EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 13, 511–524 (1988)

THE COMPLEX NATURE OF CREEP MOVEMENTS ON STEEPLY SLOPING GROUND IN SOUTHERN RWANDA

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Received 10 March 1987
Revised 7 August 1987

ABSTRACT

Long term soil creep motion is often represented as a type of laminar flow, with velocity vectors parallel to the slope and constant in time. Records on a hillslope in Southern Rwanda reveal that creep movements there compare more with turbulent flow, characterized by a A1 humic horizon superlayer, creeping over a subsoil affected by more irregular creep deformation.

KEY WORDS Creep Young-pit Creep line Slide plane

INTRODUCTION

In 1978, twenty-five Young-pits (Young, 1960) have been installed on Rwaza Hill, about 3 km to the northwest of Butare, Southern Rwanda. Rwaza Hill is an elongated outlier of a main crest, separating Mwogo from Akanyaru head-waters (Figure 1). The Young-pits are situated along three cross-profiles, whose localization is indicated on Figure 1. Figure 2 shows the three cross-sections with the 25 Young-pits from 1978 and three other trenches used as such.

Rwaza Hill displays a morphology typical for Southern Rwanda, where most hills are convex in form, with a rather flat summit. Cross-profiles RWAZA 1 and RWAZA 2 (Figure 2) are representative for this hill type. Other hills or parts of hills have a topography as in cross-section RWAZA 3, with steep, nearly rectilinear slopes and a sharply rounded short crest. It is generally accepted that the occurrence of these two hill types reflects variations in the lithology of the Precambrian substrate, whereby the flat topped hills are composed out of soft rocks as phyllites and the steep hills of more quartzite rocks (Salee, 1928). Rwaza Hill is completely formed on phyllites somewhat coarser and more quartzitic on top of RWAZA 3 than on the other cross-sections.

Southern Rwanda enjoys a moderate climate. Mean annual temperatures vary slightly around 20° C, while mean annual precipitation at Butare amounts to 1166 mm (Sirven, Gotanegre and Prioul, 1974). From our own records at Rwaza Hill, it appears that the total precipitation varies from year to year. So, a continuous decline from 1135 mm in 1979 to 713 mm in 1984 has been observed. During the subsequent years the amount of precipitation has risen again to its normal level. Two rainy seasons can be distinguished. The first one starts in the middle of September and continues till December. The big rain season goes from January till the end of May. Up to 40 per cent of the total annual precipitation can be concentrated in the months of March, April, and May. The small dry season of January is sometimes very pronounced, sometimes nearly nonexistent.

Although an important part of Rwaza Hill is under cultivation, the three cross-sections, shown in Figure 2, are situated in grassland, interrupted at a few places by small forests of *Eucalyptus* sp. The grassland serves as

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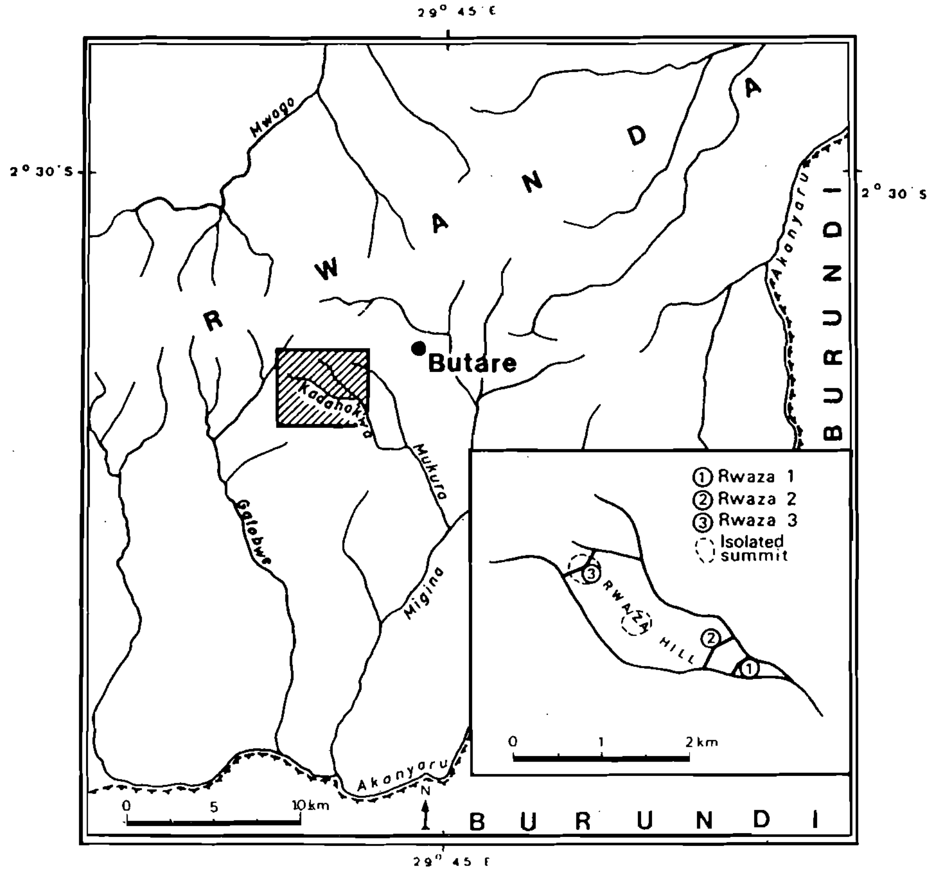

Figure 1. Localization of Rwaza Hill in Southern Rwanda

grazing ground for small herds of cows and goats. Over the last five years, the common practice of overgrazing at the end of the dry season has been greatly abandoned. Common grass types are *Cynodon dactylon*, *Brachyarya* sp., *Eragrostis* sp. and *Digitaria* sp.. Although the grass cover is generally rather dense, runoff is important during heavy rains, especially near to the end of both rainy seasons. While most of the time this runoff can be qualified as 'Horton'-runoff, saturated overland flow sporadically occurs. Our own measurements by means of erosion pins and collectors have shown that wash accounted for a mean ablation of about 2 mm yr^{-1} on slope RWAZA 3B (Figure 2). However, as grazing there has been forbidden since the end of 1984, erosion has been reduced considerably and is for the moment insignificant, as a result of increased protection by the now well-developed grass cover.

The Young-pits provided a lot of information on the soils. In Young-pit GL-78, situated on the lower half of slope RWAZA 3B (Figure 3), a kaolinitic soil mainly composed of a more than 1 m thick red earth is developed on the substrate of Precambrian coarse phyllitic rocks. This horizon is overlain by a 20 to 40 cm thick humic A1 horizon. The transition between the A1 and the red subsoil is made by a very loosely packed layer, mainly consisting of small aggregates, often in a laminated arrangement. Macropores, irregular voids, and cavities occur in this horizon. In some cavities sediment has been deposited. This transitional horizon is irregular in extension and thickness. Its location in GL-78 is indicated on Figure 3. The red homogeneous subsoil starts below this intermediate horizon. The humic horizon on top and the red subsoil below differ in texture, composition and soil mechanical behaviour (Table I). The middle horizon shows transitional textural and compositional characteristics.

An important aspect of the ground surface is the occurrence of terracettes, especially on the steep parts on slope RWAZA 1 and RWAZA 2 and on the whole slope of RWAZA 3. Some terracettes are visible on Figure 3. As can be seen, they originate along cracks or fissures (6 and 7 on Figure 3), which cross the humic

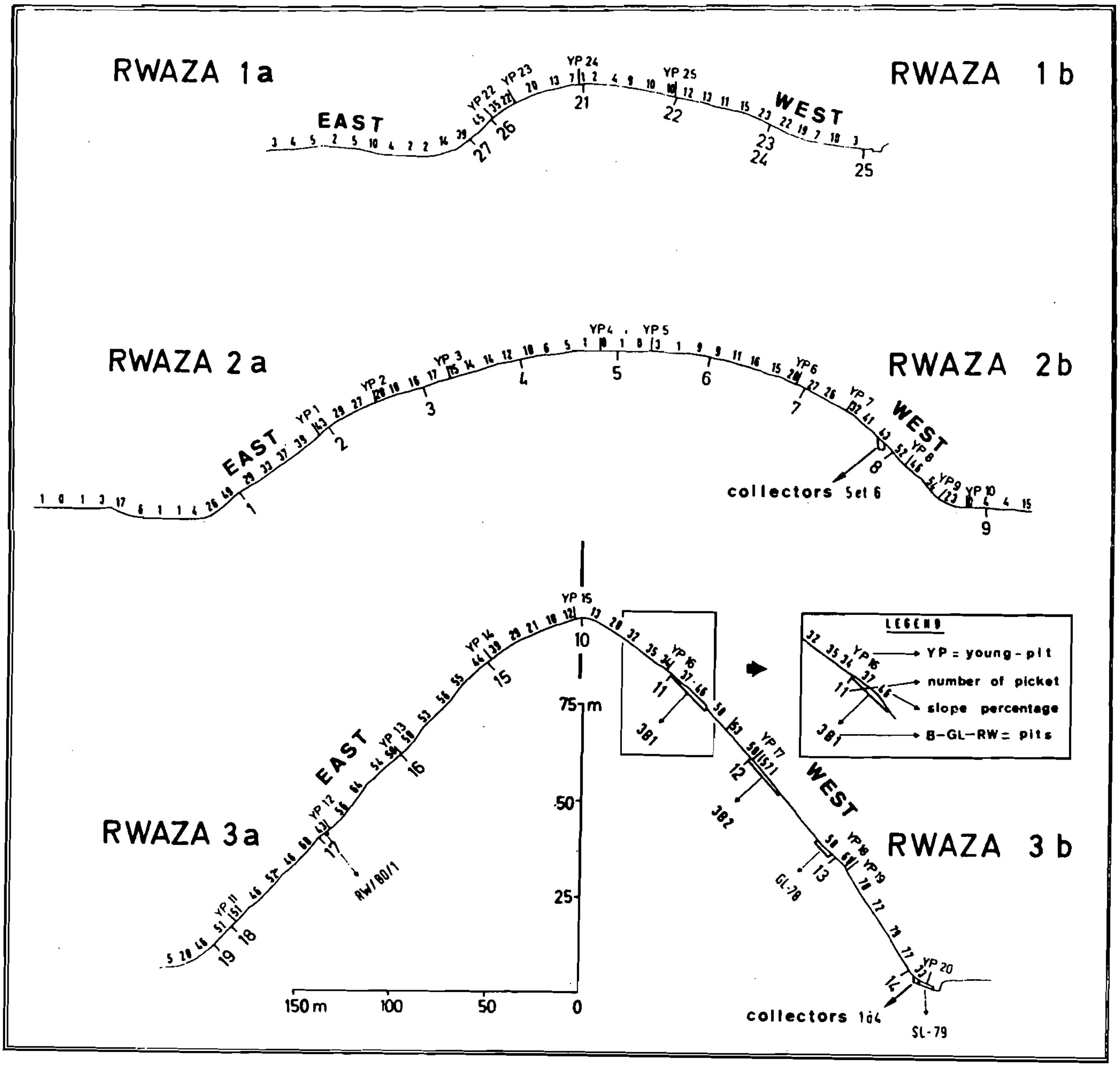

Figure 2. Localization of Young-pits along three cross-profiles of Rwaza Hill

horizon. Crack 1 corresponds to the steep side of a step, appearing about half a metre behind the pit wall. Finally, the terracette form on the left side of the wall results from displacement of block 4 over plane 2–3.

The terracetted aspect of the slopes, the bending of trees and the presence of an old slide not far from RWAZA 3B, led to the hypothesis that the slopes on Rwaza Hill should be affected by creep. The Young-pits were installed to verify this hypothesis.

CREEP: A *STATUS QUAESTIONIS*

Soil creep has been defined as 'the slow downslope movement of surficial soil or rock debris, usually imperceptible, except to observations of long duration' (Sharpe, 1938).

Generally, distinction is made between seasonal and continuous creep (Terzaghi, 1950). Seasonal creep is believed to be generated by the action of crystal growth, root development and decay, chemical changes, soil

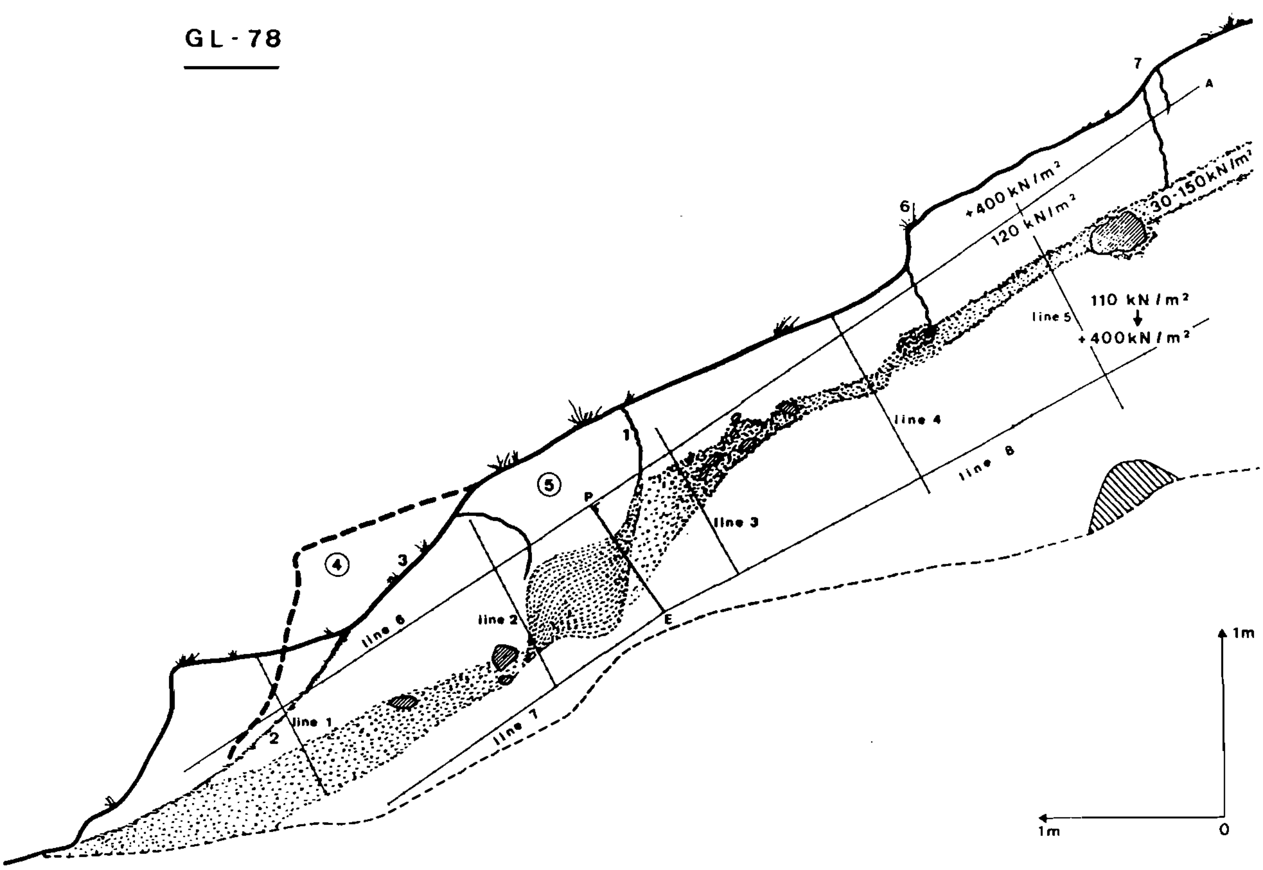

Figure 3. Soil structures in GL-78 and localization of tracer lines 1 to 8

Table I. Characteristics of the different soil horizons at Rwaza–Rwanda

	Humic horizon	Intermediate horizon	Red subsoil
texture			
clay content (< 2 μm)	12%–19%	mixture	23%–33%
sand and gravel (> 63 μm)	40%–66%	mixture	26%–35%
nature of clay	kaolinite	kaolinite	kaolinite
specific weight	25·8 kNm^{-3}		26·3 kNm^{-3}
plasticity index	3%–15%		5%–15%
unconfined strength			
(pocket penetrometer)	118 kNm^{-2}–392 kNm^{-2}	29 kNm^{-2}–147 kNm^{-2}	108 kNm^{-2}–392 kNm^{-2}
mean derived dry bulk density			
for 15% original water content	13·41 kNm^{-3}		14·58 kNm^{-3}
for 30% original water content	11·01 kNm^{-3}		13·83 kNm^{-3}
apparent cohesion *C′*			
(Torvane shear device)			
at 9% water content	61 kNm^{-2}	54 kNm^{-2}	100 kNm^{-2}
at 16% water content	41 kNm^{-2}	0 kNm^{-2}	36 kNm^{-2}
at 19% water content	32 kNm^{-2}	0 kNm^{-2}	0 kNm^{-2}
apparent angle of internal friction			
(portable soil sheargraph)			
at 10% water content	40°–43°	38° } with appreciable	53°–58°
at 30% water content	37°–41°	25° } range	29°–38°

disturbance by faunal activities, and by cyclic changes of temperature and soil moisture content (Embleton and Thornes, 1979). All these factors contribute to a rearrangement of the soil skeleton in seasonally bounded pulses, affecting essentially the upper centimetres or decimetres of the soil profile (Gaucher, 1981).

On a slope these randomly oriented disturbances are deviated in downslope direction by the gravity component parallel to the slope. As to the nature of the process, a discussion is still going on whether it corresponds to shear between individual soil particles (Kirkby, 1967) or to diffusion of soil particles from areas with low to high void density (Culling, 1983). Seasonal creep has been reported from different parts of the world (e.g. Jahn, 1981; Dedkov and Tchasovnika, 1978; Lewis, 1976; Young, 1960) and laboratory experiments have been carried out to investigate the effect of isolated factors such as soil moisture variations (Kirkby, 1967) and freeze–thaw cycles (Davison, 1889; Pissart, 1971). The velocity–depth profile from a creeping soil has sometimes been subjected to a process-oriented interpretation (Jahn, 1981). One of the problems is that theoretical considerations only provide two types of velocity profiles (Figure 4), while in nature both types as well as mixtures of both types as profiles with completely different configuration occur.

This can be illustrated by our own measurements at Rwaza. Figure 5 shows not less than seven types of velocity profiles. They represent most of the varieties of the velocity profiles recorded in the twenty-five

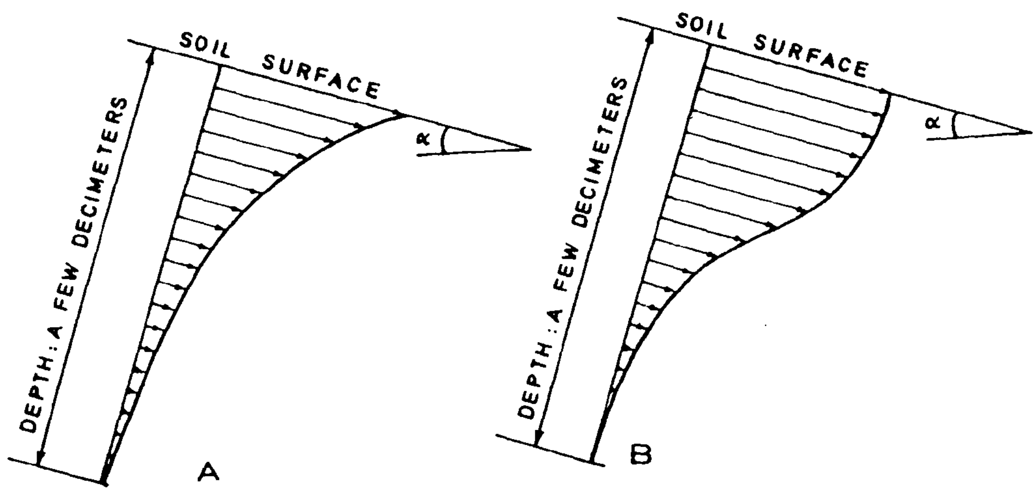

Figure 4. Theoretical velocity profiles in seasonally creeping ground, derived by Kirkby (1967). A. from the intra-cyclic soil particles' movement as assumed by Davison (1889) and B. from movements recorded by himself. Note the extra-cyclic movement representation in form of vectors parallel to the surface and in downslope direction, suggesting some type of laminar 'flow'

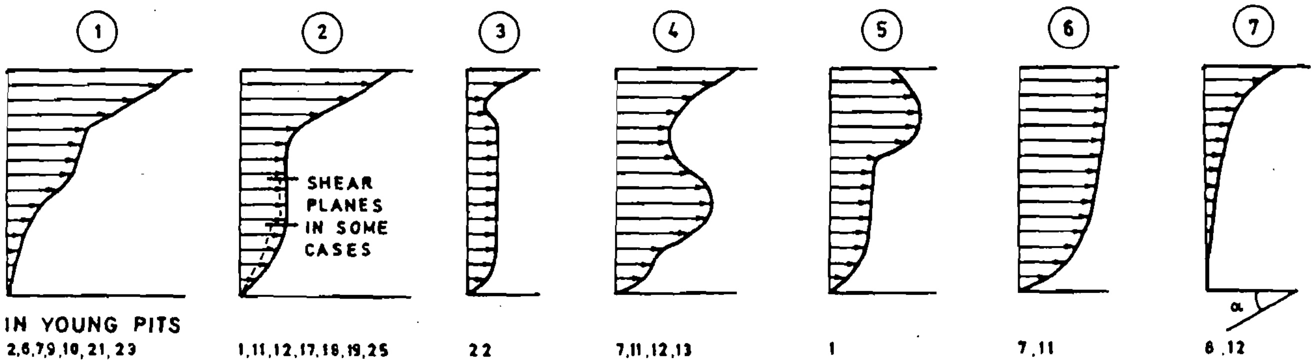

Figure 5. Seven types of velocity profiles as recorded at Rwaza (Rwanda) in 25 Young-pits, 50 cm deep. Movements are relative to the lowermost blade tracer and are exaggerated about one order of magnitude to depth. Note that different types of velocity profiles sometimes were recorded during successive measurement periods (1 to 4 years!) in the same pit. Some velocity profiles resemble records mentioned in the literature: (1) resembles the La Paguera type (Lewis, 1976), and type 6 of Jahn (1981), (4) the Mariemonte type (Lewis, 1976), (6) type 3 of Jahn (1981), (7) type 1 of Jahn (1981) and Figure 1A. As the velocity vectors indicate, only creep movement components, parallel to the slope were recorded

Young-pits after measuring periods going from 1 to 4 years. Most of the pits are 50 cm deep and the aluminium blade tracers (5 × 5 cm, half a mm thick) were originally placed on a straight line, nearly perpendicular to the surface. The measuring technique implied the reconstruction of a line with exactly the same inclination as the original one. A wooden protractor with a radius of 55 cm has been used for this purpose. The apparatus was calibrated by means of a counterweight to assure the exact vertical position of the zero line, when hanging freely on a nail inserted into a vertical wall. The reconstructed line was traced on the pit wall from the lower edge of the lowermost blade tracer. Distances between the middle of every blade and the reconstructed line indicate the respective movement components, perpendicular to the tracer line, and relative to the lowermost point of the line. The accuracy of the recorded relative movements is of the order of 1 mm.

The high number of velocity profile types and also the fact that repeated readings in the same Young-pit revealed sometimes different types of velocity profiles for two successive measuring periods (Figure 6) are very significant: it appears that the velocity profile in a seasonally creeping mantle is variable in both time and space, even in a very small area.

Unlike seasonal creep, continuous creep is brought about by the sole force of gravity, deforming soft soil material as to create a slow downslope oriented net transport on slopes (Terzaghi, 1950). The few available data suggest that continuous creep exceeds seasonal creep with one or more magnitudes in both rate—centimetres or metres per year (Ter-Stephanian, 1965) to millimetres per year (Young, 1960; Evereth, 1963; Iveronova, 1964; Leopold *et al.*, 1964; Kirkby, 1967; Skempton and Hutchinson, 1969; Eyles and Ho, 1970; Jahn, 1981)—and operational depth in the soil—metres (Ter-Stephanian, 1965; Kojan, 1968) to centimetres (Gaucher, 1981) or decimetres.

Continuous creep generally proceeds at a smooth, more or less constant rate (Fleming and Johnson, 1975). However, some cases have been recorded where dramatic accelerations have led to slope failure (Terzaghi, 1950; Skempton and Hutchinson, 1969), followed again by a creep rate, decreasing in time to characteristic low values (Terzaghi, 1950; Van Asch, 1984).

Sliding and continuous creep, therefore, have sometimes been considered as different expressions of the same process, a slide plane being merely a very narrow zone of soil deformation (Kojan, 1968). Investigations, however, have shown that long term creep can weaken the soil strength to values below the materials' peak

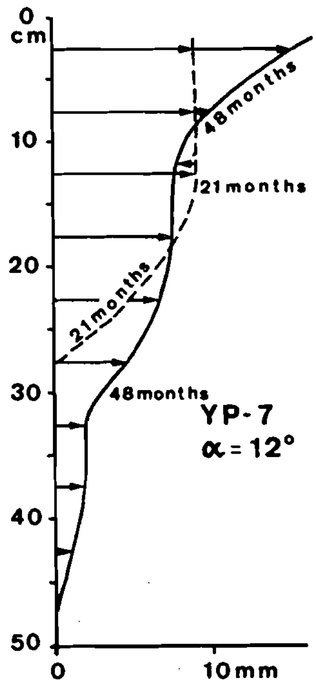

Figure 6. Creep movement records from YP-7 on Rwaza Hill. After 21 months the velocity profile corresponds to type 6 of Figure 5. After 48 months the velocity profile corresponds to type 4 of Figure 5. Only relative creep movements parallel to the slope are recorded

strength. Rearrangement of clay pellets (Goldstein *et al.*, 1961; Skempton, 1964), and the break down of internal bonds (Nelson and Thompson, 1977) play an important role. From the soil mechanical point of view, continuous creep occurs when the shear stresses in sloping ground lie between the fundamental strength (Griggs, 1936) of the soil material and the Coulomb shear strength, i.e. in the domain of elastic–plastic deformation (Ter-Stephanian, 1963).

So the phenomenon of continuous creep is generally treated mathematically as a viscous flow. This rheological approach enabled authors to describe in some detail the theoretical configuration of a velocity profile in a thick soil undergoing continuous creep (Yen, 1969).

Theoretical velocity profiles show progressive retardation with depth with a zone of rigidity on top. The few field measurements (Ter-Stephanian, 1965; Kojan, 1968) available in literature seem to confirm this picture. Our own measurements point to the same direction. Figure 7 shows the relative displacement in YP-11, which was deepened to 3 m in 1981. The measuring technique has been the same as for the 50 cm deep Young-pits, but thin nails instead of aluminium blade tracers have been used. From Figure 7 it appears that after three years the creep velocity profile becomes indeed regular with a retardation with depth. But like in some cases of near surface creep (e.g. Figure 6), the deep seated creep data for the first year reveal the presence of subsurface maxima in the velocity profile.

Although explanations about its origin have been presented in the literature for particular cases (Lewis, 1976), it has to be emphasized that they indicate a creep movement much more complex than theoretical

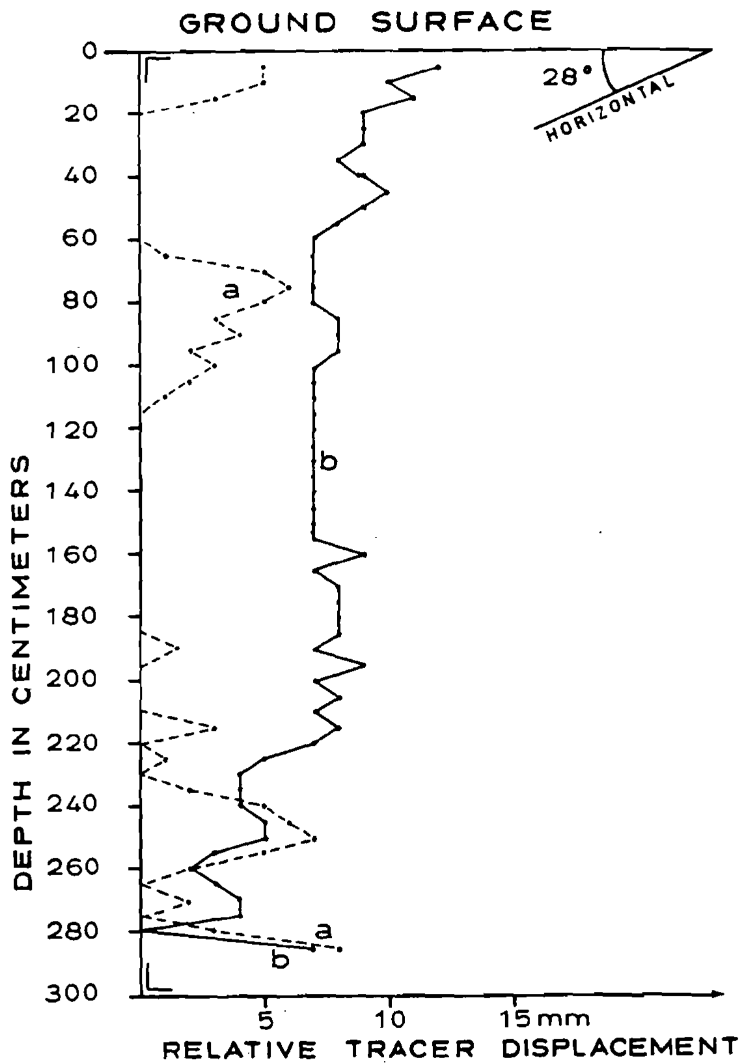

Figure 7. Relative tracer movement components parallel to the ground surface in Young-pit 11 EXT. at Rwaza. Installation: 15.10.1981. First measurement (a): 30.9.1982. Second measurement (b): 15.11.1984

considerations predict. The point to be stressed here is that in conditions of constant soil volume a subsurface maximum only can appear when the upper soil layer is prevented from following the movement of the underlaying layer. Lateral friction with, or compression against, other—slower moving—parts of the upper layer are the only possible explanations. This can only be interpreted in terms of differential creep movements in the underlaying layer. Thus the presence of subsurface maxima in the creep velocity profile in fact reveals the existence of differential creep rates in the soil at the same depth from place to place.

From the above it appears that velocity profiles in seasonally or continuously creeping soils are in many cases different from what theory predicts. The same is true when creep volume rates are considered: field measurements never show a clear relationship with one or other slope factor as would be expected on the base of theory. Our poor knowledge about creep is still better illustrated in the field of geomorphological application: although creep volume rates have been measured, only a few suggestions can be found in literature about how slopes are deformed by the displacement of—sometimes considerable—volumes of soil by creep (Schumm, 1956; Tschierske, 1979).

PRINCIPAL SHORTCOMINGS IN CURRENT CREEP MEASUREMENT TECHNIQUES

Although soil anisotropy can account for certain aberrations between theory and practice, it is felt that soil creep research has been hampered by a too simple representation of the actual movement of the soil. So it has been a tacit assumption in much previous work that the direction of the resultant creep movement is parallel to the ground surface resembling laminar flow (Iveronova, 1964). An example is given in Figure 4. In fact, this simple representation does not correspond to reality. In laboratory experiments where creep was induced by cyclic variations in soil moisture content it appeared already that the net extra-cyclic movement is not parallel with the surface and differs in orientation from point to point (Kirkby, 1967). Nevertheless, the image of parallel velocity vectors was so widely accepted that even many measuring techniques, such as pillar tracers, resting one upon another in a small auger hole (Anderson and Finlayson, 1975), in fact are designed to detect only the movement component more or less parallel to the surface. Some years ago, a twelve year creep record (Young, 1978), has finally shown that creep movements, indeed, can be far from parallel to the ground surface. In the specific case mentioned here, creep movements showed a very important vertical component, directed to the soil base. And recently, other measurements showed creep movement components which were oriented more or less randomly and not so much parallel to the slope line (Finlayson, 1981).

The different rates and orientations of the creep movement from point to point and in time and space explain why velocity profiles are so diversified and puzzling: they are merely the product of very complex movements, and cannot be understood or explained in terms of a laminar flow-like slow soil movement.

It is clear that measuring techniques, allowing movements to be monitored in two (Young, 1978) or three dimensions would greatly contribute to a better understanding of how creep operates and how soil structures and creep are interrelated. In this perspective it has been tried to record creep movements in the two dimensions of the pit wall of Young-pit GL-78 at Rwaza. One problem with field measurements, regardless of the technique used, is that they do not allow an easy distinction between continuous creep and seasonal creep. This is especially the case where both types of creep are active and where the movement of seasonal creep is superposed over the deeper seated movement of continuous creep as is suggested in the Rwaza case by the velocity profile of Figure 7. It seemed therefore opportune to use the single term 'creep' for all slow soil movement described below.

MEASURING TECHNIQUE USED IN YOUNG-PIT GL-78

Aluminium blade tracers have been inserted in the wall of Young-pit GL-78, along eight straight lines (Figure 3). Lines 1 to 5 were nearly perpendicular to the surface. The measuring technique, explained earlier, has been used here and hence allowed to record movement components, roughly parallel to the soil surface, and relative to the lower edge of the lowermost blade of every line. Relative soil movements, perpendicular to the soil surface were measured along blade tracer line 6 and line 7–8. Line 6 was situated at a depth between 10 and 40 cm. It was constructed from point A, the outer edge of the outermost blade.

Lines 7 and 8, have been constructed from point E, situated at a distance of 69.0 cm. from line 6. Lines 7 and 8 are at a depth of about one m. Lines 6, 7, and 8 could be traced and reconstructed after three and six years respectively by means of a simple technique, allowing an accuracy to the millimetre. The procedure for line 6 was as follows: during its first emplacement, a point at a distance of exactly 5 m from point A has been indicated on line 6. With a simple levelling-instrument—a transparant tube filled with water—the exact vertical distance between those two removed points could be determined. After re-excavation, line 6 could be reconstructed from A, using the same two known parameters. From the reconstructed line 6, point E could be identified again and from there, lines 7 and 8 could be reconstructed by the same technique as used for line 6, but, of course with their own parameters. Note that the reconstructed point E can have undergone a translation parallel with line 6. But this translation is measured by the deformation of lines 2 to 5.

As line 6 and lines 7–8 crossed lines 1 to 5, a resultant creep movement vector could be constructed in every point of intersection. Figure 8 shows the deformation of the original tracer lines of Figure 3 and the resultant creep vectors in the points of intersection, together with interpolated creep vectors between these points. On the basis of this result, a creep line pattern could finally be deduced (Figure 9).

The term creep line is used in analogy to the term flow line or flow path or streamline. Creep lines divide the considered surface into creep channels, between which there is no exchange of material by creep. Creep lines show thus the resultant direction of the creep movement. Converging creep lines hence indicate an acceleration of the creep movement in the direction of narrowing of the creep channel, unless soil material disappears by processes as solution or underground mechanical removal by percolating water, or by the removal of fines by worms, ants, or termites. Diverging creep lines indicate a retardation of the creep movement in the direction of widening of the creep channel, unless soil material is brought into the channel by chemical precipitation, deposition by soil fauna, or by percolating or infiltrating water. As the tracer lines were installed in 1978 and remeasured respectively in 1981 and 1984, two successive three year periods are shown on Figure 9. Also the six year global result is displayed. Some remarks should be made about the representativity of the creep line patterns. First they are rudimentary because of the still high distances between some tracer lines, so that details eventually are blurred. Second, there is probably a certain distortion of the global image. This follows from the arbitrary assumption that the lower blade tracers of lines 1 to 5 are free of creep movement components in a direction perpendicular to these lines.

In spite of these shortcomings, the patterns seem to be rather consistent and provide a lot of information about the actual creep movement, which one could never deduce from simple velocity profiles as shown in Figures 4, 5, and 7.

SOME CHARACTERISTICS OF THE CREEP LINE PATTERN IN GL-78

The most striking feature on Figure 9 is the irregular configuration of the creep lines: they are curved, converging or diverging and in no way they can be considered as straight and parallel to each other or to the ground surface. This picture is very different from the classic representation of creep as given in Figure 4. In fact, a high point to point variability both in orientation and in rate of creep movement is evidenced. Even after six years (Figure 9c), the velocity profiles along lines 1 to 5 vary considerably in form and magnitude.

In the same way a high variability in time of the movements' orientation and rate can be observed for every point. Comparison of Figure 8A with Figure 8B makes clear that the velocity profile along line 1 varies considerably in form and magnitude from the first to the second three year period. The same is true for all other lines. An extreme case is line 2, where reversed creep occurred in the upper part of the velocity profile during the second three year period.

This variability of the creep movement, from point to point and from one period to another seems to be a very characteristic phenomenon when creep is involved and it partially explains the difficulty to appreciate creep volume rates.

In this context it is very significant that the creep line patterns of Figure 9 still display a common peculiarity: in the three cases two superposed types of creep can be distinguished. Creep deeper in the soil profile, especially beneath the intermediate horizon, is characterized by the presence of whirls or cells in the

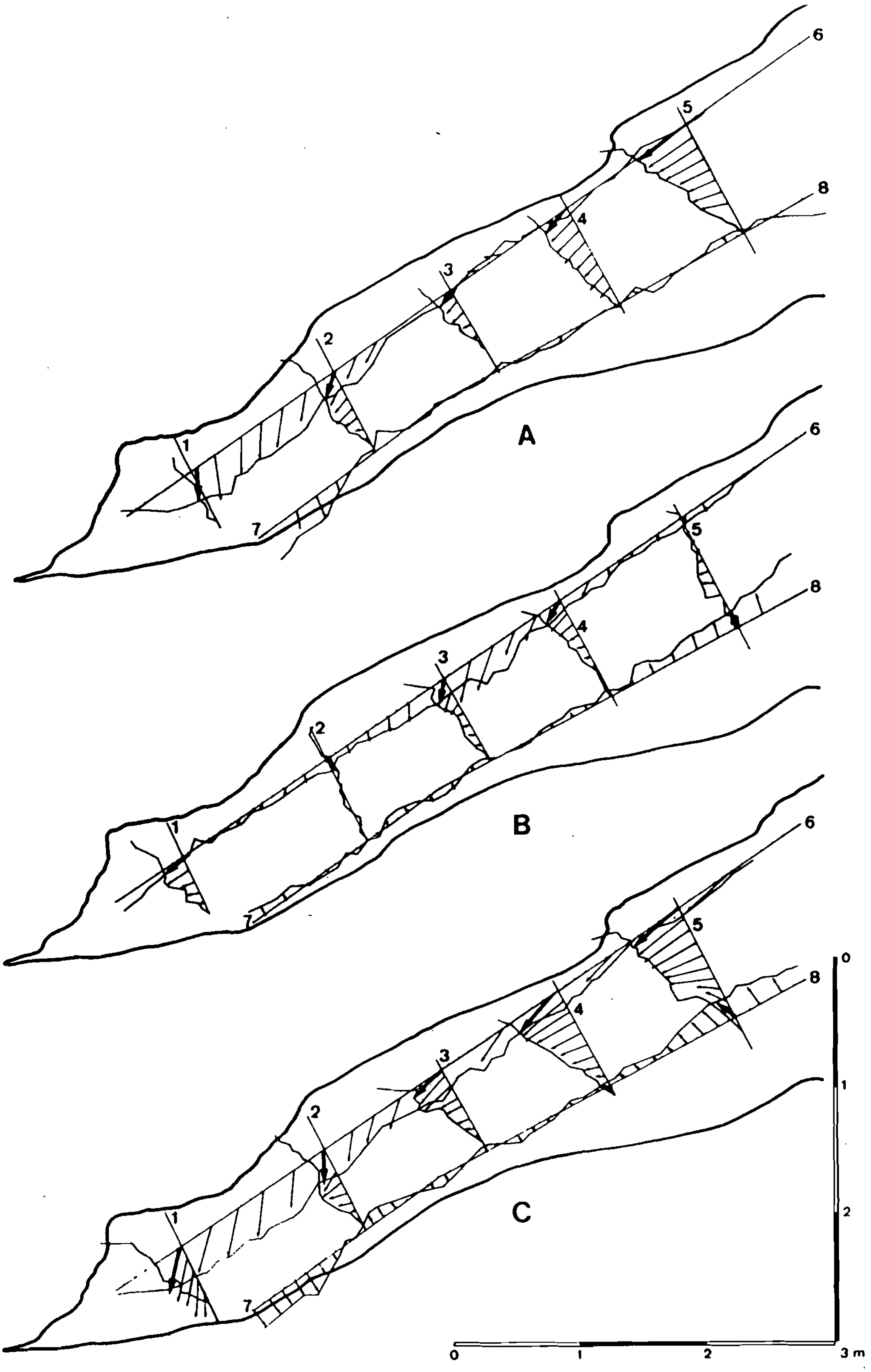

Figure 8. Deformation of tracer lines 1 to 8 in GL-78. (A) 1978–1981, (B) 1981–1984, (C) 1978–1984. B has been calculated as the difference between C and A. The scale of the deformation is exaggerated 10 times to the scale of the pit wall. Thick arrows are velocity vectors constructed at the points of intersection of the tracer lines, where movement components parallel and perpendicular to the ground surface are known. Thin arrows are interpolated velocity vectors. Mean slope inclination: 28°

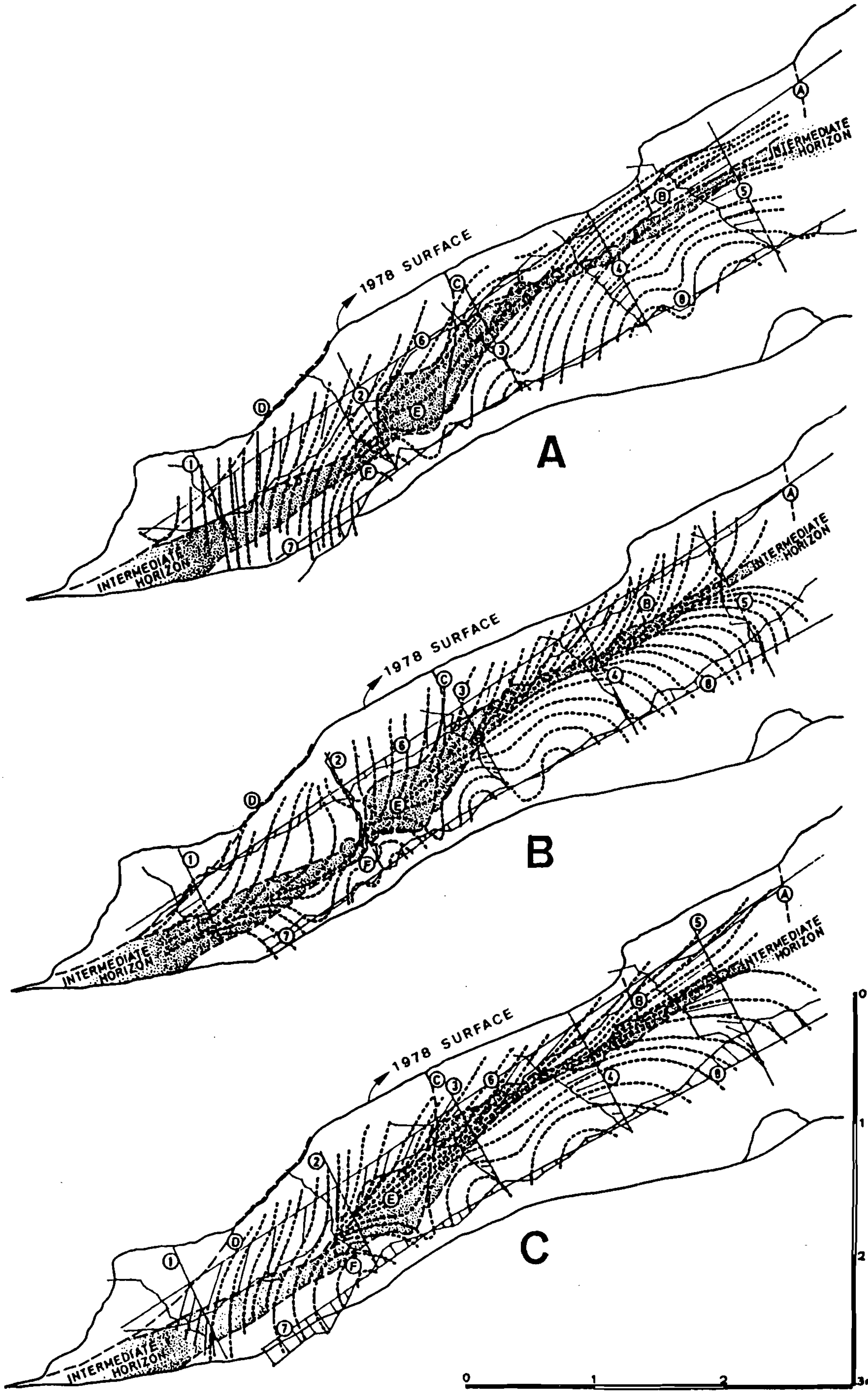

Figure 9. Creep lines constructed on base of the vector field of Figure 8. (A) 1978–1981, (B) 1981–1984, (C) 1978–1984. The position of the intermediate horizon has been indicated

creep line pattern. The localization of the whirls, despite their variations in importance, remains amazingly constant. This is the case for whirl F, which in Figures 9A, B, and C appears at the base of line 2. Another whirl is seated at the base—or a little bit to the left—of line 3. On Figure 9A, a very big whirl extends along line 8 from about 10 cm upslope of line 3 to some distance upslope of line 5, coming close to the surface between line 4 and 5. Its double centre extends along line 8 from line 4 to 5. At the end of the second three year period (Figure 9B), this whirl has shrunk considerably and its reduced centre has migrated downslope to a position on line 8, about in the middle between lines 3 and 4. The six year result of Figure 9C indicates an intermediate position.

At the end of the second three year period, a new whirl seems to be developed below line 1, but it does not appear on the global six years resultant of Figure 9C.

The consistent picture of the whirls over two three-year periods constitutes a strong argument against the possibility that they should result from imprecise readings, or that the blade tracer movements should be unrepresentative of the actual soil movements. It should also be mentioned that the whirls are constructed on the base of measured blade displacements of several millimetres, sometimes a centimetre, while the reconstruction of the lines and the readings are accurate to about 1 millimetre. The question of possible overinterpretation of the data can be excluded. Because of the high distances between the lines a number of cells or whirls might, in fact, not be detected and the image, presented here might be an oversimplification of an even more complex situation.

Above the intermediate horizon, the constructed creep line pattern is much more regular. The fact that the deformed tracer line 6 remains most of time below the reconstructed position of the original line 6 explains why there are no cells or whirls in this portion of the wall. An exception can be seen at the end of the first threee year period (Figure 9A) between line 4 and 5. But, as mentioned earlier,the updoming there seems to belong, to the big whirl with a double centre along line 8 between lines 4 and 5.

In most cases, creep velocity vectors in the A1 horizon show a slope inward direction, becoming more or less parallel to the ground surface somewhere within the intermediate horizon. From the constructed creep line patterns, one can deduce two points:

1. As creep lines seldom follow the surface, it is evident that the surface lowers where creep lines plunge into the slope and bulges up where creep lines come out.
2. But in most cases, as between lines 2 and 4 on Figure 9A and on the whole Figure 9B, creep lines plunge into the slope and converge in the intermediate horizon. In fact, creep lines in the intermediate horizon converge or diverge, respectively above and in between the whirls situated generally within the red subsoil. As can be seen on the velocity profiles, constructed along lines 1 to 5 in Figures 9A, B, and C, important subsurface primary or secundary maxima coincide with converging creep lines. Examples are lines 2, 3, and 5 on Figures 9A and B. However it is clear that these peaks in no way are sufficiently high to transmit in downslope direction the volume of soil concentrated in vertical sense.

SOME STRUCTURAL CHARACTERISTICS OF THE SOIL PROFILE AND THE RECORDED CREEP LINE PATTERN

From point 2, there appears to exist a fundamental contradiction between the field data and the constructed creep line pattern. Indeed, the intermediate horizon, where soil mass should concentrate according to the established creep line pattern, in fact appears to be a very pervious horizon with an aggregated, mottled, and crushed loose structure. It is true that ants and, to a lesser degree, termites, are active around the site. But the structure seen here doesn't correspond to the image of galleries, typical for this type of fauna. Also the big infilled cavity E on Figure 9 could not be identified with the so typical termite nests. Also the root system of the grasses cannot be held responsible for the loose structure of the immediate horizon. These roots normally concentrate closer to the surface. While it is true that tree roots, especially those of Eucalyptus concentrate in this horizon, as seen in the head of a sliding not far from RWAZA 3B, the site itself has remained free of trees for at least thirty years (oral communication of habitants).

But the structure of the intermediate horizon could result from creep. Indeed, this horizon is situated at the interface belt where the whirling creep type from the red subsoil and the more laminar-like creep from the A1 humic horizon interfere. This is especially clear on Figure 9B. But also in Figure 9A, the intermediate horizon appears to be situated where creep lines converge (lines 2 and 3) or diverge (between lines 3 and 4). Very suggestive is the big infilled cavity E, which in the three cases of Figure 9 is situated where creep lines diverge. This localization suggests that the intermediate horizon is a part of the soil profile crushed and pulverized by interference of the two superposed types of creep, each confined to an horizon with different textural, compositional, and soil mechanical characteristics. It should be mentioned that it appears clearly from the velocity profiles along lines 1 to 5 in Figure 8A, B, and C, that creep velocity vectors differ in magnitude from the top to the base of the intermediate horizon. The creep gradient between the red subsoil and the humid horizon probably contributes to the crushing of their interface.

FINAL REMARKS

The Rwaza records confirm the scarce information from the literature that creep, in frost free areas with cyclic changes in soil moisture, is a very complex movement, accompanied by the generation of appreciable stresses in the ground. The creep line pattern strongly suggest soil disturbances which might result in cryoturbation-like structures. All people concerned with the study of tropical soils should be aware of this, especially when palaeoclimatic, environmental, or even archaeological interpretations are to be made.

A surprise is the thickness of the layer affected by creep. The few cases of Figure 7 and Figure 9 reflect a general situation in Southern Rwanda: accurate triangulation has shown that big Eucalyptus trees merely float on the thick creeping mantle. It has even been argued elsewhere that deep seated creep is responsible for the general convex form of most hills in the area (Moeyersons, 1981a), where thick soils are present. Deep seated creep movements are also suggested in other hilly regions (Dietrich and Dunne, 1978). This information is important for the design of modern buildings and other infrastructural works, and for soil conservational practices.

Although creep line patterns as those in Figure 9 contribute to a better insight into the nature of the creep movement, they also raise questions which need more attention in the future. One question concerns the loss of soil volume in creeping ground. We are not the first to mention this problem. Volume decrease in creeping ground has been observed in England. There it was assumed that chemical solution causes a soil, about 60 cm thick, to shrink at a rate of 0.31 mm yr^{-1} in a direction perpendicular to the ground surface (Young, 1978). The resettlement of the soil grains in response to this shrinkage was considered to be one creep activating factor.

At Rwaza, line 6 has approached lines 7 and 8 by a mean distance of about 0.5 cm during six years. Although solution probably occurs, it is thought that this shrinkage is also partially due to the mechanical transport of fines, especially along the intermediate horizon, which probably results from the differential creep movements as stated above, but actually functions as a high hydraulic conductivity layer, evacuating infiltration water in a downslope direction (Moeyersons, 1981b). In any case, it is agreed that volume decrease might be an important cause for creep, as laboratory experiments have shown that net creep in a system of cyclic soil moisture changes corresponds to a form of resettlement in response to former soil disturbances (Moeyersons, 1978). Besides bioturbation *sensu lato*, volume decrease, whether solutional or mechanical, necessarily induces subsequent resettlement of the soil skeleton.

ACKNOWLEDGEMENTS

This research has been funded with grants provided to the 'Koninklijk Museum voor Midden-Afrika' (Belgium) in the context of a convention (1977) between Belgium and Rwanda with relation to the 'Institut National de Recherche Scientifique' (Rwanda). I wish to express my gratitude to both institutions.

REFERENCES

Anderson, E. W. and Finlayson, B. 1975. 'Instruments for measuring soil creep' *Brit. Geomorph. Res. Group. Techn. Bul.*, **16**.

Culling, W. E. H. 1983. 'Slow particulate flow in condensed media as an escape mechanism: mean translation distance', *Catena, Suppl.*, **4**, 161–190.

Davison, C. 1889. 'On the creeping of the soil cap through the action of frost', *Geol. Mag.*, **6**, 255.

Dedkov, A. P. and Tchasovnikova, K. 1978. 'Field station study of soil creep in the central Volgaland', *Z. f. Geomorph. Suppl.*, **29**, 111–116.

Dietrich, W. E. and Dunne, TH. 1978. 'Sediment budget for a small catchment in mountainous terrain', *Z. f. Geomorph. Suppl.*, **29**, 191–206.

Embleton, C. and Thornes, J. 1979. *Process in Geomorphology*, Edward Arnold, London, 436 pp.

Everett, K. R. 1963. 'Slope movement, Neotoma Valley, Southern Ohio', *Rep. Inst. Polar Stud.*, **6**.

Eyles, R. J. and Ho, R. 1970. 'Soil creep on a humid tropical slope', *Trop. Geogr.*, **31**, 40–42.

Fleming, R. W. and Johnson, A. M. 1975. 'Rates of seasonal creep of silty clay soil', *Quart. Journ. Engin. Geol.*, **8**, 1–29.

Finlayson, B. 1981. 'Field measurements of soil creep', *Earth Surf. Proc. Landf.*, **6**, 35–48.

Gaucher, E. 1981. *Traité de pédologie agricole. Tome II: Les facteurs de la pédogénèse*, G. Lelotte, Dison.

Goldstein, M. N. et al. 1961. 'The theory of probability and statistics in relation to the rheology of soils', *Proc. 5th Int. Conf. Soil Mech. Fdn Engng*, 123–126.

Griggs, D. T. 1936. 'Deformation of rocks under high confining pressures', *J. Geol.*, **44**, 541–577.

Iveronova, M. I. 1964. 'Stationary studies of the recent denudation processes on the slopes of the R. Tchon–Kizilsu basin, Tersky Alatau Ridge, Tien-Shan', *Z. f. Geomorph. Suppl.*, **5**, 206–212.

Jahn, A. 1981. 'Some regularities of soil movement on the slope as exemplified by the observations in the Sudety Mts', *Trans. Jap. Geomorph. Un.*, **2**, 321–328.

Kirkby, M. J. 1967. 'Measurement and theory of soil creep', *J. Geol.* **75**, 359–378.

Kojan, E. 1968. 'Mechanics and rates of natural soil creep', *Proc. 5th A. Symp. Engng. Geol. Soils Engng* (Pocatello, Idaho), 233–253.

Leopold, L. B. et al. 1964. *Fluvial Processes in Geomorphology*, Freeman and Company, San Francisco, 522 pp.

Lewis, L. A. 1976. 'Soil movements in the tropics—a general review', *Z. f. Geomorph. Suppl.*, **25**, 132–144.

Moeyersons, J. 1978. 'The behaviour of stones and stone implements, buried in consolidating and creeping Kalahari sands', *Earth. Surf. Proc.*, **3**, 115–128.

Moeyersons, J. 1981a. 'Les transports de masse: leur nature, leur importance et leurs effets morphologiques dans la région de Butare (Rwanda)', *Dept. geol. min., ann. rep.*, **1980**, 55–65, Royal Mus. Centr. Africa, Tervuren, Belgium.

Moeyersons. J. 1981b. 'Slumping and planar sliding on hill-slopes in Rwanda', *Earth Surface Processes*, **6**, 265–274.

Nelson, J. D. and Thompson, E. G. 1977. 'A theory of creep failure in overconsolidated clay', *J. Geotech. Engng Div. A.S.C.E.*, **103**, G. T. **11**, 1281–1294.

Pissart, A. 1971. 'Variations de volume de sols gelés subissant des fluctuations de température sous 0°C', *Actes Symp. Intern. Géomorph. Liège–Caen, Bull.* no **13–14–15** du Centre de Géomorph. du C.N.R.S. de Caen, 19–33.

Salee, A. 1928. *Constitution géologique du Rwanda oriental*, Mém. Inst. Géol. Louvain V, 1928.

Schumm, S. A. 1956. 'The role of creep rainwash on the retreat of badland slopes', *Am. J. Science*, **254**, 693–706.

Sharpe, C. F. S. 1938. *Landslides and related phenomena: a study of mass-movements of soil and rock*, Columbia University Press, New York.

Sirven, P., Gotanegre, J. F., and Prioul, C. 1974. *Géographie du Rwanda*, De Boeck, A. (Ed.) Bruxelles, 175 p.

Skempton, A. W. 1964. 'Long-term stability of clay slopes', *Geotechnique*, **14**, 77–102.

Skempton, A. W. and Hutchinson, J. M. 1969. 'Stability of natural slopes and bankment sections', *Proc. 7th Int. Conf. Soil Mech. Fdn Engng*, 291–340.

Tschierske, N. 1979. 'Uber die mögliche Fliessbewegung ganzer Tonberge', *Rock Mechanics*, **12**, 99–113.

Ter-Stephanian, G. 1963. 'On the long term slope stability of slopes', *Norw. Geotech. Inst. Publ.* **52**, 1–13.

Ter-Stephanian, G. 1965. 'In situ determination of the rheological characteristics of soil on slopes', *Proc. 6th Int. Cong. Soil Mech. Fdn Engng*, **2**, 375–377.

Terzaghi, K. 1950. 'Mechanism of landslides', *Geol. Soc. Am. Eng. Geol.*, 83–123.

Van Asch, TH. W. J. 1984. 'Creep processes in landslides', *Earth Surf. Proc. Landf.*, **9**, 573–583.

Yen, B. C. 1969. 'Stability of slopes undergoing creep deformation', *J. Soil Mech. Fdn. Div. A.S.C.E.*, **95**, 1075–1093.

Young, A. 1960. 'Soil movement by denudational processes on slopes', *Nature*, **188**, 120–122.

Young, A. 1978. 'A twelve-year record of soil movement on a slope', *Z. f. Geomorph. Suppl.*, **29**, 104–110.