Catena 75 (2008) 28–37

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Geomorphological evolution and present-day processes in the Dessie Graben (Wollo, Ethiopia)

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ARTICLE INFO

Keywords:
Geomorphological mapping
Morphotectonics
Slope processes
Rift Margin
Ethiopia

ABSTRACT

This paper presents a detailed geomorphological overview of the landforms and processes characterizing the Dessie basin, a small graben located on the western Afar Margin (Ethiopia), which is a physiographic province characterized by small, closed basins and mountain ranges produced by regional extension. Large-scale geomorphological survey and mapping of the basin allowed to point out the noteworthy morphodynamic role of the present-day slope processes, including numerous landslides of different typology and size. These processes heavily interact with the built-up area of Dessie town, one of the most important cities of Ethiopia with ca. 200,000 inhabitants, which occupies a large part of the basin floor. The potential incidence of landslides of different typology in the basin and their possible impact on the urban settlement are put in relation with the distribution of the different landform units which make up the basin surface.

1. Introduction

Based on a large-scale geomorphological survey and mapping, this paper presents a detailed overview of the landforms and geomorphic processes which characterize the Dessie Basin (Figs. 1 and 2), a small graben (ca. 7 km long and 3 km wide) located around 2600–2700 m a.s.l. on the western Afar margin (Ethiopia). The basin is crossed by the Borkena River which, at the south-eastern edge, flows towards Kombolcha through a 300 m deep narrow gorge, locally named Doro Mezleya; its south-west sector is part of the Kelina River catchment. Most of the basin floor is occupied by Dessie Town, one of the medium-sized urban settlements of Ethiopia with about 200,000 inhabitants (Central Statistics Agency, 2006).

As for most localities of the Ethiopian Plateau, the climate of Dessie is characterized by distinct wet and dry seasons (Daniel, 1977; Ethiopian Mapping Authority, 1988). According to records of the Ethiopian Meteorological Agency, the average annual temperature is 18.5 °C. Rainfall data recorded between 1974 and 2004 show that there is a bi-modal rainfall pattern with the heaviest rains occurring during the months of July and August with annual average reaching 1600 mm and that more than a third of the annual precipitation is concentrated in the same months (Fig. 3a and b).

In spite of the high yearly rainfall and the dense potential vegetation cover (Ethiopian Mapping Authority, 1988), the slopes bounding the basin are poorly vegetated, likely because of widespread anthropic deforestation (Pankhurst, 1992).

Present-day geomorphic processes and, most of all landslides, play an important role in the present geomorphological evolution of the Dessie Basin, inducing heavy risk on the built-up area (Lulseged and Vernier, 1999; Tenalem and Barbieri, 2005).

The main triggering factor of slope movements is heavy rainfall. Infiltrating rain water plays a pivotal role in triggering landslides by increasing the total weight of the slope material as well as the water table level and the pore pressure in fine-grained deposits thus weakening the links between their component particles (Canuti et al., 1985). From the analysis of 64 landslides in Ethiopia, Lulseged (1999) observed that the number and size of failures increases with increasing rainfall and number of rainy days. He also proposed a simple equation linking landslide occurrence to significantly above-average rain. Fig. 3a indicates a general increase in precipitation in the area during the last 30 years, which might be in part responsible for the increase in landslide frequency (Lulseged and Vernier, 1999; Lulseged, 1999).

Also the earthquakes which recurrently strike the area (Gouin, 1979) may be responsible for landslide triggering. It is likely that at

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0341-8162/$ – see front matter
doi:10.1016/j.catena.2008.04.001

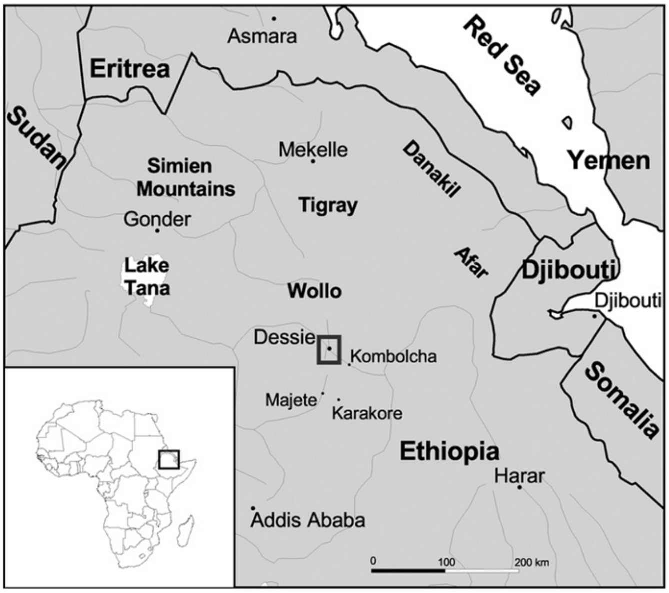

Fig. 1. Location of Dessie area.

least some of the fast moving landslides (rock falls, rock slides, debris flows, debris slides) which affected the Dessie Basin in the past were induced by earthquake shocks.

Moreover, man-made activities, such as the construction of houses, roads, bridges or leakage of water from aqueducts and pipelines, may induce slope instability by adding weight to incipient landslides, modifying slope profiles or changing groundwater levels and flow.

The spatial distribution of landslides is commonly related to bedrock lithology, geotechnical properties of involved materials, slope morphometry, land use, etc. However, a more comprehensive framework for landslide distribution may be provided by detailed geomorphological maps (Demek, 1972; Demek and Embleton,1978; Peña Monné, 1997; Dramis and Bisci, 1998), especially where gravitational movements are represented on landform units (Dramis and Bisci, 1998; Pasuto and Soldati, 1999; Oya, 2001), homogenous for bedrock geology, overburden materials, slope form and relief. These units can be characterized also in terms of land use, human settlements and infrastructures, thus allowing some general evaluation of landslide related risk. Yet, if several studies addressed the burning issue of landsliding in Dessie area, they generally fail to link up their occurrence with major geomorphic land forms.

Based on detailed field survey and mapping, this paper aims to provide an overview of the Dessie Basin geomorphology with particular reference to the present-day geomorphic processes which can impact on human settlements and activities.

2. Methods

The investigation methods included a four weeks (February 25 to March 24, 2005) geomorphological field survey and mapping of the area, using as base maps the 1:5000 topographic map of the urban area (provided by the City Administration) and the 1:5000 enlargement of the 1:50,000 Dessie topo-sheet (ser. ETH 4 — sheet 1139 D3), for the extreme south-eastern sector.

The bedrock lithology and tectonics have been also surveyed taking in account the previous geological works on the area (Gregnanin et al., in press; Ethiopian Institute of Geological Surveys, 1995; Tenalem and Barbieri, 2005).

The field work has been supported by the interpretation of air-photos at 1:10,000 and 1:50,000 scales as well as by stratigraphical analysis of superficial deposits. The legend follows the proposals by Pellegrini et al. (1993) and Dramis and Bisci (1998). The resulting geomorphological map, originally drawn at the 1:5000 scale, is shown in a reduced form in Fig. 4.

Taking into account their possible dangerous impact on the town of Dessie, particular consideration has been given to the numerous landslides which affect the slopes of the study area. One hundred-six landslides have been deeply investigated on the field in order to establish their typology and their state of activity according to the Varnes (1978) and IUGS WGL-CRA (1997) classifications. A statistical

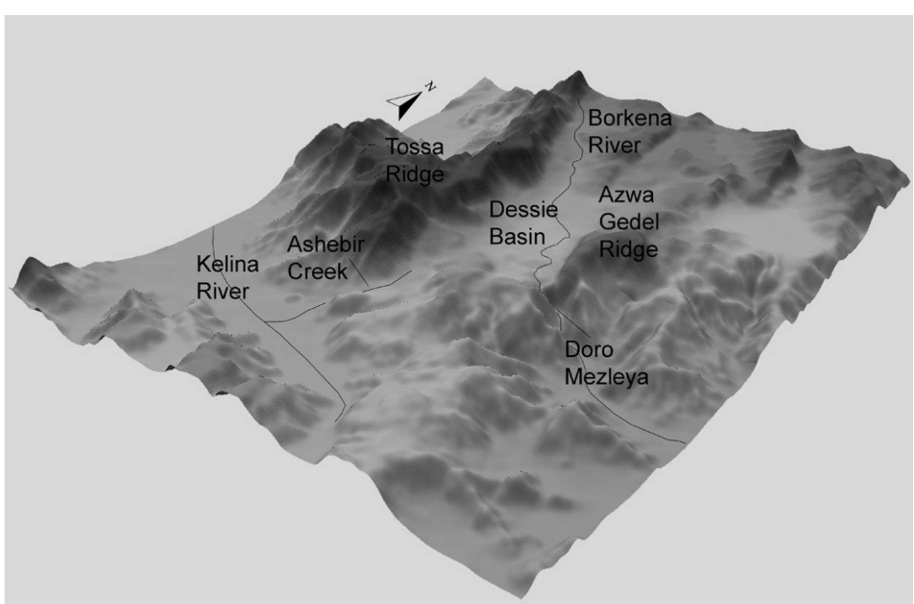

Fig. 2. Digital terrain model of the study area showing the bordering ridges and location of the mentioned localities.

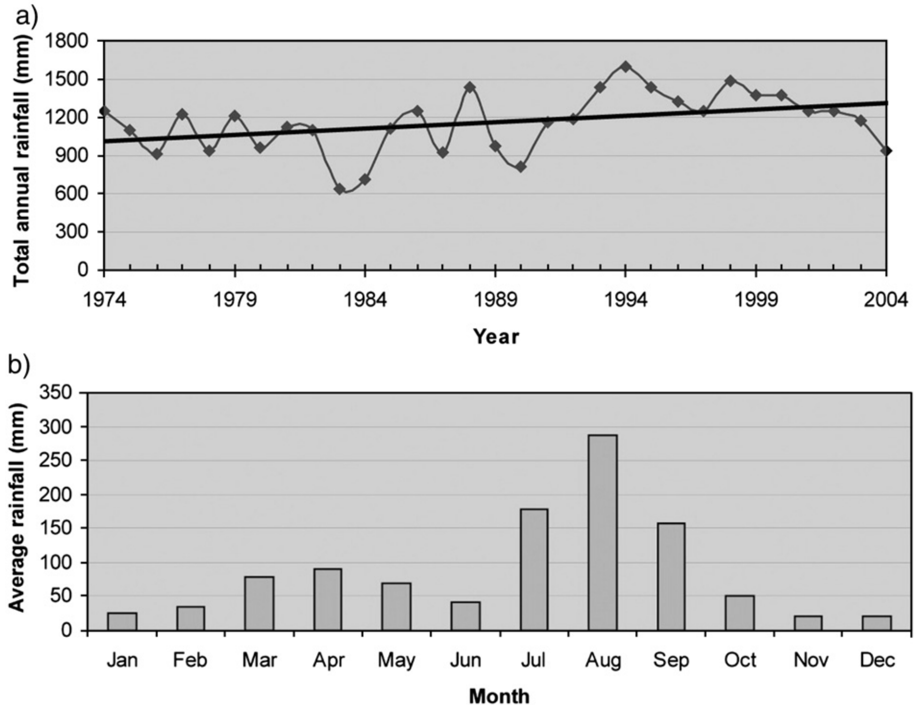

Fig. 3. Dessie rain data for the hydrological years 1974–2004: a) total annual rainfall, with linear trendline; b) monthly average rainfall between 1974 and 2004.

analysis has been carried out in order to evaluate connection between landslides typology and lithology. Also the presence of geomorphic indicators of slope instability, such as ground cracks, steps and trenches, has been taken into account.

3. Geological setting and large-scale morphotectonics

The Dessie depression is one of the numerous 'hanging' tectonic basins located along the western Afar margin (Fig. 5). It is bordered by two N–S striking normal faults: the Tossa fault to the west and the antithetic Azwa Gedel fault to the east. Both faults form high walls which bound the intermediate lowered sector crossed by the Borkena River and its tributaries. More to the east, the N–S trending faults of the Azwa Gedel horst, make a transition to the marginal basin of Kombolcha, located at around 1800 m a.s.l., 800 m below the Dessie Basin. The SW-NE trending Doro Mezleya fault is apparently a transfer zone between the Dessie and Kombolcha grabens. It is partially exhumed by fluvial erosion. Another SW-NE fault, with less geomorphic evidence, borders the basin to the north, separating it from the Seyo Kurkur depression. Other faults ranging in strike from NNW-SSE to NW-SE cross the area exerting a more or less direct control on the basin topography.

The bedrock consists of ignimbrites, volcanic agglomerates and basalt flow layers ranging in age between 30 and 25 Ma (Gregnanin et al., in press; Kazmin, 1979; Mengesha et al., 1996). In particular two different units have been recognized: a) pre-rift flood basalt and b) the graben floor post-rift basalt post-dating the main faulting. The first unit widely outcrops on the main fault escarpments and their top surfaces; the second unit is the most dominant rock type in the axial part of the Dessie graben and is exposed along the banks of the Borkena River. These rocks have undergone variable degrees of weathering and are often interbedded with reddish paleosols.

The graben floor filling sediments consist mainly of alluvial-swampy-lacustrine deposits, mostly made of yellow sands with gravelly levels, white diatomite beds, and scarce pyroclastic fragments, likely derived from volcanic products in the surrounding areas. These sediments were considered to be of Quaternary age by previous authors (Gregnanin et al., in press; Ethiopian Institute of Geological Surveys, 1995; Tenalem and Barbieri, 2005). Actually, notwithstanding the lack of chronological data, the relatively small thickness of the deposits, their flat depositional surface constantly located at 2520 m a.s.l., and the extremely rapid dynamics of the geomorphic processes affecting the area, seems to testify a very recent geological origin.

4. Main landform units and present-day geomorphic processes

From the geomorphological point of view, the Dessie graben can be divided into seven different landform units: 1) *the fault escarpments and gently sloping summit surfaces*; 2) *the talus belts*; 3) *the fluvio-denudational slopes*; 4) *the hummocky graben floor*; 5) *the alluvial fans of the Borkena River tributary streams*; 6) *the Dessie terrace*; 7) *the river beds and terraces* (Fig. 6).

4.1. The fault escarpments and gently sloping summit surfaces

The main N–S fault escarpments form imposing rocky walls over which the *basalts and ignimbrites of the continental flood basalt* outcrop. The Tossa fault escarpment (Fig. 7) is up to 400 m high and up to 80° steep. It follows a rectilinear trend being only interrupted by the upper catchments of the two western tributaries of the Borkena River. The Azwa Gedel scarp is lower (ca. 200 m) and has a more rectilinear trend, without major stream incision. The two N–S bordering escarpments are topped by gently sloping surfaces, whose maximum elevation is ca. 2950 m on the Tossa side and 2720 m a.s.l. on the opposite Azwa Gedel side. It is probable that these surfaces were fragments of the ancient depositional top of the trap volcanics before the opening of the Dessie graben.

All these escarpments are diffusely affected by rill wash and gullies as well as by different types of failures. Rock falls and topplings, generally of small size, are common on the Tossa escarpment. The

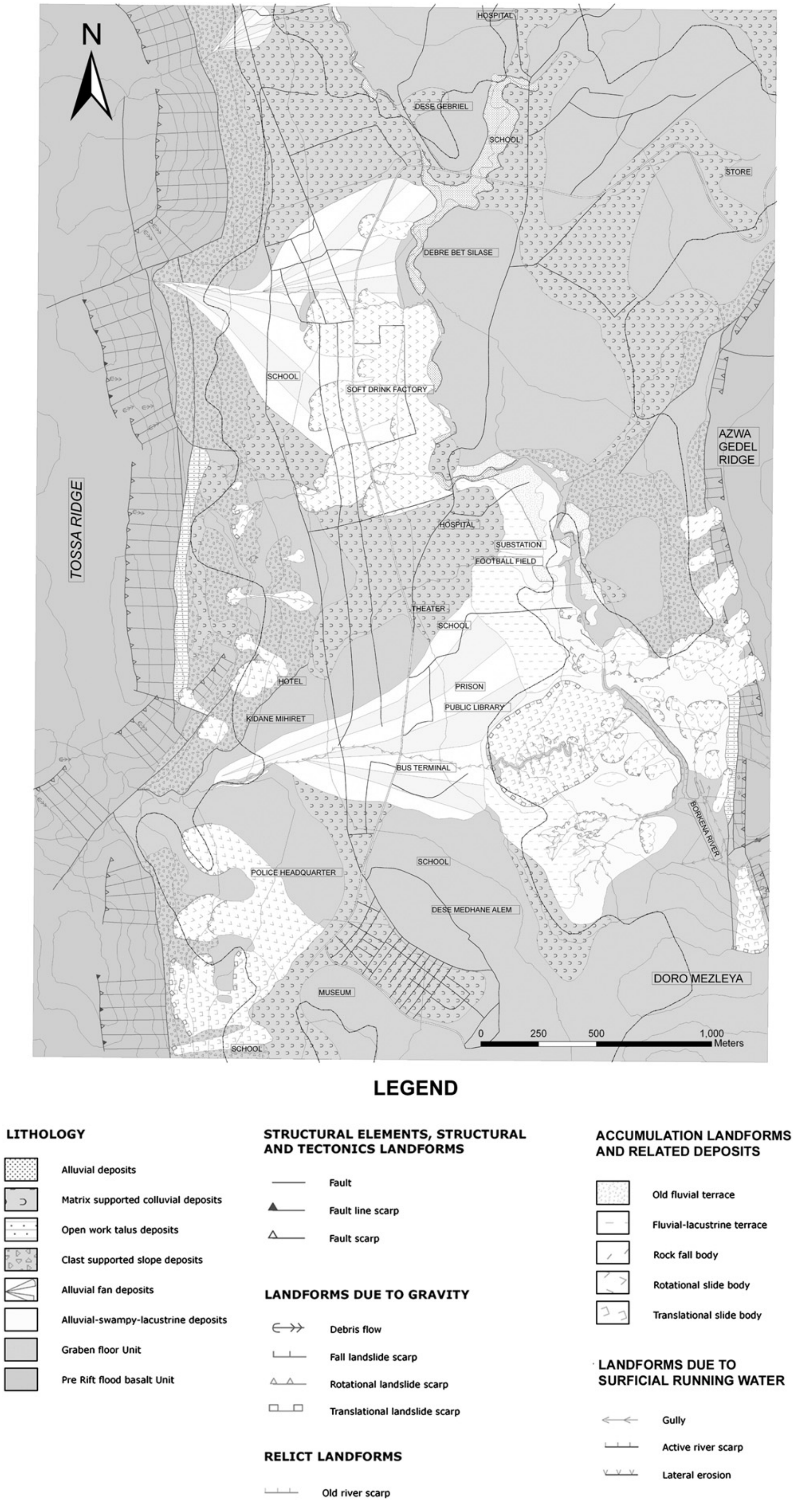

Fig. 4. Geomorphological map of Dessie.

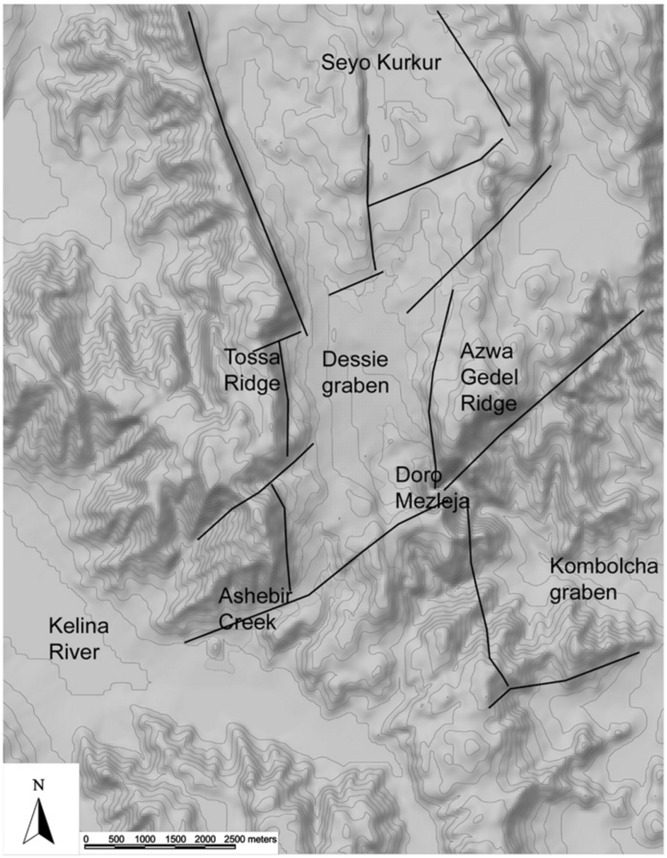

Fig. 5. Dessie Basin fault pattern.

Azwa Gedel escarpment is locally affected by rock slides which involve the outcropping pre-rift flood basalt unit (Fig. 4).

The SW-NE trending Doro Mezleya fault escarpment on the graben floor unit (Fig. 4) is affected by a huge retrogressive translational rock slide, evolving downward into a rock avalanche. This rock slide (Fig. 8) moves along the basalt cooling joints which, in this particular sector, are parallel to the slope. In the southern sector of the Tossa escarpment, a secondary fault almost parallel to the main one, puts in contact a small relief of young post-rift vesicular basalts with the basalts and ignimbrites of the main escarpment forming a morphological terrace. Prominent depressions and trenches along the fault trace, in the inner side of the terrace surface, could be related to a recent reactivation of the fault.

4.2. The talus belts

A thick (up to 15 m) belt of open work and clast-supported talus deposits, accumulated by slope wash and mass movements, outcrops on both sides of the Dessie Basin, at the foot of the Tossa and Azwa Gedel escarpments (Fig. 4). The open work deposits are made of angular heterometric clasts without matrix; the clast-supported deposits are made of scarcely rounded clasts touching each other with the space between them filled with finer sediments. These latter form layers up to 2 m thick alternating with less than 10 cm thick sandy–clayey levels.

Most of the mobilized fragments are provided by the escarpment basalts and ignimbrites which may be considered the major parent material of the graben floor surficial deposits (Tenalem and Barbieri, 2005). Scattered blocks up to few metres large, emplaced by rock falls and topplings from the densely jointed stratoid basalt of the escarpments are locally found. Two buried vertisols likely connected to more humid and vegetation-rich phases of the early–mid Holocene (Dramis et al., 2003) are present in the upper part of the sequence.

The slope deposits are poorly compacted and are rapidly incised by running waters fed by the upslope areas. Those at the foot of the Tossa escarpment are affected by translational debris slides which follow the above mentioned sandy–clayey levels or the downsloping basal volcanic surface, as in the case of the huge rock slide which affects the Tossa escarpment talus on the right side of the Ashebir Creek, in the south part of Dessie. The deep-reaching movement, whose thickness ranges between 10 and 15 m, is testified by the occurrence of sub-rectangular box-shaped trenches, with outcropping basalt at their base (Fig. 9). The frontal part of the moving mass is widely affected by single, retrogressive and successive rotational slides induced by the lateral erosion of the stream, particularly active in the rainy season (Lulseged, 1999).

4.3. The fluvio-denudational slopes

Relict fluvio-denudational slopes modelled on basalt bedrock are testified by the occurrence of wind gaps crossing the Azwa Gedel ridge. More recent slopes, carved by fluvial erosion, are those forming the upper catchments of the two tributaries of the Borkena River. Notwithstanding the high angle, these slopes are covered by a relatively thick eluvial–colluvial mantle which is frequently affected by debris flows and debris slides, particularly during the rainy season.

4.4. The hummocky graben floor

A large part of the graben floor is characterized by an irregular hummocky topography, with low round-shaped hills separated by narrow flat-floored small valleys crossed by the Borkena River and its tributaries. The low, rounded hills clearly result from selective erosion of the volcanic ridges and cones on the graben floor. They are commonly deeply weathered and covered by eluvial–colluvial materials, at places including pyroclastic materials (Tenalem and Barbieri, 2005), likely erupted by Pliocene–Quaternary volcanoes in the nearby areas (Kazmin, 1972; Mengesha et al., 1996). These materials are diffusely shifted downslope by soil-creep movements and tend to fill up small valleys and inter-hill depressions as in the case of the Mugad area (south-west of Dese Medhane Alem).

4.5. The Dessie terrace

A 75 to 100 m thick sedimentary sequence of alluvial-swampy-lacustrine facies, made of sands and clayey sands alternating with silty siliceous levees and less frequent gravelly levels, fills up the lower part of the Dessie depression.

These deposits have been incised down to their base by the Borkena River forming a wide terrace (Fig. 10), constantly 2520 m a.s.l high from Dessie (Dessie Football field) to the edge of the Borkena River gorge. Eastward, the same feature may be recognized up to the St. Michael Church, where its southward continuity is interrupted by rotational slides.

This eastern terrace sector is less developed, likely due to the reduced debris production from the Azwa Gedel escarpment, lower in altitude and relatively poor in the older escarpment rocks. The sequence overlays a sub-horizontal surface of vesicular basalt whose elevation is 2500 m a.s.l. on the Borkena River bed, close to the Doro Mezleya gorge, and 2525 m a.s.l. in the westernmost part of the Dessie terrace.

Widespread slope instability is induced in the deeply incised alluvial-swampy-lacustrine sequence by the lateral erosion of the Borkena River directly flowing over the more resistant basalt bedrock (Asfawossen et al., 1997). As a consequence, the alluvial-swampy-

Fig. 6. Main landform units of the Dessie Basin.

lacustrine sediments are affected by numerous mass movements, mostly retrogressive rotational slides of different size, which are responsible for an extremely rapid retreat of the terrace edge. Moreover, small-scale debris slides affect the colluvial materials covering the river-cut escarpments.

In sliding alluvial-swampy/lacustrine sediments immediately west of the Azwa Gedel escarpment, shear cracks with pressure ridges developed systematically. The fractures are crescent shaped and separate small blocks. Soil-creep movements, possibly seasonal and coinciding with intense precipitation, are common in the low relief

Fig. 7. Tossa fault escarpment and alluvial fan where Dessie city center is located.

areas. In case of heavy rainfall, these slow movements may radically change to rapid debris flows, as in 1994 when they caused huge damage to roads, utilities and buildings.

4.6. The alluvial fans of the Borkena River tributary streams

The fluvial sediments transported from the Tossa escarpment to the Borkena River by the two tributary streams form wide alluvial fans over which sectors of the Dessie town are located. These features are deeply affected by the regressive erosion induced by the Borkena River deep incision.

The alluvial fan deposits are made of mainly partially rounded clast-supported basalt conglomerates alternating with sandy–clayey levels, more frequent in the distal sectors of the fan. The surface slope angles are around 15–20° in the apical sectors and less than 13° in the distal parts. Their maximum thickness is ca. 30 m. The distal parts of the alluvial fans overlay (or interfinger with) the Dessie terrace sediments. The apical sectors of the fans are fed by recurrent debris flows originating from the fluvio-denudational slopes of the upper catchments.

The top part of the sequence is made of blackish soil, sediments and debris, which indicate a recent period of widespread slope denudation (Dramis et al., 2003). These materials are affected by soil-creep movements which, in one case, were able to cover with a more than 2 m thick silty–clayey mantle a masonry wall built up during the Italian occupation (1930s). The colluvial slope is also incised by gullies, whose origin is favored by the occurrence of desiccation cracks in the superficial cover at the end of the dry season; especially after scarce spring rainfall (Billi and Dramis, 2001, 2003).

Fig. 8. Rock slide/avalanche on the Doro Mezleya right slope: the landslide scarp is about 100 m wide and 25 m high.

Fig. 9. Tossa talus belt with a landslide trench.

The alluvial fan in the northern part of Dessie is diffusely affected by shallow single, retrogressive and successive rotational slides, but there is a deeper surface of rupture marked by the basalt-alluvial fan boundary. So we can assume that all these landslides are part of a bigger debris translational slide.

4.7. The river beds and terraces

The Borkena River with its tributaries, and the Ashebir Creek to the south-west, make up a network of narrow channels across the graben floor. The present channels are incised, up to 10 m, within an alluvial terrace made of clast-supported basalt cobbles and gravels with a sandy and silty matrix. The river-bed materials generally consist of basalt boulders, cobbles and gravels with a minor percentage of sand. The Borkena River terrace disappears as the river enters the Doro Mezleya gorge through a ca. 60 m high waterfall.

5. Long term geomorphological evolution

The geomorphological evolution of the Dessie Basin started after the Oligocene continental flood volcanism which erupted a sequence of basalts and ignimbrites. The first stages of the basin formation were accompanied by the emplacement of basalts between the Tossa and Azwa Gedel border faults.

In Pliocene–Quaternary times, the western Afar margin has been affected by E-directed extension (Boccaletti et al., 1998; Chorowicz et al., 1999). This extensional phase was accompanied by an important regional uplift which raised the Ethiopian plateau by 800–1000 m to attain the present altitude (Almond, 1986; Mohr, 1986).

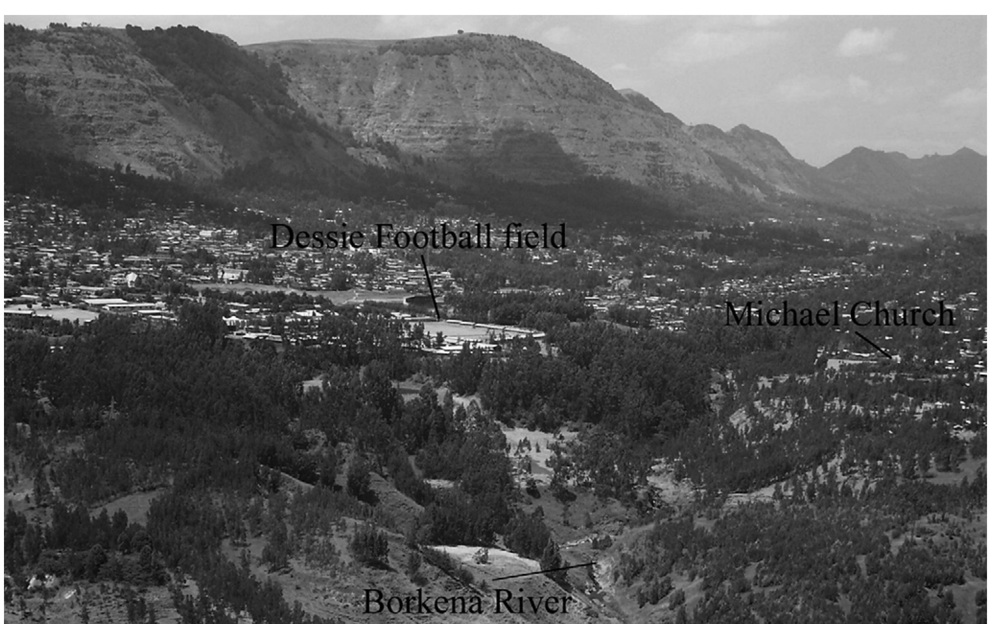

Fig. 10. The Dessie terrace.

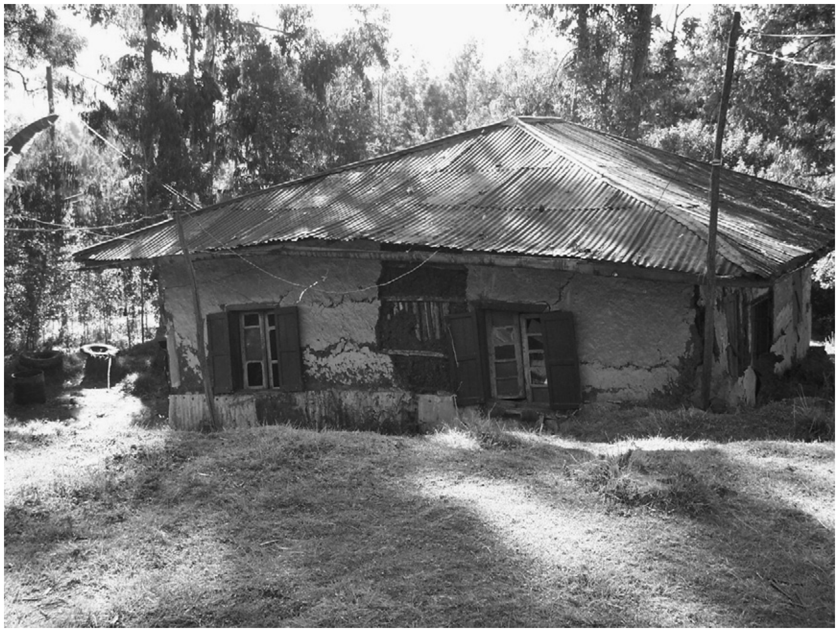

Fig. 11. House tilted by a slow moving landslide since 1994.

According to Faure (1975), the uplift rate was 0.5–1 mm/yr in the last 200,000 years.

During this time, geomorphic processes have emplaced superficial deposits in the basin floor which were evacuated by the paleo-Kelina and paleo-Borkena rivers, whose ancient hanging valleys are still recognizable by the wind gaps located at different levels across the Azwa Gedel and Doro Mezleya ridges.

It is probable that the interaction between fault activity and headward erosion of rivers produced alternating phases of basin closing and opening with related deposition and erosion in the graben. In the most recent stages, the Dessie graben has been first closed, with the deposition of the swampy-lacustrine sediments of the Dessie terrace in its lowermost part, and then re-opened by the backward erosion of the Borkena River and its tributaries. As a consequence, the swampy-lacustrine environment was drained off and the graben floor deposits underwent a rapid incision with the onset of instability conditions in the superficial deposits and, locally, also in the volcanic escarpments.

6. Slope processes and related hazard to the town of Dessie

The active geomorphic processes which affect the study area heavily impact on the Dessie town interacting with people, settlements, infrastructures and farmlands. In particular, a large number of landslide events have repeatedly struck the urban area since long time ago, causing the loss of life and property (Ethiopian Institute of Geological Surveys, 1995; Ministry of Works and Urban Development, in press; Kefialew, 2001; Tenalem and Barbieri, 2005). In 1977, two people were killed by a seismically induced landslide (Gouin, 1979) and in 1994, landslides triggered by heavy rainfall blocked a segment of the Main Dessie–Mekelle highway, destroyed a bridge and buckled the foundations of several houses (Fig. 11).

The Dessie area has been recently investigated by Tenalem and Barbieri (2005), who produced a comprehensive study of the landslide processes and a landslide susceptibility map of the area, based on overlaying maps of the major influencing factors such as geology, hydrology, geotechnical characteristics of soils and rocks, slope and land use. However, the map does not take into account the geomorphological features of the basin and their grasp relations with erosional–depositional processes and deposits. Moreover, the hazard levels have been generically referred to all landslide processes, without any consideration of their typology, which could induce different risk levels on built-up structures and human life. By adding detailed geomorphological layers in the GIS analysis, a more complete and exhaustive assessment of landslide susceptibility for the different geomorphological units would be attained, thus making reference to physically bounded land surfaces and taking into account the different landslide typologies.

The detailed geomorphological analysis of the basin shows that landslide incidence and typology vary with the different landform units (Table 1). High hazard levels, due to the possible occurrence of rapid mass movements (rock falls and topplings, rock slides, debris flows, debris slides), in connection with heavy rain or earthquakes, characterize the Tossa and Azwa Gedel escarpments and the Doro Mezleya escarpment (landform unit 1), the upper parts of the talus belts (landform unit 2), and the upper catchment slopes of the Borkena River tributaries (landform unit 3). The talus belts are also locally characterized by high hazard levels due to deep-reaching translational slides. Finally, rotational slides induce high hazard levels on the erosional escarpments of the Dessie terrace and on the incised alluvial fans of the Borkena River tributaries (landform units 6 and 5), where a large part of the town is located. On the contrary, very low

Table 1
Landslides distribution in relation to type of movement and landform units

Landslide typology	Landform unit	Frequency
Rock fall/toppling (11 cases)	Fault escarpments (unit 1)	8/11
	Graben floor (unit 4)	3/11
Rock slide/debris avalanche (10 cases)	Fault escarpments (unit 1)	6/10
	Graben floor (unit 4)	2/10
	Talus belts (unit 2)	2/10
Rotational slide (53 cases)	Dessie terrace (unit 6)	35/53
	Talus belt (unit 2)	4/53
	Alluvial fans (unit 5)	14/53
Translational slide (22 cases)	Graben floor (unit 4)	1/22
	Dessie terrace (unit 6)	1/22
	Talus belts (unit 2)	18/22
	Alluvial fans (unit 5)	2/22
Debris flow (10 cases)	Fault escarpments (unit 1)	5/10
	Fluvio-denudational slopes (unit 3)	5/10

hazard levels characterize the stable basalt outcrops of the graben floor (landform unit 4) and the flat surface of the Dessie terrace, farther away from the erosional scarps and the escarpment talus belts.

7. Conclusion

Detailed geomorphological survey and mapping, allowed to outline a comprehensive framework of landforms and processes characterizing the landscape evolution of the tectonic basin of Dessie. The detailed observations carried out in the field showed that the present-day evolution of the study area is dominated by deepening stream channels and slope processes, including landslides of different type and size which affect large sectors of the town.

Landslide incidence and typology, and related hazard conditions, vary in relation to the main landform units which make up the basin surface and its boundaries: fast moving landslides, such as rock falls and topplings, and local rock slides, are recurrent on the main bordering escarpments, modelled on weathered and densely jointed basalt and ignimbrites. Debris flows characterize the slopes of the fluvial catchments cut in the western escarpment. Single, retrogressive and successive rotational slides widely affect the edges of the Dessie terrace and the alluvial fan escarpments. Translational slides, including the huge deep-reaching movement on the western slope of Ashebir Creek involve the talus belt materials at the foot of the main N–S escarpments.

All the above mentioned phenomena may interact with people, settlements, infrastructures and farmlands inducing different levels of risk in relation to the different hazard and vulnerability levels. Mitigation measures for deep-reaching landslides (translational and rotational slides) in soft material should include: rerouting springs and rain water in order to reduce concentrated water infiltration; river channels and gullies recovery and control to counter lateral erosion; subsurface drainage to lower groundwater table, retaining walls, especially along some road segments. Planting of trees could be positively used to counter shallow landslides in soft materials (Nyssen et al., 2002). Controlling fast moving landslides (rock slides, rock falls and toppling) on steep rocky slopes is quite problematic: the best remedial measure should be to avoid any construction at the foot of steep rocky escarpments. High cost stabilization of landslides is only suggested where indispensable. In any case, appropriate site selection for buildings, transferring risky settlements, accurate geological control of works, and well designed education campaigns are strongly recommended measures.

Acknowledgement

The main part of the financial support for this study was obtained from the Ethiopian Science and Technology Commission (ESTC). We would like to thank the Commission for the unrelenting assistance and collaboration.

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