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Geological history reviews and geological aspects of shallow volcanic soil related to earthquake-induced landslide in Kumamoto 2016

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ABSTRACT

This paper aims to investigate geological conditions of shallow volcanic soil at the landslides effected area in Aso Volcanological Laboratory, Minamiaso Village, Kumamoto Prefecture, Japan that is caused by Kumamoto earthquake during April 14 to April 16, 2016. Earthquake-induced landslides occurred in Aso Volcanological Laboratory are characterized by long flows covering large areas with inclination of about 11^{o}. The slope was composed dominantly of volcanic ash layers those have been altered to soil layers with different colours and engineering properties. Geological aspect of shallow soil profile includes volcanic lava and ash-fall tephra those are younger than 31ka lies on the old Takanoobane volcanic deposit (51ka). The Kusasenrigahama pumice-derived soil has been considered as the main source of the landslide.

1. Introduction

A strong earthquake may trigger simultaneously a number of landslides on mountainous areas. Generally, earthquake-induced landslides are governed by earthquake parameters such as earthquake intensity, earthquake magnitude and location of earthquake epicenter. However, earthquake is considerably a short-term event that determines time of failure occurrence. On the other hand, geological soil conditions, morphology, and hydrology are factors identify whether a slope body has high susceptibility to slide. Somewhat a landslide on volcanic mountains can be triggered by small earthquakes. Those on volcanic soils are common characterized by large-scale failure on gentle slopes due to weak geological conditions (Chen et al., 2012). Therefore earthquake-induced landslide on the volcanic zone, the geological history plays a remarkable role.

During periods of April 14 to April 16, 2016 a series of earthquakes with the magnitude of 6.5-7 occurred in Kumamoto Prefecture, Japan at epicenters depth of about 10-11 km (Hazarika et al., 2016). Most of earthquake-induced damages appeared along the Futagawa and Hinagu fault. After the earthquake, a number of shallow gravitational landslides occurred on Minamiaso Village and surroundings within the Aso Caldera area. Those landslides swept away many houses at sites near Aso Volcanological Laboratory and Hinotori hot spring; caused collapses of Aso Bridge and a check dam in Nagano area (Hazarika et al., 2016). Combination between seismic events and geological structures is considerable factors that effecting landslides in the area. Kumamoto area locates at the western part of Aso caldera, central Kyushu Island, Japan and has a humid subtropical climate. The area composes of Aso pyroclastic flow deposits and cut by right-lateral strike-slip Futagawa and Hinagu faults. The Futagawa-Hinagu fault

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zone extends from Aso volcano to the Yatsushiro-sea (Hazarika, 2016). Aso caldera locates along the volcano chains within a rife zone running from Oita to Kumamoto extending to east-west direction (Aso Geopark). Volcanic activities of Aso volcano with 270 thousand year history has been distinguished between caldera-forming stage (>90ka) and post-caldera stage (<90ka) that has been formed a complex spatial distribution of the Aso central cones group as the present. Miyoshi et al. (2012) believed there have been three peaks of highly frequent new-growing volcanoes as: 50ka-40ka, 30ka-20ka and <10ka. Between 60ka to 50ka, volcanism was generated mainly in the southwestern part of the caldera while from 30ka until present volcanism concentrated on the northeastern and central parts of the caldera (Miyoshi et al., 2012). Tephra older than 30ka have diversified composition varying from mafic to silicic while the younger tephra have dominantly mafic composition (Takarada, 2013).

Geological of shallow soil in the landslide effected area has been reconstructed by stratigraphic relationship between lava flows and air-fall tephra layers. As promptly actions, field and experimental investigation was conducted in order to access the geological soil condition on the susceptibility of earthquake – induced landslide to occur. After visited many landslides locations, a site near Aso Volcanological Laboratory had been focused on. Field measurement of slope failure and exposed geological profiles have been carried out. Soil sample of each geological units has been taken at the landslide body. Facilities of Geotechnical Engineering Research Laboratory, Kyushu University were used to perform soil tests. In this paper, results of the investigation including geological aspects of the landslide area discussed. Furthermore, an overview of geological history of the Aso caldera is summarized. Only the post-caldera stage is discussed due to its relation to formation of shallow volcanic soils.

2. Outline of geological history

As the second largest volcano in Japan extending to 25km north-south and 18km east-west in diameter (Aso Geopark), the Aso Caldera locates in central Kyushu Island. Unique location of Aso caldera made it become one of the most dynamic volcanoes over the world. Aso caldera situates along the Oita-Kumamoto trending fault zone that induced right-lateral shear. It cut across the north-western part of the ring-shape caldera and divides it into 2 blocks: the north-northwest (15°E dip) and the south-southeast (25°NNE dip) (Newhall and Dzurisin, 1988). Main volcanic activities of Aso Caldera are emphasized of 2 stages: caldera-forming and post-caldera. In the caldera-forming stage (during 270ka to 90ka), the Aso Caldera has been created by 4 voluminous pyroclastic-flow eruptions (known as Aso-1, Aso-2, Aso-3 and Aso-4) (Aso Geopark).

The last caldera-forming eruption (i.e., Aso-4) was the Japan's largest in the past 100ka producing huge amount of volcanic ashes and pumice spreading throughout Japanese islands. The post-caldera stage has been initiated after 90ka and extruded various types of lava flows and fallout tephra layers. Those products has been ejected from a series of volcanic events inside the caldera and formed the central cones. Distinguishable 28 lava unites ejected during the post-caldera stage has been identified (Miyoshi et al., 2012). However, there are only 14 observable craters in the Aso Central cones (**Fig. 1**). It indicates historically complex volcanism including activities of ancient volcanoes and new-growing of young volcanoes which had been buried those ancient ones. Indeed, almost volcanoes those were active in early post-caldera stage formed from 90ka to 50ka has been buried (Miyoshi et al., 2012). Currently, only Nakadake volcano remains active and has erupted cycle of every 10 years (Aso Geopark).

Fig. 1. Illustrated distribution of Aso central cones group.

Current ring-shape of the Aso central cones have been formed during four phases of spatial development (**Fig. 2**):

- Phase 1: Formation of the south and south-western zones (**Fig. 2a**)

The south and south-western zones of the Aso central cones have been raised soon after the caldera-forming stage finished (after Aso-4). Almost all early post-caldera cones those have the age between 90ka-50ka have been situated in these zones including Matsuno lava (82ka), Ayugaerinotaki lava (80ka), Yoshioka lava (71ka), Nakahono lava (68ka), Tochinoki (64ka), Nagano (60ka), Yomineyama (57ka), Okamadoyama (56ka), Tateno (54ka) and Takanoobane (51ka) (Miyoshi et al., 2012). Those units have been composed of basaltic lava, basaltic pyroclastic rocks and andesite lava flows (Geological Society of Japan). Lately, most of those have been completely buried or partial overlaid by younger deposits. Only 2 exposed craters are Takanoobane volcano and Okamadoyama volcano. Both those cones are dissected andesite stratovolcanoes (Geological Society of Japan).

- Phase 2: Formation of the east, south-eastern and north-eastern zones (**Fig. 2b**)

Beginning of the east zone has been enabled by eruption of Washigamine volcano (>50ka, Miyoshi et al., 2012). Lately, it has been followed by eruptions of Maruyama volcano (43ka) and Hakusui volcano (36ka) (Miyoshi et al., 2012). While Maruyama volcano is a parasitic volcano consisting of basaltic welded pyroclastic rocks, Hakusui volcano consists of mostly pyroxene-dacite lava flows with little pumice fall and andesitic lava (Geological Society of Japan). Hakusui volcano has been buried largely by lava from Naraodake volcano (22ka) and Nakadake volcano. Both those volcanoes are stratovolcanoes consisting of basal and basaltic andesite (Geological Society of Japan). As for Nakadake volcano, the first voluminous eruption (Nak-1) occurred at around 20ka and followed by two voluminous eruptions (Nak-2 and Nak-3) at around 6ka and 1.5ka, respectively (Miyoshi et al., 2012). Subsequently, the volcano has generated frequently until the present with erupted cycling with every 10 years. The old Nakadake lava (Nak-1) has been composed of pyroclastic rocks, lava flows and dike. It overlaid nearly all Hakasui volcano and cover a large area extending from the north-eastern to the south eastern. The young Nakadake cones (Nak-2 and Nak-3) composed by layered volcanic ashes, lava flows, tuff and welded tuff breccia (Geological Society of Japan). In addition, air-fall ash from Kikai-Akahoya tephra (7.3 ka) exists between the Nak-1 and Nak-2 lavas.

- Phase 3: Formation of the central zone (**Fig. 2c**)

Generation of the west and central zones has been took place during only six thousand year's duration between 32ka to 26ka with high erupted intensity of Komatateyama volcano (32ka), Eboshidake volcano (32ka), Kusasenrigahama (31ka), Sawatsuno (27ka) and Akase (26ka) (Miyoshi et al., 2012). Both the Komatateyama volcano and Eboshidake volcano are dissected andesite stratovolcanoes composed of coarse-grained pyroclsstic rocks and lava flows (Geological Society of Japan). The Eboshidake cone situates at the central zone, but its lava flows extended to the west-southern direction and overlaid partly the Yoshioka and Tochinoki lava. After that, the central zone has been filled up largely by pumice fall deposit from a voluminous eruption of Kusasenrigahama volcano. Kusasenrigahama volcano is a large pumice cone with double craters of 0.5km and 1km diameters (Geological Society of Japan). According to the Geological Society of Japan, the Kusasenrigahama pumice fall is characterized by orange color and underlies along with ash fall of Aira-Tanzawa tephra (29ka). The orange pumice layer has been distributed widely in Aso area and surroundings, appeared as an alternately geological layer with the thickness varying from very thin to thick. On the other hand, the west zone has been covered by a black dacite lava and basaltic lava produced by Sawatsuno volcano and Akase volcanos, respectively. Sandwiched between Aira Tanzawa tephra (29ka) and Kikai Akahoya tephra (7.3ka), the pyroxence rhyolite lava covered a south-western area, the size of which was only 1km long and approximately 200m wide (Masuda et al., 2004).

- Phase 4: Formation of the north zone (**Fig. 2d**)

According to Miyoshi et al. (2012), formation of the north zone has been begun since 4.9ka when Janoo volcano erupted. However, until 4.1ka-3.3ka when large-scale basaltic eruptions of Akamizu volcano (4.1ka), Kishimadake volcano (4ka), Ojodake (3.6ka) and Komezuka (3.3ka) took place, the ring-shape of Aso central cone has been completed as the view at the present.

Formation of the Aso central cone has been gone through 90 thousand years with uncountable number of eruptions of old and young volcanoes. All of those has been created a volcanic wonder with a colourful historical image. **Fig. 3** shows completed geological map of the Aso central cones that has been adapted based on the Aso volcano geological map established by the Geological Society of Japan (1985). It represents a very complex stratigraphy with alternated tephra layers including andesite, basaltic, ash-fall and pumice-fall deposits. Along with main lava deposits ejected from 28 volcanoes, there are 15 important pumice-fall deposits as: Nojiri pumice (NjP, 89ka-68ka), Ogashiwa pumice (OgP, 89ka-68ka), Yamasaki pumice 5 to 1 (YmP5-YmP1, 67ka), Sasakura pumice 2 to 1 (SsP2-SsP1, 67k-64ka),

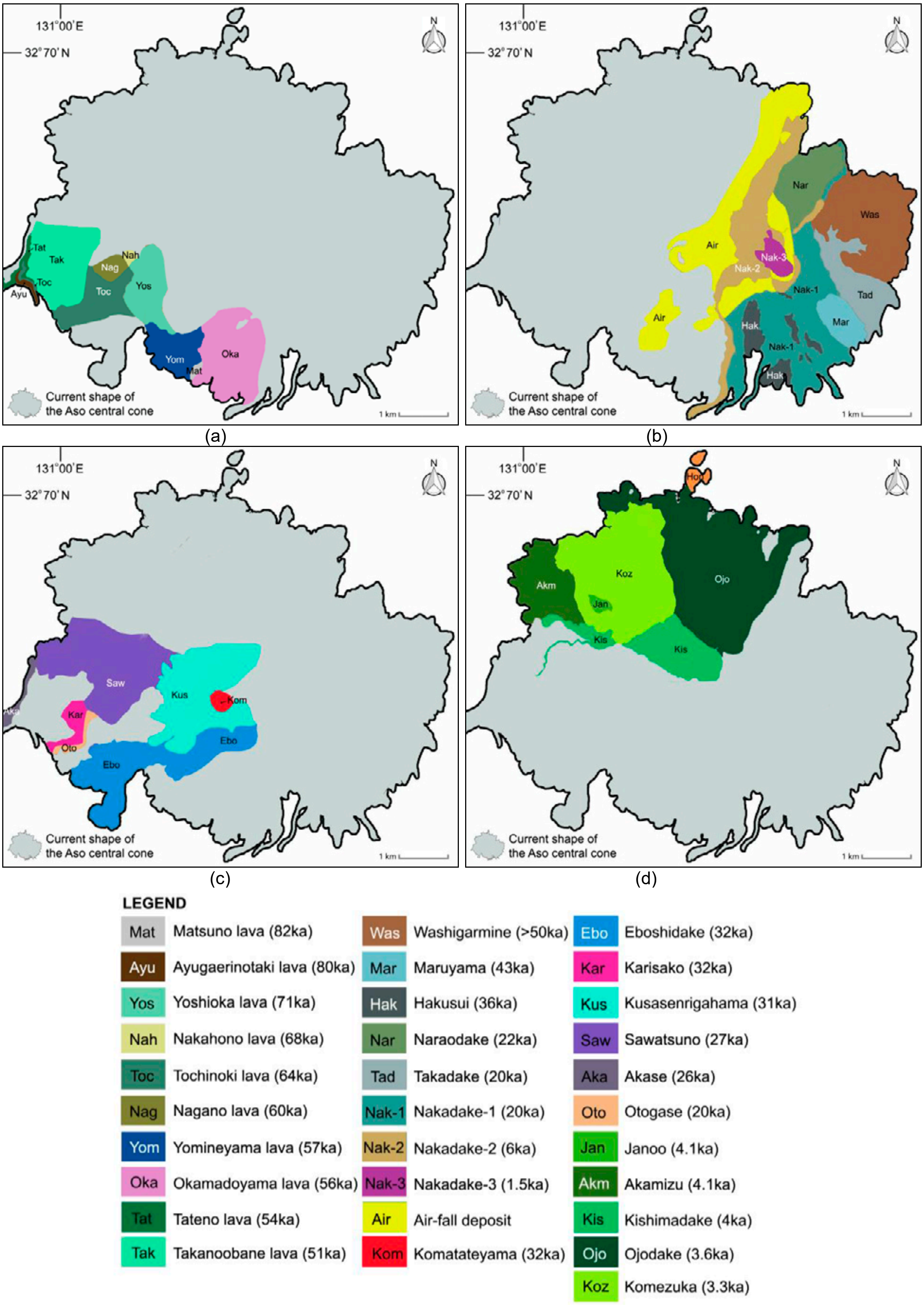


Fig. 2. Spatial development of the Aso Central Cones (a) the south and south-western zones (b) the east, south-eastern and north-eastern zones (c) the central zone (d) the north zone (After the Geological Society of Japan, 1985; Miyoshi et al., 2012; Takarada et al., 2013).

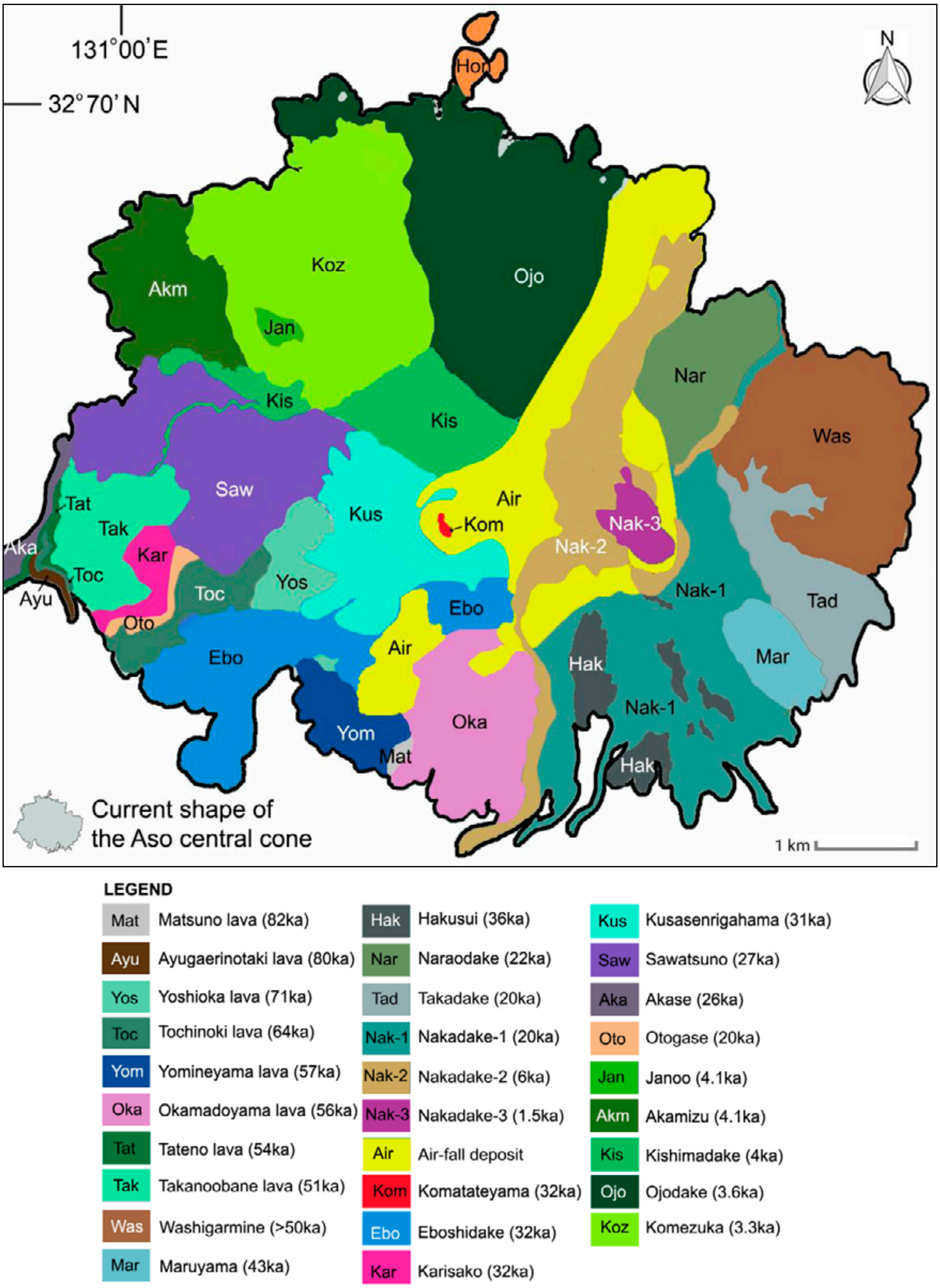


Fig. 3. Geological map of the Aso central cones. (Redeveloped from the Aso volcano geological map established by the Geological Society of Japan, 1985. https://gbank.gsj.jp/volcano/Act_Vol/aso/map/eng/volcmap04e.html#).

Aso central cone pumice 6 to 3 (ACP6-ACP3, 60ka-55ka), Kusasenrigahama pumice (Kpfa, 31ka) and Aso central cone pumice 1 (ACP1, 4.1ka) (Takarada et al., 2013). The youngest pumice-fall layer is Aso central cone pumice 1 that cover almost ground surface of the Aso caldera. It has erupted from an unknown vent in the north-western part at approximately 4.1ka (Takarada et al., 2013). Miyabuchi (2017), however, reported that the Holocene ACP1 has been produced from a post-eruption of Janoo volcano.

3. Investigation results

3.1 Characteristic of landslide in the Aso Volcanological Laboratory (京大火山研究所)

Minamiaso Villgae is located on Aso Mountain which has elevation from between 300m to more than 800m (**Fig. 4**). The slope inclination ranges from very gentle to steep (i.e., 4.1° to 32.6°).

After the earthquakes, a large earth slide occurred at a site near Aso Volcanological Laboratory (**Fig. 5)** and covered the area of 84.4 hectares causing the ruin of 4 houses, highly damage of 8 houses and local infrastructure highly damage (**Fig. 6** and **Fig. 7**). According to the Ministry of Land, Infrastructure, Transport and Tourism, a total of 9 people were killed including a 60s couple in Tateno district, 5 people in Takanodai housing complex and a couple who were on vacation in Hinotori hot spring. The slope inclination is approximately 11.3°. The Aso Volcanological Laboratory locates on the top of a hill that lies between elevations of approximately 480m and 570m above the sea level. The landslide crown locates at elevation of approximately 550m and 135m-distance from the Aso Volcanological Laboratory. The main scrap of the landslide is approximately 9m thick. The shape of the landslide body was very unique. Downward earth flows extended to the north-western, south-western and southern directions. All those flows' toes situated along a 255m-diameter arc that has the center locating right at the landslide scarp.

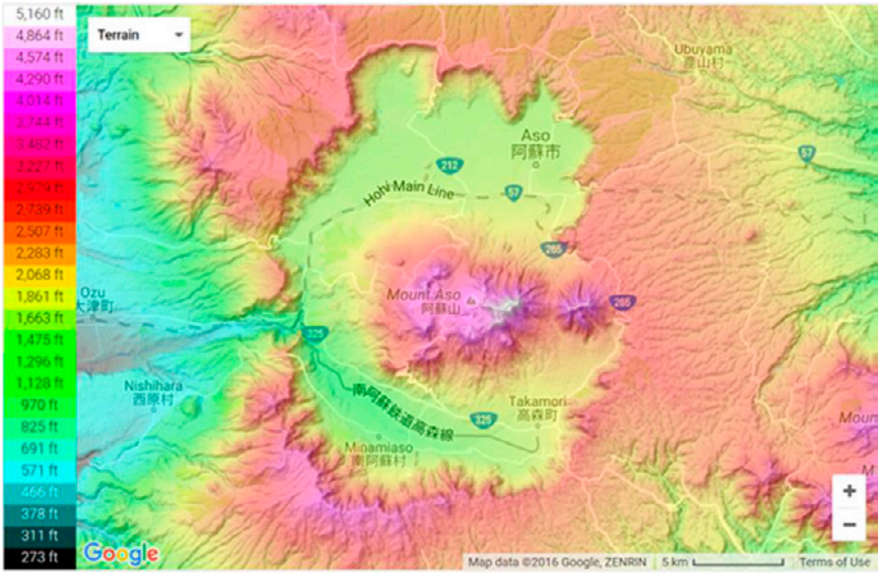


Fig. 4. Elevation map of Aso Mountain and surroundings (Source: Google Map).

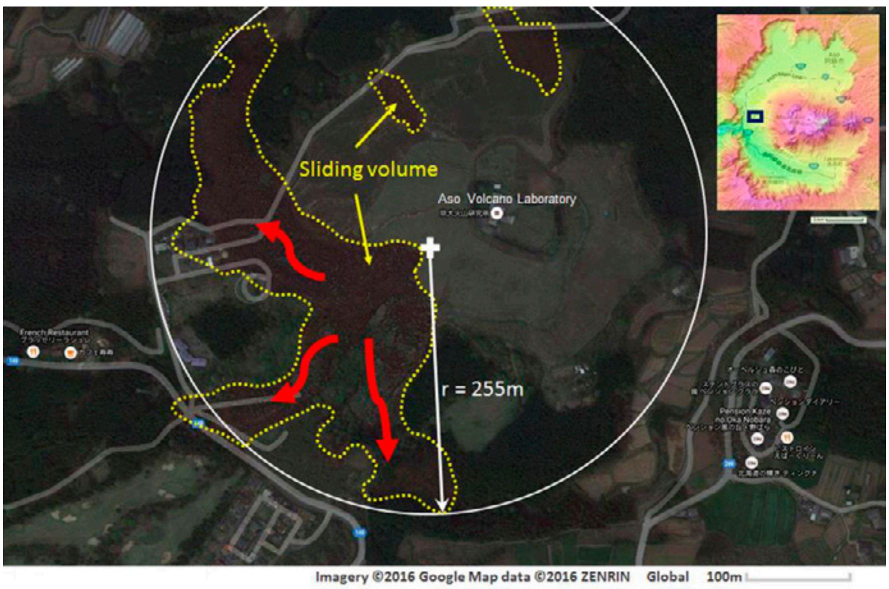
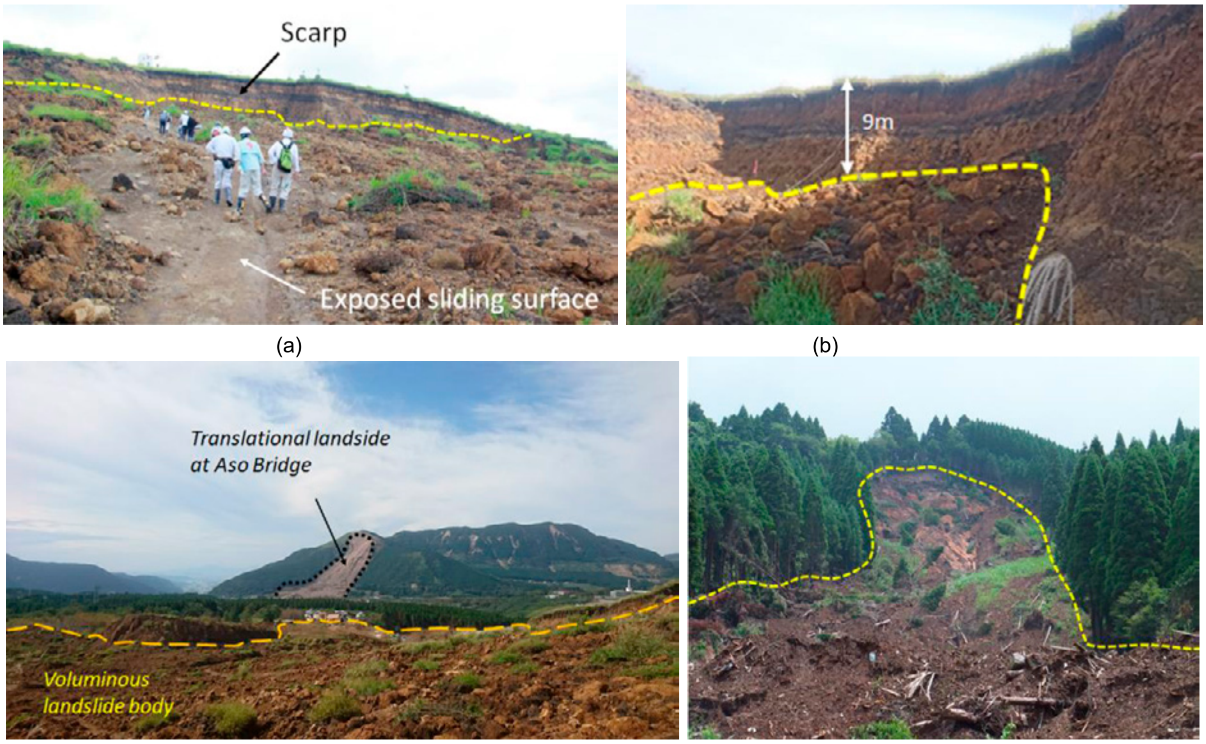


Fig. 5. Location and geometry of the landslide near Aso Volcanological Laboratory (developed base on Google Map).



(a) (b)

(c) (d)

Fig. 6. Earthquake-induced landslide near Aso Volcanological Laboratory. (a) from the toe (b)at the scrap (c) panorama view of the landslide body (another translational landslide which affected Aso Bridge could be seen from distances) (d) giant rotational landslide at Hinotori hot spring.

(a) (b)

Fig. 7. Damages produced by the landslide near Aso Volcanological Laboratory (a) damaged road (b) completely destroyed houses.

The landslide material was a mixture of volcanic deposit, ash-fall and pumice-derived soils those have age younger than 31ka. The exposed slip surface lies on the Takanoobane volcanic deposit. Somewhat the Kusasenrigahama pumice-derived soil floats above the slip surface. Scattered Kusasenrigahama pumice-derived soil has remarkable characteristics with fresh orange to yellow color, light weight, porous and very crumbly (**Fig. 8**). Another giant landslide occurred at the Hinotori hot spring (**Fig. 6d**) where locates not so far from the Aso Volcanological Laboratory. The soil has been found with very high water content and low plasticity. The landslide at Hinotori hot spring is characterized by long earth flows with occurrence of exposed slip surface within the pre-Takanoobane tephra.

Fig. 8. Kusasenrigahama pumice.

It indicates different mechanism of landslides in between Aso Volcanological Laboratory and Hinotori hot spring.

3.2 Geological aspects

From the preliminary investigation, a complicated geological condition had been discovered. Relatively similar geological profiles has been found between the Aso Volcanological Laboratory site and the Hinotori hot spring site. Six different soil profiles can be distinguished by colours from the soil surface to the slip surface (**Fig. 9, Fig. 10**). Among them the Kusasenrigahama pumice soil layer (fresh orange colour) was considered as problematic layer due to occurrence of slip surface at the bottom of this layer. No ground level was found in the preliminary investigation.

- ACP (Aso Central Cone Pumice): this layer includes Aso central cone of tephra and pumice is generated from age of 7.3ka up to now and characterized by light brown colour. It is visible to see the organic gap of 10 thousand years occurred in this soil layer.
- K-Ah: A thin layer of Kikai Akahoya ash has age of 7.3ka. The soil layer has permanent thickness of 20cm and characterized by dark brown colour.
- OtP (Otogase lava pumice): Between about 29 ka to 7.3 ka, Otogase lava pumice of Aso Volcano took place generating a thick layer of light brown soil profile. This layer contains high weather rhyolitic deposit with fragment from very tiny to 1mm in width providing occupied spaces of water (in the Aso Volcanological Laboratory site).

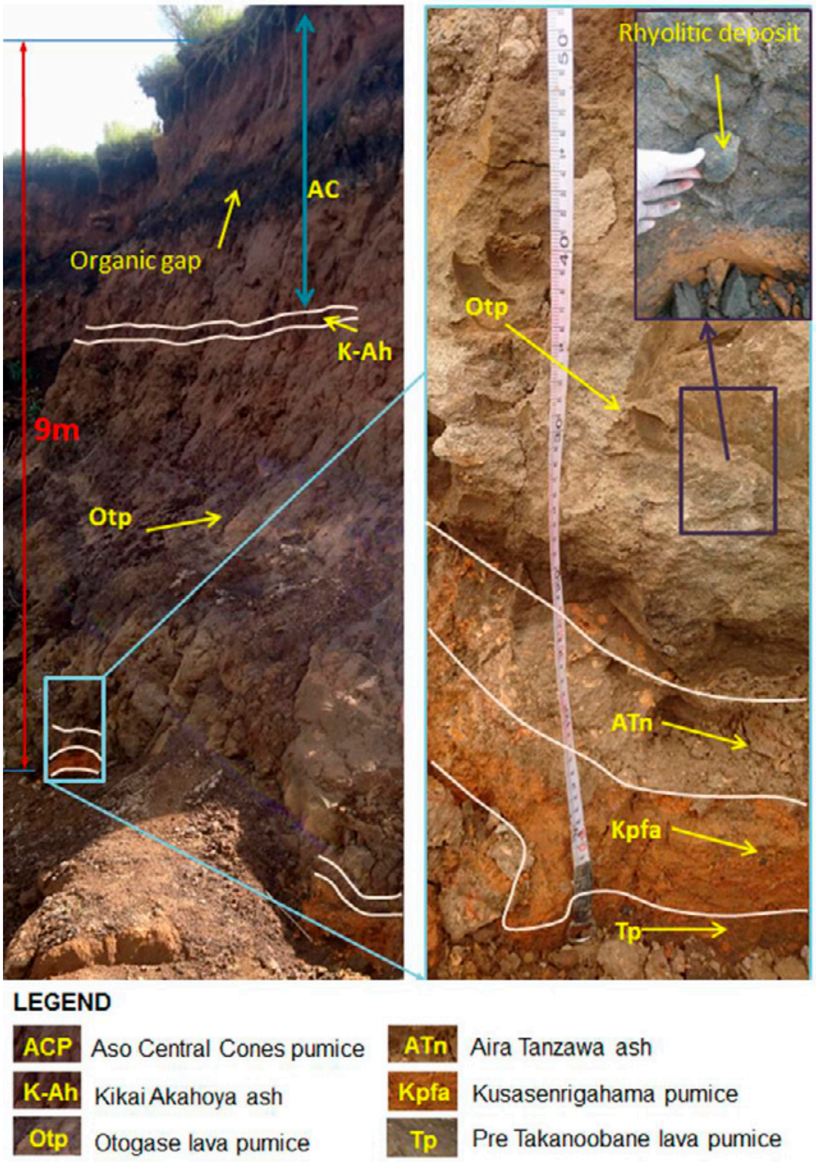


Fig. 9. Geological profile on the site of Aso Volcanological Laboratory.

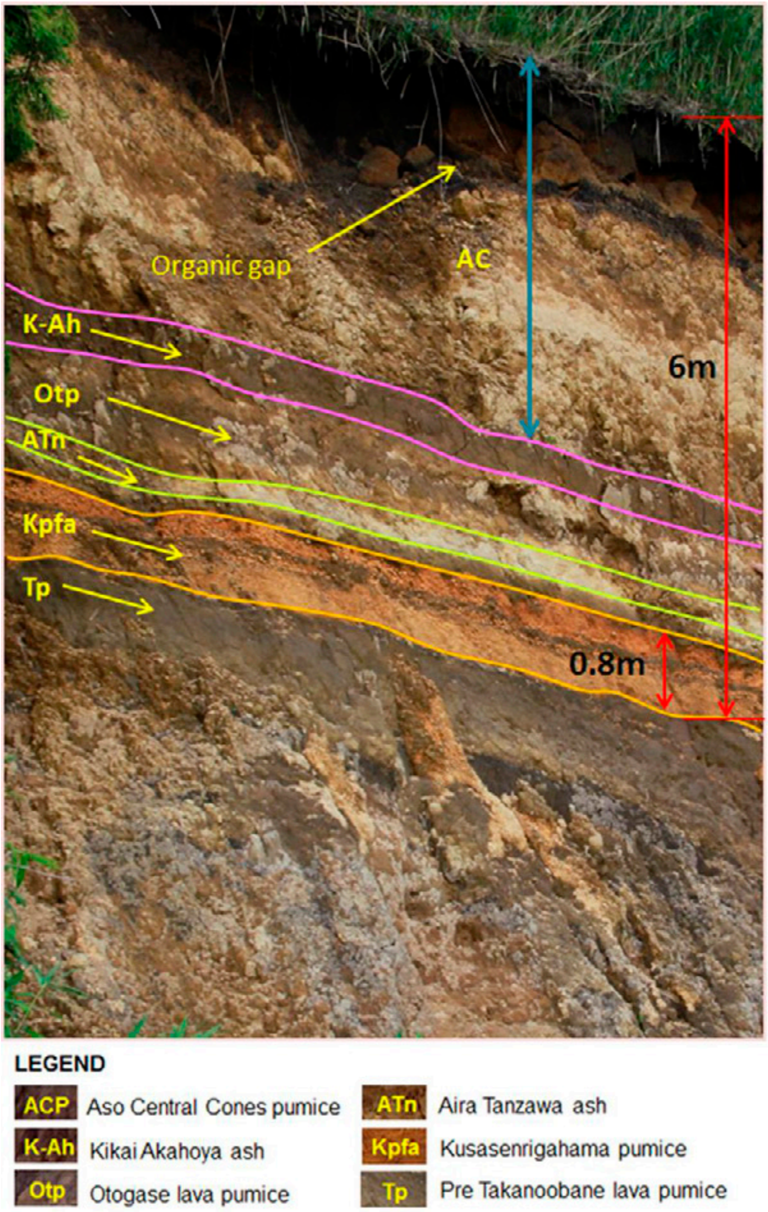


Fig. 10. Geological profile on the site of Hinotori hot spring.

- ATn (Aira Tanzawa ash): a thin Aira Tanzawa ash-fall deposit origins from Aira volcano's eruption that took place approximately 29ka. The layer has thickness varying from 12cm -20cm.
- Kpfa: this Kusasenrigahama pumice has age of about 31ka and remarked by fresh orange colour. This soil layer contains huge volume of water due to the porous structure. The layer has thickness varying from 8cm -20cm in Aso Volcanological Laboratory Site and 80cm in Hinotori hot spring site.
- Tp (Pre Takanoobane lava pumice): The Takanoobane rhyolite lava and tepra of Aso Volcano distributed in age of 51±5ka. This soil profile is characterized by blackish colour.

Based on **Fig. 4** and **Fig. 5,** there is a minor structural differ between the Aso Volcanological Laboratory Site and Hinotori hot spring site. At the Hinotori hot spring site, the Otogase lava pumice layer (Otp) has the thin thickness of only 80cm and lack of rhyolitic deposit. But this layer is 5m thick in the Aso volcanological Laboratory Site and has rhyolitic deposit up to 50cm thick. The thickness differ of soil Otp indicates that between 29-7.3ka strong soil erosion and mass wasting processes had taken place in the Hinotori hot spring site. The thickness of Kusasenrigahama pumice layer in the Hinotori hot spring site (80cm) is greater than that in the Aso Volcanological Laboratory site (8-20cm).

3.3 Soil properties

Soil sample of 7 distingue shallow geological units has been taken and brought to index and engineering properties testing. Corresponding, grain size analysis has been performed by using sieve and hydrometer following the Standard Test Method for Particle-Size Analysis of Soils (ASTM D 422), Atterberg limits test following the Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils (ASTM D 4318). Soil friction angle and cohesion has been conducted by direct shear test. **Table 1** shows index and engineering properties of soil samples are shown in **table 1**. Based on the results, almost all soil samples have fine-grain fraction more than coarse-grain fraction (i.e., fine contents are greater than 50%). Soil samples have high water content of 73%-152% that may because it had heavy rains just a day before when soil samples were taken. High water content of the soil samples near ground surface (i.e., ACP soil samples) may come from infiltration. **Fig. 11** shows a significant change on soil properties between Kusasenrigahama pumice-derived soil layer and other soil layers as well as between Kusasenrigahama soil and Takanoobane soil. The Takanoobane soil sample shows better properties among the soil samples while the Kusasenrigahama soil sample shows the weakest. Most of soil samples has specific gravity, void ratio, liquid limit and plastic limit varying from 2.48-2.59, 2.43-2.68, 71-98 and 37-77, respectively. Those properties of the Kusasenrigahama soil sample are, however, unique among the soil samples. It has with high water content of 152%, low specific gravity of 2.32, high void ratio of 3.67 and high Atterberg limits of LL-121% and PL-93%. The layer of Kusasenrigahama pumice-derived soil, then, becomes a weak layer in the geological profile of sliding slope. It indicates existence of a potential slip plane lies on the discontinuity between Kusasenrigahama soil layer and Takanoobane soil layer. Consequently, the slope would be easy to fail with triggers.

Table 1. Physical properties of the soil samples.

Soil properties		ACP	ACP-Blackish	K-Ah	Otp	Atn	Kpfa	Tp
Sand	%	41.27	46.39	-	43.05	41.77	37.86	38.98
Silt	%	28.97	20.77	-	32.88	22.37	28.63	19.04
Clay	%	29.76	31.83	-	21.07	35.87	33.51	41.61
Water content (%)	w	127.57	150.57	-	94.75	89.39	151.62	73.31
Specific gravity	G_s	2.55	2.53	-	2.51	2.48	2.32	2.59
Density (g/cm3)	ρ	1.69	1.72	-	1.33	1.32	1.25	1.31
Dry density (g/m3)	ρ_d	0.74	0.69	-	0.68	0.7	0.5	0.76
Voil ratio	e	2.43	2.69	-	2.68	2.56	3.67	2.43
Porosity (%)	n	70.86	72.87	-	72.79	71.79	78.59	70.82
Liquid limit (%)	LL	94.67	98.21	-	78.73	70.98	120.53	59.39
Plastic limit (%)	PL	75.20	76.91	-	50.12	36.68	92.90	40.09
Plasticity index	PI	19.47	21.30		28.61	24.30	27.63	19.30
Friction angle	ϕ	31.29	-	-	-	-	-	-
Cohesion (Kg/cm^2)	c	0.13	-	-	-	-	-	-

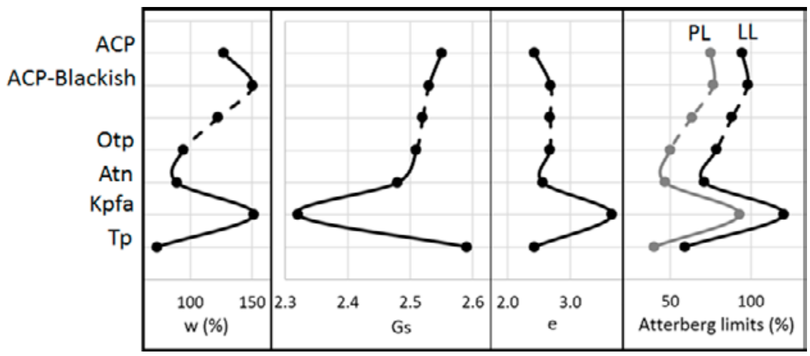


Fig. 11. Change of soil properties among soil layers.

3.4 Relationship of geological aspects and landslides

In Aso Volcanological Laboratory site, Kumamoto earthquake–induced landslide distribution was concentrated on the shallow volcanic tephra (i.e., ≤ 51ka) with very gentle inclination of about 11°. The surface deposits consisted of silt, sand and dominantly pumice tuffs. Total 7 lava pumice and ash-fall deposit layers exposed on the landslide body. Accumulated thickness of the layeres is about 9m. Among those geological layers, 3 key layers are Aira Tanzawa ash (ATn, Kusasenrigahama pumice (Kpfa) and Pre Takanoobane lava pumice (Tp). The weak Kpfa pumice layer alternated between hard ATn ash-fall layer and Tp rhyolite derived soil layer. Characteristic of this landslide indicates a strong relation between geological condition and landslides. The slip surface occurred between the Kusasenrigahama unit and the pre-Takanoobane unit. In the Aso Laboratory site, the landslide emphasized dependent relation to stratigraphic contacts between hard-older tephras (>51ka) and weak-younger tephra (<31ka). The geological gap generated different geo-mechanical properties as well as physically weathered fragment on soil structure. The thin Kusasenrigahama pumice-derived soil layer plays an important role in causing such a voluminous landslide after the earthquake. This layer had highly vesicular rough texture which contented very high water content, high Atterberg limits, high porosity while low specific gravity. Beneath the Kusasenrigahama unit is compacted dark silty soil derived from Takanoobane rhyolite lava which had low water content, low porosity and low Atterberg limits. Some parts in this unit remained rock texture with moderate to high weathering degree. Moreover, an Aira Tanzawa ash-fall unit overlie the Kusasenrigahama unit. The Aira Tanzawa unit was rhyolitic ash composed mainly bubble wall and/or plane type glasses (Machida, 2002) that had almost same properties with the Pre Takanoobane lava unit. Thus, the Kusasenrigahama soil layer generated a plane of weakness that might be the source of landslides. Shaking by earthquake not only created significant stresses but also break stable soil structures. As long as a slope is composed of poor contacts among geological units particularly where porous soil layer met less permeable soil, only small earthquake would be needed to lead to a landslide. This finding raise an alert to possibly landslides of the same type with sliding surface occurring on the Kpfa pumice layer can be initiated by future earthquake in central Kysuhu Island. This type of landslide may occur predictably on gentle slope not greater than the critical angle of 20° and consists of less permeable volcanic soils just beneath a weathered pumice (Chigira and Suzuki, 2016).

4. Conclusions

The main purpose of this paper aims to investigate geological conditions of shallow volcanic soil at the landslides effected area in Aso Volcanological Laboratory, Minamiaso Village, Kumamoto Prefecture, Japan that is caused by Kumamoto earthquake during April 14 to April 16, 2016. Earthquake-induced landslides occurred in Aso Volcanological Laboratory are characterized by long flows covering large areas with inclination of about 11°. The slope was composed dominantly of volcanic ash layers those have been altered to soil layers with different colours and engineering properties. Geological aspect of shallow soil profile includes volcanic lava and ash-fall tephra those are younger than 31ka lies on the old Takanoobane volcanic deposit (51ka). The Kusasenrigahama pumice-derived soil has been considered as the main source of the landslide.

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