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VARIABILITIES OF SOIL CATENA ON DEGRADED HILLSLOPES OF WATIYA CATCHMENT, WELO, ETHIOPIA

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ABSTRACT: The purpose of this study was to establish and explain the characteristics of soil catenas that developed on divergent and convergent hillslopes in the upper Watiya catchment. The two hillslopes have mean gradients of 20 and 16 percent, respectively, and each comprises of a crest, backslope, footslope and toeslope. To accomplish the objectives of the study, a soil pit was opened and described on each hillslope unit. Samples were collected and tested in a laboratory to determine the textural composition and chemical characteristics of the soils. Soil units were identified on the basis of the revised legend of the Soil Map of the World (FAO/UNESCO, 1990). The crests and backslopes of both hillslope types are severely eroded and marked by shallow soils that meet the requirements for Leptosols. The pedon on the convergent footslope with Ap/Bw/Cr horizon sequence was also very much truncated and hence constitutes a severely degraded Haplic Phaeozem. The soils on the convergent toeslope, having typical A/CB/Bb horizon arrangements, were identified as Eutric Regosols. The soil stratigraphic column representing the sequences of modern and buried soils on this toeslope shows ages that range from about 4000 years before present or upper Holocene to apparently a few hundred years. The oldest buried soil at the base of the stratigraphic column, identified as Eutric Vertisol, is exposed to the surface on the adjacent toeslope of the divergent hillslope. The unburied Vertisols, which also extend upslope to cover the adjacent footslope of the divergent hillslope have dark brown to very dark grey colour, thick vertical profile and A/AC or A/C/Cr horizon sequences.

Key words/phrases: Convergent hillslope, divergent hillslope, erosion catena, Leptosols, Phaeozems, Regosols, Vertisols

INTRODUCTION

A catena is described as interlocking chains of soils that "...while they fall wide apart in a natural system of classification..., are yet linked in their occurrence by conditions of topography and are repeated in the same relationships to each other wherever the same conditions are met with" (Milne, 1935, p. 197). Catenary differentiation of soils results not only from the variable influences of pedogenic processes such as leaching, eluviation, and illuviation within the profile, but also from erosion, transport and deposition of surface materials on the hillslopes (Hall, 1983). Moreover where slopes have undergone accelerated erosion for hundreds of years, the effects of soils that have moved downslope is in such a scale that the catena that develops tends to be totally different from one that would have formed naturally. The term 'erosion catena' is specifically applied where accelerated erosion on the upper and deposition on the lower slopes are the major causes of the catenary differentiation (Ollier, 1976; Gerrard, 1992).

Soil catenas whose developments have been very much influenced by land use and accelerated erosion are very common in many parts of the Welo highlands (Weigel, 1986; Belay Tegene, 1995). These erosion catenas show major variabilities because of not only their longitudinal hillslope forms but also their lateral profiles. The across-slope curvature is an important geomorphic feature in terms of controlling the distribution of soils, because moving water (one of the factors of soil differentiation) disperses on hillslopes that are laterally convex (divergent slopes) and converges on those that are concave (convergent slopes) (Hall, 1983; Pennock *et al.*, 1987).

The basis of this investigation was laid when distinct types of catenary soil, slope and erosion relationships were observed on the two most common hillslope types of the study area, i.e., the convergent and divergent hillslopes. These two hillslopes differ in that the across-slope curvature of the backslope and footslope of the former is concave, while that of the latter is convex. Following the observation, it was hypothesized that the variabilities of the soil catenas are primarily the result of the differences in the lateral cross sectional forms of the hillslopes. The postulate was tested by analysing, comparing and relating 'erosion catenas' on two representative and adjacent divergent and convergent hillslopes in the upper part of the Watiya catchment. It is believed that the findings and discussions will contribute to the understanding of not only the pattern of soil distribution on the hillslopes but also the impact of land use and soil erosion on the soilscapes. Establishing relationships between the erosional and pedogenic processes is also useful because it reveals the intensity of erosion and deposition on different slope positions (Marron and Popenoe, 1986).

MATERIALS AND METHODS

Description of the study area

The soil survey that generated the basic data for this study was conducted in February 1993, over the whole of the Wurgo catchment (area of 1700 ha). The Watiya catchment, with an area of about 300 ha, forms the northeastern part of the Wurgo catchment and is located at about 39° 13′E and 10° 49′N, immediately to the west of Akesta town (Fig. 1). The bedrock in this catchment comprises of trachyte rocks that belong to the Tertiary period. Divergent and convergent hillslopes are the most common features of the landscape. Most of the toeslopes at the base of the convergent hillslopes are covered by deposits of alluvium that in the main belong to the Quaternary. Because there were no meteorological records for the study area, the temperature and rainfall conditions were inferred from data collected in the nearby Dessie town at 2540 m.a.s.l. (about 60 km due east north east). The latter shows mean annual temperature of 15° C and rainfall of about 1200 mm. The rainfall regime is marked by a bimodal rainfall distribution with a lesser maxima from March to May, and a larger maxima from July to October. The mean annual temperature for Watiya catchment, which has a much higher elevation than Dessie, was estimated at 8 to 11° C[1]. Hence, the Watiya catchment falls within the cool sub-tropical summer rainfall zone of FAO/UNESCO's climatic classification (FAO/UNESCO, 1990).

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[1] The mean annual temperature (t) for the elevation (h, in meters) was calculated on the basis of the equation $t = 30.2°\text{C} - ah$, where 'a' is a coefficient equal to $6.5° \times 10^{-3}$ °C/m (Wielemaker and Wakatsuki, 1984).

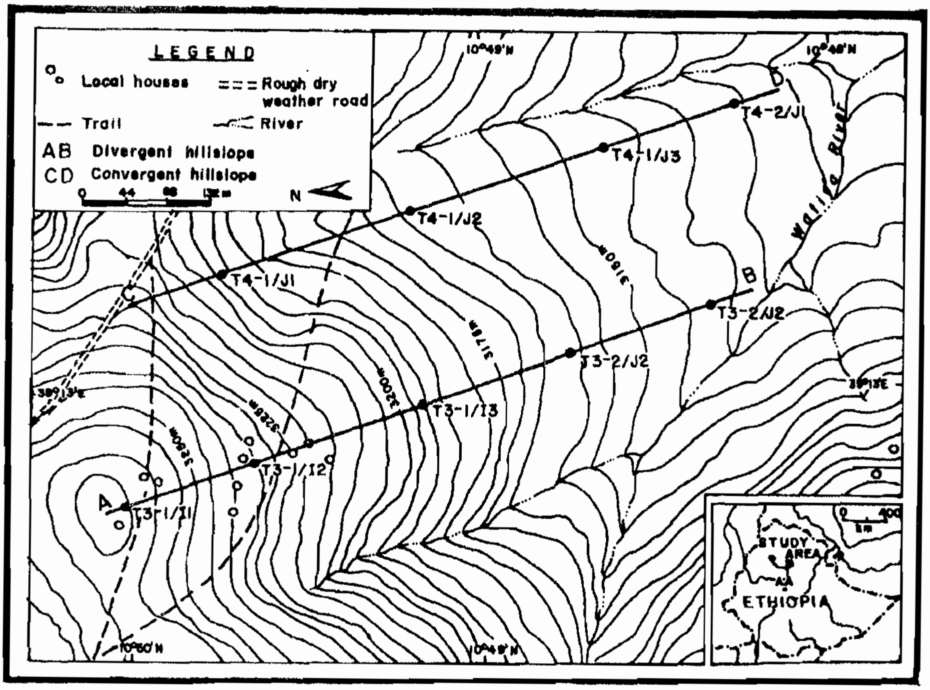

Fig. 1. Location of the Upper Watiya catchment and transects selected for the study.

Agriculture in the Watiya catchment and the surrounding areas involves small scale rainfed cultivation of a variety of cereals and oil seeds. Crop cultivation includes production of barley (*Hordeum vulgare* L.), wheat (*Triticum* spp.), emmer wheat (*Triticum dicoccon* Schrank), field peas (*Pisum sativum* L.), horse beans (*Vicia faba* L.), lentils (*Lens spp.* Medik), and fenugreek (*Trigonella foenum-graecum* L.). Livestock are also kept not only as supplementary sources of food but also to provide for draught- and pack-animals. Extensive deforestation, overgrazing, over-cultivation and subsequent soil fertility depletion are serious problems of agriculture. The soils have been severely eroded and in parts irreversibly lost because of the long history of agriculture and crop cultivation. It is to be noted that agriculture in these highlands dates back to several thousands of years (Abiy Astatke and Frew Kelemu, 1993; El Wakeel and Abiy Astatke, 1996).

The framework for investigation

The hillslope model developed by Ruhe (1960; 1975) has provided an important framework for the study of the soil catena along the longitudinal profiles of the two hillslopes. This model identifies crests (summits), shoulders, backslopes, footslopes and toeslopes as clearly separable units that have unique soil associations. However, such simple two dimensional models are inadequate for describing and explaining soils, erosion, and landscape relationships (Huggett, 1975; Conacher and Darlymple, 1977; Kreznor *et al.*, 1989). Thus soil chains on the two hillslopes were not only independently described in relation to the longitudinal slope profiles, but also compared to establish the lateral differentiation resulting from the variations in the cross-sectional hillslope forms. The longitudinal, lateral and vertical profiles of the soilscapes were also examined and related to processes of erosion and deposition.

Soil profile description, classification and dating

Two transects were fixed along the longitudinal slopes of both the divergent and convergent hillslopes, and the various slope units were demarcated. The two hillslopes located as they are in close proximity to each other were similar in length and longitudinal profile (Fig. 1). The mean gradient of the divergent hillslope was 20 percent while that of the convergent hillslope was 16 percent. Both comprise four of the five slope units, *i.e.*, the crest, backslope, footslope and toeslope, of Ruhe's hillslope model (Ruhe, 1960; 1975). The shoulder is missing in both cases because headward stream incision and subsequent retreat of the backslopes from opposite sides have resulted in contraction and narrowing of the interfluve crest.

Eight pedons representing the various slope units were described along the transect following procedures recommended in the FAO's guidelines for soil profile description (FAO/UN, 1990). Soil colour was described using standard colour charts (Munsell Colour, 1975). The revised "Legend of the Soil Map of the World" was employed in the soil classification (FAO/UNESCO, 1990). This information was supplemented with data collected from ground features and soil descriptions made at various auger hole points in a systematic grid survey. The guidelines for soil profile description (FAO/UN, 1990) were also used in the description of a soil stratigraphic column observed at the lower end of the convergent hillslope. Records and principles of soil stratigraphy were utilized to establish relative ages of the modern and buried soils. Absolute age of the buried soil constituting the base of the stratigraphic section was determined by radiocarbon (^{14}C) dating of the organic carbon in the soil (Scharpenseel, 1971). An attempt was also made to place this buried soil within the FAO/UNESCO soil classification scheme (FAO/UNESCO, 1990).

Characterization of soil physical and chemical properties

Laboratory tests were conducted on soil samples collected from representative profiles. Texture was determined using the hydrometer method (Black *et al.*, 1965). Clay-free sand index was computed from the textural data to establish degree of weathering and lithological discontinuities within the soil profiles. Calcium carbonate equivalent in percent was estimated in buried soils by acid neutralization method. Organic carbon was determined following Walkley and Black method (Black *et al.*, 1965) and percentage organic matter was calculated by multiplying the organic carbon percentage by 1.724. Total nitrogen and available phosphorus were estimated by the Kjeldahl procedure and Olsen's method, respectively. Soil pH was measured in a 1:2.5 soil-water suspension with standard glass electrode. The ammonium acetate method was employed to separately determine cation exchange capacity (CEC) and exchangeable basic cations (Black *et al.*, 1965).

RESULTS

Soil catena on the divergent hillslope

A series of profiles portraying the soil catena on the divergent hillslope are shown in Figure 2. Soils on the crest and backslope (T3–1/I1, T3–1/I2 and T3–1/I3) have formed, *in situ*, on saprolite[2] derived from trachyte tuff. The thickness of the saprolite underlying these soils range from none, on the interfluve divide line, where it disappears and rock outcrops appear, to about

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[2] The term saprolite refers to the more or less structurally coherent but thoroughly decomposed crystalline rock formed in place by chemical weathering (Graham *et al.*, 1990). In the field, saprolite is easily distinguished from fresh rock in that it is easily dug by spade.

30 cm in the other parts. The pedon on the footslope (T3-2/J1) overlies a 25 cm thick residuum[3] derived from saprolite. The occurrence of residuum on this slope position and its absence in the upper ones is attributed to differences in amounts of moisture available for weathering. The footslope receives more water from the upper slopes and this favours intensive weathering and destruction of the saprolite. The soil unit on the toeslope (T3-2/J2) has formed in an environment where slope is gentle and drainage is imperfect. The parent material here was not reached within 2 meters, but apparently this soil has also developed on residuum.

The morphological characteristics of soils constituting the catena, on the divergent hillslope, are summarized in Table 1 and the physical and chemical characteristics are presented in Tables 2 and 3. The soil catena was marked by downslope increase in hue and decrease in chroma reflecting the effects of reduced drainage. The brown colour of the soils on the crest and backslope was closer to that of the saprolite from which they were derived. The catena also showed an increasing trend in soil thickness. Depth of solum plus residuum ranged from none (*i.e.*, bare rock outcrops) on the divide, to less than 20 cm on the crest and backslope, and more than 200 cm on the toeslope.

The shallow soils on the crest and backslope are generally composed of mollic or ochric A horizons. The former frequently gives way to the latter where intensive crop cultivation has led to considerable degradation of soil organic matter. The soil surfaces on the crest, backslope and footslope are generally marked by considerable stone cover. The major sources of these surface stones are presumed to have been the rock outcrops on the divides. These stones are indicative of the extent of disturbance of the slopes and accelerated downslope movement of materials. Both soil erosion and downslope creep movements of stones are accelerated due to tillage operations.

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[3] A residuum differs from saprolite in that the continuous rock structure characterising a saprolite is lost and yet the fragments of saprolite and rock supported within the soil matrix account for the major portion of the regolith (Graham *et al.*, 1990).

Table 1. **Abbreviated[1] description of soil profiles on the divergent hillslope.**

Depth (cm)	Horizon	Colour	Structure	Consistence	Boundary	Roots[2]
Profile T3–1/I1: Slope 19%; Position, crest						
0–15	Ap	7.5YR4/4	1–vf&fgr	ds,wss,wps	as	fq,f
15–60	Cr	7.5YR5/4	Saprolite			
>60	R					
Profile T3–1/I2: Slope 6%; Position, backslope, terrace						
0–13	Ah	7.5YR3/2	2–m&csbk	ds,wss,wps	cs	fq,f,md
13–31	Bt	7.5YR4/4	3–m&csbk	dh,ws,wp	as	fq,f,md
31–70	Cr	7.5YR5/4	Saprolite			
>70	R					
Profile T3–1/I3: Slope 26%; Position, backslope						
0–9	Ap	7.5YR3/4	2–mpl	ds,wss,wps	as	fq,f
9–50	Cr	7.5YR5/4	Saprolite			
>50	R					
Profile T3–2/J1: Slope 18%; Position, footslope						
0–13	Ap	7.5YR3/2	3–csbk	dh,wvs,wvp	cs	cm,f
13–95	A2	7.5YR3/2	3–vcabk	dvh,wvs,wvp	gs	fw,f
95–118	C	7.5YR4/4	Residuum			
118–139	Cr	7.5YR5/4	Saprolite			
>139	R					
Profile T3–2/J2: Slope 9%; Position, toeslope						
0–13	Ap	10YR3/1	3–m&csbk	dvh,wvs,wvp	cs	cm,f
13–88	A2	10YR3/1	3–cabk	dvh,wvs,wvp	cs	fw,f
88–126	AC1	7.5YR4/2	3–cabk	dvh,wvs,wvp	gs	fw,f
126–162	AC2	7.5YR4/4	3–cabk	dvh,wvs,wvp	-	fw,f
>162	Soil continues below 200 cm					

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[1] Abbreviations used for the profile descriptions are in line with the procedures of the Soil Survey Staff (1969).

[2] Abbreviations for root descriptions: fq, frequent; vfq, very frequent; cm, common; fw, few; vfw, very few; f, fine; md, medium.

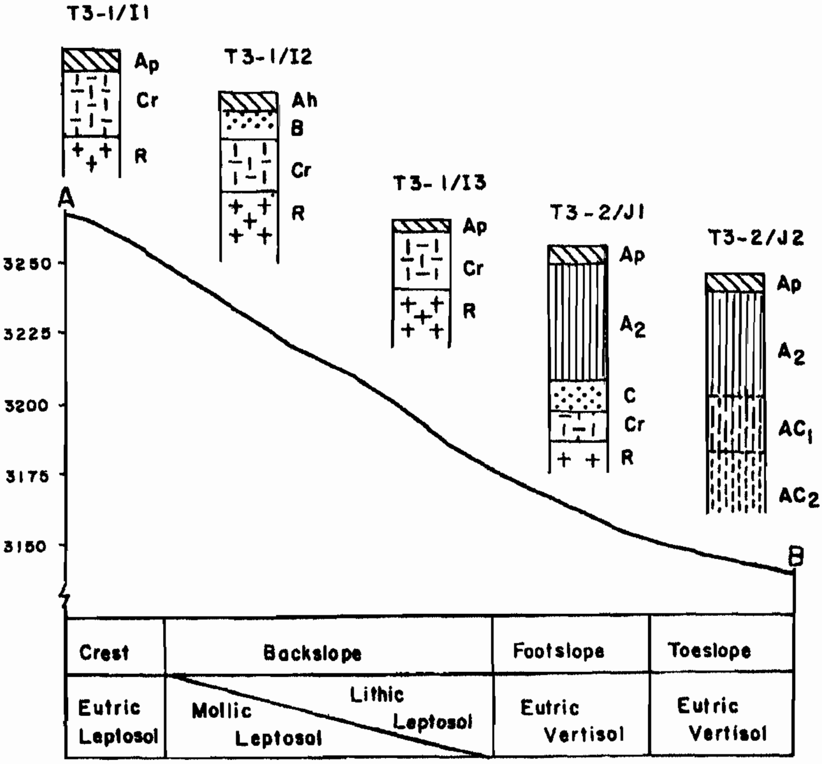


Fig. 2. Soil catena on the divergent hillslope.

Soils assume increasingly heavier texture from the crest down to the toeslope. The percentage of clay in the solum is between 19 and 23 on the crest and backslope; 54 and 68 on the footslope; and 54 and 71 on the toeslope (Table 2). A general downslope decline in silt:clay ratio and clay-free sand was also observed. This differentiation in texture is attributed to the variabilities in degree of weathering and erosion. The soils on the lower slope positions still retain their more weathered topsoil and subsoil materials while those on the upper slopes mainly constitute less weathered materials of exposed C horizons of previous soils. The sheet wash and selective removal of finer particles have also contributed to the concentration of coarser particles in the surface horizons of the eroded soils.

Table 2. Texture, organic matter, total nitrogen and available phosphorus for soils on the divergent hillslopes.

Profile no.	Depth (cm)	Texture (%)			Text. class	Silt/ clay ratio	Clay free sand (%)	Org. mat. (%)	Org. C (%)	Tot. N (%)	C/N	Avail. P [mg(kg)$^{-1}$]
		s	si	c								
T3-1/I1	0-15	47	30	23	l	1.30	61	3.89	2.26	0.29	8	131
T3-1/I2	0-13	43	34	17	l	2.00	56	6.05	3.51	0.40	9	133
	13-31	32	39	29	cl	1.34	45	1.60	0.93	0.11	9	57
T3-1/I3	0-9	49	32	19	l	1.68	60	1.95	1.13	0.11	10	71
T3-2/J1	0-13	13	31	68	c	0.46	30	2.15	1.25	0.11	11	9
	13-95	6	26	54	c	0.48	19	1.07	0.62	0.06	10	7
T3-2/J2	0-13	9	37	54	c	0.69	20	2.15	1.25	0.13	10	23
	13-88	5	24	71	c	0.34	17	1.81	1.05	0.13	8	27
	88-126	10	23	67	c	0.34	30	0.84	0.49	0.09	5	15

Table 3. Cation exchange capacity, pH and exchangeable basic cations for soils on the divergent hillslope.

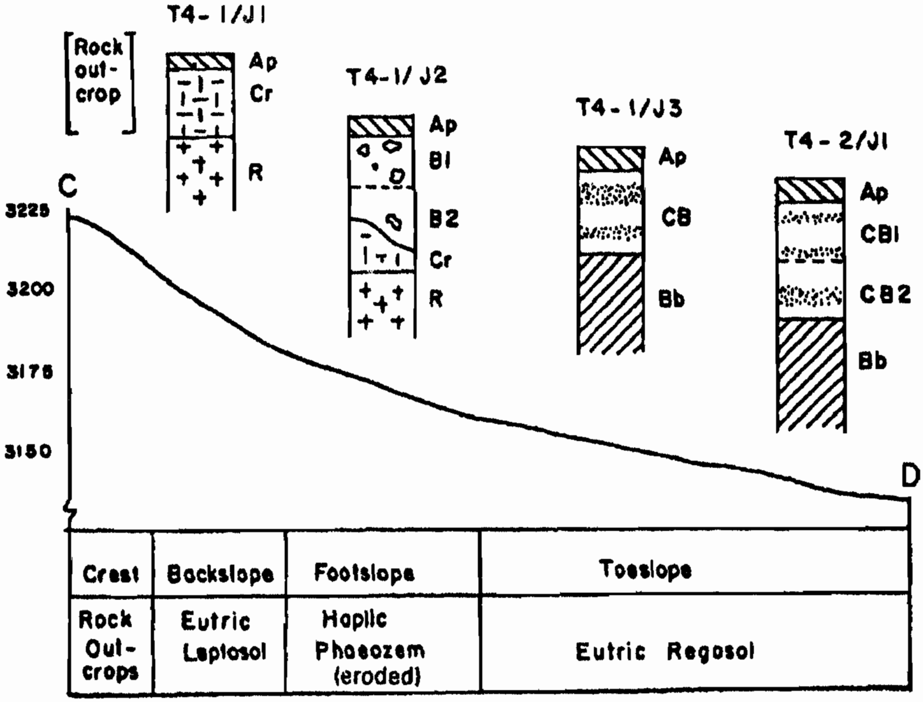
Profile no.	Depth (cm)	pH 1:1 H_2O	CEC	CEC/ clay	Exchangeable basic cations [cmol(+)kg^{-1} soil]				BS (%)	Ca/ Mg ratio	EPP (%)
					Na	K	Ca	Mg			
T3-1/I1	0-15	5.9	44	157	0.96	2.09	28.32	7.33	88	3.9	4.8
T3-1/I2	0-13	6.6	49	217	1.75	11.53	31.41	9.44	110	3.3	23.5
	13-31	4.6	47	151	1.31	5.92	30.04	11.22	103	2.7	12.6
T3-1/I3	0-9	6.9	41	196	0.88	2.64	29.47	9.94	104	3.0	6.4
T3-2/J1	0-13	6.7	49	65	0.80	0.84	37.08	11.92	104	3.1	1.7
	13-95	7.6	49	87	1.17	0.63	32.20	15.09	100	2.1	1.3
T3-2/J2	0-13	6.2	42	70	0.80	0.71	27.67	11.46	96	2.4	1.7
	13-88	7.0	54	71	1.09	0.89	32.16	13.09	88	2.5	1.7
	88-126	7.7	51	74	1.36	1.06	36.67	13.82	104	2.6	2.1

The cultivated soil on the crest registered higher organic matter (2.26%) and total nitrogen (0.29%) when compared to the less eroded cultivated soils on the footslope and toeslope (Table 2). The relatively higher organic matter and nitrogen contents of this soil probably resulted from frequent fallowing and addition of organic manure. Such degraded soils are generally more frequently fallowed and manured while the deeper soils at the base of the hillslopes are not. The low C/N ratio suggests that some of the manure applied might have been in composted form as commonly practised in many parts of the Welo highlands. The very high organic carbon and total nitrogen contents of the uncultivated soil on the backslope may be attributed to the incorporation of more organic matter from the natural vegetation cover.

The cation exchange capacity (CEC) of soils on the crest and backslope were much higher (129 to 196 $\mathrm{cmol}_{(+)}\mathrm{kg}^{-1}$ clay) when compared to those on the footslope and toeslope (65 to 87 $\mathrm{cmol}_{(+)}\mathrm{kg}^{-1}$ clay) (Table 3). The CEC in the latter, reflects the predominance of smectite clay while the higher values in the degraded soils on the crest and backslope show presence of significant amount of high exchange capacity clay minerals. A previous study conducted in the Tib mountains, to the west, has indicated the development of Mollic Andosols with very high CEC on a similar parent material (Belay Tegene, 1995). The base saturation registered for the soils covering all of the slope units was very high and in all cases above 85%. Highest subsoil base saturation was registered for the toeslope where basic cations carried downslope by throughflow accumulate and add to the total exchangeable bases on the exchange surfaces.

Soil catena on the convergent hillslope

The soil profiles representing the catena on the convergent slope are shown in Figure 3. The morphological description of the soils are presented in Table 4, and the physical and chemical characteristics are shown in Tables 5 and 6. The crest here has almost completely lost its soil cover and hence is marked by rock outcrops. The pedon on the backslope (T4–1/J1) was similar to those on the crest and backslope of the divergent hillslope in that it has shallow depth, saprolite parent material and Ap/Cr horizon sequence. The pedon on the convergent footslope (T4–1/J2) has an Ap horizon that is derived from a truncated cambic B horizon. The soil profile has developed on poorly sorted gravitationally transported colluvial materials overlying a saprolite layer. This soil profile comprises of large amounts of stones and gravels dispersed in a fine textured matrix. The toeslope on the convergent hillslope has allowed deposition of layers of alluvium and development of a sequence of modern and buried soils (T4–1/J3 and T4–2/J1).



Crest	Backslope	Footslope	Toeslope
Rock Out-crops	Eutric Leptosol	Haplic Phaeozem (eroded)	Eutric Regosol

Fig. 3. Soil catena on the convergent hillslope.

The soil catena on the convergent hillslope does not portray the strong colour differentiation observed on the divergent hillslope (Table 4). The generally brown soil colour is very close to the colour of the saprolite. Like those on the divergent hillslope, the soils on the backslope and footslope were also marked by considerable stone cover. A textural sequence with characteristic decline in sand percentage and clay-free sand was also observed from the footslope down to the toeslope (Table 5). However, this downslope increment of clay is only a reflection of the progressively finer texture of the sediment that gave rise to the soils rather than that of *in situ* weathering and pedogenesis.

Table 4. Abbreviated description of soil profiles on the convergent hillslope.

Depth (cm)	Horizon	Colour	Structure	Consistence	Boundary	Roots
Profile T4–1/J1; Slope 34%; Position, backslope						
0–10	AP	7.5YR3/4	1–fgr	ds,wss,wsp	as	fq,f
10–54	Cr	7.5YR4/6	Saprolite			
>54	R					
Profile T4–1/J2: Slope 20%; Position, footslope						
0–13	Ap	7.5YR3/4	1–f&mg	ds,wss,wsp	as	fq,f
13–46	B1	7.5YR3/4	3–csbk	ds,ws,wp	gs	cm,f
46–66/86	B2	7.5YR3/2	3–csbk	dh,ws,wp	ai	vfw,f
66/86–98	Cr	7.5YR5/4	Saprolite			
>98	R					
Profile T4–1/J3: Slope 9%; Position, toeslope						
0–16	Ap	7.5YR4/4	2–f&mgr	ds,wss,wps	cs	fq,f
16–68	CB	7.5YR4/4	3–m&csbk	dh,wss,wsp	as	cm,f
68–123	Bb	7.5YR4/4	3–m&csbk	dh,ws,wp	gs	vfw,f
>123	Soil continues below 123					
Profile T4–2/J1: Slope 9%; Position, toeslope						
0–15	Ap	7.5YR3/4	2–f&mgr	ds,ws,wp	as	fq,f,md
15–51	CB1	7.5YR3/4	3–m&csbk	dh,wvs,wvp	cs	fq,f,md
51–88	CB2	7.5YR3/4	3–m&csbk	dvh,wvs,wvp	as	fw,f
88–157	Bb	7.5YR4/4	3–m&csbk	dvh,wvs,wvp	-	vfw,f
>157	Soil continues below 157					

Note: Abbreviations as in Table 1.

Table 5. Texture, organic matter, total nitrogen and available phosphorus for soils on the convergent hillslope.

Profile no.	Depth (cm)	Texture (%)			Text. class	Silt/ clay ratio	Clay free sand (%)	Org. mat. (%)	Org. C (%)	Tot. N (%)	C/N	Avail. P [mg(kg)$^{-1}$]
		s	si	c								
T4–1/J1	0–16	30	36	34	c	1.06	46	0.49	0.28	0.06	5	31
T4–1/J2	0–13	45	31	24	c	1.29	59	1.86	1.08	0.10	11	6
	13–46	33	36	31	cl	1.16	48	2.00	1.16	0.10	12	7
	46–66/86	34	34	32	cl	1.06	50	1.86	1.08	0.08	14	19
T4–1/J3	0–16	44	36	20	cl	1.80	55	2.10	1.22	0.17	7	28
	16–68	39	47	14	l	3.36	45	0.95	0.55	0.07	8	14
	68–123	59	24	17	l	1.41	71	1.56	0.91	0.07	13	16
T4–2/J1	0–15	32	39	29	cl	1.34	45	2.81	1.63	0.12	14	33
	15–51	28	36	36	cl	1.00	44	1.52	0.88	0.11	8	12
	51–88	30	36	34	cl	1.06	45	1.05	0.61	0.08	8	23
	88–157	15	39	46	c	0.85	28	0.77	0.45	0.08	6	28

Table 6. Cation exchange capacity, pH and exchangeable basic cations for soils on the convergent hillslope.

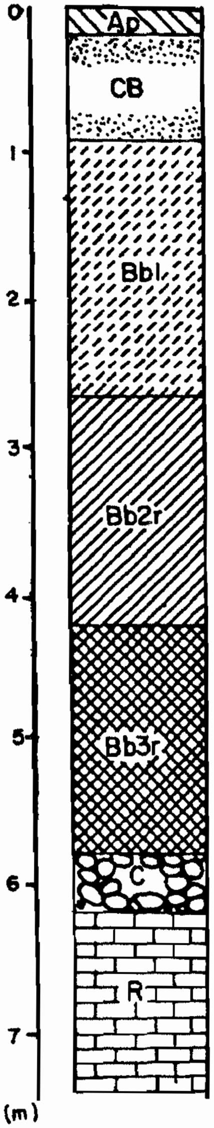
Profile no.	Depth (cm)	pH 1:1 H_2O	CEC	CEC/ clay	Exchangeable basic cations [cmol(+)kg^{-1} soil]				BS (%)	Ca/ Mg ratio	EPP (%)
					Na	K	Ca	Mg			
T4–1/J1	0–16	6.5	45	129	0.70	0.33	31.28	9.09	93	3.44	0.7
T4–1/J2	0–13	7.2	41	154	0.77	0.65	28.66	9.48	97	3.02	1.6
	13–46	6.8	50	149	0.70	0.25	36.27	9.96	94	3.64	0.5
	46–66/86	6.1	49	141	0.79	0.33	35.73	9.51	95	3.76	0.7
T4–1/J3	0–16	6.3	41	185	0.78	0.69	30.26	9.23	99	3.28	1.7
	16–68	6.7	44	300	0.61	0.21	35.19	9.98	105	3.53	0.5
	68–123	6.7	45	244	0.71	0.79	35.88	10.03	106	3.58	1.8
T4–2/J1	0–15	6.5	38	105	0.61	0.62	27.25	8.92	99	3.06	1.7
	15–51	6.5	44	121	0.79	0.25	30.95	10.12	96	3.06	0.6
	51–88	7.1	50	147	0.89	0.29	36.47	11.90	99	3.07	0.6
	88–157	6.9	53	133	0.82	0.26	36.15	12.70	94	2.85	0.5

The lowest and highest percentages of organic matter and total nitrogen were recorded for the backslope and the lower reaches of the toeslope, respectively. The very low levels on the backslope may partly be attributed to topsoil loss due to accelerated erosion. Unlike that of the divergent hillslope, the pedon on the backslope of the convergent hillslope is not cultivated nor located in a village and hence cannot receive organic manure. The generally low C/N ratio shows not only that the soils currently receive very little fresh organic matter (*e.g.*, straws) but also that they favour nitrogen mineralization.

The CEC of the soils on the convergent hillslope, as a whole, were very high (105 to 147 $\mathrm{cmol}_{(+)}\mathrm{kg}^{-1}$ clay throughout the solum) and similar to those of the soils on the crest and backslope of the divergent hillslope (Table 6). Like the soils on the crest and backslope of the divergent hillslope, these high CEC values reflect the presence of high capacity minerals in the clay and fine silt fraction. The presence of high capacity clay on the toeslope may be due to alluvial materials, colluviated stones and stone fragments derived from the crest and backslopes of both the convergent and divergent hillslopes. The base saturation recorded for the soils covering the convergent hillslope was also very high and generally above 90 percent. The highest subsoil base saturation, however, was registered for the toeslopes where cations carried downslope by leaching accumulate and add to the total exchangeable bases on the exchange complex. As on the backslope and footslope, the considerable amount of gravels, stone fragments and silt impart high fertility status by ensuring considerable nutrient reserve and continuous flow of nutrients into the soil solution.

Characteristics of the soil stratigraphic column

The combined effects of accelerated erosion on the hillslopes and the convergence of water and the sharp break of slope at the base were responsible for the accumulation of huge deposits of sediments on the toeslope of the convergent hillslope. The deposition was also very much aided by the seasonal stream that has now cut a deep gully across the strata of modern and buried soils on the slope unit. The bed of this stream currently stands 3 to 6 meters below the surface. Morphological characteristics of the stratigraphy of modern and buried soils observed on the walls of this deep gully is described in Figure 4 and the physical and chemical characteristics are shown in Tables 7 and 8.



0–15 cm	AP	Dark brown (7.5YR 3/4) slightly gravelly clay loam; moderate medium to coarse sub-angular blocky; hard, sticky, plastic; common fine roots; smooth clear boundary.
15–92 cm	CB	Dark brown (7.5YR 3/4) slightly gravelly clay loam, moderate medium to coarse sub-angular blocky; hard, dry, sticky, plastic; very few fine roots; smooth abrupt boundary.
92–265 cm	Bbl	Brown (7.5YR 4/3) slightly gravely clay loam; strong coarse angular blocky; hard friable, slightly sticky, slightly plastic, very few fine roots; common strongly weathered mineral grains smooth abrupt boundary.
265–420 cm	Bb2r	Dark brown (7.5YR 4/3) clay; strong coarse angular blocky; hard, friable sticky, plastic; shiny ped surfaces; common fine rounded bluish black (2.5/5PB) iron-manganese oxide concretions; smooth abrupt boundary.
420–580 cm	Bb3r	Black (10YR 2/1) clay; strong medium to coarse angular blocky; hard, friable, sticky, plastic; common fine rounded bluish black (2.5/5PB) iron-manganese oxide concretions; smooth clear boundary.
580–620 cm	C	Gravel layer on bedrock; angular stones (diameter, 10–20 cm) and gravels.
> 620 cm	R	Bedrock.

Fig. 4. Description of a soil-stratigraphic section, T4–2/J2, on the toeslope at the base of the convergent hillslope.

Table 7. Physico-chemical properties of soils constituting a stratigraphic section on a toeslope at the base of the convergent hillslope (section T4–2/J2).

Depth (cm)	B. D. [g(cm)$^{-3}$]	Texture (%) s	si	c	Silt/ clay ratio	Clay-free sand (%)	Org. C (%)	C/N	Tot. N (%)	Avail P [mg(kg)$^{-1}$]
0–15		18	44	38	1.16	29	1.04	6	0.17	33
15–57	1.29	28	35	37	0.95	44	0.79	8	0.10	17
57–92	1.37	46	26	28	0.93	64	0.55	8	0.07	40
92–265	1.28	40	30	30	1.00	57	0.88	11	0.08	40
265–420	1.47	20	36	44	0.82	36	0.50	13	0.04	25
420–580	1.41	40	20	40	0.50	67	1.69	11	0.15	76

Table 8. Chemical properties of soils constituting a stratigraphic section on a toeslope at the base of the convergent hillslope (section T4–2/J2).

Depth (cm)	pH 1:1 H_2O	CEC	CEC/ clay	Exchangeable basic cations [cmol $_{(+)}$kg^{-1} soil] Na	K	Ca	Mg	$CaCO_3$ equiv. (%)
15–57	6.63	48	121	0.71	0.34	38.53	12.14	3.4
57–92	6.73	4	147	0.80	0.25	36.98	11.89	3.9
92–265	6.51	43	133	0.80	0.25	36.75	12.32	4.1
265–420	6.72	40	87	2.18	0.46	25.10	7.58	2.4
420–580	6.29	42	91	2.34	0.69	24.65	5.75	1.2

The stratigraphic analysis made on the basis of the morphological characteristics shows that the boundaries of the buried soils occur at depths of 92, 265, and 420 cm from the surface. About 30 cm thick gravel layer (layer C in the stratigraphic column) directly overlying the bedrock constitutes the base of the oldest buried soil, Bb3r, and the lowest layer of the soil stratigraphic column. A soil sample (Beta-89713) collected from a surface layer of this 1.6 m thick buried soil was found to have a conventional radiocarbon age of 3900 ± 70 years before present (YBP) and calibrated age corresponding to 4520 to 4095 YBP. The gravel layer attests to the fact that even this old soil was formed from a colluvial material derived from the eroding basin. The soil is characterized by deep black clay, high bulk density [1.41 g(cm)^{3}], well-developed slickensides, and vertical cracks along the exposed gully sides. The clay content of 40 percent and CEC of 42 $\text{cmol}_{(+)}\text{kg}^{-1}$ soil [or 100 $\text{cmol}_{(+)}\text{kg}^{-1}$ clay] suggest smectite type of clay minerals (Table 7). Compared to the other layers constituting the stratigraphic section, this buried soil has the highest organic matter, total nitrogen, available phosphorus and clay free sand.

A 155 cm thick buried soil horizon, *i.e.,* Bb2r, directly overlies the soil that forms the base of the stratigraphic column. The marked decline in organic matter, total nitrogen and available phosphorus in this horizon compared to the underlying soil is indicative of the major shift in the soil characteristics. The sand content in this buried soil was 20 percent while the clay-free sand index was 35.7, very much contrasting with both the underlying soil and the overlying layers. The marked change in these two attributes and the abrupt boundary the layer forms with other horizons also indicate a major change in the parent material. The ped surfaces in the lower parts of the buried soil were also marked by clay skins suggesting that the layer may represent a relict argic horizon. As clearly shown in the stratigraphic section, an abrupt upper boundary also separates this buried soil from a third overlying buried horizon, Bb1. The profile morphology and texture of the latter, however, show lesser degree of weathering and pedogenesis compared to the underlying buried soil. The characteristics of the upper most soil constituting the stratigraphic section suggests that the sediment that was deposited last and provided the parent material of the modern soil on the convergent toeslope was only less than one meter thick.

DISCUSSION

Classification of soils

Most of the soils that currently occupy the crests and backslopes of both the divergent and convergent hillslopes generally have depths of less than 30 cm and qualify for the class of Leptosols. The predominant soils on the interfluve divides are the Lithic Leptosols which frequently occur interspersed with rock outcrops. The major units on the crests and backslopes are Eutric Leptosols although on the uncultivated natural terraces these usually give way to Mollic Leptosols. The three Leptosol units differ from each other in that the Lithic Leptosols have soil depth of less than 10 cm while the Eutric and Mollic

Leptosols have depths ranging between 10 and 30 cm. The Eutric and Mollic Leptosols have ochric and mollic A horizons, respectively (see FAO/UNESCO, 1990, for properties of mollic and ochric A horizons). The Mollic Leptosols are characterized by much darker colour (7.5YR 3/2) and better developed soil structure when compared to the Eutric Leptosols (7.5YR 4/4).

The A horizons of the soils on the divergent footslope and toeslope possess well developed slickensides, strong medium to coarse angular blocky structure, firm to very firm dry-, and sticky to plastic wet-consistence. The deep and wide cracks, that are characteristic of these soils, are evidences of significant shrink and swell properties resulting predominantly from the smectitic clay minerals. During the dry seasons these cracks open to more than 1 cm and produce fissures that extend to depths of greater than 50 cm. The subsurface soils are characterized by well developed slickensides. The soils are also marked by clay contents of more than 54 percent to depths of more than 50 cm. The base saturation throughout the solum is above 50 percent. Thus the soils qualify for Eutric Vertisols of the FAO/UNESCO legend (FAO/UNESCO, 1990).

However, the Eutric Vertisols on the footslopes and toeslopes of the divergent hillslope show significant variations in some of their characteristics. The A horizons of those on the footslopes were dark brown (7.5YR 3/2), while those on the toeslopes were very dark grey (10YR 3/2). The latter were marked by stone free surfaces, very deep solum, and wide and deep cracks when dry. The dark brown Eutric Vertisols have stony surfaces, thinner solum, and shallower and narrower cracks. The stones on the soil surfaces are reflections of the contemporary creep movements of the particles from the crest and backslope. The dark brown and the dark grey Vertisols, respectively, correspond to the "Vertisols of lithomorphic origin" and "Vertisols of topographic depressions" of the old CTCA (Commission for Technical Co-operation in Africa) Soil Map of Africa (Young, 1976).

Because erosion has removed much of the A horizon, proper classification of the pedon on the footslope of the convergent hillslope was difficult. However, the presence of considerable amount of gravels, high silt clay ratio and absence of diagnostic properties such as well developed clay skins in the subsurface soils suggest a cambic B horizon. As pointed out earlier, mollic A horizons are in equilibrium with the altitude and temperature conditions of the site, and hence the soils on the convergent footslopes apparently constitute eroded Haplic Phaeozems, whose mollic A horizon is lost and cambic B is severely truncated. The placement of this pedon under Haplic Phaeozems is further justified by the common occurrence of these soils at similar slope positions throughout the surrounding regions (Paris, 1985; Weigel, 1986; Belay Tegene, 1993).

The last deposit of alluvium on the toeslope was too young to allow significant development of modern soils. As a result the soil that covers this toeslope is marked by very thin and poorly developed ochric A horizon overlying fine textured material that can only qualify for a CB horizon. The thin laminations observed in the solum provide clear evidence for the youthfulness of the soil. The more or less uniform particle-size distribution in the solum is also indicative of the less advanced state of pedogenesis. The uniform distribution of clay shows not only very weak transformation of the parent material but also the absence of clay illuviation in the solum. Hence the soils fulfil only the requirements for Eutric Regosols.

Applying standard procedures in the classification of buried soils has limitations because the soil characteristics may be strongly modified after burial due to secondary enrichment resulting from the downward percolating water that is charged with solutions (Ruhe, 1956). Despite these limitations an attempt was made to identify the soil unit that correspond to the oldest buried soil at the base of the stratigraphic column. The high clay content, vertical cracks, slickensides and the CEC suggest that the buried soil that forms the base of the soil stratigraphic column corresponds to the Eutric Vertisols of the revised FAO/UNESCO Soil Map Legend (FAO/UNESCO, 1990). The pedon described on the toeslope at the base of the divergent hillslope may represent the unburied equivalent of this soil unit. The higher sand and lower clay contents of the buried Vertisol, however, may have resulted from incorporation of more sand and fine gravel at the initial stage of burial. The rest of the buried horizons were found difficult to classify.

Erosion, deposition and inter-catena variation

The soil catena on the divergent footslope can be established as Leptosols- severely eroded dark brown Eutric Vertisols- very deep dark grey Eutric

Vertisols, while the chain on the convergent footslope is bare rock outcrops- Leptosols- severely degraded Haplic Phaeozems- Eutric Regosols. The soil units constituting both of the catenas reflect the conditions of soil erosion and deposition that largely depend on the topography. Other studies and field observations have also shown that Leptosols constitute the upper most segments of the soil catena throughout the cultivated and degraded landscapes of Welo (Paris, 1985; Weigel, 1986; Belay Tegene, 1993). The shallow soils, i.e., the Leptosols, on the crests and backslopes and bare rock outcrops on the divides, on the one hand, and the thick sequence of modern and buried soils on the convergent toeslopes, on the other, suggest that one of the major forces that shaped the two catenas are accelerated erosion and deposition.

There are a number of evidences for the anthropogenic origin of the eroded soils on the crest and backslopes. Firstly, remnants of soils having depths of up to 150 cm are still observed in a few protected sites at similar slope positions and gradients in the Watiya catchment and surrounding areas. Phaeozems and Andosols with depths of between 60 and 150 cm were described on slopes of 30 to 50 % in the Wurgo valley (Belay Tegene, 1993; 1995). Andosols having depths of more than 100 cm were also reported on similar slopes in the Borkena catchment (Paris, 1985). Similarly, 90 to 140 cm deep Phaeozems were described on slopes of more than 40 percent under similar environment in the Maybar area (Weigel, 1986). The existence of these deep soils on such steep slopes indicates that the crest and backslopes of most hillslopes now covered by Leptosols had much deeper soils until they were deforested, cultivated and exposed to accelerated erosion. As in the case of Maybar, the predominant soils on the crests and backslopes of the Watiya and the surrounding catchments before deforestation may have been Phaeozems (Weigel, 1986).

The process of erosion on the crests and backslopes was complimented by deposition and thick accumulation of sediments on the convergent toeslope. Accelerated erosion on the crest and backslopes has produced little impact on the lower segments of the divergent hillslope and the inter-catena variation observed on the two hillslopes basically results from this difference. A clear separation between the two catenas is made on the convergent toeslope where Regosols replace the Vertisols observed on the divergent toeslopes. In the latter case very little runoff and sediment converge from the adjacent watershed and, as a result, the soils have experienced neither erosion nor deposition. Hence, thick Vertisols constitute the soil unit. The convergent toeslopes, on the other hand, have been marked by regular accumulation of alluvium, in the past, leading to the development of thick strata of buried soils.

The buried soil horizons impressed on the soil stratigraphic column show that the processes of deposition were periodic and that soil formation was intermittently interrupted by periods of intensive deposition. The cumulization process resulting from frequent cycles of deposition has effectively interrupted and prevented the development of mature soil profiles on the convergent toeslope since 4000 YBP. As Graham and Buol (1990) point out, when soils are buried by alluvium, soil formation begins again from time zero on the newly added depositional material. The Regosols now covering the surfaces of this accumulation have developed on the layer that formed recently, and hence the pedogenic alterations were only sufficient for the formation of an ochric A horizon.

CONCLUSION

Soil catenas on divergent and convergent hillslopes in the upper Watiya catchment were examined and related to slope forms and soil erosion processes. The role of longitudinal profiles of the hillslopes was very well reflected in the development of thick Vertisols at the base of both hillslopes, *i.e.*, footslopes and toeslopes, 4000 YBP. Since then erosion has resulted in the predominance of Leptosols on the crests and backslopes of both types of hillslopes. On the other hand, the cycles of deposition of sediments on the Vertisol landscape at the base of the convergent hillslope have given rise to Regosols and an underlying strata of buried soils. Because of the convex lateral profile of its superjacent hillslope, the Vertisols at the base of the divergent hillslope have remained unaffected by the cycles of accelerated erosion and deposition that took place in the last four millennia.

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REFERENCES

1. Abiy Astatke and Frew Kelemu (1993). Modifying the traditional plough-maresha for better management of Vertisols. In: *Improved Management of Vertisols for Sustainable Crop-Livestock Production in the Ethiopian Highlands*, pp. 85–101, (Tekalign Mamo, Abiy Astatke, Srivastava, K. and Asgelil Dibabe, eds). Synthesis Report 1986–1992, Technical Committee of the Joint Vertisol Project, ILCA, Addis Ababa, Ethiopia.
2. Belay Tegene (1993). Characteristics and potentials of soils in Wurgo sub-catchment, Akesta, Welo. Soil Survey Report. Italian Technical Unit, Addis Ababa University, Addis Ababa, Ethiopia (unpublished typescript), 58 pp.
3. Belay Tegene (1995). Morphological, physical and chemical characteristics of Mollic Andosols of Tib mountains, north central Ethiopian highlands. *SINET: Ethiop. J. Sci.* **18**:143–168.
4. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E. and Clark, F.E. (eds) (1965). *Methods of Soil Analysis*, Part 2. Am. Soc. of Agronomy Inc., Madison, Wisconsin, pp. 771–1572.
5. Conacher, A.J. and Dalrylmple, J.B. (1977). The nine unit landsurface model: An approach to pedogeomorphic research. *Geoderma* **18**:1–154.
6. El Wakeel, A. and Abiy Astatke (1996). Intensification of agriculture on Vertisols to minimize land degradation in parts of the Ethiopian highlands. *Land Degradation & Development* 7:57–67.
7. FAO/UN (1990). *Guidelines for Soil Profile Description*, 3rd revised ed., FAO/UN, Rome, 70 pp.

8. FAO/UNESCO (1990). *Soil Map of the World.* Revised Legend, FAO/UNESCO, Paris, 119 pp.

9. Gerrard, J. (1992). *Soil Geomorphology: An Integration of Pedology and Geomorphology.* Chapman & Hall, London, 269 pp.

10. Graham, R.C., Daniels, R.B. and Buol, S.W. (1990). Soil-geomorphic relations on the Blue Ridge Front: I. Regolith types and slope processes. *Soil Sci. Soc. Am. J.* **54**:1362–1367.

11. Graham, R.C. and Buol, S.W. (1990). Soil-geomorphic relations on the Blue Ridge Front: II. Soil characteristics and pedogenesis. *Soil Sci. Soc. Am. J.* **54**:1367–1377.

12. Hall, G.F. (1983). Pedology and geomorphology. In: *Pedogenesis and Soil Taxonomy, I. Concepts and Interactions*, pp. 117–140, (Weil-ding, L.P., Smeck, N.E. and Hall, G.F., eds). Elsavier, Amsterdam.

13. Huggett, R.J. (1975). Soil landscape systems: a model of soil genesis. *Geoderma* **13**:1–22.

14. Kreznor, W.R., Olson, K.R., Banwart W.L. and Johnson, D.L. (1989). Soil, landscape, and erosion relationships in a northwest Illinois watershed. *Soil Sci. Soc. Am. J.* **53**:1763–1771.

15. Milne, G. (1935). Some suggested units of classification and mapping particularly for East African soils. *Soil Research* **4**:183–198.

16. Munsell Colour (1975). *Munsell Soil Colour Charts.* Kollmorgen Corporation, Baltimore, Maryland.

17. Marron, D.C. and Popenoe, J.H. (1986). A soil catena schist in northwestern California. *Geoderma* **37**:307–324.

18. Ollier, C.D. (1976). Catenas in different climates. In: *Geomorphology and Climate*, pp. 137–169, (Derbyshire E., ed.). Wiley, Chichester.

19. Paris, S. (1985). *Soil Survey of the Borkena Area (Welo).* AG:DP/ETH/82/010, Field doc. 7., LUPRD/UNDP/FAO, Land Use Planning and Reg. Dept., Ministry of Agriculture, Addis Ababa, Ethiopia, 233 pp.

20. Pennock D.J., Zebeth, B.J. and De Jong, E. (1987). Landform classification and soil distribution in hummocky terrain, Saskatchewan, Canada. *Geoderma* **40**:297–315.

21. Ruhe, R.V. (1956). Geomorphic surfaces and the nature of soils. *Soil Science* **82**:441–455.

22. Ruhe, R.V. (1960). Elements of the soil landscape. In: *Trans. 7th Int. Congr. Soil Sci.*, vol. 4, pp. 165–169. Madison, Wisconsin.

23. Ruhe, R.V. (1975). *Geomorphology*. Houghton Mifflin Company, Boston, 245 pp.

24. Scharpenseel, H.W. (1971). Radiocarbon dating of soils- problems, troubles and hopes. In: *Paleopedology-Origin, Nature, and Dating of Paleosols*, pp. 77–87, (Yallon, D.H., ed.). Intern. Soc. Soil Sci. Israel Univ. Press, Jerusalem.

25. Soil Survey Staff (1969). *Soil Survey Manual.* USDA Handbook No. 18. 2nd Indian Reprint. Oxford & IBH Publishing Co. New Delhi.

26. Weigel, G. (1986). The Soils of the Maybar/Welo Area; their potential and constraints for agricultural development. *African Studies Series A4.* Geogrphica Bernensia, University of Berne, Switzerland.

27. Wielemaker, W.G. and Wakatsuki, T. (1984). Properties, weathering and classification of some soils formed in peralkaline volcanic ash in Kenya. *Geoderma* 32:21–44.

28. Young, A. (1976). *Tropical Soils and Soil Survey*. Cambridge University Press. Cambridge, 468 pp.