Historical and pre-historical gigantic landslides in Tateyama Caldera and their mechanism of occurrence

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Abstract

This paper examines the mechanism and the genesis of a cluster of deep-seated and very large landslides in the Tateyama Caldera. There is a big depression, called the "Tateyama Caldera" in the Northern Japan Alps. This caldera, however, was not formed by volcanic activities but created by mass wasting processes which are still active as the site is littered with steep unstable slopes of historic and pre-historic, deep-seated and very large landslides. The basement rocks in the region consist mostly of granodiorite which is extensively sheared and locally hydrothermally altered as the caldera is located along one of the major active fault systems in central Japan. The higher elevations and rims of the caldera are underlain by middle to late Quaternary volcanic deposits. Active erosion of the unstable slopes and the possibility of deep-seated landslides pose serious future problems. To further complicate the situation, the bottom of the caldera is underlain by thick deposits of older landslides and related debris. Furthermore, recent studies revealed that the interior of the caldera is covered with older gigantic landslide deposits and/or extremely unstable slopes. This study examines past geologic events related to the causes of deep-seated landslides and the genesis of the caldera, then discusses the mechanism of deep-seated and very large landslides, and finally, warning against possible future failures of the unstable slopes surrounding the caldera, and suggests risk reduction.

This research is based on detailed reports by Nozaki and Kikukawa (2012,2014).

Keywords: Tateyama Caldera, deep-seated landslide, earthquake, alteration

1. Introduction

It had been believed that any types of deep-seated landslide were hardly triggered by earthquake among most of the specialists until the end of the last century. In Taiwan, however, many big or gigantic landslides such as the Tsaoling and the Chiu-fen-erh-shan landslides were triggered by the 1999 Chi-Chi earthquake (Chigira et al., 2003; Wang et al. 2003). This disastrous event was followed by some big earthquakes triggering large number of hazardous slope-movements including deep-seated landslides such as the cases of the 2004 Mid-Niigata Earthquake and the 2008 Iwate-Miyagi Nairiku Earthquake in Japan, and the 2008 Wenchuan Earthquake in China (JLS, 2007, 2012; JSEG, 2009). World-wide climate change, to make matters worse, has caused many serious natural disasters including deep-seated landslides due to the heavy rainfall in recent years, not only in Asian countries but also in many parts of the world.

In this context, the author has been making researches on the mechanism of deep-seated landslides which were deeply related to the occurrence of the Tateyama Caldera, T o y a m a -

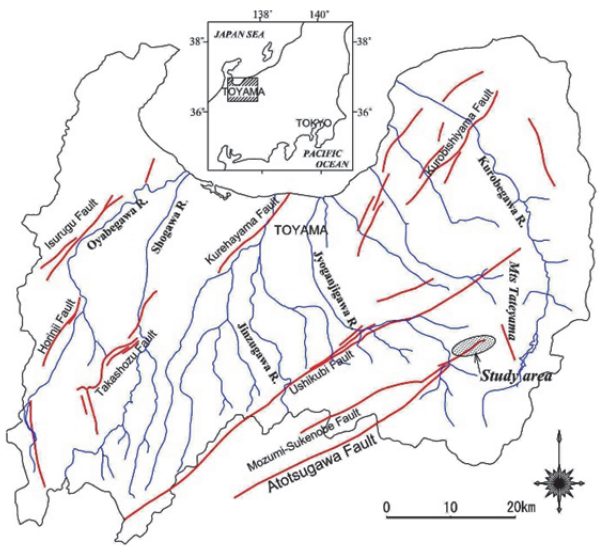


Fig.1 Location of the study area and distribution of active faults in Toyama-prefecture.

prefecture (Fig.1). There is a big oval depression at the southwestern side of Mts Tateyama in which the highest peak is

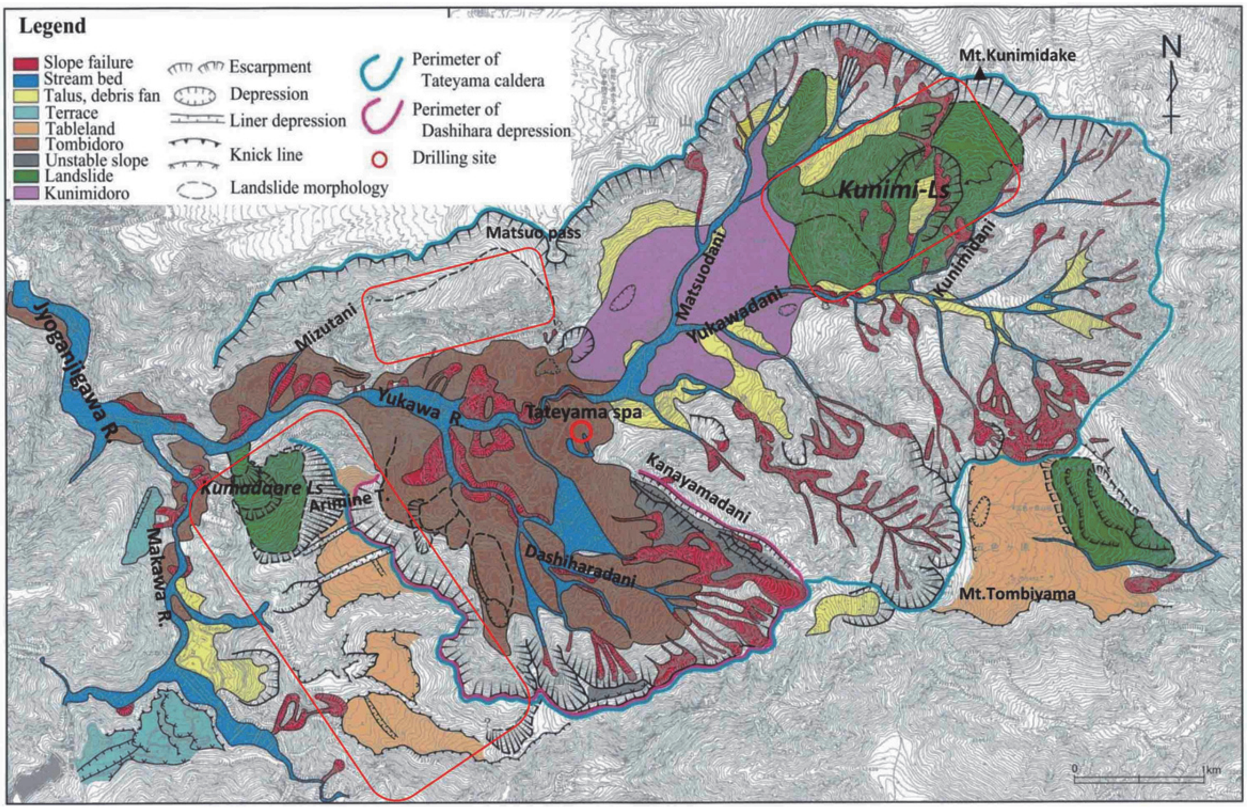


Fig.2 Topography of Tateyama Caldera and distribution of Tombi-doro, Kunimi-doro and Kunimi landslide (Nozaki & Kikukawa, 2012). Enclosed red lines indicate expected unstable slopes for future earthquakes.

3015m a.s.l. This depression so-called Tateyama Caldera, however, is not volcanic origin but erosion principally due to the active mass wasting including deep-seated landslides. The consequence of the researches is that those big or gigantic primary landslides were triggered by repeated activities of the Atotsugawa fault system and made an important role for the occurrence of the caldera.

In the early spring of 1858, the Hietsu Earthquake (Mj=7.3) hit the region of Toyama-prefecture and the northern part of Gifu-prefecture, by which a gigantic deep-seated slope failure so-called "Ootombi-kuzure" was triggered. Total volume of this slope failure had been estimated at $4.1\times10^8 m^3$ by Machida (1962). The estimation by recent researches, however, is a little more than $2.0\times10^8 m^3$ (Nozaki and Kikukawa, 2014). It depends on both of $1.0\times10^8 m^3$ by Fujii et al. (2011) at the area of Toyama plain (Jyoganjigawa alluvial fan) and $1.27\times10^8 m^3$ by Ouchi and Mizuyama (1989) at the source area including upper reaches of the Jyoganjigawa. More than half of the landslide debris run out from the limits of the caldera, and built up two landslide-dams at the confluence of the Yukawa and the Makawa (Fig.2). After that, the debris-flows which occurred with two events of landslide-dam failure, run down the main valley of the Jyoganjigawa within a few months. The debris-flow deposits so-called "Tombi-doro" extensively covered the Toyama plain and their toes reached to the Japan Sea. Many residents or farmers were killed by those debris flows, and the farm land was severely devastated for a long time. This event has been recorded as one of the three biggest historical slope-failures in Japan, and notwithstanding the longtime countermeasures against the erosion in the caldera, which have been executing by the central government for 90 years, the future threat of deep-seated slope-failures have not been removed yet at all.

2. Topographical and geological settings

Fig.2 shows the topography of the Tateyama Caldera and the distribution of late Quaternary clastics. The scale of this caldera depression is about 6.5km long to the ENE-WSW direction, 4.5km wide to the NNW-SSE direction and more than 500m deep surrounding by high escarpments. The main stream Yukawa in the caldera, which has its rise on the watershed of two river systems the Jyoganjigawa and the Kurobegawa, flows westward meeting with branch gorges from its both sides on the way to the confluence of Makawa. Although hundreds of scars due to the active slope failures are conspicuous in the caldera at present, two inner depressions should be given more attention from a view point of the occurrence of this big depression. One of them occupies its southwestern part showing the external form of parallelogram which is called “Dashihara” or “Dashihara depression” (Fig.3), and another one is located at the western side of Mt.Kunimidake showing a shape of big bowl (Fig.4 & Fig.5). The 1858 Ootombi-kuzure occurred at the southeastern part of the former one burying the old Dashihara with its thick debris of Tombi-doro, and made the floor of gentle relief. Buried under the Tombi-doro, the rock mass of “Dashihara landslide” has been found by drilling test. The latter depression used to have been believed as a remnant of volcanic crater because of the circular depression. It is now clarified, however, that the wide high-terrace so-called “Matsuo-daira” along both side of the Matsuo-dani, which is adjacent to the lower end of the circular depression, is composed of very thick debris of “Kunimi-doro” derived from this depression. Besides, it is clarified that another gentle slope “Outa-men” adjacent to the eastside of the circular depression was formed by the pre-historical rockslide “Kumini landslide” (Nozaki & Kikukawa, 2012).

Fig.3 Aerial photograph of Dashihara depression overlooking from the north (Photograph by Takashi Inokuchi)

Fig.4 Whole view of Tateyama Caldera. Circular depression of foreground is the source area of Kunimi-doro. Dashihara depression can be seen on the right. (Photograph by Takashi Inokuchi)

Basement rocks of the caldera mainly consist of Mesozoic granodiorite. They are extensively affected by the past hydrothermal alteration especially along the active fault “Yukawadani fault”, and thickly covered with Tombi-doro, Kunimi-doro and other landslide debris or debris-flow deposits at the lower portion of the caldera. On the other hand, thick Yukawadani-volcanic-rocks of the stage 1a occupy the central part of the caldera of which the lower formation looks like a sort of “green tuff”, and rocks of older 3 stages (1a-3) of the Tateyama volcano are generally distributed at the higher portion as shown in Fig.6. In particular, beyond the northern limits of the caldera the extensive gentle slope so-called “Midagahara” highland is composed of thick lava and pyroclastic flow deposits. Although the volcanic activity is dormant in the stage 4 at present, sulfurous fumarole (solfatara) activity is active at the northern part of the popular sightseeing spot “Murodo” where is close to the northeastern

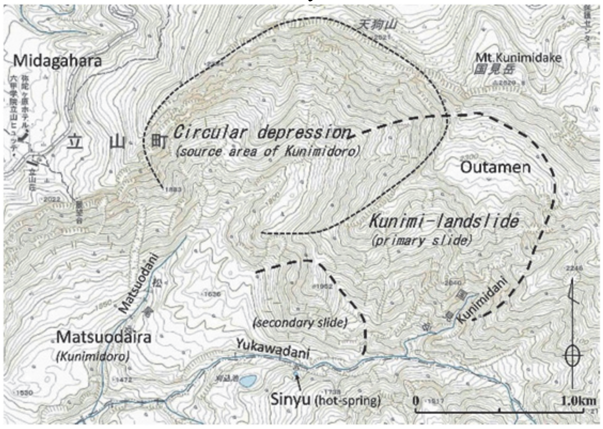


Fig.5 Topographical map of north side slope of Yukawa-dani (1/25000 map by GSI)

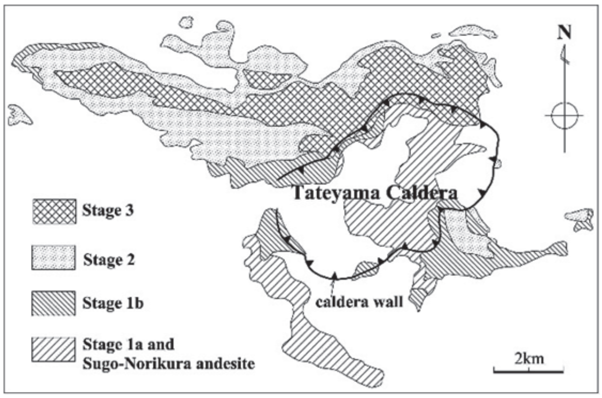


Fig.6 Classification for activity stages of Tateyama volcano and their distribution (Harayama et al., 2000)

limits of the caldera. Small fumarole activities or hot-springs can be seen even in the caldera (see Fig.10).

3. Geological events in the past

3.1 Deep-seated landslides

Fig.7 shows the distribution of Tombi-doro, Kunimi-doro, Kunimi landslide and the section line for the Dashihara landslide. With the occurrence of the 1858 Hietsu Earthquake, snow-capped two peaks of Mt.Ootombi and Mt.Kotombi, which had

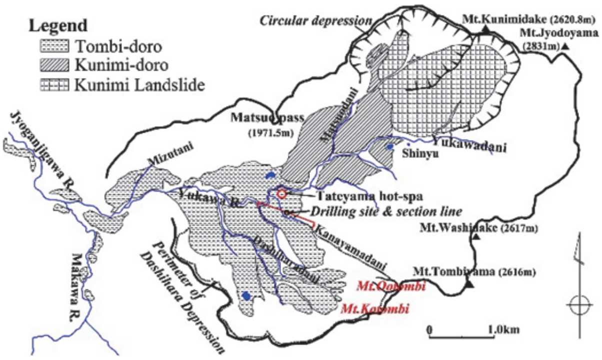
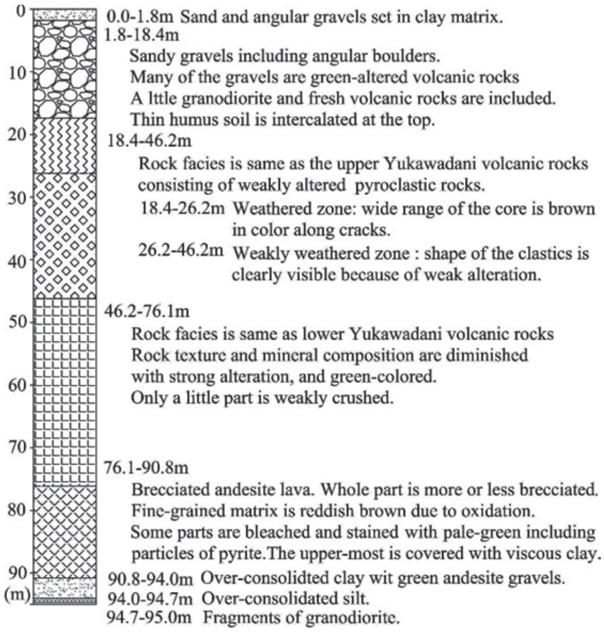


Fig.7 Distribution of Tombidoro, Kunimidoro, Kunimi landslide

been situated at the southeastern end of the Dashihara depression, run down as a gigantic rock avalanche (Ootombi-kuzure), by which about 30 people were killed at the old "Tateyama hot-spa" located at the northern end of Dashihara depression. The debris of rock avalanche dammed up making two lakes at the confluence of the Yukawa and the Makawa. Within a few months, these dams were successively broken down with overflowing water, and the debris flowed down the gorge of the Jyoganjigawa. As a result, enormous volume of debris-flow deposits extensively covered the farm land causing thousands of casualties including more than 140 loss of lives, which was called Tombi-doro by farmers after the disaster. About 100 years later in 1964, big slope failure of $2.68{\times}10^6 m^3$ took place at the head scarp of Ootombi-kuzure, but it was much smaller than the past one (see Fig.13).

Ouchi and Mizuyama (1989) had indicated the existence of landslide debris underlying the Tombi-doro. After that, 95m deep drilling test were carried out near the old Tateyama hot-spa in 2008. Fig.8 shows the geological column. The author examined the core by courtesy of MLIT Tateyama sabo office, and confirmed thick Yukawadani-volcanic-rocks. They are, however, evidently a part of old rockslide-mass overlain by Tombi-doro, because the drilling site was close to the granodiorite outcrop making high waterfall in the Kanayama-dani, and the intact Yukawadani-volcanic-rocks are originally distributed at much higher place (see Fig.14). Although the age of this landslide is unknown, it must not exceed 30ka as the same reason as the age of the Kunimi-doro described below. The author named it "Dashihara landslide", it might not have occurred with a single event though.

Harayama et al. (2000) had indicated the distribution of old debris deposits, which were extensively distributed around the confluence of Yukawa-dani and Matsuo-dani, and their origin with no detail mechanism. After that, the author



investigated its distribution, facies, chronology, and etc. As a result, it is concluded that this thick debris deposits Kunimi-doro, which is more than 100m deep including house-size boulders,

Fig.8 Geological column judged from the drilling test near the Tateyama hot-spa (Nozaki & Kikukawa, 2012)

was derived from the circular depression of the upper slope as a hazardous rock-avalanche. On the other hand, it is clear that the source area of the Kunimi-doro was the right wing of the Kunimi landslide of which the depth to the sliding surface might reach to 300m (see Fig.15).The age of these gigantic failure and rock slide is estimated around 30ka from the relation between the Kunimi-doro and the terrace deposits at the lower reaches of the Jyoganjigawa which are now covered with tephra AT of 26-29ka (Fujii &d Kaneko, 1999; Nozaki & Kikukawa, 2014). Besides, it is reported that the latest lava so-called "Tamadono-yogan" (30-60ka) erupted within the limits of eastern end of caldera and flowed northward down to the Murodo over the northeastern limits of the caldera (Shimizu et al., 1988; Harayama et al., 2000), and the old Makawa lake existed until 60ka at most (Kikukawa et al.,2005).

3.2 Active fault traversing the caldera

The 1858 Hietsu Earthquake was generated by the Atotsugawa fault, of which the outcrop has been found during the construction work in the Makawa gorge (see Fig.10) and designated as a natural monument by the government. Although the eastward extension of this fault is traceable to the western caldera-wall as one or two photo-lineaments, no farther evidence had been found in the caldera. The author, however, recently found the outcrop of active fault at the left bank of Yukawa-dani as shown in Fig.9, where is close to the confluence of Matsuo-dani. Although the ENE strike of this fault is parallel to the Atotsugawa fault, it does not likely array together on a single line. It might be conjugated with NNW faults as shown in Fig.10. It

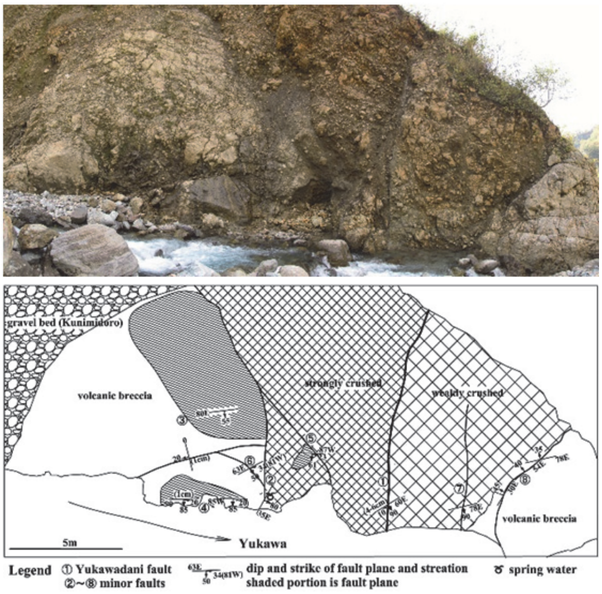


Fig.9 Outcrop of Yukawadani fault (Nozaki & Kikukawa, 2014)

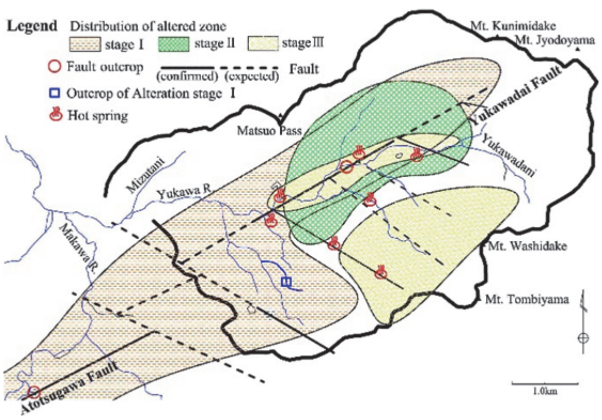
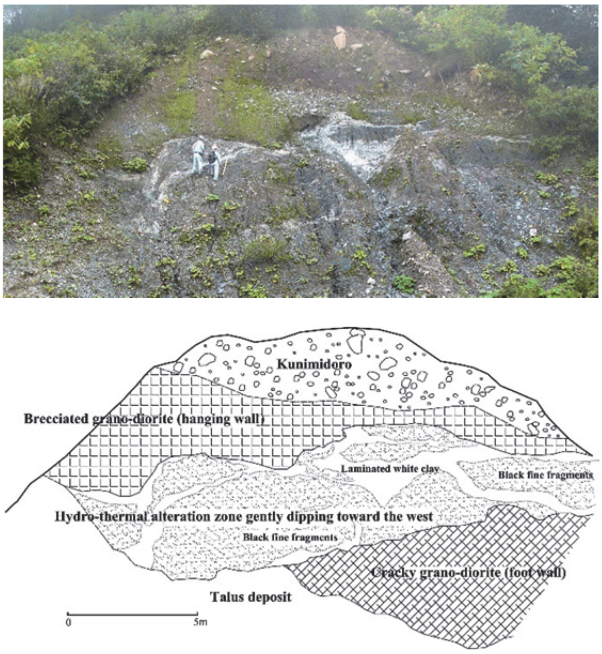


Fig.10 Distribution of active faults and three stages of alteration

has not, however, necessarily been able to identify as a part of the main fault. Hence Nozaki and Kikukawa (2014) named it "Yukawadani fault" as a local name.

3.3 Three stages of alteration

Nozaki and Kikukawa (2014) reported that three different types of alteration were recognized and partially overlapped each other in the caldera as shown in Fig.10. Fig.11 shows the outcrop of intensively deteriorated zone located at the right bank of the Dashihara-dani, which is fine-fragmented with thick kaolinite-rich clay veins due to the



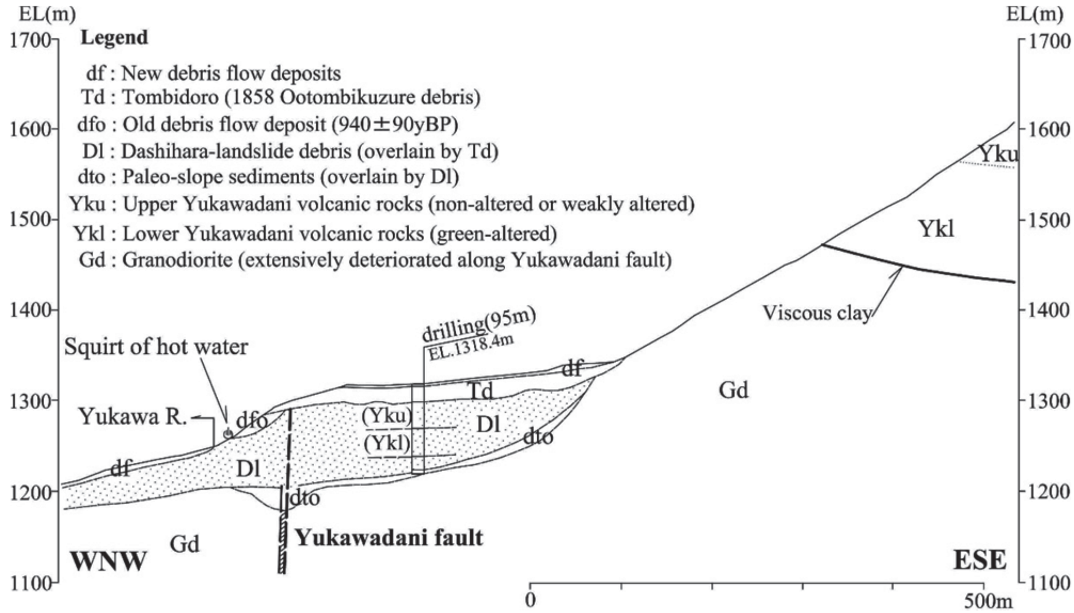
stage I hydrothermal alteration. This zone is gently tilted toward the center of the Dashihara depression. The alteration is extensively propagated and not well defined the limits, but very wide zone along the Yukawadani fault are characteristically deteriorated. The epoch of this alteration is unknown but much older than overlying volcanic rocks, because the affection is limited to the basement rocks.

The rock facies of stage II alteration looks like the Neogene "green tuff". It is reported, however, that the lower half

Fig.11 Outcrop of basement rock intensively fine-fragmented accompanying with white veins of kaolinite-rich clay (Nozaki & Kikukawa, 2012). Overlying gravel bed is Tombi-doro.

Fig.12 Outcrop of the boundary between granodiorite (left) and green-altered Yukawadani volcanic rocks (right)

of the Yukawadani volcanic rocks have been suffered by the hydrothermal alteration due to their own residual liquid in a circumstance of the ancient pond (Harayama et al., 2000). These green rocks are not so fragile, but the author found a continuous layer of viscous clay (chlorite and mixed layer of illite-smectite) between their base and the granodiorite in the Kanayama-dani as shown in Fig.12. Fig.14 shows the geological section from the Kanayama-dani to the Yukawa



through the drilling site.

The stage III alteration is due to the sulfurous fumarole (solfatara) activity, which is related to the stage 4 of volcanic activities. At the higher portion of the south side Yukawa-dani and alongside the lower banks of the Yukawa, the color of outcrops is yellowish or reddish brown with no or less vegetation, where the solfatara activity and the following oxidation must have occurred in unsaturated environment. The rocks are generally fragile associating with smectite-rich clay. This suggests that dissolution of rock-forming minerals was facilitated by sulfuric acid produced by oxidation of pyrite (Sato et al., 2013). Hence, many scars of slope failures can be seen on those fragile rock slopes.

4. Mechanism of past deep-seated landslides

4.1 Ootombi-kuzure

Fig.13 shows schematic section from the top of the pre-existed Mt.Ootombi through the center of Dashihara depression. The upper layer of Tombi-doro predominantly consists of andesite gravels including big boulders which were evidently derived from the upper portion of the caldera wall and/or the peripheral ridges, where the salfatara alteration (stage III) was dominant. The lower layer of Tombidoro, however, predominantly consists of granodiorite gravels including clayey parts at places. The author, therefore, believes that the sliding surface of this slope failure was substantially in the basement rock, and the primary cause of Ootombi-kuzure was hydrothermal alteration (stage I) in the basement rock with the

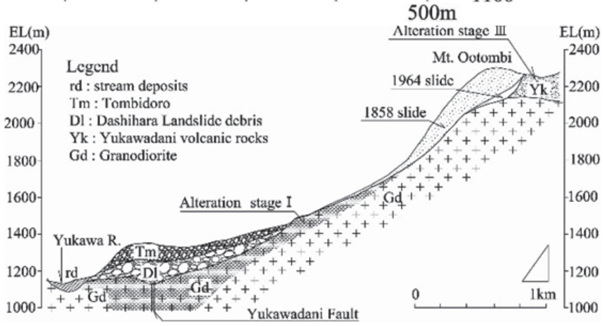


Fig.13 Schematic section of Ootombi-kuzure

aid of some potential sliding surfaces such as low angle discontinuities and/or clayey zones described above. The shallow solfatara alteration and the following oxidation must not have been main agents but only supplementary ones, and they have been the cause of 1964 slope failure or other identical ones on the higher portion of caldera walls.

4.2 Dashihara landslide

The actualities of Dashihara landslide are not well known, because the landslide mass and debris are completely covered with the Tombi-doro except for only a little at the confluence of Makawa and Dashihara-dani. Fig.8 and Fig.14 respectively show the geological column of drilling test and section in the proximity of the old Tateyama hot-spa. The formation of rock facies of the core from 18.4m - 90.8m shows those of the Yukawadani volcanic rocks, that is, the upper layer consists of weakly altered volcanic rocks, whereas the middle and lower layers consist of altered green rocks. The lower layer is cracky or partially fragmented and stained with reddish brown due to the oxidation in spite of the reduction zone filled with hydrothermal water, of which the temperature reaches to 150℃ at present, and underlain by non-oxidized soil. Of course the triggering cause cannot be clarified now, and even the primary cause has not been necessarily known yet. It is inferred, however, that this rock-slide mass slowly moved down the east wall of Dashihara depression taking advantage of the clay layer intercalated at the boundary between altered volcanic rocks and granodiorite as a potential sliding surface, because the slid-mass is not so fragmented except a part of the lower layer in spite of the relative height between the present position of intact volcanic rocks and landslide mass under the Tombi-doro.

Fig.14 Geological section of Dashihara landslide depending on drilling test near the old Tateyama spa (Nozaki & Kikukawa, 2012)

4.3 Kunimi landslide and Kunimi-doro

The estimated volume of Kunimi-doro is more than $2.0 \times 10^8 m^3$ at least, and the case of primary Kunimi landslide is roughly $7\text{-}8 \times 10^8 m^3$ including Kunimi-doro. The age of these events is not well-known, but it must not exceed 30ka so much as described above. Fig.15 shows the schematic geological section of the Kunimi landslide. Yukawadani-volcanic-rocks are gently tilted toward Yukawa-dani (Harayama et al. 2000), and there is high possibility of clay layer more or less between granodiorite and volcanic rocks, because of the same geological condition as the case of the Dashihara landslide. Hence, it is reasonably inferred that the boundary tilted toward the valley must have made a role of potential sliding surface, and this gigantic incipient landslide was triggered by the earthquake in the same manner as the Ootombi-kuzure, because it is too big to be triggered by any other agents in this deep depression. The rock avalanche of Kunimi-doro might have occurred almost simultaneously with its mother-slide, it might not have been a single event though. After that, some other minor failures must have been triggered by not only earthquakes but also heavy rainfalls and snow-melting as secondary ones of Kunimi landslide.

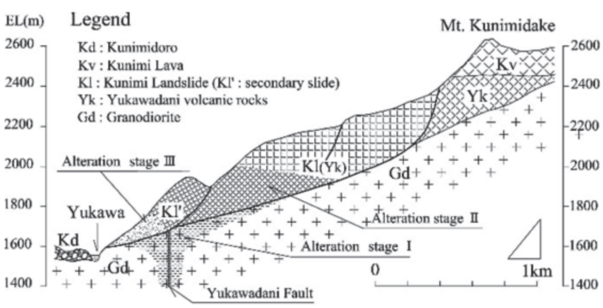


Fig.15 Schematic geological section of Kunimi-landslide

5. Forecast for future progress

In this paper, the mechanism of the historical and pre-historical deep-seated landslides were discussed, which have made a big role of building-up the present Tateyama caldera. On the basis of this study, the forecast for deep-seated landslides or the future progress of caldera is discussed here. Locations of unstable slope in the future are shown in Fig.2. Deep-seated slope failures like those scale of Tombi-doro and Kunimi-doro are too big to stop or completely avoid the disaster by our techniques in the near future. Hence, the author positively tried to predict the future events or the progress of the caldera for the purpose of the disaster-risk reduction, in particular, on the following three unstable slopes.

The highest provability is the lower slope of Kunimi-landslide in which the independent peak is located at the head of the secondary slide, and the upper ridge leading to Outa-men also looks unstable against future earthquakes (see Fig.5 & Fig.15), because of the tilted base of the Yukawadani-volcanic-rocks toward the gorge and the convex shape of the topography as indicated by many recent case-studies (JLS, 2012).

The second one is the independent E-W ridge divided by the col between its peak and Matsuo-pass. The geological condition has not been clarified yet, but most of this ridge consists of lava and pyroclastic flow units of stage 1b-3 (see Fig.6). Those are underlain by more or less altered granodiorite. Hence, it is inferred that this ridge must be unstable against future seismogenic activity (Mw>5.0). If the deep-seated slope failure takes place in the same way as

Ootombi-kuzure at this place, it will be much more dangerous for the residents at the lower reaches than the other cases, because the enormous volume of debris will directly hit the main valley building up a landslide-dam, and flow down with flood water as a result.

The third one is anywhere on the periphery of western marginal ridge of the caldera. Although the extent nor the scale of the potential failures cannot be specified at present, there are some old landslide scarps and linear depressions in this area. In fact, big failure of Mt.Kumadaore by the 1858 earthquake at the left bank of the Yukawa (see Fig.2) is recorded in old documents. Another reason of unstableness of this area is the intensive alteration in the granodiorite which have been confirmed at the chance of maintenance work for the Arimine tunnel, and the overlying lava of the volcanic stage 1b is making a role of water storage at present.

There are many other big and small unstable slopes in and around the caldera. For instance, at the vicinity of the western foot of Mt.Jyodoyama where is close to the Murodo, some precursors of primary landslide are indicated by Nozaki (2014). They must contribute to the demolition of the caldera and future disasters, therefore more comprehensive geological investigations are strongly demanded as a view point of disaster-risk reduction in and around the Tateyama caldera.

6. Conclusions

The author started the geological survey for the analysis of mechanism of the Ootombi-kuzure and Tombi-doro several years ago. After that, his interest extended to the pre-historical Kunimi-doro distributed at the upper reaches of Yukawa, and then reached to the Kunimi landslide located at the higher portion of the north bank of Yukawa-dani, and finally to the Dashihara landslide overlain by Tombi-doro. Conclusions resulted from these investigations are as follows.

The primary cause of the Ootombi-kuzure triggered by the 1858 earthquake, which was generated by the active Atotsugawa fault, was the fragile basement rocks deteriorated by the hydrothermal alteration. It was facilitated with the aid of gently tilted discontinuities and/or clayey deteriorated zones as a part of sliding surface.

The potential sliding surface of the Dashihara landslide and the Kunimi landslide must have been the clay layer due to the past hydrothermal alterations, which was intercalated between the lower Yukawadani-volcanic-rocks and the granodiorite. Both of the triggering cause are unknown, but high possibility of past earthquakes generated by the Atosugawa fault system. Kunimi-doro might have occurred almost simultaneously following its mother Kunimi landslide around 30,000 years ago.

Three potential deep-seated slope-failures and more are warned against the future earthquakes in and around the Tateyama Caldera, that is, the lower slope or the whole area of Kunimi landslide, the independent ridge on the northwestern caldera wall, the periphery of the west marginal ridge of the caldera and any other unstable slopes should be examined the stability for the future.

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