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 epigenetically 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
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 Erticho sandstone (of fluvioglacial origin) and the Edaga Arbi tillites (Bussert and Schrank 2007). The Mesozoicum is represented by the lower transgressive 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 scarp 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 Calcirosols 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. Eroductive 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.
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 weighted 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.
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:

$$FI = \frac{(d_1 + d_2)}{2d_3}$$  \hspace{1cm} (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)
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 \( 3 \times 1.5 \) 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:

\[
RI = 200 \left( \frac{\text{length of chain in cm}}{D_s} \right) \tag{9.2}
\]

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

![Fig. 9.5](image.png)

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)

### Table 9.1

<table>
<thead>
<tr>
<th>Site</th>
<th>Lithology</th>
<th>Mean slope gradient (m m(^{-1}))</th>
<th>Rock fragments at surface</th>
<th>Tracers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean cover (%)</td>
<td>(d_2)</td>
<td>FI</td>
</tr>
<tr>
<td>1. Zenako rangeland</td>
<td>Basaltic coll</td>
<td>0.55</td>
<td>62</td>
<td>6.2</td>
</tr>
<tr>
<td>2. Harena rangeland</td>
<td>Sandstone coll</td>
<td>0.72</td>
<td>30</td>
<td>5.0</td>
</tr>
<tr>
<td>3. Harena exclosure</td>
<td>Sandstone coll</td>
<td>0.85</td>
<td>14</td>
<td>6.0</td>
</tr>
</tbody>
</table>

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

---

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

<table>
<thead>
<tr>
<th>Approx. date</th>
<th>Lithology</th>
<th>Total volume (m$^3$)</th>
<th>Rock density (kg m$^{-3}$)</th>
<th>Total mass (10$^3$ kg)</th>
<th>Horizontal displacement (m)</th>
<th>Vertical displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>August 1998</td>
<td>Sandstone</td>
<td>10.49</td>
<td>2,400</td>
<td>25</td>
<td>4.0</td>
<td>150.9</td>
</tr>
<tr>
<td>August 1998</td>
<td>Limestone</td>
<td>13.36</td>
<td>2,535</td>
<td>34</td>
<td>9.2</td>
<td>35.3</td>
</tr>
<tr>
<td>August 2000</td>
<td>Sandstone</td>
<td>70.76</td>
<td>2,400</td>
<td>170</td>
<td>5.0</td>
<td>36.2</td>
</tr>
<tr>
<td>August 2001</td>
<td>Sandstone</td>
<td>37.77</td>
<td>2,400</td>
<td>91</td>
<td>14.0</td>
<td>66.5</td>
</tr>
<tr>
<td>Mean (1998–2001)</td>
<td>Sandstone</td>
<td>33.10</td>
<td>2,400</td>
<td>80</td>
<td>37.0</td>
<td>24.1</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Site</th>
<th>Percentage of tracers moved</th>
<th>Displacement distance (m) of moved tracers</th>
<th>Mean displacement distance (m) of all tracers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Zenako range</td>
<td>72</td>
<td>1.74(\pm)2.37</td>
<td>1.25</td>
</tr>
<tr>
<td>2. Harena range</td>
<td>95</td>
<td>2.31(\pm)1.97</td>
<td>1.80</td>
</tr>
<tr>
<td>3. Harena exclosure</td>
<td>66</td>
<td>0.90#(\pm)1.00</td>
<td>0.59</td>
</tr>
</tbody>
</table>

* Different symbols indicate significantly different values (\(\alpha = 0.1\)) based on unpaired Student’s t-test.
\[ Q_s = \delta \cdot d_3 \cdot R_C \cdot \rho \cdot t^{-1} \]  
(9.3)

where \( Q_s \) = yearly unit rock fragment transport rate (kg m\(^{-1}\) year\(^{-1}\)); \( \delta \) = 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; \( \rho \) = rock density.

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 \((R_C)\).
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 ($Q_s$), 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 $Q_s$ 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).

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