SINET: Ethiop. J. Sci., 21(1):91-111, 1998

ISSN: 0379-2897

PEDOGENESIS AND SOIL-GEOMORPHIC RELATIONSHIPS ON THE PIEDMONT SLOPES OF WURGO VALLEY, SOUTHERN WELO, ETHIOPIA

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ABSTRACT: The morphological, physical, chemical and mineralogical characteristics of six pedons were investigated to establish relationships that exist between soils and geomorphic processes on the piedmont slopes of the Wurgo valley of southern Welo, Ethiopia. The results revealed that slope processes have played major role in the development of Eutric Cambisols with typical A/Bw/Bb horizon sequences on the convergent footslopes, Luvic Phaeozems with A/Bt/Cr or A/Bt/Bb sequences on the non-convergent footslopes, and Eutric Vertisols with A/C/Cr or A/AC/Bb arrangements on the toeslopes. The Cambisols were weakly acid to neutral soils with loam to clay loam texture and cation exchange capacity (CEC) of 139 to 253 $\text{cmol}_{(+)}\text{kg}^{-1}$ clay. The sand fraction in these soils is dominated by pyroxenes and volcanic clasts. The Phaeozems were marked by clay loam to clay texture, CEC of 113 to 203 $\text{cmol}_{(+)}\text{kg}^{-1}$ clay and sand fractions dominated by feldspars, volcanic clasts and laterite nodules. The Vertisols are heavy clay soils having CEC of 75 to 139 $\text{cmol}_{(+)}\text{kg}^{-1}$ clay and sand fractions dominated by weathered volcanic clasts and laterite nodules. All of the characteristics used as indices of weathering suggest that the three soil units are at different stages of pedogenesis - the Cambisols being the youngest and the Vertisols the oldest soils. The major slope-related soil building process that resulted in the formation of Cambisols on the convergent footslopes was "cumulization" resulting from intermittent addition of alluvial and colluvial materials. Absence of "cumulization" on the other types of footslopes has allowed an uninterrupted operation of "lessivage" with subsequent development of argic B horizons within the subsoils of the Phaeozems. The active operation of "argilli-pedoturbation" and "haploidization" and the subsequent development of Vertisols on the toeslopes was encouraged by the gentle to almost flat surfaces and the fine textured parent materials.

Key words/phrases: Ethiopia, Eutric Cambisols, Eutric Vertisols, Luvic Phaeozems, Wurgo Valley

INTRODUCTION

Investigations carried out in different parts of the world recognize that pedogenic processes are integral parts of landscape evolution and that geomorphic processes play a major role in the genesis and distribution of soils. The theoretical basis of these relationships was established by the works of Ruhe (1960; 1975), Daniels *et al.* (1971), Huggett (1975), and Conacher and Darlymple (1977). Recent studies have also reasserted that slopes and geomorphic processes control the formation and distribution of most soils (Nettleton *et al.*, 1989; Graham *et al.*, 1990a,b).

Soil-geomorphic relationships have strong practical relevance since once they are established they can be effectively used as aid in soil mapping. As Hole and Campbell (1985) rightly point out, "most mapping endeavours rely upon the use of relatively easily observed properties as substitutes for, or indicators of, other characteristics that may not be as easily observed or measured." Because soil-geomorphic units are easily identified and mapped from remotely sensed data (based on indicator topographic features and supplementary ground observations), they can be effectively used in rapid surveys of the soils of a region. As Wall (1964) argues "mapping soils in the field by means of soil examination alone would be both slow and tedious. More rapid results are obtained by mapping features of topography which can be related to soil type".

The slope configurations of the Ethiopian highlands have given rise to distinctive and typically recurring soil, slope and geomorphic relationships. Most of the land units identified by Paris (1985) and Venema and Paris (1986; 1987), in soil surveys conducted in different parts of the country at scales of 1:50,000, attest to these strong soil-geomorphic relationships. Studies conducted in Tigray and Welo by Virgo and Munro (1978) and Belay Tegene (1996; 1997) also provide solid evidence for these relationships. A soil survey carried out at a scale of 1:12,500 has also revealed strong soil-geomorphic relationships on the piedmont slopes of the Wurgo valley in Southern Welo (Belay Tegene, 1993). The objective of this paper is to present and discuss the major features of the relationships observed in this valley by comparing and relating the soil characteristics with the corresponding slope positions and geomorphic processes.

MATERIAL AND METHODS

Description of the study site

The Wurgo valley, located at about 39° 10'E and 10° 50'N, immediately south of Akesta town, in the southern Welo highlands, forms part of the Blue Nile drainage system. The watershed of the river has an area of about 1700 ha and covers an altitudinal range of 2800 to 3600 m. The valley floor, which is the focus of this investigation, is found within a range of 2750 to 3000 m altitude. The catchment is characterized by mountainous topography and a bedrock of trap series lava cut by numerous dikes, all Tertiary in age (Cinque, 1993). Trachytic tuffs constituting the dikes commonly form the ridge crests and mountain tops.

A piedmont slope comprising two of Ruhe's (1960) hillslope units, *i.e.*, the footslopes and toeslopes, stretches for about 200 to 500 meters on each side of the Wurgo river and form the floor of the valley (Fig. 1). A distinct break of slope, *i.e.*, the piedmont angle, separates the piedmont slope from the superjacent mountain front, while the channel walls form the boundary with the river. A large proportion of the piedmont slope is mantled by two types of Quaternary deposits, *i.e.*, colluvial and alluvial deposits, while the remaining portion is marked by the trap series lava. Most of the piedmont slope has allowed the formation of deep and very productive solum. The development of piedmont slopes along the tributary valleys of Wurgo river are impeded because eroded and wasted materials supplied to these V-shaped valleys are constantly removed by the cascading (high velocity) streams during the rainy seasons (Fig. 2).

Because of lack of meteorological stations, the rainfall characteristics for the study site were inferred from data recorded for Dessie town, located at an elevation of 2540 m.a.s.l about 60 kms to the east. These data show mean annual rainfall of about 1200 mm and a typical bimodal regime with a lesser maxima from March to May (locally known as the "belg") and a larger maxima from July to October (the "meher"). The mean annual temperature (t) was estimated at 11 to 12° C, which was calculated based on the equation: $t=30.2°C-ah$, where 'a' is a coefficient equal to $6.5x10^{-3}$ °C m^{-1} and 'h' is altitude above sea level in meters (Wielemaker and Wakatsuki, 1984). The rainfall and temperature data suggest that the site falls under the cool sub-tropical summer rainfall zone of the FAO/UNESCO (1990) climatic classification.

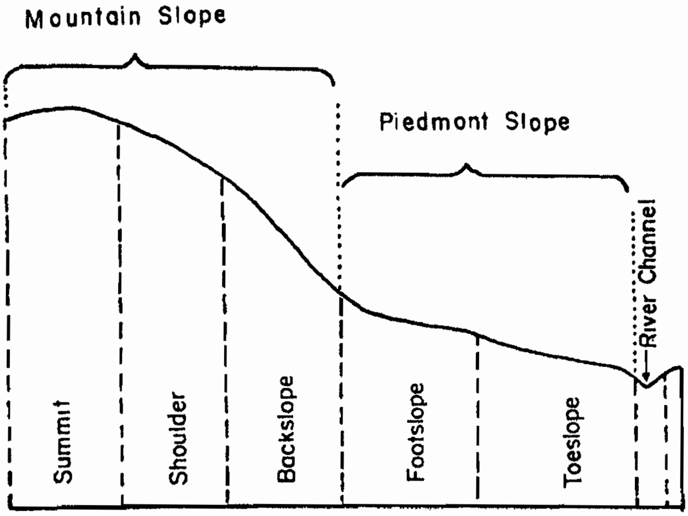

Fig. 1. Slope sequences representing segments of topographic units on either side of the main Wurgo valley.

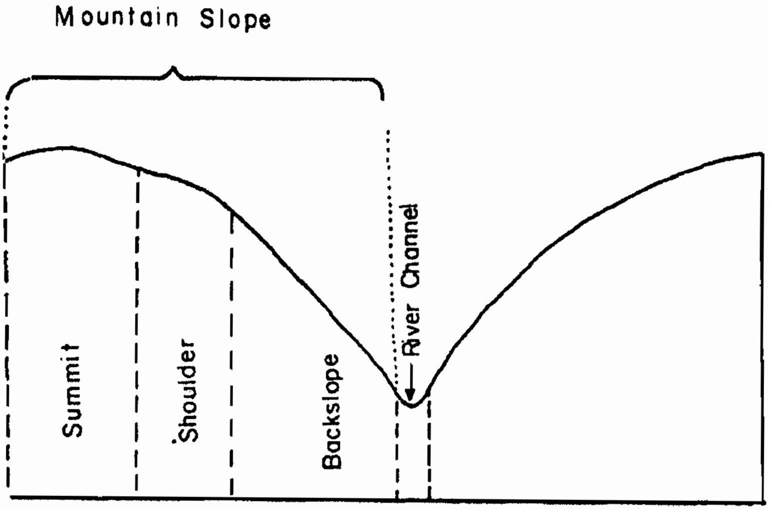

Fig. 2. Slope sequences on either side of the tributary valleys of Wurgo.

Agriculture in the valley, and the Wurgo catchment as a whole, mainly involves small-scale subsistence rainfed cultivation of crops such as wheat (*Tritcum spp.*), emmer wheat (*Triticm dicoccon* Schrank), barley (*Hordeum vulgare* L.), field peas (*Pisum sativum* L.), horse beans (*Vicia faba* L.), lentils (*Lens culinaris* Medik), and fenugreek (*Trigonella foenum-graecum* L.). Cultivation is performed in both the "belg" and "meher" seasons with very little input of chemical fertilizers, although leguminous crops are grown in rotation to maintain the nitrogen status of the soils.

Methods and procedures

A systematic soil survey (at 1:12,500 scale) was employed in the identification and classification of soils. Auger holes were drilled and described to depths of up to 100 cm at grid intervals of 250 m. Pits were also dug on representative soils and profile descriptions were carried out to depths of up to 235 cm following the procedures of the FAO (1990) guidelines. The revised legend of the FAO/UNESCO (1990) Soil Map of the World was employed in the classification of the soils. Soil-geomorphic relationships were established on the basis of features recognized on aerial photographs, topographic maps, a soil survey report (Belay Tegene, 1993) and a series of field observations.

Laboratory analysis of soil samples were performed in the National Soil Testing Laboratory of the Ministry of Agriculture. Texture was determined by the hydrometer method after dispersion with hydrogen peroxide and sodium hexametaphosphate solutions (Black *et al.*, 1965). The USDA particle size classification was adopted to specify percentages of sand (2.0–0.05 mm), silt (0.05–-0.002 mm) and clay (<0.002 mm) (Soil Survey Staff, 1969). Soil pH was measured in 1:2.5 soil-water suspension with standard glass electrode. Organic carbon was tested following Walkley and Black's method while available phosphorus and total nitrogen were tested following Olsen's method and the Kjeldahl procedure, respectively (Black *et al.*, 1965). The ammonium acetate method was employed to separately determine the cation exchange capacity and the exchangeable basic cations (Black *et al.*, 1965).

The skeletal mineralogy of the soils were determined from the sand fraction of soil samples collected from selected representative profiles. The procedure involved separating and washing the sand and preparing thin sections after impregnating the washed sand in haraldite, a synthetic resin. Thin sections were then examined under a polarizing microscope and volume percentages of the minerals were determined on a graduated mechanical stage using a point counter (modal analysis).

RESULTS

Major soil units of the piedmont slopes

The variable intensities by which water, solutes and solids are added, removed and transferred on the piedmont slopes of the Wurgo valley have led to significant differentiation of soils. The predominant soils that have formed on the convergent footslopes were identified as Eutric Cambisols, those on the linear and convex footslopes as Luvic Phaeozems, and the ones on the toeslopes as Eutric Vertisols. The morphological, physical, mineralogical and chemical characteristics of these soil units are discussed in the following sections.

Eutric cambisols

These soils are generally marked by an A/Bw/Bb horizon arrangement comprising of 47 to 82 cm thick solum and strata of buried soils (Table 1). The sola, overlying the buried horizons, are throughout characterized by dark brown (7.5YR 3/2) colour. Despite their dark value and chroma, however, the topsoils fail to fulfil the colour contrast requirements for 'mollic' or 'umbric' horizons and hence were identified as 'ochric' (Aoc). The B horizons were characterised by considerable quantities of gravel or rock fragments and uniform particle size distribution. They were also marked by high silt/clay ratios and absence of clay skins suggesting that they are cambic (Bw). Hence, the soils were identified as Eutric Cambisols.

The mineralogical analysis of the sand fraction constituting pedon T5-11/L2 indicate abundant weatherable minerals and clasts throughout the solum confirming the cambic characteristics and less advanced stage of pedogenesis (Table 2). These minerals release large amounts of nutrients and maintain high level of soil fertility upon weathering. A considerable proportion of the volcaniclastic materials (in some cases up to 84%) are also unweathered, reflecting the youthfulness of the Cambisol profile. The other major mineral groups, *i.e.*, the pyroxenes and feldspars (apparently largely composed of the plagioclase species), together account for 13.4 to 43 percent of the sand fraction in the various horizons. The large presence of these two weatherable minerals and the very small percentage of quartz (less than 4%) once again show the less advanced stage of weathering and pedogenesis.

Table 1. Morphological and physical characteristics of representative profiles of Eutric Cambisols of the Wurgo valley*.

Depth (cm)	Hori-zon	Colour (moist)	Structure	Consistence	Bou-ndary	Texture (%)			Text. class	Silt/clay ratio
						Sand	Silt	Clay		
Profile no. 24 (T5-11/L2)										
0–12	Ap	7.5YR3/2	2-f&msbk	dh,wss,wsp	cs	38	36	26	l	1.38
12–34	A2	7.5YR3/2	2-csbk	dh,wss,wsp	cs	41	33	26	l	1.27
34–82	Bw	7.5YR3/2	2-csbk	dh,ws,wp	as	49	30	21	l	1.43
82–165	Bb	7.5YR3/2	2-csbk	dh,ws,wp	-	66	19	15	sl	1.27
>165	Soil continues below 165 cm									
Profile no. 30 (T2-16/N1)										
0–12	Ap	7.5YR3/2	2-f&mgr	ds,wss,wsp	cs	26	41	33	cl	1.24
12–47	Bw	7.5YR3/2	2-m&csbk	ds,wss,wsp	as	29	37	34	cl	1.09
47–92	Bb1	7.5YR3/2	3-csbk	dh,ws,wp	cs	22	37	41	c	0.90
92–130	Bb2	7.5YR3/2	3-csbk	dh,ws,wps	cs	33	31	36	cl	0.86
130–235	Bb3	7.5YR3/2	3-m&csbk	dh,wvs,wvp	-	26	36	38	cl	0.95
>235	Soil continues below 235 cm									

* Abbreviations used for the profile descriptions are in line with the procedures of the Soil Survey Manual (Soil Survey Staff, 1969).

The low weathering ratios of the minerals constituting the sand fraction are also indicative of the youthfulness of the soils (Table 2). The generally low levels and irregular variation of laterite within the profile suggest that the iron nodules are results of deposition. These nodules have apparently formed, *in situ*, in the older soils that used to cover the superjacent slopes, and were then removed and transported to their present positions. The irregular variations in the sand mineralogy of the various horizons and the corresponding weathering ratios might indicate minor variations in the composition of the sediments from which the soil horizons have formed. In all cases, clasts of volcanic origin (weathered and unweathered) account for the largest proportion of the sand (48.3 to 86.6 %), showing that the parent materials originate in the trachyte rocks underlying the ridges and mountain slopes as reported by Belay Tegene (1995).

Table 2. Status of primary minerals within the sand fraction of a representative Eutric Cambisol; Profile no. 24 (T5-11/L2).

Depth (cm)	Primary minerals (percent by volume)									Weathering ratio			
	Qtz	Fd	Cpx	Amp	Mic	Vc	Vcw	Lat	Ox	Qz/Fd	Qz/Vcw	Qz/Cpx	Vcw/Vc
0–12	1.1	5.2	37.8	0.0	0.0	13.1	35.2	6.4	1.2	0.20	0.08	0.00	2.69
12–34	10.4	2.1	19.6	0.0	0.0	15.1	50.5	12.3	0.0	0.20	0.03	0.00	3.34
34–82	0.0	3.0	10.4	0.0	0.0	72.6	14.0	0.0	0.0	0.00	0.00	0.00	0.19
82–165	3.9	2.9	13.4	3.3	15.7	4.7	50.0	3.0	3.1	1.30	0.83	0.30	10.64

Qz, Quartz; Fd, Feldspars; Cpx, Clino-pyroxenes; Amp, Amphiboles; Mic, micrite; Vc, Volcanic clasts (fresh); Vcw, Volcanic clasts (weathered); Lat, laterite; Ox, oxides.

The A horizons of the Eutric Cambisols show weakly acid to neutral reactions while the cambic B horizons are generally neutral (Table 3). The presence of 0.10 to 0.60 percent organic carbon to depths of more than 150 cm reflects the strong influences of deposition and "cumulization". The organic carbon percentages of generally less than 1.5 percent, which are much lower than in most of the uncultivated soils in the surrounding areas, reveal the severity of soil organic matter degradation that has resulted from crop cultivation. The total nitrogen contents, which are generally related to the soil organic matter, were also low to very low and, hence, the soils may show significant response to organic manure and N-fertilizers. The concentration of available phosphorus is medium to high.

Both the Aoc and Bw horizons are characterized by very high cation exchange capacity (CEC) and high percentage base saturation. The high CEC values registered for the solum, *i.e.*, 48.42–60.99 $\text{cmol}_{(+)}\text{kg}^{-1}$ soil, and those computed against the clay fraction, *i.e.*, 139–253 cmol$_{(+)}$kg^{-1} clay, attest to the presence of considerable amount of high exchange capacity clay minerals such as allophane. The absence of vertic properties rules out the possibility of a significant presence of smectite. Allophane and imogolite were the predominant clay minerals of the soils that have developed in the 'Tib' mountains, a few kilometres to the north (Belay Tegene, 1995). The high levels of exchangeable bases in the Cambisols are attributed to the large amount of weatherable minerals which release and continuously replace those lost through leaching.

Table 3. Chemical characteristics of representative profiles of Eutric Cambisols of Wurgo valley.

Depth (cm)	Org. C (%)	Tot. N (%)	Avail. P (mg kg^{-1})	pH 1:1 H_2O	Exchangeable basic cations [cmol$_{(+)}$kg^{-1} soil]				CEC [cmol$_{(+)}$kg^{-1}]	
					Na	K	Ca	Mg	Soil	Clay
Profile no. 24 (T5-11/L2)										
0–12	0.88	0.10	13.53	6.65	0.62	0.21	49.58	14.53	53.89	201
12–34	0.32	0.06	7.86	7.10	0.80	0.13	50.51	12.46	53.72	204
34–82	0.06	0.07	8.05	7.41	0.89	0.13	49.50	12.14	53.31	253
82–165	0.10	0.07	7.88	7.34	0.98	0.13	52.49	12.49	52.77	351
Profile no. 30 (T2-16/N1)										
0–12	1.40	0.16	32.06	6.73	0.74	0.32	33.71	11.10	48.42	139
12–47	1.10	0.09	32.57	7.50	0.93	0.32	39.26	11.92	60.99	173
47–92	0.60	0.08	31.85	7.45	0.77	0.33	39.01	12.90	54.19	127
99–130	0.60	0.05	41.25	7.63	0.77	0.29	44.93	14.41	57.45	156
130–235	0.60	0.05	32.56	7.33	2.02	0.35	33.73	6.58	42.60	109

Luvic phaeozems

The morphological characteristics of typical Luvic Phaeozems of the piedmont slopes of Wurgo valley are summarized in Table 4. The surface horizons have dark brown colour (7.5YR 3/2) and moderate fine to medium crumb and fine to coarse granular structures. Much of the topsoils which apparently used to form thick mollic A horizons have been lost to erosion and only very thin layers currently remain as plough (Ap) horizons. In most cases the Ap horizons are directly underlain by argic B horizons with well developed clay skins, giving the soils typical Ap/Bt/C or Ap/Bt/Bb sequences. Poorly developed vertic characteristics are also observed in the argic B horizons suggesting a significant presence of smectitic clay. As in the case of the Cambisols, the buried horizons underlying some of the argic horizons of the Luvic Phaeozems suggest that some of these soils have developed on depositional materials. Unlike the Cambisols, however, cessation of "cumulization" long time ago has enabled the development of argic B horizons in the Luvic Phaeozems.

Table 4. Morphological and physical characteristics of representative profiles of Luvic Phaeozems of the Wurgo valley*.

Depth (cm)	Horizon	Colour (moist)	Structure	Consistence	Boundary	Texture (%)			Text. class	Silt/clay ratio
						Sand	Silt	Clay		
Profile no. 29 (T2-16/M)										
0–14	Ap	7.5YR3/2	2-f&mgr	ds,ws,wps	cs	33	34	33	cl	1.03
14–51	Bt1	7.5YR3/2	2-m&csbk	dh,ws,wps	ds	18	35	47	c	0.74
51–92	Bt2	7.5YR3/2	2-m&csbk	dvh,ws,wps	cs	26	29	45	c	0.64
92–162	Bb	7.5YR4/2	2-csbk	dvh,wvd,wvp	-	11	20	69	c	0.29
>162	Soil continues below 162 cm									
Profile no. 36 (T1-20/O)										
0–13	Ap	7.5YR3/2	2-mgr	ds,ws,wps	cs	33	38	29	cl	1.31
13–33/62	Bt	7.5YR3/2	2-msbk	dh,ws,sps	aw	31	31	38	cl	0.82
>33/62	Cr									

* Abbreviations as in Table 1.

The percentages of clay in the pedons selected to represent the Luvic Phaeozems was between 29 and 33 in the Ap, and 38 and 47 in the Bt horizons. The sand mineralogy of pedon T1-20/O shows high percentages of weatherable minerals (Table 5). The high percentages and uniform distribution of laterite nodules in this pedon, unlike those observed in the Cambisol profile, suggest more intensive weathering. The percentages of volcanic clasts are also lower than those registered for the Cambisols. The Phaeozem profile also contains large amounts of feldspars (23 to 26 %) but very little pyroxene (less than 7 %), confirming the advanced stage of pedogenesis. The higher weathering ratios of the sand fraction also provide clear evidence for the more advanced stage of weathering and soil formation.

Table 5. Status of primary minerals within the sand fraction of a representative Luvic Phaeozem; Profile no. 36 (T1-20/O)*.

Depth (cm)	Primary Minerals (percent by volume)									Weathering ratio			
	Qtz	Fd	Cpx	Amp	Mic	Vc	Vcw	Lat	Ox	Qz/Fd	Qz/Vcw	Qz/Cpx	Vcw/Vc
0–13	9.3	25.6	7.0	0.7	0.0	9.7	21.1	26.6	0.0	0.40	0.96	1.30	2.18
13–33/62	12.0	23.7	4.1	0.3	0.0	3.4	34.2	22.3	0.0	0.50	3.53	2.90	10.06

* Abbreviations as in Table 2.

The organic carbon contents of 1.1 and 1.8 percent recorded for the Ap horizons show gradual decline with depth in the solum (Table 6). The total nitrogen contents (0.08 to 0.20 percent) in these horizons also show similar trends. Like those of the Cambisols, the low to very low levels of soil organic matter and total nitrogen suggest the degrading effects of hundreds of years of crop cultivation. The status of available phosphorus in these soils can be regarded as medium to high. The CEC values are in all cases greater than 50 cmol$_{(+)}$, and in some cases exceed 60 cmol$_{(+)}$kg^{-1} soil (Table 6). The CEC calculated for the clay fraction was between 113 and 203 cmol$_{(+)}$kg^{-1} clay. Field observations have revealed vertic properties in the argic B horizons suggesting the significant presence of smectitic clay. It should be noted, however, that despite the fact that the vertic properties are limited to the B horizons, the surface layers still register very high CEC. The latter can only be explained by the considerable presence of allophane and allophane-like minerals in these layers. The synthesis of these high capacity clay minerals is apparently encouraged by continuous weathering of the clastic skeletal minerals and the colluviated stones originating in the trachytic rocks on the ridges.

Table 6. Chemical characteristics of representative profiles of Luvic Phaeozems of Wurgo valley.

Depth (cm)	Org. C (%)	Tot. N (%)	Avail. P (mg kg^{-1})	pH 1:1 H_2O	Exchangeable basic cations [cmol$_{(+)}$kg^{-1} soil]				CEC [cmol$_{(+)}$kg^{-1}]	
					Na	K	Ca	Mg	Soil	Clay
Profile no. 29 (T2-16/M)										
0–14	1.14	0.08	23.89	6.37	0.63	0.60	33.12	12.09	52.93	153
14–51	0.81	0.07	39.09	6.88	0.70	0.53	32.00	11.52	54.90	113
51–92	1.00	0.14	16.02	7.05	0.82	0.74	37.00	11.68	58.34	125
92–162	1.01	0.06	27.72	7.22	0.91	1.01	39.84	14.67	50.89	71
Profile no. 36 (T1-20/O)										
0–13	1.76	0.20	12.52	5.88	0.64	0.61	36.71	11.43	62.58	203
13–33/62	1.33	0.15	2.88	5.89	0.77	0.33	37.08	10.77	61.71	155

Eutric Vertisols

Profile descriptions of representative Eutric Vertisols of the piedmont slopes of Wurgo valley are presented in Table 7. These soils are easily recognized in the field on the basis of their dark colour, deep solum, wide and deep cracks that they develop in the dry seasons, and their A/AC/Cr and A/C/Bb horizon sequences. The deep profiles (more than 140 cm) are marked by very dark gray to dark brown A horizons (10YR 3/1 to 7.5YR 3/2) and brown to yellowish brown AC horizons (7.5YR 3/3 to 7.5YR 4/2). The A horizons possess well-developed medium to coarse angular blocky structure and firm to very firm consistence. The deep and wide cracks and slickensides provide clear evidence for the significant shrink and swell properties of the Vertisols. During the dry seasons the cracks open 5 to 10 cm, and produce fissures that extend to depths of up to 120 cm. Where alternating swelling and contraction have operated undisturbed, as in the grass-covered plains of the southern parts of the valley, the soils have developed pronounced micro-relief and gilgai topography.

These soils are also heavy textured with clay contents of 40 to 60 percent in the A horizons and 54 to 67 percent in the AC horizons. The types of minerals identified in the sand fraction of the Vertisol profile, T2-16/N3 (Table 8), are generally similar to those of the Cambisols and Phaeozems. As in the case of the two soil units, the Vertisols are marked by a considerable presence of pyroxenes, feldspars and volcanic clasts, suggesting that these soils are also endowed with considerable nutrient reserves. However, the percentage of these weatherable minerals and fresh volcanic clasts is much lower in the Vertisol profile indicating the more advanced stage of pedogenesis.

Both organic carbon and total nitrogen contents of the Vertisols are low to very low. The available phosphorus concentration in the A horizons are also generally low. The surface soils are weakly acid while the subsurface horizons are weakly alkaline (Table 9). The cation exchange capacities of the A horizons, which range from 75 to 139 cmol(+)kg^{-1} of clay, are typical of soils dominated by smectite. The exchange sites are dominated by the basic cations.

Table 7. Morphological and physical characteristics of representative profiles of Eutric Vertisols of the Wurgo valley*.

Depth (cm)	Hori-zon	Colour (moist)	Structure	Consistence	Bou-ndary	Texture (%)			Text. class	Silt/clay ratio
						Sand	Silt	Clay		
Profile no. 32: Eutric Vertisol (T2-16/N3)										
0-14	Ap	10YR 3/1	3-csbk	dvh,wvs,wvp	cs	9	51	40	c	1.28
14-96	A2	10YR 3/1	3-cabk	dvh,wvs,wvp	as	10	30	60	c	0.50
96-135	AC	7.5YR 3/3	2-m&fsbk	dh,ws,wp	as	8	25	67	c	0.37
135-193	Bb	7.5YR 3/3	2-m&csbk	dh,wvs,wvp	as	22	28	50	c	0.56
193-225	C	Alluvium (large amount of rounded gravel)								
>225	R	Bedrock								
Profile no. 30 (T2-16/N1)										
0-19	Ap	7.5YR3/2	3-c&vcsbk	dvh,wvs,wvp	cs	21	29	50	c	0.58
19-88	A2	7.5YR3/2	3-c&vcsbk	dvh,wvs,wvp	ds	28	13	59	c	0.22
88-141	AC	7.5YR4/2	3-csbk	dvh,wvs,wvp	as	12	34	54	c	0.63
>141	C	Alluvium (large amount of rounded gravel)								

* Abbreviations as in Table 1.

Table 8. Status of primary minerals within the sand fraction of a representative Eutric Vertisol; Profile no. 32 (T2-16/N3)*.

Depth (cm)	Primary minerals (percent by volume)									Weathering ratio			
	Qtz	Fd	Cpx	Amp	Mic	Vc	Vcw	Lat	Ox	Qz/Fd	Qz/Vcw	Qz/Cpx	Vcw/Vc
0–14	9.0	9.0	4.3	0.1	0.0	2.7	56.0	17.8	1.1	1.0	3.33	2.1	20.74
14–96	11.0	9.7	4.8	0.2	0.1	14.3	54.0	5.4	0.5	1.1	0.77	2.3	3.78
96–135	4.1	3.3	4.7	0.0	0.0	35.8	38.2	13.0	0.9	1.2	0.12	0.9	1.07
135–193	4.5	5.4	9.2	1.7	0.0	4.9	69.5	4.8	0.0	0.8	0.92	0.5	14.18

* Abbreviations as in Table 2.

Table 9. Chemical characteristics of representative profiles of Eutric Vertisols of Wurgo valley.

Depth (cm)	Org. C (%)	Tot. N (%)	Avail. P (mg kg^{-1})	pH 1:1 H_2O	Exchangeable basic cations [cmol$_{(+)}$kg^{-1} soil]				CEC [cmol$_{(+)}$kg^{-1}]	
					Na	K	Ca	Mg	Soil	Clay
Profile no. 32: Eutric Vertisol (T2-16/N3)										
0–14	1.52	0.12	9.01	6.73	0.76	0.57	40.14	14.91	58.46	139
14–96	1.64	0.07	1.79	7.33	0.83	0.41	36.31	13.87	57.24	90
96–135	0.78	0.07	14.63	7.85	0.83	0.94	36.00	13.20	52.08	75
135–193	0.26	0.03	42.76	7.61	3.27	0.76	31.19	8.33	43.55	86
Profile no. 30 (T2-16/N1)										
0–19	1.12	0.20	3.36	6.42	0.71	0.33	40.64	14.45	60.42	116
19–88	0.58	0.07	0.69	7.21	0.98	0.43	48.81	15.38	65.37	109
88–141	-	-	0.23	7.87	1.24	0.41	44.74	13.72	48.79	-

Topographic setting of the soil units

The distribution and topographic setting of the soil units of the piedmont slopes of Wurgo valley are shown in Fig. 3. These soils were found strongly associated with distinct landscape position and geomorphic unit. The Eutric Cambisols were predominant on the convergent footslopes while the Luvic

Phaeozems covered the divergent and linear footslopes, and the Eutric Vertisols mantled the toeslopes. The sharp slope breaks and the convergent footslopes allow intermittent deposition of materials wasted and eroded from the superjacent mountain slopes. The materials accumulated on the convergent footslopes usually assume the forms of depositional terraces and alluvial fans. The latter are commonly observed where tributary streams emerge from steep mountain slopes onto the footslopes. The depositional terraces usually form at the lower end of large gullies and mainly consist of accumulations of gravel, sand, and finer sediments (Cinque, 1993).

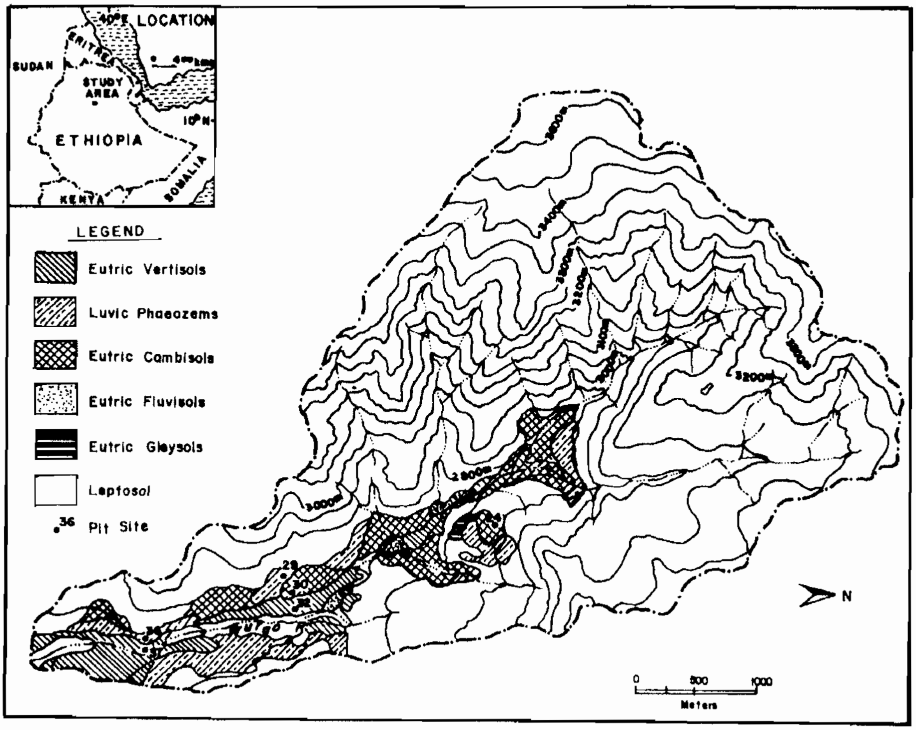

Fig. 3. Distribution and topographic setting of soils in the Wurgo valley.

The sedimentological features of the Cambisols of the Wurgo catchment can be clearly observed in the buried horizons underlying the solum. Moreover, because intermittent influxes of materials take places as pedogenesis proceeds, the solum is frequently marked by the thin laminations of the sediments. Pedons with similar sedimentological characteristics have been described on a convergent footslope outside the Wurgo valley although because these soils lack the cambic B horizons they were classified as Eutric Regosols (Belay Tegene, 1997). The only soils that are younger than Eutric Cambisols on the piedmont slopes are the Fluvisols which occur as minor soil units in parts of the valley. The Fluvisols are kept younger by regular addition of alluvium while the Cambisols receive new materials only intermittently, and hence were able to develop more mature profiles. Haplic Phaeozems appear as minor associates of the Cambisols along the boundary with the lower backslopes and non-convergent footslopes. Frequent association of Cambisols and Haplic Phaeozem have also been reported in the Borkena catchment of southeastern Welo (Paris, 1985).

Luvic Phaeozems form the typical soil units on the linear to convex footslopes. The laterally convex or linear slope forms and the marked gradients, discourage significant deposition of colluvial and alluvial materials at these positions, and as a result the Luvic Phaeozems have mainly developed on residual and, in rare cases, on old depositional materials. The surfaces of most of the Luvic Phaeozems are currently marked by considerable stone cover due to the marked disturbance of the superjacent slopes and subsequent colluviation of rock fragments. Such disturbance encourages gradual downslope wasting and movement of stones on to the footslopes and the Phaeozem soilscape by gravitational forces with water playing only a subsidiary role. Because of the increased runoff and accelerated erosion resulting from cultivation, most of the Luvic Phaeozems are also marked by frequent gullies, rills and severely truncated A horizons. Some of the Luvic Phaeozems, particularly those on the gentler slopes, show characteristics that are transitional with the adjacent Eutric Vertisols. They are generally marked by deeper solum whose topsoils develop shallower and narrower cracks during the dry seasons.

Eutric Vertisols mantle most of the toeslopes comprising the lowest gradient and lower-most segments of the piedmont slopes. These soils have formed on both residual and alluvial parent materials. Flood water of Wurgo river and its tributary streams and the surface runoff from the superjacent slopes have played a major role in the accumulation of alluvial deposits particularly along the lower segments of the toeslopes. Currently, however, the spread of flood water on to the toeslopes is reduced considerably by the pronounced incision and deepening of the stream channel. In many parts, the surfaces of the toeslopes stand more than 10 m above the bed of the Wurgo river. This channel incision is attributed to lowering of the base level due to the down cutting of the resistant dike crossing the river at the outlet of the Wurgo catchment. Thus the Vertisols were found in association with Leptosols along the steeper channel banks of the river. These soils were also found interspersed with Fluvisols on the very narrow strips of recent alluvium at the lowest edge of the toeslopes. In some cases, the Vertisols extend on to the non-convergent footslopes where they have developed on residual materials and constitute very minor associates of the Luvic Phaeozems.

DISCUSSION

Geomorphic processes have strongly influenced the formation of widely contrasting soils on the piedmont slopes of the Wurgo valley. Eutric Cambisols, Luvic Phaeozems, and Eutric Vertisols, have developed on convergent footslopes, divergent to linear footslopes, and toeslopes, respectively. The major slope-related internal soil forming process that resulted in the development of Cambisols on the convergent footslopes is "cumulization". These soils have formed in an environment where soil formation and deposition are concomitant and "cumulization" is the most dominant process. The "cumulization" process has prevented the orderly progression and development of more mature soil profiles on the convergent footslopes of Wurgo valley. As Graham and Buol (1990) have observed in the soils on the footslopes of the Blue Ridge Front, USA, when previous soils are buried by colluvium or alluvium, soil formation starts all over again from time zero on the newly added material and, under this condition, "pedogenic alterations are sufficient only for the development of a cambic horizon". Because of the strong influence of "cumulization" on the soil characteristics, Nikiforoff (1949) has coined the term 'cumulative soils' to separately refer to these unique group of pedons (Birkeland, 1974).

Currently the non-convergent footslopes do not receive alluvial and colluvial materials. Hence, pedogenic processes operate with few interruptions and, as a result, the Luvic Phaeozems were able to develop more mature profiles and more weathered materials. Furthermore, because the underground water table is deeper, very large volume of water can readily pass through the soil profiles inducing the process of "lessivage" (*i.e.*, the translocation of clay particles from the A to the B horizons) and subsequent development of argic B horizons.

Clay translocation and accumulation in the B horizons of the Luvic Phaeozems is further facilitated by the alternating wet and dry climate. The mechanism by which the wetting and drying cycles encourage the development of argic B horizons most probably involves a number of steps (Soil Survey Staff, 1969; Fanning and Fanning, 1989). Firstly, wetting of soils at the beginning of the rainy season favours the dispersion of clay particles. Secondly, when the soil dries fine cracks form in which gravitational water or water at low tension can percolate carrying the dispersed particles. Thirdly, the percolation of water is halted in the lower layers, where capillary withdrawal is favoured by the strong tendency for a dry soil to take up moisture, thus causing deposition of the translocated clay within the B horizons. Repeated operation of these cycles ultimately results in the development of the argic B horizons.

The markedly wet and dry climate, combined with the gentle to almost flat surfaces, imperfect drainage and fine textured alluvial parent material, is also responsible for the development of Vertisols on the toeslopes. The alternating wet and dry seasons and the predominantly smectitic clay allow the operation of shrink and swell cycles and the subsequent opening and closing of cracks in the soils. This condition favours a more active operation and predominance of "argilli-pedoturbation" and "haploidization" (the mixing of the soil material) and the evolution of Vertisols with deep heavy cracking clay and A/AC/Bb and A/C/Cr horizon arrangements.

Various characteristics of the soils suggest that the Eutric Vertisols are more weathered than the Luvic Phaeozems, and that the Luvic Phaeozems are more weathered than the Eutric Cambisols. For example, percentage clay contents of the solum ranged from 21 to 34 in the Cambisols, 29 to 47 in the Luvic Phaeozems and 40 to 67 in the Eutric Vertisols. The silt/clay ratios computed for the three soil units were 1.09 to 1.43, 0.64 to 1.31 and 0.22 to 1.28, respectively. The two main weatherable minerals (the feldspars and pyroxenes) together account for only 8.0 to 14.5 % in the Vertisols, as compared to 27.8 to 32.6 % in the Phaeozems and 13.4 to 43.0 % in the Cambisols. The fact that the soils are very much differentiated in their stages of pedogenesis is further reflected in the weathering ratios of their respective sand fractions.

The topographically induced downslope translocation of bases by throughflow and resulting variability in intensities of leaching, have also brought about a major differentiation in the chemical characteristics of the three soil units. Total exchangeable bases and pH, for example, assume their lowest levels on the Luvic Phaeozems and highest on the Eutric Vertisols. Among other things, this differentiation in chemical environment, combined with the associated textural variability of the parent materials, has favoured synthesis of greater amounts of smectite in the Vertisols and least amount of these species in the Cambisols.

ACKNOWLEDGMENTS

The author thanks the Technical Unit of the Italian Embassy for financing the soil survey that generated the basic data for this paper. Thanks are also due to Professor F. Dramis (Rome III University, Rome), and Professor Vicko Brancaccio (Leopold II University, Napoli). I am also extremely grateful to Giuseppe Di Crescenzo and Fabio Scarciglia for kindly availing to me their expertise in the identification of the skeletal mineralogy of the soils. My sincere thanks also go to Dr Girma Kebede, Dr D. Conway, Dr Teklewold Ayalew and Ato Berhanu Tefera for their constructive comments. Last but not least I would like to acknowledge the contributions of the anonymous reviewers of *SINET*.

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