Rain-induced rock avalanches with a sliding surface along an out-of-sequence thrust

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Abstract

2011 Typhoon Talas induced a large numbers of rock avalanches in the Kii Peninsula, where is underlain by Jurassic-lower Miocene accretionary complexes. We performed geological investigation in the Akatani area, where two huge rock avalanches with volumes of 2 million and 8 million m^3 occurred, and we found that these two rock avalanches had their sliding surfaces along a large-scale out-of-sequence thrust (OST) extending more than 5 km. This OST had been exposed on riversides by long-term river incision and overlying dip slopes had started to deform and finally failed catastrophically, being triggered by the heavy rainstorm. This finding suggests that locating a large-scale OST is essentially important to predict and interpret potential sites of rock avalanche as well as finding a gravitational slope deformation using high-resolution DEMs.

Keywords: rock avalanche, accretionary complex, out-of-sequence thrust

1. Introduction

Recently, extreme weather related to global warming frequently occurs with many record-setting rainfall events all over the world, which have induced rock avalanches. Examples of recent rain-induced rock avalanches with tens or more than a hundred of fatalities are a rock avalanche in Philippine Leyte in 2006 (Evans et al., 2007; Guthrie et al., 2009), a rock avalanche in Shiaolin village, Taiwan by 2009 Typhoon Morakot (Tsou et al., 2011), and rock avalanches induced by 2011 Typhoon Talas in the Kii Mountains, Japan (Chigira et al., 2013).

The area of landslide distribution by 2011 Typhoon Talas, which is our study area, was the same area of 1889 Totsukawa rainstorm disaster, which induced many large rock avalanches. Hirano et al.,(1984) reviewed the Totsukawa disaster, and emphasized that many rock avalanches occurred on the dip slopes. Murata and Chigira (2000) performed geological investigation around the two rock avalanche sites (Shiono and Kawarabi-Hinoseyama (Same location with the Akatani-E of this paper)) which occurred during the Totsukawa rainstorm disaster and confirmed that Akatani-E landslide had occurred on a dip slope but that the slip plane had a gentler dip angle than the dips of bedding planes. Kimura (1998, 2000) reviewed the out-of-sequence thrust (OST) in Japan and emphasized the importance of OST in accretionary complexes for landslides. However, the relationship between rock avalanches and OST has not been well understood. We performed thorough geological mapping around huge rock avalanches and examined the relationship between geological structures and two landslides. As a result, we found that two landslides had their sliding surfaces along a large-scale OST extending more than 5 km.

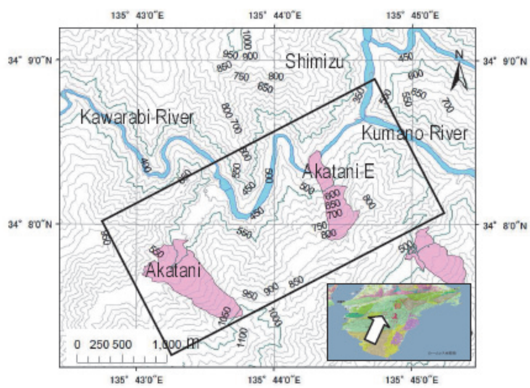

Fig.1 Locality map of the study area. The rectangle refers to the location of studied area.

Fig.2 Akatani-E landslide

Fig.3 Akatani landslide

The study area is in the catchment of the Kawarabi River, which is a tributary of the Kumano River flowing down to the south in the central part of the Kii Mountains (Fig.1). Summit elevations in the study area are 800 m - 1,000 m, and the riverbed of the Kawarabi River is at an elevation of approximately 400 m. In this area, two huge rock avalanches (Akatani-E, Akatani) with volumes of 2 million and 8 million m^3 were induced by 2011 Typhoon Talas (Chigira et al., 2013). Figures 2 and 3 show these two rock avalanches we studied and Table 1 shows the numerical data of the two rock avalanches (Chigira et al., 2013).

2. Method

In the study area, several geological surveys had been carried out and geologic maps were published, but they are not reliable enough for landslide study. Their surveys were intended to clarify the geological history rather than to make a geological map with high accuracy. Consequently, they were mainly based on the data along major rivers, and the traces of geological features on mountain ridges had not been well specified. In addition, Crush zones of faults, which are very important for slope stability, had not been well characterized and traced on geologic maps, because the most important features of faults were supposed to be displacement of beds and because the physical characteristics of their crush zones had secondary meaning in the common geologic maps instead of engineering geological maps. Previous geologic maps in the study area are thus not reliable enough to interpret the engineering geological characteristics of gravitational slope deformations and landslides.

Table 1 Akatani-E and Akatani landslides Chigira et al.,(2013)

	Akatani-E	Akatani
Landslide area(m^2)	221,400	423,700
Volume(m^3)	2.1×10^6	8.2×10^6
Slope angle(°)	29	34
Slope height(m)	450	610
Average depth(m)	11	28
Landslide dam	breached	present
Geology	Broken formations and mixed rocks	Broken formations and mixed rocks

In order to clarify the geological background of rock avalanches, we made field survey and we investigated the characteristics of faults, such as attitude, width, material (fault breccia, fault gouge etc.), and sense, and thoroughly traced major faults in the steep mountains as much as possible. In order to decrease the possibility that we miss the traces of major faults, we made continuous outcrop sketches on a scale of 1/1000 along the major rivers that cross the general trend of geological structures. We used base maps with a scale of 1:5000 or 1:10000, which we made from 1-m resolution DEMs obtained by Nara Prefecture and the Kinki Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism.

3. Result

Three kinds of units are distributed in the study area (Fig.4). One is the mixed rock of allochthonous blocks (green rocks and chert etc.) and sandstone blocks in argillaceous matrix. The second is the mixed rock of sandstone blocks in argillaceous matrix without allochthonous blocks. The third is coherent sequences and the broken formations. The strata in the study area belong to the Miyama Formation in the northern Zone of Shimanto Belt (Kishu Shimanto Research Group, 1986, Kumon et al., 1988). The broken formations show lenticular beds and boudinage, divided by small faults.

We found that the beds in the study area were cut by a large low-angle thrust fault, which we name the Kawarabi thrust (Fig.4). The Kawarabi thrust generally trends from NE-SW to ENE-WSW and dip to the northwest from 29° to 40°, being traced more than 5 km. It has a brittle crush zone, of which width exceeds 1m locally (Fig.4). We defined the width of fault as the sum of the width of gouge and fault breccia and plotted the mean of the minimum and the

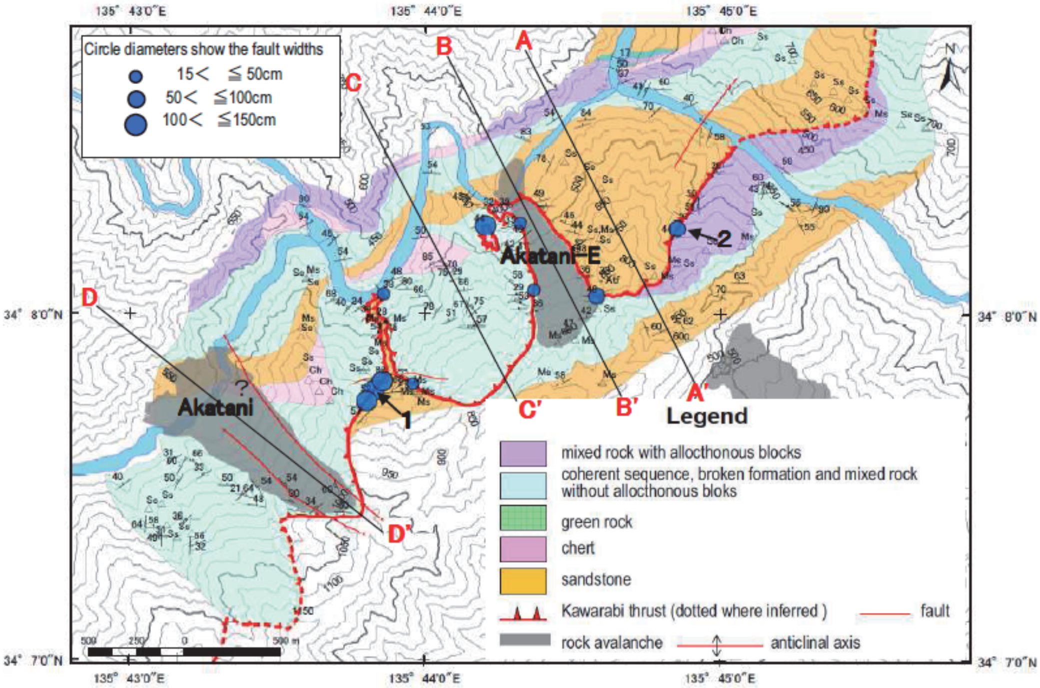

Fig.4 Geologic map of the study area. Arrows with numbers 1 and 2 show the position of Fig.6 and Fig.7.

maximum in each outcrop. The fault breccia generally consists of rock fragments and clayey materials. Figures 6 and 7 show the pictures of the Kawarabi thrust taken at the places shown in Fig.4 (arrows 1 and 2). Because the Kawarabi thrust has a brittle crush zone and extends longer than 5 km, it may be a large-scale out-of-sequence thrust in accretionary complexes (Kimura, 1998; 2000).

The crush zone of the fault shown in Fig.6 has a black gouge layer wider than 5cm along the top and bottom of the 1.5-m wide crush zone, and the inner zones of the crush zone is composed of clayey fault breccia. Along the base of the hanging wall of the fault, seepage water flowed out constantly, precipitating brown iron hydroxide. This suggests

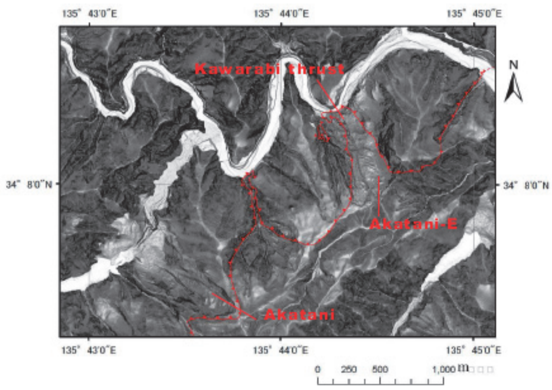

Fig.5 A slope map made from the 1-m DEMs obtained by airborne laser scanner surveys made on 7 and 23 September, 2011 after the 2011 Kii disaster by Nara Prefecture and the Kinki Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism.

that the fault would prohibit groundwater flow and would cause pore water pressure build up during rainstorms. At the outcrop of Fig.7, the fault has a 70-cm wide crush zone consisting of clayey breccia and a few layers of 3-5cm thick black gouge along the main shear planes. The relationship between the main shear plane and Riedel shear plane (Kano et al.,1991; Onishi and Kimura, 1995) suggested that the footwall displaced toward N26°E with 10° plunge. Similar sense has been obtained from other outcrops of this fault.

Besides the Kawarabi thrust, the study area has other minor low-angle faults and high-angle faults trending NW-SE or NE-SW. They have various widths as is shown in Fig.10: The width of a fault is the sum of the width of gouge and fault breccia. The mean of the minimum and the maximum of a fault width is plotted for 78 outcrops. The Kawarabi thrust, which is not included in this data, had an extraordinary width of crush zone up to 1.5m and an average of 50cm. One fault in Fig.10 had a 1.3-m width crush zone, but it is an NE-SW trending high-angle fault.

We found that the Kawarabi thrust occupied the major parts of the detachment surfaces of the Akatani-E and Akatani rock avalanches (Fig.2 and 3) as follows. Just after the landslide in 2011, undulating slickenside surface exposed in the source area of the Akatani-E landslide, which surface was confirmed to be the fault surface of the Kawarabi thrust by the following geological mapping. The 2011 Akatani landslide, on the other hand, left so large amount of debris in the source area that the base detachment surface could not be observed just after the event. A

Fig.6 Kawarabi thrust (Arrow 1 in Fig.4). Looking to the northwest. The scale bar is 70cm long

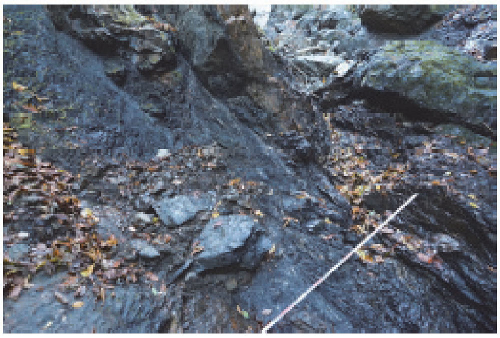

Fig.7 Kawarabi thrust (Arrow 2 in Fig.4). Looking to the southwest. The scale bar is 100cm long.

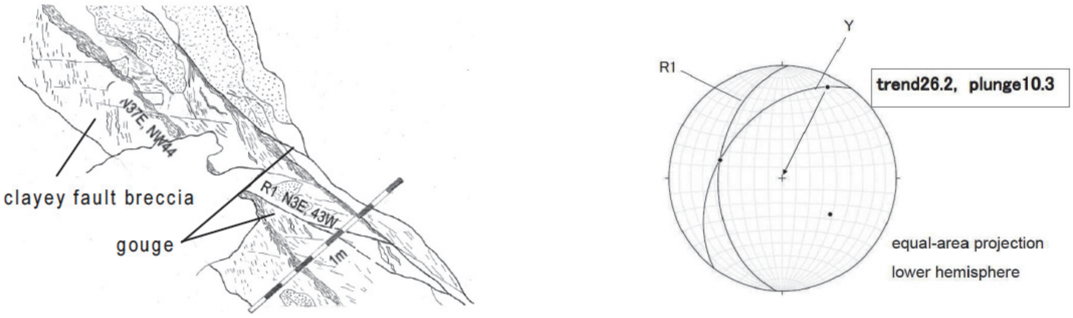

Fig.8 Sketch of Kawarabi thrust at Arrow 2 in Fig.4 and stereographic projection of the plane structures of the fault. The arrow indicates the slip vector.

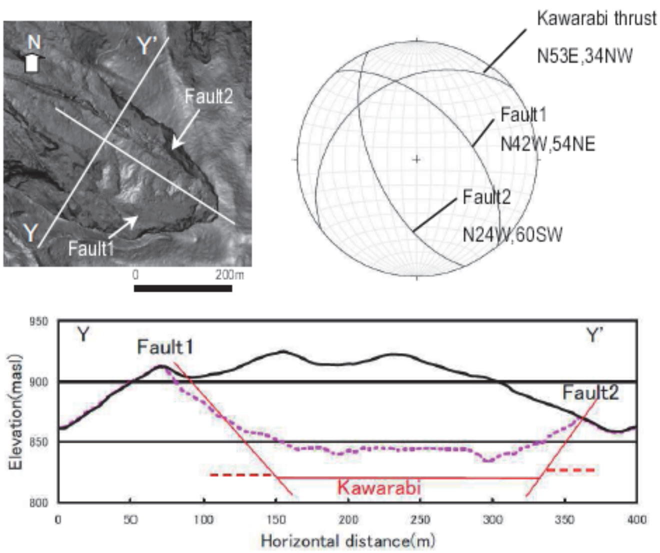

Fig.9 The relationship between the Akatani landslide and the Kawarabi thrust. Modified from Chigira et al., (2013).

few years later, most of the debris on the detachment surface had been removed during rainfall events and a slickenside surface exposed at the base of the landslide scar, which coincided with the trace of the mapped Kawarabi thrust. Chigira et al., (2013) estimated that Akatani rock avalanche had occurred under the wedge failure among the two high angle faults with NW-SE strike and small fault with E-W strike and north dip. Our new finding that the Akatani landslide had its base detachment surface, which was the Kawarabi thrust, indicate that the detachment surface was box-shaped in cross section (Fig.9). Landslide deposit of the Akatani-E landslide had been washed away by the Kawarabi River to expose its internal materials, which had a large amount of black clayey materials. They must be derived from the crush zone of the Kawarabi thrust.

4. Discussion

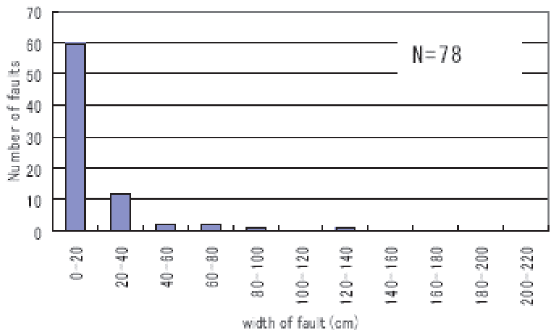

Fig.10 Histogram of the fault widths

The trace of the Kawarabi thrust enlightens its role in the formation of the rock avalanches and preceding gravitational slope deformation. The trace of the Kawarabi thrust is shown in Fig.5 on a slope image and geologic cross sections including this fault are shown in Fig.11. Geological cross sections along the slope lines of the Akatani (D-D') and Akatani-E (B-B') landslides and subparallel nearby lines suggest that the Kawarabi thrust, which was the detachment surface of both the landslides, had been almost exposed at the foots of these two landslides. This is due to the incision of meandering rivers and suggests that the materials on the weak thrust had been undercut. In addition, the Akatani and Akatani-E landslides had been preceded by gravitational slope deformation, which were indicated by small scarps in the upper parts of the landslides (Chigira et al., 2013). Furthermore, lower parts of both the landslides had been failed before the 2011 events. These two slopes had been thus under unstable conditions. The small scarps of gravitational slope deformation were located near the extention of the Kawarabi thrust, which suggests that the deformation started when the thrust became near the surface of the slope foot by river incision. Yokoyama, O. et al., (2014) investigated the Akadani (Akatani of this paper) rock avalanche and reported that the landslide occurred along the many minor faults trending NE-SW and dip 36°. We infer that these minor faults are branches of the Kawarabi thrust. Yokoyama, S. et al., (2013) performed geological investigation around the Akatani area and reported that the Akatani landslide occurred along the composite failure planes of sub-unit thrust and several dip faults. However, comparing their description on the detachment surface and our observation suggests that their sub-unit thrust may correspond to the high-angle fault in this paper.

As is seen in the geologic cross sections along A-A' and C-C' lines where no rock avalanche occurred, the level of the river has not reached the Kawarabi thrust there. Along section A-A', the rock mass of the hanging wall of the thrust mainly

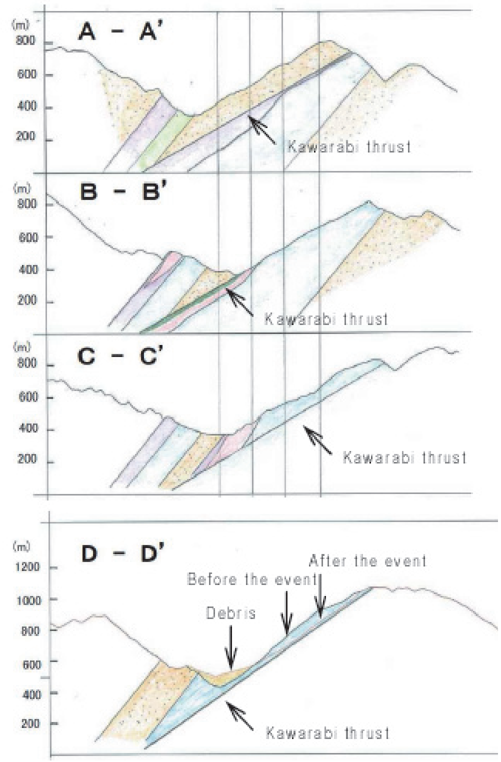

Fig.11 Geologic cross sections. Legend is the same with that of Fig.4.

composed of sandstone, which is not completely cut by the river. Sandstone has rigidities several times larger than those of mudstone in the Shimanto belt and a sandstone bed acts as a competent bed to stabilize a slope.

From the above-mentioned discussion, the Kawarabi thrust is interpreted as a major factor controlling the rock avalanches as well as preceding gravitational slope deformation. This thrust has a crush zone, which is up to 1.5 m thick and is composed of clayey fault breccia with gouge layers. These fault materials are very weak and impermeable, so the fracture zone is expected to prevent the groundwater filtration and build up the pore water pressure. Geometrically, rock avalanches occurred where the fault dip downslope and cut by river incision. These facts strongly suggest that locating a large-scale low-angle-thrust is essentially important to predict potential sites of rock avalanches and to interpret the internal structure of preceding gravitationally deformed slopes. In addition, the combination of low-angle thrust faults and high-angle faults may be a common basic cause of gravitational slope deformation and catastrophic failure by rainstorms in mountains of accretionary complexes.

5. Conclusion

2011 Typhoon Talas induced a large numbers of rock avalanches in the Kii Peninsula, where is underlain by Jurassic-lower Miocene accretionary complexes. We performed geological investigation in the Akatani area, where two huge rock avalanches with volumes of 2 million and 8 million m^3 occurred, and we found that these two rock avalanches had their sliding surfaces along a large-scale low-angle fault extending more than 5 km. This fault dips downslope and had been exposed at riversides by long-term river incision hence its hanging wall beds became gravitationally destabilized and started to deform and finally failed catastrophically during the rainstorm. Our finding suggests that locating a large-scale low-angle-thrust is essentially important to predict potential sites of rock avalanches as well as interpreting the internal structure of gravitationally deformed slopes. The combination of low-angle thrust faults dipping downslope and high-angle faults trending slope lines may be a common basic cause of gravitational slope deformation and catastrophic failure in mountains of accretionary complexes.

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