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Mekonnen Getahun Sisay * , Enyew Adgo Tsegaye , Alemayehu Regassa Tolossa , Jan Nyssen ,
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Soil Forming Factors of High-Altitude Mountains along the East-Africa Rift Valley: The Case of the Mount Guna Volcano, Ethiopia

Mekonnen Getahun [1], Enyew Adgo [1], Alemayehu Regassa [2,*], Jan Nyssen [3], Amaury Frankl [3], Eric Van Ranst [4] and Stefaan Dondeyne [3,5]

1 Department of Natural Resource Management, Bahir Dar University, Ethiopia
2 Department of Natural Resources Management, Jimma University, Ethiopia
3 Department of Geography, Ghent University, Belgium
4 Department of Geology, Ghent University, Belgium
5 Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Belgium

Abstract: The soils of the high-altitude mountains along the East African Rift Valley are poorly understood. Understanding the potential of soils for agriculture, climate change mitigation, and environmental functioning necessitates an understanding of their relationship to soil-forming factors. Therefore, this study focuses on the volcanic soils of Mount Guna. Eighty-five soil profiles, between 3000 and 4120 m a.s.l., were described and sampled along seven topographic transects. The samples were analyzed for physicochemical characteristics using standard methods and classified according to WRB 2022. The clay mineralogy of six profiles was analyzed with X-ray diffraction. The first four factor axes, which are related to elevation, parent material, climate, and land-use were found by factor analysis, explained more than 60% of the total variation. The clay portions are primarily composed of trioctahedral chlorite, trioctahedral mica (phlogopite or biotite), vermiculite, kaolinite, some quartz, some amorphous silicates (most likely pyroclastic glass), and minor feldspar. The presence of weatherable minerals (biotite, amphibole, feldspars, and so on) suggests that these soils have not been weathered extensively. The dominant Reference Soil Groups found in the study area are Andosols, Phaeozems, Leptosols, Regosols, Cambisols, Luvisols, and Vertisols. As a result, our findings suggest that altitudinal variation, climate, lithology, and their contributions to the variability of soil characteristics and development along the toposequence cannot be separated in this study; more similar studies in other high elevation/altitude mountains are required. There have been no other studies of high altitude mountains in East Africa where so many soil profiles have been examined.

Keywords: soil formation; altitude variability; soil variability; factor analysis; soil mineralogy; soil classification

1. Introduction

Knowledge of the soil properties of high-altitude altitude mountains is important for understanding their role in global climate and hydrological processes. As mountains provide over 50% of the world's river sources, changes in climate will affect their hydrologic response with large effects on people relying on these water resources for domestic use, agricultural, energy, and industrial purposes [1]. While high-altitude mountains, including the mountains along the East African Rift Valley system, play a vital role in climate, water-flow regulation, and the carbon cycle, they are also highly vulnerable to climate change. Furthermore, a recent literature review[2] , highlighted that the dynamics of soil organic carbon (SOC) in mountain regions are influenced by both natural and human-induced factors. Among the natural factors, climate change, plant community succession, and wildfires play a significant role. The impact of climate change, such as rising temperatures and heavy rainfall, tends to increase soil respiration rates, leading to the

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depletion of SOC stocks. Conversely, long-term wetting trends can enhance plant net primary productivity in dryland areas, which supports the accumulation of SOC.

Soil maps are required to provide accurate, high-resolution global data on soil properties and their relationships to ecosystem processes, as well as environmental and human-induced factors over time and space [3]. The central paradigm in soil survey – initially proposed in the late 19th century by Dokuchaev [4] and later further elaborated by [5] is that soil formation is determined by climate, organism, relief, parent material and time. McBratney, *et al.* [6] reformulated this ther

$$S = f(s,c,o,r,p,a,n)$$

where, S stands for the soil attribute or classe to be spatially estimated, s for soil classes or other previously measured properties, c for climate characteristics, o for the influence of organisms, including land cover, fauna and human activity, r the relief, topography, or landscape attributes, p the parent material, a the age of the soil, n the spatial or geographic position. The so formulated SCORPAN model enables the integration of conventional soil survey data, with geostatistical methods, and machine learning techniques in digital soil mapping at a specific resolution; however, better insights into on how soil properties relate to soil-forming factors is crucial for the improvement and increased reliability of digital soil maps.

Mountain soils are highly variable as the soil-forming factors parent material, climate, biota or organisms, topography and time may vary greatly over short distances. The soils of the high-altitude mountains and volcanoes along the East African Rift Valley have received little research attention as most soil surveys focused on lower lying agricultural areas. With high-altitude mountains we refer to mountains that reach well above 3000 m a.s.l. Along the East-African Rift Valley system there are 13 mountains, or mountain ranges, that have summits above 4000 m a.s.l. (Figure 1). For these high-altitude areas, we could find only 9 peer reviewed publications that reported detailed soil properties of in total 61 pedons. (Table 1). Similarly, the Africa Soil Profiles database [7] contains data of only 33 pedons located in these high-altitude elevation areas.

Table 1. Number of pedons reported with detailed data, from high-altitude mountains (above ca. 3000 m a.s.l.) along the East-African Rift Valley system.

Country	Mountain*	Pedons	References
Ethiopia	Simien range	6	[8]
	Simien range	5	[9]
Kenya	Mt Kenya	5	[8]
	Mt Kenya	11	[10]
	Mau escarpment**	2	[11]
Kenya/Uganda	Mt Elgon	15	[12]
Tanzania	Mt Kilimanjaro	2	[13]
	Mt Kilimanjaro	1	[14]
Rwanda	Virunga volcanoes	5	[15]
	Mt Bisoke	9	[16]

*see Figure 1 for location; **located west of the Aberdare mountains.

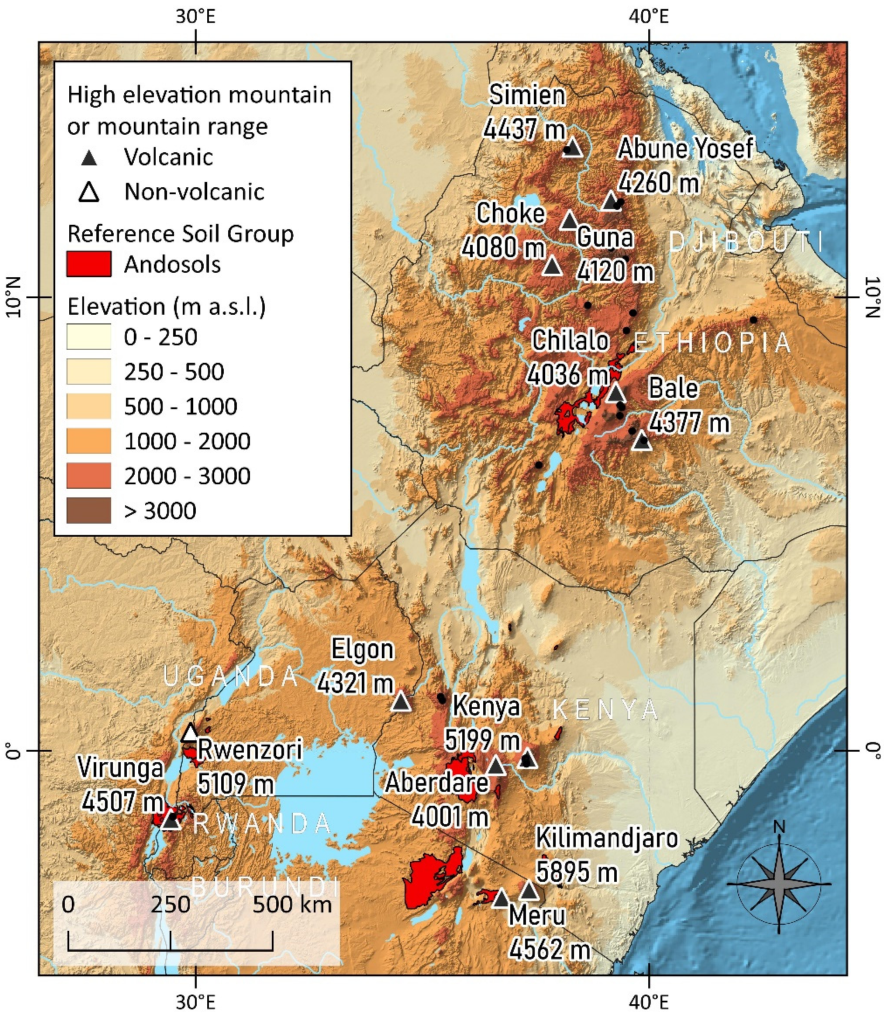

Figure 1. Thirteen high-altitude mountains, or mountain ranges, with summits above 4000 m a.s.l., occur along the East African Rift Valley system. Except for the Rwenzori mountain range, all are volcanoes. The extent of the Andosols is taken from the 2nd version of the Harmonized World Soil Database. [authors' cartography based on Global Multi-resolution Terrain Elevation Data 2010 [17] and [1]].

Mt Guna in north-western Ethiopia is one of these high-altitude mountains, the soils of which had not yet to been studied before. The western slope of this volcano is part of the Lake Tana Basin forming the upper reaches of the Blue Nile Basin. Over the last decades, Lake Tana Basin received a lot of research attention from hydrologists and geomorphologists [18]. Given the importance of soils in hydrological processes, and their relation to geomorphology, we aimed at characterizing the soils of Mt Guna. By studying a large number of soil profiles, we aimed at getting a better insight into the relationship between soils and soil forming factors of high altitude areas along the East African Rift Valley system. A related, side question, was whether Andosols do occur on this volcano, as these have not been mapped for any of the high-altitude mountains in Ethiopia.

2. Materials and Methods

2.1. Study Area

Mount Guna is a complex volcano with its base at around 3000 m a.s.l., and with its summit reaching 4120 m a.s.l. The mountain has the general appearance of a shield volcano, forming a plateau between 3500 and 3750 m a.s.l. and featuring an eroded caldera crater in the north-western sector

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(Figure 2). The study area, Mt. Guna, is located between 11^{0} 33′ to 11^{o} 50′ N and 38^{o} 6′ to 38^{o} 24′ E. Administratively, Mt. Guna is shared with four weredas (districts) of South Gondar zone namely Farta, East Estie, Lay Gaint, and Guna Begemidir. The plateau is overarched by a north-southwest oriented summital ridge featuring several volcanic necks. The geological base of Mount Guna consists of flood basalts dating back to Mid to Late Miocene[19] . The summital ridge consists of the Guna Trachyte, while the slopes of the shield are dominated by the Guna Tuff (Figure 3;[19]).

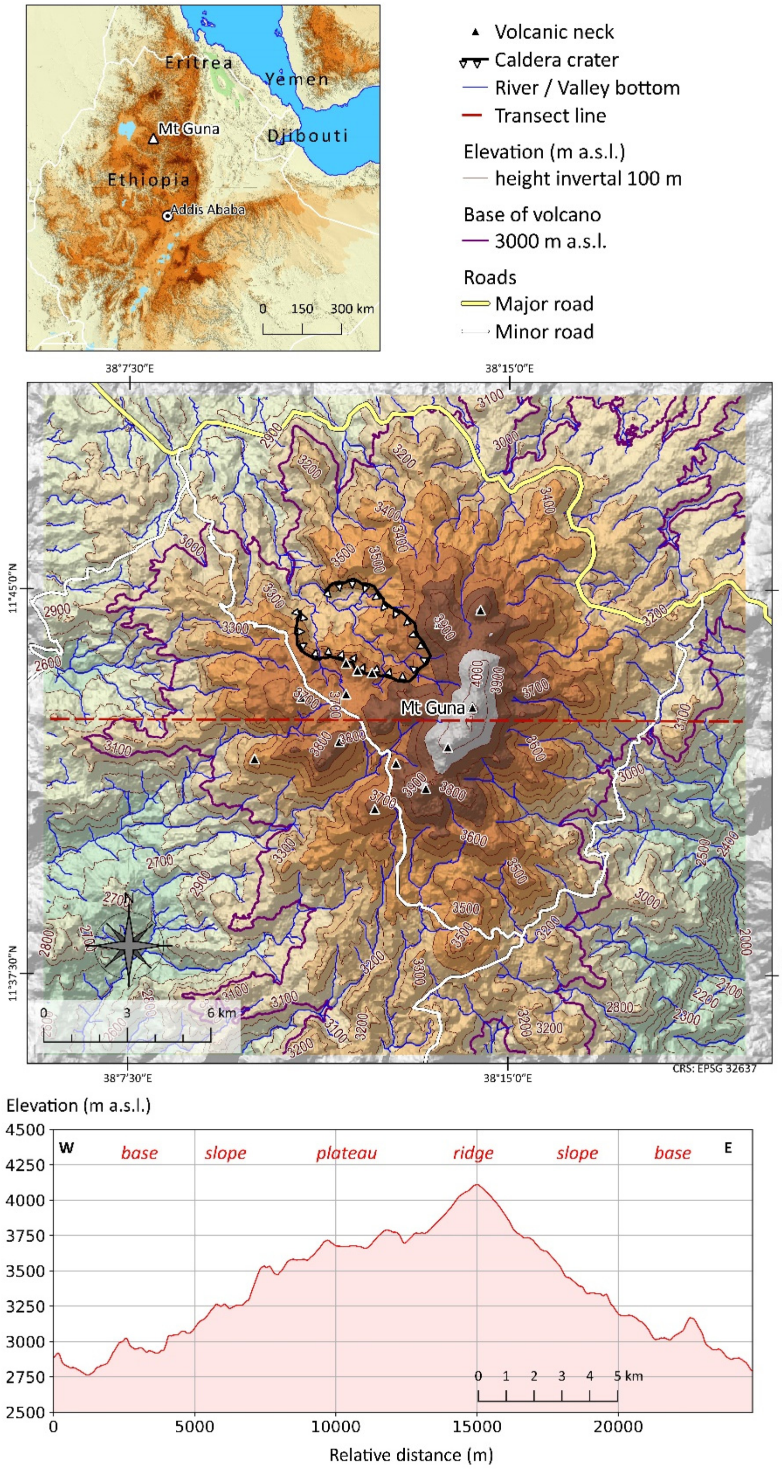

Figure 2. Topography and main geomorphologic features of Mt Guna (authors' cartography based on SRTM data – https://earthexplorer.usgs.gov/).

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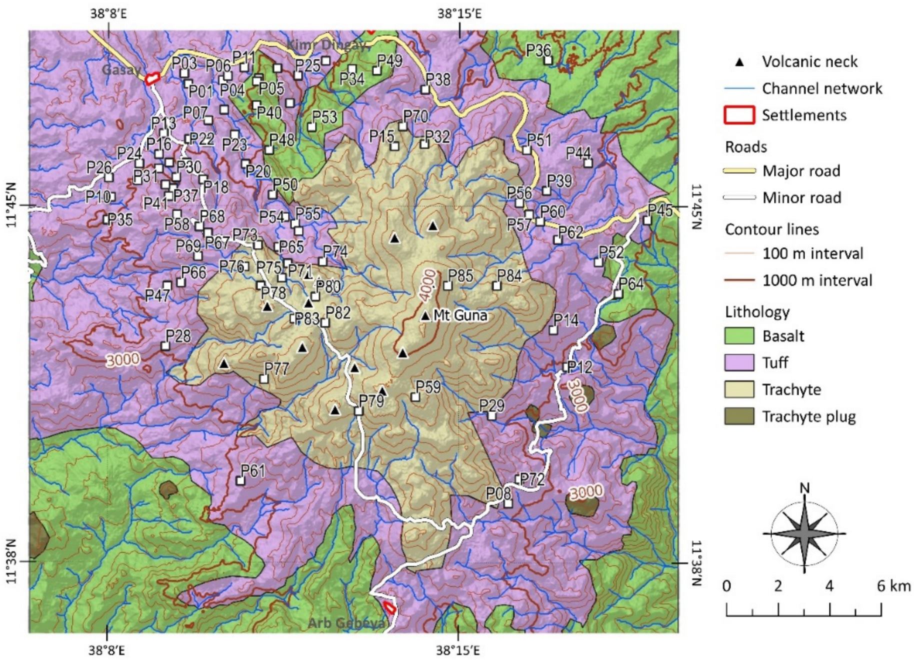

Figure 3. Simplified lithological units and location of the 85 pedons on Mount Guna [authors' cartography based on[19].

Gridded climatic data, with a spatial resolution of about 1 km x 1 km, of WORLDCLIM version 2.0 was used. Temporally, the dataset has average monthly climate variables between the years 1970 and 2000 [20]. The long-term means annual variables were used for this study through aggregate monthly precipitation and temperature datasets (Figure 4).

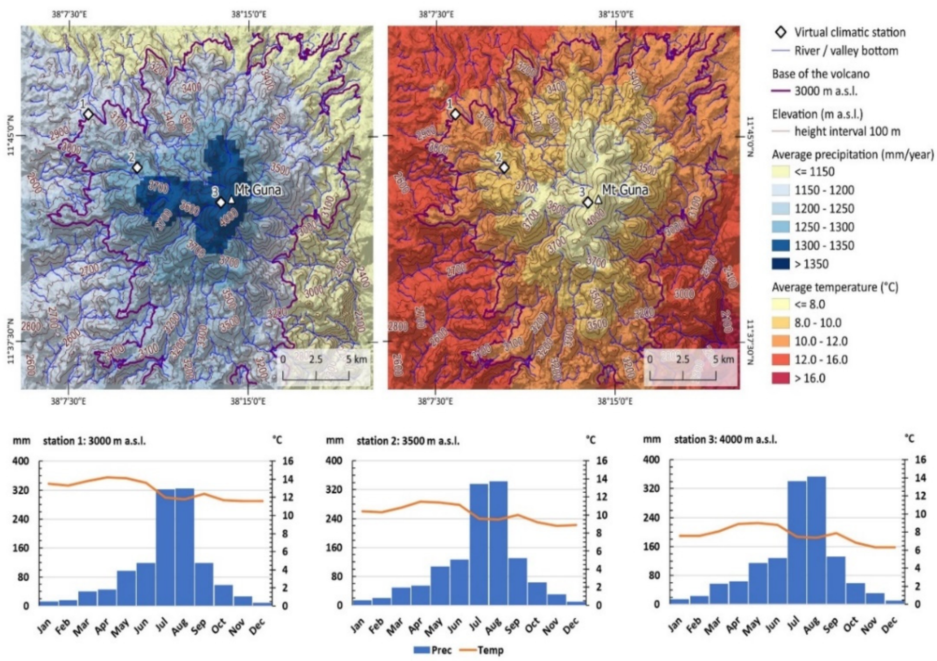

Figure 4. Average annual and monthly rainfall and temperature of Mount Guna for the years 1970-2000 [authors' cartography based on WorldClim 2 data,[20].

Land use and land cover (LULC) groups determined from satellite pictures were grouped in decreasing order as follows: crops, forests–shrublands, grasslands, bare lands, towns, and water

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bodies (Figure 5). The raising of cattle and the production of crops are the main sources of economic activity in Mount Guna and the surrounding neighbourhood. Potatoes and barley are often grown up to 3700 metres above sea level. The three most common livestock species in the research area are sheep, cattle, and horses.

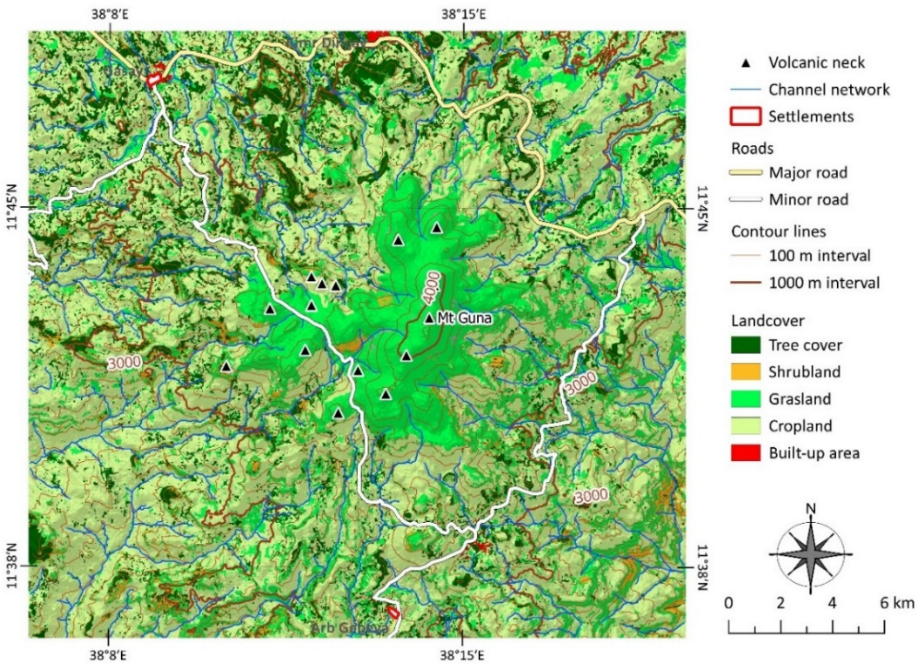

Figure 5. Land cover map of Mount Guna (authors' cartography based on, [21,22]).

2.2. Soil sampling and Analysis

Two phases of field surveys were accomplished in studying the soil of the Mount Guna area. First, a preliminary or reconnaissance survey was performed to acquire general information on the soils and environment of the proposed study area. At this level, tentative soil units and maps were prepared on the same map based on landscape vegetation relationships and surface soil characteristics (e.g. colour, structure, texture) as field guides. The detailed survey was conducted during the second phase. Soils were researched from auger holes, gully cuts, and site observations using the tentative soil map as a supplement. A total of 776 auger hole observations were made and site characteristics and land use patterns were recorded on standard form.

The proposed soil boundaries were then modified using this knowledge to modify the tentative soil units. Next, the borders of the final dirt field were marked on the 1:50000 topo-sheet. In delineation of boundaries topographic factors, vegetation characteristics, surface colour and land use patterns were used in addition to auger hole and other observation points. A toposequence was selected along east-west and north-south facing slopes encompassing landform components from the upper slope to the bottom slope of the mountain. After proper identification of soil mapping units, a total of 85 representative sites were selected for soil profile description along catenas in Mount Guna areas (Figure 3).

The profiles were dug up to the depth of consolidated rock, or up to 100-120cm depth in the case of unconsolidated rock. The soil profiles were described following the guidelines for soil description [23]. Profile observation points were geo-referenced with the help of a geographical positioning system (GPS). A total of 226 soil samples were collected from recognized genetic horizons. In order to determine soil bulk density characteristics, undisturbed soil cores per horizon were collected using a 100 cm^3 cylindrical steel sampler. Using the World Reference Base[24] classification system, all identified reference soil groups were classified. From each recognized genetic horizon, disturbed soil samples using a bag were collected, and from which 1 kg of soil was transferred into a plastic bag and labeled. Then the soil samples were transported to the National Soil Testing Center (NSTC), where they were analyzed for their physical and chemical characteristics.

The soil samples were air-dried, crushed, and passed through a 2 mm sieve before being analyzed for selected soil physic-chemical properties in the laboratory. The analyses of soil properties were determined using procedures for soil analysis [25]. Soil bulk density values were determined in undisturbed soil samples taken with a known volume of core ring samplers after drying the soil samples to consistent weights in an oven at 105 °C. The particle size analysis was determined by the Bouyoucos hydrometer method. Soil pH was measured in a 1:2.5 soil to water suspension. The Walkley and Black wet digestion method was used to estimate the organic carbon contents of the soil samples. The Kjeldahl digestion, distillation, and titration method was used to analyze total N. The Olsen method's standard technique was followed to analyze the available phosphorous (P).

Cation exchange capacity (CEC) and exchangeable bases were determined using the ammonium acetate technique. Exchangeable Ca and Mg in the extracts were analyzed using an atomic absorption spectrometer (AAS), while Na and K were analyzed by a flame photometer (Rowell 1994). The computation of percentage base saturation (PBS) involved dividing the total of the exchangeable bases (Ca, Mg, Na, and K) by the soil's CEC and then multiplying the result by 100. The CEC-clay ratio was determined by dividing CEC values by the total clay content of the soil and multiplying the value by 100. The Blakemore procedure was used in determining phosphate retention capacity, whereas extractable aluminium and iron were determined by acid oxalate procedure at pH 3.0 following a four-hour shaking of acid solution in a dark room using standard methods.

Using X-ray diffraction (XRD), the nature of the colloids was determined from six soil profiles (P-81, P-77, P-71, P-80, P-59 and P-73) all located in the afro-alpine grasslands. Soil samples were from two depth intervals topsoil (0-25 cm) and subsoil (25-50 cm). These analyses were done to determine verify whether these soils can be classified as Andosols following the 4th edition of the World Reference Base for soil resources[24].These samples were treated with 6% NaOCl, pH 8, to remove organic matter[26] and approximately 5 g of fine earth (<2 mm) was crushed by mortar and pestle and thereafter micronized in a McCrone mill. XRD powder patterns for unoriented mounts of fine powders were collected with a Bruker D8 ECO Advance system, equipped with a Cu tube anode and an energy-dispersive position-sensitive LynxEye XE detector. The incident beam was automatically collimated to an irradiated length of 17 mm for powder samples and 15 mm for dried suspensions. The tube was operated at 40 kV and 25 mA. The patterns were collected in a θ-2θ geometry from 3° 2θ to 70° 2θ, at a step of 0.010° 2θ, and a count time of 48 seconds per step. The obtained powder diffraction patterns were interpreted qualitatively using the COD database [27-29].

2.3. Statistical Analysis

Descriptive statistics and Factor Analysis (FA) methods were used to analyse the soil data collected from Mount Guna and analysed in the laboratory. To detect the relationship between the studied parameters, Pearson's correlation coefficients ($p<0.01$ and $p<0.05$) were calculated using SPSS 20 (Statistical Package for Social Science. The dataset included: soil texture(sand, silt, clay), silt to clay ratio, BD, pH, exchangeable cations(Ca, Mg, K, Na) CEC, av. P, SOC, and TN. The factors Analysis (FA) and eigenvalues >1 were retained and factors were subjected to varimax rotation to maximize the correlation between factors and measured soil characteristics (SAS Institute, 1989). To increase the interpretability of the results, the variance maximizing (Varimax) normalized factor rotation was applied. We took the four first factors, on the hypothesis, that these would correspond to topography (elevation), parent material, climate and land use. This hypothesis is further tested by checking how good the factor scores of the soil profiles correlate, with these variables.

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3. Results

3.1. Morphological characteristics

In the majority of the pedons under study, the particle size distribution did exhibit a consistent pattern with respect to both topographic position and depth (Table 2). In terms of texture, the soils on the lower slope tended to have more clay than the soils on the upper landscape. The amount of clay found in the B layers of every pedon was greater than that found in the topsoil horizons. The soil colour changed from very dark grey (10YR3/1) to black (10YR2/1) with moist in topsoil to dark grey (10YR4/1) to very dark greyish brown (10YR3/2), moist) in subsoil horizons of lower elevation, dark brown to very dark grey (7.5YR3/3 to 10YR3/1) to brown/dark yellowish brown to dark reddish brown (5YR3/2, moist) in the middle altitudinal gradient, and black (10YR2/1) to yellowish brown to light colored at a higher elevation. Each pedon's soil depth varied greatly, ranging from a very shallow to a very deep soil profile, due to the topography and slope position.

The soil depth decreased with increasing altitudinal gradients. The samples with shortened profiles and shallow depths of the C-horizon were taken at the upper shoulder and upper back slope positions. In relation to soils found on a steep slope, the deeper soil profiles are situated in a lower position. Compared to the upper slope location, the soils in the top landscape position had a more consistent Ah1-Ah2-C horizon sequence and were thicker. The upper slope, sometimes referred to as the higher slope, features well-drained soils, a high degree of stoniness, and an A-C horizon succession. Thus, variation can be seen in the horizon development along the catena. The Ap-Bt-C or Ap-AB-C genetic horizon sequences were typically associated with the deeper horizons, which were located in the middle and lower slope positions.

The structure of all pedons in the surface soils were weak, fine, granular, gradually changing in the subsurface from weak to moderate, medium angular blocky. All pedons have many to fine roots in the upper horizon, tending to decrease with depth. The horizon boundaries between the A and B horizons were clear and smooth because of the darkening effects of organic matter on the surface and also because of layering of parent materials. The dry consistence varied from slightly hard to very hard, whereas the moist consistence varied from friable to firm. On the other hand, the wet consistence ranged from slightly sticky/slightly plastic in the surface layers to very sticky/very plastic in the subsurface soil layers.

3.2. Variability of soil characteristics along the toposequence and soil depth

The effect of altitude on the physical and chemical characteristics of Mt Guna's soil is depicted in Table 1. Soil texture classes show a clear difference with the difference in altitude (Table 1). Sand fraction was recorded at the high altitudinal gradient and decreased with a decrease in altitude. Similarly, the sand fraction recorded higher mean values on topsoil horizons over the subsoil horizon in all the soil profiles(Table 2). The mean values of clay fraction increased from topsoil (0-25 cm), subsoil (25-50 cm), and deep subsoil (50-100 cm) in all profiles. In a similar vein, the results showed that the clay proportion was higher in the lower altitudinal gradient than in the mid-altitude and summit regions. In all profiles, the silt fraction (Table 2) exhibited a consistent decline with soil depth. Similarly, the mean concentration of silt fractions varied along altitudinal gradients, with a low concentration at 3200 m a.s.l. and a high concentration at 3500 m a.s.l (a.s.l.). The mean comparison indicated that the bulk density was high at the lower and mid-altitudinal gradient when compared with that of the summit (Table 2). The bulk density measurements tended to increase with depth in all of the pedons.

The soil pH (H_2O) values were lower in topsoil horizons than in subsoils. Hence, it increased with soil depth across the profile, whereas, its value decreased significantly as altitude gradients increased. All the soils contained the largest amounts of organic carbon in their topsoil horizons. The amounts of organic carbon decreased with depth. A higher level of SOC was observed in the high-altitudinal gradient of topsoil horizons when compared with the lower altitudinal gradient in all profiles. Hence, total nitrogen, soil organic carbon content, and soil organic carbon stock all increase

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significantly with altitude, to varying degrees (Table 2). Nitrogen content declined with depth in all sites and correlated with the decrease in organic carbon content.

All pedons studied show that the mean values of Ca^{2+}, Mg^{2+}, CEC, and percentage BS showed an increasing trend as soil depth increased. Whereas, at all sites, the SOC and TN contents decrease as soil depth increases (Table 1). The CEC of clay varied widely from pedon to pedon(Table 2). All pedons had relatively little available phosphorus. The pedons of the summit and lower slope have almost the same available phosphorus (5.2 mg/kg) content while the midslope recorded 4.6 mg/kg. The correlation matrices for soils in the 0– 25cm and 25 – 50cm depths show several sets of significant relationships (Tables 3). Clay content at topsoil in all profiles was highly significant but negatively correlated with the sand and Silt-to-clay ratio. Clay texture is weak and positively correlated with Bulk density and with high and positive available phosphorous. Sand and silt contents were positively correlated with each other (Table 3).

The amount of organic C in both topsoil and subsoils was negatively correlated with some soil properties, such as clay content, bulk density, and carbon-to-nitrogen ratio. In contrast, organic C was weakly and positively related to sand content, silt-to-clay ratio, Na and significantly and positively correlated with TN (Table 3). The amount of available phosphorous in topsoils and subsoil depth was positively correlated with clay content, exchangeable Ca, Mg, and CEC. In contrast, sand content, silt-to-clay ratio, and carbon-to-nitrogen ratio were positively related to available phosphorous.

Table 2. Summary statistics of the physicochemical characteristics (mean ± SD) of 85 soil profiles along seven topographic transects of Mt Guna, Ethiopia.

EEElevation (m a.s.l.)	N	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Silt: clay	BD (g.cm^{-3})	SOCS (kg C m^{-2})	SOC (%)	TN (%)	C/N	Colour
3000-3200	55	0-25	25.4 ± 9.1	28.6 ± 4.4	45.6 ± 8.6	0.7 ± 0.2	1.2 ± 0.1	8.4 ± 1.6	2.8 ± 0.7	0.21 ± 0.07	14.1 ± 2.6	**(10YR3/1) to (10YR2/1)**
	41	25-50	18.6 ± 6.5	23.8 ± 5.9	57.8 ± 9.2	0.4 ± 0.2	1.2 ± 0.1	8.0 ± 1.5	2.6 ± 0.5	0.16 ± 0.05	17.1 ± 4.1	10YR4/1 to 10YR3/2
	36	50-100	15.9 ± 5.5	20.4 ± 4.6	64.2 ± 8.5	0.3 ± 0.1	1.3 ± 0.1	12.9 ± 3.4	2.0 ± 0.5	0.12 ± 0.04	17.8 ± 0.5	10YR4/2
3200-3500	20	0-25	28.6 ± 8.7	26.8 ± 5.3	44.2 ± 9.3	0.6 ± 0.2	1.2± 0.1	8.2 ± 1.7	2.7 ± 0.6	0.20 ± 0.05	14.1 ± 2.5	7.5YR3/3 to 10YR3/1
	14	25-50	20.6 ± 6.5	22.6 ± 6.5	56.6 ± 10.9	0.4 ± 0.2	1.3 ± 0.1	7.9 ± 1.7	2.5 ± 0.6	0.15 ± 0.03	16.4 ± 3.0	10YR4/3 to10YR4/4
	12	50-100	17.9 ± 6.8	21.2 ± 5.6	60.8 ± 11.2	0.5 ± 0.2	1.3 ± 0.1	13.9 ± 3.1	2.1 ± 0.5	0.11 ± 0.02	18.8 ± 3.9	5YR3/2
3500 -4200	10	0-25	32.9 ± 8.9	30.3 ± 5.1	36.8 ± 9.2	0.9 ± 0.2	0.9 ± 0.3	10.3 ± 3.0	4.9 ± 1.7	0.42 ± 0.16	12.2 ± 1.0	10YR2/1
	10	25-50	29.4 ± 11.0	26.3 ± 5.6	44.3 ± 14.8	0.7 ± 0.3	1.0 ± 0.2	8.2 ± 2.3	3.3 ± 1.2	0.21± 0.05	16.2 ± 4.9	10YR5/4
	4	50-100	18.5 ± 8.6	22.5 ± 7.6	59.0 ± 15.4	0.4 ± 0.3	1.2 ± 0.1	12.7 ± 4.1	2.1 ± 0.6	0.11 ± 0.01	18.4 ± 4.4	10YR8/1

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Table 3. Cont.

Elevation (m a.s.l.)	N	Depth (cm)	pH (H_2O)	Ca	Mg	K	Na	CEC	CEC clay	BS (%)	Av. P (mg/ kg)
				(cmol(+)/ kg)							
3000-3200	55	0-25	5.6± 0.6	10.7± 1.4	2.8 ± 0.8	0.6 ± 0.4	0.2 ± 0.2	25.7 ± 1.8	36.5±9	55.6 ± 5.0	5.1 ± 1.6
	41	25-50	5.9 ± 0.6	11.8 ± 1.4	3.4 ± 0.8	0.6 ± 0.3	0.3 ± 0.2	27.1 ± 1.5	37.8±9	59.0 ± 5.3	4.8 ± 1.4
	36	50-100	6.1 ± 0.5	12.6 ± 1.5	3.7 ± 0.8	0.6 ± 0.4	0.3 ± 0.2	27.9 ± 1.7	21.5±12	61.6 ± 5.8	3.8 ± 1.3
3200-3500	20	0-25	5.8 ± 0.5	10.6± 0.9	3.0 ± 0.9	0.7 ± 0.3	0.3 ± 0.2	25.3 ± 1.7	32.2±6	57.5 ± 5.8	4.6 ± 1.5
	14	25-50	6.0 ± 0.5	11.7 ± 1.2	3.6 ± 1.0	0.7 ± 0.3	0.3 ± 0.2	26.7 ± 2.2	33.1±8.	60.7 ± 6.1	4.3 ± 1.1
	12	50-100	6.3 ± 0.5	12.5 ± 1.4	3.8 ± 1.2	0.6 ± 0.3	0.3 ± 0.3	27.5 ± 2.5	35.4±11	62.7 ± 5.9	3.2 ± 1.0
3500 -4200	10	0-25	5.3 ± 0.4	10.3 ± 0.8	2.7 ± 0.7	0.7 ± 0.3	0.3 ± 0.3	25.5 ± 1.6	33.5±8	55.0 ± 3.9	5.3 ± 0.8
	10	25-50	5.7 ± 0.3	11.2 ± 1.0	3.5 ± 1.3	0.6 ± 0.4	0.3 ± 0.3	26.3 ± 1.7	34.2±8	59.5 ± 6.1	4.2 ± 0.8
	4	50-100	6.1 ± 0.5	12.4 ± 1.0	3.9 ± 0.8	0.4 ± 0.2	0.2 ± 0.2	27.7 ± 0.9	36.2±9	60.8 ± 4.1	3.7 ± 0.7

Table 4. Correlation coefficients between physicochemical characteristics of 85 soil profiles on Mount Guna. The correlation coefficients of the topsoil (0 - 25 cm, n=85) are given above the diagonal (shaded in grey), and of the subsoil (25 - 50 cm, n=65) are below the diagonal.

Characteristics	Sand	Silt	Clay	Silt: clay	BD	pH	Ca	Mg	K	Na	CEC	BS	SOC	TN	P
Sand	1	.41**	-.90**	.77**	-.76**	-0.11	-0.22	-0.12	.27*	.47**	-0.19	0	.33**	.34**	-.30*
Silt	-0.25*	1	-.74**	.87**	-.40**	-0.19	-.25*	-.31*	.28*	.30*	-0.21	-0.16	0.14	0.02	-.34**
Clay	-0.85**	-.26*	1	-.94**	.72**	0.14	.25*	0.2	-.31*	-.48**	0.22	0.05	-.31*	-0.23	.33**
Silt: clay	0.50**	.68**	-.85**	1	-.70**	-0.19	-.34**	-.28*	.32**	.40**	-.27*	-0.16	.30*	.25*	-.42**
BD	-.37**	-0.14	.40**	-.42**	1	.25*	.39**	0.14	-0.18	-.38**	0.23	0.18	-.49**	-.52**	.40**
pH	-0.06	-.26*	0.2	-.27*	.34**	1	.32**	0.24	-0.07	-0.11	0.19	.27*	-0.03	0.21	0.12
Ca	-.26*	-0.03	0.28*	-.26*	.22*	0.19	1	.38**	-0.14	-0.19	.52**	.70**	-0.12	-0.21	.41**
Mg	-.23*	0.03	0.23*	-0.18	0.06	.26*	.39**	1	-0.2	-0.16	.45**	.59**	0.15	-0.09	.31*
K	0.2	0.08	-0.25*	.22*	-0.21	-0.04	-.25*	-0.06	1	.30*	-0.05	0.05	-0.01	-0.04	-0.2
Na	.28*	-0.05	-0.26*	0.19	-.24*	-0.06	-0.19	-0.13	.31**	1	-0.12	0.05	0.11	0.06	-.33**
CEC	-.27*	0.11	0.27*	-0.14	0.03	0.11	.52**	.48**	0.05	-0.11	1	0.02	0.09	-0.14	0.25*
BS	-0.08	-0.08	0.09	-0.17	0.11	.23*	.69**	.60**	0	0.09	0.05	1	-0.06	-0.14	.27*
SOC	.23*	0.12	-.25*	.35**	-.81**	-0.2	-0.16	0.02	0.19	.29**	0.2	-0.14	1	.57**	-0.07
TN	0.18	0.09	-0.19	.29**	-.79**	-0.18	-0.16	0.01	0.17	.25*	0.14	-0.14	0.96**	1	-0.19
P	-0.57**	-0.03	0.59**	-.43**	0.03	0.03	.42**	.34**	-.23*	-0.16	0.37**	.24*	0.13	0.17	1

BD = Bulk density (g/cm^3); CEC = Cation exchange capacity; OC = Organic carbon; Av. P = Available phosphorus ($mg.kg^{-1}$), TN = Total nitrogen. Ca, Mg, Na, K, CEC, ($cmol_{(+)}\ kg^{-1}$); ** Significant at the 0.01 level (2-tailed). * Significant at the 0.05 level (2-tailed).

3.2. Factor Analysis

Table 3 shows the factor loadings of the physicochemical characteristics of all studied pedons. The variation along Factor 1 for topsoil corresponds to elevation and climate (precipitation and temperature), as it has high loadings for soil organic carbon (SOC), total nitrogen (TN), and soil organic carbon stocks (SOCS), as well as strong negative loadings on BD and moderate negative loadings on the C-to-N ratio. Factor 2 reflects the parent material because it has high positive loadings for sand, moderate and positive loadings on silt-to-clay ratio and Na^{+}, high negative loadings on percentage clay, and a moderate negative loading on av. P (Table 3). Factor 3 reflects a high positive loading on BS, Ca^{2+}, Mg^{2+}, and CEC values, and it may correspond to potential fertility status (nutrient retention and availability and leaching effect). Factor 4 corresponds to the degree of weathering, with high negative loadings for silt and silt-to-clay ratio and moderate positive loadings for soil pH and clay content. For the subsoil, the variation along Factor 1 is determined by a high negative loading on clay, BD, and moderate negative loadings on av. P, as well as a high positive loading on silt and moderate negative loadings on K+ and Na+ (Table 3).

The variation along Factor 2 is again related to the nutrient potential (BS, CEC, Ca^{2+}, Mg^{2+}, pH and av. P). Factor 3 reflects the accumulation of organic matter (SOC, N) which occurs on less favorable drained soils, hence it had high positive loading on SOC, SOCS and moderate negative ladings on TN and C- to -N ratio (Table 3). Factor 4 is determined by having high negative loadings on TN and moderate negative loadings on soil pH, whereas positive loading was on C- to -N ratio. For the deep subsoil, the variation along Factor 1 corresponds to the parent material as it had high negative loading on clay, whereas high positive loadings were on the silt-to-clay ratio, sand, and silt content. Factor 2 reflects the accumulation of organic matter (OC, N) which occurs on less favourable drained soils, hence having high positive loadings on SOC, SOCS and C- to- N ratio. The variation along Factor 3 is again related to the nutrient potential (CEC, Ca^{2+}, Mg^{2+}, pH and av. P). For the deep subsoil, the variation along Factor 4 is determined by high positive loading on BD and moderate positive loading on pH and TN contents.

Table 5. Varimax rotated factor loadings and communalities of a four-factor model of physical and chemical soil characteristics in the topsoil (0–25 cm), subsoil (25-50cm) and deep subsoil (50-100 cm) soil depths.

Characteristics	0-25 cm				25-50cm				50-100cm			
	FA-1	FA-2	FA-3	FA-4	FA-1	FA-2	FA-3	FA-4	FA-1	FA-2	FA-3	FA-4
Sand (%)	-	0.88	-	-	0.88	-	-	-	0.87	-	-	-
Silt (%)	-	-	-	-0.93	0.70	-	-	-	0.80	-	-	-
Clay (%)	-	-0.85	-	0.41	-0.95	-	-	-	-0.96	-	-	-
Silt: Clay Ratio	-	0.58	-	-0.75	0.91	-	-	-	0.93	-	-	-
BD (g/ cm^3)	-0.80	-	-	-	-0.78	-	-	-	-	-	-	0.76
pH (H_2O)	-	-	-	0.47	-	0.47	-	-0.423	-	-	-	0.56
Ca^{2+} (cmolc/kg)	-	-	0.80	-	-	0.83	-	-	-	-	0.89	-
Mg^{2+} (cmolc/kg)	-	-	0.80	-	-	0.73	-	-	-	-	0.84	-
K^{+} (cmolc/ kg)	-	-	-	-	0.42	-	-	-	-	-	-	-
Na^{+} (cmolc/ kg)	-	0.49	-	-	0.60	-	-	-	-	-	-	-
CEC (cmolc/ kg)	-	-	0.57	-	-	0.48	-	-	-	-	0.64	-
BS (%)	-	-	0.82	-	-	0.85	-	-	-	-	0.71	-
OC (%)	0.95	-	-	-	-	-	0.93	-	-	0.97	-	-
TN (%)	0.97	-	-	-	-	-	0.45	-0.82	-	-	-	0.54
C: N	-0.46	-	-	-	-	-	0.44	0.82	-	0.72	-	-
av. P (mg/kg)	-	-0.66	-	-	-0.40	0.43	-	-	-	-	0.44	-
SOCS (t C/kg)	0.73	-	-	-	-	-	0.90	-	-	0.96	-	-
Total variance (%).	**23.57**	**18.38**	**14.57**	**11.1**	**28.71**	**15.99**	**13.06**	**11.042**	**20.8**	**15.2**	**16.6**	**12.7**

Cumulative variance (%)	23.6	42.0	56.5	67.6	28.71	44.69	57.75	68.79	20.8	36.1	52.7	65.4

Absolute value > 0.4.

The weights for the Reference Soil Group and elevation and parent material along the principal components are shown in (Figure 6). According to the results of the FA ordination, a higher variation was observed along the ordinate axes.

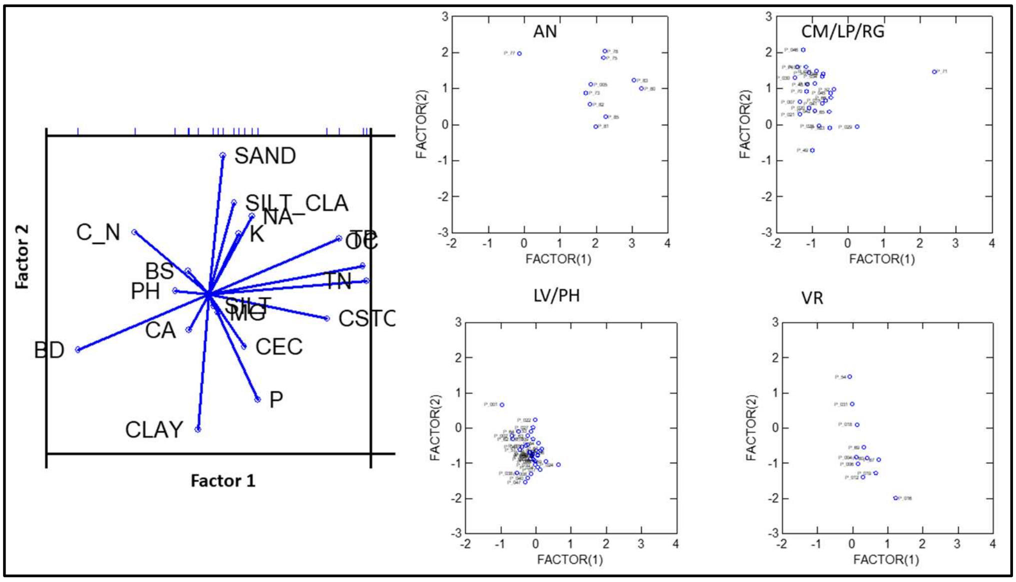

Figure 6. Left: factor loadings of the soil variables on the first two factors axes, Right: factor scores of the soil profiles grouped according to RSG (with: Andosols (AN); Cambisols (CM); Leptosols (LP); Regosols (RG); Luvisols (LV); Phaeozems (PH); Vertisols (VR).

4. Clay mineralogy

The X-ray diffractograms of the studied soil are presented in Fiure 6. The 4 analyzed clay samples show similar XRD patterns after the different treatments indicating that they have a similar mineralogical composition. The XRD patterns of the untreated clay fraction show a rational series of reflections at 1.41, 0.71, 0.472, and 0.357 nm indicating 1.4-nm spacing phyllosilicate minerals. The 1.41 nm d-spacing is not significantly affected by solvation with ethylene-glycol indicating the absence of swelling 2:1 phyllosilicates (smectites) and the persistence of the 1.41 nm peak after the heating treatment, however, with some decrease in intensity, confirms the presence of trioctahedral chlorite. When trioctahedral chlorite is heated to temperatures as high as 500°C the peak intensity of the 001 reflections (1.4 nm) normally increases. The decrease in peak intensity of the 001 reflections (1.41 nm peak) in the analyzed samples is accompanied by a significant increase in the intensity of the 1.0 (0.998) nm peak indicating that some 2:1 phyllosilicate layers collapsed, suggesting the presence of vermiculite besides chlorite. Mica (rational series of reflections at 1.0 (0.998), 0.5 (0.498), and 0.334 nm) is also present in all samples. The very weak intensity of the 002 reflections (0.5 nm) relative to the 001 reflections (1.0 nm) suggests the trioctahedral structure of the mica (biotite or phlogopite). The double peaks at 0.71 and 0.358 nm, almost completely disappeared after heating the samples at 500°C, indicating the presence of kaolinite. The double peak at 0.358 nm is the resolution of the 004 chlorites and the 002 kaolinite reflections, which can be obtained for rather well-crystallized clays. The peak at 0.447 nm is a hkl-reflection of kaolinite. Kaolinite is dehydroxylated at temperatures around and above 500°C. The peaks at 0.426 and 0.334 nm are attributed to quartz, while the small peak at 0.325 nm indicates some minor feldspar. The diffuse broad diffraction spectrum between 20 to > 30° 2θ is due to the presence of amorphous silicates (opal-A and /or pyroclastic glass). This mineralogical composition of the soil materials points in the direction of a trachytic (an extrusive igneous rock) parent material. The presence of weatherable minerals (biotite, amphibole, feldspars, etc.) indicates that these soils are not highly weathered (a more recent stage of development).

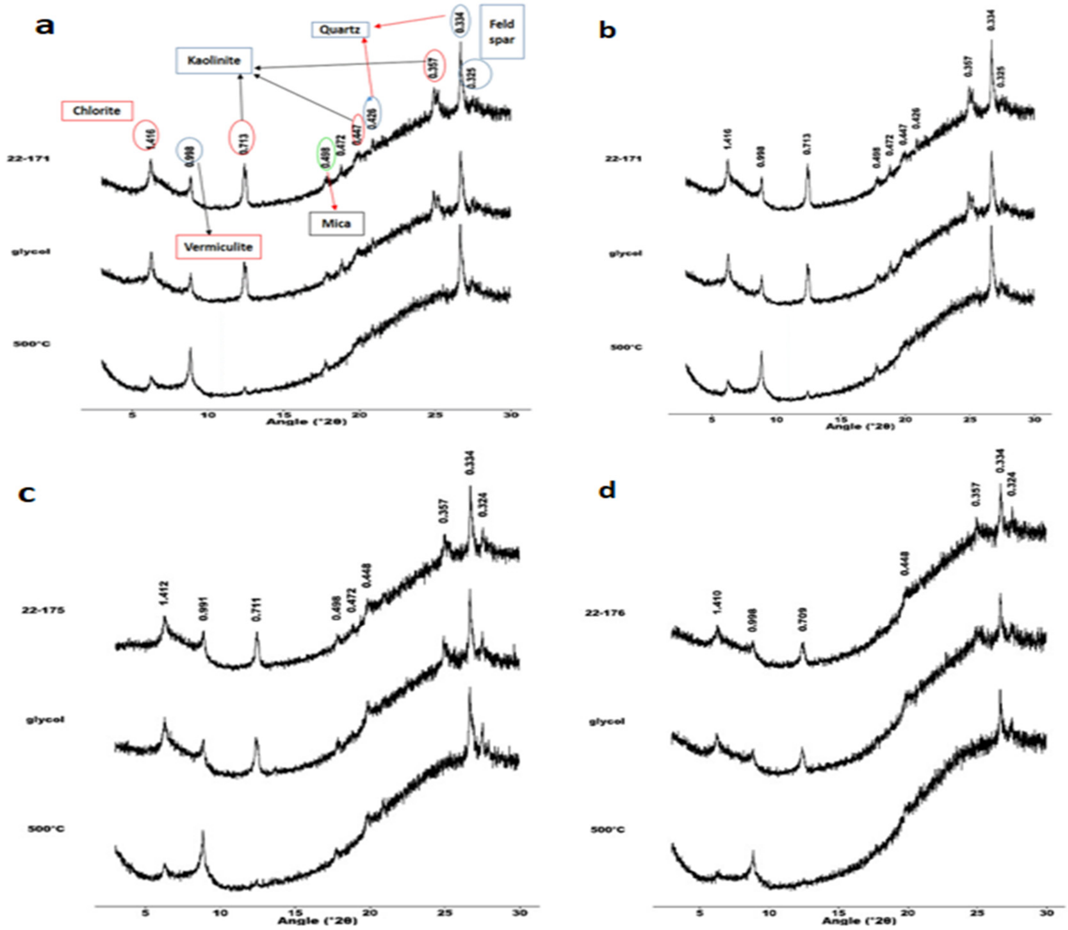

Figure 7. X-ray diffractogram of two profiles at topsoil (a & b) and subsoil's (c & d) both at depth intervals topsoil's (0-25 cm) and subsoil (25-50cm)**.**

4.1. Dominant soil types of the study area

For this study area, the dominating WRB (IUSS Working Group WRB, 2022) Reference soil groups (RSG) are: Andosols, Phaeozems, Leptosols, Cambisols, Luvisols, Regosols, and Vertisols(Table 5). Luvisols are the most RSGs (33 soil profiles). Leptosols have 14 soil profiles, Vertisols have 13, Andosols have 11, Regosols have 7, Phaeozems have 4, and Cambisols have 2 representative profiles. The summit part of the mountain dominantly classified as Andic and Vitric Andosols. According to Table 5, two of the six profiles (No. 3: P-71) and No. 4: P-80 have andic properties, while the other four studied profiles have vitric properties [24]. These soils have Mollic and Chernic A horizon and are classified as Vitric Andosols and Andic Andosols at the second level [24].

Luvisols, Phaeozems, and Regosols are found in association with Andosols. The Mollic-Skeletic Leptosols association largely occurred at lower and upper slope positions and at interfluves where rock outcrops occurred and soil depth was limited by hard rock. The Mollic Leptosols had a depth ranging from 12 to 25 cm, whereas Lithic Leptosols were less than 10 cm deep. Except in soil depth, Mollic Leptosols were very similar to the dark topsoil horizons of Mollic Andosols. They were characterized by black (10YR 2/1, moist) colour, silty texture, slightly sticky and slightly plastic to plastic wet consistency, soft dry, firm moist, abundant to common medium to fine roots, common medium pores, and abrupt smooth boundary.

Regosols are stony and rocky soils with little or no profile differentiation. These soils are encountered in the steeper areas of the mountain. They occurred as Leptic-Skeletic Regosols in the

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mountain. Luvisols are found in the mountain's drier and middle and lower parts. They tend to form a strong seal on the surface, leading to a low infiltration rate and high runoff /erosion of the more fertile topsoils.

Table 6. Acid-oxalate extractable Al and Fe, and P fixation power of topsoil horizons of some representative Vitric Andosols.

Profile	Depth (cm)	Acid oxalate extractable (%)		P retention capacity (%)	Al_{ox}+1/2 Fe_{ox} (%)
		Al	Fe		
1(P-81)	0-25	1.25	1.17	79	1.84
	25-50	1.29	1.26	83	1.92
2 (P-77)	0-25	0.68	1.23	59	1.30
	25-50	0.67	1.3	60	1.32
3(P-71)	0-25	1.71	1.05	88	2.24
	25-50	1.87	1.19	93	2.47
4(P-80)	0-25	1.32	1.43	89	2.04
	25-50	1.43	1.51	91	2.19
5(P-59)	0-25	0.37	1.01	46	0.88
	25-50	0.34	0.89	47	0.79
6(P-73)	0-25	0.66	1.65	65	1.49
	25-50	0.61	1.8	69	1.51

Table 7. Major Reference Soil Groups (RSG) with their selected quantifiers (PQ & SQ) identified in the Mt. Guna area according to [24].

RSGs	Principal qualifiers			Supplementary qualifiers		
	PQ1	PQ2	PQ3	SQ1	SQ2	SQ3
Andosols	Andic	Mollic	Tephric	Protoandic	Humic	
Andosols	Vitric	Histic	Tephric	Protoandic	Humic	
Andosols	Andic	Chernic	Tephric	Protoandic	Humic	
Luvisols	Lamellic	Rhodic		Aric	Cutanic	Hypereutric
Luvisols	Rhodic	Lamellic	Chromic	Aric	Cutanic	Hypereutric
Luvisols	Chromic			Aric	Cutanic	Hypereutric
Luvisols	Rhodic			Aric	Cutanic	Hypereutric
Luvisols	Abruptic	Vetric	Chromic	Clayic	Aric	Cutanic
Leptosols	Mollic	Cambic	Eutric	Loamic	Aric	Tephric
Leptosols	Skeletic	Rendzic	Dystric	Ochric	Nechic	Tephric
Leptosols	Skeletic	Rendzic	Dystric	Colluvic	Ochric	Turbic
Phaeozems	Leptic	Luvic	Cambic	Clayic	Aric	Chromic
Regosols	Leptic	Tephric	Eutric	Loamic	Ochric	Nechic
Regosols	Skeletic	Brunic	Tephric	Loamic	Ochric	Nechic
Regosols	Leptic	Colluvic	Tephric	Loamic	Ochric	Turbic

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Vertisols	Chromic			Aric	Hypereutric	Mazic
Vertisols	Pellic			Aric	Hypereutric	Mazic
Cambisols	Vertic	Chromic	Eutric	Clayic	Aric	Colluvic
Cambisols	Chromic	Eutric		Clayic	Aric	Colluvic

5. Discussion

The pedons have shown great variability in relation to surface soil color patterns. The soil colour changed from the summit to the lower slope position along the catena or toposequence. Numerous authors (e.g.,[30-32]) have demonstrated that differences in parent material, topography, microclimate, moisture (drainage) conditions, and OM content can all be responsible for variations in colour change within and between pedons. The relatively dark brown topsoil colour could be attributed to a relatively high content of organic matter on the surface horizons. The redder colours (5 YR or 2.5 YR, moist) in the subsoil horizons suggested that the soils had well-drained profiles, which is why they were classified as well-drained class soils. Additionally, the decrease in organic matter in the subsoil suggested that free iron had been released, which may have contributed to the reddish patterns in the soils. In general, the hue was redder and the value and chroma increased with soil depth. This is perhaps due to an illuvial accumulation of sesquioxides (i.e., Fe oxides) into a subsoil layer, which is often responsible for the apparent reddish soil coloration. Dengiz, *et al.* [33] have reported similar results that soil colour variation could be linked to OM, waterlogging, and redox reactions in the soil. The reddish and brownish colouration indicated that slope soils became well-drained with sufficient aeration and less saturated even with frequent rainfall.

Soils located in the summit landscape position were thicker than those in the upper/backslope position, and became thicker in the middle and lower landscape positions. The soil in the middle backslope position was the shallowest, probably because of more lateral surface water flow from the upper landscape and hence greater surface runoff, and because of erosion of topsoil. Such erosion was evident from the outcrops of rocks in all the soil surfaces of the study area. However, soil deposition at the lower landscape positions can be attributed to the increase in the thickness of the A horizon down the slope, supporting earlier findings [34].

The results (Table 2) showed that the sand fraction is significantly higher at the top landscape position, most likely as a result of remnant sand accumulation in the upper landscape locations and rapid erosion that removes fine particles (clay and silt) selectively. These data are in line with those of [35], who found that the mean value of sand beneath soils in higher landscape positions was high. Soils at three altitudinal positions showed a discernible increase in clay content with depth indicating vertical migration of clay down the profiles and/or high rates of clay formation in subsoil horizons. Change in clay percentages down the profile suggests pedogenic eluviation– illuviation processes[34]. It has been documented that illuviation causes a higher clay content in the B horizon of soils, whereas the surface horizon destroys clay and pedogenetic synthesis of clay occurs primarily in situ [36-38]. Besides, the in situ synthesis of secondary clay and the weathering of primary minerals in the B-horizon could have also contributed to the accumulation of clay in the subsoil horizons[31]. As a result of clay migration, the silt: clay ratio decreased with increasing depth within the profiles and from the upper to middle slope positions along the toposequence.

The low silt-to-clay ratios along the toposequence also implicate the existence of sheet erosion in topsoil horizons. The variation of bulk density among the landscape positions could be associated with tillage practice and the level of organic matter and clay content. The bulk density of soil at the summit was < 0.9gmcm-3 (except in the upper, middle, and lower landscape positions), indicative of andic soil properties[39]. The good soil structure and high organic carbon content resulted in low bulk densities and high porosity. High OM in soil makes it loose and porous, thereby reducing its bulk density[40]. In general, the values of bulk density were found to increase with the depth of soil profiles and along slope gradients in all topographic positions. This could be explained by a decrease in organic matter accumulation with depth, decreased root penetration, and compaction produced by the weight of the overlying layers[41].

All pedons showed weakly developed granular structures in the upper horizon, which graded to subangular blocky to angular blocky structure in subsoils. One possible explanation for the existence of OM in the topsoil is the development of granular soil. Pressure faces on the soil matrix due to micro-swelling, the low level of OM, reduction in the abundance of plant roots, and higher clay in subsoil may be mentioned for the formation of blocky structures. The very friable and friable consistency observed in the topsoil soils of the pedons could be attributed to the higher OM content. In consent with this finding, the contribution of OM in modifying soil consistency was pointed out by [34]. The change in consistency characteristics from topsoil to subsoil horizons reflects the high contents of clay and low contents of organic matter of subsoil horizons.

The soil pH value increased with soil depth owing to the relatively higher contents of basic cations in the subsoil than in the topsoil layers (Table 2). In addition, higher pH was recorded on gentle slope (lower altitude) position as compared to steep slopes, which could be attributed to the relatively high erosion and leaching of exchangeable bases from steep slopes. A comparatively higher pH of the soil may have resulted from the buildup of exchangeable bases on mild to moderate slopes. This result is in line with the findings of other researchers (e.g.,[42,43]), who suggested that excessive rainfall and the vertical leaching of basic cations along soil depth and movement along topo sequence could be the cause of the low pH in the majority of the examined profiles.

Table 2 shows that the mean SOC values of all currently studied soils are higher in the topsoils than in the subsoils, owing to the darker soil colour in the topsoil layers and becoming lighter in the subsoils. The difference in SOC among the landscape positions could be associated with the level of organic matter deposit and microclimate of the area. A similar study was also carried out in the southern region, where the topsoil horizons were darker than the subsurface horizons, which could be attributed to organic material accumulation and decomposition[34].

The results show that the summit slope has higher SOC concentrations because it is uncultivated, covered in Festuca (Guassa) grassland, and has experienced fewer human interventions. Organic C content increased from the lower slope to the summit. The overall tendency of organic matter is that the summit has a greater mean value than the upper slope and lower back slope. When compared to other landscape places, the summit had a high total nitrogen concentration, which might be related to the pace of organic matter mineralization and erosion (runoff) on the surface horizon. The content of exchangeable cations increased with increasing soil depth, which could be attributed to their leaching from the topsoil horizon down to the subsoil horizon.

The value of Av. P across the landscape positions was low when compared with the ratings (< 5 mgkg-1) of [44]. Previous studies [45] showed that the available P of the soils decreased down the profiles due to the increase in clay content in the lower horizons that fix phosphorous. Phosphorus fixation tends to be more pronounced and ease of phosphorus release tends to be low in those soils with higher clay content[41]. The relatively higher available P values in topsoil horizons as compared to subsoil horizons could also be attributed to the difference in organic matter contents and application of phosphorous-containing fertilizer on cultivated lands.

The Soil Atlas of Africa[46] reported that the average SOC stock for the continent at 0–30 cm depth is 35.08 t C ha−1. On the other hand, the SOC stock of the upper 30 cm soil in tropical montane was estimated to be 80 t C ha−1 [47] and the soil organic carbon stock at Abune Yosef mountain was reported to be 79.57 t C/ha [48]. The present study exhibited 83.95 ± 15.72 to 103.07 ± 30.04 t C ha-1 SOCS from lower altitude to higher altitude. Comparatively, the present study showed higher SOCS than reported by the Soil Atlas of Africa. On the other hand, it shows similarity to the IPCC default estimate and studies results at Abune Yosef Mountain for similar regions. Factor analysis grouped 17 measured soil characteristics into four factors for the topsoil (0–25 cm), subsoil (25-50 cm) and deep subsoil (50-100cm).

The four retained FAs were subjected to varimax rotation to exploit the relationship between interdependent variables by distributing each FA's variance. Elevation, climate, parent material, and land use land-cover changes were identified as the most dominant factors influencing soil physicochemical characteristics. SOC was the most dominant measured soil characteristic for both soil depths, and it can be tracked over time to determine whether soil quality is improving, degrading, or stable. This analysis also considered sand, clay, silt-to-clay ratio, BD, TP, pH, Ca, Mg, Na, CEC, BS, SOC, TN, and available P and SOCS at both depths.

6. Conclusions

Soil development along the examined transect is almost entirely regulated by topography (elevation), parent material, and climate. Mount Guna soils varied in their distribution and site traits, which were influenced by topographic features, climate, and lithology (Geology). The study's findings showed that changes in altitude had a significant impact on certain soil physicochemical properties.

The value of bulk density declined as altitudinal variation increased. Topographic differences influenced soil chemical properties such as pH, OC, total N, available P, exchangeable base cations (especially Ca and Mg), and BS. The majority of topsoils are slightly acidic, and acidity levels decline with soil depth and altitude. The surface soils have high organic matter. All decrease with depth. The distribution of SOC and total N varied across the studied profiles in reaction to differences in altitudinal variability. Festuca grass covers the uppermost high-altitude summit position and has a greater amount of organic carbon and total nitrogen than other cultivated land located at upper, middle, and lower slope positions.

Soil samples for clay mineralogy determination were collected and measured using XDR methods at higher altitudes of the summit slope location. Clay fractions comprise primarily trioctahedral chlorite, trioctahedral mica (phlogopite or biotite), vermiculite, kaolinite, some quartz, some amorphous silicates (probably volcanic glass), and minor feldspar, according to the results. Weatherable minerals (trioctahedral chlorite and trioctahedral mica) suggest that these soils have not been extensively weathered and are thus not very old (a more recent stage of development).

Although soil-forming processes handle all spatial patterns of soil distribution and development, our knowledge of the determinants, particularly topographic effect, needs to be expanded. In general, the association that has been discovered between topographic features and soil attributes will aid in our comprehension of the interactions between soil and landscape in the high-altitude volcano Mount Guna and other similar volcanic mountains. As a result, the studied area can be utilized as a model for soil formation in the high-altitudinal volcanic mountains of the East African Rift Valley, including the Ethiopian highlands, and it is appropriate for in-depth research on ecological gradients and ecosystem processes.

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