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Landslides in the Ethiopian highlands and the Rift margins

Bekele Abebe [a], Francesco Dramis [b], Giandomenico Fubelli [b,*], Mohammed Umer [a], Asfawossen Asrat [a]

[a] Department of Earth Sciences, Addis Ababa University, P.O. Box 1176, Addis Ababa, Ethiopia
[b] Department of Geological Sciences, Roma Tre University, Largo S. L. Murialdo 1, 00146 Rome, Italy

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ABSTRACT

Landslide hazard is one of the crucial environmental constraints for the development of Ethiopia, representing a limiting factor for urbanization and infrastructures. The high relief and the rugged topography induced by a strong Plio-Quaternary uplift, the occurrence of clayey horizons within the sedimentary sequences, the dense network of tectonic fractures and faults, the thick eluvial mantles on volcanic outcrops, and the thick colluvial–alluvial deposits at the foot of steep slopes are the predisposing factors for a large variety of mass movements. Heavy summer rainfall is the main triggering factor of most landslides, some of which undergo a step-like evolution with long-lasting quiescence intervals. First generation movements are commonly restricted to shallow phenomena, such as soil slips or mud flows in eluvial–colluvial material. Fast moving slope failures, such as rock slides, topplings and falls, are also triggered by earthquakes. To mitigate the landslide risk, any first priority measure should include adequate drainage of slopes in order to reduce water infiltration. On the other hand, appropriate site selection for buildings, transferring risky settlements, accurate geological control of works, and education campaigns are all strongly recommended.

1. Introduction

Landslide hazard is, without any doubt, one of the crucial environmental problems for the development of Ethiopia, representing a limiting factor for urbanization and infrastructural projects and, generally, for all the activities performed on and at the foot of slopes. The damage produced by landslides in Ethiopia is relevant: from 1993 to 1998 alone, more than 200 houses were destroyed, more than 500 km of roads were interrupted and about 300 people were killed (Ayalew, 1999).

The widespread distribution of landslides in Ethiopia is mainly related to the occurrence of several predisposing factors such as rugged morphology, high relief energy, and the nature of the outcropping rocks. The triggering factors are essentially connected with the rainfall regime and, to a minor extent, with seismicity. The role played by human impact within the context of the country's socio-economic development is being of increasing importance in causing slope instability.

The northern Omo River basin, the lower Wabe-Shebele River valley, the Wendo Genet slope, the Blue Nile Gorge, the town of Dessie, the Wudmen area in Weldiya, the Gilgel Gibe River, the Uba Dema village in Sawla, and parts of Tigray are some of the areas where imposing landslide events have been reported in the last decade (Fig. 1).

Notwithstanding the growing information on landslide occurrence in the country and the valuable papers published on the topic (Ethiopian Institute of Geological Surveys, 1994, 1995; Asrat et al., 1996; Gezahegn, 1998; Ayalew, 1999, 2000; Ayalew and Vernier, 1999; Temesgen et al., 1999, 2001; Ayalew and Yamagishi, 2002, 2004; Nyssen et al., 2002, 2003; Fubelli et al., 2008; Moeyersons et al., 2008), the sensitivity of public administrators and decision makers is still weak and only few research projects have been launched on the assessment of landslide susceptibility, hazard and risk (IUGS WGL-CRA, 1997) on a regional scale.

The authors hope that the general overview of landslides in Ethiopia presented in this paper could help making people aware of their widespread environmental/social impact all around the country and, possibly, stimulating further investigation and public intervention on potentially unstable areas.

2. Geological background

The most ancient geological unit of Ethiopia is the Precambrian–Archean crystalline-metamorphic basement (Katzmin, 1972; Tefera et al., 1996). It is made of two sub-units: the "*Upper Complex*" (Precambrian), consisting of a more than 1500 m thick sequence of low grade metamorphosed pyroclastics and rhyolithic lavas (*Tsaliet Metavolcanics*) unconformably overlain by a 2000-m thick sequence of metasediments (*Tembien Group*), and the highly

* Corresponding author. Tel.: +39 0 657338022; fax: +39 0 657338201.
E-mail address: fubelli@uniroma3.it (G. Fubelli).

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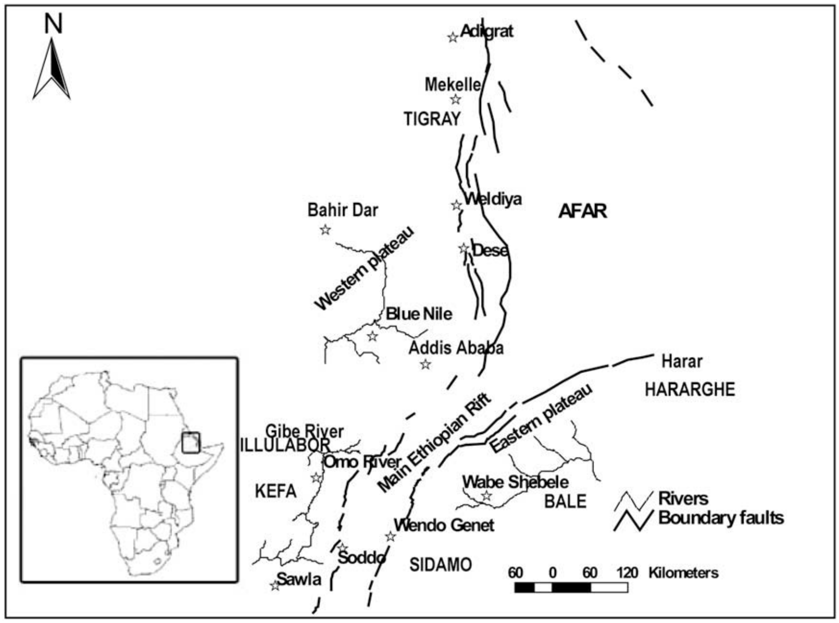

Fig. 1. Sketch map of Ethiopia showing the localities mentioned in the text.

metamorphosed "*Lower Complex*" (Archean), cropping out only in western and southern Ethiopia. At places, Late-Precambrian to Early Paleozoic granitic–dioritic batholiths and stocks cross the basement rocks.

In the Early Paleozoic extensive denudational processes affected the Precambrian relief, generating a wide planated surface (Coltorti et al., 2007) over which continental sandstones (*Enticho Sandstone*) and tillites (*Edaga Arbi Glacials*) of Ordovician age were deposited (Katzmin, 1972; Tefera et al., 1996). These sediments crop out in Tigray, in the Blue Nile Gorge, in the Illulabor, in the Kefa regions, and in the Bale area with a maximum total thickness of a few hundred meters.

After a long-lasting sedimentary gap, the *Adigrat Sandstone* (Triassic-Callovian), made of quartz sandstones with laterite layers and conglomerates, were emplaced (Bosellini et al., 1997). The upper part of the sequence includes 20–30 m of shales. The *Adigrat Sandstone* crops out all around the Mekelle Outlier, in the middle Blue Nile valley as well as in the Illubabor, Kefa, Bale, Harar, and Hararghe regions, with a thickness varying from a few meters to several hundred meters.

The following *Antalo Supersequence* (Bosellini et al., 1997) is a thick (up to more than 700 m) marly-carbonatic marine successionn of Upper Oxfordian – Kimmeridgian age, cropping out in the Mekelle Outlier, around Adigrat, in the Blue Nile Valley, and in the Harar-Dire Dawa area. The lower part of the *Antalo Supersequence* includes the *Antalo Limestone* (Blanford, 1870; Merla and Minucci, 1938), a stratified limestone unit with variable intercalations of marly-shaly layers. In the Blue Nile Valley, the *Antalo Limestone* overlays the *Goha Tsion Formation* (Assefa, 1991), a 580 m thick Early Jurassic sequence of sandy limestone, calcareous sandstone, gypsum and shales. The upper part of the *Antalo Supersequence* includes the *Agula Shales* (Merla and Minucci, 1938) consisting of shales with alternating marls, coquina limestones, quartz–arenites and gypsum. Early Tertiary dolerite sills and dykes, up to 300 m thick, cut across the stratigraphic succession in the Mekelle area. A comparable sedimentary sequence of Jurassic age, including, from the base, the *Hamanilei Formation* (limestone and dolomite), the *Urandab Formation* (shales, marls and gypsiferous limestone), and the Gabredarre Formation (marly limestone and shaly limestone), occurs in Hararghe, Sidamo and Bale.

The *Amba Aradam Formation*, a continental sequence of sandstone and conglomerate with shaly and laterite horizons of Cretaceous age (Katzmin, 1972) unconformably covers the previous units south and east of Mekelle (Coltorti et al., 2007), in the Blue Nile valley (where it reaches a thickness of 600 meters), and in the Hararghe region.

The *Amba Aradam Formation* is overlain almost everywhere by the *Traps*, a pile of lava flows, up to more than 2000 m thick, emplaced during the Oligocene, in the first stages of the East African rifting. Their lower part (*Ashangi Group*) is composed almost entirely of basalts while the upper part (*Magdala Group*) includes some rhyolites. Some volcanoes, mainly basaltic but also rhyolitic, trachytic and phonolitic, erupted during the Pliocene and the Quaternary (Zanettin and Justin-Visentin, 1973). Some of them, located in the Rift Valley, are still active.

From a structural point of view, the Ethiopian highlands include two main uplifted blocks divided by the Main Ethiopian Rift: the Western plateau and the Eastern plateau (Fig. 2). Different fault systems cross the highlands giving rise to horsts, tectonic depressions, and fault scarps (Korme et al., 2004 and references therein). Particularly striking among these are the high scarps built up by the faults which border the Rift Valley and the marginal basins. The recent activity of these faults is testified by the displacement of Tertiary-Quaternary volcanics and Quaternary alluvial deposits.

3. Landslide types and the main predisposing and triggering factors

The main predisposing factors of landsliding in the Ethiopian highlands include the high relief (on average between 2000 and 3000 m), induced by the large-scale Pliocene-Quaternary uplift (Almond, 1986; Mohr, 1986), and the resulting rugged morphology, characterized by very deep valleys and gorges with high steep slopes. Active river incision is widespread and causes further slope steepening and instability. Steep escarpments, up to several hundred meters high, are also produced by faulting which is still active on the Rift margins (Gouin, 1979).

According to the bedrock lithology and slope morphology, different types of landslides are generated in the country.

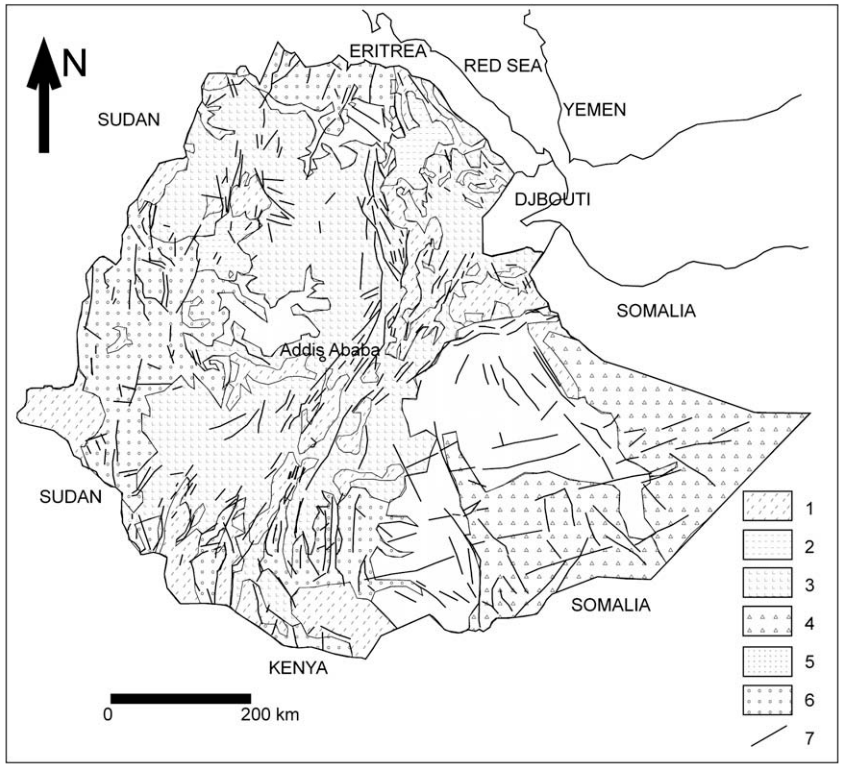

Fig. 2. Geological sketch map of Ethiopia. 1. Quaternary alluvial deposits; 2. Quaternary volcanics; 3. Oligocene-Pliocene volcanics; 4. Cretacic continental and marine successions; 5. Late Jurassic marine and continental successions; 6. Precambrian-Late Proterozoic intrusive rocks and Late Paleozoic-Triassic conglomerates and tillites; 7. Main faults.

(1) On steep slopes modeled in hard bedrock, such as basalt, welded ignimbrite, limestone (e.g. *Antalo Limestone*) and sandstone (e.g. *Enticho Sandstone*, *Adigrat Sandstone*, *Amba Aradam Formation*), often densely cut by joints, parallel and perpendicular to the cliff face (Ayalew, 2000), fast moving mass movements such as rock falls, topplings, and rock slides/avalanches (Varnes, 1978; Dikau et al., 1996) are common.

(2) Steep slopes on weathered pyroclastics and volcanic agglomerates are prone to first generation rapid landslides, such as debris slides and avalanches, debris flows, earth flows and mudflows (Varnes, 1978; Dikau et al., 1996), commonly involving the eluvial cover (Temesgen et al., 1999).

(3) Rapid collapse phenomena, such as topples and slumps (Varnes, 1978; Dikau et al., 1996), frequently affect the alluvial banks of deeply incised rivers and gullies.

(4) On clayey materials, such as shaly-marly sedimentary formations (e.g. *Agula Shales Formation, Edaga Arbi Glacials, Goha Tsion Formation*), alluvial–colluvial deposits at the foot of steep slopes, and thick weathered layers on volcanic bedrock (Canuti et al., 1986), simple and multiple retrogressive rotational slides, sometimes passing to earthflows or mudflows (Varnes, 1978; Dikau et al., 1996), are often generated. Rapid translational rock slides (block slides) moving along predisposed yelding surfaces (Varnes, 1978; Dikau et al., 1996) can be expected in bedrock where soft clayey beds, dipping downslope, are overlain by hard, competent rocky layers. Slow moving translational slides may involve in thick alluvial–colluvial deposits with intercalated finer horizons. Most of the above-mentioned slides undergo a step-like evolution, with long quiescence periods and reactivation phases after heavy rainfall (Ayalew, 2000). First generation events are commonly restricted to shallow phenomena, such as soil slips or mud flows mobilizing eluvial–colluvial material. As elsewhere in the world, the occurrence of large-scale inactive debris flow bodies may be related to past wetter climatic conditions (Nyssen et al., 2002).

(5) Where thick layers of hard rock overlie clayey formations, as in the case of the *Amba Aradam Formation* in Tigray, large-scale lateral spreading phenomena (Dramis and Sorriso-Valvo, 1994; Dikau et al., 1996), moving at an extremely slow rate, are present (Coltorti et al., 2009).

The main triggering factor of slope failures is heavy rainfall. Most of the rain in Ethiopia is concentrated in July and August, during which extremely intensive and long-lasting rainfall events may occur (Gamachu, 1977; Ethiopian Mapping Authority, 1988), with subsequent high water percolation into the ground, widespread slope wash and river-bank erosion. Infiltrating rain water plays a pivotal role in triggering landslides by increasing the total weight of the slope material, causing the water table to rise and increasing the pore pressure in fine-grained deposits (Brand et al., 1984; Canuti et al., 1985; Shimizu, 1988; Nieuwenhuis, 1991; Ayalew, 1999; Gabet et al., 2004). Clayey/marly formations overlain by hard rock, fractured aquifers, such as basalt, limestone or sandstone, that may undergo sudden water table fluctuations during heavy rain, are particularly prone to gravity driven deformation and failure (Ayalew, 2000). The infiltration of rain water in the fractured bedrock may be aided by the occurrence of deep desiccation cracks in the soil cover at the end of the dry season; especially after low spring rainfall (Billi and Dramis, 2001, 2003).

Moreover, groundwater pressure and seepage may trigger mass movements in colluvial deposits covering the hydrogeological contact between a hard rock cliff and an underlying clayey/marly aquiclude (Ayalew, 2000; Nyssen et al., 2003).

From the analysis of 64 rotational/translational slides from different parts of the Ethiopian highlands, Ayalew (1999) observed that the number and size of failures increase with increased rainfall and rainy days; he also proposed a simple equation linking landslide occurrence with significantly above-average rain.

Earthquakes are recurrent events in Ethiopia, especially along the Rift system, where magnitudes greater than 5 are not rare (Gouin, 1979; Ayele, 1995; Ayele and Arvidsson, 1998). Widespread evidence of seismic triggering of landslides, mostly first-generated rapid movements such as rock falls, rock slides, and debris-mud flows, is provided by the historical record of earthquakes and related surface effects (Gouin, 1979).

The increasing impact of human activities, such as intensive agriculture, quarrying, road construction, urbanization, land use changes, etc., is also responsible for slope instability and landslide hazard (Ayalew, 2000; Nyssen et al., 2003). Particularly prone to the initiation of slope movements seems to be the first stage of vegetation regrowth after deforestation (Collison and Anderson, 1996; Nyssen et al., 2002). In case of heavy rain, the presence of woodcutting clearings and irrigation ditches on intensively cultivated slopes may increase the infiltration of rain water and the occurrence of landslides (Temesgen et al., 1999; Nyssen et al., 2002). The construction of houses, roads, bridges, and culverts on such sites may increase slope instability by adding weight to incipient landslides or modifying the slope profile. The leakage of water into the ground from aqueducts and pipelines may also trigger mass movements.

All the above-mentioned slope movement phenomena may interact with people, settlements, infrastructures and farmlands, inducing different levels of risk in relation to the different hazard and vulnerability levels (IUGS WGL-CRA, 1997). The negative effects of landslides are generally more pronounced in developing countries because of their high "social vulnerability" to natural disasters, due to economical, social, political and cultural constraints (Alcántara-Ayala, 2002). Very high risk levels, due to the possible occurrence of rapid mass movements related to heavy rainfall, are typical of settlement areas located at the foot of steep slopes modeled in weathered volcanic rocks or at the outlet of mountain streams, from where concentrated flows of flooding water and debris can suddenly burst out. Settlements and infrastructures, located at the base or at the edge of high fault escarpments in earthquake prone areas, are also at risk.

4. Some case studies

The specific occurrences of landslides in the investigated areas, which are thought to represent general situations on the rift margins and adjacent plateaus, are discussed in the following section.

4.1. Dessie

The town of Dessie, a medium-sized urban settlement with about 200,000 inhabitants, and the surrounding area are heavily affected by landslides (Ethiopian Institute of Geological Surveys, 1995; Ayalew and Vernier, 1999; Ayenew and Barbieri, 2005; Fubelli et al., 2008). The town is located in one of the small tectonic depressions of the western Afar Margin, a physiographic province characterized by closed basins and mountain ranges produced by Tertiary–Quaternary regional extension (Ukstins et al., 2002).

The outcropping bedrock consists of a sequence of Tertiary ignimbrites and lava flows with a variable degree of weathering. They are mantled by colluvial and alluvial deposits mainly deriving from the Tosa and Azwa Gedel ridges. In the eastern part of the town, swampy-lacustrine sediments, including clays, silts and sands, locally underlie the alluvial–colluvial cover.

An outstanding feature of the Dessie graben is a marked family of faults with an overall trend varying between NNE and NNW (Fig. 3). These faults control the topographic configuration and the drainage pattern of the area, and are seen, from their relationships with the Tertiary volcanics, to be relatively young.

Due to the Plio-Quaternary regional uplift (Almond, 1986; Mohr, 1986), the Dessie graben is deeply incised by the Borkena River, forming a 300-m deep gorge, the *Doro Mezleya* stream, in its south-eastern side.

On the steep Tosa and Azwa Gedel fault scarps (70–80°) which border the Dessie graben, rock falls, rock topplings, rock slides/avalanches, as well as soil slips and mud flows, affecting the thick weathering mantle of the volcanic bedrock, are common types of failure (Fig. 4). Rotational slides, with few meters deep shearing surfaces, mainly occur in the alluvial–colluvial and lacustrine deposits of the graben floor (Fig. 5); deep reaching translational slides can move at the interface between bedrock and overlying surficial deposits (Fig. 6). Translational rock slides, moving along joints parallel to the slope, locally involve the basalt bedrock (Fig. 7).

The main triggering factor of most landslides in the area is heavy rainfall (Ayenew and Barbieri, 2005). Rapid slope failures such as rock falls and debris flows, are also triggered by earthquakes (Gouin, 1979), as it occurred during the seismic event of 8 July 1988.

Despite the extensive eucalyptus cover in most parts of Dessie, root reinforcement is apparently lacking. This is probably because tree roots do not penetrate below the soil cover. Moreover, the loss of cohesion as the saturation front reaches the basis of the root belt, has been shown to cause numerous shallow landslides in parts of Brazil (Wolle and Hachich, 1989).

4.2. Tigray

The outcropping bedrock of Tigray is characterized by a basement made of low grade metavolcanics, metasediments and plutonic rocks, unconformably overlain by sub-horizontally layered Paleozoic–Mesozoic sandstones, limestones, shales and tillites in the Mekelle Outlier (Merla and Minucci, 1938; Tefera et al., 1996 and references therein). These latter units are overlain, in turn, by Tertiary–Quaternary flood basalts and intercalated pyroclastics (Katzmin, 1972).

The *Adigrat Sandstone*, *Antalo Limestone* and Tertiary volcanic rocks are pervasively affected by fractures with an apparently random pattern, causing slope instability on steep scarps. The prominent styles of slope failures along the vertical cliffs of sandstone, limestone and basalt are rock falls, rock topplings, rock slides/avalanches (Fig. 8) and debris flows (Fig. 9). Particularly unstable are the rocky cliffs (*Adigrat Sandstone*/*Amba Aradam Formation*) overlying clayey/marly levels (*Edaga Arbi Glacials*/*Agula Shales*).

Where the *Amba Aradam Formation* overlies the *Agula Shales*, large-scale lateral spreading phenomena, locally evolving to rotational slides, are manifested (Coltorti et al., 2009) (Fig. 10).

A large number of dormant landslide bodies (earth/mud flows or rotational slides), likely generated in climatic conditions wetter than the present ones, are found in the area (Nyssen et al., 2002; Moeyersons et al., 2008; Coltorti et al., 2009). In many cases, they are partially reactivated by the incision of gullies in the landslide mass (Nyssen et al., 2002).

Widely affected by rapid mass movements (such as rock slides, falls, and topplings) are the high steep fault/fault line escarpments bordering the Rift Valley to the east.

4.3. Wendo genet

Wendo Genet is located on the inner slope of a caldera in the eastern margin of the Main Ethiopian Rift (Fig. 11a). The bedrock is made up of basalts and ignimbrites.

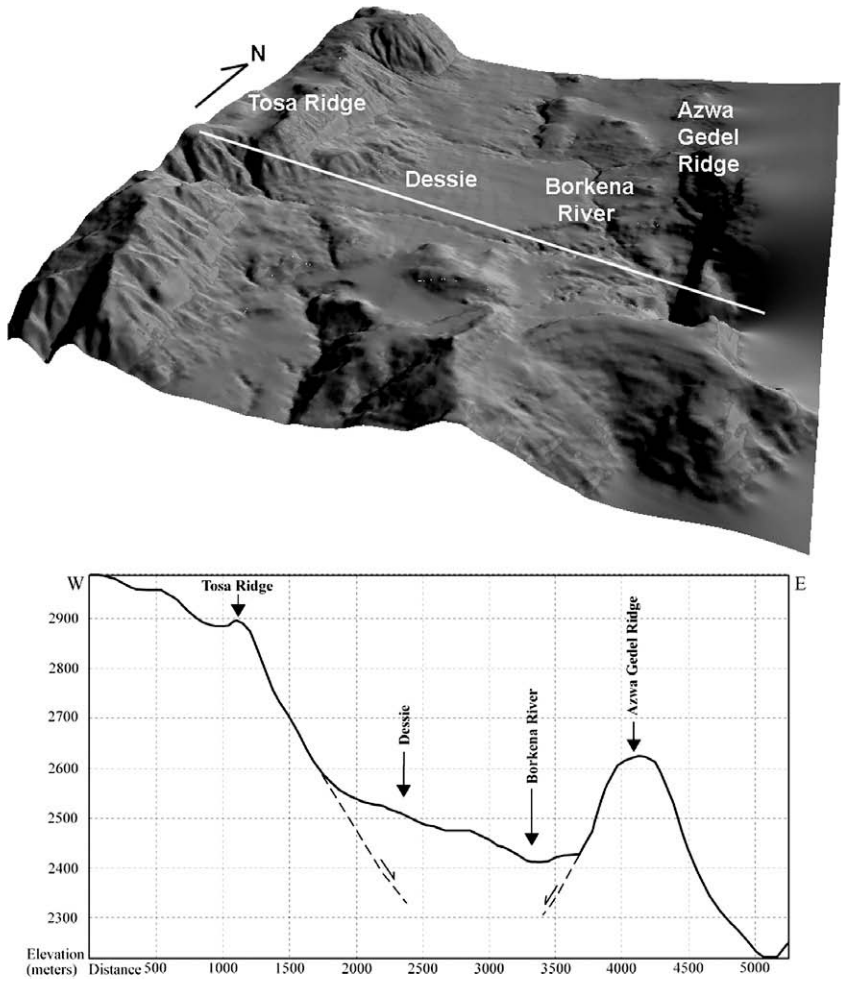

Fig. 3. 3D scene of Dessie and E–W profile sections showing the Tosa and Azwa Gedel fault slopes, and the Dessie graben.

Fig. 4. Debris slides at the Azwa Gedel scarp. Fallen blocks are visible on the accumulation zone of the right-side landslide.

Fig. 5. Rotational slides in lacustrine sediments with crescent shaped fractures.

Mass movements are frequent in Wendo Genet (Temesgen et al., 2001) in spite of the thick vegetation cover on the surrounding slopes. Mud flows and soil slips in eluvial–colluvial deposits, with basal shear surfaces at the bedrock contact (Fig. 11b) are triggered by long-lasting heavy rainfall and water infiltration into the soil. The occurrence of these failures is also favored by the intensive cultivation of the slopes with irrigation ditches parallel to the contour lines. Eight people lost their lives due to a debris flow triggered by the heavy rains of June 17, 1996 (Temesgen et al., 1999).

Rock falls commonly occur along the caldera rim, especially where the bedrock is crossed by faults and closely spaced joints. The high recurrence of these phenomena in the area may suggest ongoing seismic triggering. Local inhabitants reported that a large number of huge rock falls (Fig. 11c) were generated during the September 6, 1944 earthquake (Gouin, 1979).

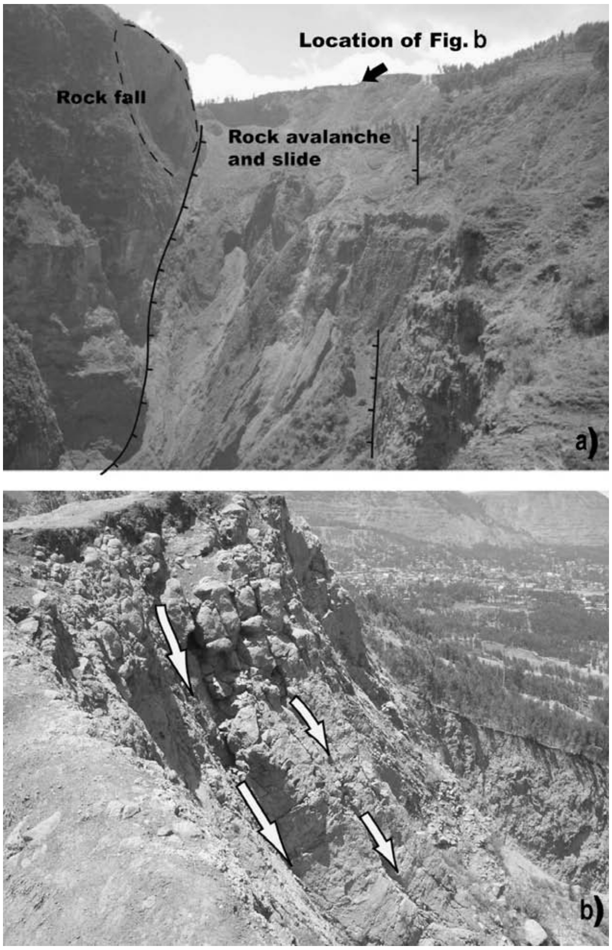

Fig. 6. Doro Mezleya slope, affected by different landslides types (a); surface of rupture along joints in the volcanic bedrock (b).

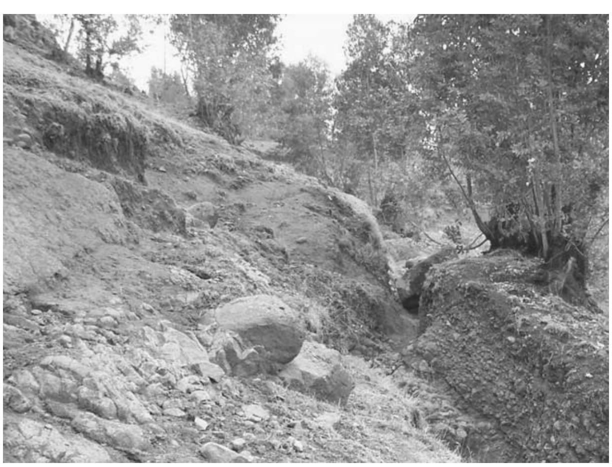

Fig. 7. Translational slides showing the surface of rupture at the debris-bedrock boundary.

4.4. Blue Nile Gorge

The Blue Nile Gorge deeply incises the Western Plateau, north of Addis Ababa. The outcropping rocks include Paleozoic to Mesozoic sandstones, limestone, gypsum, marl and shales unconformably overlain by Tertiary basaltic flows with intercalated layers of volcanic ash (Assefa, 1991).

Fig. 8. A rock slide/avalanche involving the *Adigrat Sandstone*.

Fig. 9. Debris flows in the Adigrat sandstone west of Adigrat.

The rugged topography is a result of the deep dissection by the Blue Nile drainage network following the Pliocene-Quaternary uplift (Almond, 1986; Mohr, 1986). A topographic profile between the towns of Dejen and Goha Tsion indicates that the elevation of the area ranges between ca. 1050 and 2500 m a.s. l.

The mean annual rainfall at Dejen and Goha Tsion (on the opposite sides of the Blue Nile Gorge) is nearly 1250 mm, decreasing towards the valley floor (Ayalew, 2000). The role played by anomalous rains and groundwater rise in initiating landslides has been emphasized by Ayalew and Yamagishi (2004).

The slopes of the Blue Nile Gorge are widely affected by different types of mass movements (Ethiopian Institute of Geological Surveys, 1994; Ayalew and Yamagishi, 2002, 2004) which have repeatedly damaged and interrupted the Addis Ababa – Bahir Dar road. In 1960, after a long preparatory phase, characterized by the development of small soil slips, a large-scale rotational slide

Fig. 10. Deep seated lateral spreading evolving to rotational slide on the southern slope of Mt. Amba Aradam. The gravitational movements affect the Amba Aradam sandstones and conglomerates unconformably overlying the Agula Shales.

suddenly moved downslope destroying a village and causing 45 victims (Ayalew, 1999).

Rapid failure phenomena, including rock falls and topplings, occur in the hard rock units (*Adigrat Sandstone*, *Antalo Limestone* and the overlying *Amba Aradam Formation* and Cainozoic volcanics) which, due to selective erosion, form nearly vertical cliffs. Soft rock levels, such as the *Goha Tsion Formation* (Assefa, 1991), made up of variegated shales, gypsum and marls, are mobilized by rotational slides, especially on concave slope segments where groundwater, fed by the overlying aquifers, springs out (Ayalew and Yamagishi, 2004). Massive translational slides affect hard rock layers overlying clayey/marly levels. Debris slopes, formed on gently sloping surfaces of weak sedimentary rocks, at the foot of the upper cliffs, are sites of slow-moving rotational–translational slides and debris/earth/mud flows.

5. Conclusion

The study shows clear examples of human vulnerability to landslide processes in different parts of the Ethiopian highlands. The increase in population is posing an ever growing demand for new land for settlement, infrastructure and agriculture. This and the need for power supply as well as construction materials are largely satisfied at the expense of the environment.

Gravity driven slope movements cause severe effects on cultivated land, infrastructure and human settlements, and are presently inducing strong constraints on the social and economic growth of Ethiopia. Besides the natural vulnerability of these areas to landslides, owing to their geological and hydrological conditions, human interference has played an important role in accelerating land degradation. In the case of Dessie, for example, its location on colluvial and alluvial deposits at the foot of the Tosa and Azwa Gedel ridges makes the urban settlement highly vulnerable to landslides. In addition to the destabilizing effect of spring water and seasonal rainfall, uncontrolled building, carried out on the slopes without proper site investigation and using diverse material type and quality, has aggravated the situation.

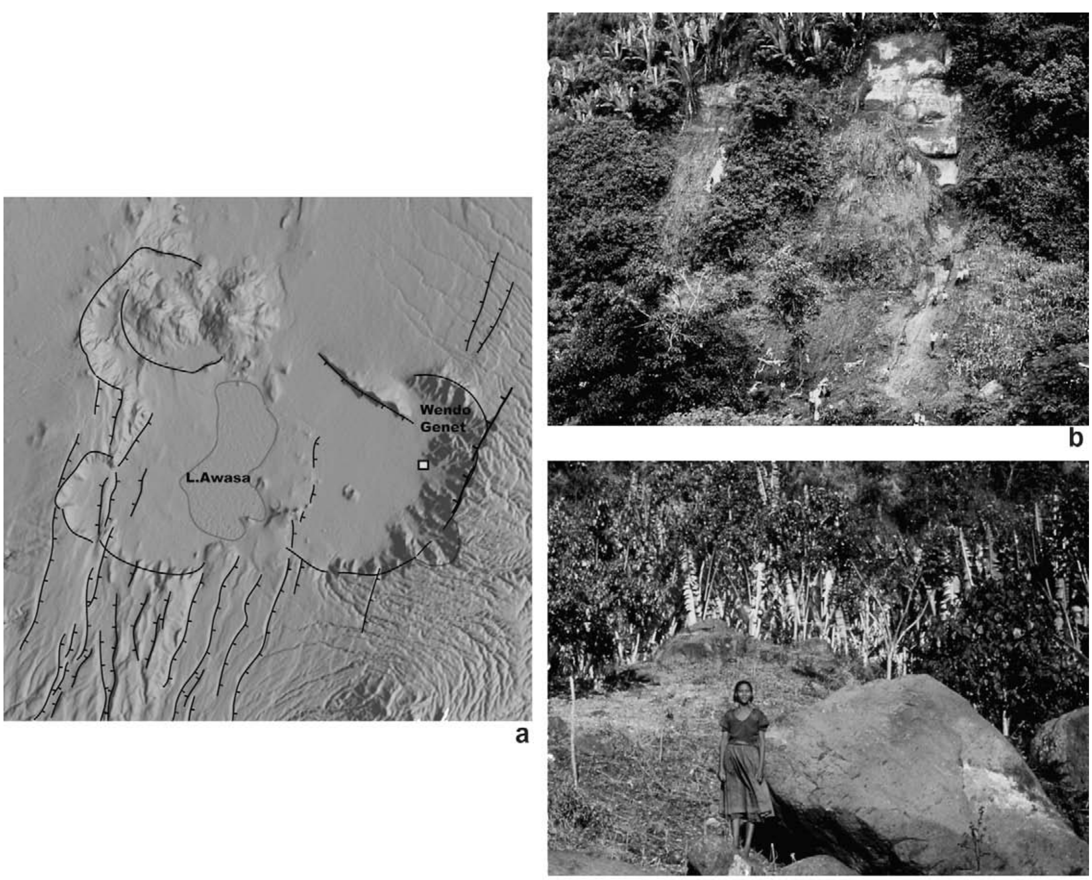

Fig. 11. The Wendo Genet Caldera (a); scars of soil slips triggered by heavy rainfall in June 1996 (b); a huge block of ignimbrite projected from the Wendo Genet caldera rim during a strong earthquake in 1944 (c).

Damage to infrastructures caused by slope instability problems in the Blue Nile gorge, is basically due to the presence of soft sedimentary levels like shale and marl.

As the community expands, landslide risk will increase unless adequate mitigation measures are put in place during development. Therefore, the assessment and control of landslide instability risks are crucial for the design and location of stable infrastructures, settlements and other development activities. These mitigation measures could include: adequate drainage (rerouting springs and rain water) out of the slopes, in order to reduce concentrated water infiltration; gully recovering and control; retaining walls, especially along some road segments; planting of trees; avoiding construction on unstable slopes or at the foot of steep rocky slopes or escarpments, in case of shallow movements. High cost stabilization of landslides is only suggested where indispensable. On the other hand, appropriate site selection for buildings, transferring risky settlements, accurate geological control works, and well-designed education campaigns are strongly recommended measures in the Ethiopian context.

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