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On the origin of rock fragment mulches on Vertisols: A case study from the Ethiopian highlands

Jan Moeyersons [a,*], Jan Nyssen [b,d], Jean Poesen [c], Jozef Deckers [d], Mitiku Haile [b]

[a] *Royal Museum for Central Africa, B-3080 Tervuren, Belgium*
[b] *Mekelle University, P.O. Box 231, Mekelle, Ethiopia*
[c] *Physical and Regional Geography Research Group, K.U. Leuven, Redingenstraat 16, B-3000 Leuven, Belgium*
[d] *Institute for Land and Water Management, K.U. Leuven, Vital Decosterstraat 102, B-3000 Leuven, Belgium*

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Abstract

Many Vertisols in Tigray, Ethiopia, typically carry a discontinuous rock fragment (RF, size $0.5\text{–}{>}40 \cdot 10^{-2}$ m) cover with 10 to 100 RFs m^{-2}. Such RF mulches are of agricultural and environmental significance because they influence the water balance in the underlying soils and the crop yield. Natural RF concentrations are mostly considered as eolian or hydraulic lag deposits, or as the result of lateral transport over the soil surface from a rock outcrop, upslope. In cultivated areas RF mulches can develop by tillage.

This paper presents the case of a natural RF mulch whose lithology indicates that the RFs are up-squeezed by the local Vertisol. The study site is located in the pass of Enda Maryam, Tigray, Northern Ethiopia (39°8′ E and 13°36′ N). A circular area of 10 m diameter, about 200 m away from the water divide in the valley has been cleared annually between 01/1999 and 05/2003. During this period, 625 RFs, 17 being $>7.5 \cdot 10^{-2}$ m in size, totalling a mass of nearly 62 kg, have been collected. After correction for measurement procedures, the rate of RF up-warping by the Vertisol at Enda Maryam is assessed at 5 RFs m^{-2} in 3 years. At this rate of appearance, the formation of current RF concentrations on top of active valley Vertisols is only a matter of 10^{1-2} years, provided the availability of RFs below the soil surface.

Although important underground displacements were measured in the Vertisol between 01/1999 and 05/2002, the supposed link between up-squeezing of RFs and plastic deformations of ‘chimney’, ‘diapir’ or ‘intrusion’-like type in the Vertisol could not be evidenced. Instead, RFs are clearly concentrated on the soil surface as well as in depth, along the existing vertical desiccation cracks, often >1 m deep which display polygonal configurations at the soil surface. Further, bundles of slickensides containing some RFs, have been mapped at the base of the Vertisol. The slickenside configuration suggests that the RF-bearing substrate is being scraped off.

While the underground displacement of RFs along active slickensides seems normal, the process of RFs ascending in ‘upright’ position in the edge of desiccation cracks needs explanation. The closure of a desiccation crack is a peristaltic-like movement, following ascent or descent of the capillary fringe. It is hypothesized that this movement gradually pushes the RF to the surface or to another place or level in the soil profile where the crack closes in last instance.

The apparent young age of the valley Vertisol mulches in Ethiopia might indicate the very recent formation of yearly recurrent desiccation cracks of Vertisols in the area. Available information confirms that most valleys in the study area used to be perennially

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[*] Corresponding author. Tel.: +32 27 69 56 09; fax: +32 27 69 56 42.
E-mail address: jan.moeyersons@africamuseum.be (J. Moeyersons).

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marshy. Under these conditions no movements of RFs in the soil profile are expected to occur. Gullying, leading to pronounced seasonal desiccation of the Vertisols, started in several cases not more than 50 years ago.

Keywords: Desiccation crack; Ethiopia; Peristaltic movement; Rock fragment mulch; Vertisol

1. Introduction

Vertisols, vertic horizons and soils with vertic properties cover an important area in the horn of Africa and the adjacent Nile valley (FAO, 1999). They undergo seasonal swell-shrink and cracking and show gilgai topography. This complicates the construction of houses and roads (Maxwell, 1994). Vertisols have a great agricultural potential but they are difficult to work, being hard when dry and very sticky when wet (Deckers et al., 2001). Further, seasonal soil cracking and slickenside (small fault planes in clays) development creates physical problems for crops in disrupting and damaging roots. Plants also easily dry out when their roots remain close to the surface. The capillary rise through the clayey soil matrix can be insufficient during the dry season and might even be cut off by the occurrence of subhorizontal soil matrix discontinuities, mainly desiccation cracks and slickensides, which develop during the organisation of the soil matrix in prismatic peds, soil islands and aggregates.

A factor in Vertisol fertility, seldom mentioned, is the frequent occurrence of a superficial mulch of rock fragments (RFs) (Fig. 1). RFs include all mineral particles over 5 mm in diameter. In the field they are currently indicated by 'stones'. Preliminary research in the Tembien Highlands in Northern Ethiopia (Nyssen et al., 2001) shows the existence of an optimum RF mulch coverage linked to maximum crop yield. Furthermore, RF mulches are known to reduce soil erosion in cropland (Poesen et al., 1994; Nyssen et al., 2001) and to increase infiltration (Poesen and Lavee, 1994) in certain circumstances. In the northern Ethiopian highlands, virtually dry from October to May, moisture conservation techniques induce substantial increases in crop yield (Mitiku and Fassil, 1996). As RF mulches control runoff coefficients, they influence the natural water harvesting capacity of the soil and have an impact on desertification.

RF mulches on top of Vertisols appear, thus, to be of interest in widely diverse fields such as agriculture, pedology, geomorphology, soil technology and water management. Furthermore, many of the RFs, squeezed up, are prehistoric stone tools coming from below the Vertisol, from a depth of about 2 m. This, of course, can complicate the study of the stratigraphical context of these artefacts and their absolute and relative age determination (Cahen and Moeyersons, 1977).

In addition, RF mulches on top of swelling clays are not limited to regions with a rainy season important enough to allow the clays to swell. They occur also in parts of the world where swell-shrink cycles are absent because of the present-day aridity. In deserts, where RF concentrations are higher, the term 'desert pavement' (Lozet and Mathieu, 2002) seems more appropriate than 'mulch'. In Africa desert pavements, resting on inactive Vertisols, frequently occur along the Nile in Egypt and Sudan, where they cover Vertisols in the Nile silts (de

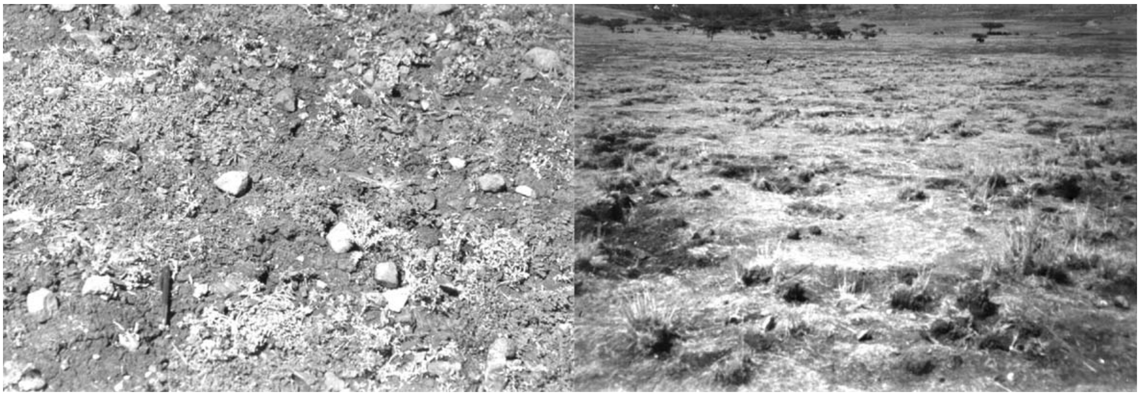

Fig. 1. Enda Maryam, 05/2002. Left: a detail of the RF mulch, the pencil is 14 cm long. Right: Vertisol topography with polygonal structures.

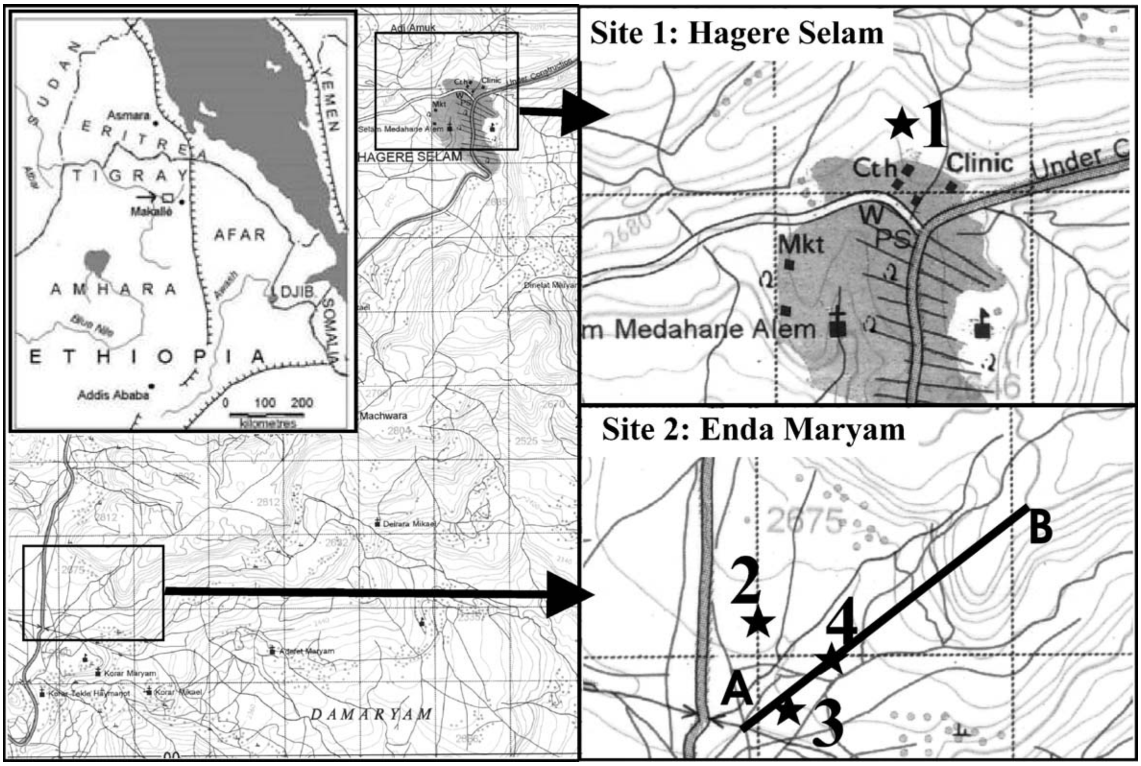

Fig. 2. Location of the study area. Site 1: Hagere Selam May Dansi (Fig. 4); site 2: blind head of Enda Maryam and sections Enda Maryam 1 North and 2 West (Figs. 5, 6 and 7); site 3: the circular experimental plot with yearly clearings (01/1999–05/2003) of RFs (0.5–>$40 \cdot 10^{-2}$ m) (Figs. 10, 11, 13 and 14); site 4: section Enda Maryam Polygon (Figs. 8, 9 and 15). Section (A)–(B): location of cross section Fig. 3.

Heinzelin, 1968). The origin of desert pavements on top of Vertisols has also been discussed in Israel (Yaalon and Kalmar, 1978).

RF mulches on Vertisols and related soils can have several origins (Nyssen et al., 2002a). At Enda Maryam, Tigray, Ethiopia, it has been preliminarily shown that the Vertisol annually squeezes up RFs at a rate high enough to form a RF mulch within a few centuries or some millennia (Nyssen et al., 2000a).

This study, based on the complete data set from the Enda Maryam experimental site (Fig. 2) for the period 01/1999–05/2003, aims to provide a better understanding of the process of up-squeezing with particular focus on the link between up-squeezing and underground structures and soil displacements.

2. Materials and methods

2.1. The study area

The study area, a rectangle of some 200 km^2 (Fig. 2), is located in the northern part of the Ethiopian Highlands, 40 km to the west of Mekelle, the capital of Tigray. Hagere Selam, the village in the center of the study area and the Enda Maryam site form each a geomorphologic saddle at ~2600 m a.s.l. between two local subcatchments of the Geba basin, which drains to the upper Tekeze-Atbara. The study area covers the north-western part of the Mekelle outlier, an 8000 km^2 circular belt on the western shoulder of the Ethiopian rift. The outlier is formed by a succession of Palaeozoic to Cainozoic subhorizontal sedimentary layers, totalling a thickness of 500 to 1000 m (Beyth, 1972; Tesfay and Gebretsadiq, 1982). These deposits fill a 75 km wide depression in the Precambrian basement (Boselli et al., 1997). The highest points in the study area are formed by two series of Tertiary basalts, separated by silicified lake deposits (SLD) of limestone, sandstone and diatomites with gastropods (Garland, 1980). Basalts and SLD rest upon the Amba Aradam sandstone, Cretaceous in age, and the Antalo limestone series, dating from Jurassic times. Due to tectonic uplift of the area since early Tertiary times, the remnants of the assumed peneplain on top of the Amba Aradam sandstone currently occur at an altitude of >2000 m a.s.l. and subsequent vertical river incision eroded an impressive and complicated canyon network in the Ethiopian highlands.

Fieldwork concerns the Vertisol which covers tabular reliefs underlain by the lower basalt series and the SLD, mentioned above. At Enda Maryam and at Hagere Selam May Dansi (Fig. 2) this soil is active. At Enda Maryam polygonal patterns of vertical desiccation cracks appear during the dry season and give rise to some gilgai-like topography (Fig. 1). The area receives 700–> 900 mm of annual precipitation, depending on slope orientation and altitude (Vandenreyken et al., 2001). Most of this falls between June and September, but small 'Belgh' rains irregularly occur from March onward. The climatic conditions $\{0.05 < (\text{annual precipitation/potential evapotranspiration}) < 0.65\}$ in the northern highlands justify the use of the term 'desertification' (UNEP, 1994).

2.2. Soil description and geological exploration

Soil descriptions were needed to explain the mechanism of appearance of RFs at the soil surface of an experimental plot at Enda Maryam, monitored yearly from 01/1999 to 05/2003. Soils have been described in soil pits at Hagere Selam May Dansi, Enda Maryam 1 North and 2 West and in the Enda Maryam Polygon section (Fig. 2).

Soil descriptions include the careful mapping of pedological horizons in pit walls, based on colours (Macbeth, 1992) and structures and on texture analysis. Structures include mainly cracks, slickensides and soil islands and peds. The visibility of soil structures and colours obviously depends on the humidity conditions of the soil profile, and, therefore, on the time of the year. Descriptions over the years always took place during the period January–March, about the driest period of the year. This appeared to be the best time for crack descriptions.

Besides pedological horizons and soil structures, the position and often the form and orientation of all RFs > 5 mm, visible in the pit walls, were drawn within the accuracy of 10^{-2} m.

Soil descriptions done for the first time in 1999 in the pits at Hagere Selam May Dansi and Enda Maryam 1 North and 2 West were repeated in 2002 to find out if structures, and especially desiccation cracks, are able to survive the conditions of water saturation of the Vertisols during a rainy season. Therefore, these pits were filled carefully after their description in 1999, ensuring enough compaction of the fill to restore the lateral confinement of the pit wall in question, but avoiding as much as possible even its superficial damage. The reopening in 2002 appeared to be much easier than expected. The local labourers found that the original pit walls did not fuse with the fill. Thick soil clumps in the fill did survive three rainy seasons.

The Enda Maryam Polygon section has only been opened once in February 2001. The geological observations in the pass of Enda Maryam indicate the relation between Vertisol and geology (Fig. 3).

2.3. Techniques to measure inter-seasonal underground soil deformations

As underground soil deformation was expected to be important in the Vertisol and to play a crucial role in the

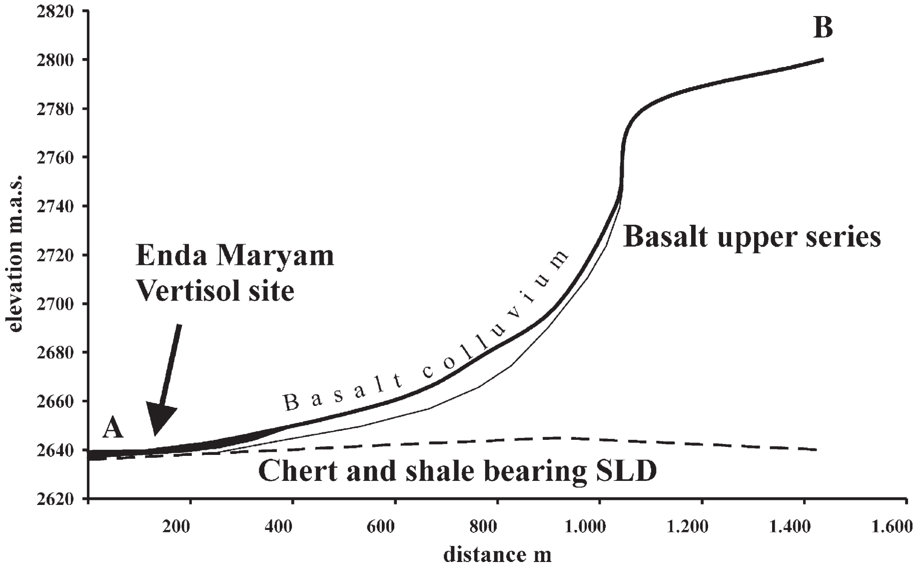

Fig. 3. Relation between geology and soils in the eastern half of the Enda Maryam pass. The A–B trajectory is indicated on Fig. 2.

up-warping of RFs to the surface, techniques used by other researchers to measure this type of deformations were investigated. The most common technique used is to put tracers like rods or coloured sand in an auger hole, or metallic blades, nails or other tracers in the wall of a 'Young-pit' (Young, 1960; Moeyersons, 1988). Another technique consists of visualizing underground creep movements by inclinometers at the surface (Anderson and Finlayson, 1975) or related instruments like the "T" pegs, used by Kirkby (1967). Also electronic creep probes like strain gauges (Auzet et al., 1986) or linear voltage displacement transducers (Harris et al., 1996) have been used in the field and/or in laboratory set ups. Finlayson and Osmaston (1977) use a tube tracer, allowing the measurement of changes between the position of the base and top of the tube by microscopic observation. These and other techniques have been described (Auzet et al., 1986; Anderson and Cox, 1978). As a general rule, the precision of measuring instruments increases with decreasing range of observable displacement. But where displacements of the order of 10^{-3}–10^{-1} m need to be monitored, the simple techniques with soil tracers are still widely applied (Clarke et al., 1999).

In this study, underground movements were measured by the 'Young-pit' technique. The opportunity was taken in 1999, when the pits were open for soil description, to insert nails ~2.5 mm thick and ~10 cm long into the walls of the soil pits. The nails were inserted in linear patterns. Changes in the distances between nails and deformations in the linear configurations of the nail tracers were recorded in 2002 using a metallic measuring tape and making readings with accuracy up to 1 mm.

This technique is subject to several criticisms. A first series of objections stems from the difference in density and structure between the pit fill and the original soil, and through the perturbation of the original pedological soil profile. This implies that the swell-shrink behaviour of the fill is different from that of the original soil. Moreover, the water content fluctuations in the fill will differ for the same reasons. This might influence the deformation of the undisturbed soil in the adjacent pit wall. Secondly, the technique of measuring deformation on a pit wall only makes sense if the movement being measured is strictly two-dimensional and parallel to the pit wall. Thirdly, it is not guaranteed that relative movement does not occur between the soil and the nails during swelling and shrinking of the soil. Finally, when recorded movements are small, of the order of a few millimeters, the question arises whether the movement is only intra-seasonal or extra-seasonal and, hence, whether it is contributing to overturning or 'churning' (Deckers et al., 2001) of the soil. All these arguments show the weakness of the technique applied in this particular case, but more than simple indications for underground movements were not expected.

2.4. Measurement procedures in the circular experimental plot at Enda Maryam

On the nearly flat (<1% inclination) valley Vertisol in the pass of Enda Maryam (Fig. 2), a more than 2 m thick Vertisol has developed. This area is used for delayed grazing after the rainy season. A discontinuous veneer of RFs is present at the surface (Fig. 1). The RF density shows important variations. The analysis of several photographs of the soil surface some 100 m south-east from the school indicates RFs with dimensions ranging between 1 and $40 \cdot 10^{-2}$ m, occurring in densities between 5 and >50 pieces m^{-2}. Taking into account the multiple use of RFs by the people, we estimate that the undisturbed RF array on the valley Vertisol might locally show densities up to 100 pieces m^{-2}. Bundles of desiccation cracks, sometimes more than $5 \cdot 10^{-2}$ m wide at the soil surface during the dry season, describe polygonal figures, ranging in diameter from 2 to 5 m. Here, a circular area with a diameter of 10 m has been chosen to monitor the yearly appearance of RFs at the surface. The circle is not delimited and remains indistinguishable from the rest of the plain in order to keep it free from intentional disturbance by passing people and cattle. In January 1999, the surface was cleared of all RFs and the three-dimensional coordinates of every RF and large crack within the circle, relative to the centre of the circle, have been input to a local topo-network built up from three remote points by means of a laser theodolite total station. After this first clearing in January 1999 (Nyssen et al., 2000a), the same operation was repeated in the years 2000, 2001, 2002 and 2003.

Cleared RFs were either resting on the soil surface or embedded in the topsoil, but having a visible area of $>10^{-4}$ m^2. Some RFs in the edge of open cracks are visible until depths of $1–5 \cdot 10^{-1}$ m. Such RFs were only measured and taken away if they were less than $5 \cdot 10^{-2}$ m below the surface.

3. The results

3.1. Soils and geological settings

Soil profiles are described at Hagere Selam May Dansi (Figs. 2 and 4) and in the pass of Enda Maryam (Figs. 2, 5–8). A complete Vertisol profile with Ap, AB, (B) and B–C pedological horizons (FAO, 1998) could

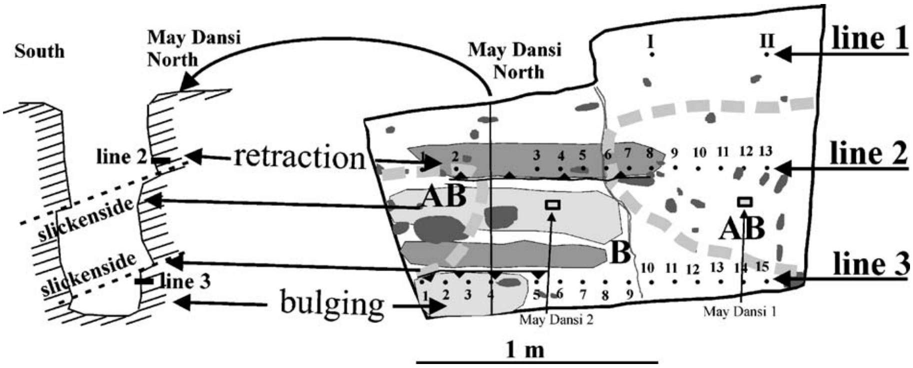

Fig. 4. Section at Hagere Selam May Dansi: 01/1999 AB, B and thick dashes: pedological soil horizons and their limits; May dansi 1 and 2: soil samples (Fig. 9); I, II…, 1, 2 …: nail tracers and their horizontal alignments; light and dark gray belts: respective belts of soil pit wall bulging and retraction in 05/2002; barbed lines in section and thin dashes in soil pit cross section are slickensides: dark patches are RFs. Vertical and horizontal scale are the same.

be distinguished at Enda Maryam 2 West (Nyssen et al., 2000a). The same horizons could be identified in the other soil pits although the deeper horizons were not always excavated. A characteristic feature in all soil pits at Hagere Selam and Enda Maryam is the occurrence of 'diapirs' (Coulombe et al., 1997), a form of plastic intrusions of B-material through the overlying AB-horizon at the edge of polygonal structures (Nyssen et al., 2000a). Special attention is given to section Enda Maryam Polygon (Fig. 8). The lateral variations in thickness and depth of the pedological horizons seem to be bound to the polygonal structures I to III recognized at the soil surface. The center of polygons II and III is occupied by a small lens of AB-horizon, what gives the impression that the polygons coincide with depressions in the pedological horizons. The same is true for the transition between the B- and BC-horizons. This boundary rises up as diapirs (Coulombe et al., 1997) below the edges of the polygons mapped at the soil surface. Diapir-like phenomena occur above 2.5–4, 7–8 and at 11.5–13 m of the horizontal axis. In the first sector, 2 patches of BC-horizon are isolated within the B-horizon above the irregularly raised boundary between both horizons. In the transitional belt between polygon I and II, a few long slickensides coincide more or less with part of the raised boundary.

While traces of plastic pedoturbations are a very common feature in both sites, the geological setting differs. At Hagere Selam, the Vertisol is developed in colluvia derived from the upper basalt. The SLD occur at a depth of about 20 m. At Enda Maryam, the Vertisol rests directly upon silicified clayey and sandy materials

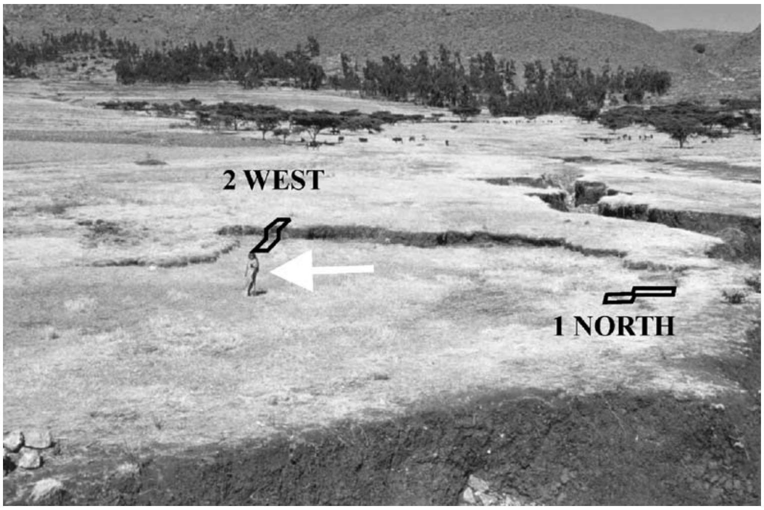

Fig. 5. The gully and the 'blind head' in a side-valley of the pass at Enda Maryam (02/2000). The locations of Enda Maryam 1 North (Fig. 6) and 2 West (Fig. 7) are indicated. Basalt outcrops in background (see Fig. 3). Scale: person indicated by arrow.

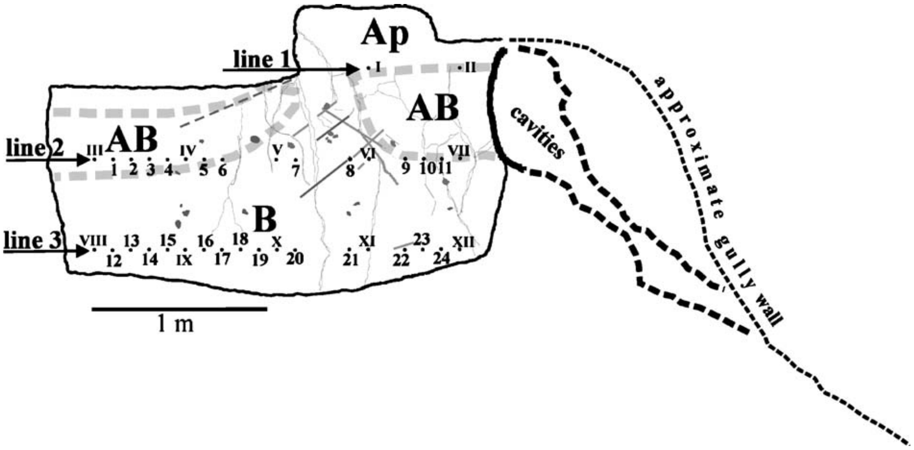

Fig. 6. Section Enda Maryam 1 North. Localisation Fig. 5. Ap, AB, B and thick dashes: 01/1999 position of soil horizons and their limits; I, II…, 1, 2 …: nail tracers and their horizontal alignments; rectilinear lines and dashes: slickensides and sphenoids; subvertical linear irregular structures starting from the soil surface: desiccation cracks. Dark patches are RFs.

and sandstone (sample Eth 01/1, compared to Eth 01/2 and 3, Fig. 9), belonging to the SLD (Figs. 3 and 8).

At the study site of Hagere Selam, the SLD seem to act as a local aquiclude or aquitard. The site is located near the bottom of an old spring-amphitheatre in the northern pass wall. From the excavations it appeared that the soil water content remains unchanged most of the year above the shrinkage limit and desiccation cracks do not develop in that area. The water table actually sits a few metres below the surface since it is exploited by a well. A gully starts from the former spring locality. The section at May Dansi (Fig. 4) crosses one of the small steps, present along both sides of the gully. At the time of excavation in 1999, the small step corresponds to an open crack in the soil, attributed to creep towards the gully. This situation is very different from Enda Maryam, where the Vertisol in the central part of the pass shows numerous desiccation cracks during the dry season (Figs. 5–7). Here, a permanent water table is not present anymore since gullies (Fig. 5) quickly drain the soil after the rainy season.

There are also some differences in texture, $CaCO_3$ and humic content between the Vertisol at Hagere Selam May Dansi and Enda Maryam (Fig. 9). The Vertisol at

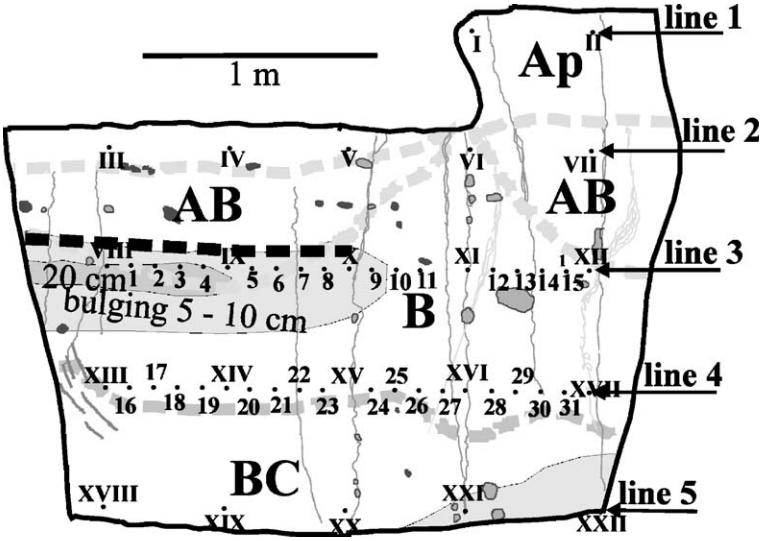

Fig. 7. Section Enda Maryam 2 West. Localisation Fig. 5. Ap, AB, B, BC and thick grey dashes indicate extension of pedeological horizons in 01/1999. I, II…, 1, 2, …: nail tracers and their horizontal alignments. Deformations of wall in 05/2002: (1) rectilinear or slightly curved lines and black thick dashes: slickensides; (2) subvertical linear irregular structures starting from the soil surface: desiccation cracks; (3) dark patches: RFs. Capillary rise 05/2002 reached tracer line 3.

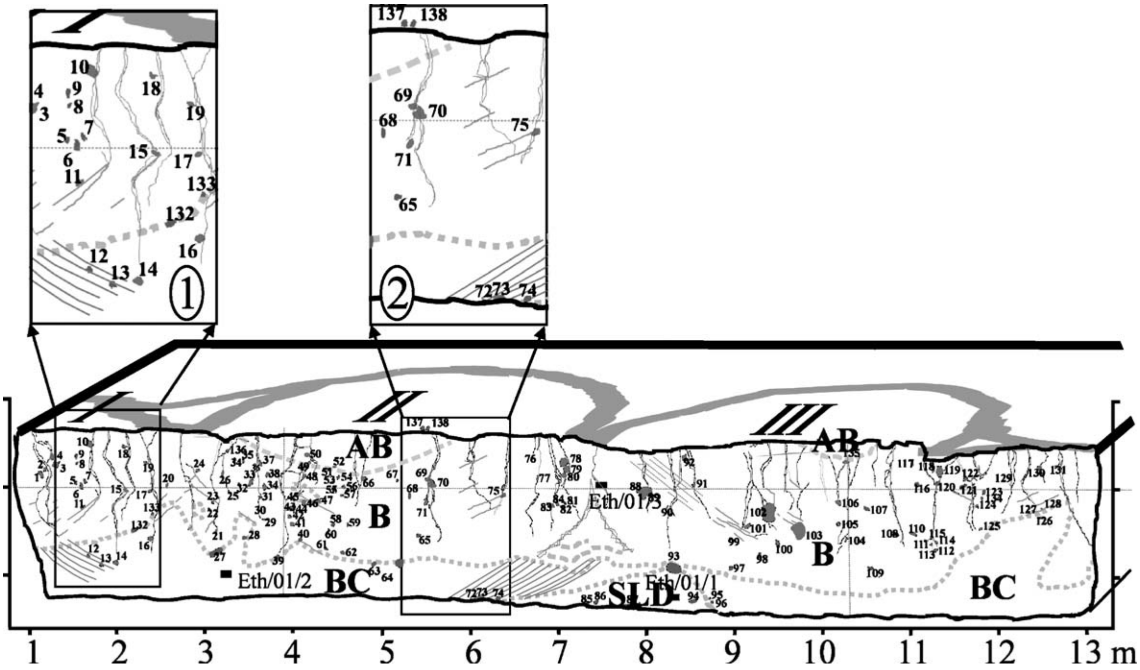

Fig. 8. Section Enda Maryam Polygon. Numbered dots: 138 RFs; Eth/01/1, 2 and 3: soil samples (Fig. 9); Dashed lines: transitions between pedological horizons (FAO, 1998) AB, B, BC and SLD; rectilinear or slightly curved structures: slickensides; subvertical irregular line patterns starting from the soil surface: desiccation cracks; I, II and III: polygonal cracks. Between 11 and 13 m, the section follows the limit between two polygons. Insets 1 and 2: see text.

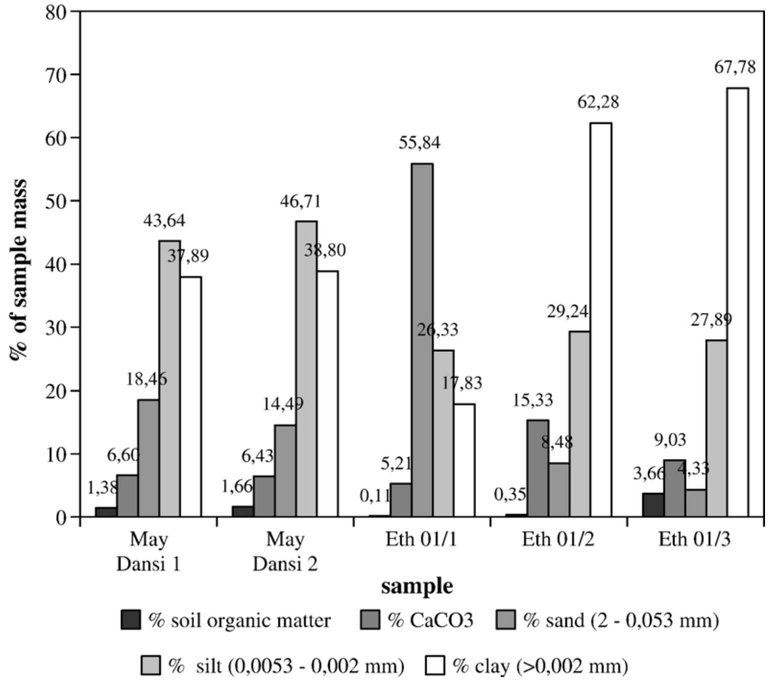

Fig. 9. Textural and mineral data for the soil horizons at Hagere Selam May Dansi, also shown in Fig. 4 and the Enda Maryam Polygon, shown in Fig. 8. Sample Eth 01/1 is taken in SLD.

the Hagere Selam study site has a clay content (<2 μm) of less than 40%, but at Enda Maryam it is more than 60%.

3.2. Rock type as an argument for the origin of RFs

Although it has been proposed that the RFs in the center of the pass of Enda Maryam have been squeezed up due to pedoturbation processes associated with true Vertisols (Nyssen et al., 2000a), here we wish to add more evidence. Rock fragments present in the soil profile at Hagere Selam are exclusively basalts, probably derived from the northern basalt pass wall, but at Enda Maryam ~90% of the RFs visible on the surface of the Vertisol are chert and shales. Our detailed field studies of the pass of Enda Maryam indicate, however, that there are only outcrops of the upper basalt series and no outcrops of 'Tertiary silicified limestone' (Russo et al., 1999) upslope of the Vertisol (Fig. 3). The chert and shale-bearing SLD are present below the Vertisol. In section Enda Maryam Polygon (Fig. 8), SLD forms a sandy layer at the base of the section and contains in its exposure 1 RF of chert and 4 RFs of shale. The 133 RFs higher in the soil profile and at the surface are also exclusively of chert and shale.

If chert and shale RFs are resting on the Vertisol surface in the center of the Enda Maryam pass, they must have lifted from the base of a 2 m thick Vertisol to its top.

3.3. The rate of RF lift in the experimental site at Enda Maryam

At the start of the clearing experiment in the circular experimental plot (Fig. 10) at Enda Maryam, distinction was made between embedded RFs, having less than half of their volume above the surface, and 'surface' RFs lying more freely on the surface. The idea was to separate RFs in a class being squeezed up and another class being arrived in the circular experimental plot by lateral transport over the soil surface. But loose RFs can also be found exactly at the place where they were squeezed up and embedded RFs might have come to the surface at some distance away, having undergone lateral displacement over the soil surface and consequent embedding. Furthermore, the rock type argument, presented above, is valid for the whole pass. Therefore, the subdivision of loose and embedded RFs is not relevant evidence for the up-warping of RFs in the pass.

Of course the monitoring technique, considering the yearly removal of RFs, has the disadvantage that it might lead to an overestimation of the rapidity of the process of RF up-squeezing. Not only does this technique prevent some of the RFs from tumbling back in the open cracks but at the same time the artificially emptied circle will receive more RFs from the surrounding area by transport over the surface than it can give back. The latter circumstance should produce a yearly decrease of RFs recovered in the circular experimental area in the first time, but also to a stabilisation of the yearly recovered RFs, due to the gradual exhaustion of the surrounding area.

Fig. 11 illustrates the distribution of RFs and cracks, visible at the surface at the moment of clearing of the 78.5 m^2 circular area in January 1999. The center of the circle is occupied by a 'polygonal' structure.

Table 1 compares the number of RFs cleared in January 1999 with the number of RFs recovered between 01/1999 and 05/2003. In 1999 RF cover

Fig. 10. The circular experimental surface at Enda Maryam in 02/2000. The rope shows the circumference of the circular experimental plot, 10 m in diameter and having an area of 78.5 m^2. The polygonal configuration of grass tussocks, growing along major cracks, is obvious.

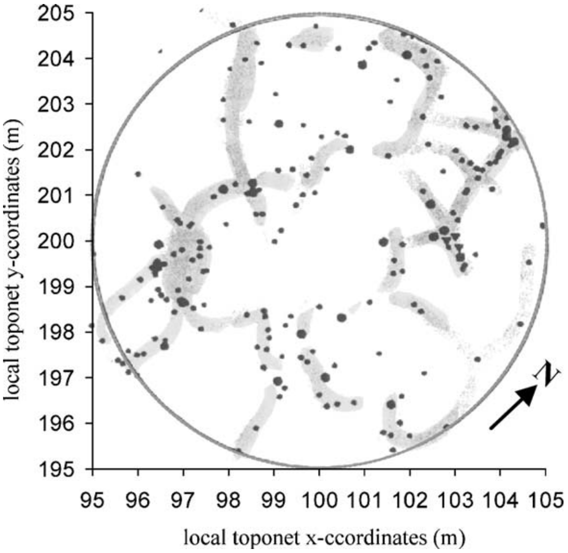

Fig. 11. The RF distribution at the soil surface in 01/1999 at the moment of the first clearing, compared to the shrinkage crack pattern visible at that time.

density before clearing was very low compared to estimations for the vicinity of the highest point in the center of the gap. The circular surface of 78.5 m^2 contained only 228 RFs. This confirms the statement of the local habitants that the concerned area had been cleared the year before for maintenance of a rural road some 100 m further upslope towards the pass. But in the subsequent 4 years 625 RFs were found on the experimental site. Even if only the 217 embedded RFs, squeezed up between 1999 and 2003, are taken into account, the phenomenon of RF replacement remains very important.

Table 2 indicates the yearly change of the appearance of RFs at the experimental site of Enda Maryam. There was a clear setback of the number of RFs recovered between 01/1999–02/2000 (234) and the three subsequent years, being, respectively, 115, 134, and 142 RFs. This chronological evolution might reflect the effect of clearance on the lateral distribution of RFs over the soil surface as discussed above. Taking this into account, the real rate of up-squeeze of RFs in the circular surface at Enda Maryam should approximate the rate of the period 02/2000–05/2003. This gives a mean value of 391 RFs, with a cumulative mass of 45.09 kg, lifted to the 78.5 m^2 experimental surface in 3 years. This equals a pavement density of nearly 5 RFs m^{-2} after 3 years.

RF clearing, which prevents RFs from falling back in open cracks, probably does not significantly exaggerate the rate at which an active Vertisol pushes up RFs. First of all, an important portion of the RFs sits in embedded position and, therefore, should not fall back easily. Secondly, the chance that loose RFs would fall back into a crack is low, because many cracks are not wide enough to receive them or to let them fall deeper than $5 \cdot 10^{-2}$ m. Further, repeated inspection of wide cracks at Enda Maryam show that they contain rather few loose RFs, although cattle and people live and walk in the valley. Most RFs visible in wide cracks are sitting embedded either in the crack wall or in the crack bottom.

These data lead to the conclusion that the formation of RF mulches in the study area is not a matter of centuries or a few millennia, as was thought earlier (Nyssen et al., 2000a), but of only a few years to some decades.

If the mass of the RFs is considered (Table 2), it clearly appears that the mean size of the RFs was much bigger during 02/2001–05/2002 than the years before and after. For the moment it is not clear whether these variations are related to the precipitation characteristics of the corresponding wet seasons or just with variations in size of the supply of RFs still available underground.

3.4. Extra-seasonal pedoturbations in the Vertisol at Enda Maryam and Hagere Selam

Observing the high rate of RF appearance at the surface, one would expect important soil perturbations and solifluxion-type phenomena like so-called 'diapirs' and 'chimneys' (Deckers et al., 2001) to transport the embedded RFs rapidly to the soil surface. According to the criticisms on the 'Young-pit' technique for measuring underground soil movements, it was expected to find perturbations in the geometrical and linear configuration of the nail tracers difficult to interpret.

Table 1
Total number of RFs recovered in the circular area near Enda Maryam

Size class	01/1999 number of RFs at clearing	RFs cleared in period 01/1999–05/2003	Sum of all RFs cleared	Embedded 01/1999–05/2003
$1–7.5 \cdot 10^{-2}$ m	203	608	811	206
$>7.5 \cdot 10^{-2}$ m	25	17	42	11
Total	228	625	853	217
RF cover density (amount m^{-2})	2.90	7.96	10.87	2.76

Table 2
Total number and mass of RFs by size class

	Number of embedded RFs				Mass of embedded RFs (kg)			
Period	01/1999 02/2000	02/2000 02/2001	02/2001 05/2002	05/2002 05/2003	01/1999 02/2000	02/2000 02/2001	02/2001 05/2002	05/2002 05/2003
Class								
$1–2\cdot10^{-2}$ m	7	16	18	4	0033	0044	0103	0060
$2–7.5\cdot10^{-2}$ m	87	30	25	19	8397	3827	2888	2872
$>7.5\cdot10^{-2}$ m	4	2	4	1	6005	0664	12,209	0815
Total	98	48	47	24	14,435	4535	15,200	3747
	Number of 'surface' RFs				Mass of 'surface' RFs (kg)			
$1–2\cdot10^{-2}$ m	72	24	56	64	0249	0109	0193	0204
$2–7.5\cdot10^{-2}$ m	64	41	28	53	2211	4163	1706	5413
$>7.5\cdot10^{-2}$ m	0	2	3	1	0	1403	5506	2908
Total	136	67	87	118	2460	5675	7405	8525
	Total number of all RFs				Total mass of all RFs			
Total	234	115	134	142	16,895	10,210	22,605	12,272

The soil deformation recorded in 05/2002 was surprisingly low as far as movement parallel to, and measured within, the plane of the pit walls was concerned (Tables 3–5). These data certainly show that the largest soil deformation within a time delay of 3 years was a $6\cdot10^{-2}$ m extension of line 1 in section Enda Maryam 1 North (Fig. 6). Other changes in distances between nails were much smaller and, therefore, might indicate intra-seasonal instead of extra-seasonal swell-shrink cycles. Plastic soil deformations, although manifestly visible in the soil profiles, could not be discerned by the measurements.

Another remarkable point is the survival of desiccation/creep cracks over a period of several seasonal swell-shrink cycles. All cracks mapped in 1999 were found back in 2002. In section Enda Maryam 2 West (Fig. 7), all cracks mapped in 01/1999 are still present in 05/2002. From somewhat above nail tracer line 3 to the bottom of the pit, the section is damp and wet, indicating the capillary rise of soil water during the small Belgh rains. In the wet part of the soil section the cracks were all closed and reduced to a hairline thin trace, only recoverable by eye because the section was thoroughly compared with the 01/1999 drawing. But in the upper dryer part of the section, the cracks were still open widely as drawn in 01/1999. In the case of an ascending capillary front, crack closure obviously would follow the position of the front and proceed as a very slow peristaltic-like movement.

Other soil movements occurred. During emptying of the pits in 05/2002, the original pit walls at Enda Maryam 2 West (Fig. 7) and Hagere Selam May Dansi (Fig. 4) were not straight anymore, but undulating with

Table 3
Section Enda Maryam 1 North

Nail tracers	Original distance 01/1999 (10^{-2} m)	Distance on 05/2002 (10^{-2} m)	Difference (10^{-2} m)
Line 1			
I–II	50.0	56.0	+6.0
Line 2			
III–IV	50.0	48.1	−1.9
IV–V	50.4	47.8	−2.6
V–VI	49.3	50.5	+1.2
VI–VII	49.9	52.0	+2.1
VI–10	30.1	31.5	+1.4
1–4	30.0	28.5	−1.5
7–8	30.0	29.5	−0.5
V–6	29.9	31.0	+1.1
Line 3			
VIII–IX	49.8	47.1	−2.7
IX–X	49.7	48.2	−1.5
X–XI	50.5	50.4	−0.1
XI–XII	49.7	50.1	+0.4
VIII–XII	197.1	196.5	−0.6
VIII–XI	149.0	147.4	−1.6
Distances between lines 1 and 2			
I–VI	49.5	50.9	+1.4
II–VII	50.0		
distances between lines 2 and 3			
III–VIII	51.4	51.0	−0.4
IV–IX	50.0		
6–17	51.0	50.5	−0.5
7–20		51.5	
VI–XI	51.0	51.5	+0.5
VII–XII	50.5	48.5	−2.0

Position of nail tracers: see Fig. 6.

Table 4
Section Enda Maryam 2 West

Nails	Original distance 01/1999 (10^{-2} m)	Distance on 05/2002 (10^{-2} m)	Difference (10^{-2} m)	Wall bulging (10^{-2} m)
Line 3				
VIII–IX	50.5	51.0	+0.5	
IX–X	50.6	49.5	−1.1	
X–XI	49.5	47.0	−1.5	
XI–XII	50.3	50.0	−0.3	
VIII				~+20
1				~+20
2				~+20
3				~+20
4				~+20
5				~+18
6				~+16
7				~+12
8				~+12
9				~+4
Line 4				
XIII–XIV	49.6	49.5	−0.1	
XIV–XV	50.0	48.5	−1.5	
XV–XVI	50.0	47.5	−2.5	
XVI–XVII	50.5	52.0	+1.5	
Line 5				
XVIII–XIX	50.0	50.5	+0.5	
XIX–XX	50.0	49.5	−0.5	
XX–XXI	50.0	51.5	+1.5	
XXI–XXII	54.0	55.0	+1.0	
XXII				+15
Distances between lines 1 and 2				
II–VII	50.0			
Distances between lines 2 and 3				
III–VIII	50.5			
V–X	49.5			
VII–XII	59.5			
Distances between lines 3 and 4				
VIII–XIII	50.5	50.0	−0.5	
X–XV	50.5			
XII–XVI	71.5	70.5	−1.0	
XI–XVII	71.4	71.0	−0.4	
XIII–VIII	50.5			
VIII–XIV	71.0	72.5	+1.5	
XIII–IX	71.1	69.0	−2.1	
Distances between lines 4 and 5				
XIII–XVIII	50.5	48.5	−2.0	
XIV–XVIII	72.1	71.5	−1.0	
XIV–XX	70.3	68.5	−1.8	
XVI–XX	71.6	71.0	−0.6	
XVI–XXII	73.5	75.0	+1.5	

Position of nail tracers: see Fig. 7. Positive values of wall bulging indicate bulging, negative value retraction.

Table 5
Section Hagere Selam May Dansi 05/2002

	Vertical displacement (10^{-2} m)	Wall bulging (10^{-2} m)
Nail number line 2		
1	None	None
2	+2.0	+5.0
3	+2.0	+8.5
4	None	+7.5
5	None	+3.0
6	None	+4.0
7	None	+5.0
8	None	+2.0
9–13	None	None
Nail number line 3		
1	−1.0	−9.0
2	−1.0	−6.0
3	−1.0	−4.0
4	None	−2.0
5–15	None	None

Position of nail tracers: see Fig. 4. Positive values of wall bulging indicate bulging, negative value retraction.

lateral bulges and retractions. The nail tracer heads coincided with the hummocky surface of the deformed pit wall, showing that cleaning of the pit wall was well done. Tables 4 and 5 present the amount of pit wall bulging as judged from the position of the nail heads. Exact measurement of pit wall bulging is impossible by the Young-pit method. Photographic evidence (Fig. 12) shows that the estimation of a bulge of $2 \cdot 10^{-1}$ m is conservative. Furthermore, the upper side of the bulge is delineated by a bundle of nearly flat lying slickensides, closely coinciding with the limit of capillary rise mentioned higher (Fig. 7).

At Hagere Selam May Dansi, the pit wall deformation was even more impressive. Table 5 shows the data, but the drawing of the pit (Fig. 4) clearly shows that two failure planes with large slickensides were active. Both dip at an angle of 19° and indicate relative displacements of more than $10 \cdot 10^{-2}$ m. The failure planes affect the short wall of the pit and in the same time the opposite long wall. Obviously, the pit simply underwent ground movements in sympathy with the surroundings. Comparable important soil movements did not take place in Enda Maryam 1 North. Maybe the current relaxation of $6 \cdot 10^{-2}$ m (Table 3) of the soil into the direction of the recent gully wall did prevent accumulation of other tensions.

One of the most important results is that soil movements, visually recorded in two pits, are oriented much more horizontally than vertically. The evolution of the crack pattern in the circular experimental plot at Enda Maryam illustrates the importance of displacements and deformations in plan view. First of all, the yearly changes

Fig. 12. The bulge in section Enda maryam 2 West on 05/2002. Compare to Fig. 7. The notebook in the upper left corner is 14 cm wide.

of the polygonal form are shown (Fig. 13A, B, C). Secondly, these three figures have been superposed to find the best fit between the major characteristic crack patterns of 1999, 2000 and 2001. The best fit between 1999 and 2000 is produced by a translation of ±30–50 cm and a clockwise rotation of ~5°. To fit the characteristic crack patterns of 2001 with 1999, the total translation increases to 45–70 cm and a rotation of nearly 10° clockwise (Fig. 13D). The Vertisol creeps or slowly slides over a basal shear plane. This movement is accompanied by rotation of the polygonal structure around its central vertical axis and by minor changes in its plan form. The mass movement is oriented in the direction of the gully, about 30 m away.

However, it remains unclear whether these soil movements, mainly sub-horizontally directed, can explain the vertical lift of so many RFs. Obviously, RFs can be transported along failure planes and slickensides, but in the study area slickensides never reach the surface, although they occur at rather low depths compared to theory (Yaalon and Kalmar, 1978).

3.5. The loci where RFs appear at the surface

Preliminary results from the circular experimental surface at Enda Maryam show that the distribution of RFs, that are observed to be moving towards the soil surface, resembles the polygonal configuration of the shrinkage crack bundles (Nyssen et al., 2000a; Nyssen et al., 2002b). The RF clearings of 05/2002 and 05/2003 clearly confirm this. Only about 50 RFs out of all 853 RFs collected at the Enda Maryam site (Table 1) are found more than 25 cm away from the nearest major crack. The RF distribution underlines the polygonal structures present (Fig. 14). It is known that RFs on the soil surface will tend to be redistributed in sorted nets if they are exposed to randomly oriented movements in small steps (Ahnert, 1994) like, for example, the trampling by passing cattle. But the sorted nets at Enda Maryam follow the configuration of the crack patterns, and RFs seem to concentrate in belts of crack junctions or crack concentrations. Therefore, it was suggested in preliminary publications that the RFs come to the surface along the cracks in the soil. This observation led to a study of the vertical distribution of the stock of RFs within the soil and their position in relation to soil structures. In view of future measurements, the circular experimental plot was not destroyed, but at a distance of about 100 m (Fig. 2) the 12 m long and 2 m deep soil pit ‘Enda Maryam Polygon’ was dug (Fig. 8). The polygonal crack pattern has been indicated. The soil section crosses part of polygons I, II and III and the boundary between two other polygons.

3.6. The underground extension of shrinkage cracks and slickensides

All visible desiccation cracks that were judged to have existed before excavation of the pit, were mapped within the precision of 1 cm (Fig. 8). Many cracks reach a depth of more than 1 m, and some penetrate into the top of BC injections in B. Such diapir-like phenomena appear below the transition between polygons I and II and to the right of polygon III where the soil profile sits on the edge of two other polygons. Inset 1 (Fig. 8) shows two soil cracks, penetrating the edge of the BC-‘diapir’.

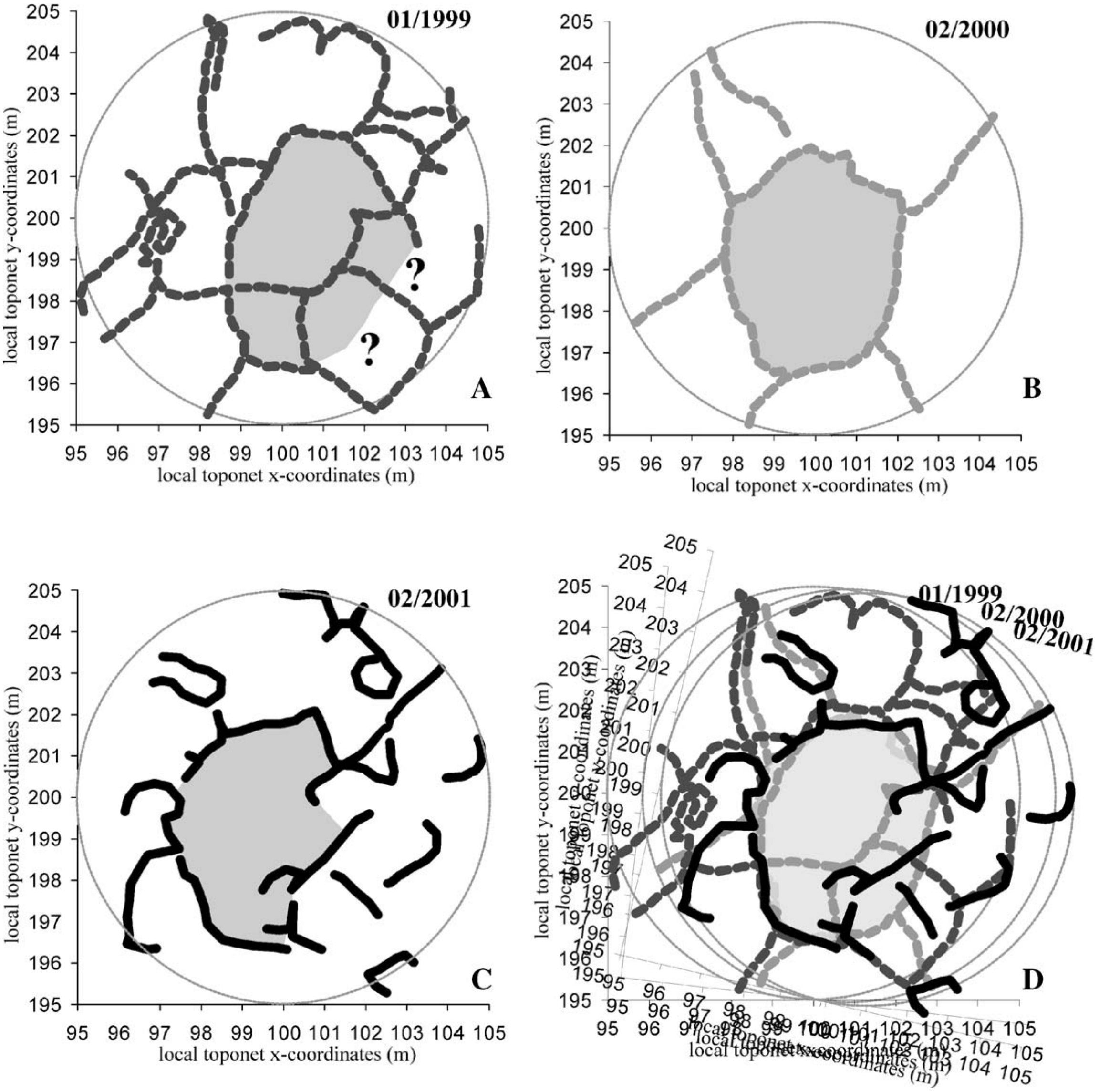

Fig. 13. Visible soil crack patterns in the circular experimental plot at Enda Maryam. (A) Pattern in 01/1999; (B) in 02/2000; (C) in 02/2001. The 02/2000 situation (B) has been derived from a photograph, situations (A) and (C) by theodolite. The central polygon is indicated in gray. Although not evident at first sight, several major cracks are common in the three pictures. The best fit of characteristic crack patterns in 1999, 2000 and 2001 (Fig. 13D) indicates combined translational (30–50 cm) and rotational (±5°) movements between 1999 and 2000. In 2001, translation increases to 45–70 cm and clockwise rotation to ±10°.

These cracks do not show a deviation at the BC–B boundary. This rules out any active plastic soil deformation since the origin of the crack.

Slickensides have also been mapped. It is assumed that many more slickensides are present but only the visible ones could be indicated (Fig. 8). At several places (e.g. above the 2 m index of the horizontal axis) the shrinkage crack with RF 14 (Fig. 8, inset 1) at its base is crossed by a slickenside which causes a dislocation of the shrinkage crack by a left-lateral-like movement. RF 15 sits on the intersection of both discontinuities. In this particular case the polished surface of the slickenside is visible, but often (e.g. the upper part of the same crack) a slickenside is not visible in spite of the angular distortion of the crack.

Two series of slickenside 'bow structures' (Dudal and Eswaran, 1988; Eswaran and Cook, 1988; Mermut et al., 1996) exist, one in the B-horizon, and one in the BC-horizon. The suggested undulations, syncline-like structures in the B-horizon, strictly coincide with the

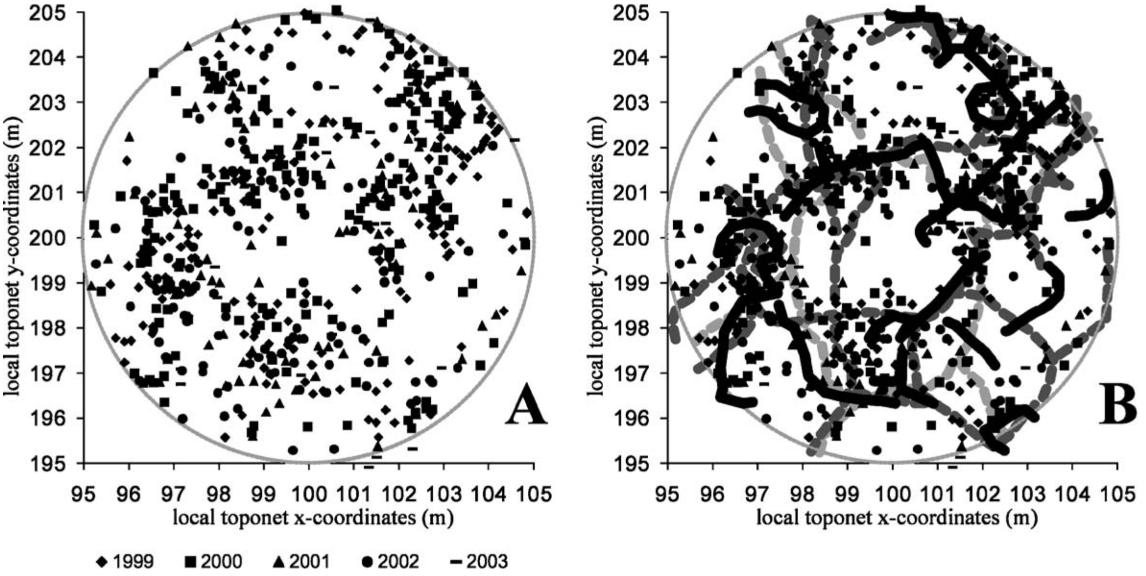

Fig. 14. (A) Position of all RFs, cleared from the circular experimental plot at Enda Maryam from 01/1999 to 05/2003. Not included are the unembedded RFs from 05/2003. (B) Comparison of (A) with crack patterns from 01/1999, 02/2000 and 02/2001.

dimensions of the polygons recognized at the soil surface. The slickensides rise up towards the edges of these polygons. In the BC-horizon, however, the visible 'bow structure' is wider than the polygons at the soil surface. It dips away at the limit between polygons II and III but it comes up only below the centre of polygon I. As far as we know, the phenomenon of two bow structures with different amplitude in the same Vertisol has never be mentioned in literature. It is hypothesized that two superposed horizons with discordant bow structures might represent the superposition of two Vertisols.

3.7. Underground RF distribution and position in section Enda Maryam Polygon

In section Enda Maryam Polygon (Fig. 8), distinction has been made between RFs in contact with a crack or a slickenside and those surrounded by unfissured earth. Out of the 136 RFs mapped within the section underground, 92 RFs are located either in the edge of shrinkage cracks or along slickensides (Fig. 15). But 5 RFs are embedded in the sandy base below the Vertisol. Further, it should be mentioned that it was nearly impossible to scrape the clay pit wall. Rectification of

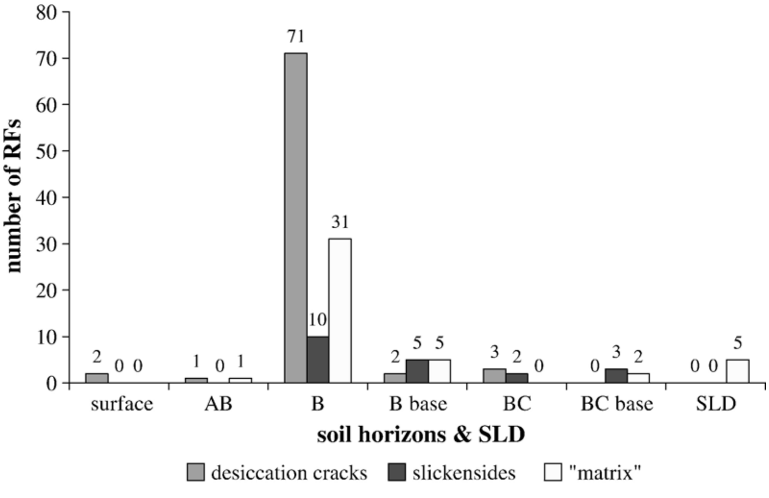

Fig. 15. The association and position of RFs in the soil horizons of section Enda polygon which was depicted in Fig. 8. Note that the total number of RFs in this graph is 143, because 5 RFs are located at the intersection of a desiccation crack with a slickenside.

the wall took mainly place by lateral removal of soil 'islands', delineated by soil fissures. This implies that the pit wall surface corresponds to multiple vertical cracks and, therefore, most RFs, mapped as 'matrix' embedded, are in reality located along a vertical crack. Taking this into account, it can be assumed that at least three quarter of the RFs in the Vertisol sit along soil matrix discontinuities. Five RFs are on the intersection of slickensides and desiccation cracks.

All RFs along a crack or a slickenside have one of their long axes parallel to the discontinuity. This means that RFs along sub-vertical joints are in an 'upright' position, except where the crack itself is locally flat lying. Below ~10^{-1} m depth, all soil fissures become smaller than the thickness of the adjacent RFs. This excludes RFs from attaining higher depths by free fall from the soil surface. In the section (Fig. 8) only RFs 92, 118 and 119 could possibly have fallen back. RFs 137 and 138 rest on the soil surface but are thin enough to tumble back into the crack containing RFs 69, 70 and 71 (Fig. 8, inset 2).

A total of 119 out of the 136 RFs occur in the B-horizon, at a mean density of 3.05 RFs m^{-2} pit wall. The BC-horizon, which separates the supposed RF stock in SLD from the B-horizon contains only 10 RFs what gives a density of 1.7 RFs m^{-2}. But taking into account that RF 126 is really close to the upper border and 5 RFs are sitting in the lower boundary, only RFs 12, 13, 14 and 16 are somewhat in the center of the horizon. This gives the impression (Fig. 8 and inset 1) that this horizon is virtually empty. The SLD outcrop is small but contains 5 RFs, which results in a density of 5.71 RFs m^{-2}. This image of vertical distribution of RFs closely resembles the theoretical vertical RF distribution in Vertisols (Nyssen et al., 2002a) with a high RF concentration in the RF-bearing basal layer, a low number at the base of the Vertisol and an increase of RFs towards the top of the Vertisol.

The tendency of RFs to concentrate along sub-vertical cracks is also observed in most other sections. In section Enda Maryam 2 West (Fig. 7), in the center of the side valley of the main pass, 6 RFs are concentrated along the 1.5 m long crack along nail tracers VI–XI–XVI–XXI. Six other RFs touch the crack between nails X and 9. At the reopening of the pit in 05/2002, not all RFs have been found again, but not one single RF along the cracks had moved significantly relative to the nail tracers. Several reasons can be invoked for having not observed underground RF movement, but we only will refer to the possibility that the pit fill influenced the behaviour of the original pit wall.

4. Discussion

4.1. Facts and consequences about the presence of RFs upon the Enda Maryam Vertisol

1) The petrographic composition of 625 RFs found in the circular experimental plot at Enda Maryam between 01/1999 and 05/2003 is clear evidence that these RFs arrived at the surface from a position originally about 2 m deep underground.
2) At the Enda Maryam experimental site, the RFs rise to the surface at a rate of 5 fragments m^{-2} in 3 years. At this rate the development of the current RF mulch on top of the Vertisol at Enda Maryam could have occurred in only a few decades to less than one century.
3) RFs at the soil surface can either be found along shrinkage cracks or in close proximity. Below the surface, a large majority of the RFs sit in an 'upright' position along the desiccation cracks. This can be seen up to depths of more than 1 m. Not one single RF of the 136 mapped in Enda polygon section (Fig. 8), could have been fallen from the surface to that depth. The only plausible interpretation is that RFs migrate to the surface along sub-vertical desiccation cracks.
4) In the deeper Vertisol horizons, RFs generally occur along slickensides.

4.2. Slickenside activity and RF displacement in the soil

In the Enda polygon section (Fig. 8), not one single desiccation crack reaches the supposed RF stock in the SLD at 2 m depth. The distance between the top of the SLD and the deepest level where desiccation cracks arrive is spanned by slickenside structures in the BC-horizon. Some of them 'scrape off' the top of the SLD and contain RFs 72, 73 and 74 (Fig. 8, inset 2). Other slickensides contain RFs 12, 13 and 14 (Fig. 8, inset 1). RF 14 is located on the intersection between the slickenside and a desiccation crack. The spatial association of the slickensides and soil horizons shows that RFs can be transported upward from the substrate to the base of the shrinkage cracks.

4.3. The process of RF lifting along subvertical desiccation cracks

It remains to explain how a RF can migrate to the soil surface once it sits along a shrinkage crack. The surface location of many RFs in a dispersed array along the desiccation crack network (Fig. 14) might indicate that the RFs arrive at the surface when the shrinkage cracks are closing or are closed. In this way RFs can undergo small displacements over the soil surface without being trapped again in the fissure along which they came to the surface. We hypothesize that the upward movement of RFs along a closing crack might be analogous to the pushing forward of an object in a peristaltic tube. The desiccation cracks' closure, progressing from deep in the soil towards the surface (Bouma and Loveday, 1988), can be compared with a peristaltic movement. It is known that crack closure during the first stage sometimes is due to swelling of the material, close to the crack edge (Fabre et al., 1997). This muddy substance can further facilitate RF lift by lubrication and by upward drag. It is not supposed that a RF, coming from 2 m depth, reaches the soil surface in a single period. Rather it will move only over some short distance during passage of the closure movement.

The process of underground movement of RFs at Enda Maryam is schematically represented (Fig. 16). This hypothesis takes into account the observed longevity of soil cracks, able to open and close repeatedly in response to the seasonal succession. Further, the direction of shrinkage crack closure is important. Closure advance from the surface to the underground, would force RFs to migrate downward. Closure starting at the same time from the top and the base of shrinkage cracks should, theoretically, result in a concentration of RFs somewhere in the middle of the soil profile, where closure occurs in last instance. In this way, the depth of concentration of RFs in a Vertisol would be indicative of the hydrological regime of this soil. RF concentration on top of the soil, which is the case at Enda Maryam, should indicate a rise of the capillary fringe from deep in the soil to the surface during the rainy season.

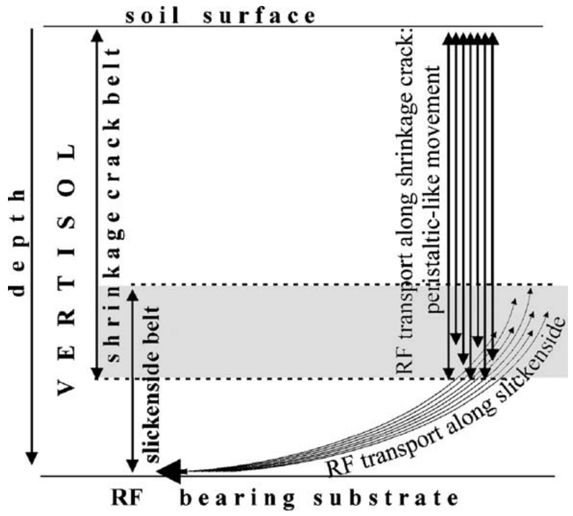

Fig. 16. Schematic representation of the process of underground RF movement in the Vertisol of Enda Maryam. Without vertical overlap of the slickenside belt with the shrinkage crack belt, a RF from the substrate is unable to reach the surface. For further explanation, see text.

5. Concluding remarks

1. The ascent of RFs from a 2 m thick Vertisol to the surface at Enda Maryam is related to active movements along slickensides deeper in the soil and to seasonal opening and closure of desiccation cracks repeated over the years. No relation could be established between the rise of RFs and plastic movements of the 'chimney' or 'diapir' or 'churning'-type, caused by differential loading or by fine earth material fallen into open cracks. Evidently, RF rise to the surface depends primarily on the presence of a stock of RFs deeper in the soil profile.
2. The important rate of up-squeezing of RFs at Enda Maryam is not an indication of important overturning and self-mixing of the soil (Buol et al., 1980), neither by brittle nor ductile behaviour of the clay matrix. The measurements rather indicate the existence of sub-horizontal movements in the soil, only seldom leading to complete overturn. This is confirmed by the existence of pedogenetic horizons, differing in texture, structure, $CaCO_3$ content and humic material. We are not the first to use this argument against the hypothesis of heavy Vertisol self-mixing (Wilding and Tessier, 1988).
3. From the previous conclusions, the up-squeezing of RFs should not be restricted to Vertisols. Every soil showing active desiccation cracks should have this capacity. In the study area, the Vertisol is the end member of the Luvisol–Leptosol–Regosol–Cambisol–Vertisol catena on basalt (De Geyndt, 2001). Many of these soils show shrinkage cracks during the dry season and often carry an interlocking RF pavement, much more important than the thin discontinuous veneer of RFs on the valley Vertisols (Nyssen et al., 2002a). In these cases a portion of the RF mulch could have been squeezed up, with tillage (Nyssen et al., 2000b) or leaching of fines only speeding up the process in its last phase.
4. The speed at which RF mulches develop on the valley Vertisol at Enda Maryam raises the question of their age. According to the measurements, the mulches should not be old. At the rate of up-squeezing of 5 fragments m^{-2} in 3 years, a mulch

with a density of 100 RFs m^{-2}, a density never measured on the valley Vertisol at Enda Maryam, should only be 60 years old. There are reasons to believe that this conclusion is right. Studies of the age of gullies in the study area shows that most Vertisol valleys were not incised by a gully 50 years ago. They were perennially wet and swampy places where sometimes people drowned (Veyret-Picot et al., 2004). At that time, soil shrinkage and slickenside formation, the driving forces for the up-squeezing of RFs, probably were not prevalent. On the other hand, this was the perfect environment to create plastic deformations in the soil by differential loading (Wilding and Tessier, 1988). It is noticed here that the study of the desiccation cracks in several sections revealed that all visible plastic perturbations are older than the cracks, because of the absence of any related deformation of the latter. It seems logical to separate in time brittle behaviour from ductile behaviour because both types normally depend on a different water content of the clay. 'Injections', 'involutions', 'intrusions' and 'diapir' formation in Vertisols should, therefore, happen either during the wettest period of the year or during the whole year, and deeper in the soil in places where water content is permanently high or during a former period of perennial soil humidity in the valleys.

5. Valley Vertisols occur not only in Ethiopia but in the whole Nile basin. While the Ethiopian valley Vertisols carry a discontinuous mulch of RFs, their counterparts in the Sudanese Sahara are covered by a pavement of interlocking clasts. At the Sudanese–Egyptian border (Van Peer et al., 2003), the Vertisols in the Nile silts are inactive due to dryness and the former pattern of shrinkage cracks and slickensides is fossilized and perfectly recognizable. We suppose that these desert pavements have the same origin as the RF mulches in Ethiopia and that they indicate former wetter conditions with seasonal variations in soil water content, oscillating from above to below the shrinkage limit of the underlying clay soil.

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