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Mass movement mapping for geomorphological understanding and sustainable development: Tigray, Ethiopia

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ABSTRACT

Mass movement topography characterises the escarpments and piedmont zones of the tabular ridges in the western part of the Mekelle outlier, Tigray, Ethiopia. Several types of mass movements can be distinguished. The first type is rockfall produced by 357 km rocky escarpments and cliffs during the rainy season. In the study area, every current kilometer of Amba Aradam sandstone cliff annually produces 3.7 m^3 of rock fragments. However, this is an under-estimation of the actual cliff and escarpment evolution, which is also characterised by debris slides and small rock slides.

In the debris flow class, three dormant flow types are recognised. The first type comprises preferential or undifferentiated mobilisations of the so-called plateau layers, the whitish sandy-clayey lacustrine deposits and the lower and upper basalts, and more especially, the swelling clays, derived from the basalts. These debris flows start on the nearly horizontal Amba Aradam Sandstone tabular extensions, jump over cliff recessions or even spurs, and go very far into the valley. In some instances parts of Amba Aradam sandstone and Antalo limestone cliffs are transported. Secondly, some debris flows take their origin in the Antalo limestone supersequence. It concerns deeply weathered layers resting upon aquicludes/aquitards. Finally, gigantic debris flows and rock slides occur around dolerite dyke ridges.

About 20% of the total surface of the study area is occupied by landslide topography. Most of the landslides affect the steep edges of the table mountains or the dykes/sills.

Mapping and listing of active and dormant mass movements increases knowledge in three domains which are crucial for sustainable development of the study area. The first one is geomorphological risk assessment. The distribution map of active rockfall and dormant landslides shows the areas where potential risks are located. Land use changes which improve the water infiltration capacity of dormant landslides, should be followed up. Secondly, the impact of global climate change on these risk areas can be assessed. The second domain is the water sector, which needs attention in the study area and in many parts of Africa. Landslides mobilised by hydrostatic pressures are related to the occurrence of aquicludes and aquifers. In the study area, landslide mapping led to the location of three aquitards, not described before. The third domain is the pedological mapping. In the study area, soil distribution is very well explained by the morphology and extension of dormant landslides.

Finally, mapping of dormant landslides stimulates the academic debate on the geomorphological significance of mass movements in hillslope retreat in tropical areas.

1. Introduction

There is a rapidly growing interest for mass movements in Ethiopia because of the considerable increase in occurrence and importance of active landsliding since the 1960s (Ayalew, 1999). Between 1993 and 1998 alone, mass movements caused the loss of about 300 lives, the destruction

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of hundreds of houses and 100 km of roads and the devastation of considerable areas of agricultural land (Ayalew, 1999). Woldearegay et al. (2006) locate in the northern part of the country 15 zones affected by more than 400 active landslides. In his analysis, Ayalew (1999) pointed out that most of the landslides are reactivations of older dormant ones or part of them. In the region between Mekelle and Hagere Selam, we reported three cases of reactivated landslides. They were ascribed to (1) increase of water infiltration due to exclosure development and (2) to slope destabilisation as a result of gullying and road construction (Nyssen et al., 2002). Taking into account that gullying mainly results from land cover changes (Nyssen et al., 2006a), the reactivations can be ascribed directly or indirectly to human activities. It is normal that displaced soil masses are more prone to later instabilities because the first-time movement of the material causes the shear resistance to drop from the original into the residual strength along the failure planes (Lambe and Whitman, 1979). For this reason, old landslides and scree slopes are always zones of higher risk compared to the surrounding area and the risk level can increase considerably as a result of improper land use.

Detailed geomorphological investigations (Nyssen et al., 2002; Moeyersons et al., 2006a) were needed to realise that landslides and related mass movement topography occupy an important part of the landscape in the Hagere Selam area. Given that information on the occurrence, nature and distribution of landslides in the study area was not available at the start of our research in 1998, this article aims to give a state of the art of our present knowledge about types of occurring mass movements and their distribution, about mass movement processes and their geological context in the Hagere Selam region. This article presents a first distribution map of landslides and rockfall-producing cliffs in a 400 km^2 area. This document allows assessing the geomorphological significance of mass movements in tabular highlands and locating areas at risk in the case of remobilisations of old landslides.

2. Materials and methods

2.1. The study area

The study area (Fig. 1) is located in Tigray, northern Ethiopia, and covers a 400 km^2 rectangle in the watershed of the Geba and Werei river basins east and north of Hagere Selam, some 50 km west of Mekelle. The area was chosen because the highest points reveal the most complete geological section of the region, including Tertiary basalts, believed to be more prone to mass wasting than the underlying formations. It concerns the tabular ridges of Enda Maryam (2912 m a.s.l.), Chini (2757 m a.s.l.), Guyeha (2600 m a.s.l.), Tsili (2700 m a.s.l.), Medayk (2835 m a.s.l.), and Imba Degoa–Amba Raeset (2611 m a.s.l.). The valleys between the ridges are several hundreds of meters deep. The ridges generally display a structural topography, reflecting the subhorizontal succession of the geological layers. The occurrence of rocky cliffs and steep escarpments is typical.

The oldest geological formation, deep in the valley of the May Zegzeg, Tsaliet and upper Tankwa rivers is the Upper-Palaeozoic Adigrat sandstone. It is overlain by the marine Antalo limestones of

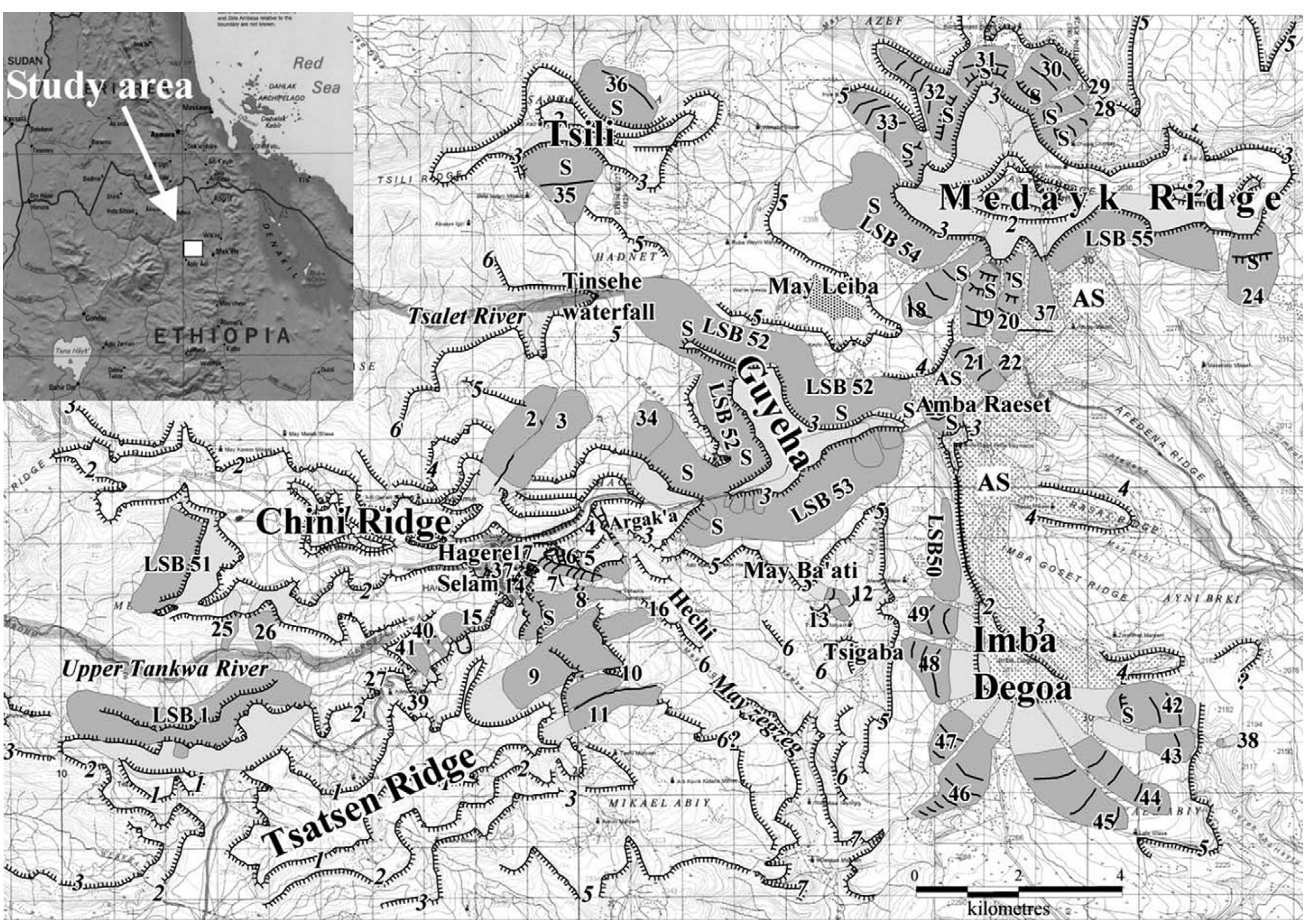

Fig. 1. Location of the study area and distribution of landslides. Landslides and landslide belts (LSB) in grey are numbered. Light grey: erosional or source area; dark grey: depositional area, accumulation lobe. Barbed lines represent rocky cliffs. Numbers of cliffs in italics are explained in Section 3.1.1. Dashed lines are cliffs covered by deposits. The light grey zone indicated by AS gives the extension of Agula shales based on Bosellini et al. (1997).

Jurassic age, about 500 m thick. Agula shales, which form the upper part of the Antalo supersequence (Bosellini et al., 1997) are present in a small belt around the Imba Degoa–Amba Raeset and on the elongated pass between the latter and the Medayk Ridge (Fig. 1). Agula shales, where present, or Antalo limestones are truncated by a peneplanation disconformity (Dramis et al., 2002), overlain by Amba Aradam sandstone of Cretaceous age and by two series of Tertiary volcanics. The latter are separated by partially silicified lacustrine deposits. The geological structure of the study area has been described by Arkin et al. (1971), Beyth (1972), Tesfaye and Gebretsadik (1982), Russo et al. (1996) and Bosellini et al. (1997). The stratigraphical column is illustrated in Fig. 2(A).

The base and lower part of most ridges in the study area typically display outcrops of the Antalo supersequence, mostly only Antalo limestones, often in the form of massive limestone cliffs. The Amba Aradam sandstone and the tertiary basalts form the tabular extensions on top of the ridges, table mountains or plateaux.

The role of mass movements as a geomorphic agent was facilitated by the tectonic upheaval of the area, related to rift tectonics (Almond, 1986; Abbate et al., 2002). At Hagere Selam this upheaval is of the order of more than 2000 m, which is about the actual altitude (2300–2400 m a.s.l.) of the peneplanation surface at the base of the Amba Aradam Sandstone. Subsequent landscape dissection led to steep canyon-like incisions and slope instabilities.

The study area enjoys a temperate tropical highland climate with an ustic moisture regime, characterised by a mono-modal mean annual precipitation of 790 mm y^{-1}, 80% of which falls within the months June, July and August. Nyssen et al. (2005) point out that these rains are extremely erosive due to the relatively large raindrop diameters.

The study area is characterised by two types of soil catenae. The basalt catena comprises a red-black Skeletic Cambisol–Vertisol sequence. Limestone weathering on the other hand yields Calcaric Regosols and Vertic and/or Colluvic Cambisols (Van de Wauw et al., 2008; Nyssen et al., in press). Important from the point of view of mass movements is the presence of swelling clays in some of these soils, especially in the Vertisol extensions in the plateau basalts and in the valleys deeper in the Antalo supersequence.

It has also been established that this subhorizontal geological succession contains a few less permeable horizons which locally act as aquicludes and sustain perched water tables. The Amba Aradam sandstones, especially the upper laterised part, form the upper aquitard in the series (Tesfaye and Gebretsadik, 1982; Vandecasteele, 2007). Other aquicludes or aquitards occur in the Antalo supersequence. Van de Wauw et al. (2008) mention the existence of a massive and hard layer, the 'Adiwerat layer', acting as an aquitard near the base of the Agula shales. Further research has shown that two other aquitards occur deeper in the Antalo limestones. In the study area they contain two very massive cliff-forming carbonate layers. Because of their massive character, both layers were first supposed to function as aquicludes and have been indicated as the Tinsehe–Hetchi and May Ba'ati aquicludes (Moeyersons et al., 2006b). These massive cliff-forming layers correspond respectively to the lower (A1 sequence) and upper (A3 sequence) stromatoporoid key beds of the Antalo supersequence, described by Bosellini et al. (1997). Recent fieldwork, however, has shown that these layers do not function as aquicludes or aquitards because of their high secondary permeability due to vertical cleavage and jointing. Along this jointing, water rises up to stand and flow above the top of the stromatopora. The real aquicludes are invariably found just below the massive beds and consist of shales and marls.

The Imba Degoa Ridge and the culminating part of the Chini Ridge do not display this geological subhorizontal structure. Our field observations show that Imba Degoa, except for the extreme northern part, is composed of dolerites with inclusions of shales, limestones and Amba Aradam sandstone. These dolerites rest above the upper stromatoporoid key beds of the Antalo supersequence, cropping out in the Tsigaba valley shoulder. Morphologically speaking, the Imba Degoa Ridge seems to be a N–S oriented dyke, feeding towards the east a huge sill. The latter can be followed in eastern direction till the eastern side of the Geba river. Geologically speaking, the Imba Degoa

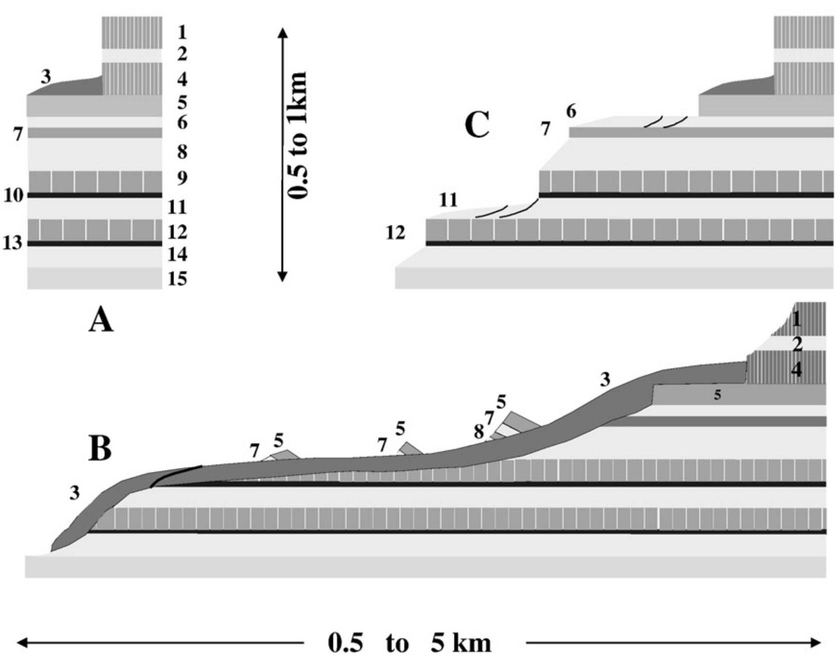

Fig. 2. A: Geology. 1: upper series of Tertiary basalts; 2: partially silicified lacustrine deposits; 3: weathering products (Vertisols!) of the lower series of Tertiary basalts; 4: lower series of Tertiary basalts; 5: Amba Aradam sandstone, Cretaceous; 6: Agula 'shales', Jurassic, only locally present; 7: Adiwerat layer, only locally present; 8: Antalo limestone, Jurassic; 9/10: upper stromatoporoid key bed (Bosellini et al., 1997) and marls below (May Ba'ati aquitard); 11: Antalo limestone, Jurassic; 12/13: lower stromatoporoid key bed (Bosellini et al., 1997) and shale/marls below (Tinsehe–Hechi aquitard); 14: Antalo limestone; 15: basal cliff-forming transition between Antalo limestone (Oxfordian) and the underlying Adigrat sandstone. B: Debris flow affecting the plateau layers. Parts of the Amba Aradam sandstone cliff are sometimes included in the flow. C: Landslides affecting the Antalo supersequence at different levels. Aquifers of weathered Antalo limestones seem to be preferentially affected.

Ridge and its eastern extension belong to the intruded plutonic rocks, comagmatic with the Tertiary trap volcanics (Arkin et al., 1971; Beyth, 1972). Also the part of the Chini Ridge at the northern side of Hagere Selam, is composed of dolerites and basalts.

2.2. Methods

The following methods have been used for data collection:

1. Geomorphological–pedological field mapping including GPS-based observations of soils, geological sections, landslide morphology and soil use;
2. Field measurements of creep at three locations. They are documented by Nyssen et al. (2002) and Moeyersons et al. (2006c);
3. Laboratory measurements of the drained shear strength of Vertisol material (Nyssen et al., 2002) in a mono-axial soil shearing apparatus;
4. Field hydro-geological exploration in relation to the aquitards in the Antalo limestone;
5. GIS-environment of MapInfo 7.8, with topographical (1:50,000) base layer and geomorphological mapping layers;
6. Stereoscopic interpretation of aerial photos and treatment and interpretation of false colour Landsat ETM (Enhanced Thematic Mapper) satellite imagery dated at 27-01 and 05-02-2000. In many instances the landslides are easily recognisable on the ETM 457 false colour channels image because the geological material from the plateau is different in false colour from the Antalo limestones in the hillsides and the valleys. The ETM image, however, did not allow distinguishing between flows and rockfall, having the same false colour. In some instances, rockfall can bridge higher distances than flows as it jumps, rolls and slides. The scale of the aerial photos is approximately 1:50,000. The quality of the photographs is high; weak contrast due to under-illumination has been increased on scanned copies.

Mapping (Fig. 1) resulted from interactivity between the field work (points 1 and 4) and remote sensing methods (point 6) with ground truth verification of tele-observations and vice versa. It should also be mentioned that the extension of depositional belts of the landslides on the map is kept very conservative, for two reasons. First it was tried to avoid inclusion of rockfall runout beyond the foot of the landslides. Secondly, landslides in the Agula shales and the Antalo limestones of Section 3.1.3 have often their toe composed of the same lithology as the substrate. This part of the slides is often not mapped. It is also assumed that a number of landslides is still not recognised as such. Our experience shows that it takes some time before even an experienced geomorphologist is able to distinguish dormant landslides in the landscape.

Description terms of landslides in this article are taken from Dikau et al. (1996).

3. Results and discussion

3.1. Types of mass movements and the geological and hydro-geological setting

3.1.1. Rockfall from steep cliffs and displacements on the scree slopes below

Rockfall from cliffs is a very common phenomenon in the area and plays an important role in the daily life of the people during the rainy season because of the large number of cliffs. The following lithological entities occasionally form rocky cliffs, indicated by a number in italics in Fig. 1: the two basalt series (cliffs 1 and 2); the Amba Aradam sandstone (3); the base (4) of the Agula shales, indicated by Van de Wauw et al. (2008) as the Adiwerat layer; the two massive Antalo limestone beds, which are the upper and lower stromatoporoid key layers in the Antalo Limestone (Bosellini et al., 1997), one (5) above shales of the May Ba'ati aquitard, the other (6) above the Hechi–Tinsehe aquitard. Also the transitional beds between the Adigrat Sandstone and the Antalo Limestone form a cliff (7) deep in the May Zegzeg valley. Occasionally, the numerous cliff tufas which occupy the edge of the Amba Aradam sandstones give also rise to cliff sections. In the study area of about 400 km^2, there are more than 357 km of rocky cliffs more than 10 m high. Observations, listing of boulders and their secondary displacements below the Amba Aradam sandstone cliff at Argak'a around landslide 4 (Fig. 1) show that rock boulders and rock fragments are released by toppling and by detachment. Holes and furrows in the soil indicate that boulders, sometimes of the size of one to several cubic meter, tumble, jump and roll till very deep in the valley, in some cases to 100 m beyond the foot of the scree slope. Rock fragments stack on the scree slopes are sometimes further displaced by the passage of cattle. Rockfall events have been observed in the field and remnants of ancient blocky debris flows have been identified. A volumetric inventory indicates that rockfall alone is responsible for a cliff recession rate up to 3.7 cm/century (Nyssen et al., 2006b). This is the equivalent of 370 m cliff recession since the last 10,000 years of the Holocene. Assuming that the other cliffs in the study area have the

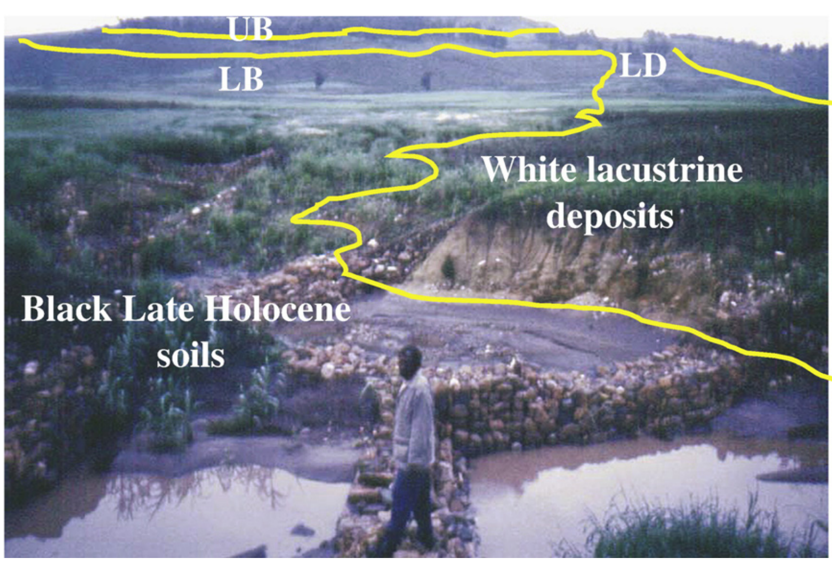

Fig. 3. View in the Upper Tankwa River valley toward the Tsatsen Ridge, from where debris flow 15 originates (Fig. 1). Upper basalt (UB), lacustrine deposits (LD) and lower basalt (LB) are visible.

Fig. 4. The May Ntebteb debris flow (no. 4 in Fig. 1). LBC: lower basalt cliff. AA–AL: Amba Aradam sandstone and Antalo limestone cliff. Weathering products of the lower basalt, mostly black swelling clays, are accumulated below the LBC. These accumulations surged over the AA. In the lower part of the picture, a gully obliquely crosses the earth flow lobe.

same rate of regression and that a cliff is at least 10 m high, which is a very conservative estimation, it can be calculated that the recession of the 357 km of cliffs in the 400 km^2 study area involves the annual detachment and fall of at least 1320 m^3 of rock.

3.1.2. Debris slides and small rock slides

The estimations of escarpment denudation and cliff retreat, based on rockfall alone, are certainly an under-estimation of the real geomorphic activity on these steep slopes. Many escarpments show multiple traces of soil slips, shallow translational slides after every rainy season. One such debris slide, observed in April 2007 is mapped (landslide 39, Fig. 1). Most escarpments show several old scars, recolonised by vegetation. The distribution and occurrence seems to be very variable from place to place and from year to year. Also small rock slides can be observed on steep escarpments. Two of them have been identified in the field (landslides 27 and 38, Fig. 1).

3.1.3. Debris flows affecting the plateau layers

The schematic representation of this type of debris flow can be found in Fig. 2B. Plateau layers are those geological layers resting upon the Amba Aradam Sandstone. It concerns the basalts and the intercalations of lacustrine silicified deposits. The flows (Dikau et al., 1996) find their origin on the plateaus but get over the Amba Aradam sandstone plateau rim to descend into the valleys.

Three landslides (15, 40, 41 in Fig. 1) are mainly composed of whitish and partly silicified sandy and clayey material of the lacustrine

Fig. 5. The Melka Maryam debris flow (no. 26 in Fig. 1). Two cliffs in Antalo limestone show wide gaps along which the flow passes.

Fig. 6. The Tsili landslide 35 did not only pass through the gap in the Amba Aradam sandstone to the left (arrow), but came also massively over the cliff to the right of the gap.

intercalations in the Tertiary plateau basalts. These flows also involve some volumes of rock boulders and fragments from the overlying basalt and can be classified as debris flows. Fig. 3 shows debris flow 15 (Fig. 1). The topographical expression of debris flow 15 is low but the contrast in colour between the whitish displaced material and the black clay material in the valley is visible. Further to the west, thick deposits of the whitish lacustrine deposits cover the Amba Aradam sandstone cliff on the southern Upper Tankwa valley side. In this complex landslide belt (landslide belt 1, Fig. 1), only one individual landslide could be morphologically recognised.

All the other flows which start from the plateau apparently indifferently affect in the same time the upper and lower basalts and the intercalated lacustrine deposits. Their source area, or erosional area, is often located on Amba Aradam sandstone plateau enlargements. In such localities the lower basalt generally is deeply weathered, giving rise to big amounts of black and reddish-black swelling clays.

The mobilisation of the black swelling clays can be understood as a result of water logging above the laterised Amba Aradam sandstone which acts as an aquiclude (Tesfaye and Gebretsadik, 1982) but which is in a nearly horizontal position. It has been recently established that these black clays, Vertisols, showing polygonal structures and gilgai topography, undergo accelerated creep movements on flat slopes if lateral confinement decreases like in the case of gully incision. Monitoring at Enda Maryam during 4 years (Moeyersons et al., 2006c) showed annual creep rates of the order of 10 cm and more at a distance of some 50 m from an eight year old gully. It is obvious that sudden clay surges, flowing and sliding over the Amba Aradam sandstone escarpment belong to the possibilities during periods of more than average water accumulation.

Although there is little doubt that the plateau flow movements are mainly induced by the clays in the plateau layers, it is obvious that they are all debris flows. All flows, visited, contain chert rock fragments, white silicified rock fragments and boulders typical for the lacustrine deposits and further also big amounts of rounded basalt columnar rocks and rounded core stone boulders, typical for the plateau basalts.

Plateau debris flows generally descend the table mountain front along valleys and embayments in the table mountain escarpment. One example is the May Ntebteb debris flow, indicated as landslide 4 (Fig. 1). In this case the depositional part of the debris flow (Fig. 4), is confined to a pre-existing river valley. The Vertisol mantle forms a tongue-like very elongated depositional body going over the Amba Aradam sandstone and the underlying Antalo limestone series. In other instances, the plateau layers flow more massively and in a wide belt over the Amba

Fig. 7. Landslide belt (LSB) 55 (Fig. 1). The arrows indicate parts of the cliff, risen down. During their downslope movement, the cliff parts underwent counterslope-wise rotation.

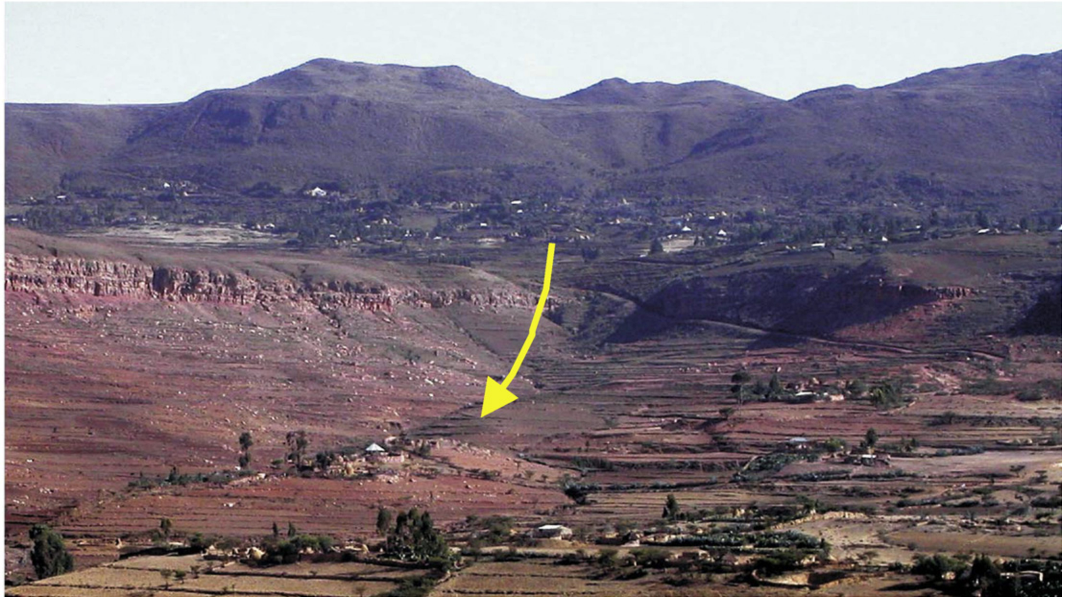

Fig. 8. Isolated Amba Aradam sandstone slab (arrow) in front of Medayk Ridge. The slab sits partly in reddish-black swelling clays, coming from above the cliff.

Aradam sandstone edge. In the case of landslide 26 (Fig. 1), two underlying Antalo limestone cliffs seem to be breached (Fig. 5). In the case of the Tsili Landslide (Fig. 6), the Amba Aradam cliff seems to partly breached, but it is obvious that there was a big surge over a very wide area, whereby the basaltic material cascaded over the cliff. Finely, cases have been recorded along the southern edge of Medayk Ridge, where consistent cliff parts have been taken into the debris flow of basaltic material and have undergone slope inward rotation during the downslope displacement. It is also clearly visible that the basaltic debris flow and the related cliff detachment arrived on a spur of the table mountain (Fig. 7). It is not known whether the basaltic flow caused the detachment of the 2 parts of the Amba Aradam sandstone cliff, or if the collapse of the cliff did trigger the flow.

The observations at the southern edge of the Medayk Ridge help to explain the actual occurrence, also in a spur position, of landslide 8, interpreted formerly as a multiple rock slump (Nyssen et al., 2002). The presence of reddish-black and black swelling clays in and around this landslide, its pronounced spur position and the form of the longitudinal profile, make deep seated rotational slump very improbable. Landslide 8, therefore, should be considered as a flow of basaltic material, contemporaneous with the downslope transport of 5 successively detached parts of the Amba Aradam sandstone cliff.

At the south-eastern edge of the Medayk Ridge and also around Guyeha Ridge, there is the marked occurrence of a number of reddish hills, which are invariably composed of a plate of Amba Aradam sandstone, sometimes covered with remnants of basaltic rocks (Fig. 8). In a few cases some limestones and shales from the stratigraphically underlying Antalo supersequence adhere to the underside of the plate. Without exception, all these Amba Aradam sandstone cliff parts are inclined counterslope-wise. However, the hypothesis that it concerns remnants of deep seated rotational slumps does not hold because the very high distance between some of these plates and the hill front. Furthermore, remnants of basaltic material, either rocky or clayey are present. For these reasons, belts 52, 53 and 54 (Fig. 1) are considered as belts of ancient and subactual basaltic debris flows. These flows could transport huge Amba Aradam sandstone cliff debris to a much higher distance from the cliffs than they could travel by simple sliding. Subsequent erosion has taken away, according to the available time span, part of the swelling clays and the oldest debris flows are morphologically unrecognisable. In landslide belt 53 (Fig. 1), it has been tried to reconstruct a few individual flows on the base of the areal clustering of Amba Aradam sandstone plates.

The complete inventory of individual debris flows or debris flow landslide belts is given in Table 1.

3.1.4. Landslides in the Antalo supersequence

Landslides are not very common in the Antalo supersequence. The small belt where Agula Shales are present in the study area (Bosellini et al., 1997) is affected by 3 old landslides (21, 22, 23 in Fig. 1) of the debris flow type. Van de Wauw et al. (2008) mention the presence of basalt and sandstone rock fragments and boulders on these debris flows. The same authors also mention the existence of a massive and hard layer, the 'Adiwerat layer', acting as an aquitard near the base of the series, on top of which most landslides in the Agula Shales should occur. Woldearegay et al. (2005) describe the shear strength parameters of the Agula shale but do not mention the occurrence of a basal layer with separate characteristics.

Two other landslides have been found within the Antalo limestone supersequence. It concerns the landslides 12 and 13. They affect deeply weathered shales and limestones, locally present in the Tsigaba valley (Fig. 1). They rest the base of the Tsigaba aquitard. They are inventoried in Table 1. The geological setting of the landslides in the Antalo supersequence is schematically given (Fig. 2C).

3.1.5. Landslides around Imba Degoa and at the northern side of the Chini Ridge

Apart from the numerous traces of older and more recent debris slides on the steep part of the ridge, it is assumed that Imba Degoa is surrounded by remnants of a series of huge landslides (42–49 and LSB 50). While the configuration of flow lobes is visible on the aerial photographs, the field observations reveal that the lobes are not really rugged bodies but localities characterised by the presence of masses of rounded and rather fresh dolerite boulders resting on a typical corestone weathering profile (Twidale, 1982). The boulders are not interpreted as lag deposits above the weathering profile from which they originate. Their big size (up to several meters/across) and their fresh state, compared to the in situ corestones in top of the weathering profile, suggest that they are coming from the steep side of the dolerite ridge. This is the reason why the source areas or erosional belts of the landslides are traced till high on the ridge, although real morphological indications are lacking (Fig. 1).

Landslides 2 and 3 (Fig. 1) on the northern side of Chini Ridge show a well developed erosional scar and a long depositional lobe with a mixture of basaltic and dolerite material.

Table 1
Inventory of landslide types and their areal extent (km^2) mapped in the 400 km^2 study area

No.	Erosion area km^2	Deposition area km^2
Debris flows affecting plateau layers		
LSB 1	2.64	3.66
4	0.09	0.05
5	0.03	0.02
6, 7	0.30	0.27
8	0.11	1.00
9	0.74	2.45
10	0.09	0.42
11	0.24	0.68
15	0.07	0.23
16	0.74	2.46
18, 19, 20, 37	1.11	3.27
24	0.32	1.22
25	0.14	0.17
26	0.47	0.33
28	0.37	0.48
29	0.11	0.48
30	0.12	1.11
31	0.24	0.81
32	0.88	1.32
33	0.84	1.25
34	0.08	0.67
35	0.38	1.64
36	0.33	1.42
40	0.02	0.12
41	0.10	0.19
LSB 51	1.18	1.48
LSB 52	2.69	9.04
LSB 53	0.99	4.65
LSB 54	1.17	2.75
LSB 55	1.46	2.20
Total	18.03	45.82
Total surface		63.86
Debris slides and small rock slides		
27	0.01	0.02
38	0.05	0.02
39	0.00	0.00
14	0.01	0.07
17	0.02	0.03
37	0.09	0.03
Total	0.18	0.17
Total surface		0.35
Landslides in Antalo supersequence		
12	0.11	0.09
13	0.03	0.07
21	0.02	0.54
22	0.02	0.18
23	0.02	0.45
Total	0.20	1.33
Total surface		1.53
Imba Degoa and Chini Ridge		
2	0.18	1.09
3	0.11	1.31
42	0.44	1.25
43	0.43	0.46
44	0.42	1.15
45	0.79	1.86
46	0.31	1.31
47	0.23	0.55
48	0.63	0.81
49	0.30	0.61
LSB 50	0.41	0.66
Total	4.24	11.06
Total surface		15.30

Numbers refer to the landslides or landslide belts (LSB) in Fig. 1. Landslides 6 and 7 and also landslides 18, 19, 20 and 37 have an erosional belt in common.

3.2. Areal distribution of mass movements and soils

Fig. 1 shows the areal distribution of rockfall-producing cliffs and landslide types, described in Sections 3.1.2, 3.1.3 and 3.1.4. In a general way, they surround the table mountain ridges. The most typical examples are certainly the Guyeha and Medayk ridges, which are completely surrounded by landslides. Table 1 classifies the individual landslides and landslide belts into the categories described above and shows their areal extent. In the study area (Fig. 1), landslides occupy some 20% of the total land surface. Taking into account the remarks of Section 2.2, this is a conservative figure.

The distribution and extension of landslides explains abnormalities in the soil distribution pattern (Van de Wauw et al., 2008; Nyssen et al., in press). Soils in the area are expected to be distributed in belts, more or less parallel to the contours because of the subhorizontal geological layering and stepped topography. But in many instances pedological mapping was facing unusual repetitions in downslope direction of soils on basalt, sandstone and limestone. These repetitions reflect the presence of slumped blocks as illustrated in Fig. 2B. In the case of flows, especially those nourished by black clays from the basalts, the relatively fertile black soils form a wide belt, descending from the tabular platform into the valley. These black soil trails cross the contour soil belts on Amba Aradam sandstone and Antalo limestone, which are generally less fertile.

4. Conclusions

4.1. The importance of mass movements in the study area

The first main conclusion of this study concerns the importance of the process of rockfall, produced by rocky cliffs. According to the foregoing calculations, and supposing an average rock boulder of 1 m^3, every current km of cliff would produce every rainy season about 3.7 boulders. Moreover, an important number of small debris and rock slides also affects escarpments every rainy season. This explains why people generally do not construct houses upon or just below scree slopes. Obviously, cliffs in the study area are localities with a certain hazard risk. The indication of cliffs in Fig. 1 as a risk locality is fully justified.

The other main conclusion is the unexpected high density of big ancient and recent landslides. Measurements in the Mapinfo GIS system indicate that the total surface of all landslides recorded (Fig. 1), including the erosion and deposition areas, amounts to about 81 km^2, some 20%, of the 400 km^2 study area (Table 1).

4.2. Mass movements and their hydro-geological significance

In areas where the subhorizontal geological structure is present, the spatial distribution of landslides reflects the presence of at least four (potential) lithological layers or combinations of layers, acting today or during former wetter periods as aquitards or aquicludes.

The upper aquitard or aquiclude is the Amba Aradam sandstone, upon which the swelling clays of the lower basalt can easily move.

The following probable aquitard is the so-called 'Adiwerat' layer (Van de Wauw et al., 2008). It concerns a massive shale layer, probably near the base of the Agula 'shales', corresponding to cliff No. 4 in Fig. 1.

The upper aquitard in the Antalo limestones is the one of May Ba'ati. It is formed by shales, sealing off the lower side of the upper (A3 sequence) stromatoporoid key bed of the Antalo supersequence (Bosellini et al., 1997). The water stands in the cracks of this carbonate rock. To mobilise the overlying landslides, the water table should rise above the top of this cliff-forming stromatoporoid layer (cliff No. 5 in Fig. 1).

Deeper in the Antalo limestone formation we find the Hechi–Tsigaba–Tinsehe aquitard. It is formed by shales, sealing the lower side of the lower (A1 sequence) stromatoporoid key bed of the Antalo supersequence (Bosellini et al., 1997). The water stands in the fissures of this carbonate rock. To mobilise the overlying landslides, the water table should rise to above the top of this cliff-forming stromatoporoid layer (cliff No. 6 in Fig. 1).

The latter two aquitards are not reported by Tesfaye and Gebretsadik (1982). Their identification is a spin-off of landslide mapping. These aquitards will certainly play a role in the water percolation model, currently established to assess the influence of increased infiltration on water table replenishment in the study area as a result of reservoir (Nigussie et al., 2005) and stone bund (Nyssen et al., 2006c) building.

But also the dolerite dykes are surrounded by landslide topography. This is ascribed to the fact that dykes and sills are known to be much less permeable either in fresh or in weathered state (Tesfaye and Gebretsadik, 1982), than the surrounding Antalo supersequence. In this way hydrostatic pressures can be built up on the sides of dykes.

4.3. Mass movements and soil distribution

The landslide mapping received an important impetus from the pedological mapping programme because the occurrence of landslides explains in a very satisfactory way the soil distribution in the study area, especially the repetitions of soils from the plateau edge in downslope direction (Fig. 2B). On the SW flank of the Medayk Ridge, geomorphological mapping was the key for pedological mapping (Van de Wauw et al., 2008).

Finally, the landslides, being ancient geomorphological events, profoundly mark the landscape at present, not only topographically but also pedologically and even economically. The original extent of basalt and dolerite fields in the study area amounts to about 101 km^2. But by debris flows, descending from the plateau basalt fields, this area has been increased with another 48 km^2 (Table 1). Taking into account that most landslides are enriched with some plateau basalts, the landslides have brought about that some 12% of the total land surface of the study area is more fertile than it would have been without landslides. In this way the landslide events in the past contribute to the agricultural potential of the study area and its development today.

4.4. Present and future mass movement risk in the study area

The discussions above and the work by Ayalew (1999) show that old landslides are also localities of potential hazard. But neither people nor authorities seem to realise the potential danger. Houses are constructed on old landslide deposits and modern infrastructure is planted in risky areas. An example is the southern flank of the Guyeha Ridge, which is covered by landslide belt (LSB) 53 and supplementary rockfall. The new road from Mekelle to Abiy Adi and part of the new electricity power line from Tekezze to Mekelle are built in this area. In other instances the soil use is changing above dormant landslides. The remobilisation of the Amba Raeset landslide after vegetation regrowth has been mentioned (Nyssen et al., 2002). Another case where human activities might complicate the future situation is the source area of the May Ntebteb flow (No. 4 in Figs. 1 and 4) where water infiltration stimulating stone bunds (Nyssen et al., 2006c) have been built. The study area, like so many other mountainous places in the world, faces the dilemma that it needs water harvesting practices in order to obtain a higher water availability and to prevent or mitigate soil degradation by hydraulic erosion while water harvesting generally implies an increase in infiltration and, hence, in mass movement risk. The map of dormant mass movements could be used by the local authorities to define areas where development activities need to be followed up from the point of view of mass movement security. The document, giving the areal distribution of landslide topography should also be useful for regional planning.

The distribution map of dormant landslides allows also to identify risk localities for first-time landslides. An example of potential risk are the empty places in the fringe of the Tsili, Tsatsen and Chini Ridges. In the actual climatic and land use context, the risk should be very limited, because it is thought that most of the dormant landslides were active during somewhat wetter conditions during the Holocene and that their activity was slowing down as a result of waning water tables (Moeyersons et al., 2006b). The places without dormant landslides should also be more stable now than during these wetter periods, but drastic changes in land use, implying strong increase in water infiltration should be carefully followed up. In this context, the innovation of runoff collectors, small ponds, locally called 'horoyo' should be mentioned. Their impermeable bottom of plastic folio meets this problem.

A question often arising in natural risk assessment is to what extent global climatic change will increase or decrease the risks of geomorphological hazards. This question is related to climate forecasting for the next years or decades, taking into account the changes in weather parameters due to the greenhouse effect as a result of air pollution (Desanker and Justice, 2001). There are only a few climate change predictions for Africa. The best known predictions today are those by Hulme et al. (2001). In a region centered on Ethiopia, most of the climate models predict an increase in annual precipitation for the year 2050. In the mean time increasing anomalies and variability are announced. Increasing variance of precipitation in equatorial regions is also predicted by Dore (2005). In the probable case that variance includes the occurrence of rains, bigger in intensity and total depth than today, sudden chronical high rises in local groundwaters have to be expected. As many dormant landslides, mapped in Fig. 1, are considered to have been active during higher groundwater levels in Late-Pleistocene and Holocene times (Moeyersons et al., 2006b), sudden important groundwater rises, even only temporary ones, might cause their reactivation. Hence, the landslide distribution map locates also the most probable landslide hazards in the future.

In the case that increased meteorological variability also includes the occurrence of more pronounced droughts, the latter will also contribute to an increased risk. Especially in Vertisols, desiccation cracks will become even more prominent than today and at the start of the rains, such cracks are an ideal situation to create high soil water pressures with minimal water supply. Knowing the proneness of these clays to accelerated creep (Moeyersons et al., 2006c), more cracking means a higher risk of the whole spectrum of mass movements in this type of soil.

4.5. Geomorphological significance of mass movements

Despite the dominance of water erosion and gully incision in the study area nowadays (Nyssen et al., 2004), landslide morphology is still very recognisable in the study area and creep and occasional landslide reactivations still occur. The dense distribution of old landslides around the ridges indicates that episodical landsliding should have played an essential role in hillslope retreat of the table mountain ridges after river incision. It is not quite clear if mass movements can lead to 'parallel' retreat of hillslopes, described in current theories of etching processes and landform development in the tropics (Thomas, 1996). But it appears, at least, that most of the landslides accentuate rather than dissimulate the stepped aspect of the retreating hillslopes in the long term. This is corroborated by the observation that most landslide types in the study area occur on 'hard', cliff-forming layers, which, in hydro-geological terms, act as aquitards. Mass wasting, therefore, seems to preferentially affect those layers, functioning as aquifers.

Only a few reports describe regions in tropical Africa where landslides, either dormant or active, occur in a very large number and density like in the Geba–Werei watershed in Tigray. One of the oldest reports mentions active and prehistoric landslides on the Nyika Plateau in Malawi (Schroder, 1976). Moeyersons (1989) reports on the very high amount of dormant landslides in the Butare area, Rwanda. Stengel (2001) mentions the occurrence of a high number of ancient landslides affecting escarpments in Namibia. Moeyersons et al. (2004) mapped in the Bukavu area, D.R. Congo, in addition to 6 seismologically driven landslides, 31 landslides driven by hydrostatic pressures. Intense active landsliding is reported on Mount Elgon (Knapen et al., 2006). In all these cases mass movements take an important place in the landscape, suggesting their significant role, past or present, in the geomorphological evolution, especially in hillslope retreat.

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