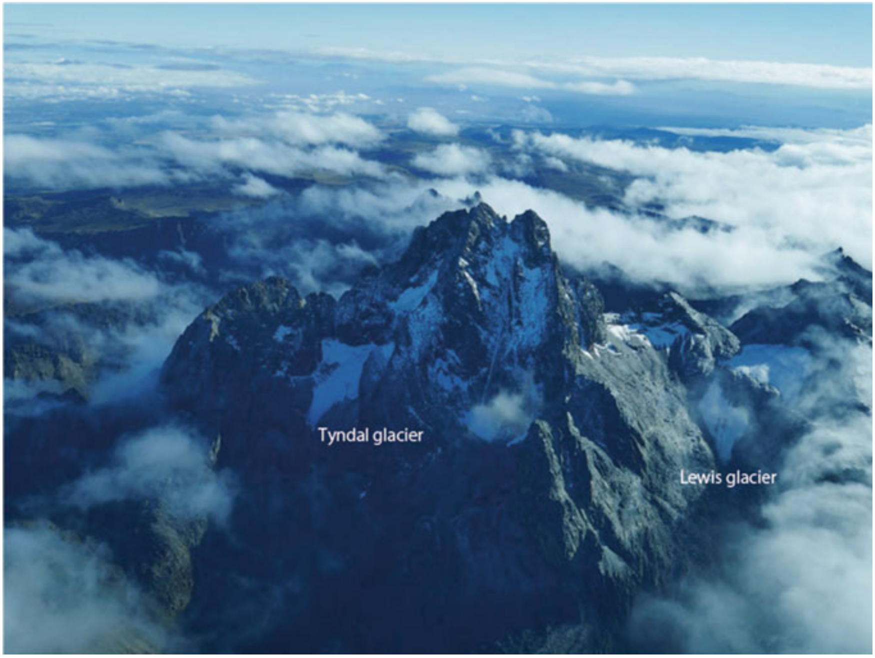
Geomorphology: Glacial Topography, Soil Development Processes in the Foreland of Tyndall Glacier on Mount Kenya

Kotaro Yamagata



The central peak area of Mount Kenya comprises volcanic plugs that have resisted glacial erosion. The slopes rise steeply on all sides with glaciers and rocky walls. This photograph was taken from the southwest direction with a view of the study areas (i.e., Tyndall and Lewis glaciers)

Abstract Glacier forelands allow us to trace back the processes of soil development by comparing the cross sections of soils that differ in time that has elapsed since the initiation of their respective development. This study discusses the relationship

---

K. Yamagata (✉)
Branch of Social Studies, Joetsu University of Education, Joetsu, Niigata 943-8512, Japan
e-mail: kotaro@juen.ac.jp

K. Mizuno and Y. Otani (eds.), *Glaciers, Nature, Water, and Local Community in Mount Kenya*, International Perspectives in Geography 17,
https://doi.org/10.1007/978-981-16-7853-0_5

between soil development process and environmental factors in the glacier forelands of Tyndall glacier on Mount Kenya. The following six moraines were classified in the foreland of Tyndall glacier: moraines of the Lewis stage (Lewis I and II), Tyndall stage (Tyndall I–IV), and Liki III. Subsequently, the age of each moraine was estimated. The soil formation process was examined based on the observations of the soil profile. It was found that the soil layers were composed of aeolian particles, which were supplied from the surrounding bare ground. The speed of soil development fell within the range of 0.03–5 mm/year. Particularly, we identified the trend that soil development speed was higher during the earlier stages of soil development. The development speed at an early soil development stage in Mount Kenya was higher than that in other regions, and it was confirmed that the long-term development speed fell within the range observed in other regions.

Keywords Soil development processes · Deglaciation · Glacial topography · Tropical high mountains · Mount Kenya

1 Introduction

Over the years, several studies have been conducted on understanding various soil development processes. However, in reality, it is not easy to continuously monitor soil development processes as they proceed very slowly. Nevertheless, there are certain landforms that allow us to trace back the soil development processes through comparison of the cross sections of diverse soil types that differ in terms of elapsed time since the start of their respective development. These lands are those whose surfaces have been previously reset a number of times; for example, those landforms that have been repeatedly destructed by volcanic eruptions or those where river erosion or sedimentation have occurred repeatedly.

Glacier forelands are such landform. The land surfaces, when covered with glaciers, get renewed by glacier erosion or sedimentation, and thereby they do not experience weathering or biological action. The development of soil starts after the glacier retreats, which frees the land surface. Therefore, it is possible to trace back the past soil development processes by comparing the cross sections of diverse soil types developed on land surfaces located in the glacier foreland because such soils differ in terms of years elapsed after the surface was freed from the glacier (Bernasconi et al. 2011; Smittenberg et al. 2012).

During the soil development process, the soil is subjected to various environmental factors, which include not only the time elapsed but also the climate, topography, geologic features, vegetation, abundance of water, and other factors of the land where the soil develops. In particular, soil changes with interactions with vegetation. In this way, soils become diversified based on the varying environmental factors that the different locations of land get subjected to. However, the relationship of these environmental factors with soil development processes and soil diversity is not yet completely understood (Theme 2019).

This study, which focuses on the forelands of Tyndall glacier in Mount Kenya, discusses the relationship between soil development processes and environmental factors in the glacier forelands during the warming periods of Holocene.

Glacier retreats induced by global warming are being commonly observed worldwide in recent times. Revealing the soil development processes in the grounds from which the glaciers have retreated is important in understanding how the region reacts to sudden environmental changes caused by global warming. Especially, the glaciers distributed on the equator have a higher rate of glacier reduction and are currently on their way to extinction (Iwata 2010). In addition, rare ecosystems exist all around the glaciers in the tropics. Therefore, evaluating the soil development processes in the glacial peripheries of the tropical regions is important for predicting the future environmental effects of glacier retreats induced by global warming.

2 Study Region

Mount Kenya has an elevation of 5199 m. It is located at approximately 150 km north-northeast of Nairobi, almost on the equator. It is the second-highest mountain in Africa and is located in the eastern margins of the East African Rift. In addition, Mount Kenya is a stratovolcano developed by volcanic activities that occurred 3–2.6 million years ago (Bhatt 1991; Fig. 1). The mountain is predominantly composed of basalt, phonolite, trachyte, and syenite.

At an elevation of 2250 m, the precipitation reaches 2500 mm; however, it decreases at points closer to the mountain peak and drops to 900 mm at elevations of 4500 m or higher (Hastenrath 1984). At an elevation of 4750 m, the temperature remains at 0 °C almost throughout the year (Hastenrath 1991). As far as vegetation is concerned, the tree line lies at approximately 3000 m. The Erica shrubbery belt lies at approximately 3600 m height. The alpine belt, which is predominated by Poaceae and alpine plants, lies at approximately 4500 m height, and the ice belt lies at 4500 m or higher (Mizuno 1994).

The mountain peak and its peripheries (shown in this Chapter's cover photograph) were subjected to intense ice erosion during the glacial period; they formed precipitous crags, and due to glacier extension, a U-shaped valley was developed from the peak to the mountainside, which is radially present up to elevations of approximately 3000 m (Fig. 2).

Mount Kenya had 18 confirmed glaciers around its peak in 1947 (Hastenrath 1984). However, the mountain has lost nine glaciers by 2020, and currently there are only nine remaining glaciers (Narama and Arie 2022). The largest one of these is Lewis glacier, and the second largest is Tyndall glacier. The changes in these glaciers during the late nineteenth century and thereafter are recorded in detail (Mizuno 1994).

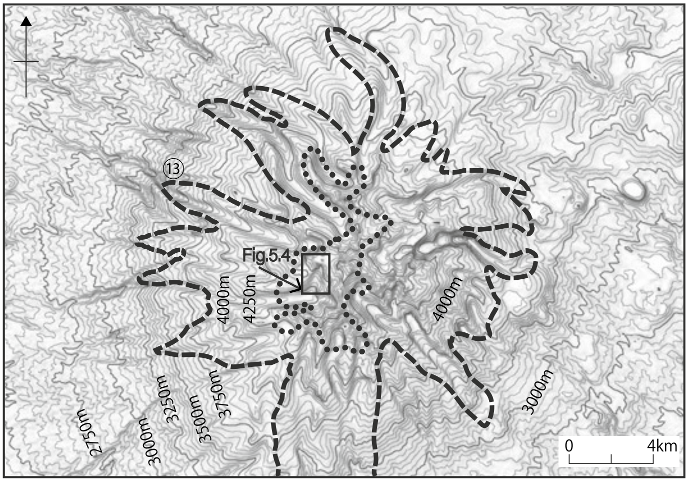


Fig. 1 Topographic map of Mount Kenya. Dashed line shows the extent of glacier expansion during the Last Glacial Maximum; Dotted line shows the extent of glacier expansion during Liki III stage (map has been modified after Mahaney et al. 1989)

Fig. 2 Naro Moru Valley, a typical U-shaped valley that was developed on the western slope. The photograph was acquired on 10th September, 2015

3 Chronology of the Foreland Topography of Tyndall Glacier

Mount Kenya has preserved the records of past glacier topographies, glacial deposits, and other traces from approximately its peak to elevations below 2900 m, which evinces that some glaciers extended in those regions (Shanahan and Zreda 2000). The moraine topography observed in Mount Kenya was classified into the following seven stages by Mahaney et al. (1989): Gorges, Lake Ellis, Naro Moru, Teleki, Liki (I–III), Tyndall, and Lewis, sorted from the oldest to the youngest. The ages of these moraines have been examined in different ways such as stratigraphic examination, paleomagnetism, radiocarbon dating, cosmogenic nuclide analysis, and lichenometry (Hastenrath 1984; Mahaney 1988; Mahaney et al. 1989; Shanahan and Zreda 2000).

Among these, analysis of cosmogenic nuclide by Shanahan and Zreda (2000) estimated that the Liki II moraine was developed during the Last Glacial Maximum (20 ka). Based on investigations on the distribution of Liki II moraine, it is believed that glaciers extended from the mountain peak to an approximate elevation of 3000 m in the Last Glacial Maximum (Fig. 1).

The age of Liki III moraine was evaluated to be approximately 12,500 years (Late Glacial Interstadial) based on radiocarbon dating of the organic materials contained in its deposits (Mahaney 1988). In addition, Shanahan and Zreda (2000) conducted a cosmogenic nuclide analysis and determined its age as approximately 10 ka. Therefore, it is considered that the age of the Liki III moraine corresponds to cold climate period of the Younger Dryas (12.8–11.5 ka) (Muscheler et al. 2008). It is believed that the glacier edges reached elevations of 4000–4200 m during this period (Fig. 1).

In the foreland of Tyndall glacier, the best moraine of Mount Kenya was developed during the Neoglaciation period, after the formation of Liki III. Baker (1967) studied Mount Kenya's glacier advancement during the Neoglaciation period, and inferred it as stage IV. Moreover, Mahaney (1984) studied stage IV moraines, and further classified this stage into advance eras of Tyndall and Lewis, which were chronologically ordered based on the physiographic positions of deposits, condition of weathering, and characteristics of cross sections of soils. Among these, the moraine in the advance era of Tyndall is found only in the foreland of Tyndall glacier.

The moraine in the Lewis stage was believed to have formed during the Little Ice Age because the degree of vegetation coverage and the lichen covering the gravels indicated it to be a new moraine that was formed later than that of the Tyndall stage (Mahaney et al. 1989; Fig. 3).

Mahaney et al. (1989) interpreted the moraines of the Tyndall and Lewis stages as individual extensions of each stage. This study further divided moraines based on aerial photointerpretation and field research. As a result, the moraines of the Lewis and Tyndall stages were further classified into two and four moraines, respectively (Fig. 4). Each of these moraines were named as Lewis I and II, and Tyndall I–IV, respectively.

In addition, another moraine that appears to block the Tyndall glacier valley can be identified at the outskirts of the Tyndall I moraine at the confluence of Tyndall

Fig. 3 View of Lewis and Tyndall-stage moraines. The degree of vegetation coverage of Lewis-stage moraine is poor, however Tyndall-stage moraines are densely covered by plants. The photograph was acquired on 9th September, 2015

glacier valley and Lewis valley (Fig. 4). This moraine was identified as the Liki III moraine as it borders the Liki III moraine, which extends to the Lewis glacier valley.

The age of the moraines of the Tyndall stage was estimated to be approximately 1,000 years based on radiocarbon dating of the organic materials contained in their deposits (Mahaney et al. 1989). However, it is uncertain which of the Tyndall moraines (i.e., I, II, III, or IV) were analyzed to obtain the age estimation. The former study was unable to obtain direct evidence of the developmental age of each moraine of the Tyndall stage. The vegetation condition and the thickness of the covering soil layers did not differ significantly between the Tyndall-stage moraines and the Liki III moraine developed during the Younger Dryas period. Therefore, it is highly possible that moraines older than 1,000 years were also included for the evaluation.

Karlen et al. (1999) examined the changes in the density of sediments and in carbon content among deposits found below the Hausberg Tarn lake, which is located adjacent to the north of Tyndall glacier astride the ridge. The study found horizons that implied six periods of cold weather during the Neoglaciation period: 5700, 4500–3900, 3500–3300, 3100–1900, 1300–1100, and 600–400 cal. years BP. It was suggested that the glacier was extended due to active transportation of materials along the slope during these periods. It is possible that these glacier extension periods correspond to Tyndall moraines I–IV. In this report, it is hypothesized that each of

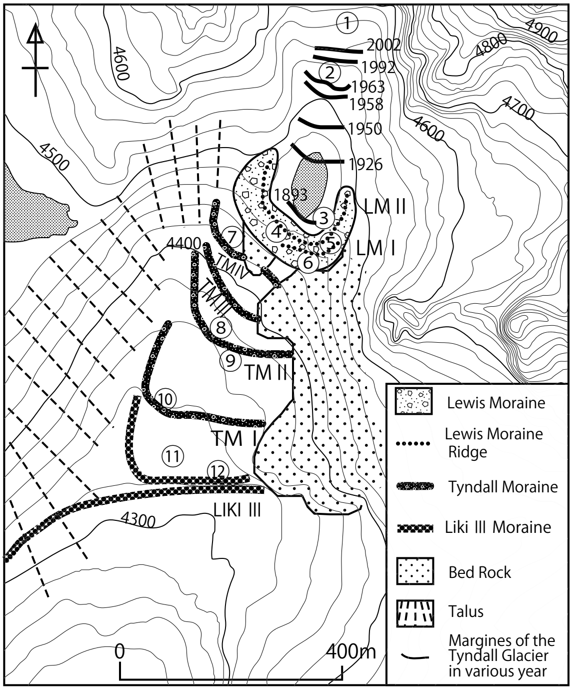


Fig. 4 Moraines and past glacier terminus position in the Tyndall glacier foreland

the Tyndall moraines I–IV correspond to the periods of cold weather, which are 5700, 4500–3900, 3500–3300, and 1300–1100 cal. years BP, respectively, because cooling indicators are commonly identified in East Africa from the sediments of these periods.

Mahaney et al. (1989) estimated the age of the moraine of the Lewis stage as Little Ice Age by lichenometry. In the present study, I re-examined this moraine by lichenometry because the moraine development has been divided into two stages in this report.

In the foreland of Tyndall glacier, no obvious moraine topography was identified on the upper stream side of the Lewis II moraine (Fig. 5). However, prior studies have identified the positions of glacier edge during several periods from 1983 to 2011 (Mizuno and Fujita 2013; Fig. 4).

The maximum diameter of *Rhizocarpon geographicum* at each location point with known ages was measured. If the diameter was significantly large, it was measured in parts using digital vernier caliper. More than 20 values were measured at one point. Figure 6 shows the relationship between the diameter measured at each location point and the age. Furthermore, a regression line was determined from these values. Onto this straight line, the diameter measured for the Lewis I and II moraines were projected to determine the age of each moraine. The study estimated that the Lewis I and Lewis II moraines were formed during 1830s and 1870s, respectively.

Fig. 5 Foreland of Tyndall glacier above Tyndall Turn. Tyndall glacier can be seen in the back. The photograph was acquired on 4th September, 2015

4 Circumstances of Soil Development on Glacier Topographies

In the foreland of the Tyndall Glacier, four rows of moraines from the Neoglaciation period (Tyndall I–IV) and two rows of moraines from the Little Ice Age (Lewis I, II) were identified, and the era of each moraine was estimated. Several observations have indicated that the present glacier terminus positions are newer than those in 1893. Based on annual data to evaluate the soil development process, the cross sections of soils observed on the topography of different eras were chronologically placed in this study.

For the moraines at the Tyndall and Lewis stages, the cross sections of soils were evaluated by creating a pit on a topography that lay between the moraine's ridge and depression. After 1919, no clear moraine topography was identified on the upper stream side of the moraines from the Lewis stage. Therefore, pits were created at arbitrary intervals between the present glacier terminus and the location of glacier terminus in 1893; subsequently the cross sections of soils were observed. The results are shown in Fig. 7.

At the time of this study in 2015, the intrusion of plants was identified up to a point located at approximately 17 m from the glacier edge. However, no soil layer

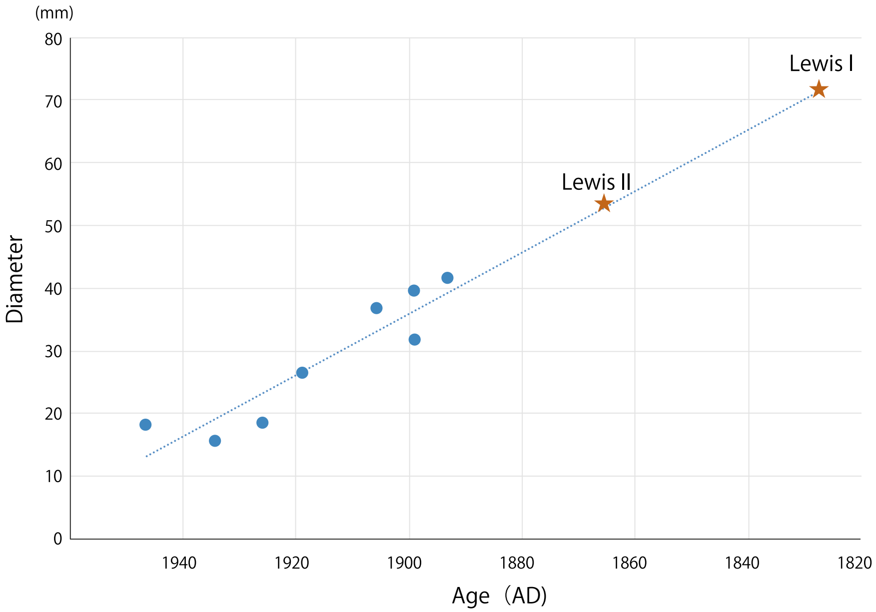


Fig. 6 Relationship between the diameters measured at each location point and the corresponding ages of the moraine. The diameter value was measured at the part where the diameter was the largest with a digital venire caliper. More than 20 values were measured at one point

was confirmed in that location. At the glacier edge position of 2011, where four years had passed since the land was freed from the glacier, the soil layer closest from the glacier terminus in 2015 (Fig. 7 column 1) was identified. While plants existed very sparsely at this location, these plants had a soil layer around their roots with a thickness of approximately 2 cm. This soil layer was sandy silt and pale brown in color. The fact that the tint was almost the same as that of the underneath glacial deposits indicates that the organic material content was very low. Near the glacier terminus of 1997, where 18 years had passed since the land was freed from the glacier, we found that the surface layer had A horizon of 6–8 cm thickness with a dark brown tint and was enriched in organic materials (Fig. 7 column 2 and Fig. 8 picture 2). Moreover, the glacier terminus position of 1893 showed a soil layer with a thickness of 10 cm (Fig. 7 column 3).

Among the moraines of the Lewis stage, which were developed during the Little Ice Age, A horizon of 10 cm was identified on the ridge of the Lewis II moraine, which was estimated by lichenometry developed in the 1870s (Fig. 7 column 4 and Fig. 8 picture 4). A horizon is a black, sandy silt layer, which is rich in organic materials and contains almost no gravel. Under A horizon, a non-sorted layer composed of sand gravel and rubble was identified. The upper 8 cm of this sand gravel layer had a gravel size of maximum 5 cm; it was brown in color and rich in matrices. On the other hand, the underneath section was dark gray in color, and contained gravels with diameter of 10 cm or more. The characteristics of this dark brown deposit indicate

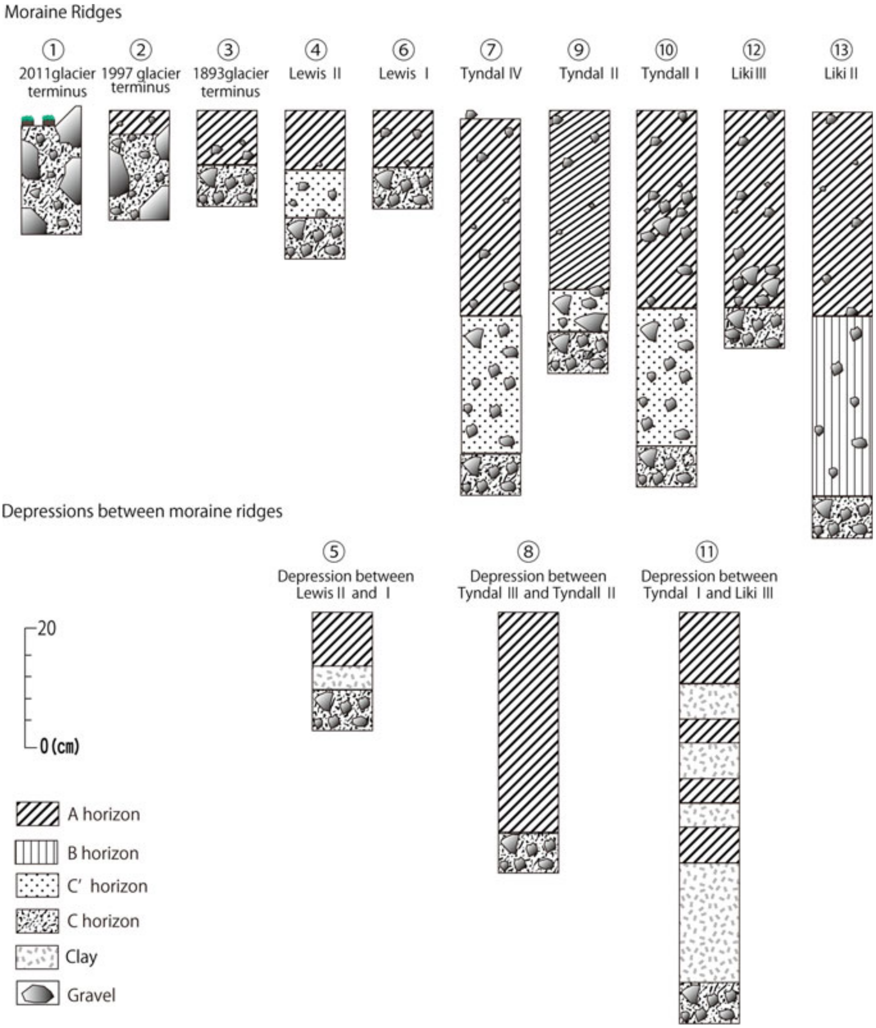


Fig. 7 Columnar sections of soil profiles in Tyndall glacier foreland. The locality of each column is shown in the Fig. 4

it to be glacial till deposit, and being un-weathered, this horizon retains the original characteristics of the glacial till deposit. Therefore, this layer was classified as C horizon.

On the other hand, despite of several similar characteristics, the upper brown layer was different from C horizon, especially in terms of tint, gravel size, and material composition. This brown layer also retained the characteristics of glacier till deposit. As this layer had characteristics different from those of the underlying C horizon, this layer was classified as C′ horizon.

② 1997 terminus position

④ Lewis II moraine

⑦ Tyndall IV moraine

⑩ Tyndall I Moraine

⑤ Depression between Lewis I and II moraine

⑧ Depression between Tyndall II and III moraine

⑫ Liki III moraine

⑬ Liki II moraine

Fig. 8 Pictures of soil profiles. The numbers are the same as in Fig. 7

An 9.5 cm organic matter enriched horizon was identified on the ridge of the Lewis I moraine, which was located immediately outside the Lewis II moraine, and was developed in the 1830s (Fig. 7 column 6). Under this, a thick, dark gray glacial till deposit was identified, and this location did not exhibit any deposit similar to C′ horizon.

There was a depression with a width of approximately 5 m between Lewis I moraine and Lewis II moraine. Although this depression had no running water during the time of this research, there were flat areas in certain places below the moraine. These flat areas were covered with fine-particle deposits, which were transported from the peripheries by running water during the melting of snow.

Pits created in these flat areas showed a surface layer deposit, which was rich in black organic materials and had a thickness of 12 cm (Fig. 7 column 5 and Fig. 8 picture 5). The deposit was composed of silt clay and had a negligible amount of gravel. Its underneath layer was made of dark brown silt clay followed by a gray-brown glacial deposit. We classified the surface layer rich in organic material as A horizon, and the layer underneath this, as C horizon. The soil at the bottom of the depression was rich in fine particles with a higher clay content compared to that of the moraine ridge's soil surface. This could be attributed to the difference in transport processes of the particles composing the soil surface.

On the ridges of the Tyndall-stage moraines (Tyndall I–IV) that were developed in the neoglacial period, the A horizon was found to be enriched in organic materials and was composed of sandy silt, similar to the outermost A horizons of the Lewis-stage moraines (Fig. 7 column 7, 9, 10 and Fig. 8 picture 7, 10). The thickness of A horizon was approximately 30 cm; the thickness of the layer increased with increasing development period of the moraines, i.e., with the age of the moraine. Sediments were present underneath A horizon; these originated in non-sorted glacial deposits and contained gravels. At every location, the uppermost layer of the glacial deposit displayed a dark brown matrix, which was poor in gravel, similar to the Lewis-stage moraines. This part was classified as C′ horizon, and the lowermost dark gray deposit showing the original characteristics of glacial deposit was referred to as C horizon. The thickness of C′ horizon ranged from 8 to 23 cm, and the trend of thicker deposits with increasing age of moraine was not necessarily evinced.

The depression between the moraines of the Tyndall stage had running water originating from melted glacier water. There was dense distribution of vegetation around the stream, and a thick soil layer was developed under this vegetation (Fig. 7 column 8 and Fig. 8 picture 8). The thickness of the layer ranged from 38 to 53 cm, and the trend in the increase of the layer's thickness with increasing age of topography was not necessarily observed.

The ridge of the Liki III moraine developed in the Younger Dryas period showed the development of 33 cm A horizon (Fig. 7 column 12 and Fig. 8 picture 12). Moreover, the Liki II moraine, developed approximately 20 ka ago during the Last Glacial Period, had a soil layer with a thickness of 65 cm. This layer had almost no gravel and covered weathered glacial deposits containing large amounts of sub-angular to sub-rounded gravels (Fig. 7 column 13 and Fig. 8 picture 13). The black layer rich in organic materials at the 35 cm depth from the surface layer was classified as A horizon, and the underneath brown part with rich clay content was classified as B horizon.

5 Soil Development Process in the Foreland of Tyndall Glacier

The soil layer developed on the glacial topography in the foreland of Tyndall glacier was classified into A–C horizons based on their respective facies. A horizon, which is a black surface layer composed of deposits of fine particles, is rich in organic materials and contains almost no gravel. Under this layer, C horizon occurs, which is a glacial till deposit with gray-brown to dark gray tints, and is composed of clay-rich matrix with copious amounts of angular to sub-rounded gravels. On the ridges of moraines that are older than those of the Lewis stage, the uppermost part of C horizon ubiquitously exhibits an area with brown to dark brown tint and negligible gravel content. This layer retains the characteristics of glacial till deposits, and is no different from C horizon with respect to the degree of weathering. However, it was classified as C′ horizon because of its distinct tint and particle size compared to that of the C horizon. As mentioned earlier, the thickness of C′ horizon does not necessarily increase with the age of the topography.

Yamagata (2016) studied the soils in the foreland of Charquini western glacier, Bolivian Andes. Based on observations, the author classified C′ horizon as the layer that has characteristics similar to the C′ horizon of the area analyzed in the present study, which is the uppermost part of C horizon. It was presumed that during the development process of C′ horizon, the surficial A horizon was mixed with the underneath glacial till deposits (C horizon) via periglacial processes. The C′ horizon of the area examined in this study can be also be considered as a product of a similar process.

No evident traces of the currently active periglacial process on the land surface of the foreland of Tyndall glacier were observed within the study area, as shown in Fig. 4. On the other hand, traces of frost pillar formation in areas of with vegetation were identifiable. It is likely that the freezing-and-thawing process might be currently restricted to an extremely shallow region near the land surface. It is believed that during the Little Ice Age and the Neoglaciation period, thawing action had effects till depths equivalent to approximately the thickness of C′ horizon under colder climatic conditions.

A horizon, which dominantly contains silt particles, had a clearly different particle composition compared to the underneath glacial till deposits (C horizon). Therefore, it is believed to have developed by a process different from that of the glacial deposits. In addition, there is almost no trace of weathering in the underneath glacial deposits, except in the Liki II stage. Furthermore, it can be observed that the A horizon was developed only four years after the land was freed from the glacier. Therefore, there is no evidence that it was developed due to weathering.

Yamagata (2016), who observed the soils in the foreland of the Charquini western glacier, Bolivian Andes, found that A horizon was composed of sand-silt sized particles, and the particles were relatively well sorted. Therefore, the layer was supposed to be composed of aeolian particles, which were supplied from the surrounding bare ground. The A horizon of the area examined in this study, which is relatively well sorted and composed of sandy silt sized particles, is also believed to be aeolian deposits. The aeolian particles, which were supplied from the bare ground around the glacier terminus or around the mountain peak were probably trapped into vegetation, and subsequently deposited to form the layer.

On the other hand, the soil layers deposited on the depressions between moraines were higher in clay content compared to those in the A horizon on the ridge. In part, stratifications were also observed. It is possible that the particles transported to the depressions by running water or through periglacial processes were relocated and

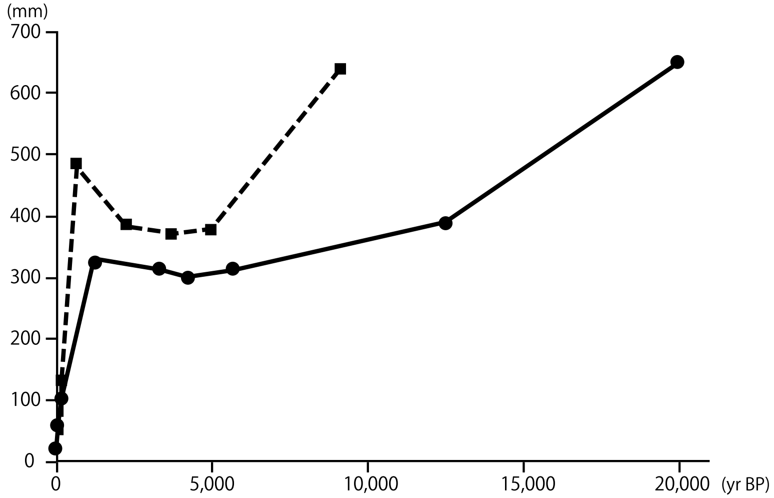


Fig. 9 Relationship between layer thicknesses of the soils and the estimated ages of topographies at the location points where the soil cross sections were observed

redeposited from the moraine or surrounding slopes by the running water. The difference in tint between layers A and B is supposed to reflect the sedimentation speed and the conditions of the surrounding vegetation, which grew when sedimentation was proceeding.

Figure 9 plots the observed thicknesses of the soil layer with respect to the estimated ages of topographies at locations where the soil cross sections were studied. The inclination in the graph represents the speed of soil development. Table 1 shows the calculated speed of soil development in each topographic unit. The soil thicknesses, which are individually classified as layers A and B, represent the sum of the thicknesses of all the layers. The graphs in Fig. 9 from left to right show the trend of thickening soil coverage of the glacial till deposit (C horizon) with increasing time that elapsed after the land was freed from the glacier.

The soil layers on moraine ridges of the Tyndall stage, which are approximately 300 mm in thickness at most of the moraines, did not show any significant differences. Some younger soil layers grew thicker than the older layers. The ages of the Tyndall I–IV moraines were hypothesized to be 5.7, 4.2, 3.4, and 1.2 ka, respectively (Fig. 9), based on the study of Karlen et al. (1999). However, it is likely that the moraines were developed in a shorter time span because there was almost no difference between the thicknesses of the individual soil layers.

The relationship between the ages of the depression between moraines and the thicknesses of soil layer also demonstrated the trend that the layer thickness increases with increased time elapsed after glacial retreat (Fig. 9). Compared to the soil on the ridges, the rate of soil development was found to be faster in the depression. This could be attributable to the differences in particle transportation through aeolian and aqueous process.

Table 1 Age, thickness of soil layer, and the rate of soil development in each topographic unit

Topography	Age (year)	Soil thickness (mm)	Soil development rate (mm/year)
Moraine ridges			
2011	4	20	5.00
1997	18	60	3.33
1893	122	90	0.74
Lewis-II	135	100	0.74
Lewis-I	150	95	0.63
Tyndall IV	1200	330	0.28
Tyndall III	3400	310	0.09
Tyndall II	4200	300	0.07
Tyndall I	5700	310	0.05
Liki-III	12,500	390	0.03
Liki-II	20,000	650	0.03
Depressions between moraines			
1893/Lewis II	129	40	0.31
Lewis II/I	143	130	0.91
Lewis I/Tyndal IV	675	480	0.71
Tyndal IV/III	2300	380	0.17
Tyndal III/II	3800	370	0.10
Tyndal II/I	4950	380	0.08
Tyndal I/Liki III	9100	640	0.07

The speed of soil development, which was determined from the thickness of soil layer on each topographic unit, varied widely from 0.03 to 5 mm/year. It was observed that soils developed relatively faster during the earlier phases of soil development, which could be attributed to the following factors: (a) effects of plant roots, (b) degraded material supply due to vegetation development, and (c) effects of erosion. The outermost soil layers were largely occupied by plant roots, and therefore, the layer thickness possibly appeared larger than the amount of the constituent particles of the soil present. In the foreland of Tyndall glacier, as more time passed since the land was freed from the glacier, the density of vegetation covering the land surface became larger. Therefore, the glacial peripheries during their infancy, after being freed from the glacier, had poor vegetation, while the aeolian particles were actively produced. In contrast, it is believed that the supply of aeolian particles from the surrounding land surfaces was reduced as the density of vegetation increased with time. Similar trend could also be identified in the aqueous deposits present in the depression.

The numerical values expressing the soil development rate in Mount Kenya obtained in this study were compared with those of other glacier forelands across the world (Table 2). The soil thicknesses on moraine ridges were compared in this table,

Table 2 Comparison of soil development rates on different moraines worldwide

Region	Age (year)	Soil development rate (mm/year)	References
Mt. Kenya	4–20,000	0.03–5.0	This study
Bolivian Andes	33–8,600	0.02–0.47	Yamagata (2016)
Swiss Alps	150–10,000	0.1–0.13	Egli et al. (2001)
southern Norway	50–250	0.05–0.11	Mellor (1987)
Sichuan, China	39–183	0.16–0.5	He and Tang (2008)
Alaska, USA	10–250	0.1–0.3	Ugolini (1968)
Kamchatka, Russia	60–2,500	0.01–0.05	Yamagata et al. (1999)

which reveals that the maximum soil development rate of 5 mm/year was obtained in the initial stages of soil development in Mount Kenya, and it was significantly greater than those observed in other regions. This is probably because this research was conducted during the initial phases of soil development process, and not long after the land was freed from the glacier. As mentioned earlier, it is believed that the layer thickness appeared larger because the soil was occupied by a large proportion of plant roots when the soil layer was still thin in its initial development stage.

However, the soil development speed of 0.6–0.7 mm/year obtained for the Lewis-stage moraines, which are believed to have developed during the Little Ice Age, was also higher than that obtained under the same criteria in other regions. This might be because the aeolian particles were actively produced due to the sparse vegetation and rough terrain near the peak of Mount Kenya, or due to the lower ratio of relocation, or erosion by wind or periglacial processes.

On the other hand, the rate of long-term soil development was obtained to be 0.03–0.1 mm/year. The speed of moraine development during the Neoglaciation period (Tyndall stage) to the Last Glacial Maximum (Liki II stage) falls within the range of the values obtained for other regions.

The soil development process in the foreland of Tyndall glacier on Mount Kenya reveals the important role of vegetation in soil development. Developed vegetation traps soil particles, and sedimentation begins. Along with continued sedimentation of soil particles, soil layers grow rapidly due to the supply of organic materials from plants.

In addition, soil development also plays a key role for vegetation. Based on a research on the retreat process of Tyndall glacier and the surrounding vegetation, Mizuno (1994) explained that a key requirement for the location of vegetation are the ages of the deposits and the stability of the land surface. In areas with younger deposits (close to the glacier terminus), it is difficult for plants to intrude and stay rooted because of relatively immature soil. Therefore, vegetation coverage and diversity are usually low. On the other hand, in places with older deposits (far from the glacier terminus), soil development proceeds rapidly and the pioneer species improve soil conditions, which favors the growth of the upcoming plants. This contributes to an increase in vegetation coverage and diversity. In this way, soil development and vegetation are believed to proceed while interacting with each other.

Due to these close relationships between soil and vegetation, soil plays a key role in the ecosystem of the region. Consequently, this serves as an important factor to monitor the changes in vegetation. As confirmed in this study, during the initial stages of soil development in the glacier foreland, the characteristics and thicknesses of soil layer show significant diversity in a small range depending on the time that elapsed after the land was freed from the glacier. The diversity also depends on the topographical conditions of the site where soil was developed, deposits composing the land surface, relocation of materials caused by frost creep, wind or running water, and vegetation conditions. This diversity connects to biodiversity. An increase in this diversity with the development of soil in glacier foreland leads to the generation of vegetation diversity in the region (Khaziev 2011).

The development of soil in the glacier foreland, which forms a thin cover of deposit onto the surfaces of rocks, plays a hydrologically important role. In a thicker soil layer, the layer itself can contain more water. This weakens the peak of water runoff and influences the upkeep of steady runoff, even during the dry season. These roles of soil will prove to be significant when glaciers will be lost in many high mountains in the future (Haeberli et al. 2007). Overall, soil plays a key role in the hydrology and ecology of glacial basins.

6 Summary

The relationship between soil development processes and environmental factors was studied by investigating soil layers that covered those land surfaces that were freed from the glacier during different eras from the foreland of Tyndall glacier on Mount Kenya.

First, the classification of the moraines developed in the foreland of Tyndall glacier was reviewed. As a result, six moraines of the Lewis stage (Lewis I and II) and the Tyndall stage (Tyndall I–IV) were classified. Subsequently, the age of each moraine was estimated using lichenometry and based on the ages of horizons that exhibited traces of cooling periods in deposits under the nearby lake. The estimation suggests that the moraines of the Lewis and Tyndall stages were developed during the Little Ice Age and the Neoglaciation period, respectively, and those of Liki III were formed during the Younger Dryas period.

In a location where four years had passed after the land was freed from the glacier, a soil layer with a thickness of 2 cm was identified in the position closest from the present glacier edge. On the moraine ridges of the Lewis stage, soil layers with thicknesses of 9.5–10 cm were identified, and on the moraines of the Tyndall stage, the layers had a thickness of 30 cm. The trend of increasing thickness of the soil layer with higher development age was evinced at the study location. A similar trend in the change of soil thickness was observed in depressions between the moraines. Relatively, the soil layers in the depression tended to be thicker than those on the ridges.

The soil layers identifiable on the ridges, which are sandy silt and are relatively well sorted, had distinctly different characteristics from the underneath glacial deposits. In addition, glacial deposits were fresh, and exhibited negligible trace of weathering. Therefore, it was evinced that the soil layers were not the weathered products of glacial deposits, and were deposited through a different mechanism. The characteristics of the deposits indicated that they were presumably aeolian dust deposits. On the other hand, the soils in the depression were believed to be fine-particle materials that were transported by running water, and subsequently deposited.

The rate of soil development was determined from the thicknesses of soil layers and the ages of land surfaces. The speed of soil development fell within the range of 0.03–5 mm/year. Particularly, we identified the trend that the speed of soil development was higher during earlier stages of soil development, the possible reasons of which might include the effects of plant roots, degraded material supply due to vegetation development, and the effects of erosion. Furthermore, the numerical value of soil development speed obtained in Mount Kenya was compared with that of the glacier forelands of other regions. While the development speed at an early soil development stage in Mount Kenya was higher than that of other regions, it was confirmed that the long-term development speed fell within the range obtained in other regions.

It was found that aeolian dusts were trapped and deposited by vegetation. On the other hand, the growth of soil seems to have played a key role in vegetation development. In this manner, soil growth and vegetation development proceeded while interacting with each other. Therefore, understanding the relationship between the two is important for evaluating the environmental changes around the glaciers, as well as their future implications.

References

Baker BH (1967) Geology of the Mount Kenya Area. Report No. 79. Geological Survey of Kenya, Nairobi, Kenya

Bernasconi SM, Bauder A, Bourdon B, Brunner I, Bünemann E, Chris I, Derungs N, Edwards P, Farinotti D, Frey B, Frossard E (2011) Chemical and biological gradients along the Damma glacier soil chronosequence Switzerland. Vadose Zone J 10(3):867–883

Bhatt N (1991) The geology of Mount Kenya. In: Allen I (ed) Guide to Mount Kenya and Kilimanjaro. The Mountain Club of Kenya, Nairobi, Kenya

Egli M, Fitze P, Mirabella A (2001) Weathering and evolution of soils formed on granitic, glacial deposits: results from chronosequences of Swiss alpine environments. CATENA 45(1):19–47

Haeberli W, Hoelzle M, Paul F, Zemp M (2007) Integrated monitoring of mountain glaciers as key indicators of global climate change: the European Alps. Ann Glaciol 46:150–160

Hastenrath S (1984) The glaciers of equatorial East Africa. Reidel, Dordrecht

Hastenrath S (1991) The climate of Mount Kenya and Kilimanjaro. In: Allen I (ed) Guide to Mount Kenya and Kilimanjaro. The Mountain Club of Kenya, Nairobi, Kenya

He L, Tang Y (2008) Soil development along primary succession sequences on moraines of Hailuogou Glacier, Gongga Mountain, Sichuan. China. Catena 72(2):259–269

Iwata S (2010) Shrinking glaciers on equatorial mountaintops. Rikkyo Univ Bull Stud Tour 12:73–92 (In Japanese with English summary)

Karlen W, Fastook JL, Holmgren K, Malmstrom M, Matthews JA, Odada E, Risberg J, Rosqvist G, Sandgren P, Shemesh A, Westerberg LO (1999) Glacier fluctuations on Mount Kenya since ~6000 Cal. Years BP: Implications for Holocene climatic change in Africa. Ambio 28(5):409–418

Khaziev FK (2011) Soil and biodiversity. Russ J Ecol 42(3):199–204

Mahaney WC (1984) Late glacial and post glacial chronology of Mount Kenya, East Africa. Palaeoecol Afr 16:327–341

Mahaney WC (1988) Holocene glaciations and paleoclimate of Mount Kenya and other East African mountains. Quat Sci Rev 7(2):211–225

Mahaney WC, Spence JR (1989) Lichenometry of Neoglacial moraines in Lewis and Tyndall cirques on Mount Kenya. Z Gletscherk Glazialgeol 25:175–186

Mahaney WC, Barendregt RW, Vortisch W (1989) Quaternary glaciations and palaeoclimate of Mount Kenya, East Africa. In: Oerlemans J (ed) Glacier fluctuations and climatic change, Springer, Dordrecht

Mellor A (1987) A pedogenic investigation of some soil chronosequences on neoglacial moraine ridges, southern Norway: examination of soil chemical data using principal components analysis. CATENA 14(5):369–381

Mizuno K (1994) Succession and environmental conditions of alpine vegetation in relation to glacial fluctuations of Tyndall Glacier of the Mt. Kenya. J Geogr 103:16–29 (In Japanese with English summary)

Mizuno K, Fujita T (2013) Vegetation succession on Mt. Kenya in relation to glacial fluctuation and global warming. J Veg Sci 25(2):559–570

Muscheler R, Kromer B, Björck S, Svensson A, Friedrich M, Kaiser KF, Southon J (2008) Tree rings and ice cores reveal 14C calibration uncertainties during the Younger Dryas. Nature Geosci 1(4):263–267

Narama C, Arie K (2022) Mass balance of very small glaciers on Mt. Kenya during 2016–2018. In this volume

Shanahan TM, Zreda M (2000) Chronology of quaternary glaciations in East Africa. Earth Planet Sci Lett 177(1–2):23–42

Smittenberg RH, Gierga M, Göransson H, Christl I, Farinotti D, Bernasconi SM (2012) Climate sensitive ecosystem carbon dynamics along the soil chronosequence of the Damma glacier forefield Switzerland. Glob Change Biol 18(6):1941–1955

Theme AJAM (2019) The uncalm development of proglacial soils in the European Alps Since 1850. In: Heckmann T, Morche, D (eds) Geomorphology of proglacial systems, topography and sediment dynamics in recently deglaciated alpine landscapes. Springer, Cham, Switzerland

Ugolini FC (1968) Soil development and alder invasion in a recently deglaciated area of Glacier Bay, Alaska. In: Trappe JM, Franklin JF, Tarrant RF, Hansen GM (eds) Biology of Alder, US Forest Service, Pacific NW forest and range experiment station, Portland, Oregon

Yamagata K, Sawaguchi S, Muravyev YD, Solomina ON (1999) Soil development in relation to vegetation and topography at the Koryto Glacier Basin, Kamchatka. Cryospheric Studies in Kamchatka II. Inst Low Temp Sci, Hokkaido Univ, Sapporo

Yamagata K (2016) Soil development process in glacial retreat area in Andes. In: Mizuno K (ed) Nature of Andes. Kokon Shoin, Tokyo (In Japanese)