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論文内容の要旨

Tangkil and Rajabasa volcanoes are neighboring subduction-zone volcanoes located within Sunda volcanic arc on the southeast tip of Sumatra Island, Lampung Province, Indonesia. These volcanoes are situated in the Sunda Strait, where Panaitan Island, Krakatau Island, Sebesi and Sebuku Islands, and the Sukadana basalt plateau form a volcanic lineament. This region is unique in term of its tectonic and volcanic activity.

Tangkil and Rajabasa volcanoes are not well studied compared to other volcanoes in Sunda Strait. The age determination and geochemical analyses of volcanic rocks from the two volcanoes have not been conducted. Detailed observation on mineral textures and zoning patterns, which could reflect the magmatic history for some extents, also has not been done. These data can give a valuable information about volcanic history and evolution of magma plumbing system. Thus, these reasons provide a good opportunity to study Tangkil and Rajabasa volcanoes.

This study introduces a new stratigraphy of lavas, radiometric ages, whole-rock chemistry, detailed observation on mineral textures and zoning, and a new set of mineral chemistry data. Stratigraphic correlation of lavas in the Tangkil-Rajabasa volcanic area is established from field observations, morphological analysis, and K-Ar dating analyses. Detailed petrography and geochemical data of 13 lava units are then integrated with the stratigraphy to show temporal

petrological variations. The description of petrological variations by a careful observation on mineral textures, compositional zoning patterns, and mineral assemblages, helps to identify the magmatic processes. The endmember magmas are identified via whole-rock and mineral chemistry, and their *T-P* conditions are estimated using thermobarometry models.

Early stage (> 4.3 Ma) effusives of Tangkil volcano are dacitic to rhyolitic (67-71 wt% SiO_2; Tklf), whereas later (*c.* 4.3 Ma) rocks are basaltic to basaltic andesite (*c.* 52 wt% SiO_2; Tklm). Then, it took *c.* 4.0 Ma to resume volcanic activity at Rajabasa volcano. Lavas of Rajabasa volcano are comparatively younger (*c.* 0.3 to 0.1 Ma) with composition ranging from basalt to andesite (51-62 wt% SiO_2; Rbs).

The rocks from the last Tklf and Rbs (except one sample) indicate open system processes. These rocks contain plagioclase and pyroxene phenocrysts that show chemically evolved cores with resorption textures and less evolved mantles or rims. The resorption textures can be formed by processes of heating, hydration, compositional change of ambient magma, or decompression. The multiple zones of dissolution-overgrowth in plagioclase crystal and the fluctuating trend in temporal whole-rock variation suggest that the changes of magmatic condition in T, H_2O, or chemical composition were repetitive.

The chemical variations of Rajabasa are accounted for by the interactions of at least three endmembers: Mg-rich medium-K basalt magma, low-Mg medium-K basalt magma, and high-K andesitic magma. Mg-rich medium-K basalt magma is a primitive magma with high contents of Cr (>250 ppm) and Ni (>114 ppm). The mixing of basalt magmas with andesite magma is indicated by two linear trends in whole-rock chemistry diagrams and supported by chemical modelling performed using MELTS. The felsic endmember magma of Rajabasa is fixed in composition (at ~62 wt% SiO_2; ~2.2 wt% MgO). Tangkil also involves bimodal magma system of basalt and felsic magma. Although the majority of samples from Tangkil do not show evidence of open system magmatic processes, one sample (last Tklf) contain phenocrysts that show disequilibrium features.

The origin of the phenocrysts is determined by core-rim compositional variations of the phenocrysts. Tangkil is divided into series of Tklf, last Tklf, and Tklm; Rajabasa is divided into series of high-Mg basaltic andesite, low-Mg basaltic andesite, andesite, and transitional basalt based on geochemical characteristics. The assemblages of early-formed crystals in an endmember magma are established by finding the mutual chemical equilibrium between series. In accordance with the bulk geochemical results, the compositional variations of phenocrysts in last Tklf, high-Mg basaltic andesite, low-Mg basaltic andesite, and andesite series suggest contributions of various

endmember magmas.

The multiple crystallization origins of phenocrysts are also indicated by the variations in *T*-*P* estimates obtained by thermobarometry calculation. The last Tklf series shows a distinct of *T* estimates (934 and 1069 °C), of which the lower temperature is similar with that of Tklf series. The series of high-Mg basalt, low-Mg basalt, and andesite also exhibit a wide range of *T* within series, but the *T* estimate of high-Mg basalt magma is averagely higher (1174 °C) than that of low-Mg basalt magma (972 °C) and andesite magma (932 °C). The magma storage region depths beneath Tangkil and Rajabasa are 11 km to 22 km, at mid- to low-crustal levels, whereas high-Mg basalt magma resided in crustal-mantle interface level (*c.* 25 km).

The magmatism in Tangkil was initially sourced from rhyolite magma at mid-crustal level. At later stage, a deeper and hotter basalt magma injected and mixed with the rhyolite magma. Ascent of another unmixed basalt magma occurred at *c.* 4.33 Ma, close before Tangkil volcano ceased its activity. The magmatism in Rajabasa during Upper Pliocene (*c.* 0.3 to 0.1 Ma) was originated from four distinct magmas. During its evolution, the upper mantle-origin high-Mg basalt magma and lower crust-origin low-Mg basalt magma repetitively replenished the middle crust-origin andesite magma. At one occasion, though, a basalt magma ascent and did not mix with the other three magmas.

Keywords: Rajabasa volcano; Tangkil volcano; Sunda Strait; temporal variation; repeating magma recharge; magma evolution; geothermometry.

論文審査結果の要旨

Reza Firmansyah Hasibuan 君は、インドネシアスマトラ島南端のタンキル火山およびラジャバサ火山の火山岩について、マグマ供給システムの進化を解明するための岩石学的研究を実施し、その成果を本論文にまとめて提出した。本研究では LiDAR に基づく地形解析、現地での地質調査、溶岩試料の全岩化学組成分析、顕微鏡による記載岩石学、SEM-EDS による鉱物組織観察、EPMA による鉱物化学組成分析等の地質・岩石学的調査が行われ、そのデータを基にマグマ供給系のモデルが構築され、その進化過程が解明された。鮮新世火山（3.4Ma 頃）であるタンキル火山はバイモーダル火山活動により特徴付けられ、一部を除いてマグマ混合の影響を受けていない。珪長質マグマと玄武岩質マグはそれぞれ別の分化系統を示す。玄武岩マグマは分化した組成を示す。タンキル火山の活動から休止期間を挟んで活動した更新世後期（0.3-0.1Ma）のラジャバサ火山のマグマは、ほとんどが二成分マグマ混合により生成したものであることを明らかにした。このことは、溶融過程を示す斜長石の鉱物組織、普

遍的に見られる逆累帯構造と正累帯構造の共存関係、直線的な全岩組成変化トレンドなどから総合的に判断できる。珪長質端成分と塩基性端成分が認識され、そのうち珪長質端成分マグマは二つの直線トレンドが収束する $SiO_2$60%付近の組成を持つ安山岩マグマであることを示した。珪長質端成分由来の鉱物として黒雲母と普通角閃石が認められるものの、これらが含まれる場合と含まれない場合がある。これは珪長質端成分マグマの温度の変動によるものと解釈した。塩基性側端成分マグマは玄武岩質であるが、その玄武岩マグマには、少なくとも分化したマグマと高 Mg の未分化マグマの二種類があることが解明された。岩石学的特性の層序変化を調べたところ、化学組成、鉱物組成は一方的な変化ではなく、脈動する傾向が認められた。二十万年にわたる活動を通して一貫して安山岩マグマと玄武岩マグマが混合したマグマが噴出していることが分かった。すなわち、ラジャバサ火山では、複数種類の玄武岩端成分マグマが繰り返し貫入し、活動期間を通してマグマ系全体の温度が変動していたことを明らかにした。このことは、斜長石斑晶で普遍的に認められる溶融と被覆成長の繰り返しによる波動累帯構造からも裏付けられる。

本研究の内容の大半は、すでに査読付き学術雑誌の論文として受理されている（IJOG に受理され, 2020 年 8 月出版予定）。予備審査で指摘された結晶分化作用を検討する際の仮定については、指摘内容に従って修正が行われ、その内容も報告された。本論文は、博士論文として十分な水準に達していると認められ、論文として合格であると判断された。