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Spatial distribution of rock fragments in cultivated soils in northern Ethiopia as affected by lateral and vertical displacement processes

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Abstract

Although, in semi-arid environments, rock fragments at the soil surface and within the topsoil play an important role in desertification control, little is known about their spatial distribution. Therefore, this study analyses spatial patterns of rock fragment cover along catenas, and the vertical variations in volumetric rock fragment content in soil profiles in the highlands of Tigray, northern Ethiopia. Natural and anthropogenic processes inducing these patterns are assessed. Volumetric rock fragment content (R_V) was analysed in 10 soil pits. All rock fragments were extracted, and their volumes determined by pedo-stratigraphic unit, size and lithology. The rock fragment cover (R_C) was determined by the point-count method using vertical photographs of the soil surface. The following processes contribute to the vertical variability of R_V: (1) in Vertisols, upsqueezing as a consequence of swell-shrink cycles (argillipedoturbation) is responsible for high R_C at the soil surface; (2) large rock fragments (> 7.5 cm) are rapidly brought to the soil surface by kinetic sieving through tillage, even in the case of continuous fine sediment deposition, what may result in a rock fragment rich subsoil, underlying a thick soil layer (up to 80 cm) without large rock fragments and a topsoil with a high R_C at the surface; (3) Skeletic Regosols at the foot of cliffs show no systematic vertical rock fragment distributions. As to rock fragment cover along the catena, some fundamental differences appear between the basalt and limestone substrate. On the basalt catena with slope gradients between 0.06 and 0.42 m m^{-1}, R_C is high everywhere (57–85%) and is unrelated to slope gradient. Vertical processes such as kinetic sieving through ploughing and argillipedoturbation determine the rock fragment distribution at the soil surface. In limestone areas, argillipedoturbation is less active and R_C is positively correlated with slope gradient ($R^2 = 0.74$; $n = 6$; $P < 0.05$), when only the rock fragments (0.5–2.0 cm across) are considered. Including the larger (>2 cm) and more kinetic sieving sensitive rock fragments lowers R^2 to 0.46 ($n = 6$; n.s.). Preconditions for the present spatial distribution of rock fragments at the soil surface in the study area are the occurrence of two geomorphic processes in the past: (1) mudflows depositing diamictons including much coarse debris and (2) intense water erosion, which occurred after deforestation and exposed rock fragments at or near to the soil surface. Generally, the

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balance between lateral and vertical movements of rock fragments now controls the spatial distribution of R_C. With respect to the lateral displacement processes: (1) lateral transport over the soil surface by trampling, tillage and concentrated runoff, especially on steep slopes, and (2) rockfall from the cliffs. Vertical supply of rock fragments to the soil surface is caused by (1) selective runoff erosion and the development of erosion pavements, (2) tillage induced kinetic sieving, bringing preferentially large rock fragments (>7.5 cm) to the soil surface, and (3) argillipedoturbation in Vertisol areas.

Keywords: Argillipedoturbation; Desertification; Ethiopia; Kinetic sieving; Pedoturbation; Rock fragment content; Rock fragment cover; Rock fragment distribution

1. Introduction

The northern Ethiopian Highlands (Fig. 1) are currently threatened by desertification and anthropogenic erosion processes (Virgo and Munro, 1978; Oldeman et al., 1991; Hurni and Perich, 1992; Nyssen, 1995). Rock fragment cover and content largely control hydrology, soil erosion and soil productivity in arid, semi-arid and sub-humid regions (Poesen and Lavee, 1994). In this paper, 'rock fragments' refers to all mineral particles >5 mm in diameter. Especially on arable land, rock fragment

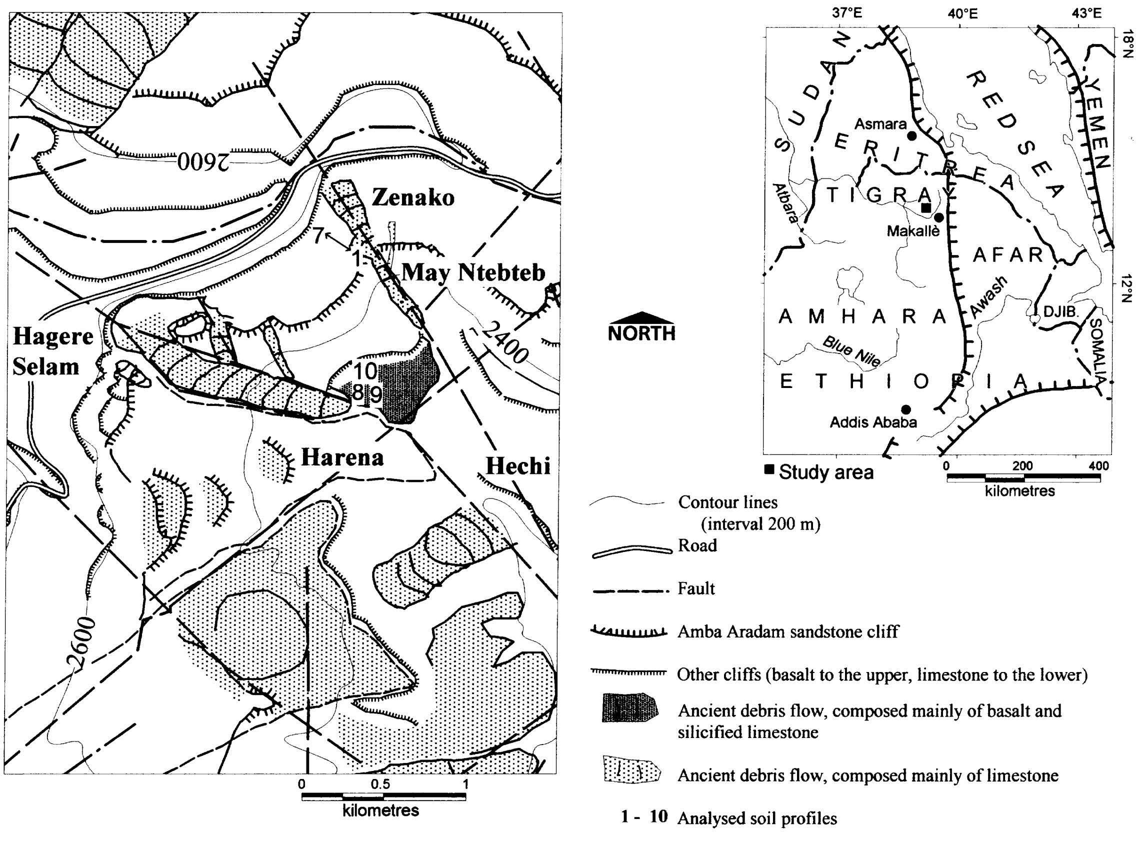

Fig. 1. Geomorphological map of the study area (Tembien Highlands in Northern Ethiopia), with indication of the position of the soil profile pits.

cover forms an efficient protection against rill and interrill erosion (Wischmeier and Smith, 1978; Römkens, 1985), which is due mainly to (1) reduction of soil erodibility by protection against raindrop impact and flow detachment; (2) reduction of physical soil degradation (surface sealing) and (3) retardation of runoff velocity, thus reducing detachment and transport capacity of the overland flow (Poesen et al., 1994). Although dense rock fragment covers are an important feature in the fields of the Ethiopian Highlands, they have not received due attention in soil erosion research. In his version of the Universal Soil Loss Equation, adapted to Ethiopian conditions, Hurni (1985) takes rock fragment cover into account. However, he does not mention the evidence used to estimate the reduction of soil loss due to rock fragment cover. With regard to rain infiltration into cultivated topsoils, Poesen and Lavee (1994) indicated that rock fragments generally increase the infiltration rate by protecting the soil from raindrop impact, thus reducing surface sealing and crusting. In the study area, we observed water storage during rain showers in cavities under rock fragments. Effects of rock fragment cover and content on productivity are usually positive in dry climatic conditions (Poesen and Lavee, 1994). In the semi-arid areas of Ethiopia, moisture conservation techniques induce substantial increases in crop yield (Mitiku and Fassil, 1996). Rock fragment cover is thus a semi-natural factor that can partially control desertification. Hence, the importance of recognising patterns in rock fragment distribution (and the related processes) when assessing the risk of desertification in such areas.

A rock fragment cover (R_C) at the soil surface develops by both natural and anthropogenic (tillage, rock fragment removal) processes. To find out which of these processes play an important role in controlling rock fragment cover and content, the vertical pattern of volumetric rock fragment content (R_V) was studied in soil profiles. Large concentrations of rock fragments at the soil surface, as often encountered in the study area, can be lag deposits or can be transported laterally over the soil surface and/or result from upward movement of rock fragments in the soil. Some processes inducing vertical displacements of rock fragments in the soil profile (Poesen and Lavee, 1994) can be excluded in the Ethiopian Highlands: floralpedoturbation (tree uprooting), cryoturbation, aeroturbation (wind erosion only occurs on unmetalled roads, paths and market areas), crystallopedoturbation and seismipedoturbation. Earthworms are rare, termites absent and burrowing mammals, if present, are mostly active outside the cultivated fields. Faunalpedoturbation is thus limited to trampling by cattle. When grazing the stubble, cattle, sheep and goats reinforce gravipedoturbation and are also thought to push small rock fragments from the soil surface to a maximum depth of 5 cm by their hoofs. The effect of the latter will be obliterated by kinetic sieving due to tillage (anthropopedoturbation). This process results in a vertical distribution where (especially the larger) rock fragments are concentrated at the top of the plough layer, the lower part of that horizon being impoverished in rock fragments (Oostwoud et al., 1997; Poesen et al., 1997). A theoretical vertical rock fragment distribution as a consequence of tillage sorting is presented in Fig. 2a.

Argillipedoturbation is observed mainly in the case of Vertisols, where alternating swell-shrink action of smectites results in an upward movement of coarser fragments. This process has been observed during one year in the study area and is relatively fast (3.2 rock fragments m^{-2} $year^{-1}$), provided the lower part of the vertic horizon (FAO et al., 1998) reaches down to a stone-rich layer. The vertical rock fragment distribution will be different between chimneys, diapir-like structures where the upsqueezing of soil material takes place (Dudal and Eswaran, 1988; Wilding et al., 1990), and areas between chimneys. In chimneys, the R_V is high. It is expected that the content of larger rock fragments is higher at its top (Fig. 2c) where it is narrowest. The concentration of smaller rock fragments will remain stable or decrease, since more small rock fragments can fall down through the wide cracks near to the soil surface and because the swell and shrink action is most efficient for large rock fragments (Yaalon and Kalmar, 1978). In between the chimneys, the vertic horizon will have a relatively low R_V, since the vertic movements will have expelled most rock fragments. Below the vertic horizon, R_V will be larger (Fig. 2d). The same holds for the topsoil, since the rock fragments which reach the soil surface through chimneys will eventually be spread over the field by tillage, cattle trampling and water erosion.

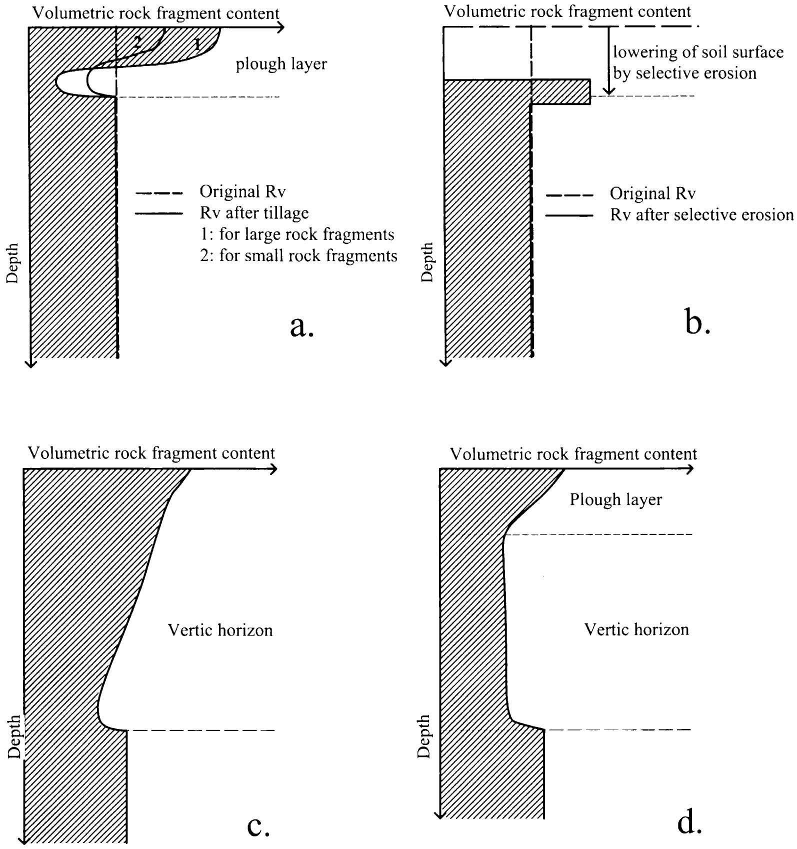

Fig. 2. Theoretical vertical rock fragment distribution as expected to be induced by different processes acting in a soil with an initial homogenous rock fragment distribution: (a) kinetic sieving due to tillage; (b) selective water erosion leading to the development of an erosion pavement; (c) in Vertisols, in chimneys, for larger rock fragments; (d) in Vertisols, in between cracks.

Erosion pavements are lag deposits after erosion of fine earth (Poesen and Lavee, 1994). In profile (Fig. 2b), an erosion pavement will have a higher R_V than the underlying soil.

Preferential downslope transport of rock fragments, generated by different processes such as rockfall, transport by concentrated flow (rills and gullies) (Poesen, 1987, 1990; Parsons et al., 1991), trampling by cattle (Govers and Poesen, 1998; Oostwoud et al., 2000) or tillage (Poesen et al., 1997) may result in a rock-fragment-rich layer on top of the profile.

It is expected that spatial patterns in rock fragment distribution in the Northern Ethiopian Highlands are not random, but are rather determined by an interaction of geomorphic and pedologic processes. This study analyses these patterns, both vertically in the soil profile and laterally along catenas, and defines their causal factors and processes. The study will also assess the relative importance of lateral and vertical processes controlling R_C in the fields at different positions along two representative catenas of the northern Ethiopian Highlands.

2. Materials and methods

2.1. The study area

For this study, the Zenak’o–Argak’a catchment (Dogua Tembien district), situated at 2280–2650 m

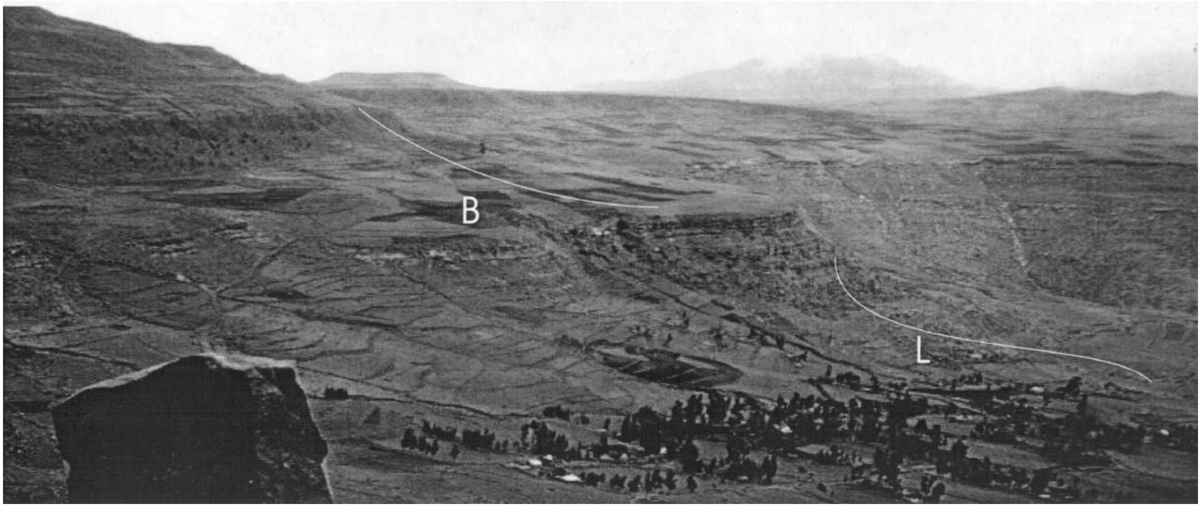

Fig. 3. View on the study area, looking eastwards from Hagere Selam. B=typical catena on basalt, L=typical catena on limestone.

a.s.l. (Figs. 1 and 3) was selected as a representative catchment for the northern Ethiopian highlands. The subhorizontal geological formations outcropping in the region (Fig. 4) comprise layers of Antalo limestone and Amba Aradam sandstone (both of Mesozoic age) in the lower parts, and Tertiary basalt flows (trapps) with silicified interbedded lake deposits in the upper parts (Merla and Minucci, 1938; Arkin et al., 1971; Merla et al., 1979). One also finds Quaternary deposits, consisting of alluvium, colluvium and tufa. 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.

The heavy rainy season (>80% of total rainfall) extends from June to September, but is preceded by three months of dispersed small rains. Average annual rainfall is 750 mm on the upper basalt catena and 100 mm less on the footslopes of the limestone cliff (own measurements, 1998–2000). Intense rains

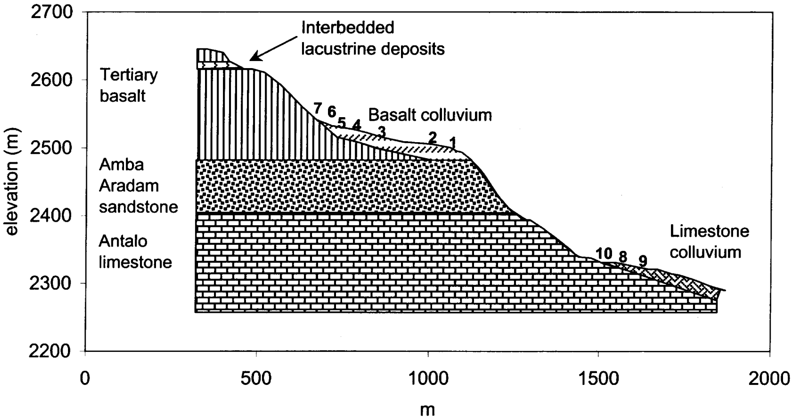

Fig. 4. Geology and location of soil profile pits (1–10).

falling on bare soils, having 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 induces a natural vulnerability of the study area to soil erosion, despite an overall low soil erodibility, due to high clay contents and high R_C. Temperature variations are high during the dry season, without however dropping below freezing point.

After deforestation, which took place over the last 2500 years (Hurni, 1985), in many places topsoil and subsoil were removed, predominantly by water and tillage erosion. In a remnant forest in the study area, a Phaeozem has 165 cm thick A, Bw and Bt horizons, all of which are totally absent in nearby deforested areas in a comparable landscape context. Similar results have been reported elsewhere in Ethiopia (Belay, 2000). Presently, there is an active policy to reforest steep slopes, which is however not expected to completely restore the original climax vegetation and soils.

The agricultural system in the Northern Ethiopian Highlands has been characterised as 'grain–plough complex' (Westphal, 1975). The main crops are barley (*Hordeum vulgare* L.), wheat (*Triticum* sp.) and tef (*Eragrostis tef*), an endemic cereal crop. Various species of pulses also take an important part in the crop rotation. After harvesting, stubble grazing is general. As a consequence, the landscape is a typical openfield. Tillage is carried out with the ox-drawn ard plough (*mahrasha* in Tigrinya, *maresha* in Amharic). Average depth of plough furrows by this implement ranges between 10.1 and 15.3 cm (Goe, 1999; Gete, 1999), whereas average depth of the reworked soil during one tillage operation is 6.8–8.1 cm (HTS, 1976; Fleur, 1987; Nyssen et al., 2000a).

Evidence of the high R_C in the fields are the numerous heaps of large rock fragments (named *zala* in the local Tigrinya language), removed from fields by the farmers. Semi-structured interviews indicate that the farmers are often reluctant to take away the smaller rock fragments (i.e. <5 cm intermediate diameter) from their fields, since they believe they have positive impacts on soil moisture conservation and topsoil protection from erosion. An on-farm experiment carried out in a field on a Vertic Cambisol (FAO et al., 1998) in the studied catchment (Nyssen et al., 2001) indicates that there is a significant negative relationship between R_C and soil loss by sheet and rill erosion.

2.2. Measurement of rock fragment content

The stoniness of a soil can be determined by different methods (Poesen and Lavee, 1994). A distinction must be made between rock fragments covering the soil surface and rock fragment content of the soil by mass or by volume. Visual estimation of R_V is only efficient for larger rock fragments (>76 mm) (Poesen and Lavee, 1994).

In July–August 1999, seven representative sites were selected on the upper red–black soil catena and three in the lower limestone area (Fig. 3). All sites were under cropland. At each site, a trench was dug in order to describe and analyse the soil profile, especially with regard to texture, structure, rock fragment content and dry soil colour. Based on the profile description, the constraints of the encountered soils (aggregate and rock fragment size) and the necessity to use a pick axe for digging, the thickness of the pedo-stratigraphic units to analyse for R_V (called soil layers) was then determined. Soil layers were $\geq$10 cm thick. A pit (0.5 m $\times$1 m) was dug out layer by layer over a depth of >1 m. Before digging, all rock fragments (>0.5 cm) lying on the soil surface, or with <50% of its volume embedded in the topsoil, were collected. Soil dug out from each layer was spread over a canvas and all rock fragments (>0.5 cm) were extracted manually. Rock fragments were washed and sorted by size and lithology. During this washing operation, each particle was tested: if it could be easily broken by hand, it was not considered as a rock fragment. Consequently, soft and shale-like silicified limestone may have been insufficiently accounted for. Lithology was determined by eye; hence, it was impossible to differentiate lime- and sandstone, since acid test on tens of thousands of rock fragments was impractical. For the rock fragment size, the intermediate diameter (the longest diameter measured perpendicularly to the greatest length) was considered. The lower size limit of rock fragments was set at 0.5 cm, since smaller rock fragments have the same physical behaviour as sand (Poesen et al., 1997). Other size class limits were set at 7.5 and 25 cm (FAO, 1977). An additional size class boundary (2 cm) was introduced.

Rock fragments were either air-dry weighed, or their volume determined by submerging moist rock fragments and reading the volume of water displacement. Conversion between mass and volume was done using rock density. Average density of rock fragments was measured in the study area for basalt (2734 kg m^{-3}) and silicified limestone (1763 kg m^{-3}). Rock fragments were dried, weighed, moistened and then the volume determined by submersion. Density of sandstone (2400 kg m^{-3}) and limestone (2535 kg m^{-3}) were obtained from data compiled by Poesen and Lavee (1994).

The method used is expected to give precise measurements of volumetric rock fragment content (R_V), but it is very labour-intensive. In total, 2568 kg of rock fragments were dug out and measured. In addition, volumes of rock fragments removed from the field and piled up in stone bunds and *zala* were estimated. Volume of rock fragments removed per m^2 was also estimated for each site, as well as the median size (D_{50}) of their intermediate diameter.

2.3. Measurement of rock fragment cover

Vertical photographs of the soil surface (1–1.2 m^2) were taken from a height of ~3.5 m in February 1999 (dry season). Six photos were taken at 15 representative places along the two catenas. A grid was superimposed on the projected image and at each node, the presence or absence of a rock fragment was noted, as well as its size class (Poesen et al., 1997). Nodes covered by stubble, weeds or straw were not taken into account. This allowed calculation of R_C. It is expected that this method slightly underestimates cover by the smallest rock fragments (<2 cm). All measurements of R_C and R_V were done on cultivated land, which is the predominant landuse in the study area.

2.4. Graphical representation and statistical analysis

For each profile, R_V is represented by a graph, the *y*-axis showing the depth and thickness of the analysed soil layers and the *x*-axis showing the percentage of volumetric rock fragment content (R_V). The rock fragments lying on the soil surface are also represented on the graph. The thickness of this 'layer' is represented approximately by the median (D_{50}) of the intermediate diameter of these rock fragments, since it was observed in the study area that, unlike in desert environments where 70% of the surface rock fragments rest with their longest axis parallel to the surface (Cooke, 1970), in tilled fields, the position of rock fragments in relation to the soil surface is random. On these graphs (Fig. 5), the volume of rock fragments removed from the soil surface (D_{50}=16.2 cm), as well as additional observations, are represented. Graphs by lithology and size class were made for each profile for the purpose of analysis (Lavrysen, 2000). Some of these profiles

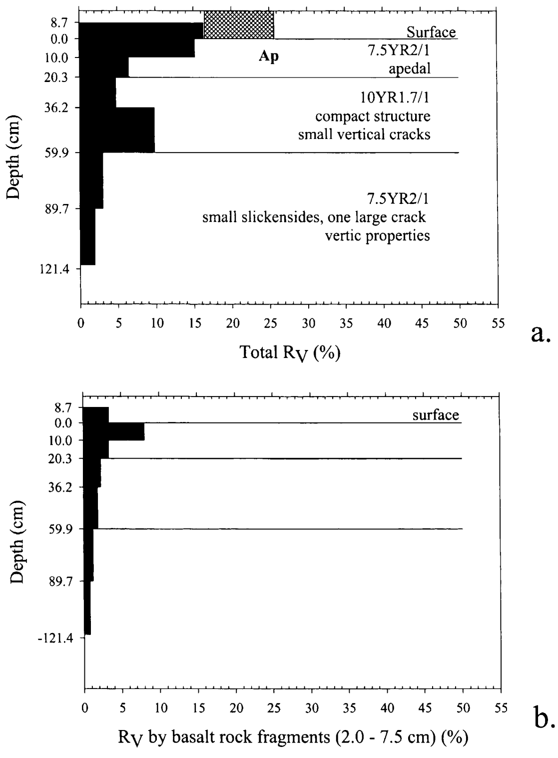

Fig. 5. Volumetric rock fragment content (R_V) for each analysed soil layer in Profile 1. (a) Distribution of total R_V. (b) Distribution of basalt rock fragments (2–7.5 cm). (The *y*-axis shows the depth and thickness of the analysed soil layers. Rock fragments resting on top of the soil surface are represented as a 'layer', of which the thickness is the median size (D_{50}) of the intermediate diameter of these rock fragments. The estimated volume of rock fragments removed from the surface and used in stone heaps (*zala*) and stone bunds is indicated by a grey rectangle, of which the thickness is the D_{50} of their intermediate diameter.)

will be discussed below. The degree of association between variables (R_C, R_V, slope gradient, D_{50}) was measured by linear and logarithmic regression and calculation of Pearson correlation coefficients. Probability levels (P) for these coefficients were obtained by F-tests (Beguin, 1979).

3. Results

3.1. Vertical patterns of rock fragment content

Profile 1 was dug at the footslope of the catena on basalt (Fig. 4) in a heavy clay soil: a 20.3-cm thick, black apedal plough layer (51.9% clay) covers at least 146 cm black heavy clay (56–58% clay) (Fig. 5a). Below a 60-cm depth, the structure of the black clay is characterised by slickensides, small and large cracks and wedge shaped aggregates. Some 6.9% of the total volume consist of rock fragments, of which 92% are basalt and 8% silicified limestone. R_V increases steadily from the bottom of the profile to the soil surface, showing a maximum at the surface and in the upper part of the plough layer. High R_V of the soil layer [36.2–59.9 cm] is only due to the presence of one rock fragment with an intermediate diameter of 25 cm. Fig. 5b (rock fragments 2.0–7.5 cm) shows the same distribution and confirms that the high R_V [36.2–59.9] in Fig. 5a is an outlier. Relatively few small rock fragments are present and these show a zone that is poor in rock fragments [20.3–59.9 cm]. The same tendency is present for silicified limestone of the same size class. In the tillage horizon, there is a clear pattern of increase in rock fragments towards the soil surface. This pattern is present for both lithologies and for all rock fragment size classes.

Profile 2 (Fig. 6a), dug in a chimney of a Vertisol, is located near Profile 1. This profile bears a black horizon [19.8–115 cm] with some vertic properties: heavy clay (51–57% clay) and strongly expressed macrostructure. The chimney is rich in rock fragments: >20% R_V, which gradually increases with depth. Basalt (96% of the rock fragments) and silicified limestone (4%) lithologies show the same tendencies. Rock fragment classes (0.5–2.0 and 2.0–7.5 cm) follow the same trend of decreasing R_V towards the soil surface, whereas rock fragments (7.5–25 cm) show a maximum around 68.4 cm. The surface and the upper part of the tillage horizon are again richer in rock fragments. Clay content of the upper horizon is also lower (43.4%).

Profile 4 was dug in a slightly sloping (0.06 m m^{-1}) field, located behind an elongated stone heap (*zala*), which, according to the farmer triggers sedimentation in the field. The clayey colluvium, down to 70.1 cm (Fig. 6b) has a very uniform structure, few rock fragments and no rock fragments >7.5 cm at all. The underlying black clay is characterised by its high R_V, especially by large rock fragments. The different origin of the two layers is furthermore proven by the presence of some silicified limestone above 70.1 cm and its total absence below this limit. Surprisingly, the tillage horizon, whose matrix can only be differentiated from the layer [12.7–70.1 cm] by the absence of structure, and the soil surface have a high R_V and contain each about 6% rock fragments (>7.5 cm).

Profile 7, in a field near the basalt cliff with a slope gradient of 0.41 m m^{-1}, has, except for the tillage horizon, a very uniform loamy matrix. The silicified limestone also adopts the vertical pattern of the generally high R_V (Fig. 6c), although it constitutes only 2% of all rock fragments. The high R_V of the lower unit [122.1–136.6 cm] is almost totally due to large basalt rock fragments (7.5–25 cm), whereas these are absent from the unit just above [105–122.1 cm].

The next three soil profiles (8, 9 and 10) are situated at lower altitude, below the sand- and limestone cliff (Fig. 4). Profile 8 was dug in a 0.1 m m^{-1} field, down from the foot of the debris slope of this cliff. Below the tillage horizon, there is a loamy dark brown upper horizon down to 37.1 cm (Fig. 6d). At this depth, there is a clear increase in clay content and presence of weathering limestone fragments. R_V is highest (18%) below 110.9 cm. Throughout the profile, basalt rock fragments are present (0.06% of total R_V). This proves the sedimentary origin of the soil. Rock fragment distribution shows a decreasing R_V from the top of the profile down to 110.9 cm, where there is a sudden increase. Remarkably, rock fragments 7.5–25 cm are absent between 11.4 and 61.4 cm.

Located in a marginal 30 m m^{-1} fallowed field near the limestone cliff, Profile 10 is dug in weath-

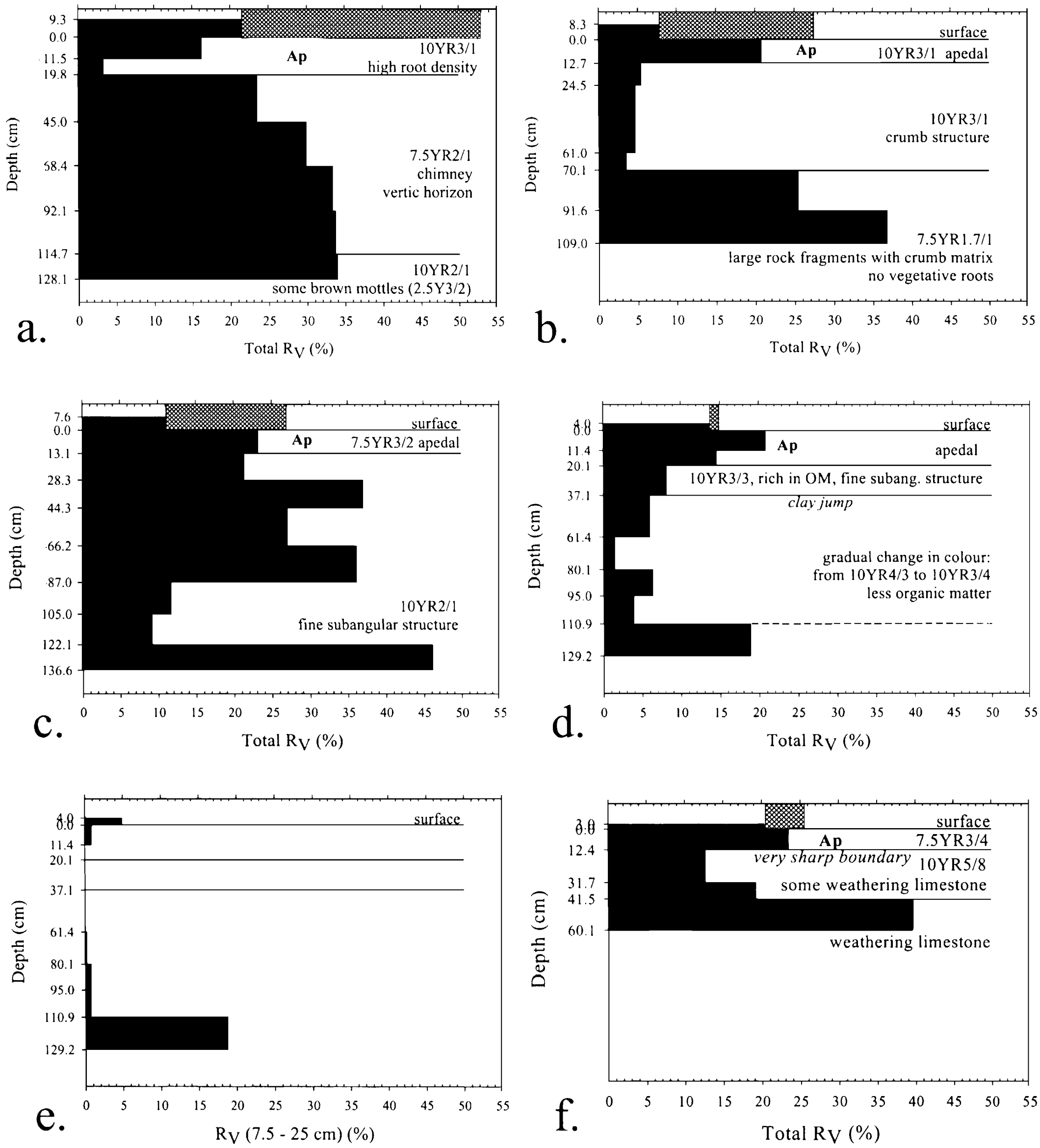

Fig. 6. Volumetric rock fragment content (R_V) distribution in selected soil profiles. See Fig. 5 for legend. (a) Profile 2: note the high R_V in this 'chimney'. (b) Profile 4: a soil layer with few rock fragments is superposed on a layer with many (large) rock fragments. (c) Profile 7 results from continuous input of colluvium (rock fragments and fine earth) from the nearby cliff. (d) Profile 8 results from a combination of continuous accumulation of colluvium and kinetic sieving. (e) Profile 8: note the hiatus of large rock fragments (7.5–25 cm). (f) Profile 10: weathering limestone in situ (sapprolite) is covered by recent colluvium.

ering bedrock, overburdened by 12.4 cm of colluvium, originating from a collapsing lynchet upslope (*daget*—Nyssen et al., 2000c), in which some small basalt rock fragments are present. Below 12.4 cm, there is a sharp decline in R_V, which increases again with depth: 40% R_V [41.5–60.1 cm] (Fig. 6f). Here, only limestone sapprolite is present. All size classes follow the same trend.

3.2. Lateral patterns of rock fragment cover

R_C at the 15 sites is presented in Fig. 7. On the basalt catena, mean R_C ranges between 57% (±3%) and 85% (±11%), of which 18–45% are large rock fragments (7.5–25 cm). Rock fragments >25 cm are virtually absent; they have probably been removed by the farmers (Nyssen et al., 2001). Mean R_C along the limestone catena is lower (and presents a greater variability): between 29% (±18%) at the footslope and 52% (±21%) near the basalt cliff. Furthermore, along this catena fields with steep slope gradients are generally occupied by rangeland; hence, the range of slope gradients is narrow (between 0.02 and 0.15 m m^{-1}).

It should be stressed that it appeared impossible to compare R_C measured at the soil surface by point count method with R_C measured in the soil profile. Many rock fragments in the plough layer partially outcrop at the surface and are included in R_C when using the point-count method. When digging out the profile layer by layer, these rock fragments will be included in the upper part of the plough layer and not counted as rock fragments on the soil surface.

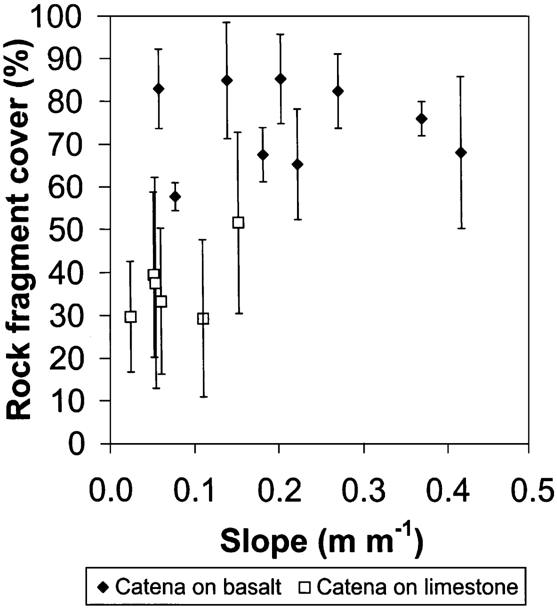

Fig. 7. Slope gradient vs. rock fragment cover at the soil surface for 15 sites. At each site, R_C was measured at six representative areas.

4. Discussion

4.1. Processes explaining the vertical rock fragment distribution in the studied profiles

The main human impact explaining the present-day high R_C in the Ethiopian Highlands is deforestation. In a remnant climax forest in the study area, on steep slopes (40–60 m m^{-1}), hardly any rock fragments can be found in the topsoil. Weathering bedrock is covered by a 165-m thick Phaeozem, without rock fragments in its upper 54 cm. From this observation, it can be inferred that most processes explaining the present spatial rock fragment distribution only started after deforestation.

The soils in Profiles 1 and 2 are Vertisols, given the high clay content (51.5–57.7% throughout the profile) and the presence of vertic properties (which are only partially visible during the rainy season). The Vertisols are covered by 20 cm of soil deposited behind soil conservation structures. This sediment is less clayey and covers (in Profile 2) the top of the chimney (see sudden change in R_V at 19.8 cm—Fig. 6a). The R_V in the chimney decreases slightly with decreasing depth, which is explained by the fact that towards the soil surface the chimney becomes narrower than the excavated trench. Rock fragment distribution by size class in the chimney corresponds to the theoretical pattern: R_V by small rock fragments 0.5–2.0 cm decreases from bottom (6.8%) to top (1.1%), whereas large rock fragments reach a maximum near the surface. In contrast to Profile 2, Profile 1 is situated in between chimneys and presents a quite different pattern. Upsqueezing as a consequence of swell-shrink cycles (argillipedoturbation) in the Vertisol of Profile 1 is responsible for the high R_V of the plough layer and the high R_C (Fig. 5a). Rock fragments 0.5–2.0 cm are under-represented in the upper soil layers. Since this is the case for both lithologies (basalt and silicified limestone), a selective rock moving process can be expected: i.e. small rock fragments fall back more easily through cracks.

In addition to these processes in Vertisols, kinetic sieving due to tillage is superposed. This process was active during the deposition of fine colluvium on top of the Vertisol. During the gradual deposition of fine earth behind the stone bunds, large rock fragments

(7.5–25 cm) that were on top of the Vertisol were continuously brought to the upper part of the tillage layer by the plough. Due to ploughing, small rock fragments (<7.5 cm) are regularly brought back from the soil surface to the tillage horizon, which explains their lower density at the surface.

The upper part of Profile 4 (Fig. 6b) is a 70.1 cm thick Cumulic Regosol, accumulated behind an elongated *zala*. It is composed of recent colluvium, which can be distinguished from the underlying soil layers by clear change in lithological composition, in R_V and in rock fragment size. Below this sediment, we find coarse basalt rock fragments, forming the top of an ancient debris flow. Most remarkably however, R_V is very low in-between the top of this formation of coarse basalt debris and the plough layer. This profile is strongly influenced by the *zala* at the lower side of the plot. At the beginning of its construction, the soil surface was some 70 cm lower, but gradual deposition of fine sediment led to a nearly horizontal field. During this accumulation, tillage continued. Due to kinetic sieving, the rock fragments from the top of the debris flow where brought up gradually. In combination with (slow but constant) sediment deposition, provoked by the presence of the *zala*, this leads to a high R_V in the plough layer. The largest rock fragments (>7.5 cm) are all involved in this process; they are totally absent in the layers [24.5–61 cm]. The smaller the rock fragment size, the more rock fragments remain in these intermediate soil layers. The process of kinetic sieving is less efficient for small size classes (Oostwoud et al., 1997).

Profile 7, at 50 m from the cliff, has a random distribution of rock fragments (Fig. 6c) which have been transported from the cliff by rockfall and different processes operating at the soil surface: tillage, trampling and transport by concentrated flow. Pedogenesis is not evident in this Regosol, which is continuously rejuvenated by material from the nearby basalt cliff. On these steep slopes, a concomitant preferential removal of fine earth and the development of an erosion pavement are certainly active.

The three soil profiles in the lower catena are all in Calcaric Regosols. The soil of Profile 8 developed on colluvium. The effect of kinetic sieving is visible in the plough horizon (Fig. 6d). At the lower side of the field, there is a 2-m high lynchet (*daget*) which has grown over years and which caused a continuous deposition of colluvium in the field. By the above-mentioned combination of slow sediment deposition and kinetic sieving, the larger rock fragments (>7.5 cm) have been continuously brought to the soil surface (Fig. 6e). The high R_V at a depth between [110.9–129.2 cm] can only be explained by the deposition history in this area.

Profile 10 (Fig. 6f) is a truncated profile of weathering limestone in situ, covered by colluvium (Regosol). The boundary is very sharp. In the sapprolite, R_V increases with depth. Only the R_V of the 12.4-cm thick colluvium is the result of geomorphic activity: the collapse (by tillage and water erosion) of a *daget* situated 5 m upslope.

4.2. Importance of vertical processes in the development of patterns of rock fragments at the soil surface

Several authors (Simanton et al., 1994; Poesen et al., 1997) reported a positive, logarithmic relationship between slope gradient and R_C, especially on non cultivated soils in semi-arid environments. Due to differences in lithology (Fig. 7), the two studied catenas have to be analysed separately. The slope gradients of the observed sites on the basalt catena range between 0.06 and 0.42 m m^{-1}. R_C is however high everywhere and cannot be explained by slope gradient (Fig. 8). On tilled fields, the expected relationship is not valid (Poesen et al., 1997), since tillage erosion and kinetic sieving strongly control R_C. Moreover, argillipedoturbation will often result in high rock fragment covers on toeslopes, even in the absence of tillage (Nyssen et al., 2000b). On this catena, the vertical processes determine the rock fragment distribution at the soil surface. Formerly existing patterns might be completely obliterated.

On the limestone catena, where the observed sites have slope gradients from 0.02 to 0.15 m m^{-1}, a positive relationship between R_C and slope gradient exists. The fields in this area do not occupy steep slopes, and the range of the slopes of the analysed sites is relatively narrow. However, slope gradient explains part of the R_C pattern in this area ($R^2 = 0.46$; $n = 6$; n.s.), especially since argillipedoturbation is not active in the flat areas of this toposequence.

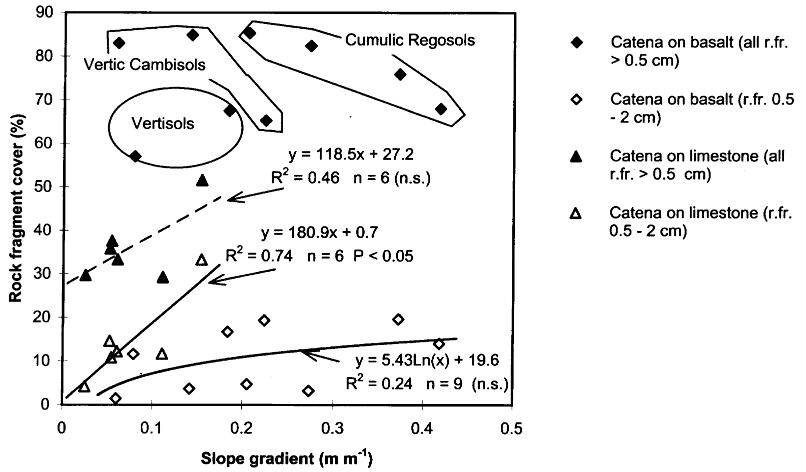

Fig. 8. Slope gradient vs. rock fragment cover, by lithology (average based on six measurements per site). Correlations are improved if only rock fragments <2 cm are taken into account.

If only small rock fragments (0.5–2.0 cm) are taken into account, the correlation between slope gradient and R_C is improved: from $R^2 = 0.002$ to $R^2 = 0.24$ ($n = 9$; n.s.) on the basalt catena, and from $R^2 = 0.46$ to $R^2 = 0.74$ ($n = 6$; $P < 0.05$) in the limestone area (Fig. 8). For this size class, there is less disturbance by kinetic sieving of the natural rock fragment distribution at the soil surface and therefore a positive relationship between slope gradient and R_C is found. Simanton et al. (1994) and Poesen et al. (1997) explain this by the formation of erosion pavements on steep slopes and deposition of fine material on the flatter areas. Probably the distance to the source area (the cliff) also plays a role in our study area. This relation also has as a consequence that the highest rates of soil erosion by water are not necessarily on the steeper slopes of this toposequence on limestone: high R_C will decrease soil erodibility in these fields, as shown by experiments in many countries in the world and also in the study area (Nyssen et al., 2001).

The strong correlation between topsoil R_V and volume of rock fragments at the soil surface furthermore stresses the importance of the vertical processes and especially kinetic sieving. Correlation coefficients are $R^2 = 0.78$ ($n = 7$; $P < 0.01$) when the upper 5 cm are taken into account, 0.86 for the upper 10 cm and 0.89 for the upper 25 cm. For these correlations, two outliers were not taken into account: the two Vertisol profiles which show abnormally high rock fragment covers but, which stress also the importance of the vertical processes.

Quantitative studies show a linear increase of average surface rock fragment size with slope gradient in dry environments (Parsons and Abrahams, 1987; Poesen et al., 1998). Since the correlation between slope gradient and rock fragment size depends strongly on lithology (and thus size and shape of the rock fragments as well as characteristics of the fine earth), the two studied toposequences were again considered separately. The median size (D_{50}) of the intermediate diameter of the surface rock fragments was plotted against slope gradient by site (average of six measurements) (Fig. 9). The obtained relationships are the opposite of those found by the above quoted authors. In our study area, this inverse relation between slope gradient and D_{50} is explained by the combination of (1) the existence, at the lower reaches of the slopes, of important debris flow deposits (i.e. a diamicton including many large rock fragments), (2) vertical processes, especially kinetic sieving by tillage and argillipedoturbation, and (3) the relation between slope gradient and erosion/deposition: on steeper slopes, more fine earth is eroded and a mixture of large and small rock fragments remains. On the footslopes, there is sediment

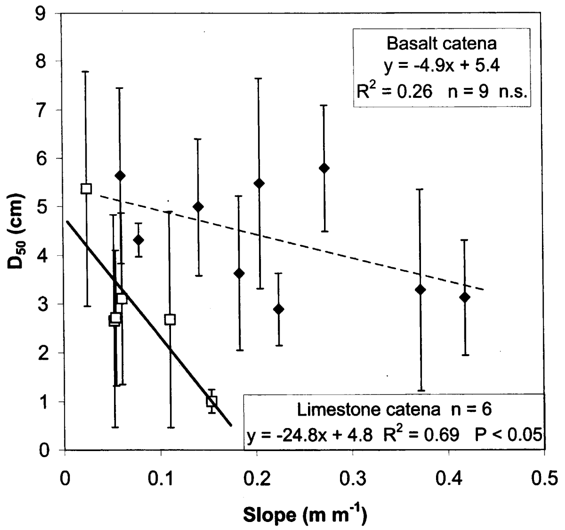

Fig. 9. Slope gradient vs. average D_{50} (intermediate diameter) of the rock fragments by site. At each site, the D_{50} was measured in six representative areas.

deposition, which covers the rock fragments deposited by debris flows. The larger rock fragments here are preferentially brought to the soil surface by kinetic sieving due to tillage and vertic movements, whereas the smaller rock fragments will be more readily buried under deposited sediment.

4.3. Spatial distribution of rock fragments and soil catenas

In the study area, on the different basalt trapps, a 'red–black soil catena' (Driesen and Dudal, 1991) is present: from truncated Luvisols in a high position over Leptosols, Regosols and Cambisols to Vertisols. The studied catena (Fig. 10) is underlain by coarse slope material: the lower horizons in Profiles 3, 4 and 5 contain significantly higher volumes of large (>7.5 cm) rock fragments. Later on, more fine material has bas been deposited and the lobe was smoothened, but it remains present as a minor 'ridge'. Cumulic Regosols are formed in those areas that are near to the steep slope and Vertisols in the temporarily moist, flat areas at the lower side of the catena. Table 1 presents an overview of the processes that are active at each soil profile site. Rock fragments are displaced laterally or vertically, resulting in higher concentrations of rock fragments at the soil surface in certain positions along the catena. Since the analysed catena is totally occupied by cultivated fields, kinetic sieving and downslope movement of rock fragments due to tillage is important everywhere. In Profiles 3, 4 and 5, kinetic sieving combined to slow sediment deposition results in an important hiatus in rock fragments over some 60 cm. The downslope movement is strongly dependent

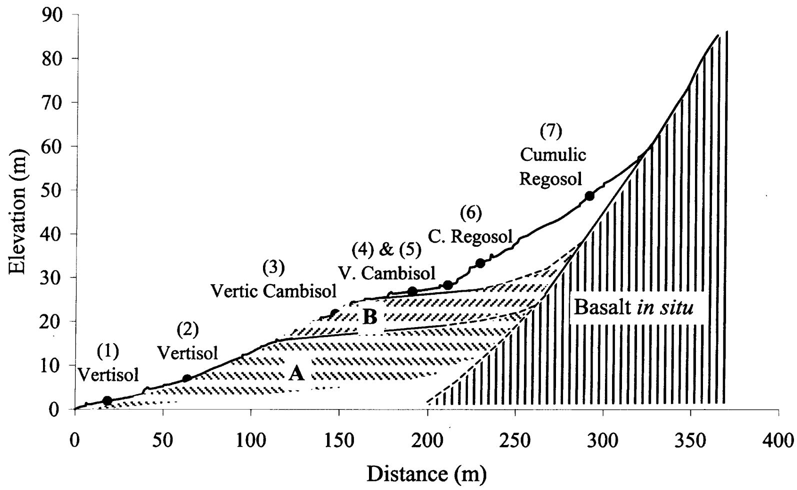

Fig. 10. Soil catena on basalt trapp. Note that most soils are covered by 20–100 cm of recent colluvium (Regosol). Topography was measured by theodolite. See Table 1 for a synthesis of the processes which explain the rock fragment distribution. (A) and (B) are ancient debris flow deposits.

Table 1
Processes which caused vertical and lateral rock fragement distribution at the seven analysed sites on the basalt catena

Processes	Soil profile						
	1	2	3	4	5	6	7
Vertical displacement by:							
Tillage	+	+	+	+	+	+	+
Argillipedoturbation	+	+	(+)	(+)	(+)	–	–
Erosion pavement	–	–	?	–	–	+	+
Lateral displacement by:							
Water	–	–	(+)	–	–	+	+
Tillage	(+)	(+)	(+)	(+)	(+)	+	+
Trampling	–	–	(+)	–	–	+	+
Rockfall	–	–	–	–	–	+	+

+: process is active.
(+): process is moderately active.
−: absence of process.
?: process theoretically possible, but not observed in the field.

on slope gradient and will especially be active near Profiles 6 and 7. Rockfall, transport by concentrated flow and by cattle trampling and the formation of an erosion pavement will be mainly limited to these steeper slopes near the cliff. Argillipedoturbation is active in Vertisol areas (Profiles 1 and 2).

The geomorphological processes that occurred over ages are important to understand the soil distribution in the lower area below the limestone cliff. Lobes of marl and weathering limestone (Nyssen et al., submitted) form the footslope of this cliff (Figs. 1 and 4). Often, truncated soils are found on these lobes, on which colluvium has been deposited. It is composed of fine material (weathered sand-and limestone) and of boulders originating from the cliff in Amba Aradam sandstone. Here, we mostly find Calcaric Regosols. Near to the cliff, soils developed in situ on weathering limestone (Profile 10) and marl are deeply eroded. Tillage is an important factor in rock fragment distribution here also and kinetic sieving together with continuous sediment deposition provoked a hiatus in coarse rock fragments between the plough layer and a depth of 111 cm in Profile 8. Formation of an erosion pavement is expected to take place, especially on the steep slopes near Profile 10, but, like on the basalt catena, the presence of this process is difficult to recognise in the vertical rock fragment distribution. The other processes are also slope related (rockfall, trampling by cattle, tillage, transport in rills) and this makes clear how it is especially in this catena on limestone that there is a strong relation between slope gradient and R_C (Fig. 8).

5. Conclusions

The analysis of vertical and lateral rock fragment distributions allows one to understand the processes responsible for the high R_C in the fields of Tigray. The type of soil, as well as the environmental factors, was taken into account. We recognised numerous ancient debris flow deposits on which the present soils developed. At present, the slope processes are of a lesser magnitude but can still transport significant volumes of fine earth and rock fragments.

Especially on the catena developed on basalt, soil formation is dependent on the topographical position: from Vertisol in the flat areas over Cambisol and Regosol to Luvisols on ridges. Here, R_C is high everywhere and thus not related to slope gradient. In the limestone area, most soils are Calcaric Regosols. R_C is higher on the steeper areas, closer to the cliff.

Due to a combination of kinetic sieving as a consequence of tillage and slow deposition of fine earth at the lower side of the catenas, average rock fragment size significantly increases with decreasing slope gradient.

Precondition for the present spatial distribution of rock fragments at the soil surface in the study area are the occurrence of two geomorphic processes in the past: (1) debris flows, having created coarse colluvial deposits, and (2) intense water erosion, which occurred after deforestation and exposed rock fragments at or near to the soil surface. Generally, the balance between lateral and vertical movements of rock fragments now controls the spatial distribution of R_C. With respect to the lateral displacement processes, one can distinguish between (1) lateral transport over the soil surface by trampling, tillage and concentrated flow, especially on steep slopes, and (2) rockfall from the cliffs. 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 runoff erosion and the development of erosion pavements.

Advantages of the presence of rock fragments at the soil surface for desertification control are: increased infiltration rates, decreased evaporation, topsoil protection from raindrop impact and water erosion (Poesen and Lavee, 1994). Measurements in the study area show a significant negative relationship between R_C and soil loss (Nyssen et al., 2001). A recommendation resulting from this last study is to rely on the farmers' wisdom: smaller rock fragments should never be removed from the fields' surface, but a limited number of larger rock fragments can be removed in order to increase crop yield. It must however be remembered that the upward movement of large rock fragments by tillage (kinetic sieving) will reach an equilibrium where the net flux of rock fragments moving to the soil surface becomes nil. In this case, removal of rock fragments will result in reactivating the process. Argillipedoturbation will ultimately also reach an equilibrium after a rock fragment mantle is formed that is important enough to be a buffer against desiccation and swell-shrink action. But this buffer would probably be too important to allow any cultivation. Lateral transport of rock fragments is a process, which will not reach a situation of equilibrium. Removal of a certain number of large rock fragments can thus be useful in those areas where argillipedoturbation and lateral transport over steep slopes are active. If the rock fragments are only brought to the soil surface by tillage, the effect of their removal will be lost after a few tillage operations.

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