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Characteristics of landslides in unwelded pyroclastic flow deposits, southern Kyushu, Japan

M. Yamao[a,†], R. C. Sidle[1], T. Gomi[2], and F. Imaizumi[3]

[1]Sustainability Research Centre, University of the Sunshine Coast, Locked Bag 4, Maroochydore DC, Queensland, 4558, Australia
[2]Department of International Environmental and Agriculture Science, Tokyo University of Agriculture and Technology, Saiwai 3-5-8, Fuchu, Tokyo, 1585809, Japan
[3]Faculty of Agriculture, Shizuoka University, 836, Ohya, Suruga-ku, Shizuoka, 4228529, Japan
[a]formerly at: Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto, 6110011, Japan
[†]deceased

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Correspondence to: R. C. Sidle (rsidle@usc.edu.au)

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Abstract

We investigated 184 landslides that occurred in unwelded pyroclastic flow deposits (Shirasu) on southern Kyushu Island, Japan, that included detailed data on the rainfall characteristics and the timing of slope failure. Localized rainfall intensity, antecedent rainfall, and topography affected the hydrologic processes that triggered landslides. Antecedent rainfall (adjusted for evapotranspiration losses) for large ($> 200\,\text{mm}$) storms that triggered landslides was much lower than for smaller ($\leq 200\,\text{mm}$) storms. Mean storm intensity and antecedent 7 day rainfall (API$_7$) thresholds of $> 5\,\text{mm}\,\text{h}^{-1}$ and $\leq 30\,\text{mm}$ (or API$_{30} \leq 60\,\text{mm}$), respectively, were useful to identify landslides triggered by rapid pore water pressure response, especially for shorter ($< 20\,\text{h}$) duration events. During smaller storms with lower intensity, landslides are likely affected by a combined increase in soil weight and loss of suction when API$_{30} \geq 150\,\text{mm}$; simulations indicated that these weight and suction changes due to rainfall accumulation decreased factor of safety in steep Shirasu slopes, but did not necessarily trigger the landslides. All but two of the 21 landslides that plotted below a general rainfall intensity-duration threshold for landslide initiation had API$_{30}$ values $> 235\,\text{mm}$, indicating that they were highly influenced by the combined effects of the accumulated weight of rainfall and loss of suction. Our findings show that both event rainfall characteristics and antecedent conditions affect the hydrogeomorphic processes that trigger different types of landslides in Shirasu. This knowledge and the thresholds we have identified are useful for predicting the occurrence of different types of landslides in Shirasu deposits and improving sediment disaster prevention practices, including real-time warning systems.

1 Introduction

Volcanic deposits are highly susceptible to mass wasting and many related sediment disasters have been reported (e.g., Shimokawa et al., 1989; Crosta and Dal Negro, 2003; Ngeu et al., 2004; Bernard et al., 2009; Navarro et al., 2009; Cimarelli et al., 2010; De Falco et al., 2012). Various types of landslides occur in these volcanic materials, including rock falls, flank collapses, rotational slumps, earthflows, debris slides, lahars, and debris flows depending on the characteristics of the deposits and triggering mechanisms. For example, in the western Oregon Cascade Range, competent andesite and basalt lava flows overlie weathered volcanoclastic rocks that are highly altered due to water infiltration through caprock fissures (Swanson and Swanston, 1977). These areas are susceptible to deep-seated mass movements and, where exposed in gorges, promote large rotational slumps (Palmer, 1977). Landslide frequency in the Hong Kong region was higher in areas underlain by dacitic and rhyolitic volcanic rocks compared to other lithologies (Dai and Lee, 2001). Because of the discontinuous nature of deposits on flanks of volcanoes, residual weak soil layers may act as slip surfaces of large landslides (Hürlimann et al., 2001). Such unique depositional patterns in volcanic residuals alter the hydrologic pathways and affect localized weathering of these materials. Interactions amongst hydrology, tectonics, lithology, can increase the occurrence of landslides in volcanic deposits (Sidle and Ochiai, 2006). Furthermore, high and intense rainfall on weathered volcanic materials (including ash) can trigger debris flows and devastating lahars (e.g., Suwa and Yamakoshi, 1999; Palacios et al., 2001; Lavigne and Thouret, 2003).

Shirasu is an unwelded pyroclastic flow deposit composed of dacitic tuff that covers large areas of southern Kyushu Island, Japan, particularly more than half of Kagoshima Prefecture (e.g., Yokota, 1997; Hyodo et al., 2005). These Quaternary deposits have spread in a radius of more than 50 km by the eruptions of the Aira caldera about 25 000 years ago (Miyagi, 1977; Aramaki, 1984; Nakaoka, 1988). Shirasu terrain is steep and often includes isolated butte and mesa landforms. Shirasu deposits are easily weathered and their strength and bulk density progressively decreases as weathering proceeds (Yokota, 1997). Porosity in the upper highly weathered portion of the Shirasu mantle can exceed 60 % and bulk density is often $< 1\,\mathrm{g\,cm^{-3}}$ (Yokoyama, 1970; Chigira and Yokoyama, 2005). Distinct hydrological pathways (including soil pipes) and processes occur in Shirasu deposits because of the high porosity and low density of the soil (Jitousono et al., 2002).

The areas covered by Shirasu in southern Kyushu are often affected by heavy rainfall during typhoons and Baiu frontal storms. Typhoons typically occur from August through October, while Baiu frontal systems occur in early June through late July. Most of these storms approach Kyushu Island from the south delivering moist air from the sea causing heavy rainfall once they strike land in Kagoshima Prefecture. Thus, landslides in Shirasu deposits occur during most years and cause substantial property damage and causalities. For example, in early September 1993, typhoon Yancy delivered precipitation ranging from 180 to 543 mm in a 24 h period throughout south-central Kyushu, causing numerous landslides resulting in extensive loss of life and property damage. In September 2005, typhoon Nabi struck southern Kyushu triggering landslides, debris flows, and flash flooding with a combined death toll of 27 (Teramoto et al., 2006; Taniguchi, 2008).

Various types of landslides occur in Shirasu deposits and cause different sediment-related disasters. For example, during the devastating typhoon Yancy in 1993 (229 mm of total rainfall in Kagoshima; maximum 1 h intensity 46.5 mm h^{-1}), more than 90 % of the landslides occurred on slopes $\geq 30^\circ$ (Fukuda, 2011). On very steep slopes, typically $\geq 50^\circ$, exfoliations with depths < 1 m repeatedly occur (Haruyama, 1974). Deeper rotational or planar landslides are less frequent in Shirasu deposits and typically occur in more deeply weathered mantles and on gentler slopes. An accumulation of more than 400 mm of rain over a 3 day period triggered a large, deep-seated landslide-debris flow near Harihara, Izumi City that claimed 21 lives in July 2007 (Shimokawa and Jitousono, 1999). These previous reports suggest that the types of landslides in Shirasu are associated with rainfall patterns.

As with other mass failures, the internal hydrological processes and dominant flow pathways with respect to soil moisture conditions may dictate the timing, mode, and type of failure in Shirasu deposits (e.g., Bogaard et al., 2000; Jitousono et al., 2002; Sidle and Ochiai, 2006). Unweathered or slightly weathered Shirasu is rather strong in the dry state and supports slope gradients $> 60^{\circ}$. However, water ingress rapidly weakens Shirasu creating instabilities during periods of rainfall (Haruyama, 1974). Many slope failures in steep Shirasu deposits have been attributed to the increased weight of this highly porous material during progressive rainfall along with the associated loss of suction, and thus, reduced soil strength (Sako et al., 2000; Kitamura et al., 2003; Chigira and Yokoyama, 2005). Other landslides in Shirasu are triggered by the build-up of pore water pressure at depth during storms, sometimes affected by soil piping (Haruyama, 1974; Teramoto et al., 2006). Earthquakes also initiate occasional landslides in these deposits (Kubota and Omura, 2006). Once a landslide occurs, the surface Shirasu rapidly weathers facilitating another landslide occurrence within decades to several hundreds of years (Shimokawa et al., 1989; Yokoto and Iwamatsu, 2000).

The timing of landslide occurrence with respect to storm duration, intensity, and antecedent precipitation is critical (e.g., Guzzetti et al., 2004). For instance, shallow rapid failures typically occur during large precipitation events with a period of high intensity (e.g., Sidle and Swanston, 1982; Terlien, 1997), while storm duration and total accumulation of water in the regolith is often more important for the initiation of deeper failures (e.g., Keefer and Johnson, 1983; Simoni et al., 2004). Therefore, the timing of landslide occurrence relative to precipitation inputs is a key factor for understanding the hydrogeomorphic processes that trigger different types of slope failures. Thus, the objectives of this study are to: (1) investigate the range of landslide types that occur in Shirasu based on archived data and field inspections, and (2) develop relationships between rainfall characteristics and the timing of landslides. We obtained detailed data for occurrence time of landslides based on surveys by local government offices and analysed the full range of landslide types. Triggering mechanisms of different types of landslides that we explored include analyses of rainfall amount, intensity, duration, and antecedent conditions. Our findings are aimed at developing prediction methods for different landslide types and resultant sediment disasters in terrain formed by pyroclastic flow deposits.

2 Study site, historical context, and methods

This study was conducted in areas covered by Shirasu deposits in Kagoshima Prefecture, southern Kyushu, Japan (Fig. 1). The active volcano Sakurajima is located in Kagoshima Bay just south of Kagoshima City. Climate in this area is subtropical and humid, with no real dry season. Precipitation is heaviest during the warm months of June and July and least during December and January. Record high and low annual precipitation values were 4044 mm in 1993 and 1398 mm in 1894; mean annual precipitation is 2265 mm. No significant trends in annual, June, or July precipitation since 1883 were found. Mean annual temperature at Kagoshima WMO Station is 17.3 °C with minimum and maximum values of 15.5 (in 1917) and 19.8 °C (in 1998), respectively. There has been a significant increase in mean annual temperature of about 2.3 °C over the 132-year period or about 0.0176 °C yr^{-1}.

The Shirasu deposits derived from Ito pyroclastic flows are concentrated in an arc that surrounds Kagoshima Bay where they originated from the Aira caldera (Fig. 1). These deposits filled the dissected valleys around Kagoshima Prefecture up to an altitude of about 400 m and formed a plateau (Yokoyama, 1970; Miyagi, 1977) (Fig. 2). Evidence suggests that these Ito pyroclastic flow deposits have not been affected by any crustal movement after emplacement (Yokoyama, 1970). Because of the highly erodible nature of these deposits, it is believed that they were dissected within less than 1500 years after initial deposition (Yokoyama, 1999). The mid-Holocene transgression of sea level resulted in coastal erosion of these deposits, while inland deposits continued to be eroded by mass wasting and fluvial processes in steep slopes and incised valleys. An illustration of the past and contemporary volcanic and hydrogeomorphic processes that have sculpted this terrain is given in Fig. 2.

The present area of southern Kyushu covered by unwelded pyroclastic flow deposits contains erosional remnants including isolated buttes and mesas with shallow landslides along the margins (Fig. 3a). Large, incised valleys have eroded into deep Shirasu deposits with mass failures along the inner gorges (Fig. 3d). In the valleys where landslide deposits accumulate, there is a risk of future debris flows once a critical level of sediment accumulates together with the occurrence of a large runoff event (e.g., Benda and Dunne, 1997; Sidle and Ochiai, 2006). Although Haruyama (1974) classified eight types of landslides in Shirasu deposits, most of these landslides can categorized into two types based on the depth of failure. We define these two types as: (1) shallow (< 1 m deep) "slab-type" failures on very steep slopes (Fig. 3b), and (2) deep (one to several meters deep) planer landslides on less steep slopes (Fig. 3c). The slab-type failures in these highly porous deposits occur at high frequencies, whereas the deeper landslides in Shirasu are less frequent. The mean gradient of slab-type failures is $> 71°$ and slope lengths range from about 20 to 100 m. Occurrence of slab-type failures is influenced by increased mass due to long-term rainfall and decreased matric suction or by a combination of both mechanisms. Deeper landslides (one to several meters in depth) occurred on slope gradients ranging from 37 to 46°. These deeper landslides are typically triggered by positive pore water accretion, but can also be influenced or caused by increased weight due to accumulated rainwater and loss of matric suction. These deep landslides cause considerably more damage. As noted by others (Haruyama, 1974; Jitousono et al., 2002), we found evidence of soil piping in both types of landslides (Fig. 3e and f).

Landslide inventories from 1985 to 2005 were obtained via surveys conducted by the Erosion and Sedimentation Control Division and Forest Management Division of Kagoshima Prefecture. Among these data, landslides with clearly defined occurrence times were selected for further analysis. We then overlayed the locations of these landslides onto digital topographic and geologic maps with scales of 1 : 200 000 to ascertain which landslides occurred in Shirasu areas. In total, 184 Shirasu landslides with complete information (i.e., accurate dates, times, locations, and rainfall records) were selected from the 1153 landslides recorded from 1985 to 2005. We conducted field investigations at selected landslide sites.

Rainfall information for events that triggered the landslides were compiled from AMeDAS (Automated Meteorological Data Acquisition System by the Japanese

Meteorological Agency). As a further criterion for landslide selection, we only chose landslides with rainfall records within 5 km. We compiled the following rainfall parameters: (1) total storm precipitation, (2) storm duration, (3) average storm intensity, (4) total event precipitation until the occurrence of the landslide (also, duration and average intensity during this period); and (5) the sum of antecedent 7 and 30 day precipitation (API_7 and API_{30}, respectively). API_7 reflects soil moisture conditions in the near-surface, while API_{30} represents moisture conditions deeper in the soil profile (Sidle et al., 2000). To more accurately represent soil moisture, we subtracted the mean evapotranspiration rate in southern Kyushu (2.6 mm d^{-1}; Takagi, 2013) from API for the period of assessment (i.e., 7 or 30 days). Additionally, we used a simple infinite slope model to calculate the effects of increases in water content (i.e., weight) and decreases in cohesion (i.e., via loss of suction) on the stability of steep Shirasu slopes.

3 Results

3.1 Overview of rainfall conditions that triggered landslides

We documented 184 landslides in Shirasu deposits from 1985 to 2005 that occurred on 57 separate days. In many cases, the landslides that occurred on the same days were triggered by somewhat different rainfall conditions due to location. In all cases we used the AMeDAS rainfall record closest to the landslide site for subsequent analysis. The largest number of landslides reported in the database occurred in 1993 (38 total) during which the region was attacked by typhoon Yancy. Twenty five landslides in the database occurred in 2004; 23 and 22 landslides occurred in 2001 and 2002, respectively. Detailed information on the occurrence of landslides showed that the timing of failures varied depending on location. For instance, during the 5–6 September 2005 storm, some landslides occurred during or just before the onset of intense rainfall, while other landslides occurred just after intense rainfall (Fig. 4).

Wide ranges of rainfall and antecedent precipitation triggered landslides. Total storm duration and duration up to landslide occurrence ranged from 5 to 271 h and 2.5 to 141 h, respectively. Average storm intensity for the entire storm and during the period up to landslide initiation ranged from 1.3 to 28.6 and 0.3 to 32 mm h^{-1}, respectively. Total storm precipitation and cumulative precipitation up until the landslide ranged from 45 to 650 and 4 to 621 mm, respectively. Maximum 1 h intensity of storms that triggered landslides ranged from 7 to 80 mm h^{-1}.

3.2 Storm size, antecedent rainfall, and landslide initiation

We categorized the 184 landslides into storms with large (> 200 mm) and small (≤ 200 mm) total amounts of rainfall up to the occurrence of landslides. Both adjusted 7 and 30 day antecedent rainfall for large (> 200 mm) storms that triggered landslides was much lower than for smaller (≤ 200 mm) storms (Fig. 5). For example, of the 93 large storms, 78.5 % had an adjusted $API_7 \leq 60$ mm; only 4 % of these larger storms had an adjusted $API_7 > 150$ mm. In contrast, of the 91 smaller storms, 56 % had an adjusted $API_7 > 60$ mm. Similarly, 71 % of large storms that triggered landslides had adjusted $API_{30} \leq 180$ mm, while only 41 % of the small storms had adjusted $API_{30} \leq 180$ mm. In particular, the high numbers of landslides that occurred during smaller storms when API indices were high (i.e., $API_7 > 210$ mm and $API_{30} > 240$ mm) strongly suggests that these were heavily influenced by an accumulation of water in the weathered Shirasu (Fig. 5). Conversely, the larger numbers of landslides that occurred during large storms when API indices were low to moderate (i.e., $API_7 < 90$ mm and $API_{30} < 120$ mm) implies that many of these failures were triggered by pore water pressure response during individual storms (Fig. 5).

3.3 Effects of changes in weight and cohesion due to accumulated rainfall

The effects of increased soil weight due to rainwater accumulation as well as the concurrent loss of cohesion (suction decrease) on the stability of steep Shirasu hillslopes were assessed using a simple infinite slope model:

$$\mathrm{FS} = \frac{C + \left(\gamma_\mathrm{f} d \cos^2\alpha - u\right)\tan\phi}{\gamma_\mathrm{f}\, d \,\cos\alpha \sin\alpha}, \qquad (1)$$

where FS is the factor of safety ($\mathrm{FS} \leq 1$ indicates conditions of failure), γ_f is the unit weight of soil at field moisture ($\mathrm{kN\,m^{-3}}$), d is the vertical soil depth (m), C is soil cohesion (kPa), α is slope gradient (degrees), ϕ is internal angle of friction (degrees), and u is pore water pressure (kPa, set to zero in these unsaturated examples). Two cases were examined, one with shallow soils (0.5 m) and very steep slope gradient (72°) typical of slab-type failures, and another with deeper soils (1 m) and a slope gradient of 40°. The values selected for C and ϕ are typical for Shirasu soils in southern Kyushu (Haruyama, 1974; Iwamatsu et al., 1989; Sako et al., 2000; Chigira and Yokoyama, 2005). In calculations, unit soil weight was allowed to vary from totally dry up to near-saturated conditions. In simulations of both site conditions, cohesion was determined as a function of soil suction described by an exponential distribution fitted to Sako et al. (2000)'s Shirasu data. Soil suction was related to water content via a simple log-log function that fit these data. Alternatively, soil cohesion was considered static ($C = 5$ kPa) for both cases to assess only the effects of increased soil weight. In these simulations, the increased weight of rainwater alone decreases FS by about 1.4 for shallow soils on steep slopes (slab-type failures) and about 0.4 for the deeper soils going from driest to wettest conditions (Fig. 6). However, if the effects of reduced cohesion are also included, FS declines more rapidly during initial wetting and ultimately approaches failure conditions ($\mathrm{FS} = 1$) in both slope conditions as the soil reaches saturation. Clearly the combined loss of suction and increase in soil weight play a role in destabilizing both types of hillslopes, but the amount of reduction in FS is much greater in the potential steep, slab-type failures. Nevertheless, in many cases, it may also be necessary for a positive pore water pressure to develop to induce slope failure.

3.4 Storm precipitation – duration relationships associated with landslide initiation

Relationships between total storm precipitation and storm duration (both up until the occurrence of landslides) were established for relatively low ($\leq 5\,\text{mm}\,\text{h}^{-1}$) and higher ($> 5\,\text{mm}\,\text{h}^{-1}$) intensity events. For each of these populations, total storm precipitation was significantly correlated to the respective storm duration ($p < 0.01$; R^2 values ranged from 0.73 to 0.74) (Fig. 7). Higher intensity storms ($> 5\,\text{mm}\,\text{h}^{-1}$) that triggered landslides were shorter in duration and the slope of the cumulative precipitation vs. storm duration line was more than twice as steep as the slope of the lower intensity ($< 5\,\text{mm}\,\text{h}^{-1}$) line. These differences suggest that different landslide types and mechanisms may be associated with the two populations.

To further analyse these relationships between cumulative precipitation and storm duration up until landslide occurrence, we examined whether antecedent precipitation helped discriminate causal effects in both the > 5 and $\leq 5\,\text{mm}\,\text{h}^{-1}$ storm populations. For the 93 storms with average intensities $> 5\,\text{mm}\,\text{h}^{-1}$, an adjusted $\text{API}_7 \leq 30\,\text{mm}$ was used to distinguish storms that would likely trigger landslides by pore water pressure accretion during the event; whereas, $\text{API}_7 > 30\,\text{mm}$ would more likely be associated with landslide triggering mechanisms that partially involved an increase in mass due to accumulated rainwater and possibly loss of suction. Both the $\text{API}_7 \leq 30$ and $\text{API}_7 > 30\,\text{mm}$ subclasses had significant correlations between storm precipitation and duration ($p < 0.01$; $R^2 = 0.70$ and 0.80, respectively), and, for storm durations $> 20\,\text{h}$, the $\text{API}_7 \leq 30\,\text{mm}$ events generally required substantially more cumulative rainfall to trigger a landslide compared to storms preceded by an adjusted $\text{API}_7 > 30\,\text{mm}$ (Fig. 8a).

It was more difficult to segregate the 91 landslide-triggering storms with low average intensity ($\leq 5\,\text{mm}\,\text{h}^{-1}$) using an API_{30} threshold. While relationships between cumulative precipitation and storm duration up until landslide occurrence were poorly correlated ($R^2 = 0.41$ and 0.047 for $\text{API}_{30} \leq 150$ and $\text{API}_{30} > 150\,\text{mm}$, respectively;

Fig. 8b), during multi-day storms, the $\mathrm{API}_{30} \leq 150\,\mathrm{mm}$ events generally required substantially more cumulative rainfall to trigger a landslide compared to storms preceded by an adjusted $\mathrm{API}_{30} > 150\,\mathrm{mm}$. In six storms with high event rainfall ($\geq$ 315 mm) prior to slope failure, the triggering mechanism for these landslides was likely pore water accretion during the event (see highlighted portion in Fig. 8b).

4 Discussion

Antecedent rainfall is known to influence landslide initiation with wetter conditions promoting more rapid pore water pressure response near potential failure planes (Sidle, 1984, 1992; Crozier, 1999). Furthermore, instability can be enhanced by accumulations of antecedent rainfall within highly porous regoliths on steep slopes (Kitamura et al., 2003; Ali et al., 2014), increasing the downslope component of the regolith mass as well as decreasing the matric suction as soil and weathered bedrock becomes wetter (Fredlund and Rahardjo, 1993; Chigira and Yokoyama, 2005).

4.1 Comparisons with intensity-duration thresholds for landslide initiation

Caine (1980) developed a relationship between mean rainfall intensity and storm duration based on 73 events worldwide that triggered landslides and debris flows. The lower bound of this relationship, above which most landslides occur is

$$I = 14.82\,D_\mathrm{s}^{-0.39}, \tag{2}$$

where I is the mean storm intensity ($\mathrm{mm\,h^{-1}}$) and D_s is the storm duration (h). Sidle and Ochiai (2006) modified this general relationship by excluding very short and long duration events and including additional data:

$$I = 13.58\,D_\mathrm{s}^{-0.38}. \tag{3}$$

Such thresholds are useful for establishing the minimum rainfall inputs that trigger landslides and debris flows. Here we plot the total storm rainfall – duration data for all 184 rainfall events and compare these with Eq. (3) to help understand the conditions that caused slope failure (Fig. 9). We used total storm rainfall and average intensity (not the values for rainfall up until the landslide occurrence) to be consistent with the data used to develop Eqs. (2) and (3).

While many landslide producing storms plot near the Sidle and Ochiai (2006) threshold, 21 landslides were triggered by events plotting below the threshold (Fig. 9). Only two of these 21 events had API_{30} values < 235 mm and more than half had API_{30} values > 300 mm. These storms and the events positioned just above the threshold are likely influenced by the combined effects of the accumulated mass of rainfall and associated loss of matric suction within the highly porous Shirasu deposits.

Based on our analyses and understanding of threshold behaviour for different types of landslides, the following criteria were used to identify landslides triggered primarily by pore water pressure during individual large storms: $\mathrm{API}_{30} \leq 60$ mm, average storm intensity $> 5\,\mathrm{mm\,h^{-1}}$, and duration < 20 h. These lower adjusted API_{30} values indicate that the associated landslides are not likely caused by increases in mass and decreases in suction due to long-term accumulated water in the regolith. Additionally, an average storm intensity of $5\,\mathrm{mm\,h^{-1}}$ provides a good segregation criterion for landslide populations based on total precipitation – duration plots (Fig. 7). Of the 93 landslide events during large storms, 40 occurred when $\mathrm{API}_{30} \leq 60$ mm and average storm intensity $> 5\,\mathrm{mm\,h^{-1}}$, thus strongly suggesting rapid pore water pressure response as the cause. Additionally, the six large, lower intensity storms highlighted in Fig. 8b (total precipitation > 300 mm and average intensities $\leq 5\,\mathrm{mm\,h^{-1}}$) likely triggered landslides due to pore pressure response. For the smaller storm category (≤ 200 mm), we can assume that higher average intensities ($> 10\,\mathrm{mm\,h^{-1}}$), together with > 75 and ≤ 200 mm of rainfall up until slope failure, will trigger landslides by pore pressure response during storms. These criteria account for 14 landslide events from the small storm category that could be triggered by pore pressure. In cases where API values are high, it is difficult to use API to separate landslide-producing storms in which the trigger mechanism was the combined increase in soil mass and loss of suction from those triggered by pore water pressure because many of these events were large enough to initiate landslides via pore pressure accretion alone. During smaller storms, and especially less intense storms, landslides are likely caused by a combined increase in soil mass and loss of suction when API_{30} is high. Our analyses could not account for soil piping effects as this was not noted in the landslide records.

5 Summary and conclusions

Our study lends insights into the relationships between rainfall characteristics and different types of landslides in unwelded pyroclastic flow deposits. These Shirasu landslides inflict heavy damages every year in southern Kyushu during the storm seasons. Two distinct rainfall conditions trigger different types of landslides in Shirasu deposits. The first scenario involves long-term (i.e., weeks) accumulated rainfall stored in highly porous Shirasu on very steep slopes (often $> 60°$) followed by a small to large rain event with typically low intensity. This antecedent moisture together with the additional mass of event rain and the associated decrease in matric suction tends to promote "slab-type" and other shallow failures (< 1 m depth) in highly weathered Shirasu. These failures have a high frequency of recurrence as exposed material weathers rapidly promoting a new failure within the weathered rind. In the second rainfall scenario, shorter duration, higher intensity storms with large total precipitation up until landslide occurrence trigger slightly deeper (> 1 m depth) landslides via pore water pressure response at a hydrologic discontinuity (i.e., weathered–unweathered Shirasu boundary) or by piping mechanisms. These slightly deeper landslides are typically larger, occur on gentler slopes, and initiate as the result of individual storm events. They can be influenced by shorter-term antecedent precipitation as well.

For the 184 landslide events in our database, antecedent precipitation was clearly lower for large (> 200 mm) landslide-producing storms compared to smaller ($\leq$

200 mm) storms, lending support to the importance of the influence of long-term antecedent precipitation (increasing mass and reducing suction) on shallow (slab-type) failures. Additionally, two clear populations of landslides in Shirasu emerged from the average storm intensity-duration rainfall relationship: those triggered by storms with average intensities up until landslide occurrence of $> 5\,\mathrm{mm\,h^{-1}}$ and those triggered by storms with average intensities $\leq 5\,\mathrm{mm\,h^{-1}}$. Further inspection based on antecedent precipitation provided additional insights into landslide responses. For higher average intensity ($> 5\,\mathrm{mm\,h^{-1}}$) storms, $\mathrm{API}_7 \leq 30\,\mathrm{mm}$ was useful to identify landslides triggered by rapid pore water pressure response, especially for shorter ($< 20\,\mathrm{h}$) duration events. Landslides that initiated during low intensity ($\leq 5\,\mathrm{mm\,h^{-1}}$) storms were strongly influenced by increased mass and loss of suction associated with API_{30} values $> 150\,\mathrm{mm}$. Even for the low intensity events with $\mathrm{API}_{30} \leq 150\,\mathrm{mm}$, only about six landslides were attributed specifically to pore pressure accretion during the event – these occurred during large ($> 300\,\mathrm{mm}$) storms; the remaining landslides were likely influenced in part by accumulated mass due to prior rainfall as well as loss of suction.

The results of this study show that different storm and antecedent precipitation conditions need to be considered in predicting the occurrence of different types of landslides in Shirasu deposits. This new information is quite valuable for sediment disaster prevention, including real-time warning systems.

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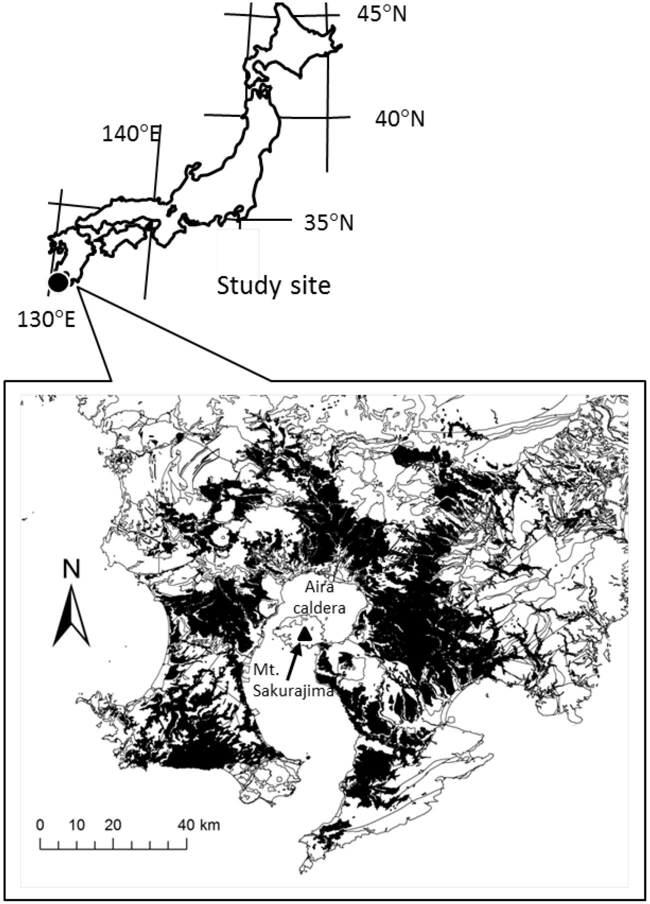

Figure 1. Study site showing the distribution of Shirasu deposits.

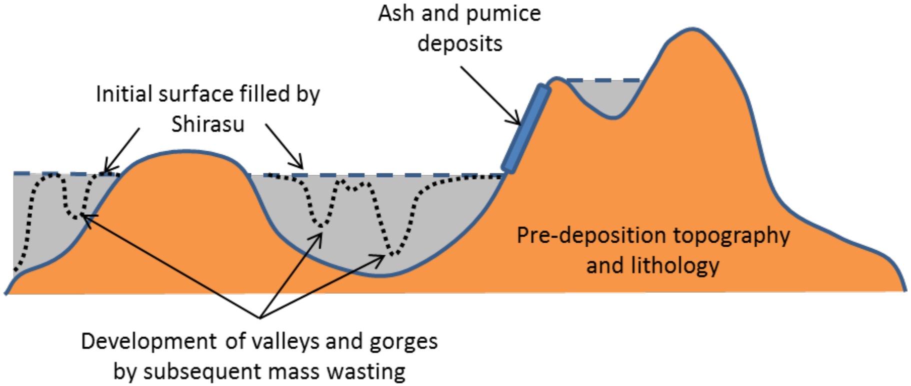

Figure 2. Schematic illustration of the dominant deposition patterns of pyroclastic materials (Shirasu) and the subsequent hydrogeomorphic processes that induced various types of sediment movements.

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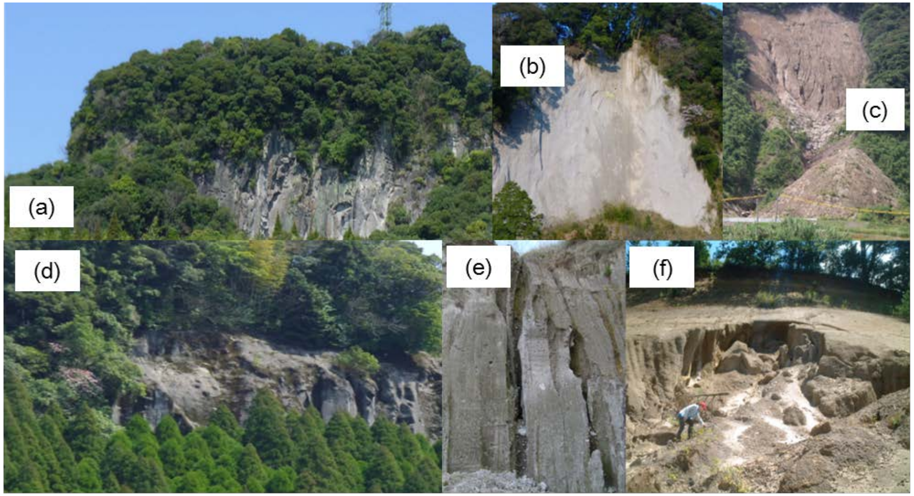

Figure 3. Characteristics of geomorphic features in Shirasu areas: **(a)** isolated buttes and mesas with active mass wasting along margins; **(b)** "slab-type" failures on steep slopes; **(c)** deeper planar failures on less steep slopes; **(d)** shallow landslides along inner valley gorges; **(e)** shallow piping phenomena; and **(f)** soil piping and subsequent gully formation.

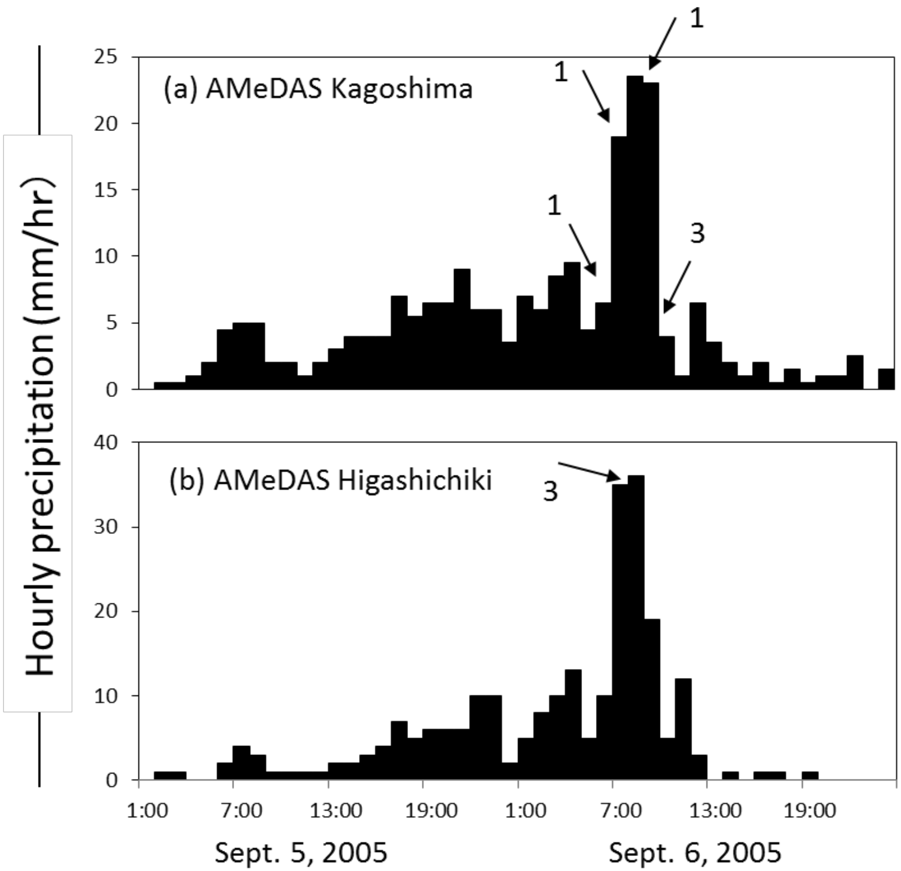

Figure 4. Examples for rainfall hyetographs in two locations of Kagoshima Prefecture showing the occurrence of landslides during typhoon Nabi, 5–6 September 2005. Arrows and values indicate the timing and numbers of landslides, respectively.

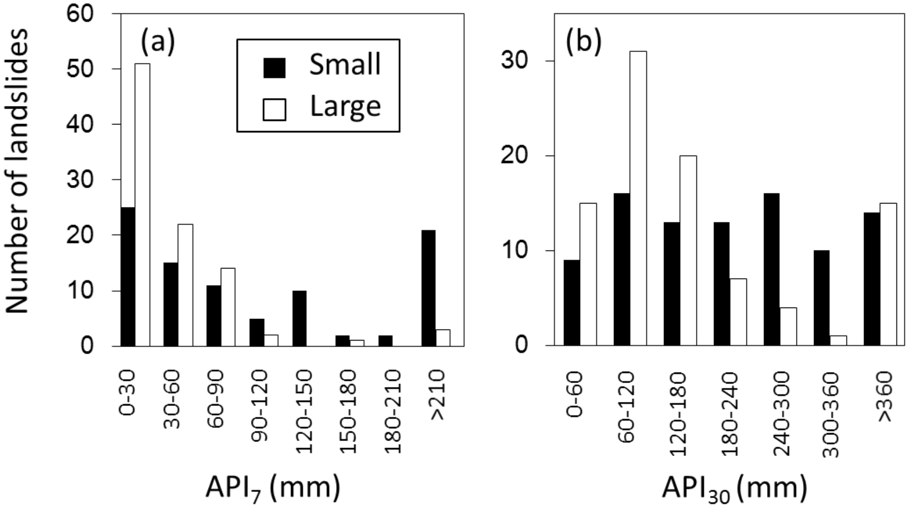

Figure 5. Distributions of small (≤ 200 of storm precipitation up until the occurrence of the landslide) and large (> 200 mm precipitation until the landslide) storms that triggered landslides for different levels of adjusted API$_7$ **(a)** and API$_{30}$ **(b)**.

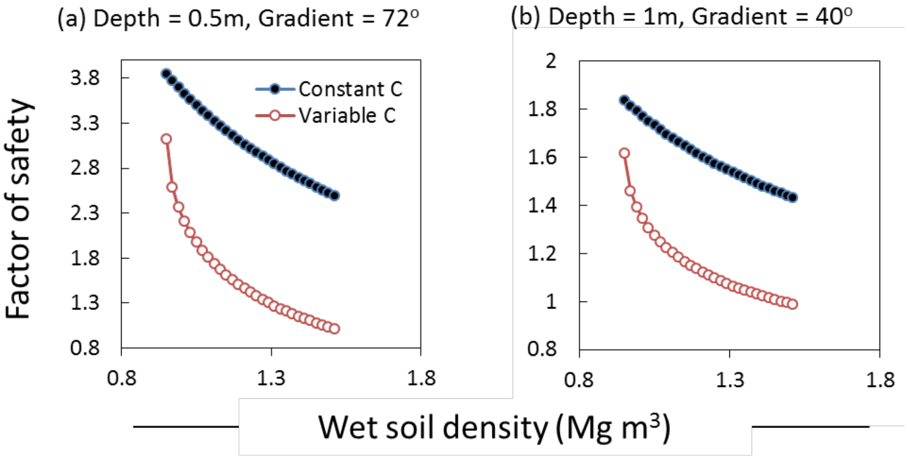

Figure 6. Changes in factor of safety of Shirasu hillslopes with increases in wet density with constant cohesion ($C = 5\,\text{kPa}$) and variable soil cohesion based on cohesion – suction relationships for Shirasu (Sako et al., 2000). Two slope stability cases are considered: **(a)** shallow soil ($d = 0.5\,\text{m}$) mantle on very steep slopes (72°); and **(b)** deeper soils ($d = 1\,\text{m}$) on 40° slopes. For both cases, $\phi = 32^\circ$, $u = 0\,\text{kPa}$, and γ_f ranged from 9.32 (driest conditions) to $14.81\,\text{kN}\,\text{m}^{-3}$ (nearly saturated conditions).

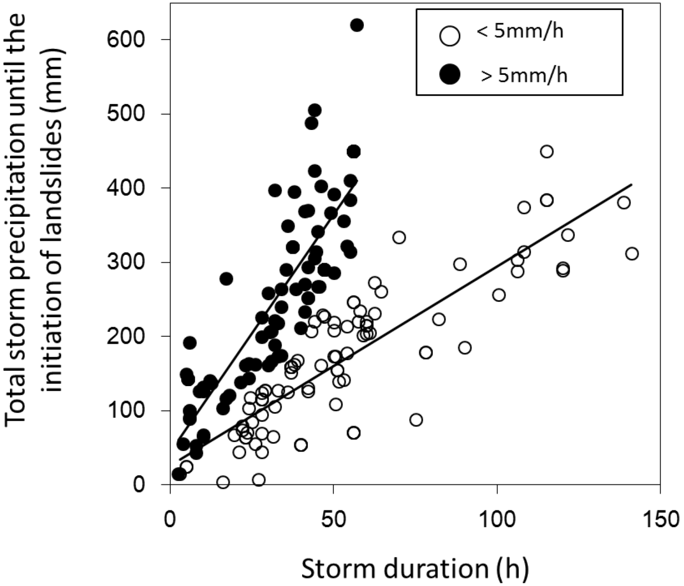

Figure 7. Storm rainfall–duration relationships with average intensities > 5 and < 5 mm h^{-1}.

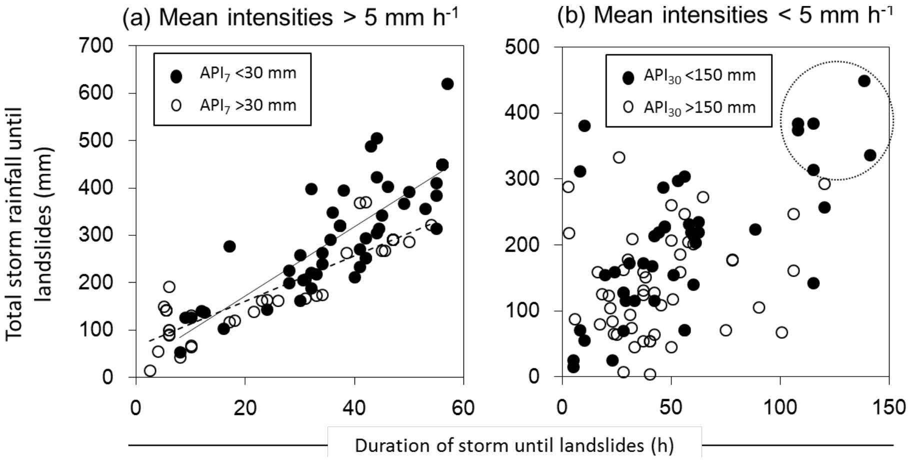

Figure 8. Total storm rainfall–duration relationships with different API conditions: **(a)** mean intensities $> 5\,\mathrm{mm\,h^{-1}}$ **(b)** mean intensities $< 5\,\mathrm{mm\,h^{-1}}$; dashed circle indicates six large and long duration events that probably triggered landslides due to an accumulation of pore water pressure during the individual storms.

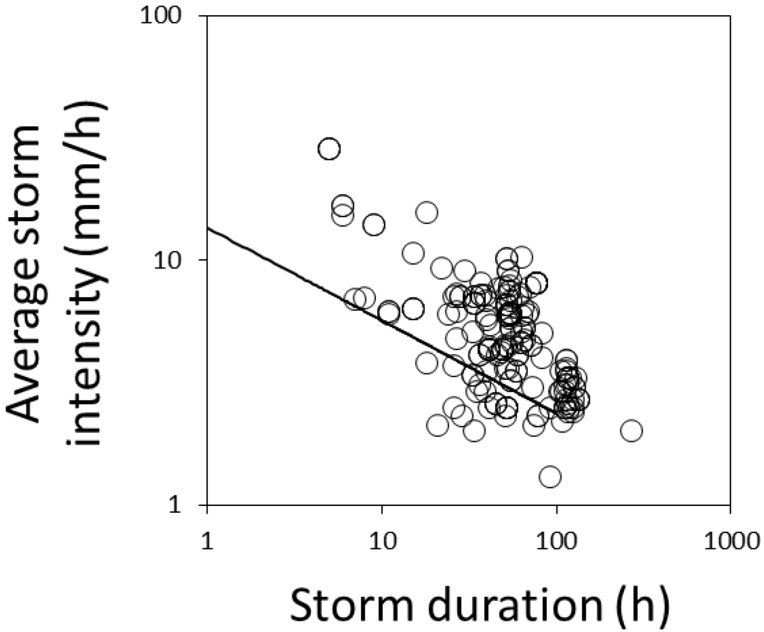

Figure 9. Average storm intensity vs. storm duration for the events that triggered landslides. Solid line is the lower landslide threshold based on Eq. (3) (Sidle and Ochiai, 2006).