Geological determination of a landslide body based on drilled cores

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Abstract

In the case of a landslide along a dam reservoir, an old landslide which has already stopped moving sometimes starts to move again as the reservoir water level changes. When assessing a landslide body, information about movements obtained by borehole inclinometers is not useful for such old landslides. Instead, geological observation of drilled cores is the only way to determine the range of a landslide body. However, it is very difficult to distinguish crushed rocks of landslide origin and those of tectonic fault origin based on such observation of drilled cores. Recently, Wakizaka et al. (2012) and Wakizaka (2013) reported that crushed rocks of landslide origin can be distinguished from those of tectonic fault origin: the former show a random texture, whereas the latter have some composite planar texture. Wakizaka et al. (2012) and Wakizaka (2013) examined a total of only four landslide bodies, all of which were in accretionary complexes. Therefore, the present study observed drilled cores of 60 other landslide bodies distributed in various accretionary complexes, normal sediments, schist, granite, and Miocene volcanic rocks. As a result, the same conclusion that crushed rocks of landslide origin show a random texture, whereas those of tectonic fault have some composite texture was obtained. However, there are important points to note when distinguishing crushed rocks of landslide origin and those of tectonic fault origin: 1) crushed rocks with a random texture are distributed under the slip surface, 2) some crushed rocks of tectonic fault origin do not have a clear texture, 3) clay which composes the slip surface shows some textures such as a banded structure which makes it difficult to distinguish a fault gouge, 4) crushed rocks of tectonic fault origin are sometimes distributed in a landslide body, and 5) it is difficult to distinguish crushed rocks with a random texture of landslide origin and weathered and loosened originally brecciated and gravelly rocks such as auto-brecciated lava, tuff breccia and conglomerate.

Keywords: landslide body, crushed rock, tectonic fault, composite planar fabric

1. Introduction

A landslide body is analyzed by topographical and geological features and the results of movement measurements such as by a borehole inclinometer. The depth of the slip surface is determined by movement measurements and/or geological features, although the depth must be determined from only geological features in the case of an old landslide which has already stopped moving. The presence of crushed rocks which were formed by landslide movement is an example of a geological feature of a landslide body. Slip surface clay is a part crushed at the boundary between the landslide body and bedrock.

Fault breccia, fault gouge hydrothermally crushed rocks, and crushed rocks in a mud volcano, are examples of crushed rocks distributed near the ground surface other than crushed rocks of landslide origin. Among these rocks, fault breccia and gouge are widespread, and so geological determination of a landslide body is difficult. When usual drilling methods are used for core sampling, it is impossible to distinguish between crushed rocks of landslide origin and fault breccia, because it is not possible to sample undisturbed cores in a crushed part.

Recently, drilling methods using a surfactant or thickener have been developed that enable sampling of undisturbed cores (high-quality cores) in crushed parts. Wakizaka et al. (2009) and Wakizaka et al. (2012) found distinguishing characteristics between crushed rocks of landslide origin and crushed rocks of tectonic fault origin based on observations of drilled cores obtained from 19 drill holes in a landslide body located in the Shimanto belt, southern Kyushu. This report describes the results of geological observation on high-quality cores obtained in 65 landslide bodies in 26 regions.

2. Crushed rocks of landslide origin

2.1 Review on crushed rocks of landslide origin

There have been various previous studies on crushed rocks of landslide origin as follows. Oyagi (1994) reported a "coagulated layer" observed in the Nishitani landslide located in the Shimanto belt. He stated that: "the coagulated layer is somewhat compacted and consists of angular sandstone breccia and powdery fine grained mudstone matrix". Tajika (1995) divided three landslide deposits in an area of sedimentary rocks in Hokkaido into four facies: fractured rock, debris soil, clayey soil and surface soil. Fractured rock is crushed and broken rocks of the initial structures of bedrocks by cracks; debris soil is composed of clasts of boulder to fine gravel size and sand, silt and clay matrixes. Morita et al. (2002) divided the crushing degree of the body of the Utsugi landslide into seven categories based on observations of drilled cores.

2.1 Cracky rocks

This section describes the characteristics of crushed rocks (called crushed rocks of landslide origin) in a landslide body (a landslide body in region A) located in the Shimanto belt, according to Wakizaka et al. (2012). Slip surfaces were determined by cumulative displacement measured by borehole inclinometers, and a landslide body was identified as a part which was shallower than the slip surface.

One of the distinctive characteristics of crushed rocks of landslide origin is cracky rocks. Wakizaka et al. (2012) classified these cracky rocks into the following two categories.

1) Cr1a: Irregular cracks such as jagged cracks with nearly vertical dip are observed (Fig. 1(1)). These cracks are oblique to the bedding planes. These irregular cracks are considered to be tension cracks based on their vertical dips and shape.

2) Cr1b: In some cases, fine-grained breccia fill the above cracks (Fig. 1(2)). Two types of origin of these fine-grained breccia are considered: breccia was formed when such cracks formed, or breccia was filled from the upper parts.

2.2 Breccia and clayey rocks

Another distinctive characteristic of crushed rocks of landslide origin is the presence of various breccia which consist of relatively coarse-grained fragments and fine-grained matrix. This breccia is very similar to fault breccia. The grain size of fragments and the ratio of fragments to matrix are variable (Fig. 2). Figure 2 shows, in order, the size of fragments and the amount of matrix; (1) shows breccia which has the largest fragments and the smallest amounts of matrix. Figure 2 (5) indicates the drilled core where cumulative displacement was measured, so this part makes clayey rock of the slip surface.

Fig. 1 Distinctive cracks of cores drilled in a landslide body in region A (Wakizaka et al. 2012).

A distinctive feature of this breccia is that the size between fragments and matrix varies; larger fragments are distributed in fine-grained matrix. No planar fabrics such as a shear plane are observed in breccias and clayey rocks, indicating a random fabric. The characteristics described above are found throughout the landslide body such as the top and toe parts, as well as surface and deep parts.

Wakizaka et al. (2012) divided breccias into the following four categories based on the median diameter of fragments and the amounts of fragments and matrix.

1) Cr2: Breccias with random fabric. The amount of matrix is less than 30%, the median diameter of fragments is larger than 15 mm, and the breccia is fragment-supported (Fig. 2 (1) and (2)).

2) Cr3: Breccias with random fabric. The amount of matrix is 30 to 60%, the median diameter of fragments is 15 to 5 mm, and the breccia changes to matrix-supported when fragments become small and the matrix increases (Fig. 2 (3)).

3) Cr4: Breccias with random fabric. The amount of matrix is more than 60%, the median diameter of fragments is 5 to 2 mm, and the breccia is matrix-supported (Fig. 2 (4)). Sometimes Cr4 forms a slip surface.

4) Cl: Sand to clay without fragments. Sometimes Cl forms a slip surface (Fig. 2 (5)).

2.3 Characteristics of crushed rocks except for region A

Wakizaka (2013) found that the same characteristics of crushed rocks in a landslide body in

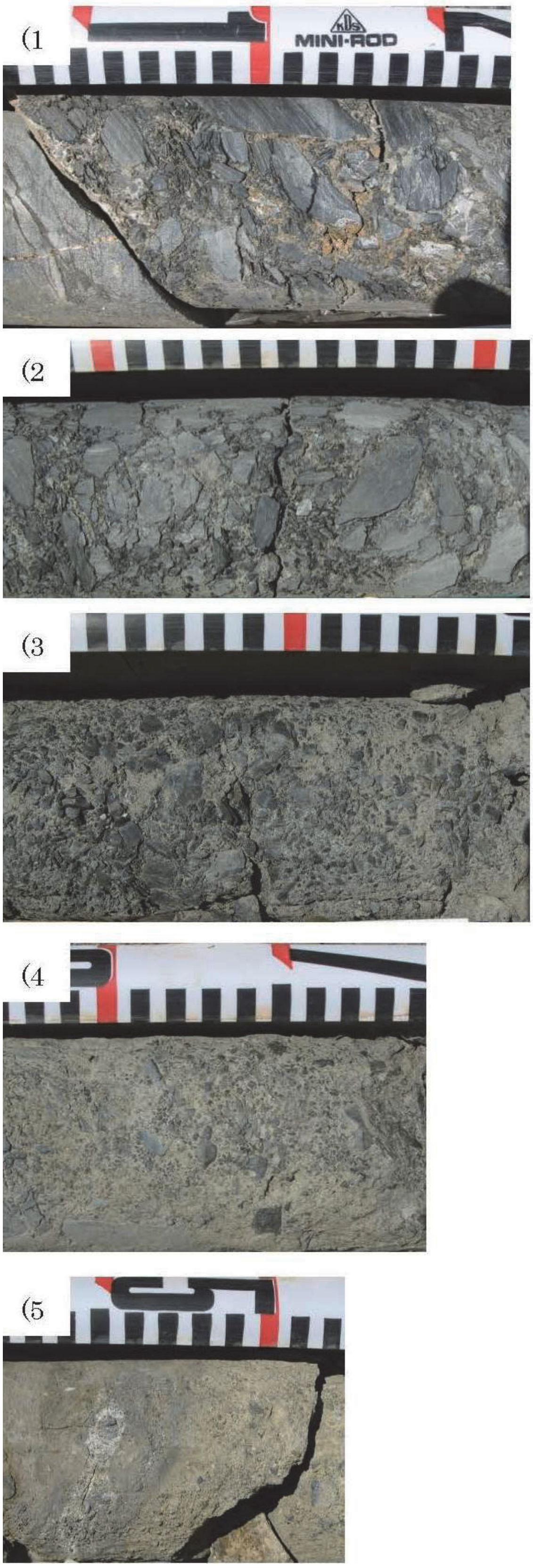

Fig. 2 Distinctive breccia and clayey rock of cores drilled in a landslide body in region A (Wakizaka et al. 2012).

Table 1 Geology and number of observed landslide bodies.

Region	Geology		Number of landslide body
A	Accretionary Prism	Shimanto belt	1
B-1		Chichibu belt	1
B-2			4
C-1		Chichibu belt	2
C-2			6
D-1		Shimanto belt	1
D-2			3
E		Chichibu belt	1
F		Chichibu belt	1
G		Chichibu belt	1
H		Ultra-Tanba belt	1
I		Shimanto belt	3
J		Ashio belt	7
K	Normal sediments except for accretionary prism	Yezo supergroup	2
L		Yezo supergroup	2
M		Yezo supergroup	1
N		Izumi group	1
O	Schist, Sanbagawa belt		1
P	Schist, Suo belt		1
Q	Miocene pyroclastics, sediments		9
R	Miocene sediments, pyroclastics		8
S	Miocene sediments, rhyolite		3
T	Miocene volcanics, Cretaceous rhyolite		2
U	Miocene pyroclastics, sediments		1
V	Cretaceous granite		1
W	Gneiss, granite, Hida belt		1
Total number of landslide bodies			65

region A were observed in other landslide bodies (B-1, C-1 and D-1 regions in Table 1). Excluding the above four regions, the same characteristics of crushed rocks in landslide bodies were observed in 60 landslide bodies in 22 regions (Table 1). Figure 3 shows the features of crushed rocks in six typical examples; the constituent geology of each region is as follows: region B-1 is sedimentary rocks consisting of accretionary prisms in the Chichibu belt, region L is sedimentary rocks of normal sediments except for accretionary prisms in the Yezo supergroup, region P is schist in the Suo belt, region Q is Miocene pyroclastics and sediments, and region V is Cretaceous granite. As shown in Fig. 3, all breccias are random fabric with various sizes of fragments and various amounts of matrix; these features are the

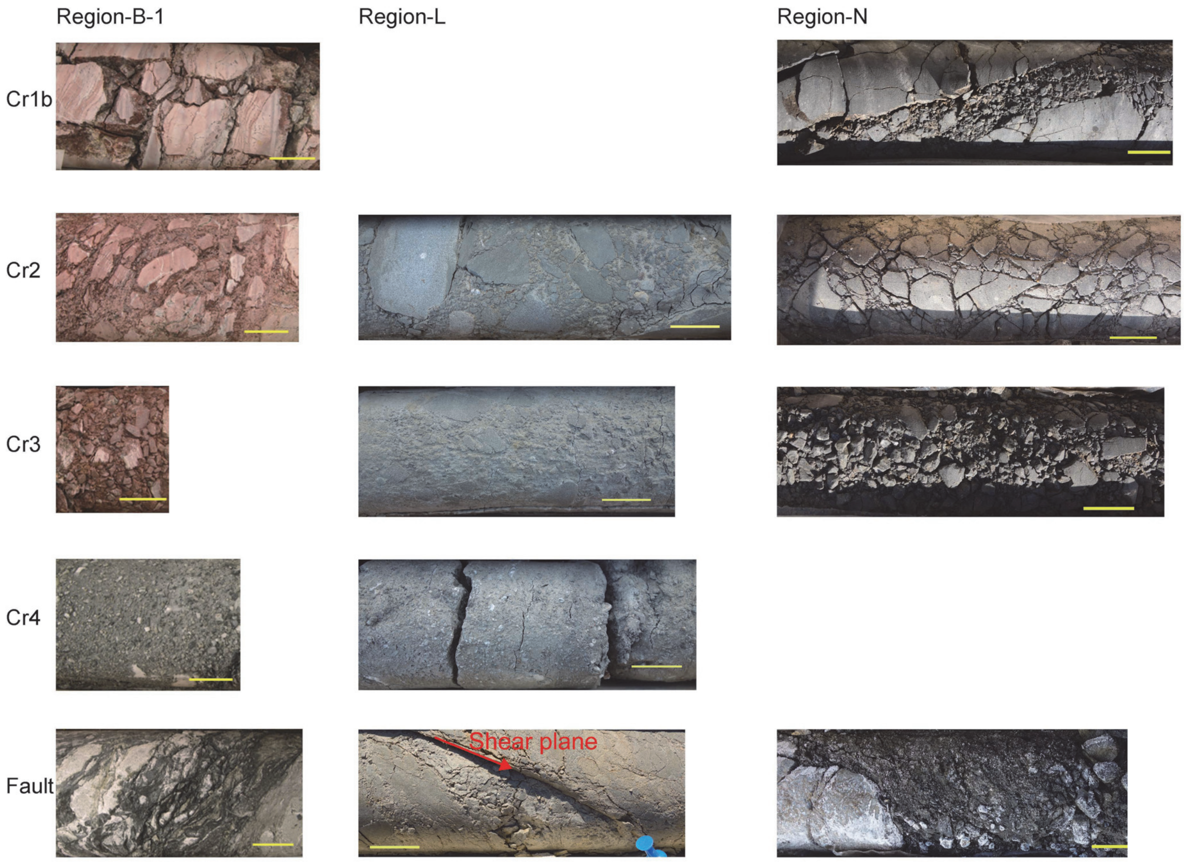

Fig. 3 (1) Features of crushed rocks of landslide origin and tectonic fault origin observed in high-quality drilled cores in six landslide bodies. A yellow bar in each photograph shows 2 cm length.

same as those of the landslide body in region A.

All landslide bodies shown in Table 1 are classified into landslides in rocks and landslides in weathered rocks based on the classification proposed by Watari and Sakai (1975). The characteristics of crushed rocks of landslide origin observed in the landslide body in region A are considered to be universal characteristics in a landslide body classified as landslides in rocks and weathered rocks.

No fabrics were observed in clayey rocks which consisted of a slip surface in the landslide body in region A. However, sometimes some fabrics were observed in other landslide bodies, and slickenside and striation were found along such fabrics.

3. Crushed rocks of tectonic fault origin

Geological observations of fault breccia and gouges which indicated a certain displacement in outcrops and adits near the landslide body in region A were performed. As a result, R1 shear (Barlett, 1980) and/or P foliation were recognized in fault breccia, whereas sometimes Y plane (Barlett, 1980) was recognized, and sometimes Y plane was not recognized in the fault gouge.

In the cores of the landslide body in region A, these fabrics were also found in deeper parts than the slip surface. In landslide bodies in other regions, crushed rocks with some fabrics were observed in deeper parts than the slip surface.

Intervals of R1 shear or P foliation were several centimeters in accretionary prisms such as the Shimanto belt and the Chichibu belt, whereas the intervals were more than several dozen centimeters in tertiary normal sediments. The development of fabrics is poor in tertiary normal sediments compared with accretionary prisms.

Grain size was continuously distributed in fault breccia compared with breccia of landslide origin.

4. Distinguishing crushed rocks of landslide origin from those of tectonic fault origin

4.1 Differences between crushed rocks of landslide origin and those of tectonic fault origin

A distinctive difference between crushed rocks of landslide origin and those of tectonic fault origin is the presence or absence of fabrics (Wakizaka et al. 2009; Wakizaka et al. 2012). Crushed rocks, which are considered to be of landslide origin because they are distributed in shallower parts than the slip surface, do not have fabrics. However, sometimes crushed

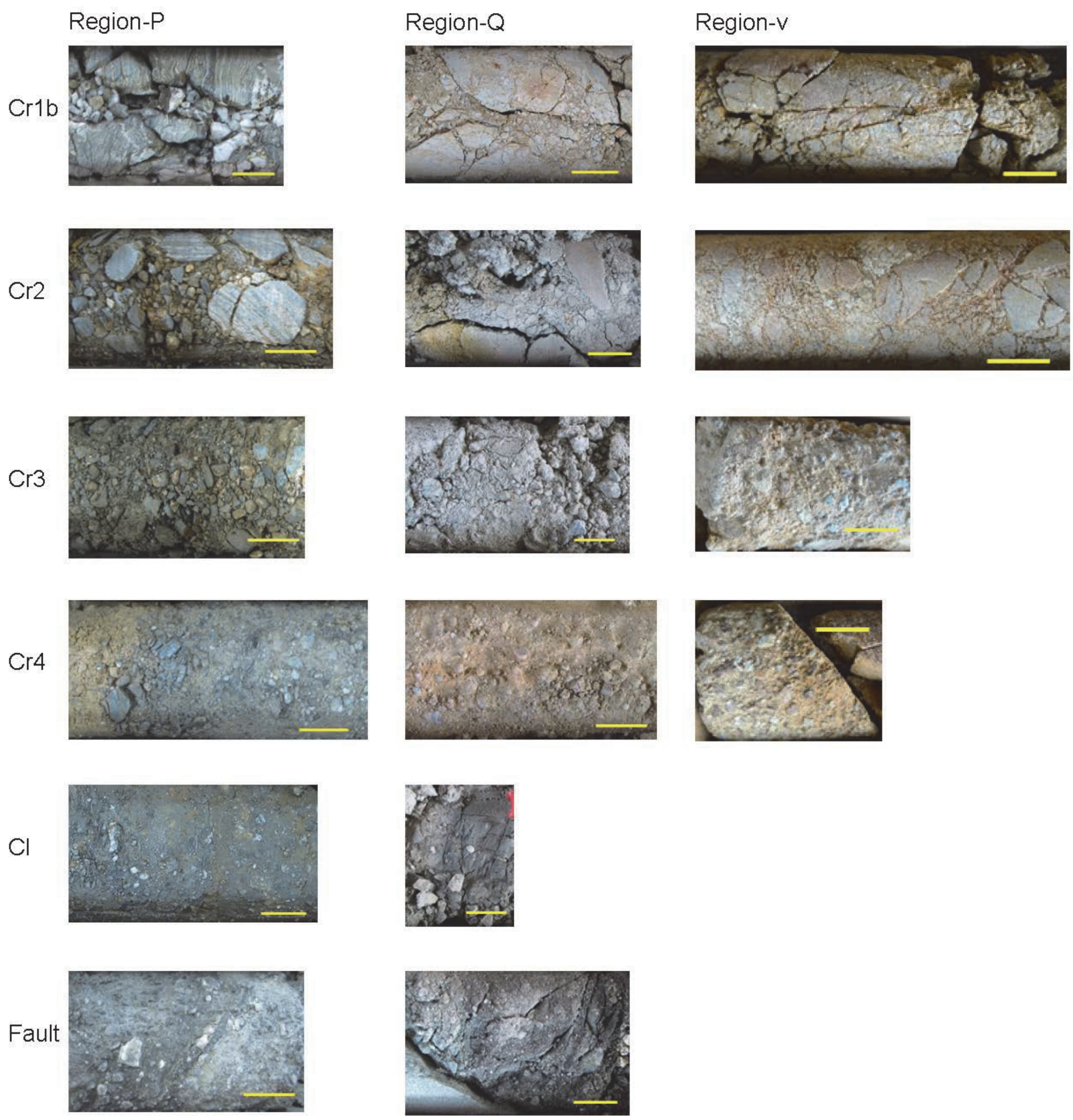

Fig. 3 (2) Features of crushed rocks of landslide origin and tectonic fault origin observed in high-quality drilled cores in six landslide bodies. A yellow bar in each photograph shows 2 cm length.

rocks such as clayey rocks which consist of slip surfaces indicate some fabrics. In contrast, crushed rocks of certain tectonic fault origin located in outcrops and crushed rocks located in deeper parts than the slip surface show some fabrics.

The distribution of grain size between fragments and matrix is discontinuous in breccia of landslide origin, whereas it is continuous in breccia of tectonic fault origin (Wakizaka et al. 2012).

4.2 Controlled factor of fabrics of crushed rocks of landslide and fault origin

Wakizaka et al. (2012) considered that the controlled factor of the presence or absence of fabrics in crushed rocks of landslide and tectonic fault origin was attributed to the difference of confining pressure when rocks were crushed, based on relationships between confining pressure and deformation features in triaxial tests. According to Hoshino et al. (1972) and Paterson (1978), relationships between confining pressure and deformation features in triaxial tests are as follows.

1) Cracks of split shape along the σ1 direction are formed when no confining pressure acts, that is, the uniaxial state.
2) Shear planes of fixed direction oblique to σ1 are formed when confining pressure acts.
3) Conjugate shear planes are formed as the

confining pressure increases.

According to data indicated in Hoshino et al. (2001), confining pressure when the deformation mode changes from a split-shape crack to a shear plane, shear plane to conjugate shear plane are correlated with the initial strength of the rocks. At low initial strength, low confining pressure is required to change the deformation mode. However, the confining pressure needed to change the deformation mode was not obtained by Hoshino et al. (2001), because there were few cases of low confining pressure. Nevertheless, based on the uniaxial strength of pre-Miocene sedimentary rocks, volcanic rocks and granite, it is considered that high confining pressure is required when composite planar fabrics such as R1 shear and P foliation are formed. The formation depth of mélange, which does not show plastic deformation of quartz grain, is estimated to be around 5-6 km to15 km (Kimura and Kinoshita, 2009), so the formation depth of a fault in mélange is considered to be the same depth, whereas the depth of the slip surface is usually less than 100 m. The difference of formation depth between crushed rocks of landslide origin and tectonic fault origin creates a difference of confining pressure when both crushed rocks were formed, and consequently a difference of confining pressure controls the presence or absence of fabrics.

4.3 Distinguishing crushed rocks of landslide origin from those of tectonic fault origin

Basically, crushed rocks without fabrics (random fabric) are considered to be of landslide origin, whereas crushed rocks with fabrics are considered to be of tectonic fault origin; therefore, it is possible to distinguish crushed rocks of landslide origin and those of tectonic fault origin. However, there are some important matters when distinguishing the origin of crushed rocks using the presence or absence of of fabrics:

1) Crushed rocks with random fabrics are sometimes observed below certain slip surfaces. Therefore, when the bottom of the landslide body is determined by the presence of crushed rocks with random fabric, the determined bottom is deeper than the true bottom. It is considered that the origin of these crushed rocks distributed in deeper parts than the slip surface is crushed rocks formed by gravitational deformation before landslide movement, or crushed rocks affected by upper landslide movement (Wakizaka et al.2012).

Chigira et al. (2013) classified plastically deformed rock masses into cracked, jigsaw-1, jigsaw-2, disintegrated, or pulverized, based on observation of high-quality cores obtained in a gravitationally deformed slope. This classification corresponds to Cr1a, Cr1b, Cr2, Cr3, Cr4 and Cl of Wakizaka et al. (2012). Crushed rocks with random fabric are also distributed in a gravitationally deformed slope.

2) Sometimes crushed rocks of tectonic fault origin may not always have clear fabrics. Especially, faults in post-Oligocene sediment do not have fabrics, or if some fabrics are present, the intervals of fabrics are wide. The concept of fabric on fault breccia and gouges was absent in Higgins (1971) and Sibson (1977), who studied the initial classification of fault rocks. Chester et al. (1985) first described that fault breccia had fabrics. They reported a foliated gouge in Punchbowl fault, USA based on observation of outcrops. McClay (1987) and other researchers added foliated fault breccia and foliated fault gouge to fault rocks.

Based on the relationships between confining pressure and deformation mode, faults formed under low confining pressure do not have fabrics. A fault gouge without fabrics was observed in tectonic faults in region A (Wakizaka et al., 2012).

3) The Y plane, which is observed as a banded structure, is recognized in slip surface clay determined by movement measurement. So, such a slip surface clay is difficult to distinguish from fault gouges. Morgenstern and Tchalenko (1967) reported that two systems of shear plane were present in London clay. Inoue et al. (2001) described that D-shear (corresponds to Y plane) and P shear developed in slip surface clay. Many studies indicated that slickenside was observed in slip surface clay.

Some fabrics such as the banded structure are observed in clayey parts excluding the slip surface. In some landslide bodies, the slip surface originated in tectonic faults. Therefore, slip surface clay is not determined by only the presence or absence of fabrics.

Yamane et al. (2013) and Yamane et al. (2015) investigated the microstructures of resin-fixing specimens of half-cut high-quality cores in and around slip surfaces located in region B-1 as shown in Table 1. They reported that reverse and normal fault senses determined by composite planar fabric and asymmetric structures were found. The parts which show normal fault sense are considered to be the slip surface, while the parts which show reverse fault sense are estimated to be tectonic faults.

4) A certain landslide body sometimes includes crushed rocks of tectonic fault origin (Wakizaka, 2014). Usually, crushed rocks of tectonic fault origin are not present in a landslide body. The absence of crushed rocks of fault origin is attributed to the strength of the fault, which is very low compared with the surrounding bedrocks, so the fault is selectively re-deformed by landslide movement. The presence of crushed rocks of tectonic fault origin indicates bedrock.

However, crushed rocks of tectonic fault origin were found in the landslide bodies located in regions

B-2 and L. In the landslide bodies in regions B-2 and L, crushed rocks of tectonic fault origin were found in weakly crushed blocks by landslide movements. Therefore, the presence of crushed rocks of tectonic fault origin is not an indicator of bedrock.

5) It is difficult to distinguish crushed rocks of landslide origin from loosened initially brecciated and gravelly rocks such as auto-brecciated lava, tuff breccia and conglomerate. When initially brecciated rocks and conglomerate distributed near the ground surface were affected by weathering and release of in situ stress, these rocks became loose. Loosened rocks are composed of fine grained matrix along cracks and fragments, and the distribution of matrix and fragments is random. Fragments consist of the original rock, so the appearance of these loosened rocks is very similar to that of crushed rocks of landslide origin. Thus, observation of matrix and fragments of these loosened initially brecciated rocks and conglomerate is very important.

5. Conclusions

It is difficult to distinguish crushed rocks of landslide origin and those of tectonic fault origin, because both crushed rocks are very similar. Detailed structures can be observed in undisturbed cores drilled by high-quality drilling methods. As a result of observing such high-quality cores obtained from various geologies, crushed rocks of landslide origin show a random fabric, whereas those of tectonic fault origin indicate some fabrics such as R1 shear and /or P foliation and/or Y plane. Therefore, crushed rocks of landslide origin and tectonic fault origin can be distinguished by the presence or absence of fabrics. However, there are some important issues when using the presence or absence of fabrics as such an indicator.

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(JwE): written in Japanese with English abstract
(J): written in Japanese