Matjaž Mikoš · Binod Tiwari
Yueping Yin · Kyoji Sassa *Editors*

# Advancing Culture of Living with Landslides

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*Editors*
Matjaž Mikoš
Faculty of Civil and Geodetic Engineering
University of Ljubljana
Ljubljana
Slovenia

Binod Tiwari
Civil and Environmental Engineering Department
California State University, Fullerton
Fullerton, CA
USA

Yueping Yin
China Institute of Geo-Environment Monitoring
China Geological Survey
Beijing
China

Kyoji Sassa
International Consortium on Landslides
Kyoto
Japan

*Associate editors*
Mateja Jemec Auflič
Geological Survey of Slovenia
Ljubljana
Slovenia

Adrin Tohari
Research Center for Geotechnology
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Bandung
Indonesia

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Center for Disaster Studies
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Pulchowk
Nepal

Beena Ajmera
California State University
Fullerton, CA
USA

Snježana Mihalić Arbanas
Faculty of Mining, Geology and Petroleum Engineering
University of Zagreb
Zagreb
Croatia

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# Landslide Diversity in the Rwenzori Mountains (Uganda)

Liesbet Jacobs, Olivier Dewitte, Clovis Kabaseke, François Kervyn, Jan Maes, Kewan Mertens, Adriano Nobile, John Sekajugo, Jean Poesen, Denis Samyn, and Matthieu Kervyn

**Abstract**

In the Rwenzori Mountains, at the border between Uganda and the D.R. Congo, landslides frequently occur and cause fatalities and substantial damage to agricultural land and infrastructure. Up until recently, no information on the landslide characteristics, occurrence or spatial distribution was available. The use of archive inventories and field surveys however allowed identifying the key mass wasting processes in this region and their triggering and controlling factors. Here, we present the results of these multi-temporal archive and field inventories. The Rwenzori mountains are diverse in lithology, topography and land use patterns. This diversity in landslide controlling factors is also reflected in the types of landslides that occur in this 3000 $km^2$ large region. The majority of the Rwenzori Mountains consists of steep slopes on gneiss, mica-schists and amphibolite lithologies. A dominance of shallow translational soil slides is observed in gneiss while the amphibolite is found not to be prone to such landslides. This is in sharp contrast to the lowlands, which are characterized by gentle slopes and a rift alluvium lithology. In contrast to what was expected, the largest landslide densities are found in these lowlands where large, deep-seated rotational soil slides with head scarps up to 30 m depth prevail. In both the lowlands and the uplands, slope gradients appears to be the main topographic predictor for the spatial occurrence of landslides. Finally, concerning landslide triggering events, in both the archive inventory and the field surveys, rainfall-triggered landslides are the most common but co-seismic slides were also observed.

**Keywords**

Landslides • Rwenzori Mountains • East-African rift

L. Jacobs · O. Dewitte · F. Kervyn · A. Nobile · D. Samyn
Department of Earth Sciences, Royal Museum for Central Africa, Leuvensesteenweg 13, 3080 Tervuren, Belgium

L. Jacobs (✉) · J. Maes · M. Kervyn
Department of Geography Earth System Science, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Elsene, Belgium
e-mail: liesbet.jacobs@africamuseum.be

C. Kabaseke
School of Agricultural and Environmental Sciences, Mountains of the Moon University, Fort Portal, Uganda

J. Maes · J. Poesen
Division of Geography and Tourism, KU Leuven, Celestijnenlaan 200E, 3001 Heverlee, Belgium

J. Sekajugo
Department of Natural Resource Economics, Busitema University, P.O. Box 236, Tororo, Uganda

K. Mertens
Division of Bio-Economics, KU Leuven, Celestijnenlaan 200E, 3001 Heverlee, Belgium


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## Introduction

In the East-African highlands, landslides frequently lead to loss of life, livelihood and property and cause extensive damage to public infrastructure. The Rwenzori mountains—Africa's third highest mountain range—is only recently identified as a landslide-prone region. Over the past decades, landslides have caused dozens of casualties and extensive damage to public infrastructure (Jacobs et al. 2016a). Moreover, these events are identified as the cause of major income loss among small-holder farmers in the region (Mertens et al. 2016). Despite of their significant impacts, relatively little is known on these hazards. This is not only true for the Rwenzori Mountains, but in general, the lack of landslide research in the tropical highlands of Africa in comparison to other landslide-prone regions globally, is striking (Maes et al. 2017).

In this proceeding we present the state of knowledge on the occurrence of landslides in the Rwenzori Mountain by summarizing the results of different types of data-collection. By doing so we provide an overview of the main mass wasting processes in the region, together with their controlling and triggering factors and geomorphologic characteristics.

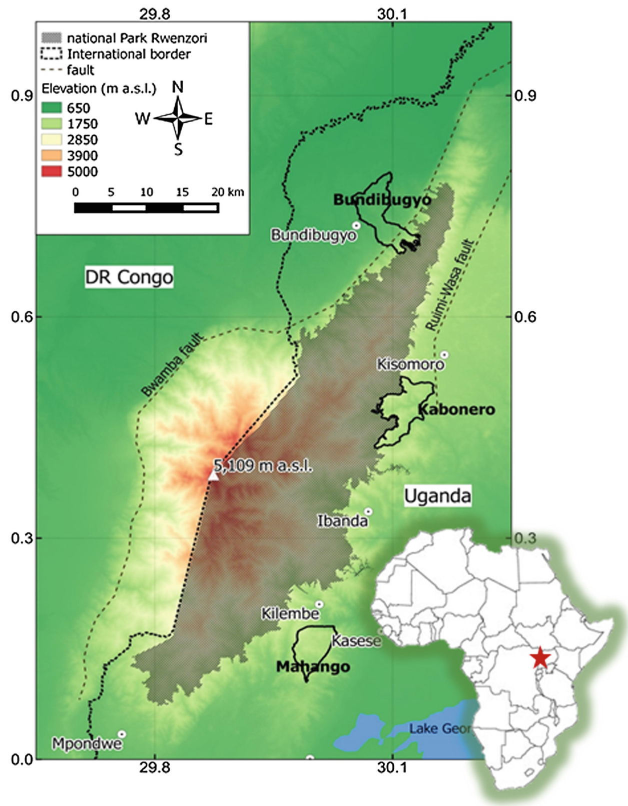


**Fig. 1** Location of the study areas for field inventories (adjusted from Jacobs et al. 2016b)

## Study Area

The Rwenzori Mountains lie on the border of D.R. Congo and Uganda. They cover an area of ca. 3000 $km^2$ and reach an altitude of 5109 m a.s.l. (Fig. 1). Due to its unique geomorphological features, its tectonic character, the bio-diversity of its ecosystems and the presence of glaciers on its highest peaks, this asymmetric horst mountain has been the subject of research in various disciplines.

## Morphology

In contrast to other mountain systems in East-Africa exceeding 5000 m (Mount Kilimanjaro and Mount Kenya), the Rwenzori Mountains are not of volcanic origin (Bauer et al. 2012). The morphology of the horst mountain is the result of Paleogene and Neogene uplift, with a marked acceleration in Plio/Pleistocene times (Bauer et al. 2012), rendering the topography rugged with locally very steep slopes. The slopes on the east side are in general less steep than on the west side where elevation can increase from 1000 to 4500 m a.s.l. in less than 15 km. The quaternary glaciation cycles further shaped the topography. The last three glaciation maxima took place ~300 thousand, ~100 thousand and 22–15 thousand years ago. During these glacial maxima, glacier erosion formed U-shaped valleys with oversteepened walls (Roller et al. 2012; Bauer et al. 2012). Currently these mountains still host glaciers but their overall size has strongly reduced over the past decades.

## Lithology and Structural Features

The geology of the horst mountain is mainly built up of Precambrian metamorphic rock which consists of gneiss, schists and amphibolites. Gneiss dominates in the northern part of the mountain range, while gneiss with schists of the Kilembe and Bugoye group prevail in the southern part (Bauer et al. 2012; Roller et al. 2012).

Concerning tectonics, the Rwenzori Mountains are bounded by the Albertine rift on the west and the Lake George rift on the east (Lindenfeld et al. 2012). On its west side the normal Bwamba fault borders the Rwenzori Mountains, while in the NE, the normal Ruimi-Wasa fault is present (Fig. 1) (Koehn et al. 2010). Around the center of the eastern flank, a more complex faulting structure is apparent (Koehn et al. 2010). The Rwenzori Mountains are one of the most seismically active regions in East-Africa (Fig. 2c).

liesbet.jacobs@africamuseum.be

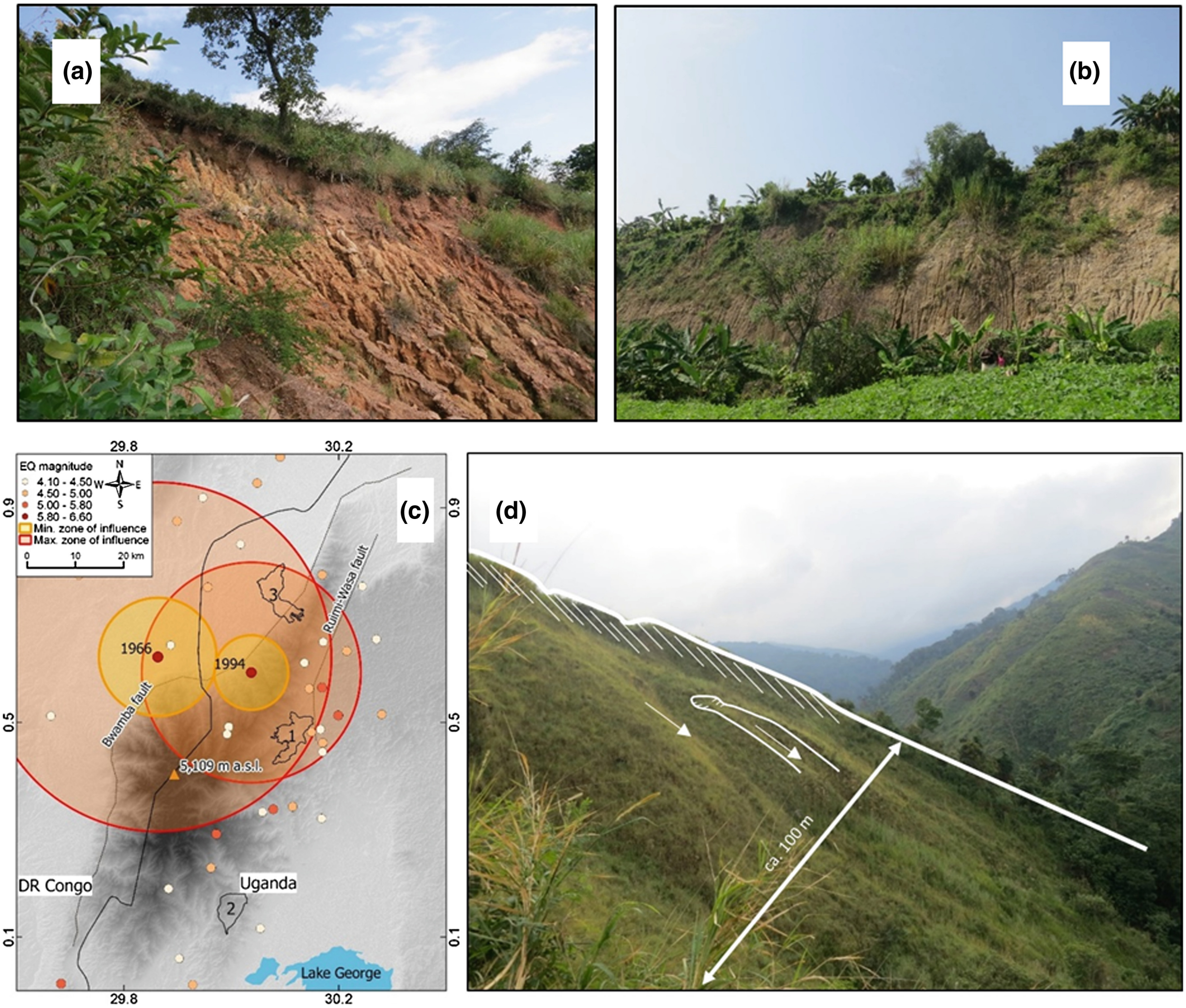


**Fig. 2** **a** Example of a shallow translational soil slide on metamorphic lithology, **b** example of a deepseated rotational soil slide in rift alluvium, **c** distribution of major earthquakes of the past century (USGS 2014) and location and zone of influence (Eq. 1) of the 1966 and 1994 Earhquakes, **d** example of an earthquake-triggered landslide in Kabonero, *white arrows* indicate flow direction, *hatched lines* indicate landslide scarp. Adjusted from Jacobs et al. (2016b)

## Population Growth and Environment

The population density roughly doubled in just more than two decades in the three Rwenzori Mountains districts. Due to population increase, pressure on natural resources is high. In East-Africa, deforestation occurred at rates of 0.22 and 0.39% per year between 1990–2000 and 2000–2010 respectively (Brink et al. 2014). However, for the Rwenzori Mountains, this trend of deforestation seems to have stopped at least from 2003 onwards (Jagger and Shively 2014). The stabilization in forest cover is attributed to the effective forest management and an increase in area for woodlots and tree plantations (Jagger and Shively 2014).

## Precipitation

Rainfall is an important landslide trigger in equatorial Africa. In the Rwenzori Mountains temporal variation of rainfall is characterized by a bimodal pattern with a rainy season from March to May and one from August to November while spatial distribution is controlled by orographic variation (Taylor et al. 2009). Precipitation is highest on the NW flank and is generated by orographically-induced convection of moist air transported from the Congo River Basin into the Albertine rift through a gap in elevation at 0.5° latitude. As a result, precipitation exceeds 7000 mm/y at an altitude of 4000–5000 m a.s.l. Average annual

**Table 1** Overview of study areas for the field inventory construction

| Study area | Area ($km^2$) | Average slope angle (°) | Lithology | # Land-slides |
|---|---|---|---|---|
| Kabonero | 41 | 20 | Gneiss, amphibolite | 70 |
| Mahango | 30 | 20 | Gneiss | 91 |
| Bundibugyo | 43 | 14 | Rift alluvium, gneiss, mica-schists | 210 |
| Total | 114 | NA | NA | 371 |

precipitation on the NW flank is 1835 mm/y while this is only 785 mm/y on the SE flank, the rain shadow side of the Rwenzori Mountains (Jacobs et al. 2016a).

Because of its steep topography, seismic activity, recent deglaciation and intense rainfall patters combined with high population densities, the Rwenzori Mountains are comparable to other mountainous regions in tropical Africa and elsewhere, where landslides are common disasters. This was also suggested by Knapen et al. (2006), who mentioned Kasese and Bundibugyo as landslide-prone districts in the Rwenzori Mountains.

## Methodology

### Archive Inventory

As a first action to gain insight in landslide processes in the region, an exploratory study was conducted (Jacobs et al. 2016a). Because field information is scarce, archive sources were used to reconstruct an inventory of past landslide and flash flood events. The sources used are newspaper articles, governmental and non-governmental reports, and freely accessible internet sources such as personal blogs. A full detail on the sources used can be found in Jacobs et al. (2016a). Together with date and area of occurrence, the damage inflicted by the landslides were also registered. This data is then used as the basis for planning field surveys.

### Field Surveys

Archive inventories are a straightforward tool to allow a first understanding of landslides in a certain region. However, the information available is strongly determined by the report quality, often produced by laymen. These archive inventories are limited in their potential to expose sliding mechanism and slide morphology. To fill this gap, several field investigations were conducted. In this region, field inventories are also particularly interesting because of the ability to recognize landslides years after their first occurrence, in contrast to visual remote sensing identification where the landslide bodies are generally rapidly covered by vegetation and often undetectable. In total three affected regions were selected below the national park in the inhabited region (Fig. 1): Bundibugyo, Kabonero and Mahango. Details on these study areas are given in Table 1. For a full description on the study areas we refer to Jacobs et al. (2016b). These study areas cover the main lithological units of the horst mountain and represent contrasting conditions in terms of rainfall regimes and seismic activity (Jacobs et al. 2016b). They are therefore considered representative for the inhabited region of the Rwenzori Mountains.

The field studies were conducted in a systematic way and key characteristics about the landslides' morphology, triggering and predisposing factors were registered. A selection of the most important factors considered are summarized in Table 2.

## Results: Landslide Processes in the Rwenzori Mountains

The exploration of archive sources allowed the identification of 48 landslide or flash flood events. The earliest record reports landslides and rock falls triggered by tremors in February 1929 (Simmons 1930; UNESCO 1966). This archive inventory allowed exposing the two main sliding triggers: intense rainfall and earthquake activity. Although the majority of events were situated in the two rainy seasons, those landslides situated outside the rainy seasons were reported to be triggered by major earthquake events (Mw > 6 in 1929, 1966 and 1994; Jacobs et al. 2016a). However, with this inventory it was impossible to assess the spatial distribution of mass wasting processes because most events can only be located at a sub-county scale and a reporting-bias exists towards events occurring in more densely populated regions (Jacobs et al. 2016a).

The field inventories, in contrast, allowed to accurately locate the landslides and infer about their controlling factors. In Kabonero, 70 landslides were mapped, compared to 91 in Mahango and 210 in Bundibugyo (Fig. 3). In Bundibugyo, maximum densities amounted to 19 slides/$km^2$ and landslides cover 5% of the territory. Both maximum and average densities here are twice as high as in the two other study regions.

The dominant sliding mechanisms are very diverse among these regions (Table 3). In Kabonero and Mahango,

**Table 2** Simplified overview of factors considered in the field inventory (for a full list we refer to Jacobs et al. 2016b)

| Type | Characteristic | Descriptor |
|---|---|---|
| Geometry of the slide | Depth of main scarp | m |
| | Width of main scarp | m |
| | Plan shape of scarp | Circular/rectilinear |
| | Length of run-out | m |
| Material | Type of material moved | Rock/debris/soil |
| | Bedrock reached | Y/N |
| Topography of the slide | Presence of reverse slope(s), stagnation water, drainage | Y/N + location |
| | Presence of secondary scarps | Y/N + location |
| Activity of the slide | Recent activity on (secondary) scarp | Y/N |
| | Recent activity in slide body | Y/N |
| Triggering factors | Timing of landslide, timing of reactivation | date |
| | Reports of heavy rainfall before occurrence | Y/N |
| | Reports of earthquake activity before occurrence | Y/N |
| Preparatory factors | Road cut | Y/N + type of road + location of contact |
| | River undercutting | Y/N |

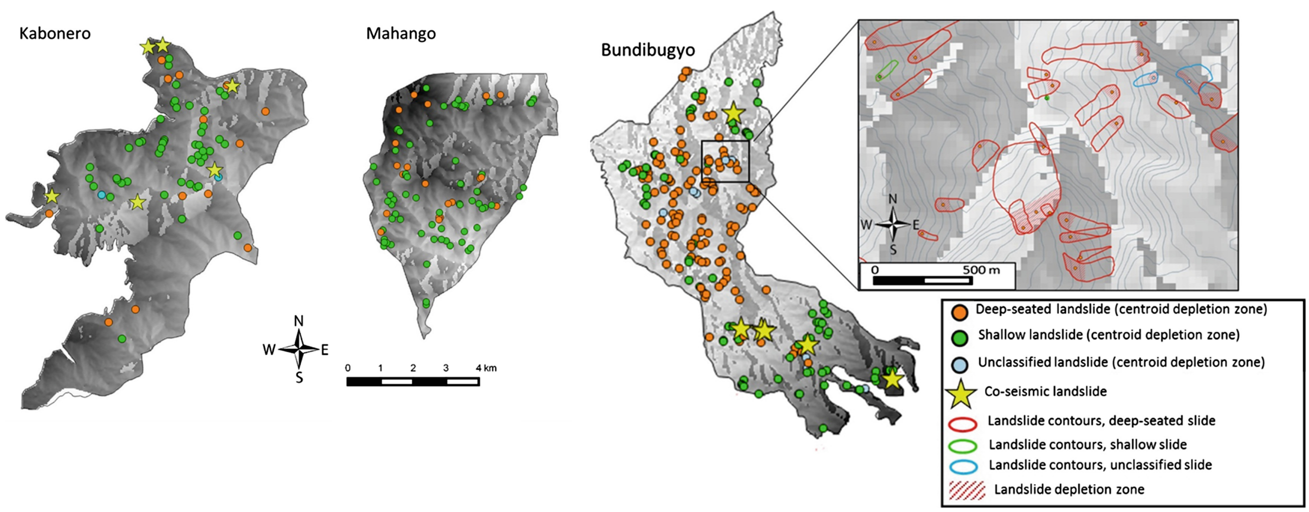


**Fig. 3** Landslide distribution maps for the three study areas (adjusted from Jacobs et al. 2016b)

translational soil slides are the most common and approximately 75% of the landslides here were shallow (Table 3, Fig. 2a). This is in sharp contrast to the Bundibugyo region. Here, deep-seated landslides are more frequent than shallow slides (125 vs. 76). Translational and rotational landslides are almost equally present in this study area, however, the vast majority of rotational (n = 88) and deep-seated slides (n = 113) are located in the rift alluvium (Fig. 2b) while shallow and translational slides are much more common in the upland regions of the study area. The dominance of deep-seated landslides in the lowlands is because here, deep profiles without bedrock are occurring. The prevalence of shallow landslides on the highlands of Bundibugyo but also Kabonero and Mahango is due to the presence of shallow soils in the upland region where loose eroded materials are underlain by metamorphic bedrock. Landslides in these highlands are typically 0.5–3 m deep where the depth of the landslide is limited by the depth of the weathered regolith.

The data on landslide dimensions is summarized in Table 4. Landslide sizes include the run-out and detachment zone of the slide. There is a large difference in landslide size between the study areas. The average landslide size in Bundibugyo is almost four times larger than that in Mahango where the smallest slides are found. Furthermore, within

**Table 3** Number of landslides per sliding mechanism and material displaced for the three study areas, the boxes indicate the most common landslide type in each study area

| | Kabonero | | | | Mahango | | | | Bundibugyo | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Displaced material | | | | | | | | | | | |
| | Soil | Debris | Rock | N/A | Soil | Debris | Rock | N/A | Soil | Debris | Rock | N/A |
| Rot.slide | 3 | 0 | 0 | 3 | 7 | 3 | 1 | 1 | 84 | 3 | 0 | 1 |
| Transl. slide | 41 | 7 | 1 | 4 | 55 | 7 | 2 | 5 | 68 | 13 | 1 | 8 |
| Flow | 3 | 3 | 0 | 0 | 7 | 2 | 0 | 0 | 2 | 0 | 0 | 0 |
| Complex slides | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| N/A | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 27 | 1 | 0 | 2 |

*N/A* means not available

**Table 4** Landslide dimensions for the three study areas

| Characteristic | n | Average | s.d. | Min. | Max. |
|---|---|---|---|---|---|
| *Kabonero study area* | | | | | |
| Landslide area (ha) | 54 | 0.64 | 1.3 | 0.012 | 7.12 |
| Landslide length (m) | 56 | 116 | 86 | 18 | 352 |
| Width main scarp (m) | 57 | 45 | 51 | 5 | 266 |
| Depth main scarp (m) | 16 | 2.3 | 1.9 | 0.7 | 8 |
| *Mahango study area* | | | | | |
| Landslide area (ha) | 74 | 0.28 | 0.62 | 0.002 | 5.06 |
| Landslide length (m) | 74 | 98.9 | 79.8 | 8 | 420 |
| Width main scarp (m) | 79 | 30.3 | 31.2 | 3 | 193 |
| Depth main scarp (m) | 37 | 1.7 | 1.2 | 0.4 | 5 |
| *Bundibugyo study area* | | | | | |
| Landslide area (ha) | 142 | 1.05 | 1.55 | 0.017 | 10.6 |
| Landslide length (m) | 143 | 144 | 115 | 10 | 670 |
| Width main scarp (m) | 165 | 72 | 67 | 5 | 330 |
| Depth main scarp (m) | 95 | 8 | 7.7 | 0.3 | 30 |

n = number of landslides

each study area, the large standard deviation indicates a significant variation in individual landslide area. The landslide width to length ratio is larger in Bundibugyo uplands (0.6) and lowlands (0.7) than in Kabonero and Mahango (0.4) which is to be expected with a higher count of rotational slides in Bundibugyo. With an average depth of 8 m and a maximum depth of 30 m, landslides are much deeper in Bundibugyo than in Kabonero or Mahango. For a full report on frequency-size analysis of the mapped landslide we refer to Jacobs et al. (2016b).

When considering the controlling factors a set of lithological factors and topographic conditions were checked for their prevalence of slides (Jacobs et al. 2016b). In general, amphibolites were found not to be prone to landslides while the rift alluvium of the Bundibugyo lowlands was found to produce high landslide densities. Lithology furthermore significantly influenced the type of landslide occurring (Fig. 4). Rift Alluvium produces in general very deep rotational soil slides while in both Gneiss and Mica-schists, shallow translational soil slides are most commonly found. Concerning topography, again a distinction between the uplands of Bundibugyo, Mahango and Kabonero and the lowlands of Bundibugyo can be observed. In the upland regions (Kabonero, Mahango and the uplands of Bundibugyo) slope angles above 25° are most prone to landslides. This is in contrast to the Bundibugyo lowlands, where slope angles are in general much lower, and landslides concentrate on slopes above 10°–15°. This is comparable to slope angles susceptible to landslides in similar lowland regions with clay-rich soils and subsoils (e.g. Ost et al. 2003).

Concerning triggering factors, over 95% of the landslides mapped over these 3 study areas was reported during the field surveys to be triggered by rainfall. However, in both Kabonero and Bundibugyo, six landslides were reported to be triggered by earthquakes (location, see Fig. 3). This confirms the earlier findings from the archive inventory.

liesbet.jacobs@africamuseum.be

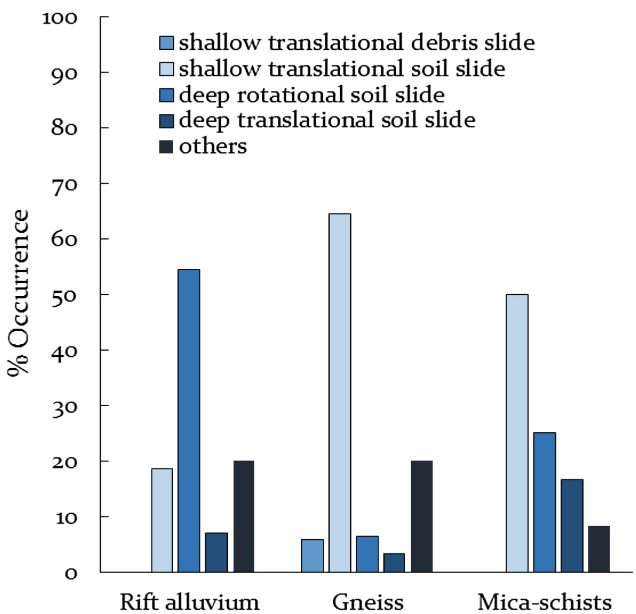


**Fig. 4** Landslide type distribution per lithology. As only 3 events on amphibolite were observed, this lithology was not included

In Kabonero the average size of co-seismic landslides is almost double (1.23 ha) of the average rainfall-triggered landslide size. An example of a co-seismic landslide in Kabonero is given in Fig. 2d. In both study areas the triggering earthquake events occurred in 1994 and 1966. These earthquakes are depicted in Fig. 2c with their location, magnitude (USGS 2015) and minimum and maximum zone of influence according to the following equation (Keefer 2002):

$$\mathrm{Log}_{10}\mathrm{A} = \mathrm{M} - 3.46(\pm 0.47) \quad (1)$$

where M is the moment magnitude of the earthquakes (between 5.5 and 9.2) and A the area ($km^2$) potentially affected by co-seismic slides. From this figure it is clear that Bundibugyo and Kabonero lie within the zone of influence of these earthquakes.

## Discussion

The results of these diverse inventories confirm that landslide mechanisms strongly depend on prevailing topographic and lithological conditions at the study areas investigated. While landslides are mostly shallow, translational, soil slides in the upper regions of the Rwenzori, dominated by shallow soils on steep slopes, deep rotational soil slides dominate on the much flatter region of the Bundibugyo lowlands. In these lowlands, limited slope gradients can already cause very deep (up to 30 m) landslides and landslide densities were found to be the highest of the regions investigated. While the most common trigger of landslides in this region is intense rainfall, seismic activity can also trigger mass wasting in their zones of influence.

## Perspectives

Recent field work in the national park of the Rwenzori Mountains (January 2016) allowed to identify debris flows and rock falls commonly occurring around the peaks, from 4000 m a.s.l. up to the glaciated areas around 5000 m a.s.l. In this area, climate, vegetation and topography are not comparable to previously studied regions of the mountain range and (de)glaciation processes are expected to significantly influence both controlling and predisposing factors for the observed mass wasting processes. The recently assembled field inventory—together with aerial photograph and Google Earth analysis—is expected to increase our understanding of these events in the near future.

The study conducted so far is limited to the inhabited region below the national park. For future research, the recent availability of a TanDEM-X digital elevation model (5 m spatial resolution) and the increasing availability of very high resolution imagery through Google Earth will strongly improve the quality of landslide inventories in the entire Rwenzori region, including less accessible regions. Finally, the TanDEM-X DEM provides more detailed information on topography and structural morphology. This information is necessary for reliable landslide susceptibility analysis.

## Conclusion

By combining archive inventories with field work a first comprehensive overview of landslides in this under-researched region was assembled. While a detailed archive inventory allows forming a first idea on landslide occurrence and triggering factors in an unstudied region, detailed field investigations enable identifying the prevalent sliding mechanisms and their strong dependency on lithology and topography. The largest landslide densities and deepest landslides were found in regions with relatively small slope gradients, while shallow, smaller landslides were found on very steep slopes underlain by metamorphic rock. Rainfall was identified as the main triggering factor for landslides but both the field-inventory as well as the archive inventory revealed that large earthquakes ($M > 6$) can also trigger landslides in the region, which are generally larger than the rainfall-triggered slides. Complementary to these inventories, the analysis of freely available Google Earth imagery and detailed topographic information such as the TanDEM-X DEM is expected to further increase the understanding of landslide occurrence on the regional level.

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