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The environmental significance of the remobilisation of ancient mass movements in the Atbara–Tekeze headwaters, Northern Ethiopia

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Abstract

Old landslides are prominent features in the landscape around Hagere Selam, Tigray Highlands, Ethiopia. The available evidence suggests their Late Pleistocene to Middle Holocene age and conditions of soil humidity. The affected geological layers, often silicified lacustrine deposits prone to sliding, rest upon or above the water holding Amba Aradam sandstone aquifer.

Three examples of present-day (remobilisation of old) mass movements are illustrated and discussed. The aims of the study were to unravel the environmental conditions of the present-day remobilisation of ancient flows, as well as those of first-time landslides. The first two mass movements discussed are slumps, located in areas with vigorous regeneration of (grassy) vegetation. Their activation is thought to be the consequence of an increase in infiltration capacity of the soils under regenerating vegetation. One of these slumps had a horizontal movement of the order of 10–20 m in 1 day.

The other case is the remobilisation of the May Ntebteb debris flow below the Amba Aradam sandstone cliff. The debris flow presently creeps downslope at a rate of 3–6 cm year^{-1}. Palynological evidence from tufa shows that the reactivation of the flow started 70 years ago. Shear resistance measurements indicate the danger for continuous or prefailure creep. From the soil mechanics point of view, the reactivation of the debris flow is due to the combination of two factors: (1) the reduction of flow confining pressures as a result of gully incision over the last hundred years, and (2) the increase of seepage pressure as a consequence of the cumulative effect of this incision and the increase in infiltration rates on the lobe since grazing and woodcutting have been prohibited 8 years ago. The role of such exclosures as possible landslide triggers is discussed.

From the geomorphological point of view, the ancient movements and their present-day reactivation cannot be compared: the ancient movements led to the development of debris flows, whereas the reactivations relate to the dissection of these mass movement deposits.

Keywords: Ethiopia; Landscape; Soil

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1. Introduction

Field observations near Hagere Selam, Tigray, Northern Ethiopia, show the presence of many ancient mass movement features in the landscape. They generally consist of elongated lobe-shaped bodies of colluvium, descending the steep valley sides. Such mass movement deposits can supply information about the palaeoenvironmental evolution of the study area, located on "the roof of Africa." Furthermore, old landslides, especially in high relief zones, constitute a risk because of their potential remobilisation (Chorley et al., 1984). The Ethiopian Highlands are no exception (Ayalew, 1999). It was shown that active landsliding in Ethiopia is often related to undercutting by gullies or roads (Canuti et al., 1986; Asfawossen Asras et al., 1997; NEDECO, 1997; Almaz Gezahegn, 1998).

The objectives of this study are (1) to illustrate the importance of ancient mass movements in the geomorphology of the Ethiopian Highlands, (2) to assess their age of origin, (3) to unravel the environmental conditions triggering the original movement and (4) to understand the environmental significance of the present-day remobilisation of ancient debris flows, as well as that of first-time slides.

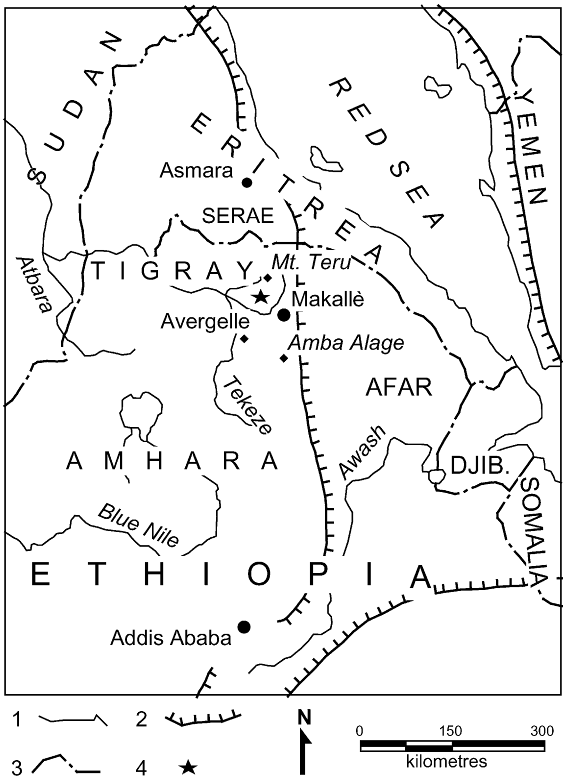

Fig. 1. Location of the study area in the Northern Ethiopian Highlands. 1) river; 2) Rift Valley escarpment; 3) political boundary; 4) study area.

2. The study area

A 200-km^2 area around Hagere Selam (13°40′N, 39°10′E), located on the rift shoulder to the West of the Danakil depression, about 50 km WNW of Makalle (Fig. 1), was selected for this study as it presents high elevations and a subhorizontal structural relief, typical for the northern Ethiopian Highlands. The Atbara–Tekeze river system drains the waters of the study area to the Nile.

The heavy rainy season (>80% of total rainfall) extends from June to September but is preceded by 3 months of dispersed less intense rains. Average yearly precipitation is 769 mm. Fig. 2 shows that 1998 and 1999 were rainy years whereas 2000 and 2001 were slightly below average. Field measurements also show that yearly rainfall is more than 100 mm lower in the 300–500-m deep valleys at both sides of the saddle (Nyssen et al., 2001). At the higher elevations, the average monthly air temperature varies between 12 and 19 °C (Nyssen, 1996). Mean air temperatures were observed to be higher in the lower areas, as already mentioned by HTS (1976) and Krauer (1988).

The local geology comprises subhorizontal series of alternating hard and soft Antalo limestone layers, some 400 m thick, overlain by Amba Aradam sandstone (Hutchinson and Engels, 1970). Two series of Tertiary lava flows, separated by silicified lacustrine deposits (Merla, 1938; Arkin et al., 1971; Merla et al., 1979), bury these Mesozoic sedimentary rocks. The Amba Aradam formation has undergone subaerial alteration at its summit and then a contact metamorphism when the lava flowed over it. Hence, the upper 8 m of this 50–100-m thick formation are very resistant and impervious.

Erosion, in response to the Miocene and Plio-Pleistocene tectonic uplifts (order of 2500 m), resulted in the formation of tabular, stepped landforms, reflecting the subhorizontal geological structure. The upper-

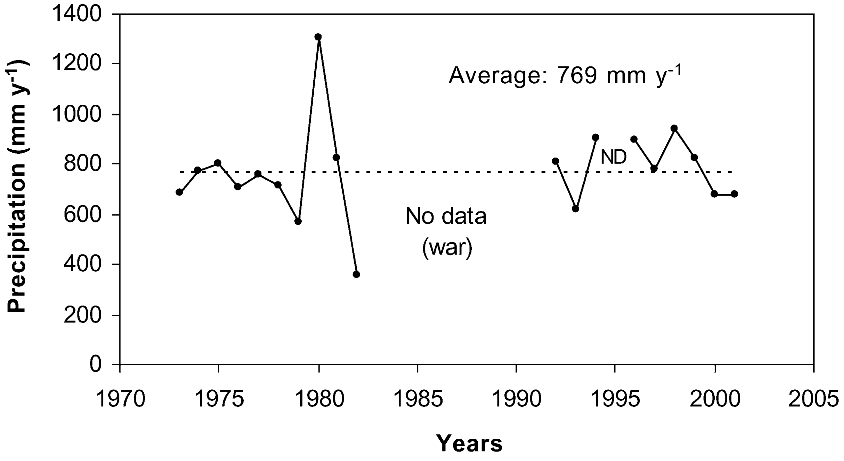

Fig. 2. Yearly precipitation in Hagere Selam. Sources: National Meteorological Services Agency (1973–1982 and 1996–1997), Dogu'a Tembien Woreda Agricultural Office (1992–1994), own measurements (1998–2001).

most levels of the landscape at about 2700–2800 m a.s.l. are formed in the basalt series. Other structural levels correspond to the top of the Amba Aradam sandstone and to the top of hard layers within the Antalo limestone (Nyssen, 2001).

3. Materials and methods

3.1. Field observations and measurements

The study area was prospected systematically; all mass movement phenomena were surveyed and classified according to Varnes (1978). Present-day creep movement was measured on two ancient debris flow deposits: the annual change in position of basaltic boulders (0.4–1 m across), embedded within the colluvium, was measured. These boulders are considered as 'floating' in the debris flow and as such they are considered to trace the average movement at the surface. Their displacement relatively to each other, as well as to marks on an outcrop of the Amba Aradam sandstone cliff in the flow, has been measured by theodolite in the dry seasons of 1998–1999, 1999–2000 and 2000–2001. Due to stone bund building in 1999, the site was disturbed and the distances on which creep observations have been done were only 83 and 128 m on the two respective deposits.

3.2. Laboratory methods

Major geological and geomorphological features were interpreted on aerial photographs (± 1:50,000) (Ethiopian Mapping Authority, 1994) and on topographical maps (Ethiopian Mapping Authority, 1996) of the study area around Hagere Selam (Fig. 3) and controlled in the field.

Subrecent tufa deposits, stratigraphically younger than observed present-day mass movements, were analysed. Pollen content of tufa samples was analysed by microscopic observation at CEREGE, Aix-en-Provence, France.

Older tufa was dated by U/Th method (alpha-spectrometry; Ivanovitch and Harmon, 1992) at the "Centre d'Etudes et de Recherches Appliquées au Karst," Mons, Belgium (Quinif, 1989, 1998).

Shear resistance experiments were conducted in laboratory, using a manual monoaxial shear strength measuring device (M&O, Montrouge, France). Disturbed soil samples (Lambe and Whitman, 1979), taken in toe and sides of the lobes, were first saturated with water and then consolidated under a normal pressure of 59 kN m^{-2} in an attempt to simulate a soil depth of ± 3 m, which is similar to the thickness of the May Ntebteb flow where it leaves the Amba Aradam sandstone cliff. Water was allowed to be absorbed by the soil samples till field capacity was reached, in equilibrium with the attained state of

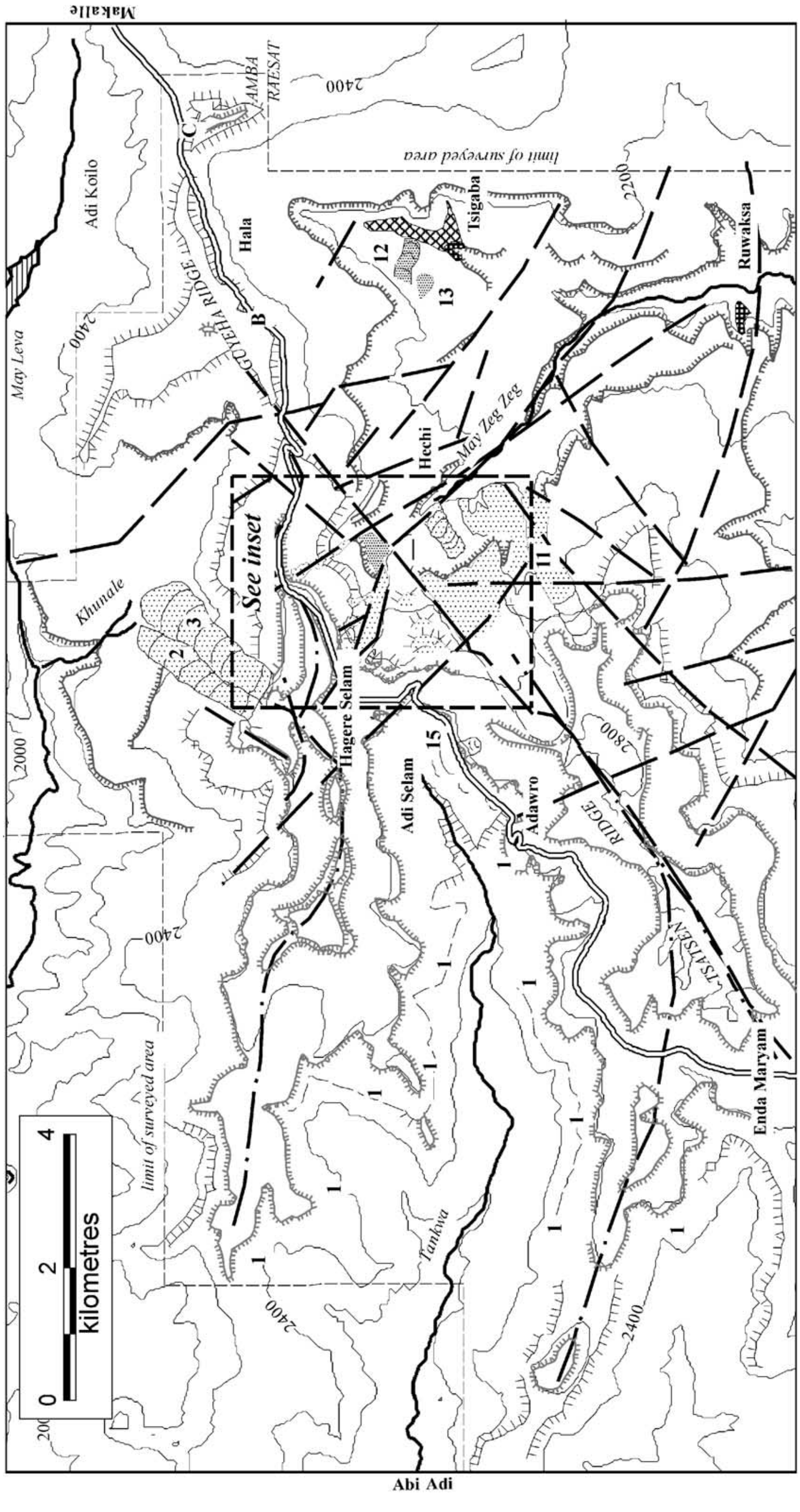

Fig. 3. Geomorphological map of the study area.

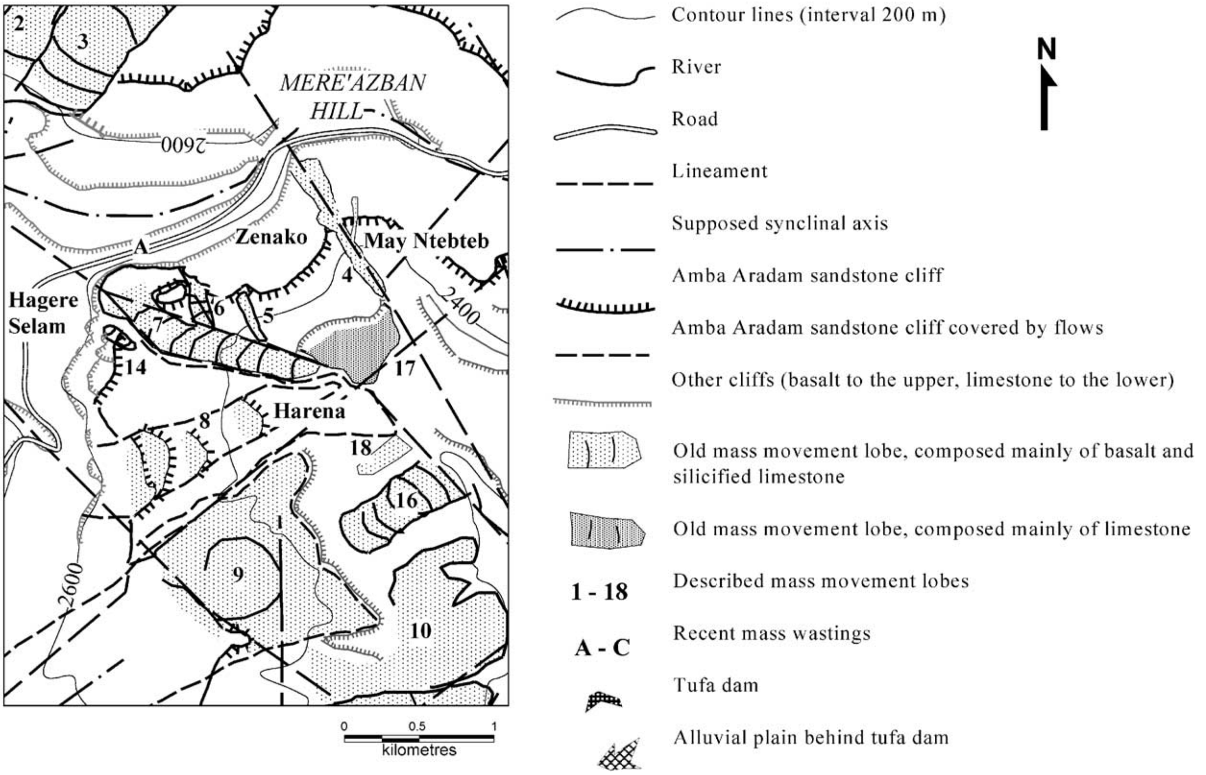

Fig. 3 (*continued*).

consolidation (i.e. saturation). The samples were then submitted to shear tests at normal stresses of approximately 60, 40, 20 and 0 kN m^{-2}. Slow tests with a shear stress increase of 981 N m^{-2}/3 min have been conducted in order to assure a drained test. Creep displacement was measured at each increment of the shear stress and the critical shear stress was determined when the soil sample failed, i.e. when displacement of the upper half of the shear box exceeded 1 mm min^{-1}.

4. Results and discussion

4.1. Genesis and morphology of the Amba Aradam sandstone cliff

The position of river incisions in the study area, the direction of escarpments and other morphological details can often be related to linear features such as faults (Fig. 3). The Chelekwot fault system, with SE–NW orientation, affects the study area. As faulting occurred at the end of the Jurassic era, after the deposition of Antalo limestone, these faults affect essentially this formation, and to a lesser extent the overlying Amba Aradam sandstone and the basalt. A secondary system of lineaments, oriented SW–NE, appears also. This Chelekwot fault belt is not related to the N–S-oriented lineaments, which are part of the Rift Valley system (Beyth, 1972).

The major physiographic characteristics, especially the general distribution of the high land masses and deep valley incisions in the study area, seem also to be linked to the slightly undulating structure of the subhorizontal geological layers, especially of the Amba Aradam sandstone. The latter outcrops on the edge of most interfluves, forming a riser or a cliff, but dips often slightly slope inwards, as illustrated in Fig. 4. It seems, therefore, that the high basalt ridges in the study area rest in the synclinal axes of the slightly undulating layers of the Mesozoic substrate. The inferred synclinal axes are indicated in Fig. 3, and

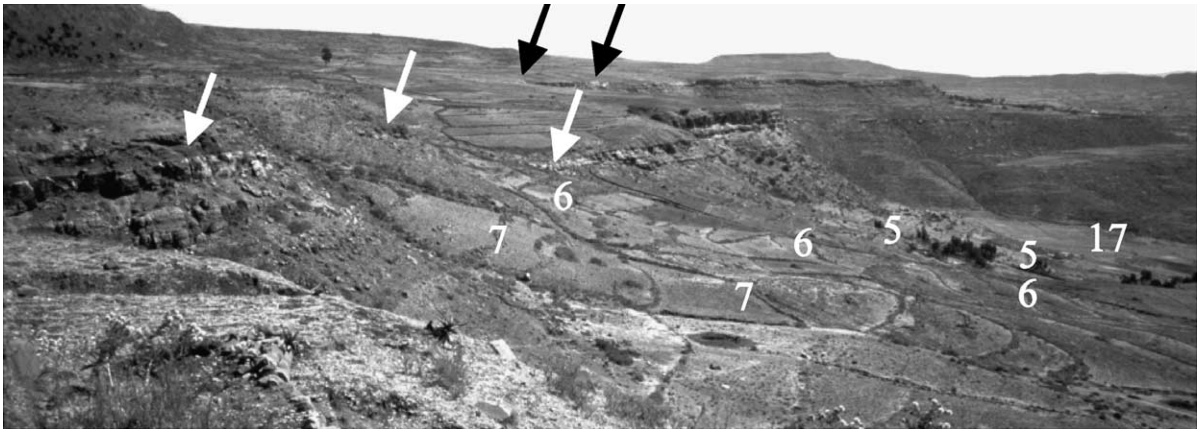

Fig. 4. Debris flows (6) and (7) came through gaps in the Amba Aradam sandstone (AA) cliff. White arrows indicate a vertical jump in altitude of the order of 20 m in the AA cliff on both sides of flow (6). Debris flow (5) and the toe of slide (17) are also visible. Black arrows indicate gaps in the AA cliff where the May Ntebteb debris flow ((4) on Fig. 3) descends the plateau. Note that the Amba Aradam sandstone cliff (beneath the white arrows) slightly dips slope inwards. View from Hagere Selam towards the east, summer 1999.

appear to be parallel to the long axis of the mountain ranges.

Where the Amba Aradam sandstone outcrops, a subvertical cliff is often present. Examples are the Guyeha ridge and the adjacent ridge, to the west (Fig. 3). These rock cliffs are about 50 m high and produce important rockfall during the rainy season. This cliff is a major tool of reconnaissance in the field and by aerial photo interpretation.

4.2. Ancient mass movements

4.2.1. Distribution in the study area

Many ancient mass movement features have been observed in the study area. The more prominent features have been numbered from 1 to 18 (Fig. 3 and Table 1).

In a few places, the Amba Aradam rock cliff shows fault-related gaps, some tens to a few hundred metres wide, occupied by a simple or composite body of colluvium composed of basalt and silicified limestone debris. These mass movement deposits, (labelled (4)–(7) in Figs. 3 and 4) start within the Vertisols and vertic Cambisols that cover the top of the Amba Aradam sandstone and continue through gaps in the cliff till deep in the valley, where they cover the limestone bedrock. In a number of cases, the body starts in a 100–200-m wide amphitheatre-like scar in the basalt. The cross-section of the upper part of these deposits generally shows a slightly convex topography. These

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Notes to Table 1:

[a] Mostly, the toe is located on a structural flat—if not, there is a footnote.

[b] Difference between elevation of lower part of geological formation (in situ) composing the flow and the elevation of the toe of the flow.

[c] Difference between elevation of lower part of geological formation (in situ) composing the flow and elevation of the approximate middle of the flow mass.

[d] Locally counterslope of 0.01–0.02 m m^{-1}.

[e] Might be up to 200 m deep seated.

[f] Presence of cambering in AA sandstone, which is probably simultaneous with multiple rock slump.

[g] Locally horizontal (0 m m^{-1}).

[h] Cambering in AA sandstone might indicate that a deep-seated slump occurred in this formation before or simultaneously with the basaltic flow.

[i] Reached the thalweg.

[j] Rock slum covers Amba Aradam sandstone cliff, then stops.

[k] Slides 16 and 18 are offshoot of slide 9.

deposits are considered as creep and/or solifluction lobes, in analogy with similar phenomena in Rwanda (Moeyersons, 1989, 2001). More stony debris slides (labelled (9)–(11) in Fig. 3) occur to the W of the upper May Zeg Zeg course. Other important debris slide deposits occur in the upper Khunale waters (labelled (2) and (3) in Fig. 3). In the headwaters of the Tankwa, the Amba Aradam sandstone cliff is very well expressed at Adi Selam (Fig. 3), but suddenly becomes less well expressed in both valley sides, 1.5 km more

Table 1
Characteristics of the mass movement deposits in the study area

Type (Varnes, 1978)	Width (m)	Length (m)	Thickness (m)	Area (km^2)	Volume $(10^6\ m^3)$	Upper slope $(m\ m^{-1})$	Slope of toe $(m\ m^{-1})$[a]	Minimal extent of vertical displacement (m)[b]	Minimal average vertical displacement (m)[c]	Type of material
(2) Debris slide	425	2125	35	0.903	31.6	1.20	0.15[d]	320	210	Coarse basaltic and dioritic material (0.1–10 m)
(3) Debris slide	510	2380	22	1.214	26.7	1.50	0.18[d]	320	210	id.
(4) Debris flow	100	1100	15	0.110	1.7	0.52	0.13	200	100	Black clay, many large basaltic rock fragments, silicified limestone inclusions
(5) Debris flow	50	340	8	0.017	0.1	0.44	0.15	150	100	id.
(6) Debris flow	200	1300	18	0.260	4.7	0.36	0.11[d]	210	150	id.
(7) Debris flow	250	600	10	0.150	1.5	0.42	0.15	100	50	id.
(8) Multiple rock slump	320	1600	100[e]	0.512	51.2	0.67	0.08[d]	250	150	Amba Aradam sandstone, with basalt boulders on top of each slumped block[f]
(9) Debris slide	1050	900	15	0.945	14.2	0.37	0.13	120	80	Weathering basalt (1–20 cm, exceptionally 1 m), no clay. Silicified limestone, sandstone and limestone fragments at the edges
(10) Debris slide	700	1400	5	0.980	4.9	0.56	0.04	250	150	Weathering basalt (1–20 cm, exceptionally 50 cm), no clay
(11) Debris slide	422	1785	10	0.753	7.5	1.10	0.09[g]	400	200	Weathering basalt (1–20 cm, exceptionally 1 m), no clay[h]
(12) Debris slide	255	595	20	0.152	3.0	0.65	0.15[i]	60	40	Marl fine earth, with many limestone r.f. (< 1 m)
(13) Debris slide	270	255	15	0.069	1.0	0.65	0.09	40	20	id.
(14) Rock slump	125	300	18	0.038	0.7	0.65	0.45[j]	150	100	Slumped basalt bedrock and metre-sized boulders.
(15) Debris slide	270	850	3	0.230	0.7	0.59	0.07	130	90	Silicified limestone
(16) Debris slide[k]	300	750	15	0.225	3.4	0.37	0.09	300	220	Weathering basalt (1–20 cm, exceptionally 1 m), no clay. Silicified limestone, sandstone and limestone fragments at the edges
(17) Debris slide	500	400	20	0.200	4.0	0.34	0.04	50	30	Marl fine earth, with many limestone r.f. (< 1 m), locally sandstone inclusions
(18) Debris slide[k]	100	300	25	0.030	0.8	0.39	0.00	300	220	Weathering basalt (1–20 cm, exceptionally 1 m), no clay
Minimum	50	255	3	0.017	0.1	0.34	0.00	40	20	
Maximum	1050	2380	100	1.214	51.2	1.50	0.45	400	220	
Average	344	999	21	0.399	9.3	0.63	0.12	197	125	
S.D.	249	669	22	0.398	14.2	0.33	0.10	108	70	
Total				6.787	157.6					

downstream. The Amba Aradam sandstone platform of Adi Selam carries a debris slide (15), which starts in the above basalt and ends on the platform before the cliff. Observations downstream of Adi Selam show that over a distance of about 6 km, the cliff is hidden below a cover of mass movement deposits (1) of basalt colluvium with inclusions of silicified limestone. Aerial photo interpretation shows the presence of several flat and wide superposed lobes, covering the sandstone platform, the sandstone cliff and the lower lying limestone. In several localities, traces of multiple slumping are recognisable (Fig. 5).

Many of the landslide causes quoted by Selby (1993) can possibly have triggered the ancient mass movements in the study area: removal of lateral support by gullying, laterally penetrating water, presence of impervious geological layers, soil composition and texture, swell-shrink capacity of clays, heavy rain, positive pore water pressure and earthquakes. Periglacial and snow action can be excluded since the lower limit of periglacial action in the Ethiopian Highlands is believed to have been around 3000 m a.s.l. during the last glacial maximum (Messerli and Rognon, 1980). Influence of sloping geological discontinuities can also be excluded given the subhorizontal structural relief in the study area. In the following sections, some of the possible causes will be discussed.

4.2.2. Underlying geology

Debris slides (1), (2), (3), (9), (11) and (15) (Fig. 3) have their origin in the silicified limestone deposits. Some of the slides, such as (15), are composed completely of silicified limestone. These deposits are poorly described in literature. Besides brief notes on geological maps (Arkin et al., 1971; Merla et al., 1979), we must go back to Merla (1938) to find a description of these "continental, lacustrine sediments, at least partially formed to the expense of volcanic materials." On the Amba Alage (Fig. 1), interbedded, lacustrine white clay and marls appear in an elevated position. The same formation appears in between volcanic layers in different areas in Tigray and Eritrea (Avergelle, Mount Teru, Seraè) (Fig. 1). At this last place, lignite is included in a lacustrine deposit near the base of the basalt series (Merla, 1938). Widespread lacustrine sediments are deposited on top of the lower series of basalt flows, at the elevation of Hagere Selam. The prominent white Mere'azban Hill, 2 km east of Hagere Selam along the road to Makalle, is composed of lacustrine material (silicified limestone) and capped by thin basalt remnants. Hard layers are composed of right-edged brownish chert blocks, with dimensions between 10 and 30 cm. Gastropod fossils (*Melanopsis*, according to Merla, 1938) are abundant. Interbedded are layers of white-grey clay-rich silicified mudstone with a low density (1763 kg m^{-3}). The rock contains many fractures, filled with iron oxide. Low density, high clay content and soft consistency make these lacustrine deposits prone to failure.

Other mass movement lobes are essentially made up of a basalt colluvium but contain also silicified

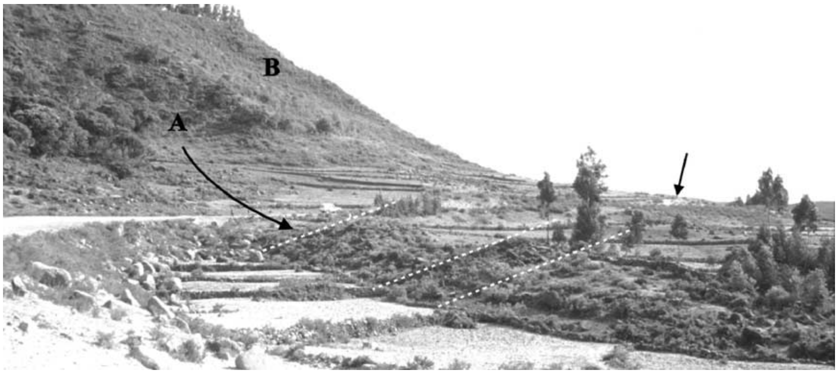

Fig. 5. Ancient slump and its scar A. Dotted lines indicate changes in lithological composition in the slumped block, which correspond to the originally subhorizontal layers. The arrow at the horizon indicates the correlative deposits of scar B. Adawro, 3 km SW of Hagere Selam, belt (1) on Fig. 3, January 1998.

limestone. Generally, a flat-bottomed amphitheatre-like hollow is developed in the upper basalt series, as if the disappeared basalt mass has floated away with the underlying "stream" of silicified lacustrine deposits. Downstream of Adi Selam, the typically whitish silicified limestone constitutes the body of the mass movements (1) over the Amba Aradam sandstone escarpment. The silicified lacustrine deposits were prone to plastic deformation, as testified by the numerous distortions, involutions and other deformations seen in the outcrops.

4.2.3. Palaeo-hydrological conditions of sliding

Debris flows (4–7) (Figs. 3 and 4) take their origin in the colluvial mixture of basalt and debris of silicified lacustrine beds, resting on the Amba Aradam sandstone. Flowing is thought to have been correlated with water pressures, which, during humid periods, built up in the colluvium upon the impervious sandstone. Near Hagere Selam, the Amba Aradam formation acts as an aquifer (Tesfaye Chernet and Gebretsadio Eshete, 1982). Its capacity to hold up water in the soil profile is testified by the presence of a spring line, locally with active tufa deposits, on the top of the Amba Aradam cliffs. Rock slump (14) (Fig. 6), affecting the in situ basalt substrate, has the same geological context. South of this rock slump, a few amphitheatres, not indicated in Fig. 3, are also perched upon the top of the Amba Aradam sandstone.

Very different in form and size is the deep-seated, more than 1.5-km long multiple rock slump (8). Three of the five slumped blocks are indicated on the map (Fig. 3). On their top, they carry basalt material, resting on greatly intact, 300-m wide Amba Aradam sandstone plates, showing an appreciable counter-slope. The lower of the three indicated plates has its top more than 200 m below the escarpment from which the whole mass detached. The question arises how such a huge feature could originate. Observations in the riverbed between the multiple slump (8) and debris slide (9) show the presence, about 200 m upstream of Harena church, of a sandy facies in the Antalo limestone, which dips towards the valley. The observed outcrop is at about 2350 m a.s.l., and is positioned below the second slumped block. The local dip of the sandy layers and their apparent capacity to hold a perched water table, like the Amba Aradam sandstone, are believed to have played a role in the origin of multiple slump (8). Movements in the recent geological past resulted in the present plan form of the toe, which controls the local pattern of the May Zeg Zeg course and the tributary in between (8) and (7).

Other mass movement features occur deep in the valleys, affecting only the Antalo limestone series, such as debris slides (12), (13) and (17) (Fig. 3). Exposures in (12) and (17) invariably show a mixture of fines and coarse debris, the latter varying in size from the order of 10^{-2}–10^{1} m. This colluvium

Fig. 6. Rock slump (14), to the west of Harena. The amphitheatre-like scar is developed within the lower basalt (B). The lobe 'flows' over the Amba Aradam sandstone (AA) cliff, February 2000.

differs clearly in structure from the in situ Antalo limestone rocks.

4.2.4. The age of the mass movements

It is difficult to put a precise age on most of the mass wastings, but their relatively young age is confirmed by their recognisable lobe forms.

Debris slide (12) reaches the Tsigaba valley bottom, which is at present incised by an ephemeral river. In the river banks, up to 30 m downstream from the landslide toe, reworked marly slide material is present below fluvio-lacustrine deposits, which accumulated in an ancient lake upstream of the tufa dam of Tsigaba (Fig. 3). Datings of the tufa dam resulted in ages older than 14,000 years (Nyssen, 2001). Since the reworked slide material underlies the fluvio-lacustrine deposits, the slide is thought to be contemporary to the existence of a lake behind the tufa dam. Sliding here is probably correlated to a raised water table induced by the presence of the lake.

Some information on the age of the three mass movement deposits (17), (7) and (8) was gained in the May Zeg Zeg valley, where they converge. Stratigraphically, the marly slide (17) appears to be older as its side disappears below debris flow (7), composed of basalt colluvium. On the other hand, in the gully sections at the separation between the ‘black’ debris flow (7) and the ‘red’ (Amba Aradam sandstone) multiple rock slump (8), there are alternations in the overlap, suggesting that both movements were discontinuous and repetitive in nature and occurring during the same time span.

The black debris flows (4–7), which rest upon older lobe (17), are issued from Vertisol areas. Vertisols and valley bottom deposits in the northern Ethiopian Highlands are mostly Holocene in age, the oldest dated deposit being 8300 ± 100 BP (radiocarbon dating on humic matter, extracted by NaOH leaching, no laboratory number provided, Brancaccio et al., 1997). Hence, these debris flows (4–7) can be estimated younger than 8000 BP. They can, however, not be considered very recent; at its foot, debris flow (4) has been totally eroded and the toe is isolated from its source.

With respect to slide (15) at Adi Selam, the upstream depression behind the lobe is filled with a sequence of black clay deposits. Also in this case, the blackish postlobe deposits are without doubt of Holocene age and, therefore, indicate the probable pre-or Early Holocene age of the landslide deposits (15), on the edge of which they repose.

Indications for the age of the other mass wastings in Fig. 3 are scanty. The working hypothesis is that many of these mass movements have been active, intermittently or not, during a long time span, from Late Pleistocene to Middle Holocene times.

4.3. The present-day remobilisation of the May Ntebteb flow

4.3.1. Field evidence

In the Ethiopian Highlands above 1750 m a.s.l., landslides increased in size and number over the last three decades and they are often reactivated ancient mass movements (Ayalew, 1999). Such is the case of the May Ntebteb debris flow ((4) in Fig. 3). Since 1991, land use on this debris flow (Fig. 7) has changed from grazing land to exclosure, i.e. land under strict conservation management, controlled by the community. There is no grazing, nor any other agricultural activity. Except for yearly grass cutting by the community, there is no human interference with vegetation regrowth. The debris flow contains over its whole length many silicified limestone and basalt inclusions, manifestly originating from the geological layers above the Amba Aradam sandstone. At the place where the debris flow passes through the gap in the Amba Aradam sandstone cliff, terracettes (Vincent and Clarke, 1976), separated by active cracks in the soil, give evidence for its recent remobilisation. Furthermore, sandstone outcrops in the gap indicate places where the overlying colluvium (locally) slid downslope over a distance of a few metres. These phenomena are manifest signs that the lobe is slowly moving in that section. A ca. 20-cm thick recent tufa on such a rock outcrop (Fig. 7) was analysed for its pollen content in order to deduce its age from recorded changes in vegetation. Preliminary counts of 100–170 pollen grains revealed fairly diversified pollen assemblages between the base (near the bedrock), the middle and the top of the tufa (Bonnefille and Buchet, 2000). The herbaceous taxa with grasses, Cyperaceae (sedges) and Compositae altogether account for 60–70% of the total pollen, indicating that the tufa was formed after deforestation. A few additional herba-

Fig. 7. Debris flow (4) at May Ntebteb (September 1998) moves through a gap in the Amba Aradam sandstone (AA) cliff. Cliff outcrops in the debris flow (upper arrow) constitute reference points for creep measurements. Gullies on both sides of the lobe are actively incising (lower left arrows). The Acacia trees are about 6 m high. The better development of grasses and trees on the flow is due to the exclosure practice. Longitudinal (a) and cross (b)-sections are detailed on Fig. 8. Length of (a) is 260 m. Tufa deposits are on the cliff outcrops (upper arrow) (August 2000).

ceous plants, among which *Lobelia*, *Aloe*, *Kniphofia*, *Asparagus*, *Aerva*, *Achyranthes* and *Hypoestes*, have also been identified, together with *Typha* and ferns spores. The arboreal component is represented by rare occurrences of *Olea*, *Acacia*, *Podocarpus*, *Dracaena* and Celastraceae, recorded by one or two grains. The outer, most recent deposit differs from the lower deposits by its higher proportion of grasses (30% against 18% and 12%), its smaller proportion of Compositae (8% against 23%), its greater percentage of *Rumex* (6%) and its more abundant and more diversified signal of arboreal pollen. It contains *Xanthium*, which is recently introduced (Bonnefille and Buchet, 2000). All these differences testify of the recent (1991) exclosure with regrowth of trees and of *Rumex nervosus*, as well as a clear dominance of grasses in the herbaceous stratum. Since at least 1/9 of the tufa growth (thickness of the most recent sample) took place after exclosure (8 years before the moment of sampling), the initial tufa is thought to be less than 70 years old. This would also be the approximate age of the remobilisation of the May Ntebteb lobe, which exposed the Amba Aradam sandstone outcrop on which the initial tufa developed.

4.3.2. Creep movement

Field evidence for the occurrence of slow ongoing movements on the May Ntebteb debris flow (4) has been seized to undertake creep measurements on it. Creep movements theoretically imply the absence of a failure plane at the base of the creeping soil mass, but the presence of small rock outcrops points to the function of the top of the Amba Aradam sandstone as a local sliding plane.

The ancient May Ntebteb debris flow (4), below the sandstone cliff, is some 800 m long, of which some 260 m, above the gully incision (arrow, Fig. 8a), are affected by creep. The steeper part of the longitudinal profile shows a slope gradient of 0.43–0.47 m m^{-1}. The colluvium is derived from weathered basalt with many silicified limestone inclusions. High water holding capacity (Table 2) is due to the presence of smectites in this basalt-derived colluvium. In a cross-section, perpendicular to the steepest slope (Fig. 8b), the lobe is clearly visible. Drainage lines on both sides of the lobe were recently (according to our informants, since less than 30 years) incised by gullying. Observed creep rate, parallel to the soil surface, over the upper 83 m below the rock outcrop is 6.4 cm in 2 years (increase in distance to fixed point on rock outcrop).

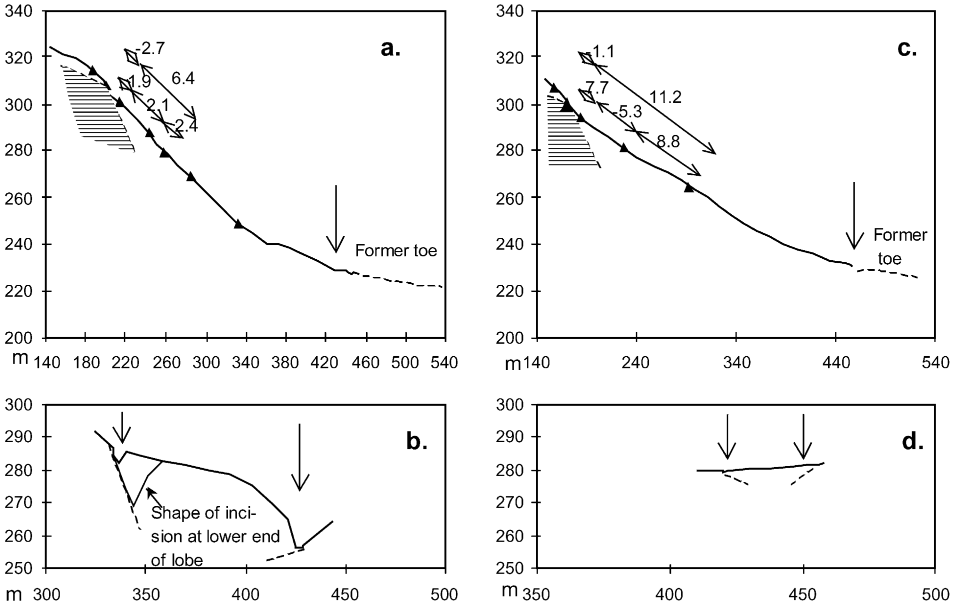

Fig. 8. Longitudinal (a, c) and cross (b, d)-sections of the May Ntebteb debris flow (see Fig. 7) and its feeder from May Toqem. Hatching shows the hypothetical position of the Amba Aradam sandstone bedrock. Triangles show the position of the bedrock outcrop and the embedded boulders between which creep movement was measured. Creep distances parallel to the soil surface between October 1998 and March 2001 are expressed in centimeters. The lower line of distances indicates the relative movement between boulders, the upper the absolute creep movement relatively to the outcropping bedrock. Cross-sections show the difference between deposits of basaltic colluvium in the May Toqem area (d) and the ancient flow in May Ntebteb (b). Arrows indicate recent gullying, which is overdeepening existing drainage lines in May Ntebteb (b). The incisions cutting off the former toe are also indicated by arrows (a, c).

The shallower mass of basaltic colluvium which came over the cliff at May Toqem (Fig. 8c and d) can be considered as a feeder of the May Ntebteb debris flow. This area consists of heavily overgrazed land, the last marginal fields having been abandoned some 20 years ago. Slope gradients in the upper part are also $0.43–0.47\ \mathrm{m\ m^{-1}}$ and creep movement over 128 m is 11.2 cm, spread over both observation years.

On both sites, the creep movement indicates a longitudinal extension of the lobe from the gap in the Amba Aradam cliff in downslope direction. Extension here suggests probably progressive creep, similar to the concept of progressive failure (Bishop, 1967), starting where the flow toe has been cut off and extending in upslope direction. The question whether it concerns transient creep or prefailure creep and in how far failure is imminent will be discussed below.

Table 2
Analysis of soil samples from the May Ntebteb flow and from the Amba Raesat slide

	May Ntebteb (swelling clays)	Amba Raesat (marl)
i = steepest slope angle (°)	23–25	29
tan$i$	0.43–0.47	0.56
w = field capacity[a] ($\mathrm{kN\ kN^{-1}}$)	0.471	0.263
γ_t = unit weight at field capacity ($\mathrm{kN\ m^{-3}}$)	15.77	17.67
C = cohesion ($\mathrm{kN\ m^{-2}}$)	6.18	11.58
φ = angle of friction (°)	24	20
tanφ	0.44	0.37

[a] Under effective normal stress of $59\ \mathrm{kN\ m^{-2}}$.

4.4. Present-day landsliding

At two locations in the study area, transformed into exclosure a few years ago, important slumps occurred. The first appeared in the East of the study area, in an amphitheatre-like valley head on the northern edge of the Amba Raesat ridge, south of Adi Koilo village ((C) in Fig. 3). The new Makalle–Hagere Selam road has been interrupted twice by slumping since its construction in 1994. The area is located in the upper marly layers of the Antalo limestone (Russo et al., 1999), covered by 1–2-m thick colluvium originating from the Amba Aradam sandstone cliff. The vegetation consists of well-growing grasses and some shrubs. The slope gradient around the slump head amounts to 0.56 m m^{-1}. During the rainy season of 1998 and 1999, which were years with above average rain (Fig. 2), a more than 2-m thick colluvial mass slid out of the head scar and flowed over and beyond the road (Fig. 9). The displacement distance of the slumped mass is of the order of 10–20 m. In both years, the toe was unloaded for road maintenance. No visible movement occurred in the less rainy years 2000 and 2001. At the moment of road building, the footslope has been undercut by a temporary bypass (visible on the 1994 aerial photographs) of a culvert under construction. There is also clear evidence for the slump to have been activated by important subsurface flow as temporary springs occur in the second part of the rainy season, above the slide plane in the cut-off toe. The timing of the mass wasting, a few years after exclosure of the area, seems not to be a coincidence. The well-developed grassy vegetation in this exclosure (Fig. 9) led to increased infiltration capacity. Landslide risk in the first stage of vegetation regrowth is a known phenomenon, especially on soils with medium to low permeability (Collison and Anderson, 1996). Similar mass wastings, though of lesser magnitude, also occurred in 1998 at a roadcut in the same parent material, 4 km to the West, in Ksad Hala ((B) in Fig. 3), where it passes through a 2-year

Fig. 9. Slump on the northern slope of Amba Raesat ((C) on Fig. 3) (photographs: February 2000). The upper image shows the slump head in weathered Amba Aradam sandstone colluvium and marl belonging to the upper Antalo limestone. The person is standing at the slide head, on the junction between the main scarp and the slide plane, roughly parallel to the surface, sloping with a gradient of 0.56 m m^{-1}. The bottom picture shows the slump toe (white arrow) after cleaning of the 12-m wide road (foreground). The slumped mass is dissected by gullies (smaller arrows). The slope gradient here approximates 0.2 m m^{-1}.

exclosure. The area in Ksad Hala shares several characteristics with the Amba Raesat slope: important vegetation growth, marly parent material belonging to the upper Antalo limestone and destabilisation by undercutting due to road construction works.

The two landslides discussed, together with one near Hagere Selam ((A) in Fig. 3), provoked by road building on a cliff edge at the very place where springs occur (Nyssen, 1996), are the only important active landslides known in a wide surrounding.

4.5. Factors involved in present-day sliding and in the remobilisation of ancient mass movements

4.5.1. Assessment of the natural stability of the May Ntebteb debris flow

Creep movement rates as measured on the May Ntebteb flow and on its feeder are much higher than on adjacent slopes. Below the Amba Aradam sandstone cliff, the slopes have a structurally determined step-like topography, reflecting the alternance of hard and soft layers of Amba Aradam sandstone and especially of Antalo limestone. These layers are not bent down where they outcrop, suggesting that they are not undergoing creep. The thin patches of soil, collected downslope of every riser on the steps, might undergo creep, but it is assumed that the annual creep rate of these patches is much lower than on the mass movement deposits of May Ntebteb because of their reduced thickness, generally less than 1 m.

The question arises whether the creep movements, occurring on the debris flow are the early stage of an imminent remobilisation or if they are transient. An analysis of the natural stability of the May Ntebteb deposit can give an answer. The material involved shows a high field capacity (Table 2), due to the presence of smectites in the basalt-derived colluvium. The black colour, the clay content and the desiccation cracks at the surface during the dry season suggest vertic characteristics of the debris flow material. Vertic material, undergoing seasonal swell-shrink is assumed as very prone to creep.

Shear stress needed to obtain failure of the Amba Raesat ((C) in Fig. 3) and May Ntebteb (flow 4) samples, at different values of normal stress, is represented in Fig. 10. The material from May Ntebteb has an apparent cohesion of $C=6.18$ kN m^{-2} and its angle of internal friction is 24° at field capacity.

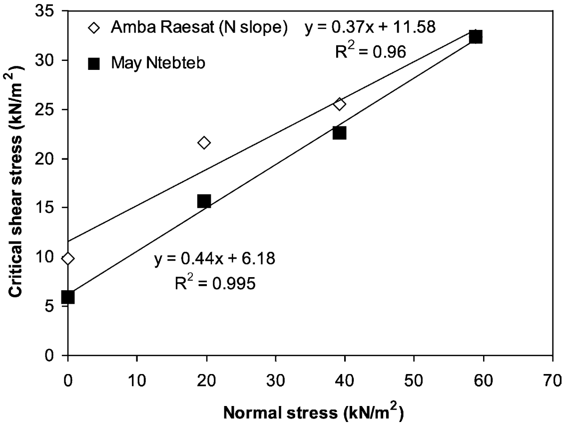

Fig. 10. Shear strength vs. normal stress, for the landslide on the Northern slope of Amba Raesat and for the reactivated debris flow in May Ntebteb. The parameters describing the linear relationship between shear stress and normal stress at failure are the cohesion C (intercept with y-axis) and the angle of internal friction φ (slope of the regression line).

Infinite slope analysis is applied to the May Ntebteb flow in a first attempt to evaluate its present-day stability conditions. The order of magnitude of the value of apparent cohesion C (Table 2) allows the use of the infinite slope analysis equation (Selby, 1993):

$$F=\frac{C+(\gamma_t-m\gamma_w)H_c\cos^2 i\tan\varphi}{\gamma_t H_c \sin i\cos i} \tag{1}$$

where F = stability factor (resisting forces divided by driving forces), C = apparent cohesion (kN m^{-2}), γ_t = unit weight at field capacity (kN m^{-3}), γ_w = unit weight of water (9.81 kN m^{-3}), H_c = depth of failure plane (m), i = slope angle (°), φ = friction angle (°) and m = height of the water table, expressed as a fraction of the soil thickness above the plane ($0 \le m \le 1$).

For a stability factor $F=1$ (threshold for instability), Eq. (1) allows to calculate the depth of the potential failure plane H_c in function of the variation of the phreatic surface. Introduction of the values of Table 2 in Eq. (1) shows that if m were equal to 0 (phreatic surface below potential depth of failure), the sliding body should be 87.47 m thick for a slope angle of 24° but only 17.66 m for a slope angle of 25° and less than 9.90 m for a slope angle of 26°. From Fig. 8b, it can be deduced that the May Ntebteb lobe is about 30 m thick whereas the slope angle varies between 24° and 25°. This shows that the equilibrium is very precarious, even with $m=0$ but with the soil water content at field condition (γ_t). This is a situation which might occur at the first part of the rainy season, when springs at the foot of the mass movement deposit do not yet flow.

In the calculation of H_c for $F=1$ and $m=1$, the cohesion value of 6.18 kN m^{-2} (Table 2) has been used. It appears that for slope angles between 24° and 26°, the depth of the potential slide plane should only be about 1.7–1.5 m below the surface, instead of the 30 m observed in Fig. 8b. The approximate equilibrium slope angle, after introduction of $m=1$, as well as the thickness of 30 m (H_c) as observed in Fig. 8b, in Eq. (1) amounts only to about 11°. Hence, the $m=1$ situation never occurs, since this would introduce the complete reactivation of the flow on its actual 24° slope angle. From the whole set of calculations, it appears that even without the occurrence of seepage forces, part of the flow below the Amba Aradam sandstone cliff is in a very precarious equilibrium and that the confining forces of the toe, resting lower on less sloping terrain, play an important role in the stabilisation of the steeper part of the flow.

Despite the lack of soil moisture data in the field, we have indications of saturation during the rainy season up to a depth of several decimetres from the soil surface. Moreover, in the deep incisions at both sides of the May Ntebteb flow (Fig. 8b), temporary springs appear during the rainy season and their presence proves temporary conditions of seepage deep in the debris flow.

It should also be mentioned that the shear resistance tests show the susceptibility of the black clay for creep deformation at field capacity, long before the shear strength of the material is reached. Záruba and Mencl (1982) have shown that permanent creep occurs when shear stress reaches more than 85% of the shear strength. Laboratory experiments at smaller shear stress result in a transient creep, which stops after a certain number of days (Moeyersons, 1989). In the case of the May Ntebteb flow, the infinite slope analysis suggests that the stress level is above 85% of the soil strength, at least during the wet periods of the year. If 85% of the measured shear strength is taken (sample May Ntebteb, Fig. 10), the slope gradient on which permanent creep would occur, amounts to 0.37 m m^{-1}.

These arguments show that the stability of the May Ntebteb debris flow, especially during the rainy season, can be questioned for the steepest section (0.47 m m^{-1}). In such conditions, factors such as toe unloading or a substantial increase in the infiltration capacity of the soil might contribute to a remobilisation of the debris flow.

The slope gradient at the head of the slump in Amba Raesat amounts to 0.56 m m^{-1}. If this value and the parameters for the Amba Raesat colluvium (Table 2) are introduced in Eq. (1), the sliding plane is to be found at a depth of 3.9 m for conditions without seepage and at 1.87 m with seepage parallel to the surface. In the field, the failure plane or failure belt is estimated to vary in depth between 2 and less than 4 m, which confirms the role of the aforementioned seepage to mobilise the slump.

4.5.2. The impact of gullying

In the case of debris flow (4) in May Ntebteb, observations and measurements (Fig. 8b, arrows) show that the drainage lines, developed at both sides of the debris flow since its stabilisation during presumed Holocene times, become increasingly incised as a result of present-day gullying (Fig. 7). The incision along the right side of the May Ntebteb debris flow is about 20 m deep (Fig. 8b), and somewhat more downslope, the left incision becomes also very important. More downslope, where the longitudinal slope of the debris flow decreases, new gullies develop across it (Fig. 8a and c) and have cut off the original debris flow toe. Virgo and Munro (1978) and Nyssen et al. (2000a,b, in press) have shown that gullying is a general problem in Tigray. Gully incision can contribute in two ways to the destabilisation of ancient debris flows. First, it contributes to the relief of confining pressures. Incisions along the sides of the lobes reduce their lateral anchoring in the bedrock, and on places where a gully cuts across a debris flow, the upstream part of the debris flow becomes devoid of mechanical support from downslope. Secondly, gully drainage of the water table increases the curving of the phreatic surface and, hence, increases the hydraulic gradient and the seepage forces towards the gully. This further increases the tangential stress (Young, 1972). Road cutting has similar impacts, leading to destabilisation.

It is obvious that the observed creep movements expand in the upslope direction from the gully crossings (Fig. 8a and c). The gully incision in the toe of the debris flow, and the consequent stress redistribution in the flow upstream of the incision, reactivated the May Ntebteb debris flow.

4.5.3. Grazing and woodcutting exclosure

Gullying is not the only factor that can lead to higher seepage forces. An increase in the infiltration capacity of the soil leading to higher water table levels in the interfluves between the drainage lines during the rainy season can have the same effect.

The two described recent slumps, as well as the remobilised May Ntebteb debris flow, originate in an exclosure area. In the latter case, creep movement was however already active before exclosure. It is known from many parts in the world that the infiltration capacity of a soil protected by grasses, shrubs and trees, and reworked by root activity, is much higher than that of grazing land, where grasses are short throughout the year and the soil is compacted by cattle. It is assumed that the somewhat more developed vegetation, visible on Figs. 7 and 9, has contributed recently to higher infiltration rates, higher water table and, hence, increased seepage pressures. These might partly explain the high creep rate and landslide risk occurring nowadays in several exclosures on steep slopes.

From their recent experience with exclosures in the Tigray region, farmers observed that springs flow during a longer period of the year and that their discharges are increasing. The remobilisation of old landslides in exclosures of a few years old is, therefore, not surprising, and constitutes additional evidence for increasing soil moisture content in such areas. This increase is attributed to the accelerated development of essentially herbaceous vegetation, but the exclosures will have to last for a longer time to find out whether rain interception by leaves and

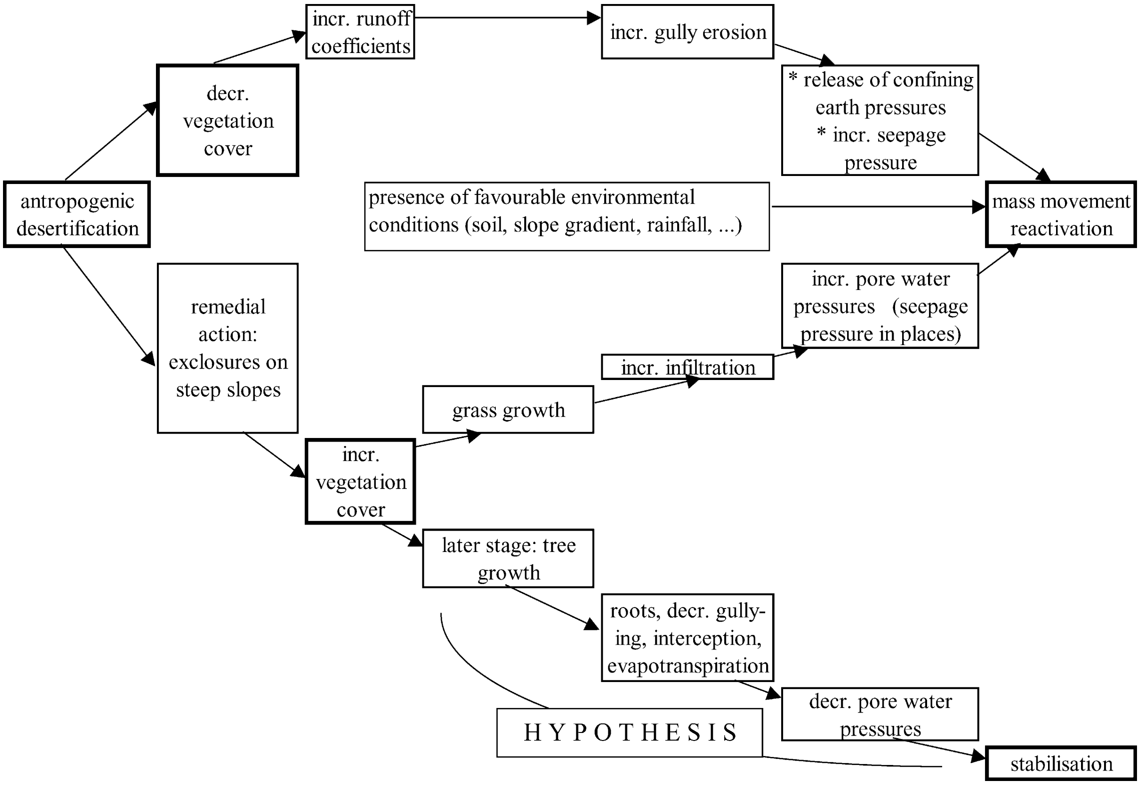

Fig. 11. Impact of land use changes on present-day mass movement activity in the Hagere Selam area.

evapotranspiration by the restoring vegetation will compensate in the long run for the increased soil infiltration capacity. Apparently, the mechanical effects of the roots (Mulder, 1991) of the increased vegetation of the few first years after exclosure seem to be unable to fix the potential landsliding mass. Vegetation roots might even not be able to stabilise thick colluvial masses. In Rwanda, under more humid conditions, a Eucalyptus forest was reported to 'float' on a 3-m thick creeping lobe (Moeyersons, 1989). Future study of the impact of growing trees on the stabilisation of landslide-prone areas must include the elaboration of a hydrological balance, especially for the period most at risk, i.e. the second part of the rainy season, as well as an analysis of the interactions between tree roots, water table and soil mass (Collison and Anderson, 1996).

4.5.4. Land use changes

The above sections indicate that an important cause of present-day landslides and reactivation of ancient mass movements are changes in land use, as shown in Fig. 11. Both vegetation removal and the first stage of exclosure may result in landsliding. Spontaneous regeneration of various tree species in 10-year old exclosures is important. Eucalyptus trees are sometimes planted in such areas. The hypothesis must be tested if this can stabilise the colluvial masses in the long term. As stated above, root growth might prove insufficient on the thicker lobes, but rainfall interception by leaves and evapotranspiration might increase, especially during short dry spells within the rainy season. Collison and Anderson (1996) show how, for soils with medium permeability, the factor of safety decreases in a first stage after tree establishment; but after the trees start growing, the factor of safety increases rapidly. A positive impact is also expected from the recovery of gullies.

4.5.5. Other environmental factors

Earthquakes are quite common in this rift shoulder area (Gouin, 1970) and have possibly been a triggering factor in the above discussed ancient flows and slides. According to local inhabitants, the last earthquake (1979 in Makalle) was not felt in the study area. Present-day first-time slides cannot be ascribed to earthquakes.

Recent slides occurred during the rainy years 1998 and 1999. There is a slight decrease in average yearly rainfall over the Ethiopian Highlands since the beginning of the 20th century, without any significant tendency (Beltrando and Camberlin, 1995; Conway, 2000). However, seasonal rain is thought to become increasingly irregular and in Central Ethiopia, increased landslide risk is reported to occur especially in years with above average seasonal rain (Ayalew, 1999).

The two described recent landslides might also have been triggered by road building, which has undercut slope deposits, leading also to an increase of the hydraulic gradient. In another case in the study area, it was reported how the load of a road embankment triggered landsliding (Nyssen, 1996).

The impact of the different factors in ancient and present-day mass movements is presented in Table 3. It can be seen that conditions for the occurrence of ancient slides and their present-day remobilisation are quite different in the study area. From the geomorphic point of view, the ancient movements and their present-day reactivation cannot be compared: the ancient movements led to the development of lobe-shaped forms, while the reactivations relate to the

Table 3
Factors involved in ancient and present-day sliding in the Northern Ethiopian Highlands

	Ancient mass movements	Present-day creep in ancient mass movement deposits	Present-day slides
Nature of parent material	* * *	* * *	* * *
Seismicity	* *	*	0
High average annual rain	* * *	0	0
Importance of years with above average rain	?	*	* * *
Gullying	0	* * *	* *
Dense vegetation	* * *	* * *	* * *
Road building	0	0	* *

* Possible.
** Probable.
*** Very probable.
^{0} Unlikely.

dissection of the old lobes. The present-day environmental evolution towards a more dense dissection of the landscape by increased gully development is not only characteristic for the Ethiopian Highlands, but for most of the African continent outside the tropical forest belt and is considered as diagnostic for drying conditions and depletion of water tables (Moeyersons, 2000).

5. Conclusions

In an area of about 200 km^2, centred on the town of Hagere Selam, clear traces of at least 17 ancient mass movements have been identified. Furthermore, a multitude of traces of ancient landslides covers the Amba Aradam sandstone cliff along the upper Tankwa River ((1) in Fig. 3). Most mass movements have their origin in the Tertiary basalts above the Amba Aradam sandstone aquifer. The interbasaltic silicified lacustrine deposits seem especially prone to sliding. Based on stratigraphic and dating evidence, the working hypothesis is that most of these movements were active during Late Pleistocene and Early to Middle Holocene times. On the base of our geotechnical and soil-mechanical knowledge, the development of slumps and earth and debris flows should be related to high water tables and conditions of soil humidity.

The present-day remobilisation of these ancient mass movements is evidenced by the presence of terracettes and by creep measurements. New landslides occurred on the footslopes of the Amba Aradam cliff. The slump movements are of the order of several metres during a few hours while the creep movements amount to 3–6 cm year^{-1} at the surface.

Shear resistance measurements indicate that the steepest part of the May Ntebteb debris flow with a matrix of swelling clays might be close to the verge of failure in the present-day conditions of soil water content and seepage during the second half of the rainy season. The observed creep movement would be permanent creep, maybe prefailure creep.

It is assumed that the degree of soil weathering remained unchanged; seismicity was absent over the last 20 years. Besides the increase in number of years with large rain depth, gully incision, caused by an increase in runoff coefficients, can explain the reactivation of the May Ntebteb flow and its feeder since 70 years. This process leads to mechanical destabilisation because the debris flow body becomes laterally disconnected from the stable valley sides and from the original toe of the debris flow. Furthermore, gully incision below the water table will also create larger seepage pressures. Information gained from the study area indicates that gullying is closely linked to human activities such as removal of vegetation and road building (Nyssen et al., 2000b, in press). It is felt that efficient measures against the reactivation of ancient mass movements include gully control.

The exclosure strategy leads to increased infiltration capacity of the soil and, hence, contributes to higher seepage pressures. Two types of information indicate that soil water content increases after the first years of exclosure and growth of grasses. First, local farmers report increased spring discharges in and downslope from exclosure areas. The other type of information is the observation, in the study area, that new slides apparently occur preferentially in exclosure areas of a few years old. This points to a possible danger during the first years after introduction of exclosures in areas prone to landsliding. Especially, ancient mass movement bodies might, at least during the first years of exclosure, be in danger of remobilisation. The observation of ongoing experiments with exclosures in Ethiopia has to be continued to find out whether the higher soil moisture content will be maintained in the long term. Further development of the vegetation might increase interception of rain and evapotranspiration and lead to dryer soils, while growing roots finally might reinforce the soil (O'Loughlin and Ziemer, 1982; Mulder, 1991). Such is only the case where the unstable slope deposits are not too thick.

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