えられる．10気圧の実験では，メルトが勢いよく発泡したため，気泡は一方向に楕円形に伸長していた．溶解中の気泡は球形であったが，その周囲の高塩素濃度領域は楕円形であった．このことは，この気泡も初めは伸長していたが，溶解し気泡半径が小さくなると表面張力による形状緩和が強く働き，現在では球形になったものと考えられる．

＜展望＞

塩素濃度マッピングを用いれば，発泡試料中の１つ１つの気泡が成長中なのか，溶解中なのか，明確に区別することが可能であることが分かった．また，気泡を含まない領域でも，かつて気泡が存在した痕跡が見出され，その位置を特定したり，当時の気泡形状を推定することも可能である．さらに，拡散プロファイルの解析

を組み合わせれば，気泡形成イベントの回数，気泡が形成されてからの時間，気泡溶解時間などを解読することができ，火道内での脱ガス過程を詳細に解明できるようになると期待される．

キーワード：塩素、発泡、気泡再溶解
Keywords: chlorine, vesiculation, bubble resorption

Orientation of eruption fissures controlled by shallow magma plumbing system; example of the fissure pattern in Miyakejima

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Orientation of the eruption fissures and composition of the lavas of the Miyakejima volcano indicate the competitive processes of the regional tectonic stress and the local stress generated by the activity of a magma plumbing system beneath the volcano. We investigated the distributions and magmatic compositions of the recent 23 fissures that formed within the last 2800 years, based on a field survey. Some fissures are also confirmed their eruption date by new datasets of ^{14}C ages. The result highlights the tectonic influence of shallow magma chamber on the development of feeder dikes in a composite volcano.
As previously known, the dominant orientation of the eruption fissures in the central portion of the Miyakejima volcano was NE-SW during the last centuries, which is perpendicular to the direction of regional maximum horizontal compressive stress (σ_{Hmax}) indicated by the regional seismicity. Our field survey reveals that the magmas that show evidence of mixing between basaltic and andesitic compositions erupted mainly from the eruption fissures with a higher offset angle from the regional σ_{Hmax} direction.
The dike pattern perpendicular to the direction of maximum compression σ_{Hmax} is an unusual and uncommon feature in volcanoes. The distribution and magmatic compositions of the eruption fissures in Miyakejima volcano can be explained by the tectonic influence of shallow magma chamber on the development of feeder dikes in a composite volcano. The presence of a shallow dike-shaped magma chamber controls the eccentric distribution of the eruption fissures perpendicular to the present direction of σ_{Hmax}. Injection of basaltic magma into the shallow andesitic magma chamber caused the temporal rise of internal magmatic pressure in the shallow magma chamber which elongates in NE-SW direction. Dikes extending from the andesitic magma chamber intrude along the local stress field which is generated by the internal excess pressure of the andesitic magma chamber. As the result, the eruption fissures trend parallel to the elongation direction of the shallow magma chamber. The dikes propagated from the andesitic magma chamber provide the evidences for magma mixing between the stored andesitic and injected basaltic magmas. Some basaltic dikes from the deep-seated magma chamber reach the ground surface without intersection with the andesitic magma chamber. These basaltic dikes develop parallel to the regional compressive stress in NW-SE direction. The patterns of the eruption fissures can be modified in the future as was observed in the case of the destruction of the shallow magma chamber during the 2000 AD eruption.

キーワード：噴火、噴火割れ目、マグマ溜まり、岩脈、三宅島
Keywords: eruption, eruption fissure, magma chamber, dike, Miyakejima

非噴火時における火山浅部熱水系の時間発展と地上観測への応答
Numerical investigation of temporal changes in field observations associated with volcanic hydrothermal systems during inter-eruptive stages

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火口からの噴気活動が観察される火山において，非噴火時に噴気活動の消長，地磁気全磁力変化，地盤変動がしばしば同期して観測される（十勝岳，雌阿寒岳，樽前山，口永良部島など）．本研究では，非噴火時に山体内の状態変化をもたらすメカニズムとして，噴気火道の浅部における浸透率低下と，深部からの熱水供給率の変化に着目する．数値計算を用いることで，これらのメカニズムが地上の各種観測量にどのような応答をもたらすかを系統的に検討することができる．そこで，本研究では，火山体浅部における温度・間隙圧の時間発展，地表における観測項目（噴気放熱率・地盤変動・全磁力）の応答を，熱水流動数値計算によって明らかにし，類型化することを試みる．

熱水流動数値計算は数値計算プログラムSTARと状態方程式BRNGAS(Pritchett, 1995)を用い，多孔質媒質中を流動する液相，気相，および気液2相の流れと，それらの流れに伴う岩石部への熱伝達を計算した．状態方程式BRNGASでは，流体の成分としてH_2Oと空気を，温度0~350 ºCの範囲で取り扱うことができる．計算は以下の手順で行った．計算領域を円錐の山体を模した地形を考慮した2次元円筒座標系に設定した．計算領域の軸中心には高浸透率の火道を配置し，それ以外の山体（母岩）は浸透率及び空隙率を一様とした簡単な構造とした．境界条件として計算領域の上端には温度圧力一定の空気に接する条件を，低標高側端には温度圧力一定の水と接する条件を与えた．高標高側端および下端には断熱不透水条件を与えた．また，上端グリッドには年間降水量相当の水の流入のソース，下端グリッドには地殻熱流量に相当する熱のソースを配置した．火口（火道最上部）からの噴気放熱率が100 MWとなるように火道最深部から熱水を供給し，準定常状態を計算した．その後，火道最深部からの熱水供給率を増加させた場合（熱水供給率増加），火道内の1つのグリッドの浸透率を低下させた場合（火道閉塞），これらの効果を同時に導入した場合，それぞれの温度および間隙圧の変化を観察した．

火道閉塞は，火道閉塞部より上部の火道周辺の低温化および間隙圧の減少，火道閉塞部より下部の火道周辺の高温化および間隙圧の増加を引き起こす．一方，熱水供給率増加は火道およびその周辺での温度，間隙圧の増加を引き起こす．火道閉塞と熱水供給率増加が同時に起こった場合には，火道閉塞部より上部の火道周辺での温度，間隙圧の変化傾向は火道閉塞部の浸透率低下量と熱水供給率増加量のバランスに影響される．ただし，火道閉塞部の低下後の浸透率が母岩の浸透率よりも小さい場合，熱水供給率増加量によらず，火道閉塞部上部における温度，間隙圧の低下が観察された．

発表では，これらの温度，間隙圧の変化により地表で観察されうる噴気放熱率，地磁気全磁力，地盤変動の変化傾向の組み合わせについても議論する．また，今後，母岩の浸透率，火道閉塞部の深さ，母岩中の難透水層の存在が火道閉塞および熱水供給率増加による温度および間隙圧変化に与える影響を検討する．

キーワード：熱水系、火道閉塞、熱水流動数値計算
Keywords: hydrothermal system, hydrothermal sealing, numerical simulation

