9 The Amba Landscape of the Ethiopian Highlands, Shaped by Rockfall

J. Nyssen, J. Moeyersons, J. Deckers, Mitiku Haile, and J. Poesen

Abstract

Cliff retreat occurs on the *ambas* or structurally determined stepped mountains of the northern Ethiopian highlands. This chapter describes the rock fragment detachment from cliffs by rockfall, quantifies its annual rate and identifies factors controlling rock fragment movement on the scree slopes. It further presents a conceptual model explaining rock fragment cover at the soil surface in these landscapes. In the May Zegzeg catchment (Dogu'a Tembien district, Tigray), rockfall from cliffs and rock fragment movement on debris slopes by run-off and livestock trampling were monitored over a 4-year period (1998–2001). Rockfall and rock fragment transport mainly induced by livestock trampling appear to be important geomorphic processes. Along a 1500 m long section of the Amba Aradam sandstone cliff, at least 80 t of rocks are detached yearly and fall over a mean vertical distance of 24 m resulting in a mean annual cliff retreat rate of 0.37 mm year^{-1}. Yearly unit rock fragment transport rates on scree slopes ranged between 23.1 and 37.9 kg m^{-1} year^{-1}. This process is virtually stopped when exclosures are established. A conceptual model indicates that besides rockfall from cliffs and argillipedoturbation, all factors and processes of rock fragment redistribution in the study area are of anthropogenic origin.

Keywords

Debris slope • Livestock trampling • Rock fragment redistribution • Subhorizontal structural relief

9.1 Introduction

The subhorizontal geological formations of the Ethiopian highlands have been epirogenically uplifted over the last 25 million years. This has led to important incision and cliff retreat. Taking into account the high rates of other mass movements (landsliding, sheet and rill erosion), fallen material is rapidly removed and cliff retreat processes are maintained. The process immediately following rockfall which occurs downslope is the further removal of rock fragments by rolling, mainly induced by animal trampling.

Previous studies in the northern Ethiopian highlands (Nyssen et al. 2000, 2002a; Moeyersons et al. 2006a) have also analysed the origin of the extensive rock fragment covers. The rock fragment cover (R_C) of Vertisols and soils with vertic properties is clearly a result of swell–shrink action in these soils. The rapid appearance of new rock fragments at the surface after field clearing has been related to the active polygonal structures of the Vertisols. Rock fragments, appearing yearly at the surface of Vertisols, have been shown to belong lithologically to deposits underlying the Vertisols. Given this stratigraphical situation and the activity of Vertisols in the study area, the rock fragment

J. Nyssen (✉)
Department of Geography, Ghent University, Krijgslaan 281 (S8), 9000 Ghent, Belgium
e-mail: jan.nyssen@ugent.be

J. Moeyersons
Royal Museum for Central Africa, 3080 Tervuren, Belgium

J. Deckers · J. Poesen
Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, 3001 Heverlee, Belgium

M. Haile
Department of Land Resource Management and Environmental Protection, Mekelle University, P.O. Box 231, Mekelle, Ethiopia

P. Billi (ed.), *Landscapes and Landforms of Ethiopia*, World Geomorphological Landscapes,
DOI 10.1007/978-94-017-8026-1_9, © Springer Science+Business Media Dordrecht 2015

covers are thought to be squeezed up as a consequence of argillipedoturbation accompanying swell–shrink cycles in the vertic horizon.

Another study in the northern Ethiopian highlands (Nyssen et al. 2002b) showed that the balance between lateral and vertical movements of rock fragments controls the spatial distribution of rock fragment cover. Vertical supply of rock fragments to the soil surface is caused by (1) tillage-induced kinetic sieving, bringing preferentially large rock fragments (>7.5 cm) to the surface, even in the case of continuous fine sediment deposition, (2) argillipedoturbation in Vertisol areas and (3) selective run-off erosion and the development of erosion pavements. With respect to the lateral displacement processes, one can distinguish between (1) lateral transport over the soil surface by trampling and concentrated overland flow, especially on steep slopes and (2) rockfall from the cliffs. The latter two processes are studied in detail in this chapter, based on observations in the northern Ethiopian highlands.

Gardner (1970), Lee et al. (1994), Govers and Poesen (1998) and Oostwoud Wijdenes et al. (2001) showed that the above two processes play a significant role in slope development of some mountain areas. Ayalew and Yamagishi (2004) also insisted on the importance of rockfall, concurrently with landsliding in shaping of the Blue Nile gorge. Therefore, it was expected that these processes partly explain the presence of rock-fragment-rich layers in Skeletic Regosols on debris slopes reported from the study area (Nyssen et al. 2008). Hence, in this chapter, based on an earlier publication (Nyssen et al. 2006), we will (1) introduce the nature of stepped topography present so widely in northern Ethiopia, (2) quantify the annual rock fragment transport rate caused by these processes in the northern Ethiopian highlands, (3) analyse the factors controlling rock fragment movement on scree slopes and (4) develop a conceptual model explaining R_C at the soil surfaces based on major controlling factors.

9.2 The *Amba* Landscape

9.2.1 Geomorphic Context

In Ethiopia, most of peneplained Palaeozoic and Mesozoic sedimentary rocks have been concealed by Tertiary basaltic flows (Mohr 1963; Merla et al. 1979; Coltorti et al. 2007). The dome-like uplift of the Arabo-Ethiopian region started during the Oligocene and had two periods of intense tectonic activity: in the Miocene, about 25 million years ago and in the Plio-Pleistocene (Williams and Williams 1980). The elevation above sea level of the base of the basalt—about 500 m in 25 million years in the southernmost areas of Ethiopia and up to 2,500 m in the north—shows the importance of this uplift. All the rivers are deeply incised (Adamson and Williams 1980), and various lithologies are exposed giving rise to a typical structural subhorizontal relief with tabular, stepped landforms.

Major geological formations outcropping in the region comprise Precambrian metamorphic rocks at the base, the only formations that are strongly folded and faulted and that were subsequently truncated by erosion. Next, the subhorizontal formations comprise the Palaeozoic Enticho sandstone (of fluvioglacial origin) and the Edaga Arbi tillites (Bussert and Schrank 2007). The Mesozoicum is represented by the lower transgressional Adigrat sandstone (particularly cliff-forming—Fig. 9.1), overlain by alternating hard and soft Antalo limestone layers, some 400 m thick, and by Amba Aradam sandstone (Hutchinson and Engels 1970) (Fig. 9.2). Two series of Tertiary lava flows, separated by silicified lacustrine deposits (Merla and Minucci 1938; Arkin et al. 1971; Merla et al. 1979) cap these Mesozoic sedimentary rocks. As a consequence of the vertical succession of numerous subhorizontal sedimentary rock formations as well as Tertiary sills and lava flows, a subhorizontal structural landscape of scarps and dips (Young 1987; Young and Wray 2000) has come into existence. This stepped topography, resulting from the variable hardness of the different geological formations, is locally described as *amba* landscape.

9.2.2 Study Area

For this study, the May Zegzeg catchment (Dogu'a Tembien district), a 199-ha subcatchment of Geba and Tekezze (Fig. 9.3), situated at 2,280–2,650 m a.s.l., was selected as a representative catchment for the northern Ethiopian highlands. The subhorizontal geological formations in the catchment comprise layers of the Mesozoic Antalo limestone and Amba Aradam sandstone in the lower parts, and Tertiary basalt flows (traps) with silicified interbedded lake deposits in the upper parts. Quaternary deposits, consisting of alluvium, colluvium and tufa, are also found. The study area comprises a typical red-black soil catena (Driesen and Dudal 1991) on basalt and Calcisols and Calcaric Regosols at the foot of the limestone cliff (Nyssen et al. 2008).

The main rainy season (>80 % of total rainfall) extends from June to September, but is preceded by 3 months of dispersed small rains. Average annual rainfall is 750 mm (Nyssen et al. 2005). Intense rains falling on bare soils, which have already lost most of their natural vegetation by century-long action of human society, cause severe soil erosion. Erosive rains and the predominance of steep slopes induce a natural vulnerability of the study area to soil erosion, despite overall low soil erodibility due to high clay contents and high rock fragment content. Daily air–temperature variations are large (range of more than 20 °C, with 5 and 28 °C as extreme range values) during the dry season, without, however, dropping below freezing point.

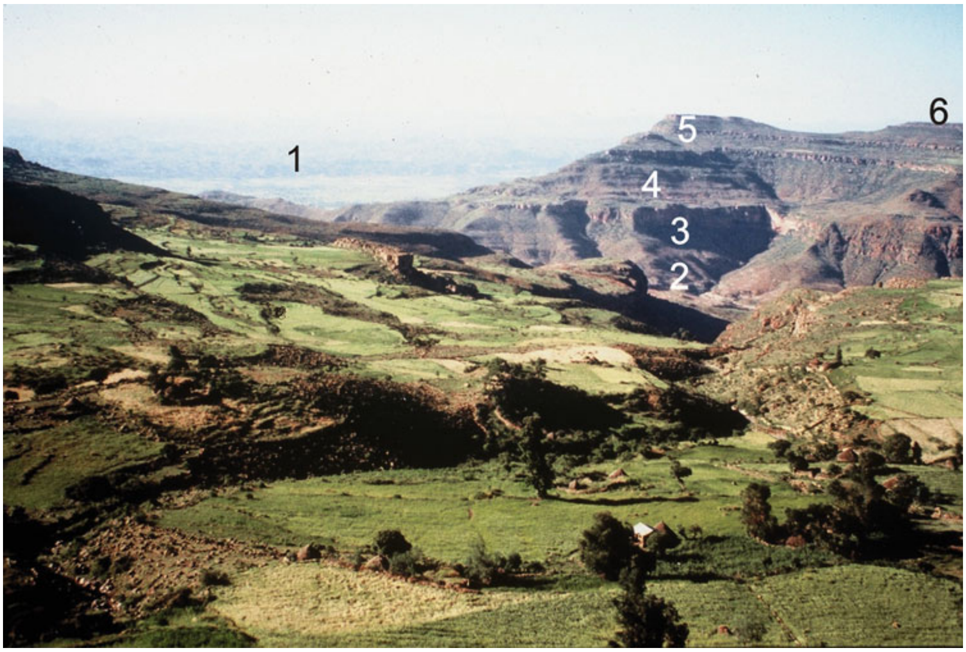

Fig. 9.1 The Tsaliet valley draining the Tembien highlands in Tigray towards the north, seen from Ba'ati Woyane (13.670704°N, 39.162169°E). At the lower position, in stratigraphical order, are the folded Precambrian rocks, visible at the far end, that result in an undulating topography (*1*). All subsequent subhorizontal formations are part of the *amba* landscape. From bottom to top in the opposite valley flank: Edaga Arbi tillites, a relatively soft rock that is easily eroded away (*2*); subvertical, high cliffs in Adigrat sandstone (*3*); alternating hard and soft rock layers of Antalo limestone (*4*); again a subvertical cliff of Amba Aradam sandstone (*5*); and finally the typical trap basalt (*6*) that caps the sedimentary transgression–regression series

After deforestation, which took place over the last 4000 years (Hurni 1985; Moeyersons et al. 2006b), topsoil and subsoil were removed in many places, predominantly by water and tillage erosion. In remnant forests of the study area, thick Phaeozems are found which are totally absent in nearby deforested areas in a comparable geomorphic context. Presently, there is an active policy to reforest steep slopes, which is, however, not expected to completely restore the original climax vegetation and soils (Descheemaeker et al. 2006).

Field observations indicate that two geomorphic processes occur on steep slope sections of the study area: (1) rock fall at the end of the rainy season, inferred from the presence of fresh sand- and limestone blocks, up to 3 m across, on debris slopes below cliffs; (2) rock fragment transport triggered by livestock trampling, inferred from the noise of rolling and falling rock fragments, when livestock, especially goats but also cattle and sheep, grazes on steep slopes.

9.3 Materials and Methods

9.3.1 Rockfall Monitoring

Rockfall was monitored along the 60-m-high and 1,500-m-long Amba Aradam sandstone and limestone cliff line (elevation: around 2,500 m a.s.l.), which forms an amphitheatre-shaped slope section in the middle of the study catchment, and the 30-m-high and 1,327-m-long basalt cliff line (elevation: around 2,600 m a.s.l.) in the upper part of the catchment (Fig. 9.3).

From 1998 to 2001, the slopes below both cliffs were inspected twice a year (at the end of the rainy season and in the middle of the dry season) in order to record rockfall events as indicated by (1) straight downslope scars of damaged vegetation along the path of the rockfall; (2) bright colour of freshly fallen and broken rocks; (3) up to 10 cm deep impacts of falling rocks in cropland soil; and (4) information provided by shepherds about the moment, conditions and magnitude of the event. For each major rockfall event (Fig. 9.4), the volume of the fallen rock fragments was measured with a metre stick and horizontal and vertical displacement distances with a theodolite. A weighed average displacement distance was calculated, taking into account the volumes of transported rock fragments (Fig. 9.5).

9.3.2 Livestock Trampling Monitoring

Medium-term monitoring of individual rock fragment movement along steep slope sections, especially by livestock trampling, was conducted on three slope sections

Fig. 9.2 A typical *amba* landscape reflects the presence of subhorizontal lithological structure and rapid incision. At Guyeha, near the study area, a prominent Amba Aradam sandstone cliff occurs (total height is ca. 40 m). People on the road for scale (*Photo* J Nyssen)

representative for the selected catchment and its surroundings (Table 9.1; Fig. 9.4). Sites 1 and 2 (Fig. 9.4) were situated in an intensely grazed rangeland. Site 3 was located in a 5-year-old exclosure, where no livestock is allowed to enter, but where people come once a year to cut grass, especially for roofing. This last site, like the rangelands, bears some rills generated by run-off, which overtops the upslope cliff.

Since painted rock fragments risked to be picked up by shepherds, limestone rock fragments were used as tracers in these basalt and sandstone environments. Their three main diameters were measured and the flatness index (*FI*; Cailleux 1945) was calculated as:

$$\mathrm{FI} = (d_1 + d_2)/(2d_3) \tag{9.1}$$

where

d_1 longest diameter;
d_3 shortest diameter, perpendicular to d_1;
d_2 intermediate diameter, perpendicular to d_1 and d_3.

Although the aim was to use tracers similar to the rock fragments naturally present on the slope, it should be noted that, at site 1, the basalt rock fragments were somewhat flatter compared to the tracers (Table 9.1). The tracers were installed in July 1999. At each site, a 20–50 m long line along the contour was materialised by a rope, following straight sections between large rocks, on which markings were painted. Rock fragments on the soil surface, or embedded for less than half their volume, which were crossed by this line, were removed and replaced by tracers of similar shape and size (1–4 tracers per m). In March 2001 (20 months later), the ropes were installed again (Fig. 9.6), tracers were recovered, and if they had moved from their original position, the shortest distance (which was along the steepest slope) to the rope was measured. In rangeland, recovery rates were relatively low (56–67 %). That is probably due to (1) recent rockfall deposits which in places visibly covered the original soil surface and (2) the shepherds might have picked up some of the tracers by curiosity,

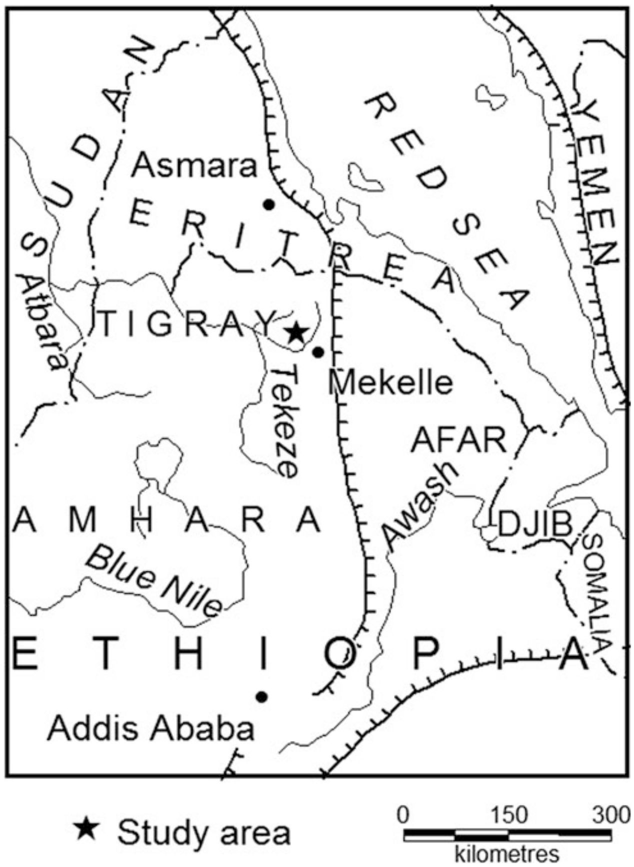

Fig. 9.3 Location of the May Zegzeg catchment in the northern Ethiopian highlands (after Nyssen et al. 2006)

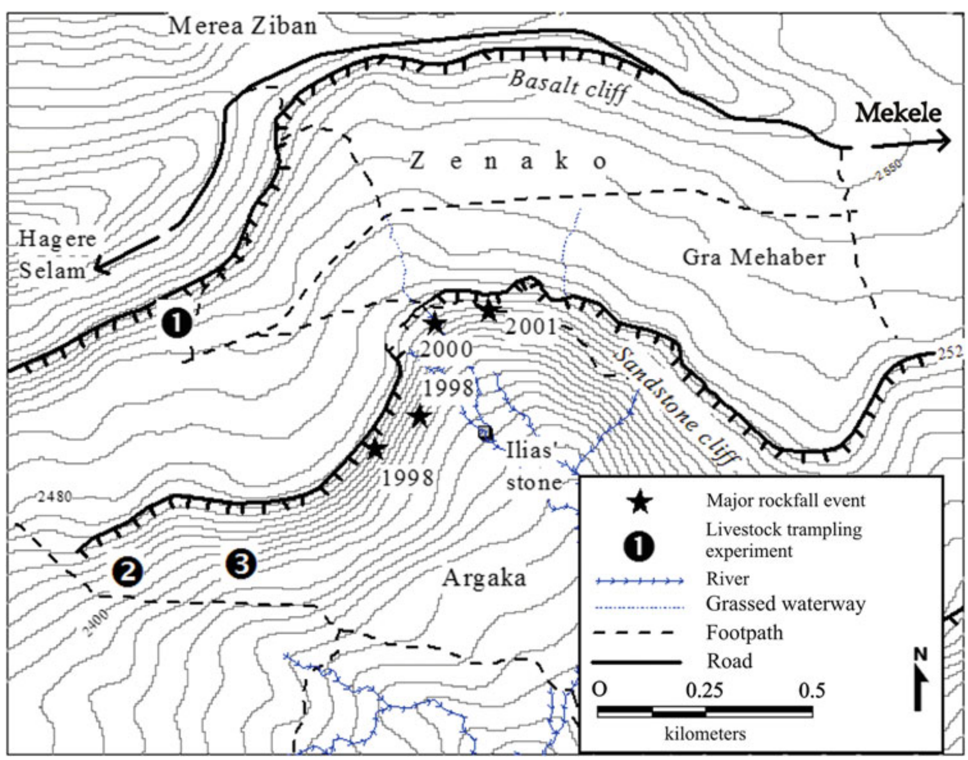

Fig. 9.4 Location map of major rockfall events (1998–2001) and of livestock trampling monitoring sites within the May Zegzeg catchment (after Nyssen et al. 2006)

Fig. 9.5 Three months after the occurrence of a rockfall event (August 1998) on the sandstone cliff. Fresh rock fragments (*arrows*) are easily recognisable by their bright colour. The *upper arrow* indicates the place of origin of these rocks on the cliff. Despite recovering vegetation, the rockfall path can still be recognised on the backslope (after Nyssen et al. 2006)

since their colour contrasted with that of the surrounding area.

At each site, the following environmental characteristics were measured or assessed: mean slope gradient, mean areal percentage of soil covered by short grass, long grass, shrubs or rock fragments, and that of the bare soil. The roughness index (*RI*; Oostwoud Wijdenes et al. 2000) was determined 4–8 times at each site, using a 200-cm long chain with 3 × 1.5 cm links, which was placed on the surface in a downslope direction following all irregularities of the soil surface, while the shortest distance between its beginning and end (D_s, in cm) was measured:

$$\mathrm{RI} = 200\ (\text{length of chain in cm}) - D_s \qquad (9.2)$$

Unfortunately, grazing intensity could not be measured at the experimental sites, and official data, organised per municipality, could not be used because (1) they were computed for large areas and (2) access to rangeland is also open to livestock from Hagere Selam town and other neighbouring villages. In a qualitative way, it can be stated that the much degraded rangeland near Harena Village (site 2) is most intensively grazed, especially by goats. Grazing pressure is somewhat less in the Zenako rangeland (site 1), which is used by cattle, sheep and goats. In the exclosure (site 3), there is no grazing.

9.3.3 Rainfall Analysis

Monthly and daily rainfall data of the nearby Hagere Selam station were analysed to assess the representativeness of the rain events triggering rockfall. Antecedent rain depth since the start of the rainy season in the years with observed rockfall was also compared to rain depths of a 20-year long series.

9.4 Results and Discussion

9.4.1 Yearly Rockfall

No major rockfall events were observed on the basalt cliff during the four years of observation. Here, rockfall seems to occur primarily in the form of toppling of parts of individual basalt columns.

Along the sandstone and limestone cliffs, four events were recorded, always in August, when the soils around and in between the rocks are saturated by water (Table 9.2). Some young shepherds from the area (Fig. 9.5) observed one

Table 9.1 Characteristics of the monitoring sites for livestock trampling and experimental conditions (after Nyssen et al. 2006)

Site	Lithology	Mean slope gradient (m m^{-1})	Rock fragments at surface			Tracers				
			Mean cover (%)	d_2	FI	d_2	FI	Installed	Recovered	Recovery rate (%)
1. Zenako rangeland	Basaltic coll	0.55	62	6.2	2.60	5.8	1.84	64	43	67
2. Harena rangeland	Sandstone coll	0.72	30	5.0	2.07	5.7	1.88	81	45	56
3. Harena exclosure	Sandstone coll	0.85	14	6.0	2.07	4.6	1.88	60	53	88

d_2 mean intermediate diameter (cm); *FI* flatness index. They are based on measurements of 30–40 randomly selected rock fragments/tracers

Fig. 9.6 Harena monitoring sites #2 and #3 for individual rock fragment movement (July 1999). *2* rangeland; *3* exclosure. Between both sites is a cropland on an ancient debris flow deposit (after Nyssen et al. 2006)

Table 9.2 Rockfall events at the sandstone and limestone cliffs (1998–2001) (after Nyssen et al. 2006)

Approx. date	Lithology	Total volume (m^3)	Rock density (kg m^{-3})	Total mass (10^3 kg)	Horizontal displacement (m)			Vertical displacement (m)		
					Min	Max	Weighted average	Min	Max	Weighted average
August 1998	Sandstone	10.49	2,400	25	4.0	150.9	80.8	1.1	77.9	46.9
August 1998	Limestone	13.36	2,535	34	9.2	35.3	14.0	8.5	24.0	11.6
August 2000	Sandstone	70.76	2,400	170	5.0	36.2	20.8	1.5	24.0	17.6
August 2001	Sandstone	37.77	2,400	91	14.0	66.5	32.5	11.2	33.1	20.2
Mean (1998–2001)		33.10		80			37.0			24.1

major rockfall event: *We saw one big rock rolling from the top of the cliff; it broke into pieces when rolling along the slope. Some large rocks reached the cropland and they broke into pieces at different sites. It was during daytime, in August 1998. It was raining. We were not very far with our cattle. The villagers came quickly when they heard the noise, because they were afraid for us. Fortunately nobody was hurt. Rockfall with big noise like this is exceptional.*

All rockfall events in 1998, 2000 and 2001 occurred at the peak of the rainy season. Unlike temperate mountain areas, where rockfall is strongly correlated with temperature variations (Perret et al. 2006), rainfall is the main triggering factor for rockfall in the study area. Rainfall analysis shows that the maximum daily rain depths in August during the study period correspond to 20-year average values of around 40 mm day^{-1}. Extreme daily rainfall events, such as those occurring in 1975 (67 mm) and 1980 (66 mm), were not observed during the study period.

Antecedent rain depth since the beginning of the rainy season and rain depth for August showed average conditions during three years, but in 1998, they had the second highest value in the 20-year series. Hence, it is anticipated that rockfall events reported here are representative for both average and extreme rainfall conditions of the region.

The mean yearly rockfall of 80 t, observed along a 1,500-m long section (parallel to the contour) of the Amba Aradam sandstone cliff over an average vertical distance of 24 m (Table 9.2), should be considered as a minimum, since we did neither account for many small events involving only a few rock fragments of some kg, nor for possible extreme rockfall events related to exceptionally high daily rain. An extrapolation of the observed rockfall rates to the 1,500-m-long and 60-m-high cliff indicates that the cliff would retreat by at least 0.37 mm year^{-1} or 3.7 cm century^{-1}. One of the few studies on sandstone cliff retreat in (sub)tropical regions (Young and Wray 2000) reported geological scarp retreat

Fig. 9.7 Tracers (*white limestone*) displaced over a distance of 6 m in 20 months (Harena rangeland, March 2001). The rope at the back shows the original tracer position (after Nyssen et al. 2006)

Table 9.3 Tracer displacement in 20 months, perpendicular to the contour (after Nyssen et al. 2006)

Site	Percentage of tracers moved	Displacement distance (m) of moved tracers		Mean displacement distance (m) of all tracers
		Mean[a]	Standard deviation	
1. Zenako range	72	1.74*	±2.37	1.25
2. Harena range	95	2.31*	±1.97	1.80
3. Harena exclosure	66	0.90#	±1.00	0.59

[a] Different symbols indicate significantly different values ($\alpha = 0.1$) based on unpaired Student's t-test

rates ranging between 1.5 and 2.5 cm century^{-1}. On the Colorado Plateau, scarp retreat rate averages 1.6 cm century^{-1} (Young 1985). These mean long-term values are lower though of a similar order of magnitude as our observed short-term cliff retreat rates.

9.4.2 Rock Fragment Movement over Debris Slopes

Twenty months after their placement, most tracers had left their original position (Fig. 9.7). In the two rangelands, 72 and 95 % of the tracers had moved, but it appeared that also in the exclosure, 66 % of the tracers received an impulse which was strong enough to initiate their movement (Table 9.3). Besides exceptional illegal livestock grazing, such impulses can also be caused by rock fragments falling and rolling from the cliff, by wild animals such as hare, jackal, hyena, caracal and porcupine (Yami et al. 2007), by run-off produced above the cliff, by forest guard and by people who come occasionally in the area, especially to harvest grass. Mean displacement distance of the transported tracers is, however, significantly smaller in the exclosure (0.9 m) than in the rangelands (1.74 and 2.31 m) (Table 9.3). In particular, the difference in tracer displacement distance between the rangeland and the exclosure on the Harena scree slope is highly significant ($\alpha = 0.001$). The percentage of tracers moved as well as the mean distances of tracer movement increase with increasing grazing pressure (Harena rangeland > Zenako rangeland > Harena exclosure).

Looking at other environmental characteristics of the three sites, further reasons for the differences in displacement distances become clear. If mean surface roughness is similar at the study sites (roughness index between 34 and 46), vegetation cover, and especially long grass cover, seems to be the primary explanatory factor for the observation that tracers moved over much smaller distances in the exclosure. Major explanatory factor for smaller tracer displacement distances in Zenako, compared to Harena, is the difference in area of smooth surface in the latter (53 %) as compared to the former (20 %).

A yearly unit rock fragment transport rate can be calculated, similar to the unit soil transport rate for contour ploughing (Poesen et al. 1997):

Table 9.4 Calculation of the yearly unit rock fragment transport rate (Qs) for the three monitored sites (t = 1.67 year) (after Nyssen et al. 2006)

Site	Mean displacement distance (m) along the slope of all tracers	Slope gradient (m m^{-1})	δ (m)	d_3 (m)	R_C (%)	ρ (kg m^{-3})	Qs (kg m^{-1} $year^{-1}$)
1. Zenako range	1.25	0.55	1.10	0.034	62	2734	37.9
2. Harena range	1.80	0.72	1.46	0.035	30	2511	23.1
3. Harena exclosure	0.59	0.85	0.45	0.035	14	2511	3.3

δ horizontal component of the net mean downslope displacement distance of all tracers (including those that did not move), in the direction of the steepest slope; d_3 shortest stone diameter perpendicular to the longest diameter; R_C rock fragment cover; ρ rock density

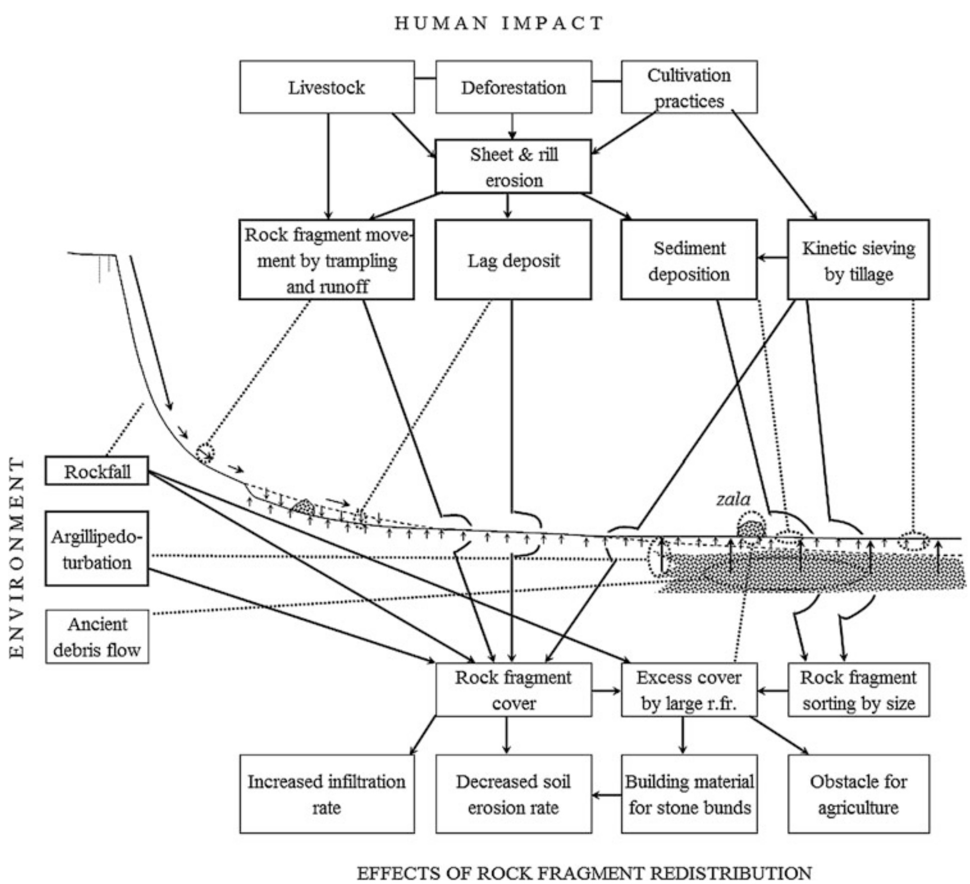

Fig. 9.8 Major factors in rock fragment redistribution, characterising the present day landscape and agricultural system. *Dotted lines* refer to rock fragment movements, schematically represented by *short arrows* on the figure, and *solid lines* indicate relations between factors and processes (*bold frames*) (after Nyssen et al. 2006)

$$Qs = \delta \cdot d_3 \cdot R_C \cdot \rho \cdot t^{-1} \quad (9.3)$$

where Qs = yearly unit rock fragment transport rate (kg m^{-1} $year^{-1}$); δ = horizontal component of the net mean downslope displacement distance of all tracers (including those that did not move), in the direction of the steepest slope (m); ρ = rock density (kg m^{-3}); and t = period over which tracer displacement was monitored (year).

The yearly unit rock fragment transport rate is larger in the Zenako rangeland (site 1) than in Harena (site 2) (Table 9.4), which is due to a high rock fragment content (R_C).

9.4.3 Cliffs and Scree Slopes as Part of Catenas

The current understanding of the detachment processes on cliffs and transport processes over scree slopes can now be integrated with results of previous studies to analyse rock fragment redistribution along catenas on stepped mountains in the northern Ethiopian highlands (Fig. 9.8).

The yearly unit rock fragment transport rate for cliffs (≥53 kg m^{-1} $year^{-1}$) is of the same order of magnitude as that for rangeland (38 and 23 kg m^{-1} $year^{-1}$), but significantly larger than the transport rate measured in an exclosure (3 kg m^{-1} $year^{-1}$). Corresponding rock fragment transport coefficients (K) for rangeland (32–69 kg m^{-1} $year^{-1}$) are much larger than K for densely vegetated exclosures (3.9 kg m^{-1} $year^{-1}$). This indicates that rocks fallen from cliffs into rangeland are transported downslope mainly by livestock trampling. By contrast, rockfall into exclosures is largely stored at the upper part of the escarpment face. Rock fragments found in remnant forests on steep slopes are also generally located at the foot of the cliffs. These forests act as "protection forests" against rockfall, similar to those found in the Alps (Stoffel et al. 2005).

Downslope from cliffs and scree slopes, the overall R_C at the soil surface on the catena developed on basalt is large (55–85 %) everywhere and is not related to slope gradient but to the location of mass movement bodies, as indicated by Nyssen et al. (2002c). In the limestone area, R_C is larger on the steeper areas close to the cliff. Due to the combination of kinetic sieving as a consequence of tillage (Oostwoud et al. 1997) and slow deposition of fine earth at the lower side of the catenas, mean rock fragment size significantly increases with decreasing slope gradient (Nyssen et al. 2002b).

The vertical processes supplying rock fragments to the soil surface include (1) tillage-induced kinetic sieving, (2) selective run-off erosion and the development of erosion pavements and (3) vertic movements (argillipedoturbation; Poesen and Lavee 1994; Nyssen et al. 2002a; Moeyersons et al. 2006a).

Surface covers of large rock fragments sometimes hinder agriculture, and therefore, farmers remove and concentrate these on stone heaps (*zala*). However, dense rock fragment covers bring also some advantage to agriculture. They increase infiltration rates, decrease evaporation and protect topsoil against water erosion (Poesen and Lavee 1994). Indeed, Nyssen et al. (2001) reported a significant negative relationship between R_C and soil loss in the study area. A recommendation resulting from this study is to rely on the following farmers' wisdom: smaller rock fragments should never be removed from the field surface, but a limited number of larger rock fragments can be removed in order to increase crop yield.

9.5 Conclusions

Rockfall from cliffs and rock fragment transport on debris slopes under rangeland, mainly by livestock trampling, appear to be important geomorphic processes in the northern Ethiopian highlands. Along a 1,500 m long section (parallel to the contour) of the Amba Aradam sandstone cliff, at least 80 t of rock are detached and fall annually over a mean vertical distance of 24 m, resulting in a mean annual cliff retreat rate of 0.37 mm $year^{-1}$. The hard rock of the Amba Aradam sandstone formation and especially its ferruginous cap provide structural control on the geomorphological evolution. Our observed sandstone cliff retreat rates are of the same order of magnitude as long-term sandstone cliff retreat rates reported from other (sub)tropical regions, indicating that the anthropogenic impact on the process of rock fragment detachment from cliffs is minimal.

Yearly unit rock fragment transport rates (Qs), mainly induced by animal trampling, were 37.9 kg m^{-1} $year^{-1}$ in rangeland on basalt (slope gradient S = 0.55 m m^{-1}) and 23.1 kg m^{-1} $year^{-1}$ in rangeland on sandstone colluvium (S = 0.72 m m^{-1}). Similar to sheet and rill erosion and gullying (Descheemaeker et al. 2006), this process is also virtually stopped after exclosures are established with Qs equalling only 3.9 kg m^{-1} $year^{-1}$ on a 0.85 m m^{-1} slope. The importance of rock fragment movement on debris slopes is positively correlated with grazing pressure and the areal percentage of smooth surface, and inversely with the percentage of long grass cover.

Rock fragment redistribution on the lower part of the catena is controlled by the occurrence of ancient debris flow bodies as well as current processes such as kinetic sieving by tillage, argillipedoturbation, development of erosion pavements by water erosion, and manual removal by farmers. Besides rockfall from cliffs and argillipedoturbation, all the discussed factors and processes of rockfall redistribution in the study area are of anthropogenic origin (Fig. 9.8).

Acknowledgments This study was conducted in the framework of research programme G006598.N funded by the Fund for Scientific Research—Flanders, Belgium and of the Zala-Daget project (VLIR-UOS, Belgium). JN was affiliated with KU Leuven while the research was carried out. Thanks go to Berhanu Gebremedhin Abay for assistance with all the fieldwork. Local farmers and shepherds shared their knowledge with us. The local Agricultural Office, REST (Relief Society of Tigray) branch, and the authorities of the concerned villages and district facilitated the research. Conceptual discussions with Andrew Goudie, Robert Wray and David Alexander are gratefully acknowledged.

References

Adamson D, Williams F (1980) Structural geology, tectonics and the control of drainage in the Nile basin. In: Williams M, Faure H (eds) The Sahara and the Nile. Quaternary environments and prehistoric occupation in northern Africa, Balkema, Rotterdam, pp 225–252

Arkin Y, Beyth M, Dow DB, Levitte D, Temesgen Haile TH (1971) Geological map of mekele sheet area ND 37-11, Tigre Province, 1:250.000, Imperial Ethiopian Government, Ministry of Mines, Geological Survey, Addis Ababa

Ayalew L, Yamagishi H (2004) Slope failures in the Blue Nile basin, as seen from landscape evolution perspective. Geomorphology 57:95–116

Bussert R, Schrank E (2007) Palynological evidences for a latest carboniferous-early permian glaciation in Northern Ethiopia. J Afr Earth Sci 49:201–210

Cailleux A (1945) Distinction des galets marins et fluviatiles. Bulletin de la Société géologique de France 15:375–404

Coltorti M, Dramis F, Ollier CD (2007) Planation surfaces in Northern Ethiopia. Geomorphology 89:287–296

Descheemaeker K, Nyssen J, Rossi J, Poesen J, Haile M, Moeyersons J, Deckers J (2006) Sediment deposition and pedogenesis in exclosures in the Tigray highlands, Ethiopia. Geoderma 132:291–314

Driesen P, Dudal R (1991) The major soils of the world. Wageningen Agricultural University and KU Leuven, The Netherlands

Gardner J (1970) Rockfall: a geomorphic process in high mountain terrain. Albertan Geogr 6:15–20

Govers G, Poesen J (1998) Field experiments on the transport of rock fragments by animal trampling on scree slopes. Geomorphology 23:193–203

Hurni H (1985) Erosion—productivity—conservation systems in Ethiopia. In: Proceedings of 4th international conference on soil conservation, Maracay, Venezuela, pp 654–674, 3–9 Nov 1985

Hutchinson RW, Engels GG (1970) Tectonic significance of regional geology and evaporite lithofacies in northeastern Ethiopia. Phil Trans Roy Soc Lond A Math Phys Sci 267:313–330

Lee FT, Odum JK, Lee JD (1994) Rockfalls and debris avalanches in the Smugglers Notch area, Vermont. US Geol Surv Bull 2075:1–33

Merla G, Minucci E (1938) Missione geologica nel Tigrai. Volume primo: la serie dei terreni. Reale Accademia d'Italia, Centro Studi per l'AOI, Roma

Merla G, Abbate E, Azzaroli A, Bruni P, Canuti P, Fazzuoli M, Sagri M, Tacconi P (1979) A geological map of Ethiopia and Somalia (1973) 1:2.000.000 and comment. University of Florence, Italy

Moeyersons J, Nyssen J, Poesen J, Deckers J, Haile M (2006a) On the origin of rock fragment mulches on Vertisols: a case study from the Ethiopian Highlands. Geomorphology 76(3–4):411–429

Moeyersons J, Nyssen J, Poesen J, Deckers J, Haile M, Lang A (2006b) New insights in timing and steering of environmental changes in Northern Ethiopia since Late-Pleistocene times: a view from the Highlands. Palaeogeogr Palaeoclimatol Palaeoecol 230:165–181

Mohr P (1963) The geology of Ethiopia. University College of Addis Ababa Press, 270 p

Nyssen J, Moeyersons J, Deckers J, Haile M, Poesen J (2000) Vertic movements and the developments of stone covers and gullies, Tigray highlands, Ethiopia. Zeitschrift für Geomorphologie NF 44:145–164

Nyssen J, Haile M, Poesen J, Deckers J, Moeyersons J (2001) Removal of rock fragments and its effect on soil loss and crop yield Tigray Ethiopia. Soil Use Manag 171:179–187

Nyssen J, Moeyersons J, Poesen J, Haile M, Deckers J (2002a) Argillipedo-turbation and the development of rock fragment covers on vertisols in the Ethiopian highlands. Belgeo 2:183–193

Nyssen J, Poesen J, Moeyersons J, Lavrysen E, Haile M, Deckers J (2002b) Spatial distribution of rock fragments in cultivated soils in Northern Ethiopia as affected by lateral and vertical displacement processes. Geomorphology 43:1–16

Nyssen J, Moeyersons J, Poesen J, Deckers J, Haile M (2002c) The environmental significance of the remobilisation of ancient mass movements in the Atbara-Tekeze headwaters, Northern Ethiopia. Geomorphology 49:303–322

Nyssen J, Vandenreyken H, Poesen J, Moeyersons J, Deckers J, Haile M, Salles C, Govers G (2005) Rainfall erosivity and variability in the Northern Ethiopian highlands. J Hydrol 311:172–187

Nyssen J, Poesen J, Moeyersons J, Deckers J, Haile M (2006) Processes and rates of rock fragment displacement on cliffs and scree slopes in an amba landscape, Ethiopia. Geomorphology 81:265–275

Nyssen J, Naudts J, De Geyndt K, Haile M, Poesen J, Moeyersons J, Deckers J (2008) Soils and land use in the Tigray highlands (Northern Ethiopia). Land Degrad Dev 19:257–274

Oostwoud Wijdenes D, Poesen J, Vandekerckhove L, De Luna E (1997) Chiselling effects on the vertical distribution of rock fragments in the tilled layer of a Mediterranean soil. Soil Tillage Res 44:55–66

Oostwoud Wijdenes D, Poesen J, Vandekerckhove L, Kosmas C (2000) The use of marked rock fragments as tracers to assess rock fragments transported by sheep trampling on Lesvos, Greece. In: Foster I (ed) Tracers in geomorphology. Wiley, Chichester, pp 201–220

Oostwoud Wijdenes D, Poesen J, Vandekerckhove L, Kosmas C (2001) Measurements at one-year interval of rock-fragment fluxes by sheep trampling on degraded rocky slopes in the Mediterranean. Zeitschrift für Geomorphologie NF 45:477–500

Perret S, Stoffel M, Kienholz H (2006) Spatial and temporal rockfall activity in a forest stand in the Swiss Prealps—A dendrogeomorphological case study. Geomorphology 74:219–231

Poesen J, Lavee H (1994) Rock fragments in top soils: significance and processes. Catena 23:1–28

Poesen J, Van Wesemael B, Govers G, Martinez-Fernandez J, Desmet P, Vandaele K, Quine T, Degraer G (1997) Patterns of rock fragment cover generated by tillage erosion. Geomorphology 18:183–197

Stoffel M, Schneuwly D, Bollschweiler M, Lièvre I, Delaloye R, Myint M, Monbaron M (2005) Analyzing rockfall activity (1600–2002) in a protection forest—a case study using dendrogeomorphology. Geomorphology 68:224–241

Williams M, Williams F (1980) Evolution of the Nile basin. In: Williams M, Faure H (eds) The Sahara and the Nile. Quaternary environments and prehistoric occupation in Northern Africa, Balkema, Rotterdam, pp 207–224

Yami M, Gebrehiwot K, Moe S, Mekuria W (2007) Impact of area enclosures on density and diversity of large wild mammals: the case of May Ba'ati, Douga Tembien Woreda, Central Tigray, Ethiopia. East Afr J Sci 1:1–14

Young RA (1985) Geomorphic evolution of the Colorado plateau margin in west-central Arizona: a tectonic model to distinguish between the causes of rapid symmetrical scarp retreat and scarp dissection. In: Hack JT, Morisawa M (eds) Tectonic geomorphology. Allen & Unwin, London, pp 261–278

Young RW (1987) Sandstone landforms of the tropical East Kimberley region, Northwestern Australia. J Geol 95:205–218

Young RW, Wray R (2000) Contribution to the theory of scarpland development from observations in Central Queensland, Australia. J Geol 108:705–719