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知床硫黄山中腹火口の地下浅部構造と溶融硫黄噴火のしくみ
Near surface structure of a Crater on mountain side of Mt. Shiretokoiozan and its mechanism of molten sulfur eruption

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Mt. Shiretokoiozan, located in the middle of the Shiretoko Peninsula in Hokkaido Japan, is famous as molten sulfur eruption. Since 1857, Mt. Shiretokoiozan has erupted with molten sulfur four times. At the last eruption from February through October in 1936, approximately 200,000 tons of molten sulfur welled out of the Crater I, located on the northwestern mountain side, and the brown liquid sulfur flowed into the Kamuiwakka Creek. The eruption was closely observed and documented for ten days in September by Watanabe. He presumed the underground structure and possible existence of a molten sulfur reservoir under the crater based on the periodic activity.

Since 2005 we have implemented further researches to find out the near-surface underground structure of the Crater I for discussing the mechanism of molten sulfur eruption. The methods are various; geological survey, DC resistivity survey, self-potential exploration, and chemical analysis of gas and hot spring.

As a result, we found that the crater had been created by depression due to hydrothermally altering of andesite lava sheet and the following running-off of material. We suggest that there is a chamber under the crater and molten sulfur is supplied from the aquifer at the eruption where the sulfur had been generated during the inter-eruption period by chemical reactions of volcanic gasses.

The geology of the Crater I and its vicinity is mostly composed of hydrothermally altered clay, gravel and onion structured floats. Originally this area was composed of several-meters-thick sheet lava layers of andesite, which had flowed from the summit of mountain. The volcanic gasses, mostly hydrogen sulfide and carbon dioxide, come out through fumaroles and craters located directionally along conjugate faults cutting through this area. Original andesite rocks suffered weathering by the reaction with those acid gasses into onion structured boulders and seems to change to white gravels and clay. Because the small clay particles and the gravel at ground surface have been drained, large boulders in several meters were left on the ground and they covered most of this area.

In the cross section around the Crater I, we conclude that the crater is a depression hole opening in the hydrothermally altered lava. An aquifer among sheet lava goes under the Crater I and hot spring wells in the crater. At the higher elevation than the Crater I, there is a small creek called the Io Creek. And at the lower altitude, the Kamuiwakka Creek is located. We interpret that the underground water comes from the Io Creek and flows through lava-sheet aquifer, and upwells at the Crater I as well as hot springs in the Kamuiwakka Creek.

Volcanic gasses, hydrogen sulfide and sulfur dioxide, dissolve into the underground water, and were involved in the chemical reaction to generate the accumulation of sulfur in the aquifer. At the fumarole in the Crater I, water soluble sulfur dioxide is just barely detected. At the same time, the gas temperature has never been higher than boiling point of water. These are the evidences that most of volcanic gas passed through underground water.

We suggest that the sulfur in the aquifer melts and flows into the chamber under the Crater I at the active term of volcano, and may eject molten sulfur periodically. The amount of the molten sulfur erupted in 1936 was approximately 200,000 tons. If the chamber had reserved all amount of sulfur erupted in 1936, its volume might have been as much as 100,000 cubic meters. We suppose the possible chamber size is much smaller than the estimation. It is concluded that the aquifer supplied the molten sulfur continuously to the chamber, while the chamber made a periodic eruptions.

キーワード: 溶融硫黄噴火, 熱水変質, 知床硫黄山, 1 号火口, 電気探査, カムイワッカ川の温泉
Keywords: Molten sulfur eruption, Hydrothermal alteration, Shiretokoiozan, The Crater I, DC resistivity survey, Hot springs in

the Kamuiwakka Creek

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火山噴出物中に含まれる非マグマ性物質の物質科学的特徴：北海道十勝岳火山の例
Mineralogical study of non-juvenile material in volcanic products at Tokachidake volcano, Japan

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Temperatures, depths, and fluid chemistry of sub-volcanic hydrothermal system were estimated based on mineralogical analysis of eruptive products of the 1926 and the 4.7-3.3ka eruptions at Tokachidake volcano, Japan. The deposit of the 1926 eruption can be divided into three layers according to volcanic phenomena; the lower debris avalanche deposit, the middle hydrothermal surge deposit and the upper debris avalanche deposit. The deposits of the 4.7-3.3 ka eruption can be divided into four pyroclastic flow deposits layers; one from the 4.7 ka eruption and other three from the 3.3 ka eruption. Every deposit contains abundant hydrothermally-altered lithic fragments. Three layers of the 1926 eruption exclusively consist of altered lithic fragments without any juvenile fragments. Minerals identified in the bulk sample of the 1926 eruption deposit are cristobalite, smectite, sericite, kaolinite, alunite, gypsum and pyrite, and those in the deposits of the 4.7-3.3ka eruptions are cristbalite, tridymite, quartz, sericite, pyrophyllite, alunite, plagioclase and hyperthene. Mineral assemblages of individual fragments were also determined with combination of SEM-EDS and XRD. The 1926 eruption product is characterized by the coexistence of cristobalite, alunite and/or smectite in the fragments, whereas the 4.7-3.3 ka eruption product is characterized by the coexistence of pyrophyllite and quartz. The mineralogical contrast implies difference in hydrothermal condition between the 4.7-3.3 ka and the 1926 eruptions. The former eruptions were derived from hotter (>230 C) and deep (1-2 km) hydrothermal systems and the latter from a colder (<100 C) and shallow (near-surface) hydrothermal system, although both volcanic products are characterized by sulfuric acid fluid which is typical in hydrothermal systems at volcanic centres.

キーワード: 火山熱水系, 熱水変質岩片, 十勝岳火山, 1926 年噴火噴出物, 4700—3300 年前噴火火砕流堆積物
Keywords: sub-volcanic hydrothermal system, hydrothermally-altered lithic fragment, Tokachidake volcano, eruption products in 1926, pyoroclastic flow deposits in 4.7-3.3 ka

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焼岳南部地熱地域の地熱系
Resistivity structure of geothermal area at south area of Yakedake Volcano

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Resistivity structure of geothermal system at south area of Yakedake Volcano

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Some hot-springs and fumaroles are seen around the Yakedake Volcano. High temperature hot springs such as Nakanoyu and Shirahone hot springs are located at the south area of the Yakedake volcano, but the relations between the volcano and geothermal system have not been clarified yet. Geophysical studies concerning the structure of geothermal fluid reservoir and heat source of the hot springs have never been performed in this area.

Hokkaido University carried out a MT survey to clarify the subsurface structure at six sites between Sirahone hot spring and Sawando area in 2013 and indicated distribution of geothermal fluid reservoir beneath Shirahone hot springs and Sawando area (Yamaya et al., 2014). But they did not clarify the extent of geothermal fluid reservoir under these area. We installed two additional MT sites each at outside of the previous survey area in 2014 to investigate extension of these reservoirs.

We recorded MT signals for about 48 hours at each site, and obtained the apparent resistivity and phase at a frequency range of 0.03-100Hz. We applied the remote magnetic reference (Gamble et al., 1979) and manual data editing by MTEDITOR to remove local electromagnetic noises.

The magnetotelluric phase tensors (Caldwell et al., 2004) and induction vectors were calculated to verify structural dimensionality and to determine the 2D strike direction for the 2D inversion. According to the phase tensor ellipse and induction vector at the lower frequency range, the deeper layer have 2D structure and we decided that 2D strike direction is N60W in this area.

We performed two types of 2D inversion, which used the TM mode and TE+TM modes, respectively. We used the inversion code proposed by Ogawa and Uchida (1996), which minimized ABIC as convergent criterion in the iteration process. The ABIC criterion includes smoothness, least square mean error and static shift correction.

As a result, we indicate that geothermal fluid reservoir correspond with low resistivity is extending at directly under the Shirahone hot spring area, and it ranges in the limestone body. Dissolved limestone is origin of milky hot spring that characterizing the Shirahone hot spring. The low resistivity zone was also found at the depths of 500m down in the Sawando area. Although no geothermal manifestation is recognized at the surface of the Sawando area, but this low resistivity zone probably indicates a geothermal reservoir.

Furthermore, these two low resistivity structures corresponding each geothermal fluid reservoir join together at the depths of 2 km below. The columnar low resistivity zone extends to deep. Comparing the geology, the Sakaitouge fault runs through at the columnar low resistivity zone. The resistivity structure suggests that geothermal fluid ascends from deeper zone along the Sakaitouge fault. Based on this result, we can propose two possibilities of the heat source of geothermal fluid. One possibility is that hot volcanic fluid flows out from the Yakedake volcano along the fault. The other is that heating water is ascending along the fault from the hot rock area extending in the Japanese Northern Alps area.

キーワード: 地熱地域, 比抵抗構造, 焼岳
Keywords: Geothermal area, Resistivity structure, Yakedake

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中部九州火山地域周辺における表層電気伝導度分布（序報）
Conductivity distribution of the surface layer around volcanic area in central Kyushu

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中部九州には，別府から阿蘇にかけてドームを主体とする火山群や優勢な地熱活動域が東西に並んでいる．また，これらの地域には断層も数多く確認されている．火山活動と地熱活動の関係を考えると，マグマからの脱ガスが大きい場合には，周辺に地熱活動が発達し，火山噴火は非爆発的なドーム生成や水蒸気噴火，噴火未遂などになることが期待される．こうした視点から著者らは中部九州の火山周辺において表層電気伝導度分布調査を行ってきた．ここでは，それらの結果の概要を報告する．

阿蘇カルデラ：阿蘇カルデラの表層電気伝導度は大きく 2 つに大別される．カルデラ床である阿蘇谷・南郷谷は，100 μ S/cm 以上の高電気伝導度を示し，かつ比較的均質である．一方，中央火口丘群は低電気伝導度から高電気伝導度まで幅広い値をとる．多くの火口丘は 30 μ S/cm 以下の低電気伝導度であるが，中岳火口近傍や草千里，西部の吉岡，湯之谷，地獄，垂玉などの温泉地周辺では，300 μ S/cm 以上の高電気伝導度域となっている．また，中岳の北側山麓および南側山麓では高電気伝導度となっており，中岳の湯だまりから熱水が流下していることを示唆している．カルデラ床はほぼ全域で高電気伝導度を示すが，内牧温泉から三重塚にかけての領域で 300 μ S/cm 以上を示している．内牧ー三重塚の延長には中岳が位置しており，なんらかの構造があるのかもしれない．また，内牧温泉の高電気伝導度領域は西南西ー東北東方向に伸びる傾向があり，この線は温泉の並びや阿蘇カルデラ北部の地震活動の並びに一致する．こうした結果は，阿蘇カルデラにおいて，マグマから火山ガスがなんらかの構造線に支配されつつ発散されており，その脱ガス量が高電気伝導度領域の広さからかなり大きいことを示している．

九重火山群：九重火山群を構成する火山体は阿蘇の火口丘と同様に 30 μ S/cm 以下の低電気伝導度を示している．また，九重火山群の山麓には高電気伝導度領域が見られる．たとえば，大船山付近から七里田温泉を経て長湯温泉に延びる領域が比較的高い電気伝導度を示し，山田・他 (2005) の「九重火山群のマグマから供給された二酸化炭素が九重火山群南東山腹で涵養された地下水に付加されて南東方向に流下している」という主張と整合的である．硫黄山から長者原を経て北麓に延びる領域，大船山から北東麓の阿蘇野にいたる領域などでも九重火山群のマグマ起源の揮発性成分が地下水とともに流下して形成された可能性がある．このようなマグマからの脱ガスにより形成される高電気伝導度域とは別に構造線に規定されていると思われる高電気伝導度域も見られる．大分ー熊本構造線に沿う領域，由布院断層から野上川流域にいたる領域，由布院川西地区から大分川流域を経て下湯平，湯平温泉，山下池にいたる領域などで 50 μ S/cm 以上の高電気伝導度領域を示す．この領域は，崩平山ー万年山地溝北縁断層帯とほぼ一致する方向性を持っている．

鶴見・伽藍・由布地域：これらの火山群においても，前 2 者とほぼ同じ特徴が見られる．鶴見岳や由布岳山体は低電気伝導度を示し，山麓部に高電気伝導度域が広がっている．また，伽藍岳の塚原温泉ー鍋山ー明礬温泉ー鉄輪温泉にいたる東西の高電気伝導度領域は，断層に規定されている．

以上のことから，中部九州においては，マグマに含まれている揮発性成分が脱ガスして周辺に拡散することによって生じる高電気伝導度域に加えて，断層などの構造線に規定されて揮発性成分が上昇している高電気伝導度領域が存在することが明らかとなった．この領域で放出される揮発性成分は，マグマからの脱ガスではなく，スラブ脱水流体である可能性もあり，今後，より詳しい調査が必要である．

キーワード: 活火山, 電気伝導度, 中部九州, 地熱活動
Keywords: Active volcano, Electrical conductivity, Central Kyushu, Geothermal activity