Geological and geomorphological features of landslides induced by 2011 Typhoon Talas in a granite porphyry area

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Abstract

Typhoon Talas brought heavy rain in the Kii Peninsula, Japan on September 2-5, 2011, causing hundreds of debris avalanches and debris flows in granite porphyry areas in the southeastern part of the peninsula. We made field investigation to clarify the geological and geomorphological background of the landslides, and found that most of the debris avalanches contained a lot of boulders commonly larger than 1 m in diameter. Their source materials involved many boulders of granite porphyry, some of which were in a weathered zone in-situ and others were in debris on nearby sedimentary rocks. These landslides had volumes less than 50,000 m^3 each and low equivalent frictional coefficients (0.20-0.46), which are similar to landslides of grus. However, these landslides involved many big spherical boulders, so that they were much more destructive than those of grus. The boulders are corestones made by the spheroidal weathering of granite porphyry, which had well-developed, high-angle columnar joints and sheeting joints near slope surfaces. The granite porphyry is weathered from the joint surfaces, forming rindlets outside and spherical corestones inside. The weathering zones involving corestones form a thick mantle on low-relief surfaces in higher elevations, which are incised by erosion and mass movements. The rain-induced debris avalanches occurred near the margins of the thick weathering mantle and went down to nearby valleys as debris flows.

Keywords: corestone, spheroidal weathering, debris avalanche

1. Introduction

Granitic rocks commonly weather deeper than 10 m and weathered granitic rocks are often subjected to innumerable landslides induced by rainfall. A typical weathering profile of granite in subtropical climate consists of decomposed granite, which is also called grus, with corestones in the lower part and saprolite in upper part (Ruxton and Berry, 1957). The corestones are formed by spheroidal weathering (Ollier, 1967). Another type of weathering profile consists of saprolite in the upper part and a zone of micro-sheeting joints in the lower part, lying on bedrock with sheeting joint (Hashikawa and Miyahara, 1974). Sheeting joints, which are low-angle and widely spaced, strike roughly parallel to slope contours and dip gently downslope (Chigira, 2001, Hamaoki et al., 2007). The micro-sheeting joints are a several millimeters to centimeters spaced and parallel to the sheeting joints (Chigira, 2001). They are also called as laminations (Twidale, 1973). These macro and micro-sheeting joints are thought to be made by buttressed expansion mainly due to unloading (Folk and Patton, 1982).

Chigira (2001) pointed out the vulnerability of the weathered granite with micro-sheeting from the case study on landslides induced by the rainfall of 250 mm/ 5 hours in Hiroshima on June 1999. Tobe et al. (2007) found that the landslide densities in granite area was 293 /km^2 and was ten times as large as that in granodiorite area (13 /km^2), even though both the areas had experienced a strong precipitation of about 200 mm/ 5hours in Obara village in 1972 and they suggested that it results from difference in the weathering profiles of the two rocks.

On the other hand, landslides often occur in weathering mantles of granitic rocks that contains boulders; for example, during the Uetsu disaster in 1967 (Okuda et al., 1968). Debris-flows consisting of spherical boulders would move rapidly with high inertia, destroying materials on the way, but this type of landslide has not been studied sufficiently.

We report rain-induced landslides containing many boulders of granite porphyry in association with the geological and geomorphological background in the Kii Peninsula, Japan (Fig. 1). The case study we made was for hundreds of debris avalanches and debris flows induced by Typhoon Talas in the southeastern part of the peninsula on September 2-5, 2011. Debris flows that included many large boulders occurred and destroyed houses and infrastructures. 23 people were killed by the landslides and floods, most of which occurred in Nachikatsuura Town from 2:30 to 3:00 a.m. on September 4 (Sato et al., 2013).

2. Geological and climatic setting

The southeast part of the Kii Peninsula is underlain by the Miocene Kumano Acidic Rocks (KARs) on higher elevations and by the Miocene Kumano group or Cretaceous Shimanto Supergroup (both sedimentary rocks) on lower elevations (Fig. 1). KARs, which spreads in an area of 600 km^2, intruded into or partially covered the sedimentary rocks (Aramaki, 1965), and formed a caldera (Miura, 1999). KAR is now separated into the northern mass and the southern mass. Granite porphyry occupies 80% of KARs.

The stricken area is one of the regions that have a large amount of rainfall (2500 mm/yr) in Japan, but little damage had been caused by landslides for over several decades. Sato et al. (2013) reported there was only one disaster with debris-flows that damaged to houses in Nachikatuura Town from 1944 to 2011. However according to Seta et al. (1983), there were debris-flow disasters in 1693, 1846 and 1929. The debris-flows contained large boulders up to 2-20 m, killing 22 people in total. In Shigu, one debris-flow occurred with three fatalities in October 1997. Wakatsuki et al. (2014) calculated return periods of rainfall during the 2011 event and showed that the return period for 1 hour rainfall is 100-160 yrs and that for 6 hours rainfall is 240-330 yrs in Nachikatsuura and Shingu, but the return period for both in Owase is relatively short (<10 yrs).

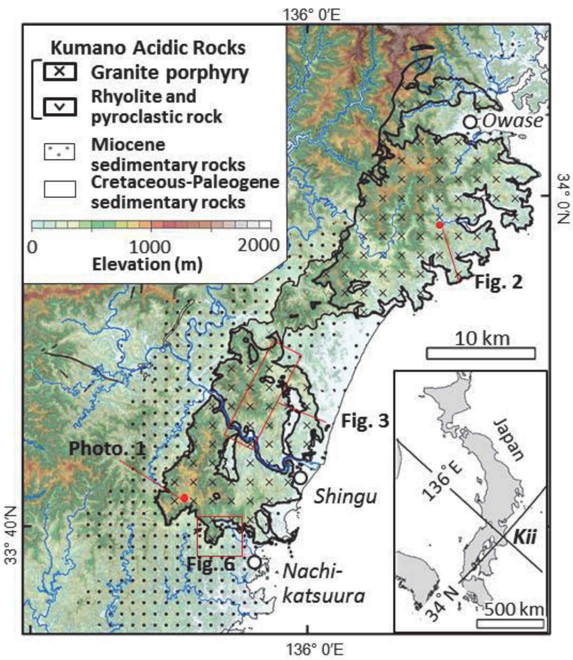

Fig. 1 Geological and topological map in the southeastern part of the Kii Peninsula.

3. Method

We interpreted aerial photos of on a scale of 1: 20,000 taken in September 7 or 8 by the Ministry of Land, Infrastructure, Transport and Tourism, Japan (MILT) or GeoEye, Inc., comparing with Google Earth images taken on April. Then, we plotted all the landslides on a GIS-based map, drawing polygons for landslide scars or source area, and for transporting or depositional areas, separately. Geological boundaries are basically based on the seamless digital geological map of Japan 1:200,000 (Geological Survey of Japan, 2012), Miura (1999), and Kawakami and Hoshi (2007). Rainfall distribution maps were made from 1-km mesh hourly precipitation data of radar-AMeDAS provided by MILT. For the statistical analysis of landslides, we used 10m-mesh DEMs supplied by MILT. Landslide densities are calculated for each cell as the number of landslide sources in a 1-km^2 circle with the center on that cell.

We made field investigations mainly in Nachikatsuura Town, measured dimensions of source areas by a laser distance measuring instrument, and observed landslide materials and weathering grade. The weathering grades of granite porphyry are classified into fresh, slightly weathered, moderately weathered and highly weathered. Slightly weathered rock is intact but it is discolored on its surface part. Moderately weathered rock has a wider area of rock than a grus in an outcrop. When an area of grus is larger than rock, it is classified as highly weathered rock.

4. Result

4.1 Weathering of granite porphyry

Granite porphyry has columnar joints and sheeting joints. Columnar joints are almost vertical and each column has 1-6 m diameters. On large outcrops like a quarry we can observe that the rock body of granite porphyry is intersected by low-angle sheeting joints, which are subparallel to the slopes near the ground surface. The sheeting joints are undulating and anastomosing, and essentially do not displace columnar joints except for loosened rock masses (Fig. 2). The intervals of sheeting joints are 2-5 m and tend to be smaller toward slope surfaces. Dips of sheeting joints were mainly 20-30° with an average of 26° from the data obtained at 21 locations.

Spheroidal weathering is a common weathering scheme for the granite porphyry in the study area. A block of granite porphyry is weathered from the joint surfaces to form a spheroidal corestone surrounded by rindlets (Photo. 1). The surface part of a corestone is a brown layer surrounding the inner whitish-gray

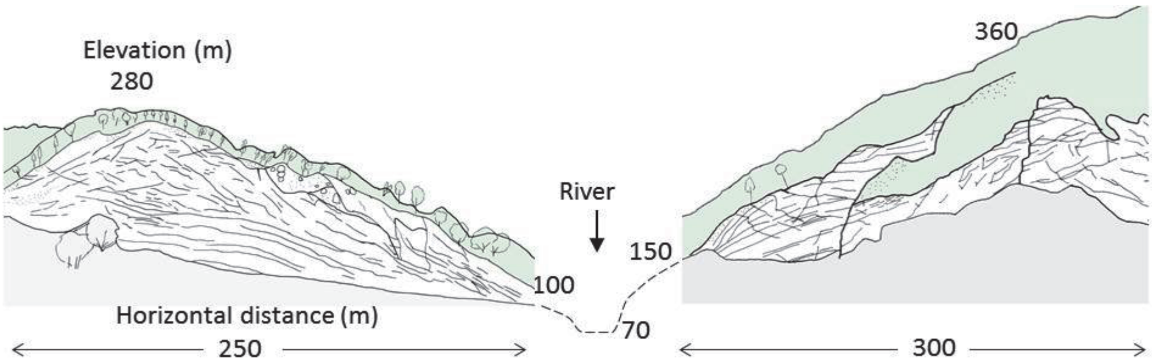

Fig. 2 Sketch of excavation walls of granite porphyry. Most of the narrow lines seem like sheeting joints.

portion. Rindlets are separated from the corestone. They are also called as shells or scales (Ollier, 1967). When we closely look at the rindlets, we know that they are not like a spherical shell but a contact lens.

The study area has low-relief surfaces on top of the mountains, where we observe thick highly -moderately weathered rock up to 100 m of depth (Fig. 3). These weathering mantles have many spheroidal corestones embedded in grus. These low-relief surfaces may be paleo-surfaces, below which granite porphyry has been weathered for a long time without denudation.

4.2 Distribution of landslides

Overlaying the geological map with the landslide distribution suggests that most of the landslides are related with granite porphyry in the survey area (Fig. 4). 623 scars are plotted on granite porphyry area; 54 are on its surrounding slopes on sedimentary rocks; 22 are on the other acidic rocks; and 11 are on sedimentary rocks far from granite porphyry area.

During the heavy rainfalls from 11 p.m. on September 3 to 4 a.m. on September 4, the maximum hourly rainfall was over 80 mm and cumulative rainfall for the 5 hours was 200-470 mm in granite porphyry area. The preceding cumulative precipitation before the intense rainfall was 400-800 mm for 4 days.

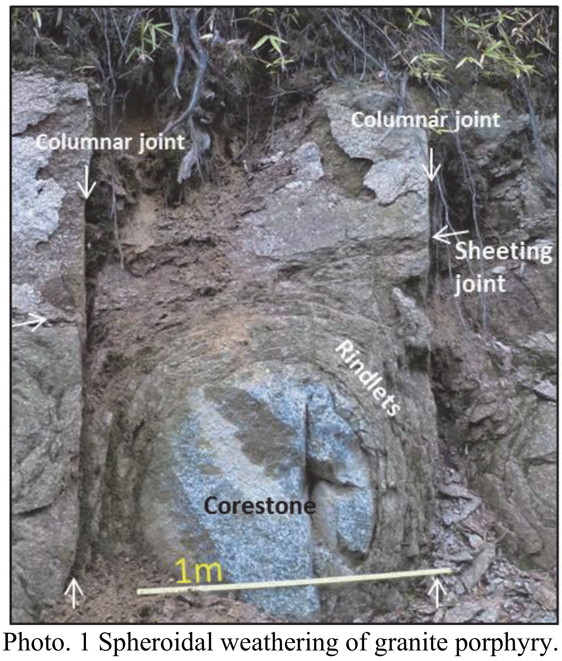

Photo. 1 Spheroidal weathering of granite porphyry.

Landslides occurred at high ratio in granite porphyry area where 5-hour cumulative rainfall exceeded 250 mm. Landslide densities were 1-4 /km^2 in the local areas of 330 km^2 (Fig. 5). The maximum density of landslides was about 18 /km^2 in the Nachigawa watershed. The mean slope of source areas in granite porphyry area was 33° (1σ ± 7°), on the other hand, the mean slope of the local areas in granite porphyry was 31° (1σ ± 10°).

4.3 Feature of landslides in and around the granite porphyry

In the field survey, we found that large boulders (> 1 m in diameter) of granite porphyry were included in the deposits of most landslides, whose sources were located in the weathered granite porphyry area or along the boundary between granite porphyry and sedimentary rock (Fig. 6).

(1) Debris avalanches of weathered granite porphyry

Within granite porphyry area, some debris-flows including the boulders moved downward over 1 km length. One of the largest debris avalanches and following debris flows ran 2.4 km and resulted in catastrophic damage to the Iseki area in Nachikatsuura Town (Fig. 6a). Its source consisted of two adjacent planar scars. The west portion has a horizontal length of 90 m, an average width of 50 m and an average depth of 10 m. The east portion is 50 m long, 35 m wide and 5 m deep on average. Their total volume was estimated to be 50,000 m^3. The landslide source scars had spheroidally weathered corestones in the upper part and slightly weathered granite porphyry with columnar joints in the low part. This landslide may have occurred by the sliding of rock columns along the axis of the columns. Where the debris flow went out to a wide valley bottom at Iseki (Fig. 6), the debris flows spread over the full width of a few tens of meters and deposited the

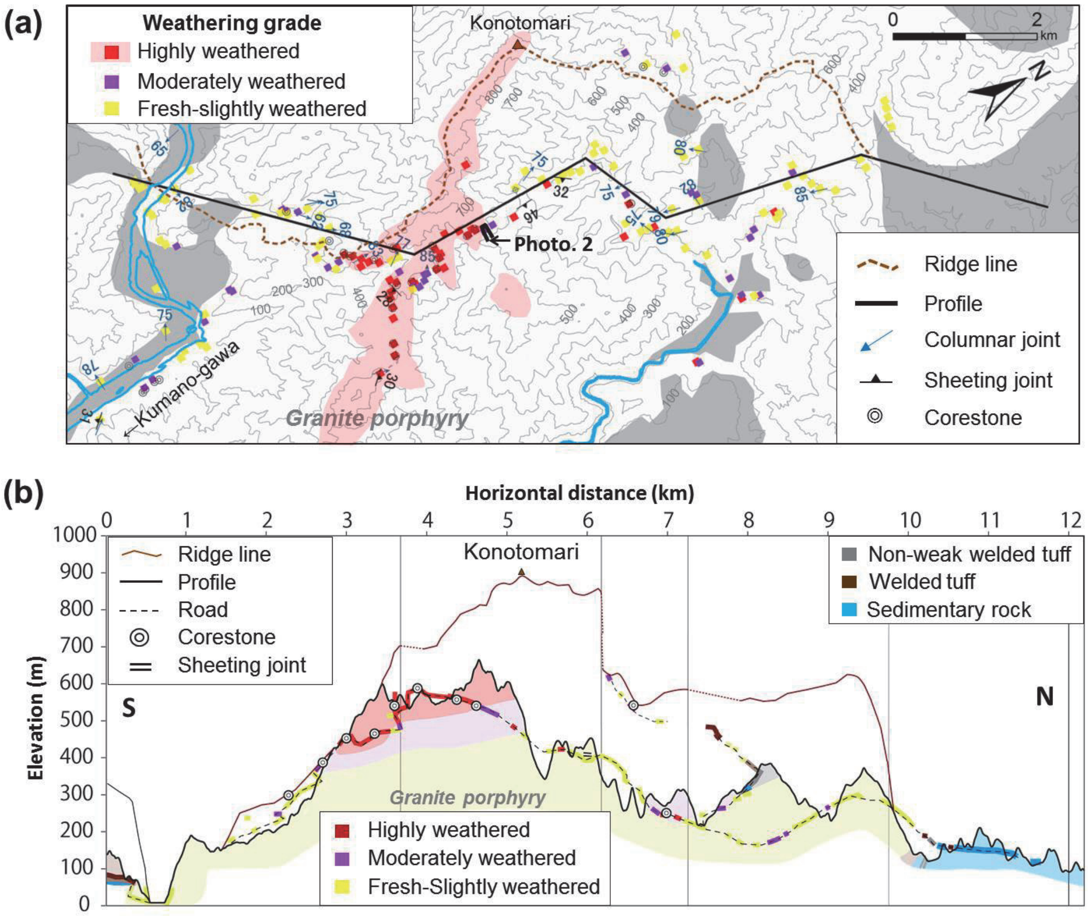

Fig. 3 Weathering mantle in granite porphyry. (a) Plane view. (b) Cross section along the profile line.

boulders with the maximum diameter of 5 m. On top of the original ground surface with angular gravel layer, granitic sand and fine driftwood was seen to fill the space between spherical boulders with diameters of 0.5-3 m. The size of the granite porphyry boulders became smaller than 1.5 m further downstream with occasionally big boulders up to 3 m of diameter.

There were shallow small landslide scars where corestones failed downslope near the edge of gentle ridges with thick weathering mantles. One example is shown in Fig. 6b; it had a horizontal length of 20 m, an average width of 20 m and an average depth of 0.5

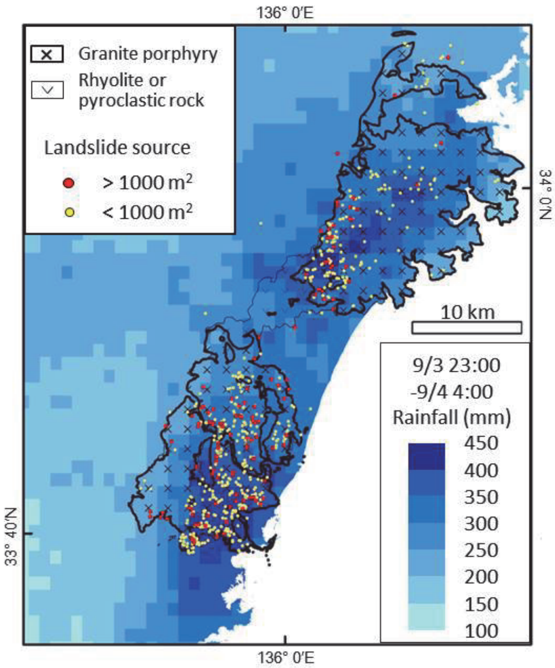

Fig. 4 Distribution of source areas and rainfall cumulated for 5 hours during this 2011 event.

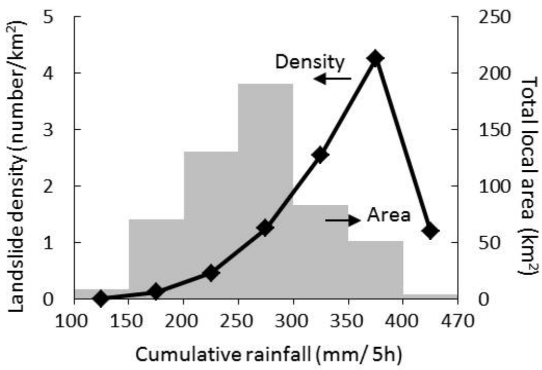

Fig. 5 Landslide densities and total local areas in granite porphyry as a function of the 5 hour cumulative rainfall.

m (Fig. 7b). The lower part of the scar showed rock columns with discoloration. In the upper part, corestones embedded in grus, where was the main portion of the landslide.

Rock avalanches of granite porphyry with sliding along sheeting joints occurred there (Photo 2). This landslide slope consisted of moderately to highly weathered granite porphyry in the higher portion and slightly weathered in the middle to lower. Rock blocks separated by the columnar and sheeting joints were observed to have rotated in a slump manner on the side scarp of the landslide, which suggests that displacement along the sheeting joints had already occurred before the 2011 event.

(2) Debris avalanches of talus deposit

Landslides of thin talus deposit occurred near the boundary between granite porphyry and the Kumano Group. For example, landslides in the south of Mt. Myoho were shallow and tabular in shape (Fig. 6c). Figure 7c shows this type of landslide, of which source area had a horizontal length of 20 m, an average width 10 m and an average depth 1 m. Debris slid down on mudstone, which was altered to clay and very weak. We found a small old scarp above the 2011 landslide crown and that trees on the slopes above this old scarp had been bent, which suggests that slow slope movement had been continuing before the 2011 landslide.

On the slopes surrounding granite porphyry body, debris of granite porphyry is usually lying on dark gray clayey materials, in which we found visible pyrite. These clayey materials are probably due to the hydrothermal alteration caused by the intrusion of the granite porphyry into the shale of the Mitsuno Formation, the top of the Kumano Group.

4.4 Mobility of debris-flows

To evaluate the mobility of landslides, equivalent frictional coefficient (H/L) was calculated from the relative height (H) and horizontal distance (L) between the crown of a scar and the tip of depositional area interpreted from the aerial photos. The equivalent friction coefficients of all 75 debris flows which moved over 500 m are estimated to be 0.34 ± 0.08 on the topographical map. We also estimated volumes of some debris-avalanches to be from 10^2 to 5×10^4 m^3 in the field, and their equivalent friction coefficients were 0.20-0.46 (Fig. 8).

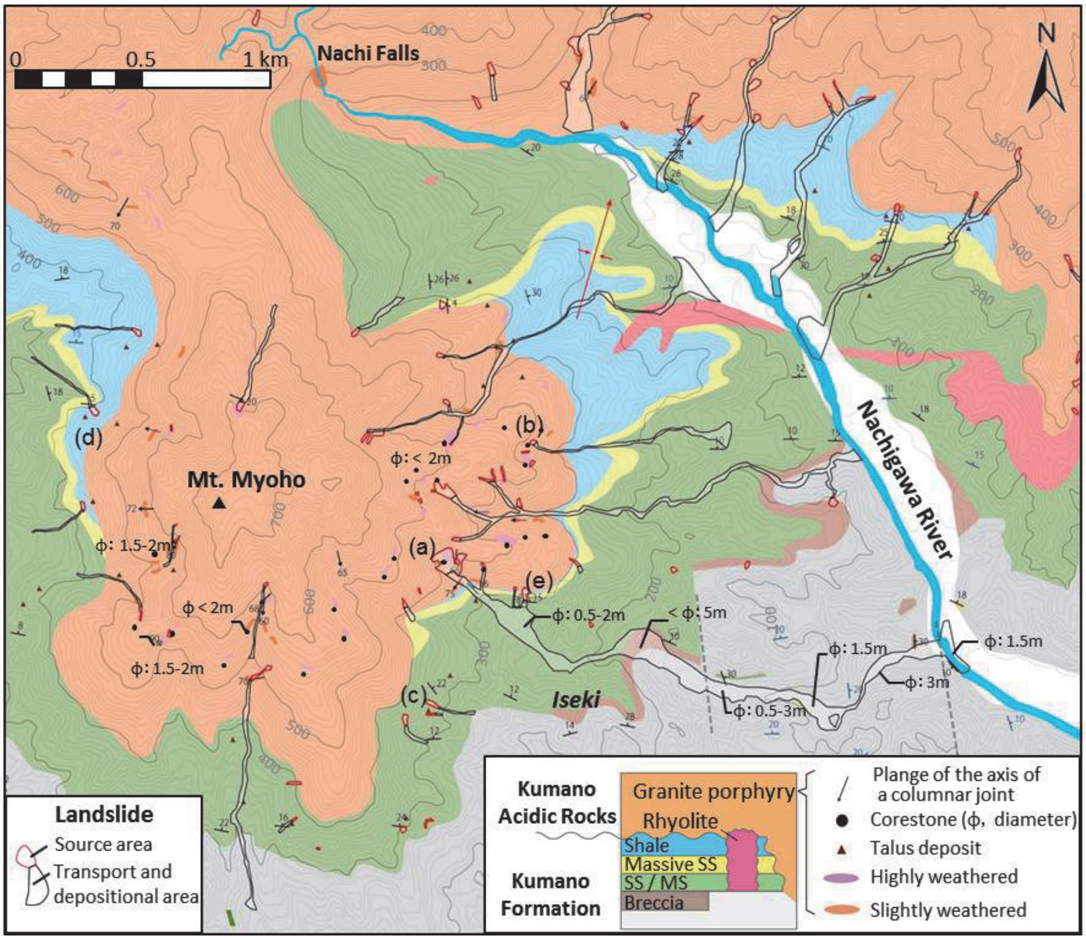

Fig. 6 Landslide distribution on a geological map in Nachikatsuura Town. (a)-(e) indicates the landslide location in Fig. 7. Bedding plains plotted in blue and geological boundaries were modified from Mizuno (1957).

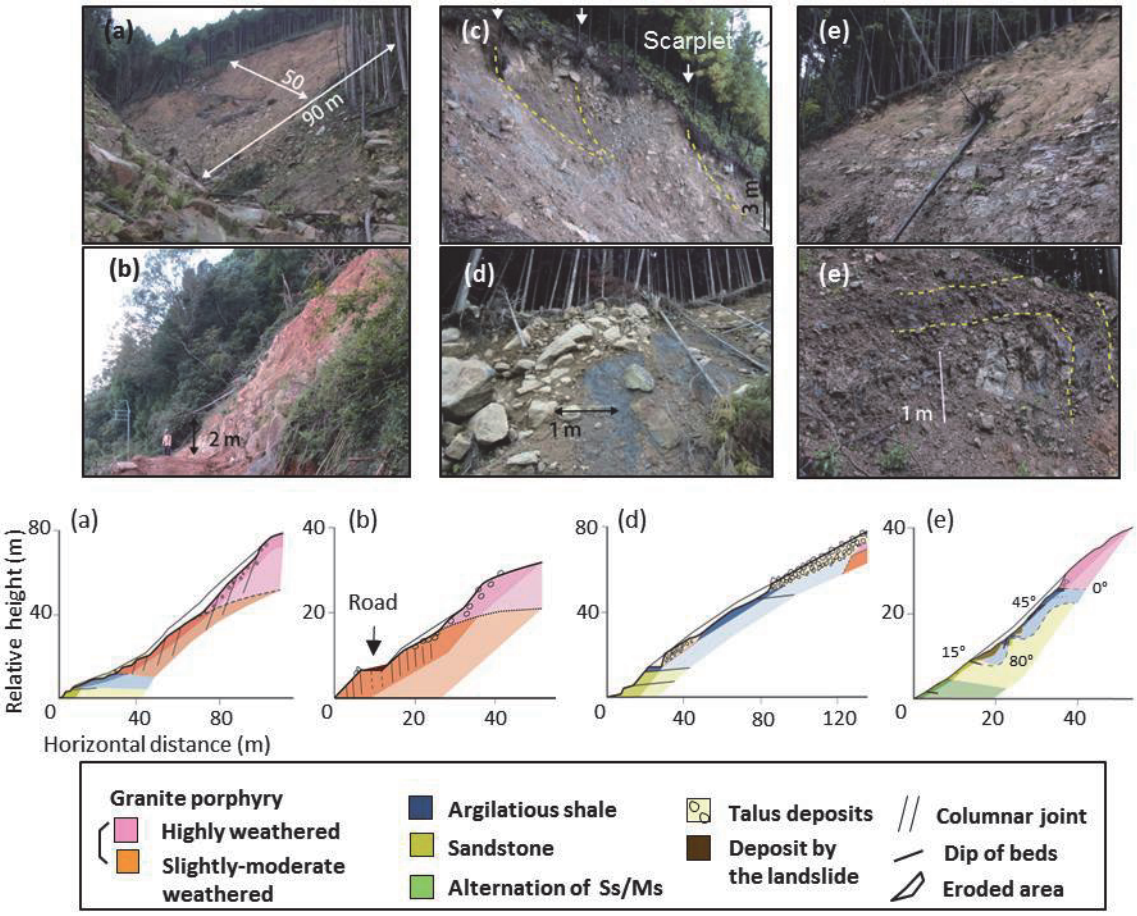

Fig. 7 Photos and cross sections of typical source areas in Nachikatsuura Town in Fig. 6. (a) and (b) Landslides of in-situ weathered granite porphyry. (c) and (d) Those of talus deposit. (e) landslide on a boundary between granite porphyry and sedimentary rocks.

5. Discussion

Shallow landslides have been commonly believed that their occurrence sites are not controlled by bedrock geology except for special bedrock types like unwelded ignimbrite (Yokota and Iwamatsu, 2000) or deeply weathered massive granite (Chigira, 2001), but the experience of the 2011 rainstorm in the south of the Kii Peninsula strongly suggests that they are affected by bedrock geology in a geological setting that granite porphyry with intensive columnar joints intruded into sedimentary rocks. Landslides occurred in a concentrated manner on the granite porphyry slopes and on sedimentary rock slopes near the contact with the granite porphyry.

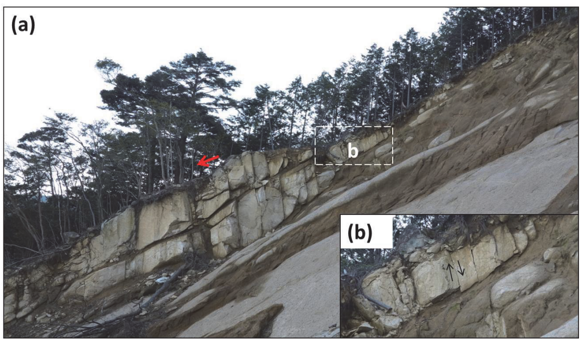

Photo. 2 Right side wall of a landslide scar. (a) Middle-highly weathered rock mass with sheeting joints. The depth of the scar is about 9 m. (b) Close image of the square b.

The granite porphyry in the study area has well-developed columnar joints and has sheeting joints near the slope surfaces, which joints gave the landslide susceptible features to this granite porphyry. Sheeting joints are well known in granite rock body (Ollier, 1965), but probably not known from granitic rocks with intense columnar joints. However, we found that sheeting joints are well developed in this rock type and several rockslides occurred with detachment surfaces along sheeting joints. This type of slide could be triggered by earthquakes as well as by rainfall. Aizawa et al. (2009) reported that large rock-falls in this granite porphyry were caused not only by heavy rainfall but by small earthquakes (an intensity of 4 on the Japanese seven-stage seismic scale) or even in normal period.

Chemical weathering from the surfaces of these

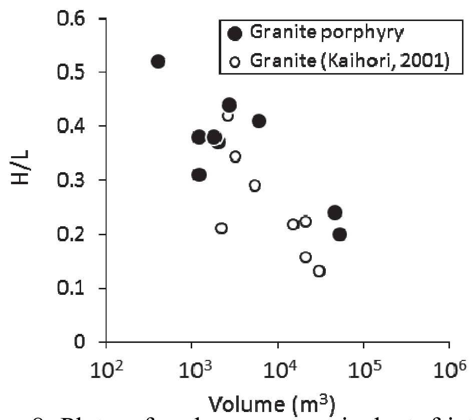

Fig. 8 Plots of volume vs equivalent frictional coefficient (H/L) of landslides.

two types of joints forms unstable structures on slopes. It forms large corestones embedded in grus, leaving a thick weathering mantle on higher elevations. This weathering profile is not stable on slopes and landslides were induced by heavy rainfall as much as 300 mm for 5 hours. Steep riverside slopes, on the other hand, consist of weakly weathered or fresh rocks and are stable and few landslides occurred there.

Landslide densities in the granite porphyry area of this study were up to 18 /km^2 in the area with rainfall of 350-400 mm for 5 hours and were much less than the average landslide density of 293 /km^2 in granite areas with the rainfall of about 200 mm/5h of the 1975 Nishimikawa rainstorm disaster (Tobe et al., 2007). This difference may be due to the difference in weathering profiles between these two rock types. Typical weathering profile in our study site was corestones embedded on grus and underlying rock columns, which are sheeted. The combination of these two joints fosters loosening of rocks, which likely drains groundwater in the bedrock. On the other hand, the materials of landslides induced by the Nishimikawa rainstorm were loosened surface soil layer on much intact weathered granite; the permeability contrast must be much larger than the case of our study area.

Landslides that occurred on sedimentary rocks near the contact with the granite porphyry are also controlled by the geological history, which is a hydrothermal alteration during the igneous intrusion, and the resultant rock properties. The sedimentary rocks near the contact with the granite porphyry in the study area are generally hydrothermally altered to become clayey materials, which is impervious and would prohibit ground water flow. Geomorphologically, the slope surfaces of granite porphyry are generally higher than the juxtaposing slopes of sedimentary rocks, on which boulders of granite porphyry have accumulated. Debris are thus lying on an impervious bed, which is preferable that pore water pressure in the debris would increase during heavy rainstorms. This is probably the reason why landslides occurred intensively on sedimentary rocks near the igneous contacts.

The mobility of landslides of the study site is compared with that of landslides induced by the 1999 Hiroshima rainstorm, which resulted in a similar mobility as follows. The landslide mobility is commonly represented by H/L, which is known as an equivalent coefficient of friction. When comparing the coefficients of the landslides in the study site and those of weathered granite during 1999 Hiroshima rainstorm disaster (Kaihori, 2001), they are plotted on a similar trend (Fig. 8). In the case of weathered granite in Hiroshima, however, corestones were rarely made and microsheeting developed instead (Chigira, 2001). On the other hand, the landslides in our study site involved many big spherical boulders, which probably had higher kinetic energy in motion and struck objects strongly, so that they were much more destructive than those of grus. Round shape of rocks could have led the landslides to high mobility.

6. Conclusions

In the southeastern part of the Kii Peninsula, over 700 of debris avalanches and following debris flows were triggered in and near the granite porphyry area by an intense rainfall of about 250 mm in 5 hours in 2011. The materials of the landslides included many large spherical boulders of granite porphyry, of which shape probably enhanced the mobility during transportation. These spherical boulders are mostly corestones made by the spheroidal weathering of granite porphyry, which had well-developed columnar joints and sheeting joints near ground surface. The granite porphyry is weathered from these joints to make a corestone inside. Corestones are widely distributed below low-relief surfaces in higher elevations, where weathering must have continued for a long time. Landslide volumes were not so large (10^2 - 5×10^4 m^3) and their equivalent friction coefficients were 0.20-0.46, which is similar to those of debris flows of grus. However, considering the inertia of debris flows suggests that the debris flows with large corestones must be much higher than those of grus. Weathering schemes of granitic rocks thus control the destructive power of landslide-debris flows of weathered granite.

The geological features of granite porphyry also characterize density and distribution of landslides. Landslide density in granite porphyry area was 1-4 /km^2 in the intense rainfall zone and 18 /km^2 at the most. It is much sparser than a granite case which was given less rainfall, probably owing to presence of vertical joints. In addition, some sheeting joints played a role of detachment surface of rockslide. Landslides occurred on the Kumano Group near the boundary with granite porphyry were mostly debris slide on clayey materials made by hydrothermal alteration, which occurred during the intrusion of granite porphyry. Clayey materials prohibit groundwater flow and may cause a buildup of pore water pressure to induce landslide.

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