

31. Rockfall shapes the *amba* landscape

(largely based on Nyssen et al., 2006)

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Distinct rock fragment displacements occur on the *ambas*, or structurally determined stepped mountains of the Northern Ethiopian Highlands. Here we discuss the rock fragment detachment from cliffs by rockfall, quantify its annual rates, and identify factors controlling rock fragment displacement distances on the scree slopes.

The rockfall that can be seen on the escarpment near Wukro occurred in 2006. Characteristics and triggering factors of this particular landslide have never been studied. The general setting is one where the upper part of the escarpment is relatively resistant sandstone, and the lower part consists of soft tillites, that are easily eroded (Fig. 1).

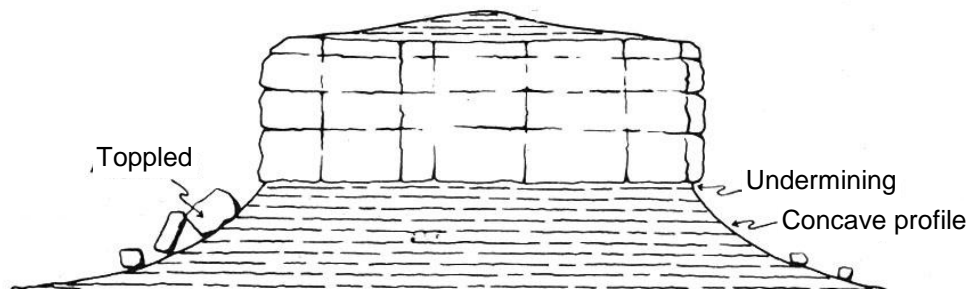


Fig. 1. The resistant rock is undermined and topples. This results in a vertical retreating cliff (After Pannekoek & Van Straalen, 1992).

In case of cliffs without particularly soft underlying material (which is the most common case in Ethiopia), the cliffs become less high when retreating (Fig. 2).

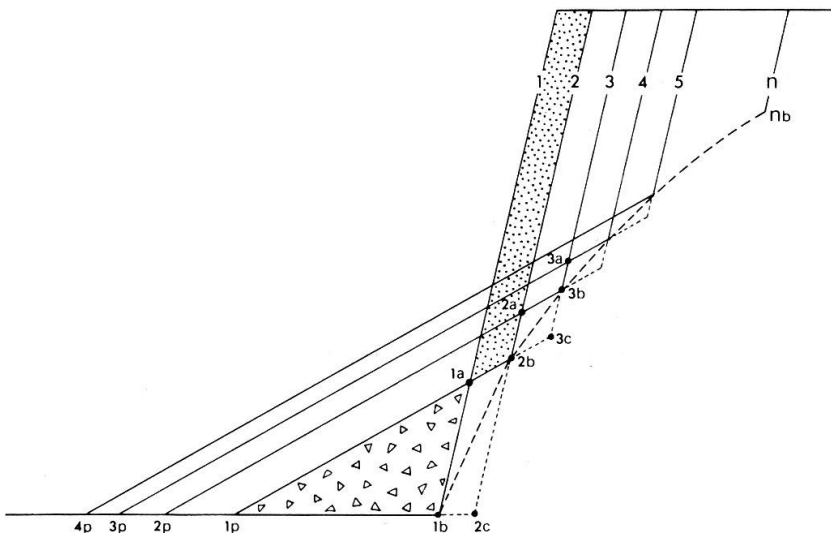


Fig. 2. Cliff retreat in a homogeneous rock formation, without removal of debris by fluvial processes. The debris deposit 1a-1b-1p is formed with cliff retreat from 1 to 2 (After Lehmann, 1933).

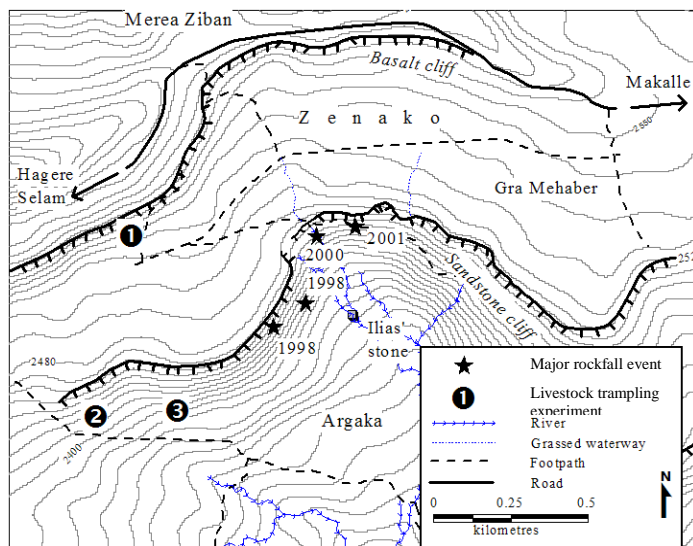


Fig. 3. Location map of major rockfall events (1998 – 2001) and of livestock trampling monitoring sites within the May Zeg-zeg catchment.

In the May Zeg-zeg catchment (Fig. 3), rockfall from cliffs and rock fragment movement on debris slopes by runoff 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 (Fig. 4, Table 1) over a mean vertical distance of 24 m resulting in a mean annual horizontal cliff retreat rate of 0.37 mm y^{-1} . One of the few studies on sandstone cliff retreat in (sub)tropical regions (Young and Wray, 2000) reported geological scarp retreat rates ranging between 0.15 and 0.25 mm y^{-1} . On the Colorado Plateau, scarp retreat rate averages 0.16 mm y^{-1} (Young, 1985). These mean long-term values are of a similar order of magnitude as our observed short-term cliff retreat rates.



Fig. 4. Photo taken three months after the occurrence of a rockfall event (August 1998) on the sandstone cliff in May Zeg-zeg catchment. Fresh rock fragments (black arrows at the bottom) are easily recognisable by their bright colour. The upper white arrow indicates the origin of these rock fragments at the cliff. Despite vegetation growth, the rockfall path can still be recognised on the backslope.

Table 1. Rockfall events at the 1500 m long sandstone and limestone cliff (1998-2001).

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	2400	25	4.0	150.9	80.8	1.1	77.9	46.9
August 1998	Limestone	13.36	2535	34	9.2	35.3	14.0	8.5	24.0	11.6
August 2000	Sandstone	70.76	2400	170	5.0	36.2	20.8	1.5	24.0	17.6
August 2001	Sandstone	37.77	2400	91	14.0	66.5	32.5	11.2	33.1	20.2
Mean (1998-2001)		33.10		80			37.0			24.1

Yearly unit rock fragment transport rates on scree slopes ranged between 23.1 and 37.9 kg m⁻¹ y⁻¹ (Fig. 5, Table 2). This process is virtually stopped when exclosures are established (Table 3).



Fig. 5. Tracers (white limestone) displaced over a distance of 6 m in 20 months (Harena rangeland, March 2001). The horizontal rope at the back witnesses original tracer position.

Table 2. Tracer displacement in 20 months, perpendicular to the contour

Site	% 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 t-student test.

Table 3. Explanatory factors of mean rock fragment movement distance (over 20 months) for the three experimental sites

	Displacement distance (m) of moved tracers	RI	R_C (%)	d_2 (m)	Shrub cover (%)	Long grass cover (%)	Vegetation cover (%)	Smooth surface (%)
1 Zenako range	1.74	46.3	62.4	0.062	21.0	0.0	41.1	20.2
2 Harena range	2.31	29.7	29.7	0.05	21.1	1.3	31.6	53.4
3 Harena closed	0.90	33.8	13.5	0.06	21.7	42.6	65.1	17.9

RI: Roughness index (Eq. 2); R_C : Rock fragment cover; d_2 : Intermediate rock fragment diameter

Corresponding mean rock fragment transport coefficients (K) are $32 - 69 \text{ kg m}^{-1} \text{ y}^{-1}$ on rangeland but only $3.9 \text{ kg m}^{-1} \text{ y}^{-1}$ in densely vegetated exclosures. A conceptual model (Fig. 6) indicates that besides rockfall from cliffs and argillipedoturbation, all factors and processes of rock fragment redistribution in the study area are of anthropogenic origin.

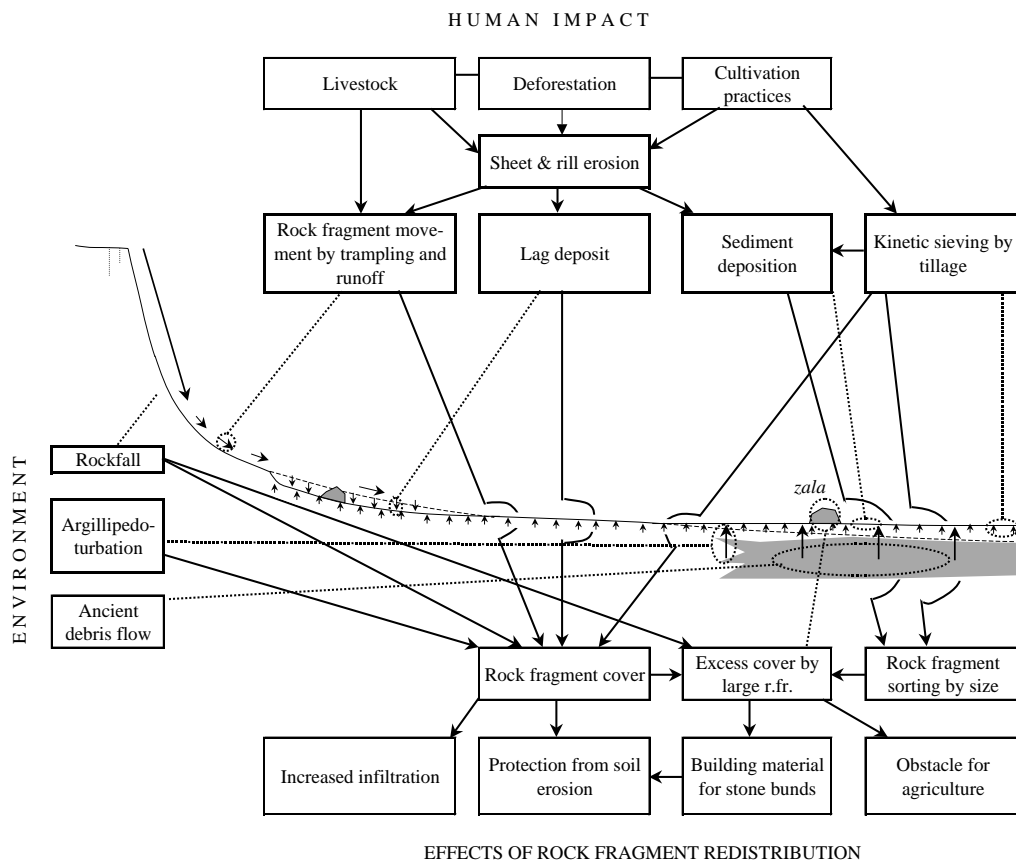


Fig. 6. Major factors in rock fragment redistributions, characterising the present day landscape and agricultural system. Dotted lines refer to rock fragment movements, schematically represented by short arrows in the figure and solid lines indicate relations between factors and processes (bold frames).

References

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