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Engineering Geology 72 (2004) 73–87

ENGINEERING
GEOLOGY

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A geomorphological assessment of landslide origin at Bukavu, Democratic Republic of the Congo

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Received 10 September 2002; accepted 24 June 2003

Abstract

Bukavu, on the south coast of Lake Kivu in the Democratic Republic of the Congo, suffers from slow but never ending landsliding. This leads to the continuous degradation and destruction of houses, buildings and of the roads, waterworks and sewerage infrastructure in several districts of the town.

Research of mass-wasting processes is hampered by the limited geotechnical and hydrogeological information concerning the deeply weathered Tertiary and Quaternary lavas. There is also a disagreement about the exact location of active faults, believed to play a role in the mass wasting. Additionally, there is little information about the exact location and the rate of soil movements and whether ground instability is caused by tectonics and seismics or by increase in hydrostatic pressure.

Based on aerial photographic interpretation, landslides cover more than 15% of the town of Bukavu.

Thirty-one landslides occur outside the Bukavu “microrift” and do not contact active faults. Rather, they occur in actively incising river basins, ostensibly caused by neotectonic activity.

Four from the six landslides within the “micrograben” are bigger and wider than the others, apparently governed by pre-existing tectonically induced landforms. They are adjacent to or crossed by active faults. They also fall far below the envelope of topographic thresholds for landslides established for North America and verified in Rwanda.

Therefore, this threshold, a combination of slope at the head of the slide and surface drained to it, seems a promising tool to discriminate hydrologically from tectonically seismically induced landslides.

Recent soil movements in Bukavu generally correspond to landslide distribution portrayed on the geomorphologic map.

Most Bukavu soil movements occur on previous slides. Therefore, from an engineering–geologic standpoint, old landslides should be avoided, or, if economically feasible, be mitigated.

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Keywords: Democratic Republic of Congo; Geomorphology; Landslides; Neotectonics; Topographic thresholds for landsliding

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1. Introduction and objectives

The town of Bukavu on the west bank of the Ruzizi outlet of Lake Kivu (Fig. 1) is regularly affected by

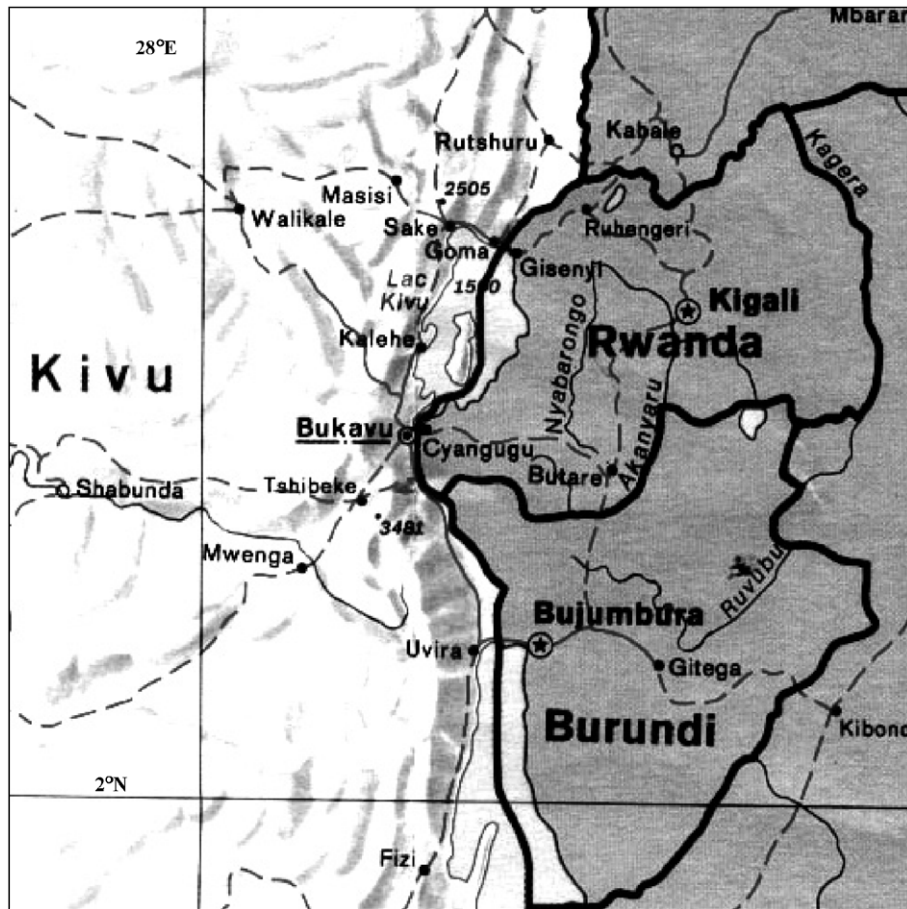


Fig. 1. Location of Bukavu, Democratic Republic of the Congo.

slow ground movements. Accelerated landsliding and sudden gully development also occur. In many districts, houses have to be constantly rebuilt, roads are generally in poor condition, and waterworks and the sewerage systems are frequently disrupted. In essence, the town is in a continuous state of repair and rebuilding. However, this has not discouraged immigration to Bukavu. The population increased from 147,647 to 450,000 inhabitants between 1977 and 2002 (UNESCO, 2002).

Slope instability and erosion in and around Bukavu have always been of concern to the government. As early as 1945, the Belgian authority installed the so-called “Mission anti-érosive” in Kivu. Unfortunately, however, the deployment of soil conservative measures was not very successful in halting the move-

ments. Two reasons explain this failure. Firstly, the measure taken was to install soil- and water-conserving trenches, spaced at distances of tens of meters and directed along the contour lines. By 1959 (Fig. 2), most hills in Bukavu were trenched. Such methods can stop soil wash but, as proven in neighbouring Rwanda, contribute to mass wasting (Moeyersons, 1989; Moeyersons, 2003). However, it was 20 years later that it became fully realised that the problem in Bukavu is mass wasting (Lambert, 1981). Second, it took time to recognize that mass wasting might not only be driven hydrogeologically but also tectonically–seismically. Geologic exploration demonstrated that Bukavu is crossed by a N–S trending micrograben and that it lies on the crossroad of tectonic lineaments trending SSE–NNW (Tanganyika trend)

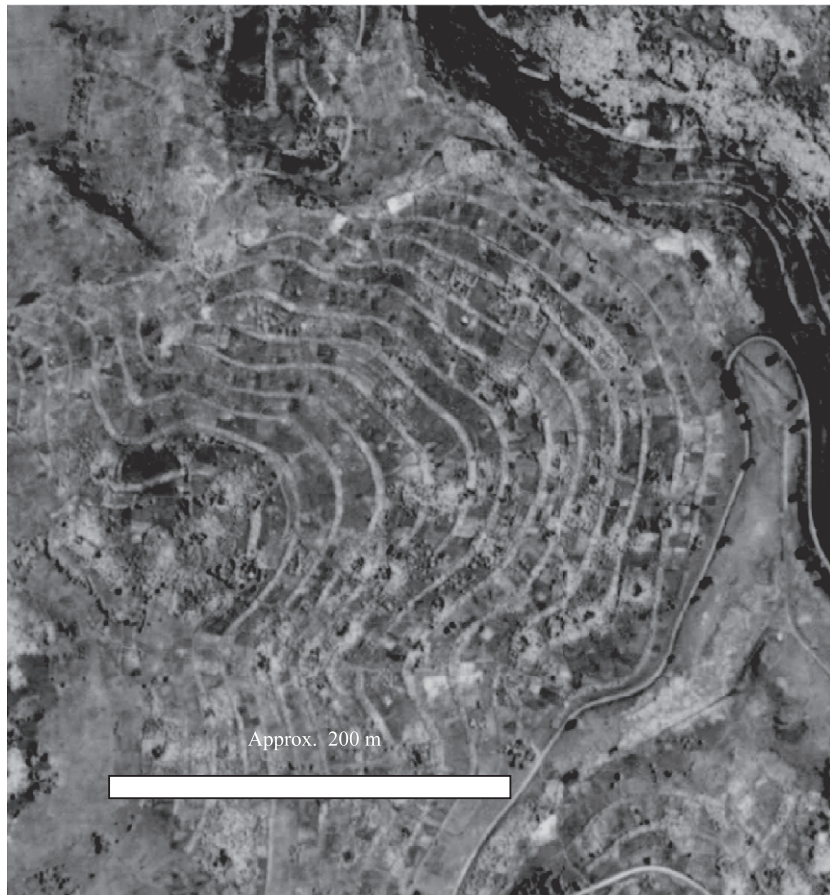


Fig. 2. Soil and water conservation trenches in Bukavu, 1959.

and SSW–NNE (Albertine trend) (Cahen, 1954; Ilunga, 1989; UNESCO, 2002).

The debate concerning the origin of landsliding in Bukavu still continues. First, it was thought that low quality of house roofs, leakages in waterworks and other construction defects contributed to high water infiltration and to landsliding and creep. In order to reduce human impact on the environment, the Mission d’Etalement de la Population (M.E.P.) program started in 1958 to redistribute the population from high density to low density districts. There is still a tendency to consider all large mass failures as the result of mismanagement by man (Ischebeck et al., 1984). However, in 1989, a double and apparently active fault step (Fig. 3) was recognised and, more recently, a seismic origin for landsliding at Bukavu has been suggested (Munyololo et al., 1999).

Although the infrastructure of Bukavu was severely damaged over the years, there is still little information about mass wasting in Bukavu. Detailed geological mapping is only starting. Synoptic geomorphic descriptions as well as movement measurements are still lacking, and, unfortunately, geotechnical investigations are not cited in the literature. Accordingly, at the occasion of the UNESCO project “Géologie urbaine de Bukavu: interaction entre la stabilité du sol et la pression démographique” (2002), it was decided to prepare a geomorphologic map of Bukavu from existing aerial photographs.

The purpose of this investigation is to determine the origin and relative activity of several mass movements that have, and are expected, to detrimentally impact the rapidly urbanizing area within and around the town of Bukavu. The investigation is accomplished by aerial-



Fig. 3. In 1989, the escarpment in the middle of the photograph (a) was tentatively interpreted as a fault scarp. However, from the stereoscopic analysis, it appears now (Section 3.2) that it is related to the wide and elongated Funu headscar (V), in the prolongation of the Karhorha active line. To the right (b), behind the tree, is Tshimbunda Hill, thrown down along the Cimpunda fault step. The escarpment to the left (c) corresponds with the huge crown-crack-like escarpment in the head of the lower Funu depression (Section 3.5).

photograph interpretations, by ground reconnaissance, by comparison with similar phenomena and investigations carried out in adjacent Rwanda, and by application of theoretical landslide models produced in the United States. This information may thus prove useful for urban planning and for the general mitigation of mass movements in the Bukavu area and perhaps elsewhere in developing African nations.

2. Materials and methods

2.1. The study area: geomorphology, geology and tectonics

Bukavu lies on the west bank of the Ruzizi gorge (Fig. 4). It is a rolling landscape of convex and elongated hills, developed on the weathered lavas of Panzi–Muhungu–Dendere (1550–1650 m asl). This landscape is interrupted in the west by an asymmetrical N–S trending corridor. This so-called micrograben of Bukavu (UNESCO, 2002) starts from the Bay of Bukavu, gradually disappears south of Boholo, and is 1–1.5 km wide and about 4.5 km long. The Kawa River (1470 m asl) flows through the corridor, mainly at the east side of the valley. The Kawa Valley is generally bordered on the west by three successive N–S trending escarpments that give rise to more or less levelled crest lines at ± 1550 m (Kabumba–Bugabo–Boholo), 1700–1750 m (Tshimbunda) and

1800–2000 m asl (Karhale). We herein categorize Bukavu, recognizing that the Ruzizi, instead of the Kawa Valley, might be the axis of the micrograben. For convenience, the term micrograben is used in this article to indicate the asymmetric valley of the Kawa River.

In the Bukavu area, folded and faulted Precambrian strata are covered by thick Tertiary and Quaternary lava flows. The oldest series, not present at Bukavu itself, predates local rifting and is dated between 7 and 10 millions of years (Pasteels et al., 1989). The middle and upper series are present at Bukavu. The middle series, of Mio-Pliocene age (Kampunzu et al., 1983; Pasteels et al., 1989), is intimately related to the rift faults. The upper series started during the Pleistocene and continued to the last century. The distribution of these deposits at Bukavu is shown (Fig. 5). The chemical composition of these three series evolves from subalkaline over moderately alkaline to strongly alkaline (Pouclet, 1980).

Every lava series consists of many individual flows, separated in time (UNESCO, 2002). The complex geometry of the present lava layers resulted from successive rifting and eruptive episodes. Weathering and erosion, as well as normal faulting, occurred between successive lava flow series, explaining the occurrence of palaeorelief, contact metamorphism, smectite layers, probably Vertic palaeosoils, and clastic deposits having an alluvial and colluvial origin. Owing to fissures,

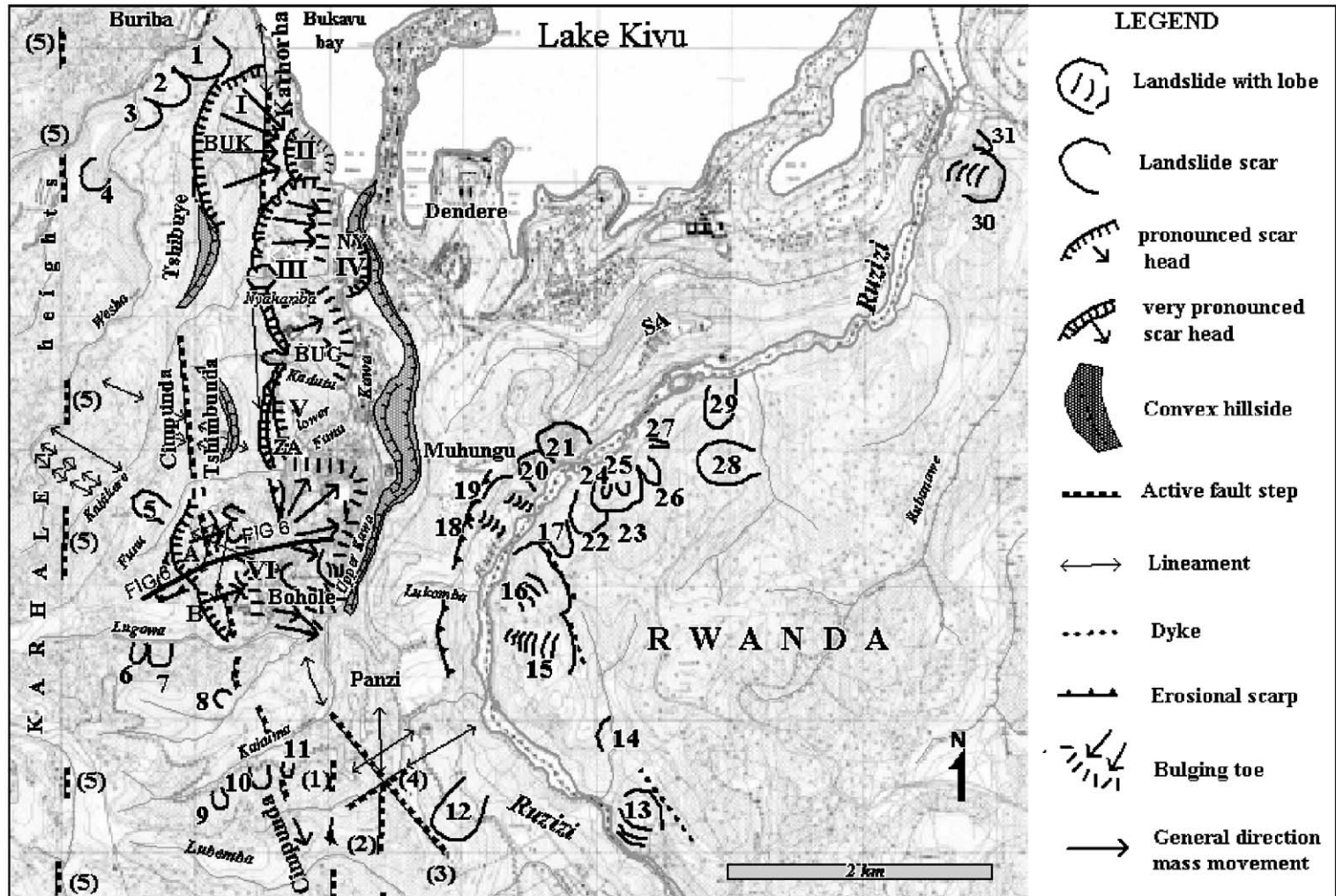


Fig. 4. Geomorphologic map of Bukavu. BUK: Bukavu; BUG: Bugabo and Lyceum WIMA; ZA: Camp Zaire; NY: Nyagongo; SA: Camp Saio; (1)–(5): escarpment; 1–31: landslide outside the micrograben; I, II, III, IV, V, VI: landslides inside the micrograben. The black line through landslide (VI) indicates the location of the longitudinal section shown in Fig. 6.

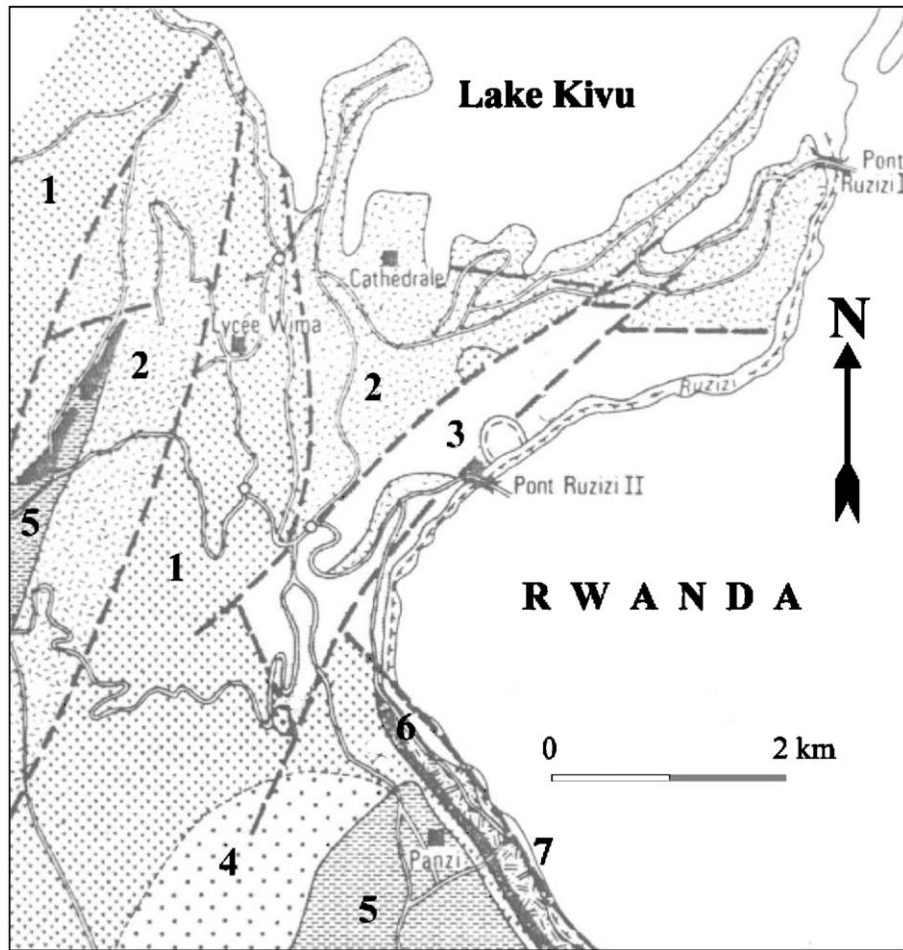


Fig. 5. Geological map of Bukavu, after [Kampunzu et al., 1983](#). 1: Basalts of the upper series; 2–7: Mio-Pliocene alkaline lavas; 2: basanite; 3: Hawaiites and mugearites; 4: Ankaratrite; 5: benmoreites; 6: Panzi pyroclastics; 7: phonolites and trachytes. The dashed lines are faults.

inherited from the unweathered rocks, soils in Bukavu, although often loamy and clayey, have permeability rates of $0.03\text{--}0.05\text{ cm s}^{-1}$ ([UNESCO, 2002](#)). This, of course, leads to rapid humectation and high hydrostatic pressures. The same report indicates that the basal weathering front in basaltic rocks is a potential slide plane.

Faults are probably expressed geomorphologically by the many escarpments in the town ([Fig. 3](#)). However, many faults are not yet accurately located, and there is a wide difference of interpretation as shown on various geological maps ([Lambert, 1981](#); [Kampunzu et al., 1983](#); Mweze, mentioned in [Munyololo et al., 1999](#)).

2.2. Methods of geomorphologic mapping

The aerial photographs of Bukavu were studied by means of a Sokkisha 6502 stereoscope. In the absence of site-specific geological data, we used geomorphologic evidence to locate active faults and landslides in Bukavu. The following features were plotted on the topographical map of Bukavu–Cyangugu at scale 1:10,000 and with contour interval 10 m ([I.G.C.B., 1957](#)):

1. Escarpments affected by active erosion processes. Erosion is considered active where the vegetation cover is visibly interrupted on the aerial pho-

tograph and where the soil is affected by light colour patches. In some cases, gullies are distinguished.

2. Lineaments, dykes and fractures, not based on subjective elements like the configuration of rivers, but on visible lithological, structural or pedological structures (lineaments) or differences on both sides of the lineament (fractures), or on the presence of a more-or-less resistant rock fill within the lineaments (dykes). This type of mapping is most secure, but provides only minimal data because the lava layers and their derived pyroclastics are, in most places, deeply weathered over tens of meters.
3. Escarpments with no visible erosion, but constituting a major morphometric element in the landscape.
4. Amphitheatre-like, cirque-like and other circular, semi-circular, and elongated depressions, containing evidence for being old or active landslides such as crown-cracks, displaced earth lobes, slumps and other morphological indications. Special attention is given to the delimitation of lobes or ‘flows’ (Dikau et al., 1996), ending downslope in a ridge, convex in cross-section, as can be expected for so-called creep lobes (Moeyersons, 1989).

A comparison of the aerial photographs taken in 1959, 1974 and a few field pictures taken in 1989 has been made to investigate landscape evolution. Although changes occurred in the number of gullies and in active slow slide or creep, the scale of the aerial photographs ($\pm 1:50,000$) was insufficient to quantify changes reasonably.

Accordingly, the accuracy of the geomorphologic map is not very high (Fig. 4). Taking into account the aerial photographic scale, objects need to have dimensions about of 5–10 m and contrast with their surroundings for accurate portrayal. The smallest objects visible are individual trees in a grass plain, roads and large houses. Relief is only visible over surfaces of more than 1 ha, which equals 4 mm² on the photographs. Linear structures, of course, might be much smaller.

The geomorphologic map gives the situation of 1974, whereas the lineaments correspond mainly with the situation of 1959. This should be mandatory both because of spatial resolution and time.

2.3. The use of a DEM to measure slopes and the topographical map to measure distances

A Digital Elevation Model (DEM) has been computed based on the existing topographical map of Bukavu–Cyangugu (1:10,000). This model is used to measure the slope in the three to five pixels above identifiable landslide scars. The pixel size is 5 m. Although the accuracy of the DEM has not been field-checked, comparisons between different interpolation algorithms and smoothing filters show that the different methods are similar in accuracy. The mean difference and standard deviation between two DEMs obtained from different algorithms are 0.15° and 1.1°, respectively, and the round mean square error (RMSE) between them is 1.1°.

Other elements like length, width and surface of the landslides visible on the aerial photographs were measured on the 1:10,000 topographical map after they were manually transferred to it. Neglecting transfer error, the accuracy of map measurement is about 1 mm. This induces probable errors in length of less than 10 m. In order to identify the topographical thresholds, as defined by Montgomery and Dietrich (1994), the drainage area to the head of the slide is distinguishable. As shown in adjacent Rwanda (Moeyersons, 2003), the soil slip (Chorley et al., 1984) landslides there fall close to the topographic threshold for North America (Montgomery and Dietrich, 1994) if one takes into account the total surface, draining into the headscar. This surface is calculated by multiplying the mean distance between the head of the scar and the crest line by the width of the scar. These distances, measured on the topographical map, may have errors up to 20% owing to lack of slope inclination control.

3. The geomorphology of Bukavu: cartographic results

The resulting geomorphic map (Fig. 4) is similar to earlier mapping by Lambert (1981), especially with respect to landslide depressions and fault trends. We were able to interpret the following geomorphic features.

3.1. Active faults

A rectilinear escarpment occurs south of where the Kabikere river changes direction from SSW–NNE to WSW–ENE and descends from <1700 m at Karhale into the micrograben of Bukavu (Fig. 4). Other rivers crossing this escarpment are the Funu, the Lugowa and its tributaries, the upper Kawa River and the Kahuma Gully. Between the Funu and Lugowa rivers, the escarpment is covered by a 10–50 m thick mantle of debris, which extends from headscars (A) and (B) over the very hummocky topography, near Bohole and ends in composite lobes against the upper Kawa River (Fig. 4). South of the Lugowa, the escarpment is discontinuous.

The following geomorphic evidence indicates fault activity:

- (1) Between the Kabikere and Funu rivers, the cliff slope is more than 36° and, therefore, is affected by secondary mass movements. In this area, the escarpment cuts across a hill and the downthrown part is identified as Tshimbunda (Fig. 4). The high side of the escarpment forms divide between the Karikere river and the escarpment. The throw along the escarpment is about 50 m.
- (2) South of Lugona River the upper part of the interfluvies are slightly dislocated. The fault step is visible where it crosses the upper parts of the hills and undergoes active erosion. The fault is invisible on the lower parts of the hills and in the valleys. Measurements in Rwanda (Moeyersons, 1990) show that runoff-induced diffuse erosion affects the upper part of the hillslopes, but that the adjacent lower parts and the lower lying flat valleys receive accelerated correlative deposition. This probably explains the invisibility of active faulting in the lower parts of the landscape.
- (3) Upstream of the escarpment, active regressive erosion occurs along the rivers Karikere, Funu, Lugowa and, in a less pronounced way, along the Lubemba.

This active fault step coincides with a section of the Cimpunda fault (Munyololo et al., 1999) as shown in Fig. 4.

Another important N–S trending lineament occurs at Karhorha, between Bukavu Bay and Buriba (Fig.

4). About 200 m inland, the lineament becomes a slightly expressed topographic step where it crosses the amphitheatre-like structure (I), described in Section 3.3. The Karhorha active fault extends south to the base of Tshimbunda Hill (Fig. 4) and its presence as far south as Bohole is suggested by the geometry of secondary landslides in that sector, visible on the aerial photographs.

The following evidence indicates that the Karhorha–Bohole lineament is probably an active fault:

- (1) The slight vertical dislocation of the loose deposits in the bottom of depression (I) points to active faulting which occurred some time before 1974.
- (2) The secondary landslides at Bohole are known to be active (Munyololo et al., 1999).

Other active fault escarpments are numbered from (1) to (5) in Fig. 4. We interpret escarpments (2), (3) and (4) as the geomorphic expression of active faults. Less certain, however, is the origin of the discontinuous escarpment, labelled “(5)” in Fig. 4.

For completeness, several non-fault-related but actively eroded escarpments are also pointed out. One occurs along the Ruzizi River on both sides of the Lukomba affluent (Fig. 4). From the stereo-photographic interpretation, this escarpment is not fault-related, but rather is the edge of a resistant sedimentary bed. The escarpment, therefore, is an erosion feature, apparently originally caused by active incision of the Ruzizi River.

Other escarpments are convex in cross-section, occur at the SE side of Tshibuye Hill and at the eastern foot of Tshimbunda Hill, and are the product of normal hillside erosion.

The eastern shoulder of the Kawa River valley forms another, not very pronounced escarpment. It is about 50 m high and 250 m wide but steepening considerably along the upper Kawa and further downstream at Nyagongo (Fig. 4). Because there is no evidence for a tectonic origin, this escarpment is judged to be another hillside.

3.2. Landslide headscars and advancing lobes in the Bukavu micrograben

The significance of two important escarpments within the Bukavu micrograben is discussed here.

The first escarpment extends along the eastern side of the Karhorha active fault between Bukavu Bay and Bohole. From Bukavu Bay, it meanders to the south, turning along the west side of depressions (II), (III) and (V) (Fig. 4). The escarpment varies in height between 100 and 150 m, and has slope gradients of 20–40°. The photograph shows that it gradually disappears below the deposits of Bohole and that, south of the Lugowa, it has completely disappeared. The escarpment cannot be considered as a fault:

- (1) It is not a rectilinear structure like the Cimpunda and Karhorha faults. It terminates against the active Karhorha structure at the latitude of the centre of the Kabumba–Bugago (III) and the lower Funu (V) depressions, but at the depression of Bukavu (II) it lies about 200 m to the east.
- (2) Its morphology differs from the fault steps. Unlike the fault of Cimpunda, the Boholo escarpment has considerable change in slope gradient and width.

Given the general configuration of three juxtaposed amphitheatre-like cirques, and also the observation of vertical dislocation and probably rotational slumping near Camp Zaire, the escarpment is more likely a composite headscar along which the depres-

sions (II), (III) and (V) were, or still are, sagging. Recent or active sagging is suggested by the relatively slight incision in the escarpment by the rivers Nyakariba, Kadutu and Funu. Normally, a deep gully should form on such steep slopes. In 1989, we observed that the Karikere–Nyakariba gully in the escarpment was much larger than depicted on the 1959 photographs. It thus appears that drainage across the escarpment was established shortly before 1959. Observations in Rwanda show that initial drainage occurs in the headscar area shortly after a landslide or soil slip (Moeyersons, 1989). We thus suggest that this process is also operative at Bukavu and may account for occurrence of mass movements along the Nyakariba, Kadutu and Funu rivers not long before 1959.

The second escarpment in question is the western side of the Kawa Valley which forms a step between the small alluvial plain of the Kawa (1470 m asl) and the Bukavu–Kabumba–Bugabo–Funu–Boholo topographic level (1550–1600 m asl). This escarpment is traced from the edge of the depression (II) of Bukavu in the north, to the confluence of the Lugowa with Kahuma gully in the south (Fig. 4). The escarpment is discontinuous and lobated in plan, showing protrusions and incursions. According to DEM measure-

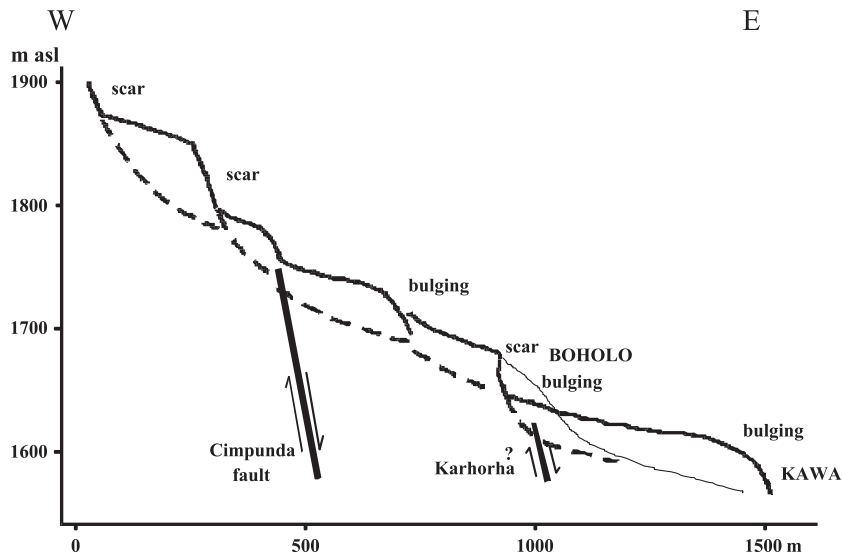


Fig. 6. Longitudinal section through landslide (VI), on the base of the topographic map 1:10,000 (I.G.C.B., 1957) and with additions based on aerial photographic interpretation. The dashed lines are inferred slide planes. The location is indicated in Fig. 4. The general slope of the composite lobe is of the order of 15°.

ments, the escarpment slope is locally up to 20°. The aerial photographs show that the escarpment cross-section is increasingly convex downslope and ends with only a short concave curvature, nearly a “knick-point”, to the valley. These characteristics are quite similar to those on landslide, earthflow and creep lobes in Rwanda (Moeyersons, 1989, 2001). We thus consider the western side of the Kawa Valley to be a composite toe front of slowly sliding or creeping lobes. We recognize three distinct lobes (Fig. 4):

- (1) A small lobe, creeping out of the Bukavu depression (II).
- (2) A large lobe slowly exiting the Kabumba–Bugabo amphitheatre-like depression (III). This lobe is actively incised by the Nyakariba River. Nevertheless, the southern part of the lobe (Bugabo and Lyceum WIMA, Fig. 4) seems to creep forward. This is deduced from the configuration of the Kawa river channel, which is here pushed eastward by the advancing lobal front. The alluvial fan sediments of the Nyakariba River, however, have a higher rate of deposition and therefore have pushed the Kawa River against the eastern side of its valley.
- (3) The lobe of Bohole (VI) is a mass of loose deposits, covering more than 204 ha. It starts at the foot of cliffs (A) and (B), jumps over the Cimpunda fault step, shows a hummocky topography and several traces of secondary rotational slumps, crosses over the southern extension of the Karhorha–Bohole line and finally dies out near the confluence of Kahuma Gully and the Lugoma River. A general longitudinal section through this complex landslide is shown in Fig. 6.

3.3. Other landslides in Bukavu

In addition to the large landslide complexes (II), (III) and (VI), we recognize additional slope failures in the micrograben of Bukavu. First, there is the very large scar (I), affecting the SE flank of Tshibuye Hill. The downhill end of the accumulation lobe leaving this scar is not visible on aerial photographs, but is seemingly affected by secondary Bukavu slide (II) and partially by the Kabumba–Bugabu incision (III).

Table 1

Dimensions of landslides 1–31 and (I)–(VI) and their topographical characteristics

Landslide	Width (m)	Length (m)	Approximate size (ha)	Drained surface (ha)	Slope (m/m) at landslide head
1	314	314	9.8	0.90	0.31
2	242	328	7.9	2.08	0.32
3	200	185	3.7	2.86	0.40
4	171	171	3.1	4.90	0.32
5	185	314	5.8	not measured	not measured
6	71	142	1.0	0.92	0.92
7	128	171	2.2	1.29	1.29
8	114	114	1.3	not measured	not measured
9	100	157	1.5	not measured	not measured
10	114	142	1.6	0.98	0.42
11	57	85	0.4	not measured	not measured
12	285	485	13.8	1.22	0.34
13	357	428	15.3	0.51	0.31
14	85	357	3.0	0.61	0.29
15	428	500	21.4	not measured	not measured
16	428	457	19.5	1.84	0.29
17	157	300	4.7	1.57	0.36
18	214	285	6.1	3.37	0.11
19	214	385	8.2	4.29	0.09
20	228	228	5.2	5.55	0.21
21	257	285	7.3	6.24	0.18
22	171	357	6.1	2.20	0.19
23	357	357	12.7	3.57	0.16
24	57	100	0.5	not measured	0.31
25	57	85	0.4	not measured	0.27
26	114	285	3.2	2.12	0.31
27	42	200	0.8	0.61	0.25
28	314	428	13.4	2.69	0.27
29	171	314	5.3	0.98	0.23
30	328	442	14.5	0.47	0.27
31	57	142	0.8	0.65	0.25
32 (I)	1285	857	110.2	3.26	0.05
33 (II)	371	228	8.4	7.95	0.14
34 (III)	1285	500	64.2	12.00	0.03
35 (IV)	471	171	8.0	2.69	0.12
36 (V)	642	428	27.5	0.08	0.29
37 (VI)	1428	1428	204.0	2.04	0.03
Total surface of landslides 1–32, outside the micrograben					202.0 ha
Mean surface of landslides 1–32					6.5 ha
Total surface of landslides I–VI, inside the micrograben					422.6 ha
Mean surface of landslides I–VI					84.5 ha
Percentage of study area covered by landslides					15.7%

Another zone of landsliding occurs in the depression of the lower Funu (V). The hummocky topography is now being eroded by the Funu River. Nevertheless, the presence of sink-like depressions, hummocky topography and a well-defined headscar indicate that the slides here are active.

Finally, we hypothesize that landslide (IV) originated by undercutting of the Kawa River where the river was pushed against the eastern valley wall by the Nyakariba River.

The stereoscopic interpretation of aerial photographs also shows many landslides outside the Bukavu micrograben. In many cases, landslide lobes fill, in whole or part, the topographic depressions. We recognize 31 such depressions (Fig. 4). One, no. 21, may be the remnant of a volcanic crater (Munyololo et al., 1999). Nineteen depressions, interpreted as the product of landsliding, occur along the Rizizi gorge and one (no. 28) is present along a tributary of the Ruzizi in Rwanda. Four others occur along the Wesha River, and the remaining seven are present along the Funu, Lugowa and Kahuma rivers upstream of the Cimpunda and another active fault scarp. It thus appears that the 31 landslides occur along rivers that are, or recently were, actively incising their channels. The photographic interpretation also suggests that not 1 of the 31 landslides is located upon or near active faults. Only landslides 13 and 15 have headscars that terminate against a dyke.

Table 1 shows the importance of landslides as a geomorphologic feature in the Bukavu area. More than 15% of the surface is covered by landslides, and many of them are active, especially in the Bukavu micrograben.

4. Discussions

4.1. Reasons for landsliding in Bukavu

The increased frequency of landslides in and around Bukavu since 1997 was associated with an intensification of tectonically induced earthquakes (Munyololo, 1999). However, there is not necessarily a direct correlation, for other geomorphic and anthropic activities play an important role. A seismic origin for landslides is often difficult to prove because of a delay in effect toward the end of the rainy season.

Furthermore, landslides themselves can generate seismic vibrations. For example, a huge landslide, like (VI), an estimated 40×10^6 tons, might produce earthquake-like vibrations, undistinguishable from weak seismic–tectonic movement.

The aerial photographs clearly show recently active tectonics, at least inside and close to the micrograben of Bukavu. Many lineaments (Fig. 4) apparently cross actively moving slides, e.g. landslide (I), the Funu depression (V), and composite lobe (VI). They point to tectonic activity shortly before 1959. On the 1974 photographs, the lineaments in moving terrain are already much less clear or even invisible.

The distinction between landslides, triggered by seismic–tectonic movements or by gravity and interstitial water pressures, is theoretically possible. However, new techniques (e.g., the Newmark-displacement analysis of Newmark, 1965, and Jibson et al., 1998) are still experimental. Therefore, we discuss here the application of some simple geometric and topographic characteristics as criteria to subdivide the Bukavu slides.

Montgomery and Dietrich (1994) defined slope/drainage area combinations for landslides in North America. Also, landslides in Rwanda develop at comparable topographic thresholds (Moeyersons, 2003). Table 1 shows that the 31 landslides outside the micrograben correspond to the topographic threshold envelope as defined in North America and in Rwanda (Fig. 7). Their origin, therefore, corresponds to hydrologic and main seismic conditions for the tectonically more stable plateaus away from the rift, e.g., the plateau of Butare, Rwanda (Moeyersons, 2003). Also, slides (II) and (IV), although located inside the micrograben, have ‘normal’ topographic thresholds. In contrast, landslides (I), (III), (V) and (VI) fall clearly below the Montgomery–Dietrich topographic threshold envelope (Fig. 7). Their movement is probably not induced by hydrostatic pressures alone, but in combination with tectonic and/or seismic activity, stronger than on the more stable rift shoulders. The validity of the topographic threshold criterion is supported by the fact that landslides (I), (III), (V) and (VI) are the only ones crossed or delimited by active faults.

In the geological–geomorphological context of Bukavu, the tectonic and seismic components might be difficult to distinguish. First, vertical sagging

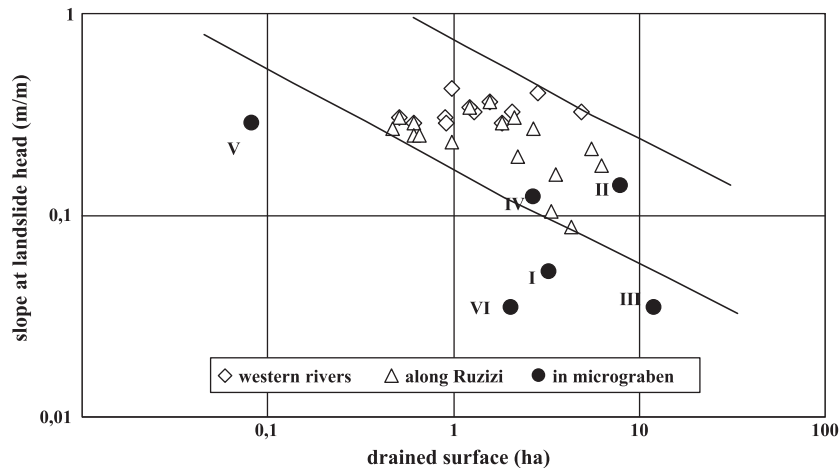


Fig. 7. Most Bukavu landslides fit within the topographic threshold envelope for North America (Montgomery and Dietrich, 1994) and Rwanda (Moeyersons, 2003), as delimited by the two lines. Landslides along western rivers are located in the basins of the Weshu, Funu, Lugowa and tributary, and along the Kahuma Gully.

along an active normal fault can destabilize the masses on the uphill side of the fault because sagging of the low side acts in the same way as conventional toe unloading. The landslide scar will thus be located at a certain distance upslope of the fault as is the case for the composite head scars (A) and (B) of compound landslide (VI). Second, liquefaction generated by seismic vibrations might also intervene and temporarily reduce the effective soil strength (Lambe and Whitman, 1979; Selby, 1993). The relative importance of both factors is not yet established for the study area. However, in the case of landslide (VI), the volume of the composite lobe, an estimated $20 \times 10^6 \text{ m}^3$, cannot be supplied by the head depressions (A) and (B) alone. We therefore propose, as a working hypothesis, that a hill, upslope of Bohole in the Lugowa–Funu compartment, was offset and, at the same time or shortly thereafter, was liquefied owing to seismic energy released along the Cimpunda fault.

The case of landslide (III) shows that the tectonic–seismic influence can be very complicated. If the whole Karikere basin above the scar (175 ha) is taken into account, landslide (III) falls outside the right edge of Fig. 7, and fits about in the middle of the Montgomery–Dietrich envelope. However, this ‘normal’ topographic threshold probably resulted by movement of the Cimpunda fault. We hypothesize that before the fault became active, the Karikere River was not

captured within the micrograben but rather flowed straight NNW along the east side of Tshibuye Hill, which was still intact at that time. At present, the Nyakaribe section of the Karikere River flows over the scar, cuts the lobe in two parts and drains it instead of supplying water to it. We believe that river cutting causes landsliding toward the river, but water from the Karikere is not the cause for the general eastward movements of the two lobes, now separated and drained by this stream incision. At present, only an estimated 12-ha surface area (Table 1) supplies water directly to the scar and the lobe.

The formation of the micrograben of Bukavu has also changed the course of Funu, Lugowa and Kahuma rivers. Tectonically–seismically induced changes in drainage areas and slopes are the rule rather than the exception. However, these rivers now drain the sides and not the centres of the respective lobes and thus do not currently supply water to the lobes in the present-day situation.

The subdivision of the Bukavu landslides by the topographic threshold criteria is further supported by simple landslide characteristics of size and form. Table 1 shows that the average surface of a landslide outside the micrograben is ± 6.5 ha whereas the mean size of the landslides in the micrograben is nearly 85 ha. A detailed investigation (Fig. 8) shows that landslides (I), (III), (V) and (VI) in the Micrograben excel in size. All Bukavu micrograben landslides are also

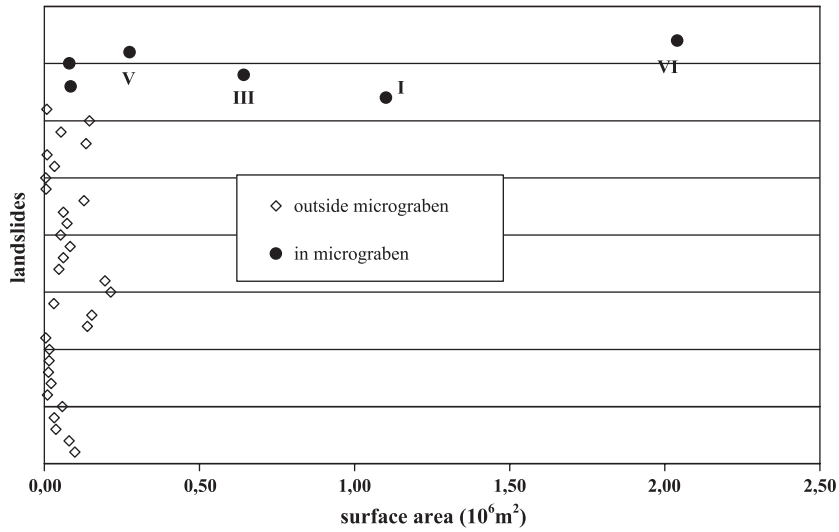


Fig. 8. Size of the landslides. Landslides (I), (III), (V) and (VI) are visibly larger than the others.

relatively wider and shorter, suggesting some structural influence (Fig. 9). Along the Lugabano Lake fault in the Ethiopian rift valley, gravitational collapse on the downthrust part of active faults has been recently described and associated with fault activity (Coltorti et al., 2002). Also in that case, the landslide is about 800 m wide and apparently much shorter. This similarity in form likewise suggests a seismic–tectonic origin for the Bukavu landslides (I), (III), (V) and (VI).

4.2. Possible explanation of the movements observed in the field

The soil movements, reported in 1997 (Munyololo et al., 1999), can be readily interpreted in light of the analysis of the aerial photographic analysis.

- The landslide near the Lyceum WIMA is identified as well as a further deepening of the scar by forward displacement of the Lobe of Bugabo (III).

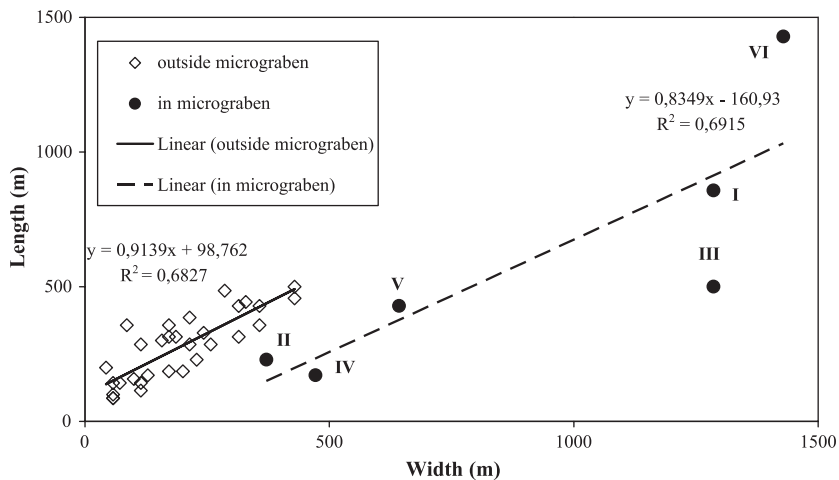


Fig. 9. The linear regression lines (Linears) show that the landslides in the micrograben are relatively wider than the others.

Secondary slidings have also occurred along the Kabikere–Nyakariba rivers incision (Fig. 4).

- The Camp Saio slide is probably a remobilisation, accompanied by the opening of crown cracks of landslide 21. This depression is not located upon a fault and falls within the Montgomery–Dietrich envelope.
- The mass movement of Funu–Cimpunda is identified by sagging of the area inside a sharp crown-crack-like ridge. It is located at the foot of the Kahorha–Bohole escarpment and passes near Camp Zaire.
- The landslide called “Buholo IV” could not be localised, but it might relate to a sudden forward pulse of the composite toe front downslope of Boholo.
- The Rukumbuba movement occurs on the active trace of the Cimpunda fault.
- Squeezing of the Kawa pipe near Bukavu Bay might be due to continued movement of the northern half of lobe (III) at Kabumba.

It thus appears that the landslides, identified on 1974 aerial photographs, were still active in 1997, and therefore demonstrating the value of the geomorphic map.

4.3. Dangers, endangered zones and urbanisation

One possible danger from large earthquakes is liquefaction of thick earth masses. This apparently happened in the Lugowa–Funu area and gave rise to the thick, composite-earthflow lobe of landslide (VI). The event took place before Bukavu came into existence. All movements in composite lobe (VI), as recorded today, are judged to be post-failure creep, slides or remobilisations. However, we point out that other hills are also prone to liquefaction, for they are located either upon or on the extension of the Cimpunda fault. This is illustrated by the Tshimbunda Hill in the adjacent Funu–Karikere compartment. This hill has already been displaced along the fault. Also, Tshibuye Hill, located on an extension of the active Cimpunda fault, probably has a similar potential for failure. However, other localities are also probably vulnerable because they consist of remoulded materials with a high water content. We think that many lobe fronts, especially those along the western side of the

Kawa Valley, are likewise susceptible to rejuvenated liquefaction. The failure of Tshimbunda Hill would, analogous to the origin of earthflows (VI), result in complete destruction of Tshimbunda and Funu. Bursting of the Bugabo lobe might lead to the complete destruction of the industrial field across the Kawa. These examples illustrate the potential impact of a large earthquake on slope stability in the Bukavu region.

We cannot predict if and when such slope failure might take place. Nevertheless, that such has occurred is reflected by the existence of landslide (VI). We can, however, identify trends in slope movement. Our analysis and interpretation of aerial photographs and the repeated visits to Bukavu, reported by Ilunga (1978, 1989, 1991), Munyololo et al. (1999) and UNESCO (2002), seem to indicate that some sectors of the micrograben are less stable than others. Few movements are reported on landslides (I), (II) and (IV) (Fig. 4). On the other hand, both the northern and the southern parts of lobe (III) seem to be very active. Apart from the numerous secondary slides, caused by the Nyakariba incision, the present Kawa River course is probably related to eastward advancement of the lobe of Bugabo. Another strongly endangered sector is the lower Funu depression (V), where slides have been caused by river incision and movements in the headscar. According to aerial photographs interpretation, landslide (VI) mostly affects the town of Bukavu.

Outside the micrograben, it is difficult to foresee when and where new landslides will develop or old ones will be remobilised. However, the non-tectonically induced landslides are concentrated in three zones where river incision is ongoing or has been occurring in very recent geological times. One is along the coastal zone of the Wesha River basin. A second consists of the NNE- or NE-flowing river sections of Karikere, Funu, Lugowa and Kahuma rivers, upstream of the Cimpunda fault scarp. A third concentration occurs along the Ruzizi gorge.

In the absence of detailed geological, geotechnical, hydrological and topographic data needed to calculate reliable safety factors, we rely on the report by Munyololo et al. (1999), showing that most mass movements are remobilisations of older ones. These authors noted that new immigrants put their houses in landslide scars, on landslide lobes

and other dangerous places. Accordingly, a first step to make Bukavu safer is to take into account the geomorphic and geotechnical constraints posed by active faults and landslides within and near Bukavu, and to guide new urban development in places with lower risk. It is hoped that this report might be a first contribution.

Acknowledgements

This research was supported by the project “Géologie Urbaine de Bukavu. Interaction entre la stabilité du sol et la pression démographique”, contract SC/RP205.580.1 between the Royal Museum of Central Africa, Belgium, and the UNESCO, as part of the «Geological Networking (GEONET) Programme», Ph. Trefois (chercheur principal), P. Lahogue and J. Lavreau, in collaboration with the ‘Centre Universitaire de Bukavu’ (RDC) and the University of Bujumbura (Burundi).

The authors thank the reviewers, Profs. Schlemon and Crosta, for their constructive remarks.

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