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Deteriorating Process of Dacitic Pyroclastic Flow Deposits at Steep Slopes based on Hardness Distribution

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1. Introduction

Slope failures during a rainy season are annual occurrences in southern Kyushu, Japan, where most of slopes are underlain by the Quaternary pyroclastic flow deposits as shown in Figure 1. They are non-welded or weakly welded dacitic tuff characterized by soft and permeable properties. These deposits, mainly composed of coarse grained volcanic glass and pumice's fragments, are sometimes called as "Shirasu", a local name for "whitish sand" (Iwamatsu *et al.*,1989).

Many studies have been made to obtain the characteristics of slope failures occurring on steep slopes of "Shirasu", and to understand mechanical relations between slope failures and properties of the deposits (for example, Shimokawa *et al.*, 1989; Yokota, 1995). As a result, soft and permeable properties of the deposits have been believed to be primary cause for slope failures apart from steep

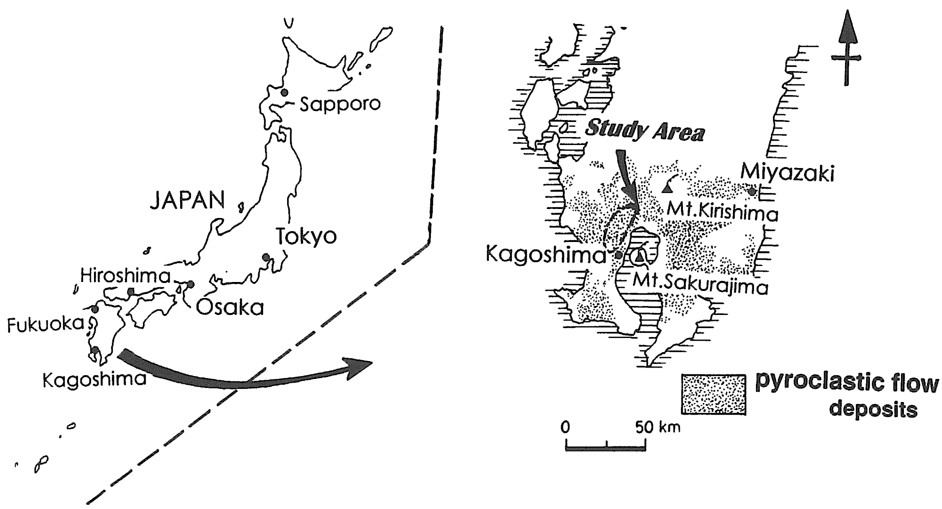

Figure 1 Wide distribution of "Shirasu", the Quaternary pyroclastic flow deposits in southern Kyushu, Japan. Data sampling were made in and around Kagoshima City as indicated by 'study area' in the figure.

slopes (Yokota, 1995). However, considering that extent of individual failures is restricted within surface portion in such slopes, much attention should be paid to the properties in surface portion where the deposits are remarkably weathered. In other word, remarkable and rapid weathering within the surface portion and its style in the slope may be one of the fundamental primary cause for slope failure in this region. Therefore, the gradation distribution of weathering and deterioration in such steep slopes may be an important factor affecting the mechanism of slope failures in addition to infiltration of rain water as triggering cause.

2. Deterioration of "Shirasu" and slope failures

The pyroclastic flow deposits, "Shirasu" is geologically defined as the Ito pyroclastic flow deposits (Aramaki, 1969, 1984) which has believed to have erupted from the Aira Caldera, southern Kyushu, about twenty five thousand years ago (Nagaoka, 1988). "Shirasu" also tends to shape characteristic topography of plateaus and steep slopes in this region.

Numerous slope failures have occurred on such steep slopes due to triggering by heavy rainfall every year. Considering that remarkable and rapid weathering of the deposits is one of primary causes, occurrences of slope failures and their extent may have been controlled by the proceeding of weathering. Figure 2 shows the relation between weathering and occurrence of slope failures. Weathering may proceed from the surface of slopes. The surface portion may become unstable as weathering proceeds, and a slope failure may occur when the thickness of weathered portion attains to a threshold value (Shimokawa *et al.*, 1989). Such slope failures are restricted within only surface portion on the slopes. These cycles of proceeding of weathering and occurrence of slope failures may continue repeatedly.

The deposits are dacitic or rhyolitic, and therefore contain much volcanic glass and pumice's fragments. Process of weathering and deterioration (weakening) may include not only changes of physical and mechanical properties but also chemical decomposition of coarse grained materials. Ferrous components contained as oxides in the deposits may dissolve out with rain water at earlier stages. Some of volcanic glass may change to clay minerals such as allophen or 10 Å halloysite (Tomita and Onishi, 1976). This may bring about physical and mechanical changes such as increase of porosity. As a result, changes of physical properties such as porosity, density and

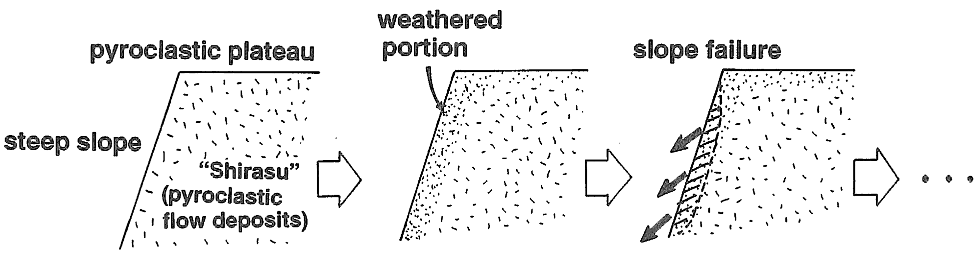

Figure 2 Weathering and deterioration of "Shirasu" and occurrences of slope failures. Weathering and deterioration proceed inward from the surface of slopes, and slope failures occur in surface portion of steep slopes.

strength may also proceed with chemical changes (alteration) as shown in Figure 3. Dry density and strength may decrease with the increase of porosity. This may influence the unstability of the slope. Weathering and deterioration of a rock mass may also proceed along fractured and opened of cracks in addition to the change in characteristics of the deposits.

3. Hardness distribution inside "Shirasu" slopes

Pyroclastic flow deposits, "Shirasu" is homogeneous and isotropic, and therefore, it is difficult to discriminate the grade of weathering in the deposits. Therefore, the author has tried to measure values of hardness using a handy hardness tester for soil (Fujiwara Manufacturing Co.), and to obtain their spatial distribution. In this case, hardness is regarded as an indicator of grade of weathering and deterioration of the deposits. A distinct relation has been known experimentally between values of hardness obtained using the tester and uni-axial compressive strengths of these materials.

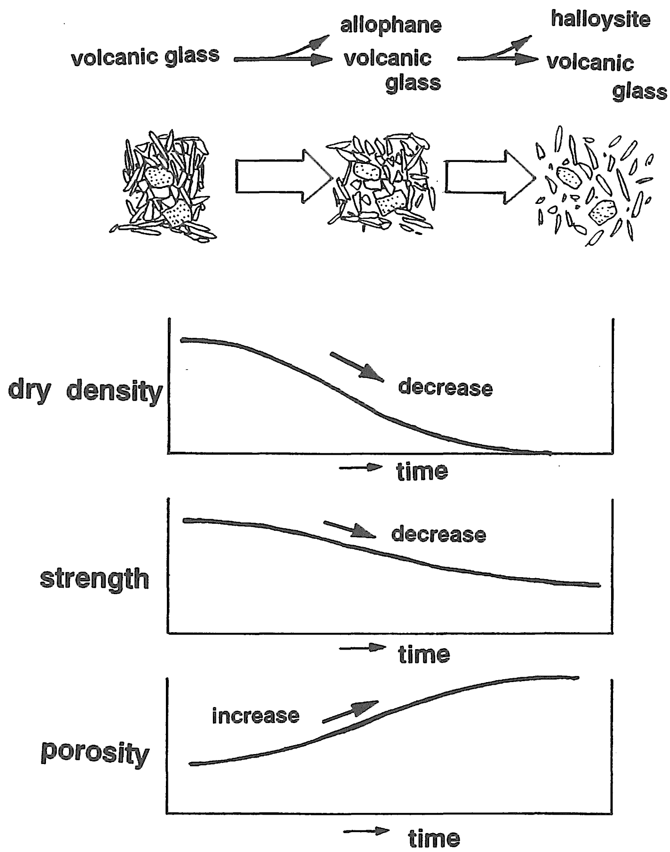

Figure 3 Temporal changes of chemical components and physical properties in "Shirasu" during weathering process.

Some target slopes composed of "Shirasu" were selected in and around Kagoshima City, southern Kyushu (Figure 1). They are naturally formed steep slopes, but some of which are covered with ash fall and others. Measurement of hardness has been made on artificially excavated surfaces crossing natural slopes. Hardness was measured at 10 cm intervals along the base line set on excavated surfaces. Detail methods and results measured in each slopes have been already reported by Yokota (1996) with explanation of topographical and geological features.

Figures 4(a), (b), (c) show examples of hardness distribution in three slopes. (a) and (b) are ones measured at relatively high elevation of slopes where the deposits are covered with thick ash falls and talus deposits. Based on geological features, both slopes are considered to have been well-weathered without occurrence of slope failures during long period. On the contrary, (c) is the case situated at the foot of the slope. Probably, the surface of slopes may have been subjected to fluvial erosion.

Although variation is large in each data, smoothed curves indicate gradual changes of hardness with respect to the distance from the surface of slopes. The value of hardness attains to 26 or 27 and is almost constant in the portion at a long distance from the surface in the case (a), but it decreases in a short distance and takes values around 20 at distance 7～8 meters, and 17 or 18 at 2～5 meters finally. Converting the values of 27 and 17 in hardness index into those of compressive strength, the former is larger than about 5 times as compared to the latter. Large values recognized in talus deposits at 2 meters in the case of (a) can be attributed to the chemical cohesion such as secondary oxidation. On the other hand, extent of decreasing of hardness is only 1.5 or 2 meters from the surface of the slope in the case of (c).

Consequently, hardness of the deposits which expresses the grade of weathering and deterioration is distributed continuously and changes gradually. And, although weathered and deteriorated portion are up 7～8 meters from the surface of the slopes in the cases of (a) and (b), it is only 1.5～2 meters in the case (c).

These curves of hardness distribution obtained in several locations are summarized in Figure 5. Distance on abscissa is normalized to that from the surface of the pyroclastic flow deposits themselves. A curve of Loc. 4 was obtained inside wall of an artificial adit in same region. The values are relatively larger than others. Tendencies of changes expressed in each curves resemble each other. Hardness index takes a constant value at long distance from the surface of slopes, and is ranging from 26 to 29. These curves are also similar to vertical changes obtained in vertical shaft on the pyroclastic plateau (Yokota and Otosu, 1994).

4. Disintegration of "Shirasu" as characteristics style of weathering and deterioration

As already stated, "Shirasu" is composed of coarse grained materials with fragments of pumice. When it has weathered, grains may disintegrate. Degree of disintegration may depend upon the grade of weathering at each position. This can be obtained as grain size distribution by sieving tests. Figure 6 shows some results of sieving test. Grain size distribution is expressed in cumulative curves of weight percent. Samples for the test were obtained at distances 2.0, 3.9, 4.9, 5.7, 15.7 and 20.0 meters respectively along the same line in the location of (a) in Figure 4.

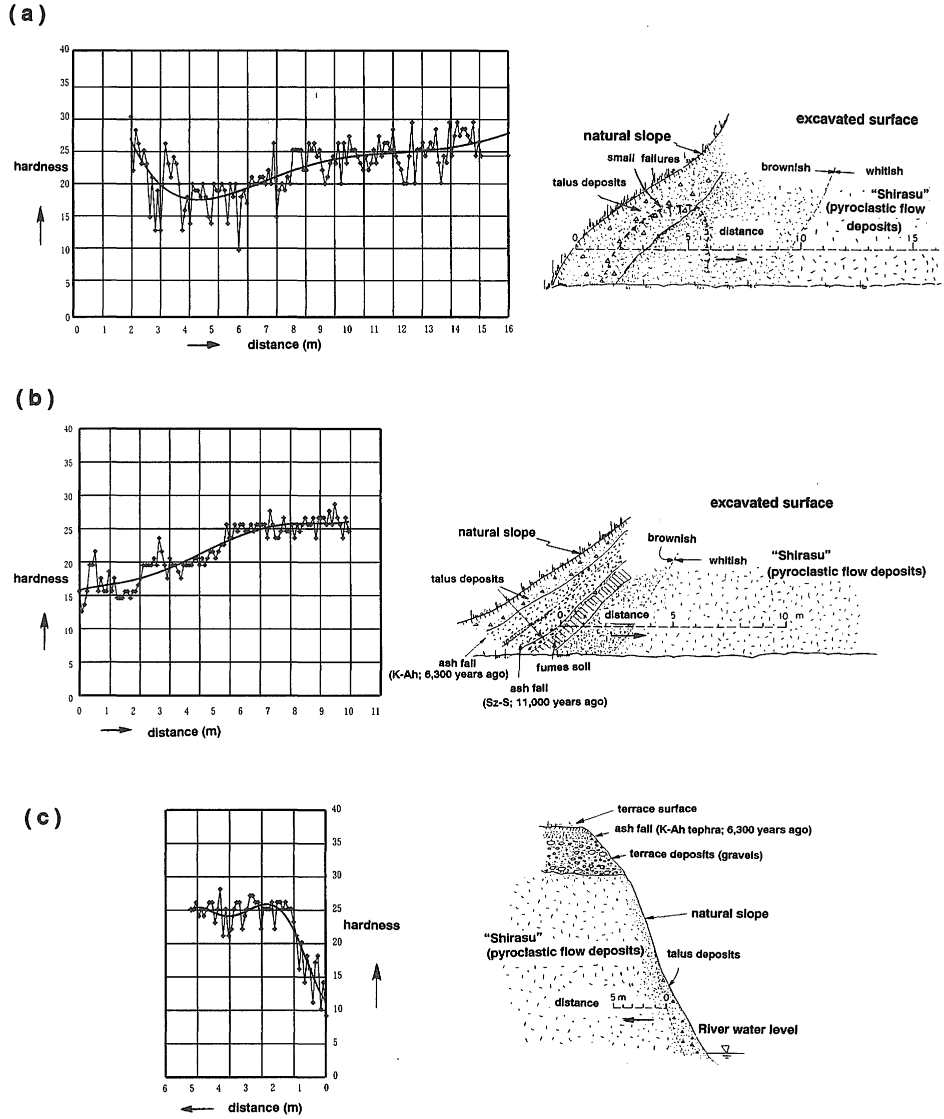

Figure 4 Examples of hardness distribution with distance measured on three slopes of "Shirasu" (after Yokota, 1996). Smoothed curves are shown in each data set.
(a) Measured data at Gotanda, Yoshida Town, northeast of Kagoshima City
(b) Measured data at Nishi-Beppu, Kagoshima City.
(c) Measured data at bottom of the Honmyo River at Yoshida Town, northeast of Kagoshima City.

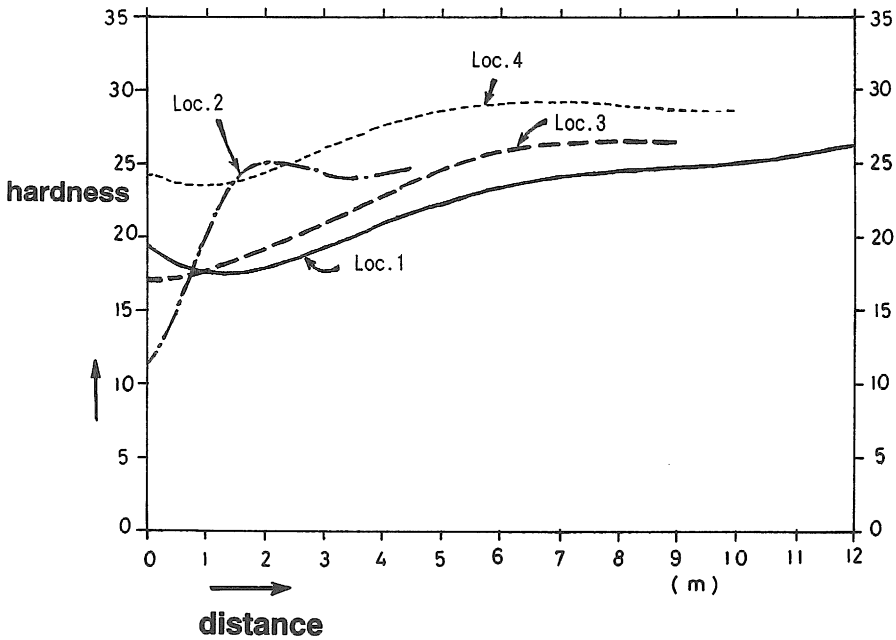

Figure 5 Inward changes of hardness distribution with the distance from the surface of slope. Loc. 1, 2 and 3 are (a), (b) and (c) in Figure. 4 respectively. Origin of distance is defined at the surface of "Shirasu" except Loc. 4.

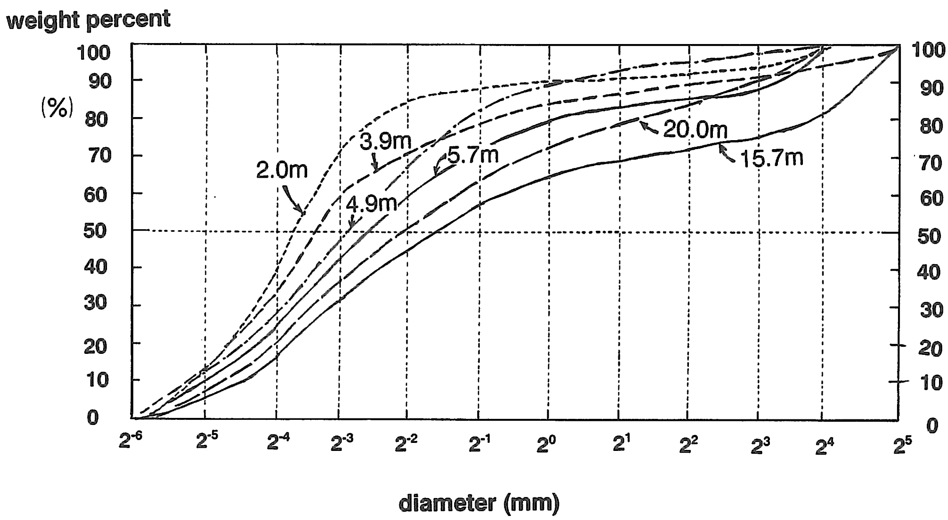

Figure 6. Cumulative curves of grain size distribution obtained by sieving test. Samples were obtained on the base line in the location of (a) in Fig. 4

Each cumulative curve and the difference in them shows that disintegration occurs as characteristics of weathering process in "Shirasu". The closer the surface of the slope, the finer the grain size becomes. However, difference between 15.7 and 20.0 is considered to be negligible in these curves.

Figure 7 shows the changes of mean grain size D_{50} calculated from individual curves in Figure 6. D_{50} is lower than 0.1 mm at both 2.0 and 3.9 meters, but it attains to 0.2 mm at 5.7 meters. Consequently, D_{50} value increases with the distance from the slope surface.

Disintegration of grains may bring about the increase of porosity. Moreover, the dry density may decrease as the increase of porosity. The change of dry density with the distance was also recognized in these samples, and it is almost similar to that in vertical changes (Yokota and Otosu, 1994).

5. Clay mineralization of volcanic glass due to weathering and deterioration

It has been believed that volcanic glass tends to change to clay minerals such as allophen or halloysite by weathering (Tomita and Onishi, 1976). These clay mineralization has been recognized in many locations as chemical changes of "Shirasu". However, no distinct relationship between these chemical changes and physical changes mentioned above has been hitherto known. Therefore, clay minerals contained in each samples treated in the previous section were analyzed by X-ray diffraction. The results are shown in Table 1.

10 Å halloysite which is a clay mineral chemically altered from volcanic glass was recognized in samples at 2.0, 3.9 and 5.6 meters. But, it was not recognized in those at 15.7 and 20.0

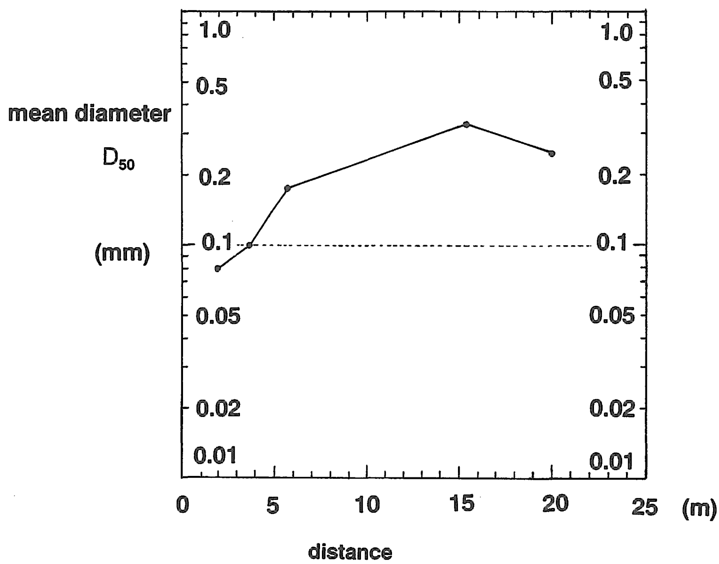

Figure 7 Changes of mean diameter D_{50} with distance.

Table. 1 Clay minerals recognized in each samples using X-ray diffraction. Sampling were done each points on the base line of location (a) in Figure 4.

sample no.	distance	clay minerals
1	2.0 m	10 Å halloysite, smectite
2	3.9 m	10 Å halloysite, smectite
3	4.9 m	10 Å halloysite
4	5.7 m	10 Å halloysite
5	15.7 m	smectite, illite
6	20.0 m	smectite, illite

meters. Figure 8 shows an example of the X-ray diffraction curves indicating the existence of 10 Å halloysite. As a result, 10 Å halloysite seems to exist within surface portion in a short distance from the slope surface. And the extent of this clay mineralization almost coincides with brownish colored portion on excavated surface. Moreover, the boundary between existence and no existence of halloysite is almost equivalent to values 23～24 in hardness index in the case of this location.

6. Weathering and deteriorating process of "Shirasu"

Figure 9 shows a generalized distribution of weathered and deteriorated zone of "Shirasu"

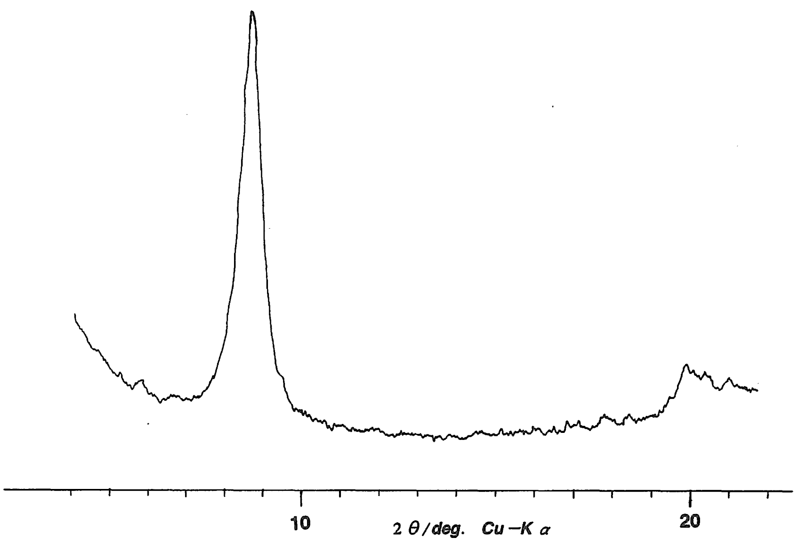

Figure 8 Peak of 10 Å halloysite on X-ray diffraction chart as an example.
Sample was obtained at the distance 4.9 m in the location (a) in Fig. 4

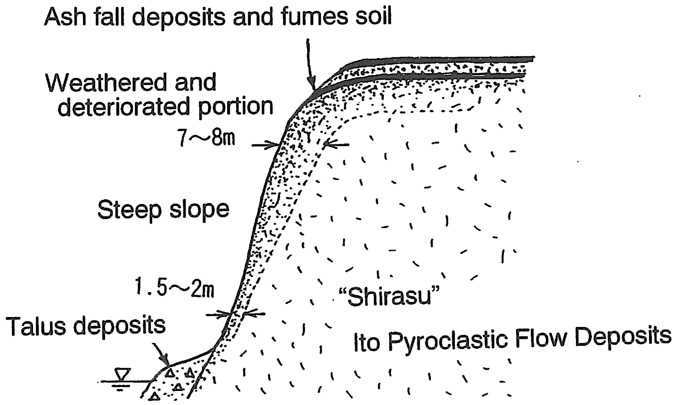

Figure 9 Inward change of deteriorating of "Shirasu" from the surface of slopes

based on hardness distribution mentioned in previous sections. Weathering and deterioration used here include disintegration of grains, clay mineralization, and the decrease of physical indices such as hardness and strength. Therefore, the zone may also approximate the extent of these clay mineralization. Although the zone attains to 7～8 meters from the surface at higher elevation of slopes, it is only 1.5～2 meters at the foot of slopes. This difference in weathered zone can be understood as the difference in the balance of rate between weathering and erosion in each positions. These distribution may influence the extent and amount of the slope failure when a failure occurs under any triggering rainfall. On the contrary, measuring and analyzing of graded distribution of weathering and deterioration enables us to estimate the extent and amount the slope failures, and degree of unstability on the slope at a given time. Moreover, considering the study of triggering cause such as infiltration of rainwater (Yokota *et al.*, 1997) with the present study, it may enable us to predict slope failures in future.

Figure 10 shows an image of the process of weathering and deterioration of "Shirasu" as a temporal change. At the time just after cooling of the pyroclastic flow deposits, hardness distribution may be constant throughout the deposits as indicated in the curve at $t=t_0$. After that, hardness may decrease in outer portion, and it may proceed gradually inside the slope as weathering proceeds. Values of hardness at a long distance from the surface are almost constant even in these stages. Temporal change of the hardness distribution in the slope may proceed inward like this, and it may result in thick weathered zone in outer portion. However, if a slope failure occurs at foot of the slope and surface portion is eroded out, such process may re-start since the time. As a result, narrow weathered zone may form as shown in lower portion of the Figure 10. In this manner, variation of gradual distribution of weathering and deterioration may be revealed in the slope in accordance with the cycle of weathering and erosion. Consequently, occurrence of slope failures and its extent on the slopes may strongly depend on the style of weathering distribution in "Shirasu".

Yokota (1992) proposed a following simple equation which approximates temporal proceeding

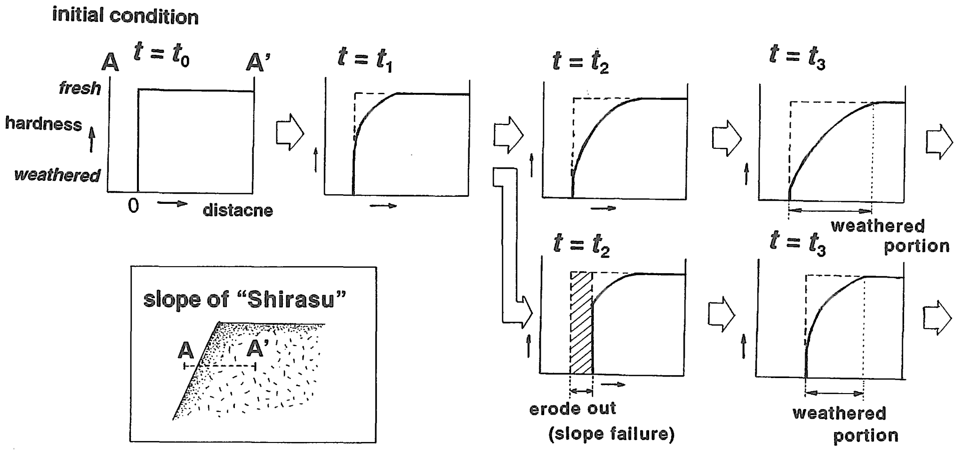

Figure 10 Deteriorating process of "Shirasu" and changes of hardness distribution.

of weathering from a joint plane in a rock mass. The equation means that the decrease rate $-\partial \phi / \partial t$ of a grade of weathering ϕ at any point is proportional to the spatial gradient $\partial \phi / \partial x$ there, that is,

$$-\frac{\partial \phi}{\partial t}=k\frac{\partial \phi}{\partial x} \tag{1}$$

where, coefficient *"k"* is a constant, and it represents the horizontally proceeding velocity of the front surface of any grade zone. Equation (1) seems to appropriately express the generalized characteristics of changes in rock masses (Yokota, 1992, 1993). Of course, other relations may otherwise express such changes suitably. For example, relations that $-\partial \phi / \partial t$ is proportional to ϕ, or proportional to $\partial^2 \phi / \partial x^2$ can also considored. According to field evidences, it may be better to add the 2nd differentials terms $\partial^2 \phi / \partial x^2$ to the right member in equation (1) (Yokota, 1992, 1993).

Weathering process from the surface of slopes discussed here is almost similar to these, and it can also expressed as the equation (1). Then, substituting hardness distribution in the case (a) or (b) in Figure 4 into the equation (1), a proceeding velocity k can be estimated to be 7~8 meters/11,000 years. Because, the deposits are covered with ash fall (Sz-S) dated 11,000 years ago. Assuming that a proceeding velocity is constant during this period, it becomes $k=0.07\sim0.08$ cm/year. Probably, the velocity may be larger than this value in earlier stage. This value is too 10 times larger than those obtained in granite and limestone (Yatsu, 1981).

7. Concluding Remarks

Based on not only hardness distribution, but also grain disintegration and clay mineralization, a mechanism of weathering and deterioration condition inside the slope of pyroclastic flow deposits, "Shirasu" have been attributed as the primary cause of slope failures. Based on the present investigations, the following conclusions are made:

(1) Gradation distribution of hardness in slopes shows that the grade of weathering and deterioration of "Shirasu" is distributed continuously, and changes gradually.

(2) Although the weathered zone attains to 7～8 meters from the surface of slopes at higher level of the slope, it is only 1.5～2 meters at the foot of slopes.

(3) Based on the grain-size distribution, disintegration is recognized as characteristics of weathering and deterioration. And it is remarkable in outer portion of slopes.

(4) Based on the X-ray analysis, changes of volcanic glass to 10 Å halloysite is recognized within the distance of several meters from the surface of slope. This extent nearly coincides with brownish colored zone, and the boundary is almost equivalent to the position where the values of hardness are 23～24.

(5) Several gradation distribution of weathering in progress can be understood as the balance of rate between weathering and erosion.

(6) Based on a simple assumption of geological condition, the proceeding velocity of weathering and deterioration is estimated to be 0.07～0.08 cm/year in these slopes.

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